The mold halves are usually built as a stacked series of plates, as opposed to a single block of material. The individual plates each serve a function and provide access for machining during the mold-building process. The removal of upper-level plates allows access to features at a lower stack level. Having individual plates also potentially allows a single plate to be swapped out if damaged. The design of plastic injection molds is itself a specialty, and the design of optical molds even more so. Most plastic optic injection molders have a mold designer on staff or work closely with a design house that is experienced in the design of optical molds. A poorly designed (or fabricated) mold can have a detrimental effect on a project. Two general rules of optical injection molds are: "parts can only be as good as the mold they come from" (although they certainly can be worse), and "you get what you pay for."

Most production tools are made out of stainless or hardened tool steel, or a combination of the two, which enables a longer tool life along with the ability to withstand the large forces that occur during injection molding. As a point of reference, during injection the mold may see cavity pressures of 700 kg/cm^2 (10,000 psi) or more. With inserted and moving parts of the mold, two different material grades are typically used to avoid galling. For lower volume or prototype tools, alternate softer materials (such as aluminum) are sometimes used.

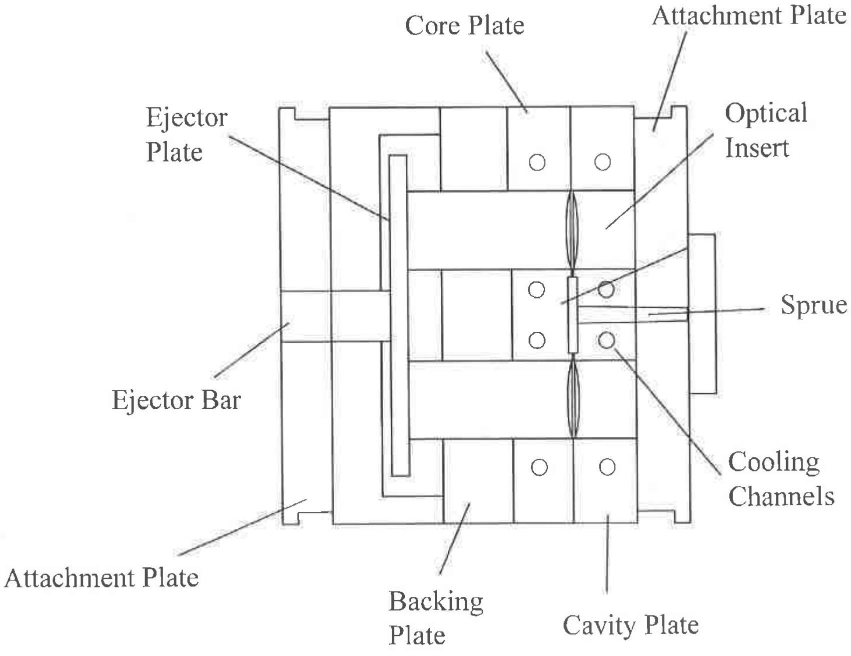

Figure 3.6 Schematic of an injection mold for producing lenses.

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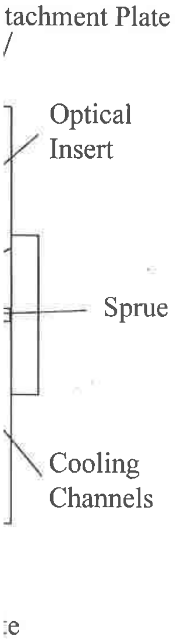

lenses.

Referring to Fig. 3.6, which shows a schematic of a lens mold, we discuss the roles of each of the tool's constituent plates. Beginning on the right-hand side, we first have an attachment plate, which supplies support to the mold and is used to attach it to the platen. Moving to the left, the next plate is the "cavity" plate. This plate houses the features that form one of the sides of the lens. Adjacent to the cavity plate is the "core" plate. This houses the features that form the other side of the lens. The mold splits between the core and cavity plates at the boundary referred to as the parting line. Behind the core plate is a backing plate, which provides support and structure to the mold. Behind this backing plate is the ejection mechanism, discussed later, followed by another attachment plate, which attaches to the moving platen. Thermal insulating plates are often mounted on the exterior of the attachment plates to help with the thermal management of the mold during the manufacturing process.

Alignment of the mold halves upon closure of the mold is usually achieved through sets of guide pins and taper interlocks. These features can be seen in the outer portion of each quadrant of the mold half seen in Fig. 3.7. The two sets act together as somewhat of a coarse/fine adjustment scheme. The larger guide pins engage while the mold halve faces are still apart, and as the mold faces come close to one another, the taper interlocks engage, bringing the mold halves to their final alignment.

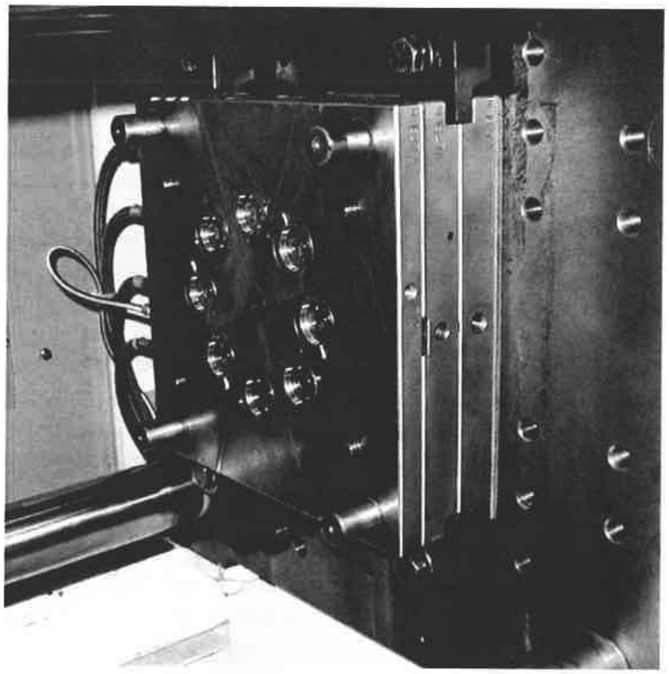

Figure 3.7 Eight-cavity mold half showing guide pins and taper interlocks. (Photograph courtesy of Alan Symmons.)

We can see a feature on the right-hand side of Fig. 3.6 that is labeled "sprue." The sprue is the point where the molten plastic enters the mold. Once into the mold, the plastic passes through a series of channels leading to the lens area. These channels are known as "runners" and can be clearly seen in Fig. 3.5. The runners lead to the "gate," which is the area where the plastic enters the mold cavities. As mentioned previously, the cavities are the empty spaces in the mold where the lenses are formed. In the particular case of Fig. 3.5, we would say it is a four-cavity mold because spaces for four lenses have been created.

The runner systems in molds come in two general categories: hot and cold. In a cold runner system, a groove is cut into the face of the mold plate, which fills with plastic upon injection. Both the part being molded and the plastic in the runner (as well as the gate and the sprue) cool and harden during the cooling time. When the parts are ejected from the mold, the runner is ejected as well, with the parts attached to it. At some later point in time the parts are removed from the runner in a process called "degating." The runner material is typically collected and ground up, becoming "regrind" as mentioned earlier. In most optical parts regrind is not used, so there is a material amount and cost beyond just the lens volume that must be factored in to the lens production. Cold runner systems typically have a semicircular or circular profile, known as "half round" or "full round" runners. This shape is used instead of a square profile to facilitate pulling the runner from the fixed half of the tool during the opening of the mold and ejection of the runner during the ejection motion. A square- or sharp-cornered profile is more likely to stick in the mold than a round profile during pulling or ejecting.

In a hot runner system, the runner is internal to the mold plates. The runner is kept at an elevated temperature (hence it is a hot runner) such that the plastic material in it remains molten. While the part cools and hardens during the cooling time, the runner does not. When the mold is opened, the parts pull with the moving platen, but there is no runner to be pulled. The parts alone can now be ejected from the moving half of the mold. Instead of grabbing the sprue or runner upon ejection, the parts themselves must now be captured, which is often done using suction cups.

Compared to a cold runner system, a hot runner system has the advantage that there is less material used, since a runner system is not produced with each part or set of parts. In addition, the parts are already separated from the runner, which removes the need for the degating process. However, compared to a hot runner system, a mold with a cold runner system is less complex, significantly less costly, and easier to maintain and operate. In some cases, the runner system in a cold runner mold is specifically designed to be used as a handling feature in later operations, such as coating, degating, and/or assembly. Finally, having a cold runner system allows for the mold "packing" described earlier, which can help produce superior-quality optical parts. As a result of these factors, most optical injection molds use cold runner systems. In some cases, a semihot runner, a hybrid between the two systems, is used. This allows a shorter cold runner,

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The gates, while seemingly a small part of the mold, are critical to its ultimate performance. The gate size and shape determine how the plastic will flow into the mold cavity, as well as impact the freeze-off time and packing. Poor flow can result in lens defects. To get the desired flow pattern, gates for optical parts are typically much larger than for equivalent nonoptical parts. This is because the tolerances for optical surfaces are usually much tighter than surfaces on nonoptical parts. The size of the gate required must be kept in mind during the optical design, as it sets a minimum required edge thickness.

It is common for molds to possess a number of cavities that are a power of two, that is, one, two, four, eight, 16, or even 32. This is not a necessity, but it works well for having a symmetric Cartesian layout of the cavities within the tool. The reason that a symmetric layout is desired is to have each of the cavities the same distance from the sprue, where the plastic enters the mold. This creates, theoretically, a situation where each cavity will receive the molten plastic at the same time, under identical temperature and pressure conditions. The design and machining to achieve this state is called "balancing the tool." Since we generally want all the lenses produced at a given time (in a single shot), and over time as well, to be (nearly) identical, it makes sense that we would want each cavity to have identical conditions.

Another method to achieve equal flow lengths is to use a radial (or spoke) runner system. In this case, it is easy to achieve the equal-length runners because the parts lie on a circle with the sprue at the center. The number of cavities do not need to be a power of two but can be set at the desired angular spacing. This form of runner system can be useful later in the production process. The runner system, with lenses attached, can be placed onto a rotary table for easy manual or automated handling of the lenses. Intermediate structures or indexing features can also be added to the runner system to help with automation.

Having discussed how the plastic gets to the lens cavities, we now consider the cavities themselves. The cavities are the spaces generally (but not necessarily exactly) complementary to the shape of the lens. They typically have a region to form the mechanical structure of the lens, such as flanging, and another region that forms the optical surface. There are three general methods of creating cavities. The first, and simplest, is to directly machine the cavity shape into the cavity plate. This reduces the complexity of the mold and requires no additional pieces to be fabricated. As mentioned previously, most production tools are made from hardened materials, which can make it difficult to achieve an optical quality surface. The material can be polished; however, this can be time consuming and difficult, particularly if the optic surface is significantly recessed from the face of the mold. Another downside to this method is that it does not allow for the cavity to be easily replaced if it is damaged. Because of these two reasons, this method is more likely to be used in a tool for prototype or low-volume production when a softer mold material and reduced mold lifetime are acceptable.

The second method is to insert the areas that form the optical surfaces, while putting the mechanical features of the lens directly into the mold plate. The optical surface is typically formed by the "optic pin" or "optic insert," which is a pin or rod that is inserted into a hole cut into the mold plate. The optic pin is fabricated separately from the mold plate, typically from a different material or material grade. The optic pin may consist of a solid steel pin with an optical surface polished onto the end. In the case of production tools, this method requires the polishing of hardened steel pins. Polaroid extensively used this particular method of fabricating optic pins during the production of plastic lenses for their cameras.

Alternately, and more commonly, the optic pin starts as a steel rod into which a sphere or an approximate or identical displaced surface to the final optic surface is first machined. A layer of nickel is then coated onto the end of the pin, and the desired optical surface is diamond turned into the nickel. Compared to polishing hardened steel, the advantages of the nickel-plating method are reduced cost and schedule, as well as removing the need for highly trained opticians or other personnel to polish the inserts. If the nickel is sufficiently thick, it allows for recutting of the optic surface, which may be required if the mold process changes or if there is damage to the optic pin. The downside of the nickel plating method is that diamond-turnable nickel is much softer than hardened steel. It is more susceptible to scratching and other damage that can occur during molding, mold maintenance and cleaning, or when swapping inserts (if the same mold cavity is used to form different lenses). Because of this, it is common to have additional optic pins on hand as spares. Based on the thickness of the nickel, there are a limited number of recuts that can occur before the diamond-turning tool breaks through the nickel to the steel, usually resulting in damage to the diamond tool. It may be possible to machine or strip the nickel, replate the optic pin, and cut a new optical surface. This can sometimes be required if the underlying approximate surface machined in the steel was not accurate enough, or if there is extensive pin damage.

The availability of modern diamond-turning equipment has made the manufacture of optic pins by nickel plating and diamond turning a fairly routine process, and has in many cases eliminated the need for polished steel pins. In the case of low-volume or prototype tools, the steel- and nickel-plating process may be eliminated, with the optic pin made directly from a diamond-turnable material, such as copper-nickel or aluminum. This will again result in a softer optical pin, which is more prone to damage, but repeating the diamond-turning process fairly easily repairs the optic surface of this type of pin.

When using inserted optic pins, shims are typically used to adjust their axial position. The axial position of the optic pins will set both the center thickness of the optical element and the distance from the optic surface to a reference feature on the element, such as a flange. This flange offset distance is referred to as the "stack." The standard method of shimming is to use thick metal shims, which start at a thickness greater than or equal to that needed to set the appropriate pin

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The third method of creating the cavities is to insert the cavity itself into the mold plate. In this method, a hole is cut into the mold plate and a separate cavity insert is machined. When inserting the cavities, it is common to insert the optic pins as well. A hole is machined in the mold plate to take the cavity piece, and a hole is machined in the cavity piece to take the optic pin. In this case, the piece containing the cavity and the hole for the optic pin is often called a "receiver," "receiver set," or "cavity set" when referring to the cavity inserts for both sides of the mold. A photo of such a cavity set is shown in Fig. 3.8, where the two sides of the cavity set are apart.

This method of creating the cavities has several advantages. With inserted cavity sets, each cavity can be machined as a separate piece from the mold plate. This allows the production of spare cavities, which can be swapped out in the case of damage to one of the cavities being used in the mold. Individual cavities can also be removed from the mold, to be reworked or repaired, without having to remove the mold from the molding machine. In a higher cavitation mold, one

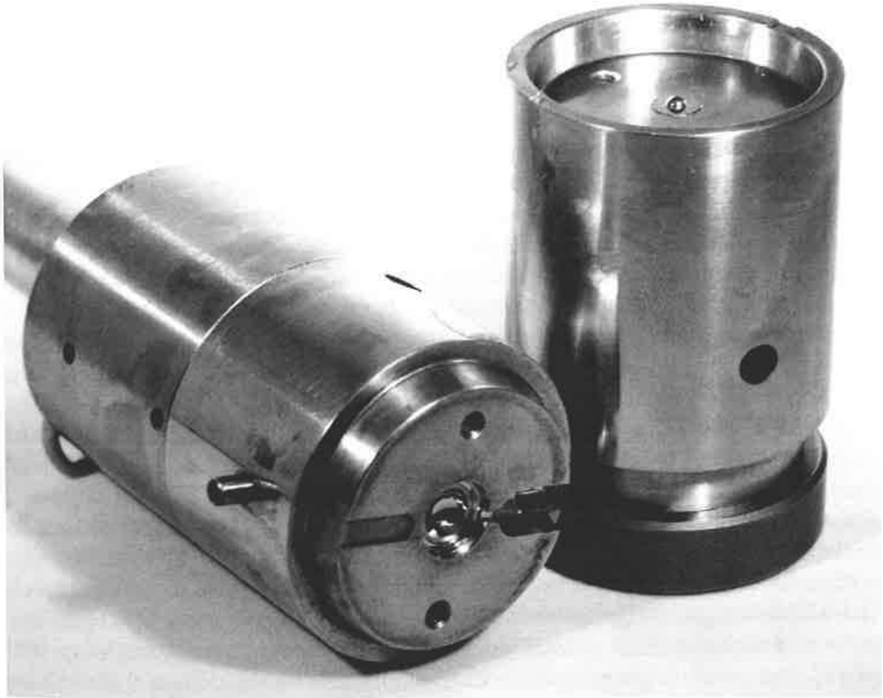

Figure 3.8 Inserted cavity set for injection mold. Note the tapers on the two halves, which interlock the cavity set. (Photograph courtesy of Alan Symmons.)

or a few cavities can be machined and tested before a commitment is made to machine all the cavities. In this way, a single mold can be built, with the capability to increase the molding capacity as product demand increases. The holes where the other cavity sets would go are typically plugged with a receiver that has not had the cavity features machined, or by using shut offs in the runner system. In addition to swapping out cavities that form a single lens, it is possible, with reasonably similar lens sizes, to swap all the cavity sets out and replace them with the cavity sets of another lens. In this way, the mold base becomes common, and multiple lenses can be made from it.

The mold can also be configured with a combination of cavities for multiple lenses. As an example, an eight-cavity mold may have four cavity sets of one lens form, and four cavity sets of a different lens form. This situation, where one mold is configured to make multiple part forms, is known as a "family mold." A family mold does not require inserted cavities but can be made by any of the three cavity creation methods. Even though the family mold could theoretically make two types of lenses at the same time (of the same material), this is not commonly done. The reason is that the mold process parameters are likely to be different for the two lenses, even if the lenses are somewhat similar to one another. We mentioned earlier the concept of having a balanced mold. Having two different lens form cavities in the mold at the same time is unlikely to result in a balanced mold. If the mold is processed for the first lens, the other lens will likely not meet its quality requirements, and vice versa. Balancing the process between the two lenses often results in both lenses being of inferior quality. As a result, a family mold is typically run by shutting off the second set of lenses, molding the first set, then shutting off the first set and molding the second set of lenses.

The downside to cavity-inserted molds is the potentially higher cost associated with the additional pieces and machining. In the case of a common mold base used with multiple lens form cavity sets, there is the risk of stopping production on multiple lens elements if the mold base is damaged and down for repair. However, the flexibility that the inserted cavity sets allow, particularly in high-rate production, often outweighs the initial additional cost and risk of this mold form.

In addition to the insertion of the optic pins and cavities, the gates of the mold can also be inserted. Inserting the gates allows them to be adjusted without having to machine the mold plate directly. This allows for different sizes and shapes of gates to be evaluated, without the risk of opening up the gate too much. In the case of a mold with a large number of cavities, inserting the gate may help with balancing the tool by allowing the individual cavity gates to be adjusted. It also allows the gate to be replaced in the event of damage.

Since the mold is not normally operated under vacuum conditions, when first closed, the runners, gates, and cavities are filled with air. When the injection cycle begins, plastic flows through the runners, the gates, and into the cavities. The air in the runners, gates, and cavities, if not allowed to escape, will end up being trapped in the mold. In order to allow the air to escape, "vents" are often

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incorporated. Venting usually takes place in one or both of two ways. The first method is to cut a series of shallow grooves into the face of the mold. This type of vent can be seen in Fig. 3.5 as the diagonal grooves coming from the cavities, as well as the grooves coming from the runners. A vent is also visible (the horizontal groove) on the left-hand side of the cavity set shown in Fig. 3.8. The deeper groove on the right-hand side of the receiver is the end of the runner and the gate.

The second method of venting is to have the air go around and down the pin that forms the optical surface. If there is improper venting, the air in the mold will be trapped and will end up being compressed by the injected plastic. This can result in "burning" due to the rapid compression, which leads to a scorched optic pin surface or the part. In some cases, a poor venting condition will appear as a small spherical imprint in the part due to the bubble of highly compressed trapped air. Improper venting can occur due to poor vent design, or due to the vents gradually clogging as the tool is used. Injection molds are regularly taken out of service for a short period of time to receive cleaning and maintenance in order to prevent this and other potential failures.

Another feature of the mold is a system of heating and cooling channels. These channels run through the mold plates, typically near the cavities. Occasionally, channels are also run up the center of the optic pin, where they are referred to as "bubblers." In the channels, water or oil is circulated through the mold. For optical parts oil is more common, as the higher mold temperatures associated with them can turn the water to steam. In addition, depending on the material used to construct the mold, using oil instead of water will prevent corrosion. The channels are connected to hoses, which are in turn connected to a thermal conditioning device known as a thermolater. The thermolater maintains the proper oil or water temperature. As mentioned earlier, once the molten plastic is injected, heat transfer determines how long the mold must remain closed. The fluid moving through the channels will be at a lower temperature than the plastic, so it will draw heat from the molded part. Since the oil or water is also hotter than room temperature, it will also heat the mold base. Depending upon the mold and molding application, electrical heating elements may also be added to the mold, or separate heating and cooling channels may be used. These additional mold complexities would typically be used for more difficult parts, such as those containing high-aspect-ratio microstructures.

Having discussed several features of the mold and how the molten plastic arrives to form the part, we now discuss how the (cooled) parts are removed (or ejected) from the mold. As mentioned earlier, when the part is sufficiently hardened, the mold is opened and the parts are "pulled" with the moving half of the mold. The need to pull the parts is considered during the design of the mold. For instance, depending on the part shape and profile, it may be oriented in the mold with a particular part side on the fixed side of the mold. The runner system can also be used to help pull the parts. If a half-round runner is put into the moving side of the mold, the runner is much more likely to stay with the moving half than with the fixed half when the mold opens. If there is difficulty getting the parts to pull, "grippers" can be added to mold. These are small features put into the part or runner that provide added pulling power. If they are added to the part, they are typically placed in an inconspicuous, noncritical area. Sometimes additional pulling power can be achieved by slightly roughening an overly polished noncritical surface.

With the mold opened and pulling achieved, the parts must now be ejected from the mold. There are three main ejection methods used, sometimes in conjunction with each other. The first method relies upon pins, blades, sleeves or plates to push the parts out of the moving half of the mold. Ejection (or ejector) pins are the most common of these devices, so we generically use the term pin in the rest of our discussion. The ejector pins run back through the core and backing plate to the ejector mechanism or ejector plate. When the time comes to eject the parts, the ejector plate is driven forward by the ejector bar. This moves the ejector pins forward, pushing the molded parts out of the moving mold half cavities. The ejector pins are typically fairly small in diameter compared to the part, and often several of them are positioned around the part. Pushing from several points around the part helps prevent tilt during the ejection motion, which could cause the part to become stuck in the cavity. Closing the mold on a part that did not properly eject can damage the cavity or optic inserts. Sensors are sometimes used to prevent the mold from closing if all of the cavities are not clear.

The ejector pins are normally positioned at or slightly off the face of part. As a result, the pin leaves a witness mark on the part. During the design of the mold and the part, "keep-out zones" for ejector marks must be considered if ejector pins are to be used. In addition to pushing the part out of the cavity, in a mold with a cold runner system (the most common case) the runner must be pushed out of the mold as well. Additional ejector pins are positioned along the runner system to push it out. These pins are normally attached to the same ejector plate as those that push out the part, so the runner and part come out together.

The second ejection method uses the optic pin as the ejection pin. This method is often referred to as "optical eject." In this case, the optic pin runs through the mold plates and is connected to the ejection plate. Similar to the ejector pin case, the ejection plate moves forward, and the optic pin pushes the part out of the cavity. Figure 3.9 shows a cavity insert with the optic pin pushed forward. The bar attaching the optic pin to the ejector mechanism can be seen on the far left side of the photograph. Since the optic surface is often a significant percentage of the area of the lens, ejecting with the optic pin reduces the chance of the part tilting during ejection. As in the previous method, in the case of a cold runner system, additional ejector pins can be used to eject the runners.

The third ejection mechanism uses compressed air instead of physical ejector pins. This method is less commonly used, as it requires additional equipment and is not as easily controlled as the motion of an ejector pin. Compressed air is sometimes used as an assisting ejection mechanism for the above two methods.

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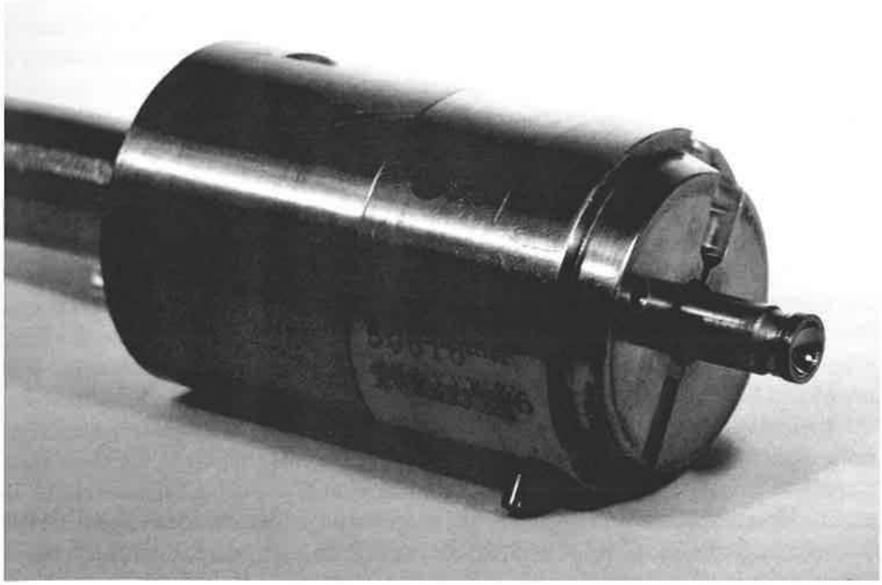

Figure 3.9 Cavity insert with optic pin moved forward showing optical ejection method. (Photograph courtesy of Alan Symmons.)

There is sometimes a debate among or within vendors as to the best ejection method to use. Some argue that using ejector pins on optical parts can introduce distortion of the optic surface due to nonuniform push-out forces over the part diameter. On the other hand, using optical eject requires the optic pin to slide back and forth, which requires a slightly larger gap between the optic insert and its hole, possibly resulting in a larger decenter of the optical surface. In some cases, the part size may rule out one method or the other. For instance, on very small optics, there may not be room to use ejector pins, requiring the use of the optical injection method. When either method (ejector pins or optic pin) is acceptable, the choice may come down to the vendor's experience and preference.

To enable pulling upon the mold opening, and to allow for easy injection, molded parts are typically designed with "draft" on them. Draft is the angling of surfaces that would otherwise be parallel to the mold opening direction. For a standard horizontal molding machine, as shown earlier, draft would be added to horizontal surfaces. The amount of draft required depends upon the length of the horizontal surface, as well as the material that is used, as different materials have varying tendencies to stick in the mold cavities.

We discussed earlier that one of the advantages of plastic optics is the ability to create complex parts. The molds that we have discussed so far are simple "straight-draw" tools. By straight draw, we mean that there is only one motion: the linear translation of the moving mold half involved in opening the mold. This type of mold is the most common, and it works well for standard lens elements. However, due to their complexity, certain parts cannot be molded using a straight-draw tool.

Figure 3.10 shows an example of a part that would not normally be molded with a simple straight-draw tool. This is a four-channel telecom device, where a fiber-optic ferrule would be inserted into the left-hand side. After passing through the collimating lens, the four wavelengths of light emerging from the fiber would reflect off the TIR mirror surface and pass through a filter/mirror assembly, which would separate the four signals (wavelengths), sending each to one lens of the four-channel array. The axis of the collimating lens is perpendicular to that of the four reimaging (lens array) lenses. The optical surfaces are arranged in such a way that they cannot be formed by parallel optic inserts. In this case, the part could still be made in a tool that opens similar to the molds discussed above, but the mold would require "side action." A side action tool allows the removal of an optic insert from the part in a direction that is not perpendicular to the mold face. This side action can be created through the use of a "slide." The slide is an additional mechanism on the mold, often consisting of an angled rod and a plate with an angled slot or hole into which the angled rod passes. As the mold is opened, the hole on the slide plate travels along the angled rod, drawing the optic pin perpendicular to the mold draw direction. Once the slide plate optic pin is clear of the part and the mold is fully opened, the part can be ejected as before. Using a slide rod and plate is one way of forming features that are not in the mold draw direction. Another way of forming such features is the use of collapsing or expanding cores. In this case, a section of the mold expands or collapses during the mold opening stroke in order to provide clearance for an undercut feature.

Another way of forming features incompatible with straight draw, particularly threads, is the use of an unscrewing mold. Thread features may be seen on lens barrels, for instance, on web cameras that have a manual focus adjustment. Threaded features can also be put onto optical parts, either for

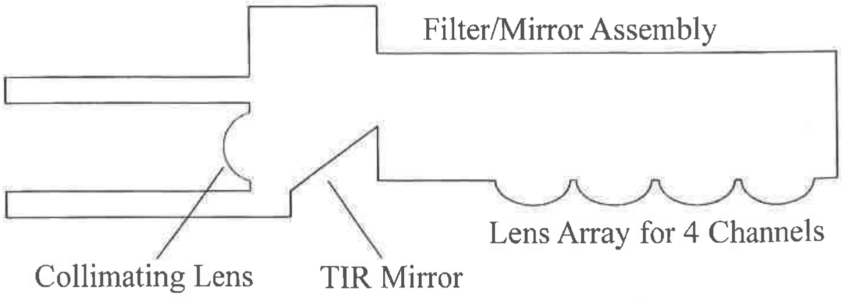

Figure 3.10 Telecom device that would not be molded in a simple straight-draw tool.

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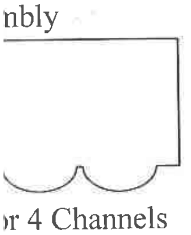

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adjustment or assembly purposes. An unscrewing mold, as the name implies, has a mechanism that unscrews the threads, allowing the part to be pulled and ejected from the mold. The unscrewing mechanism often consists of a rack and pinion, with the rack moving upward and downward to rotate the threaded insert in and out of the molding position. There is a relationship between the number of threads, thread diameter, and the gearing of the rack that will determine how large a linear motion is required to move the threaded insert over its unscrewing range.

In addition to unscrewing molds, threads can be molded into parts using slides. This may require having incomplete threads, or thread flats, as the two slides forming the threads will not necessarily be perfectly aligned. To deal with this mismatch, the thread depth is reduced to zero at the edges of the two slides where they come together. For many applications the thread flat is not a concern, as there is sufficient thread engagement to secure the barrel and provide a smooth motion.

It can be imagined that combinations of multiple slides, collapsing cores, and unscrewing mechanisms can be used to produce highly complex parts. Of course, the more complex the mold, and the more features it has, the higher the cost and the harder to run and maintain the tool. For standard slides or more complex motions, the mechanisms must be designed and adjusted for proper timing and movement. In lower volume or prototype production, it may be possible to reduce the mold complexity by using "hand-loaded" molds. In this case, a mechanism is not put into the mold but is replaced with a separate metal insert forming the desired features. The insert is removed from the tool with the molded part, removed from the molded part, and reinserted (hand loaded) into the tool for the next injection cycle. Multiple hand-loaded inserts may be created so as not to delay the next molding cycle while an insert is removed from the last molded part. An example of a hand-loaded insert would be an internally threaded sleeve to form external threads on a part. The sleeve is inserted into the mold, the plastic injected and cooled, and the threaded insert/part combination removed from the mold. The insert is then manually unthreaded from the part. In this case, the use of a hand-loaded threaded insert removes the need to build an unscrewing mechanism for the mold. This can save cost and schedule on the mold, at the cost of additional manual labor during the molding process. An alternative to using either a hand-loaded or complex tool is to perform a secondary machining operation on the molded parts. For instance, threads can be machined into a part that has been molded in a straight draw tool. Obviously, this extra operation will increase the price of the part, as well as increase yield risk due to handling. The crossover point between the cost, schedule, and risk of secondary operations versus those of a complex tool need to be weighed.

Whatever style mold is designed and fabricated, to produce useful parts a mold process must be developed. This is typically performed by a mold-process engineer. Most plastic optics vendors have at least one, if not more, experienced mold-process engineers. Mold processing essentially determines the best molding parameters to use in producing parts. Before the mold is placed in a molding machine for the first time, it is usually put through a few dry cycles on the mold bench in the tool room. The mold halves are slid together, and the fit and alignment of the two is checked. This can be a visual inspection, or it can be mechanically assessed using gauge pins or other methods. Once the alignment has been verified, the mold is slid apart, as if being opened, and the ejection or side action mechanisms checked. Once the mold has passed its bench check, it is taken to the molding floor and put in the appropriate molding machine.

With the mold now hung in the machine, the various connections to the mold are made, such as the cooling channel hoses. The first process step is usually to perform a machine check similar to the bench check. The mold is slowly closed and opened, the ejection and other mechanisms checked, and the proper stroke of the platen set. In production, the mold will operate at an elevated temperature, which will cause expansion of the metal. It may be that the mold fit or mechanisms work fine at room temperature but bind at the process temperature. For this reason, the check may be performed twice, once with the mold cold, and once with the mold heated to near the expected process temperature.

Modern injection-molding machines are computer controlled, with a variety of sensors and feedback systems. From our discussion above on the injection-molding process, it should be clear that there are a large number of parameters that can be varied. These parameters include the settings on the barrel heater bands, the mold heating and cooling (by adjusting the thermolaters and/or heaters), the injection speed and pressure, and the packing time and pressure profile. The ejection stroke can also be controlled for speed and length. In some cases, the ejector mechanism can use a two-step process: a small bump of the ejectors to free the parts, and then a longer ejection stroke to push the parts out of the mold. With all these parameters available, the process engineer often relies on experience to set the initial process values. Depending on the material used, there will be a certain standard range of values for the parameters. For instance, if the lens is made of acrylic, a standard acrylic process, based on experience, is entered.

The next step in the process development is typically to perform a series of "short shots." Short shots are injections of a volume of plastic that is less than what is required to fill the mold cavities. By running a series of short shots with increasing volume, the flow of the material can be monitored and evaluated. Based on the evaluation, the process parameters are appropriately adjusted, and shots continue until the appropriate flow is achieved and initial parts are molded.

A common question asked by those unfamiliar with the molding of plastic optic parts is, "If the flow isn't good, why don't you just add more gates?" This is a fairly logical question, and in fact, multiple gates are sometimes used on nonoptical parts. The problem with using multiple gates on plastic optics is the defect that often results when the flow fronts from the two gates combine. The general goal of the mold processor is to produce a smooth flow front of the molten injected plastic as it fills out the part. The desire is to have the flow front move from the gate portion of the optic to the other edges of the optics without doubling back on itself. If the flow does double back, at the point where the two

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portions of flow front meet, they do not combine smoothly. This results in a discontinuity—a defect known as a "knit line." The knit line is usually quite visible in the optic and results in degradation of the optic surface or the wavefront passing through the element. When using multiple gates, the flow fronts from each gate need to be adjusted so that they do not combine inside the clear aperture of the optic. For standard lens forms, this is generally not possible, and thus only single gates are used. For more complex parts, such as long lens arrays, it may be possible to use multiple gates and adjust the process so that the knit lines end up in the nonoptical portion of the part. In this case, it must first be determined if it is acceptable to have knit lines anywhere on the part.

Once initial parts are produced, they are measured and compared to the part prints. At this point the mold (or cavity sets) may be removed from the molding machine, so that the center thickness and stack can be adjusted using the shim method described above. The optical surfaces are compared to their requirements and the next appropriate action determined. If the surfaces are close to what is desired, the mold may be returned to the molding machine and the process adjusted in an attempt to achieve conforming parts. If the surfaces are too far out to be processed into specification, the mold may require compensation.

Mold compensation refers to altering the dimensions of the cavities or the optical surfaces of the optic inserts to achieve parts that meet specification. The need for mold compensation arises from the simple fact that optical plastics, like other plastics, shrink when molded. The typical range of shrinkage for optical plastics is 0.25% to 1%. When the mold is designed and fabricated, this shrinkage is taken into account. However, it can be difficult to accurately predict the exact amount of shrinkage, especially for complex parts. Parts with varying thickness can have varying amounts of shrinkage, as opposed to a straight scaling of the optical element. It may be that a spherical surface cut into an optic pin produces an aspheric molded lens surface, and that an aspheric surface on an optic pin results in a molded surface that is aspheric but of the wrong prescription.

To compensate the mold, in the case of the optical surfaces, the initial part surfaces are measured, the departure from the desired surface is calculated, and the delta (or a fraction of the delta) between the measured and desired surface is added to the optic pin. Since material is not typically added to optic pins, what actually happens is that the new surface is cut into the end of the optic pin, shortening it and possibly requiring adjustment of the axial locator shim. As discussed previously, if using nickel-plated pins, there needs to be enough nickel left on the pin to perform the recut without breaking through.

The reason that a fraction of the delta between the actual and desired part is often used (as opposed to the full delta) is because the shrinkage can be nonlinear. Using the full delta may result in a part that has been overcompensated, turning delta peaks into valleys or vice versa. It can be better to creep up on the actual compensation in a few steps rather than making one large compensation step. Of course, each step requires the mold to be removed from the machine, the optic pins removed, recut, reassembled into the mold, and the mold rehung. This takes time and money, so there is a trade-off between these and the number of compensation steps performed. In some molding contracts, the price includes a specific number of mold compensations.

Once conforming parts are being produced, through process adjustment and/or mold compensation, the final processing occurs. We stated that mold processing is determining the "best" process parameters. From the economic standpoint of the vendor, the best process is the one that produces acceptable parts in the least amount of time. Reducing the cycle time reduces the cost of manufacturing the parts, which for the case of a fixed piece price results in additional vendor profit and potentially frees up the molding machine to run other jobs. Process engineers may spend significant time trying to reduce cycle time. At some point, however, the fundamental physics of the injection molding process, along with the part's specifications, set a lower limit on the cycle time.

The processing of an optical injection mold is a specialty that is still both art and science. While there are several injection-molding educational courses, most do not deal with optical parts because they are just a fraction of the total injection molding industry. But let there be no doubt, molding optical elements is not the same as molding caps for bottles. Neither practice should be considered superior to other, as they both require a great deal of knowledge and problem-solving skills. However, expertise in one does not immediately translate to expertise in the other. Most optical mold processors learned their skills under the tutelage of an experienced optics processor or suffered through the long and painful trial-and-error process. When evaluating potential plastic optics injection-molding vendors, it is important to consider their process experience and capability, as this could have a significant impact on the project.

Mold-processing techniques (beyond the basic description above) and the process parameters that result from them are normally considered proprietary information by the molding vendor. Unless it is explicitly called out in the contract, which may sometimes lead to the vendor no-bidding, do not expect to be provided with the mold-processing parameters. Ownership of the mold does not typically imply ownership of the molding process. I have personally seen cases where the customer pulled the mold from one vendor and sent it to another with the stated reason of getting lower-priced parts, only to come back a few months later (tail between legs) because the second, cheaper molder could not get the mold to perform adequately. Moving a mold between vendors is generally not a decision that should be taken lightly. With that said, it is not uncommon today to begin production in one facility and then have the later, higher volume production moved to a lower-cost facility, potentially owned by the same vendor.

In high-volume consumer applications, the large corporations involved may demand full transparency, to the point of having resident engineers in the molding and/or assembly facilities. Disclosure of certain information that is normally considered proprietary may, in these cases, simply be a cost of doing business. The disclosure of proprietary information, from the vendor as well as the client, is a decision that must be made in each particular situation. We discuss general issues of vendors and vendor interactions in the next chapter.

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A frequent concern to the purchaser of plastic optics is the number of parts that a given mold can make or, alternately, the number of molds needed to produce a given production volume. This calculation is fairly straightforward and is scalable with the input assumptions. As an example, we calculate the number of lenses that can be produced in a month with a single mold. We first assume that the mold will be run 24 hours day for 30 days a month. This is equivalent to 43,200 available run minutes per month (60 min/h × 24 h/d × 30 d/month). We next assume that the mold has eight (8) cavities, so eight lenses will be produced during each mold cycle. To account for maintenance, cleaning, and delays due to ancillary equipment, we use an up-time factor of 0.9. Finally, we assume a cycle time of 1.5 minutes. Based on these assumptions, we would predict that our eight-cavity mold is capable of producing 207,360 lenses per month [(43,200 × 8 × 0.9) / 1.5].

We now consider the choice and implications of our assumptions. Our first assumption was that the mold would be run essentially continuously. Most vendors have the capability to run continuously, but they may or may not do so based on the production quantities required for their various jobs. Vendors that specialize in high volumes, such as those required for commercial products, may run two twelve-hour shifts, seven days a week. Including the lunch (or dinner) break, the shifts are often overlapped slightly so that production information may be passed between the sets of personnel. Vendors that perform smaller production jobs (for example, military contracts) may run fewer shifts or shut down on weekends. Obviously, the number of lenses produced will be directly related to the amount of time that the mold is run.

Our second assumption was the use of an eight-cavity tool. The number of cavities selected is usually based on the predicted production required. The cost of a mold increases with the number of cavities, so it does not make sense to machine more cavities (and spares) than are needed, unless they are produced with the expectation of future increased production demand. The number of lenses that can be produced directly scales with the number of cavities in the mold. Alternately, we could reduce the amount of time needed to produce a given quantity of lenses. If we were to double the number of cavities, we would cut the amount of time that the mold needs to be run in half. This may be a consideration if we want to use the inserted cavity common mold base approach to produce several sets of lenses.

Our third assumption was an up-time factor of 0.9. This factor is meant to take into account the fact that the mold will not truly be run continuously. In reality, the mold must occasionally be taken down for cleaning and maintenance. Additionally, there are always some delays during production, such as allowing the mold to come up to temperature when it is first put into the molding machine, adjustments of ancillary equipment, or the need to purge the barrel. This factor does not have as much influence as the others because it unlikely to vary by a great deal once production is established. If the up-time factor drops significantly, there is likely a problem with the mold, production equipment, or the vendor that needs to be addressed.

The final factor in the calculation is the cycle time. As described above, the process engineer attempts to minimize the cycle time, although some of the factors influencing it are out of his or her control. The cycle time depends on a number of factors, such as the quality requirements and thickness of the part. The designer can have some influence on the cycle time and in general should seek to design for the minimum cycle time. However, there will always be some fundamental minimum required cycle time to produce acceptable parts, and this, along with the other factors, will determine the maximum production per month that can be achieved using a single tool.

Another factor that plays into the decision of mold configuration (number of cavities) is risk. Suppose we have performed the calculation above and determined that we can meet our production needs with a single sixteen-cavity tool that is run continuously. We then need to ask ourselves if this is the most prudent approach. From a risk-mitigation standpoint, it might make sense to produce two eight-cavity molds instead of the single sixteen-cavity mold. It must be remembered that the use of a single mold, particularly in a high-production-volume situation, can be a potential single-point failure. If the lone mold "crashes," production can come to a complete stop. This can be especially important for products that have a relatively short marketing lifetime and high initial demand, such as consumer applications. In these cases, the designer may use multiple molds, or even multiple vendors, to mitigate risk.

The cost of injection molds and the parts that are produced from them is an important issue for designers choosing to use plastic optics. We noted earlier that cost is the primary reason that plastic optics are considered. Given that, the general answer to the question of cost is the somewhat unsatisfying "it depends." The cost of a plastic optic, and the mold it is made from, depend on a variety of factors. For the optics themselves, it includes the material selected, the size, thickness, and complexity of the part, the quality requirements of the part, as well as any secondary processes that need to be performed, such as degating, machining, coating, and assembly. Size, complexity, quality, and production volume, as well as the expected lifetime, usually determined by the number of mold open-close cycles required, all factor into the cost of the mold. Where the molds are built and where the optics are produced can also have a significant impact on cost.

In many applications, and consumer electronics in particular, the cost of plastic optics has been driven dramatically lower. In the mid-1990s, based on my experience, a good rule of thumb for a plastic imaging system (such as a web camera) was that the price would be approximately $0.75 per lens.[ix] So a three-element imaging system, fully assembled in a barrel, with an IR blocking filter and a sunshade would cost about $2.25. In the article by Ning, which was written in 1998, he provides a table that compares component costs for plastic and glass elements.[55] For medium-volume production of plastic optics, which he defines as 1,000 to 10,000 parts, the typical piece price is listed at $1 to $10. For high

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[ix] All prices are in U.S. dollars.

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volume, defined as greater than 10,000 parts, he lists a piece price of $0.25 to $3. Today (2009), in high volumes, the price per lens has been reduced to about a third of these costs.

Within a given region, cost across vendors will usually not vary a great deal. This is because the cost of the production of plastic optics tends to be driven by labor and shop floor rates. A good rule of thumb for the cost of a plastic optics element is to take the standard shop floor rate, perhaps $100 to $150 per, and divide it by the number of parts that can be produced in an hour. For a four-cavity tool with a one-minute cycle time, this will result in an approximate cost of $0.50 per element.

Given the cost dependence on labor and shop floor rates, much of the production of plastic optics for high-volume consumer systems has moved to lower labor cost regions such as China. It is easy to see that manufacturing in a low-cost labor region may cut the cost of an element in half. As a result of this price pressure, many vendors in higher-cost regions have upgraded their automation and molding equipment and are focusing on less cost-driven markets, such as defense and medical applications. In addition, some vendors have multiple production facilities, one in a higher-cost region, where the initial design, prototyping, and process development is performed, and another in a lower-cost region, where the high-volume production is transitioned.

The cost of a mold to produce plastic optic elements will depend in part on the material it is made from, the complexity of the machining required, and the warranty on the tool lifetime. For example, Class A tools are expected to be able to run at least 1 million cycles. Cost for a typical lens mold can run from $10K to $30K. More complex, multicavity tools can cost as much as $100,000. There are a number of different methods of paying for a tool. In some cases, the vendor will want 25% to 50% of the mold cost up front, with the rest payable upon acceptance of the tool. In other cases, the vendor will assume the upfront costs, with intermediary progress payments made. Another way to pay for the mold is to amortize it over the production run. In this way, the tool is "free" or at a reduced rate, and the cost to pay for the mold is included in the part price of the elements that the tool produces. If this approach is taken, the contract will often contain a cancellation clause to protect the molder if the predicted production does not occur.

When purchasing a mold, it is important that the ownership of the tool and any hardware associated with it is clearly defined. In most cases, it is a straightforward matter. The mold should generally be defined as the machined plates that comprise it; any inserted items such as gates, optics pins, or cavities; and any devices, such as internal electric heaters, that are necessary to effectively run it. Problems can potentially arise if the vendor is using specialized, custom-developed equipment that they consider their own. As an example, if the vendor has developed a common mold base into which they routinely insert machined cavity sets for individual projects, they may consider that the customer has ownership of the inserted cavities but not of the mold base. In this case, if the customer wanted to move production to a competing vendor, they might receive just the cavity inserts, which would be fairly useless to them without an equivalent mold base. These situations arise infrequently, but it is better to find out such things in advance rather than to find out too late.

Given the increasingly short product development and life cycle of many consumer electronics, the time to create a mold and produce parts has been significantly reduced. A decade ago, the standard lead time for a production tool was approximately 12 to 14 weeks. Today, this has been reduced by about a half, with molds typically taking six to eight weeks to produce.[36] The use of standard bases and inserted cavities, as discussed above, can shorten this time even further.

In addition to standard injection molding, there is another type of molding, referred to as injection-compression molding. Injection-compression molding is somewhat of a hybrid between compression molding and standard injection molding. In compression molding, as mentioned earlier, plastic is inserted, heated to soften or melt, and compressed with a master to form the part; in injection molding, the plastic is first melted, followed by injection into the master. In injection-compression molding, the plastic is melted, injected into the master, and then compressed. We discussed earlier the use of packing the mold to achieve quality optical surfaces. Injection-compression molding can be considered the next step in packing. Instead of just pushing on the plastic with the injection screw until the gate freezes off, injection-compression molding allows the plastic to be pushed on by the optical insert itself, both before and after the gate freezes. In this way, the mold can move to compensate for the shrinkage that occurs during the cooling time.

To the observer, a standard injection and an injection-compression mold look similar. They are run in the same or similar injection-molding machines as standard injection molds. Due to the additional compression mechanism, injection-compression molds are more costly than standard injection molds. Injection-compression molding of optical parts is a subset of optical injection molding. Many vendors who injection mold optics do not use injection-compression, although most injection-compression molders perform both standard and injection-compression molding. Like most specialists in plastic optics, injection-compression molders have significant experience in their particular area. There are a few well-known companies dedicated to optical injection-compression molding. Injection-compression molding, due to its increased mold cost and complexity is typically used in special situations. For instance, thin high-area parts (such as Fresnel lenses) can benefit from injection-compression molding. Parts with high aspect ratio microfeatures, or parts with large thickness variation (such as prisms), can also benefit from it. If a part design is not suitable for standard injection molding and cannot be changed to be so, or if the quality required cannot be achieved using it, injection-compression molding should certainly be considered.

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Chapter 4

Design Guidelines

In this chapter, we discuss guidelines that apply to the design of plastic optical systems. We begin by reviewing some basics of optical design, consider tolerances and their effects, and cover various element parameters, such as thickness, shape, and different surface types. We also discuss guidelines for optomechanical design, stray light prevention and analysis, issues associated with drawings, and interacting with vendors.

We noted in the last chapter that injection molding is the most popular method of producing plastic optical elements. As such, most of the guidelines discussed are associated with the injection-molding production process. In some cases, the guidelines for injection-molded optics may differ from optics made from other processes, such as diamond turning. In these situations, I will attempt to point out the differences.

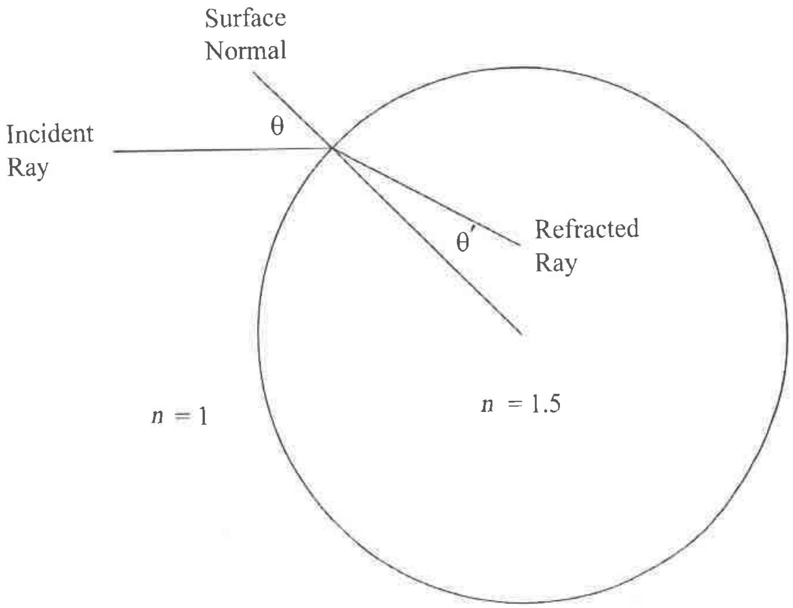
It should be kept in mind that what we discuss in this chapter are guidelines, not hard and fast rules. The guidelines presented are based mostly on practical experience (often bad experiences) and an understanding of the manufacturing process. Various designers and vendors may have different opinions regarding any given guideline, and trades can often be made between cost, performance, and producibility.

4.1 Design Basics

Optical design is a skill that previously was learned under the guidance of an experienced designer in somewhat of an apprentice relationship. The optical design community was relatively small; there were few courses of instruction and limited opportunities to enter the field. With the advent of personal computers and a number of commercially available optical design programs, access to tools to easily perform optical design has greatly increased. Currently, almost any company or individual with a computer and enough money to buy or lease an optical design program can get into the field. In this section, we present a brief discussion of the basics of optical design, beginning with a short, general review of geometric optics and aberrations. There are entire books and classes devoted to geometric optics and optical design, and given the length of this text, we will not cover the subject in great depth. We refer the reader to any (or all) of several well-known works for more detailed study.[56-58]

A basic assumption in our discussion is that light can be represented by rays, and that light rays travel in straight lines (at least in homogeneous media). In Chapter 2, we discussed the refraction of a ray at the boundary between two media of different refractive indices. The rule that governs the refraction of the ray is known as Snell's law. We explained that the refraction of the ray is determined by the angle of the ray with respect to the normal to the surface and by the ratio of the refractive indices of the two media. We also showed that the higher the ratio of refractive indices between the two materials, the larger the amount of refraction (or bending) of the ray.

In the refraction example discussed above, we considered a single ray at an interface. Although in Fig. 2.3 we drew a planar interface, the boundary between the two media could take any shape. In this general case, Snell's law still applies, with the ray angles taken with respect to the normal to the surface at the point of intersection of the ray. We now consider the situation of a ray crossing an interface that is spherical, such as when a light ray is incident on the surface of a conventional spherical lens. Figure 4.1 illustrates the geometry of this situation, where we have shown the lens as a sphere. We assume the material to the left of the interface to have a refractive index of 1 and the lens material to have a refractive index of 1.5. Similar to our earlier example, we find the angle between the ray and the normal to the surface (at the point of intersection of the ray), and with the values of the refractive indices, we determine the angle between the surface normal and the refracted ray. We can imagine extending the ray further to the right, where it will intersect the second surface of the lens. At this interface, the rear surface of the lens, we can again find the angle of the ray with respect to the surface normal, calculate the angle of refraction, and determine the direction of the ray after it passes through the surface. We have thus computed the path of a ray through a lens.



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If we now increase from one ray to several rays, we have the case of a finite-sized beam of light incident on and passing through a lens, as was shown in Fig. 2.4. We can see that the parallel ray bundle incident on the lens is converging after having passed through it. Because of this, the lens is known as a converging (positive) lens. If the ray bundle had been diverging after passing through the lens, it would be known as a diverging (negative) lens.

A lens, to the first order, is described by the location of a set of points known as the cardinal points. The cardinal points consist of the principal points, the nodal points, and the focal points. Each of the cardinal point types come in pairs. There is a front principal point and a rear principal point. The same is true for the nodal and focal points. Figure 4.2 shows a biconvex lens with the cardinal points labeled. The principal points are points of unit magnification. If a plane is drawn perpendicular to the axis, through a principal point, it is known as a principal plane. The principal plane can be considered the representative plane of bending of the rays in the lens. This can be seen by extending the input and output rays and noting that their intersection occurs at the (rear) principal plane. If we were to bring a ray from the rear side of the lens, it will appear to bend at the front principal plane. In a real system, the principal surfaces (which represent the ray-bending surfaces) are not truly planes, but for our discussions it is acceptable to consider them as such.

The nodal points are the points of unit angular magnification. That is, if a ray is aimed at the front nodal point, it will appear to emerge from the rear nodal

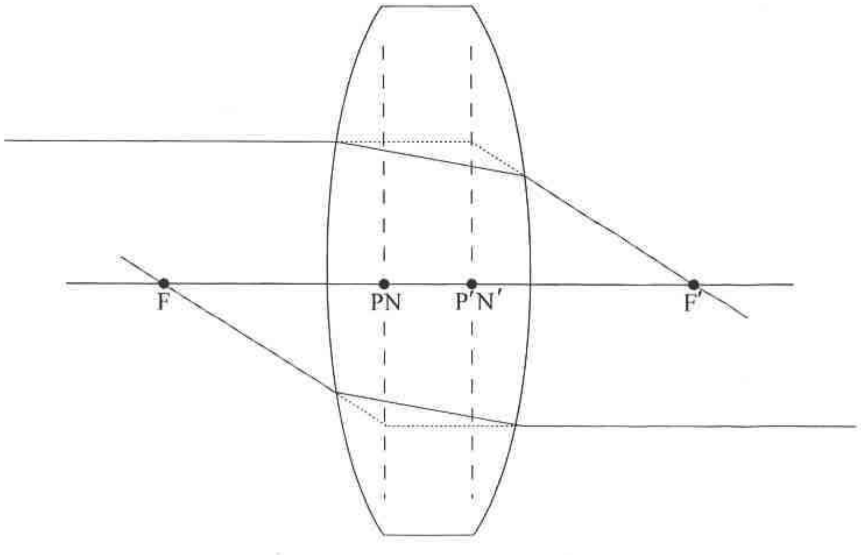

Figure 4.2 Biconvex lens with cardinal points labeled.

point at the same angle. If the lens system is in air, the nodal points will coincide with the principal points.

The focal points are the positions where an input ray that is parallel to the optical axis crosses the axis after passing through the lens. This can be seen for the input ray coming from the left in Fig. 4.2, which crosses the axis at the rear focal point, *F*′. A ray parallel to the axis coming from the right of the rear surface of the lens would cross the axis at the front focal point, *F*.

The distance from the principal point to the focal point is known as the effective focal length (EFL) of the lens. Most people have some familiarity with the concept of effective focal length. For a thin lens, the focal length is approximately the distance from the center of the lens to the location along the axis where an input collimated beam comes to focus. For a thick lens, or for a system made of multiple lenses, the focal length is not measured from the center of the lens system. To find the effective focal length, we extend an input ray (parallel and near to the axis of the system) as well as the corresponding output ray and find their intersection. The intersection of the two rays is the principal plane, and as before, the distance from the principal plane to where the output ray crosses the axis is the effective focal length. Depending on the powers and positions of the elements within the system, the principal plane may be in front of, inside of, or behind the physical system.

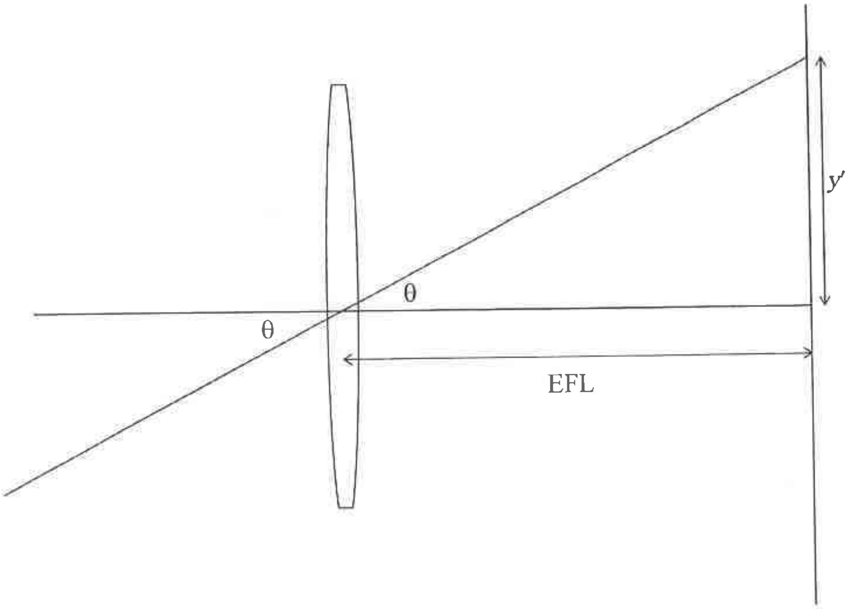

Figure 4.3 Relationship between focal length and image height.

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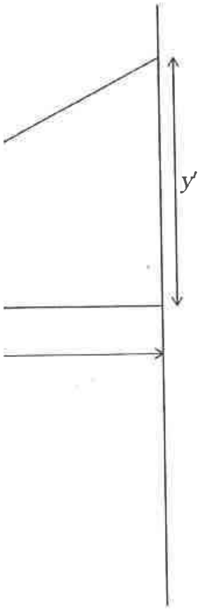

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The distance from the last optical surface of the system to the image is known as the back focal length (BFL), while the distance from the last piece of mechanical structure to the image is known as the flange focal length (FFL). In some systems there will be a required length of the BFL and/or FFL in order to provide necessary clearance for other elements, such as a fold mirror.

The focal length of a single lens can be calculated from knowledge of its radii of curvature, its thickness, and its refractive index. The equation for the focal length of a lens in air is shown in Eq. (4.1):

$$\frac{1}{\text{EFL}} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{t(n-1)}{nR_1R_2}\right], \tag{4.1}$$

where n is the refractive index of the lens material, R_1 is the radius of the first surface of the lens, R_2 is the radius of the second surface of the lens, and t is the center thickness of the lens. The sign convention for the radii is that the distance is positive if the center of curvature is to the right of the vertex of the surface and negative if the center of curvature is to the left of the vertex. As an example for the biconvex lens shown in Fig. 4.2, the front surface of the lens (left-hand surface) has a positive radius, while the rear surface has a negative radius.

The focal length of a lens or lens system provides the scaling factor between input angles for collimated beams and the height of the image formed by the lens, as is shown in Fig. 4.3. Collimated input beams can be considered to come from object points at an infinite distance (or very far) from the lens. We can see from the figure that the height of the image is related to the focal length and input angle through the equation

$$y' = \text{EFL} \tan\theta\,. \tag{4.2}$$

Using this equation for any given focal length lens, we can determine the image height as a function of input angle. Alternatively, if we have selected a particular detector and a desired field of view, we can calculate the focal length required to achieve it.

In the case of finite object distances, we can determine the location and size of an image by knowing the focal length of the system and the distance of the object from the front focal point. An example of a finite imaging situation is shown in Fig. 4.4. The relationship between the object and image distances is given by

$$xx' = -ff', \tag{4.3}$$

where x is the distance of the object from the front focal point, x' is the distance of the image from the rear focal point, f is the front focal length, and f' is the rear focal length of the system. For a system in air, f and f' are equal. Setting $f = f'$ and solving for the image distance x', we obtain

$$x' = -\frac{f^2}{x}. \tag{4.4}$$

The height of the image h' can be determined from

$$h' = \frac{hf}{x} = \frac{-hx'}{f}, \tag{4.5}$$

where h is the height of the object. The ratio of the image height to the object height (h'/h) is known as the magnification and is usually denoted by m. Using Eqs. (4.4) and (4.5), we can determine the image location and size for any object height and position when imaged with a given focal length lens or lens system.

We next consider the concepts of the aperture stop and the pupils. In any optical system, there is some aperture that limits the size of light beam that can pass through the system. In some cases, this aperture may be the diameter of a lens. Alternately, it could be the mounting flange or retaining ring of a lens. In many cases an aperture (such as an iris) is specifically positioned to set the beam size. The limiting aperture is called the aperture stop of the system. In most photographic cameras, there is an adjustable aperture that is the aperture stop. When the aperture is closed down to a smaller opening, it is referred to as "stopping down" the system.

The entrance and exit pupils are nothing more than the images of the aperture stop when viewed through all the elements in front of and behind the aperture stop, respectively. All of the light entering the system appears to go into the

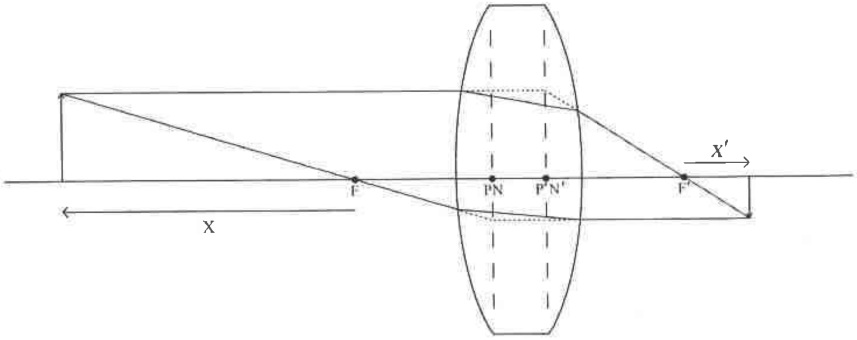

Figure 4.4 Example of imaging at finite conjugates.

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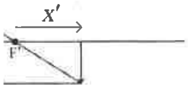

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entrance pupil, and all of the light exiting the system appears to come out of the exit pupil. When we look into the front of a lens system and see the limiting aperture, we are looking at the entrance pupil. Similarly, when looking into the rear of the lens system, we see the exit pupil.

The ratio of the focal length of the lens system to the entrance pupil diameter is the *f* number (*f*/#) of the system. The *f*/# describes the system's light capturing ability. Smaller values of *f*/# (such as *f*/2 versus *f*/4) are associated with more light capturing ability. Smaller *f*/# systems are referred to as "faster" systems; that is, an *f*/2 system is faster than an *f*/4 system. The term comes from early film cameras, where a faster system required the shutter to be open for a shorter period of time than a slower system (i.e., the picture could be taken faster).

Up to this point in our discussion, we have considered only the first-order properties of lenses. We have discussed that we can determine the size and location of an image, but we have not yet concerned ourselves with the quality of that image. By image quality, we refer to how much the image of a point object looks like a point. If we consider a generic object to be made up of a collection of points, the quality of the image will depend on how well the lens system images each point making up the object to a corresponding point in the image.

In general, a point in the object is not imaged to a point in the image but (at best) to a small blur. This is due to diffraction as well as the aberrations of the lens system. Diffraction deals with the wave nature of light and sets a lower limit on how small the image of a point can be in the absence of aberrations. At the moment, we do not concern ourselves with diffraction, only with aberrations. Aberrations are the departure from perfect imaging. When an optical system has aberrations, the image of a point does not look like a point, and/or the image of a point is in the wrong location. We next consider some common aberrations seen in optical systems as well as some general techniques for controlling them. More extensive discussion of aberrations, aberration theory, and techniques for aberration control are found in several works.[59–61]

We begin our discussion of aberrations by considering chromatic aberrations. Chromatic aberrations can be thought of simply as the variation in first-order characteristics of the lens (or lens system) with the wavelength of light. Consider, for instance, a singlet lens used with the visible spectrum. We know that the different colors in the visible spectrum are associated with light of different wavelengths, with red being longer and blue being shorter wavelengths. Earlier, we discussed the fact that materials have different refractive indices for different wavelengths, which is known as dispersion. We also saw in this section [from Eq. (4.1)] that the focal length of a single lens depends in part on its refractive index. It follows that since the lens has different refractive indices for different wavelengths, it will also have different focal lengths for different wavelengths. This is shown in Fig. 4.5. The rays representing the blue light, for which the lens material has a higher index, focus nearer to the lens than the rays representing the red light, for which the lens has a lower refractive index. The higher blue-light refractive index results in a shorter focal length than the lower red-light refractive

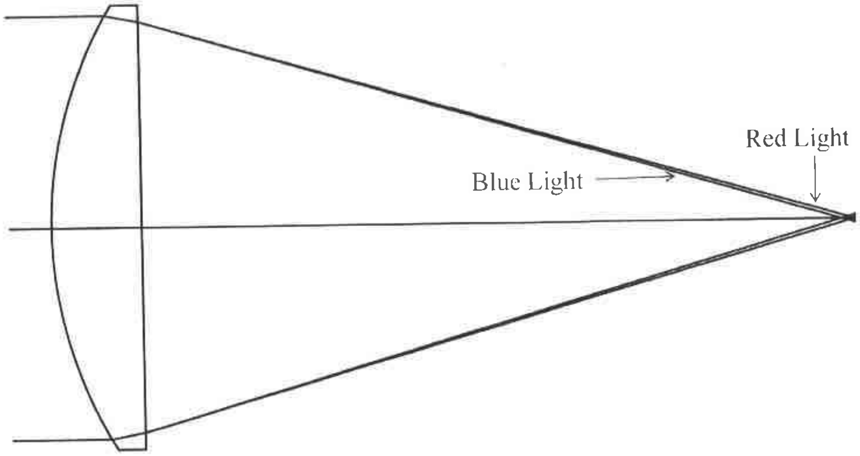
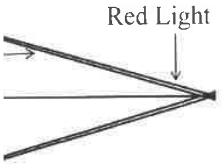


Figure 4.5 Lens exhibiting axial chromatic aberration.

index. This axial separation of the foci of the different wavelengths of light is known as axial chromatic aberration or axial color. The effect of axial color is to create color blurring in the image. If we were to place a screen at the axial position of the focus of the blue light, we would (in geometric terms) see a bright blue spot surrounded by a red blur. The red blur would be due to the fact that the red light had not yet come to focus. In reality, we would not just see a red blur because all the wavelengths between blue and red would be striking the screen, somewhat out of focus.

Now that we understand the potential variation of focal length with wavelength, we can predict what happens due to this variation in the case of an off-axis image point. We stated earlier in Eq. (4.5) that the height of the image depends on the focal length of the lens. If the focal length varies with wavelength, then the image height will also vary with wavelength, and for a given object, different wavelengths (colors) will end up at different image heights. Using the same lens as the previous case, we have a shorter blue focal length and a longer red focal length. This results in the blue light being imaged to a different height than the red light. This separation in height of the different colors is known as lateral chromatic aberration or lateral color.

In addition to chromatic aberrations, there are geometric and nongeometric aberrations. Geometric aberrations result in the rays from a point object not coming together to form a point image, regardless of the image surface location or shape. With nongeometric aberrations, we can adjust the image surface position and shape such that we can obtain a point image for a given point object. We consider the geometric aberrations known as spherical aberration, coma, and astigmatism, and the nongeometric aberrations of Petzval curvature and distortion. Each of these aberrations can vary with color, so we could have spherochromatism, which is the variation of spherical aberration with



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wavelength. The variation of these aberrations with wavelength is a higher-order consideration, which we will not discuss in detail here. In our discussion of geometric and nongeometric aberrations, we assume we are using light of only one wavelength.

The first geometric aberration we consider is spherical aberration. Spherical aberration can be thought of (in the case of a simple lens where the pupil and lens are colocated) as a variation in focus with lens aperture radial position. For more complex multielement lenses, it is the variation of focus with respect to the radial position of a ray in the entrance pupil. Figure 4.6 shows a lens with a planar front and a spherical rear surface that is exhibiting spherical aberration. In this case, rays from the outer edge of the lens focus closer to the lens than do rays from the central portion of the lens. The existence of spherical aberration can be fairly simply understood by considering Snell's law. As the rays move farther out from the axis of this lens, the angle of incidence on the rear lens surface increases. Correspondingly, the angle of refraction increases, but not at the rate that would be required for the rays to all pass through the same point on the axis. In the case shown, the rays refract at larger angles than would be desired for perfect imaging. When the rays from the outer portion of the lens (or pupil) focus closer to the lens than the rays near the center, the spherical aberration is said to be "undercorrected." If the reverse were true, and the rays from the outer portion focused further away, the spherical aberration would be "overcorrected." The amount of spherical aberration, that is, how far the rays from the edge of the pupil intersect the image plane compared to the intersection of the ray through the center of the pupil, varies as the third power of the pupil size, but it is constant with field angle.

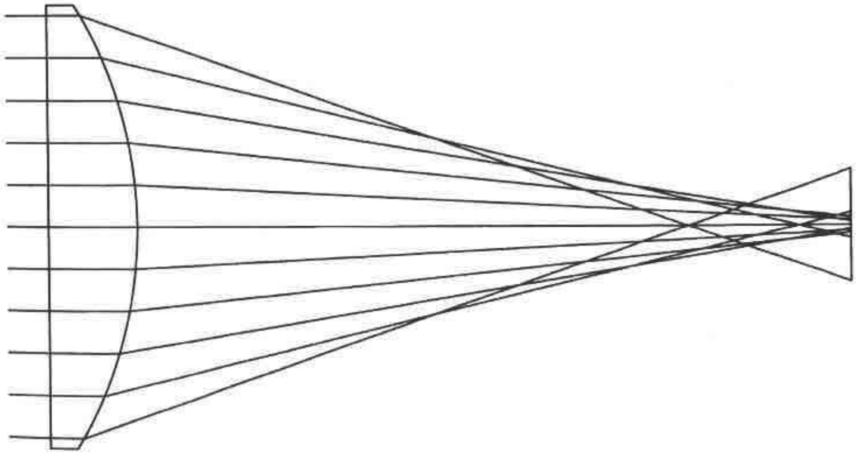

Figure 4.6 Plano-convex lens with spherical rear surface exhibiting a large amount of spherical aberration.

There are several design methods to control spherical aberration. One method is to change the shape of the lens such that the angles of incidence on the surfaces are adjusted (typically reduced). Changing the lens shape while maintaining its focal length is referred to as "bending" the lens. Figure 4.7 shows a lens with a different shape but with the same focal length as the lens shown in Fig. 4.6. We can see that this "bent" lens shape has much less spherical aberration. Another method to reduce spherical aberration is to "split" the lens, dividing the power of the lens amongst multiple elements. This method also reduces the angles of incidence on the surfaces, which reduces the amount of spherical aberration. Yet another method to control the spherical aberration is to use an aspheric surface. By selecting the correct surface shape, we can adjust the angles of incidence such that the rays are all properly refracted to go through the same axial image point. An example of this is shown in Fig. 4.8, where the rear surface of the lens is a conic surface with a conic constant equal to the negative of the square of the refractive index of the lens.

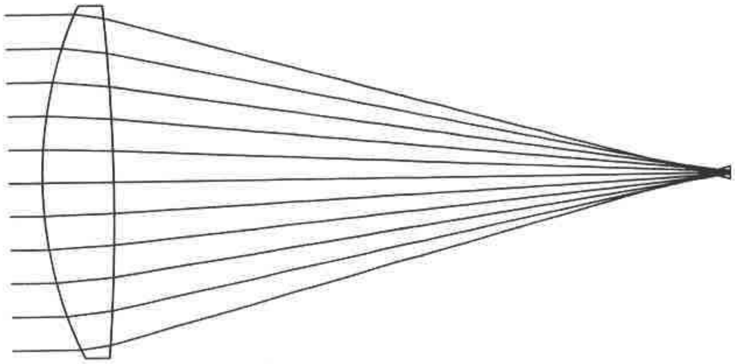

Figure 4.7 "Bent" lens showing reduced spherical aberration.

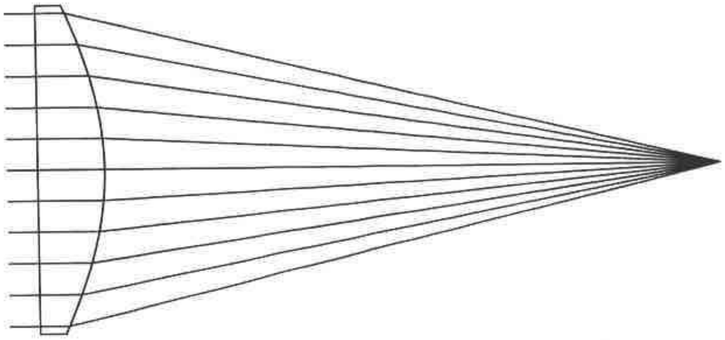

Figure 4.8 Plano-convex lens with rear conic surface, exhibiting no spherical aberration.

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The second geometric aberration we discuss is coma. The name for coma comes from the comet-like appearance of a point image when this aberration is present. Coma is a variation in magnification as a function of radial position in the entrance pupil. Rays from different annular zones within the pupil strike the image plane at different heights, as shown in Fig. 4.9. We can see in this figure that the rays from the outer edge of the pupil come together at a different height than the ray from the center of the pupil. The amount of coma varies with the square of the pupil diameter and linearly with the field angle. Coma can be a particularly annoying aberration because it produces an asymmetric image of a point object. There are several methods used to control coma. One method is to move the axial location of the aperture stop, which adjusts where the beam of rays strike the lens. Another way to control coma is through the use of symmetry. If a lens system is symmetric about the aperture stop, the coma introduced by the lenses before the aperture stop will be cancelled by the lenses after the aperture stop. This is technically true only if the object and image distances are the same, which would give a magnification of one. However, even if the system is not used symmetrically, the coma is to a large extent cancelled between the two halves of the lens system.

The third geometric aberration we consider is astigmatism. Some readers may be familiar with astigmatism due to having it in their visual system. When astigmatism is present, rays in two orthogonal planes through the lens system

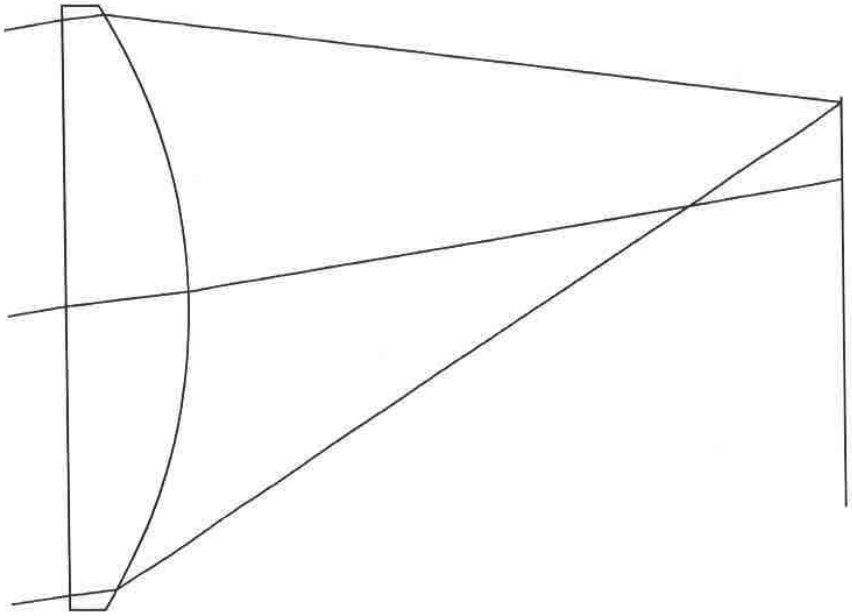

Figure 4.9 Plano-convex lens exhibiting coma.

focus at two different axial locations. At each focus, the image of a point object is a line, due to the rays in one plane being out of focus. In between these two foci, the image of a point object has an elliptical shape. Midway between the foci, the shape is circular. Astigmatism arises from the fact that as the beam strikes the lens at an off-axis position, the height and width of the beam are different. As a result, rays in the two directions have different angles of incidence and are refracted by different amounts. The amount of astigmatism depends upon the shape of the lens, as well as its distance from the aperture stop. For a given lens, astigmatism depends linearly on the pupil size and with the square of the field angle. By adjusting the shape of a lens and its distance from the aperture stop, the astigmatism of an element can be controlled. It can also be controlled through the use of an aspheric surface, which will change the angles of incidence that the beam sees when it strikes the surface.

Having discussed the geometric aberrations, we now consider the nongeometric aberrations. Again, we refer to them as nongeometric because they do not cause the image of a point object to blur; instead, they change where the point-like image of a point object is located. The first nongeometric aberration we discuss is Petzval curvature, which is an inherent curvature of the image surface of a lens. While we often refer to the "image plane" (because our film or detectors are typically planar), the preferred shape for a positive lens, if all other aberrations were corrected, would not be a plane but an inward-curving surface. This curved image plane is known as the Petzval surface and is illustrated in Fig. 4.10. The use of a planar image surface, instead of a curved one, results in the off-axis points being out of focus. The blur depends linearly on the pupil size and quadraticly with field height. It should be noted that some optical systems, such as the human eye and the Schmidt camera, use a curved image surface.

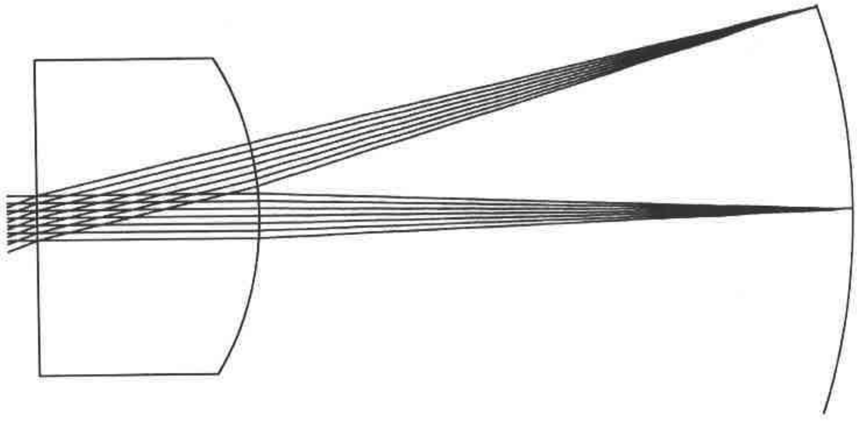

Figure 4.10 Lens showing a curved image surface, known as Petzval curvature.

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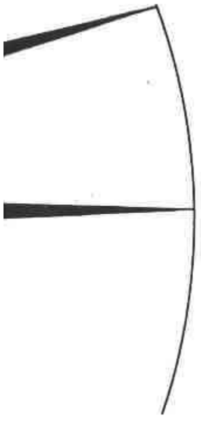
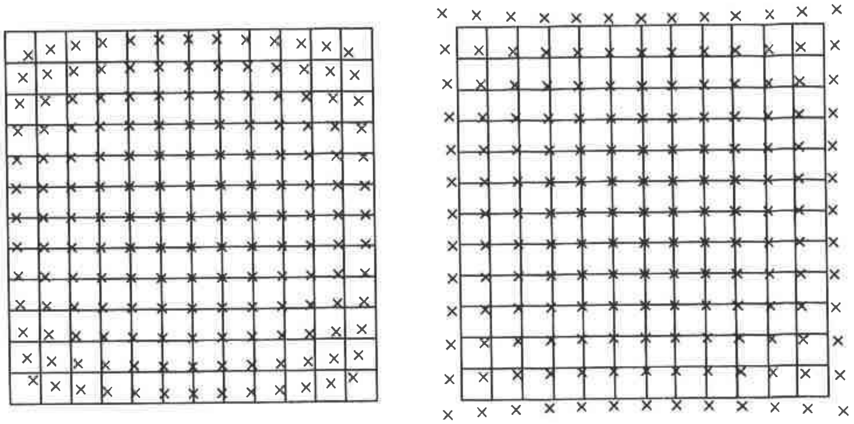


Petzval curvature.

The amount of Petzval curvature depends directly upon the power of a lens and inversely on its refractive index. Being an inherent property of the lens, the Petzval curvature contribution of a lens does not depend upon its position within a system of lenses. While the Petzval surface of a positive lens is inward curving, the opposite is true for a negative lens; a negative lens has an outward curving Petzval surface. Thus, it would seem logical that one way to reduce the amount of Petzval curvature would be to combine positive and negative lenses. If we were to take a positive and a negative lens with equal and opposite power and combine them in a doublet, we would end up with no Petzval curvature—that is, with a flat image plane. The problem with this arrangement (assuming thin lenses are in direct contact) would be that the powers of the lenses would cancel each other (they are equal and opposite), so we would up without any optical power. However, while the contribution of any lens element to the Petzval curvature does not depend on its location within the system, the contribution of its power to the total system power does. Therefore, we can separate the two components, which will create optical power, while maintaining the sum of their Petzval contributions, which is zero. Using separated positive and negative elements is a common optical design technique to reduce the Petzval sum. An example of this can be seen in the Cooke triplet, which consists of a positive element, a negative element, and a positive element, all of which are axially separated.

Another method of reducing the Petzval curvature, also known as "flattening the field," is the use of a negative field lens placed near the image plane. A field lens is a lens that is placed near the image plane or at an intermediate image. We can understand how a negative lens placed near the image plane flattens the field by considering the fact that it provides increasing glass thickness as a function of field height. When a converging beam passes through a block of glass, the focus position of the beam is shifted by an amount related to the thickness and refractive index of the glass. In the case of a negative field lens, the glass thickness increases as a function of the field, so the image is increasingly shifted as a function of the field height. By choosing the correct surfaces on the field lens, that is, by setting the correct thickness variation, the image is shifted by the appropriate amount to make it lie on, or nearly on, a plane. One potential problem with a lens of this type, often referred to as a "field flattener," is its location near the image plane, where the converging beams have a small cross-sectional area. Any small defect on the lens (such as a dig) or any contamination can block a large portion of the beam heading to a given field point.

The last aberration we discuss is distortion. Most people are familiar with distortion, having seen the distorted image from a wide-angle camera lens. We discussed earlier how to compute the height of an image, given a focal length and field angle. This image height assumes that there is no distortion in the system. If distortion is present, the image of a point object will not be at the expected height, but it will be displaced. The distance that the actual image is displaced from the predicted image is the amount of distortion of the system. The amount of distortion is often quoted as a percentage—the ratio of the displacement of the image to the predicted image height times 100.



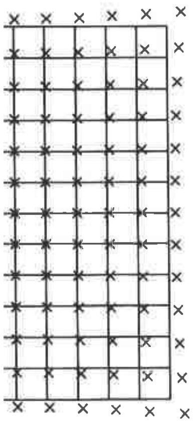
Barrel Distortion Pincushion Distortion

Figure 4.11 Effect of barrel and pincushion distortion on the image of a grid object.

The distortion contribution of an element depends upon the distance of the element from the aperture stop of the system as well as on the element's thickness. The distortion of a system is constant with pupil size and varies with the third power of the field. Because of this cubic dependence, the image of a grid object has the familiar "barrel" or "pincushion" appearance associated with distortion, depending on whether the distortion is positive or negative. Examples of these are shown in Fig. 4.11, where the crosses in the plots show the location in the image of the corners of the squares forming the grid object.

Distortion, like coma, can be eliminated or reduced through the use of symmetric lens element arrangement. The distortion introduced by the front half of the system will be cancelled by the contributions of the rear half of the system. Distortion can also be controlled by the use of aspheric surfaces. In many imaging applications, small amounts of distortion (up to about 2%) can easily be tolerated.

Having briefly reviewed geometric optics, as well as aberrations and some techniques to control them, we now consider the basic process of optical design, the role of the designer, and the role of optical design software. There are several excellent texts that discuss these topics in greater depth than will be covered here.[62–64] The process of optical design begins with an understanding of the requirements that the completed design must meet. Basic requirements such as focal length, field of view, *f*/#, and wavelength range are typically imposed. In many cases, specific numbers are not available, but a general desired range is known. Some type of performance requirement, such as encircled energy, modulation transfer function (MTF) value, or resolution is also usually stated. In addition to these basic optical requirements, there are often additional constraints,



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such as packaging volume. For plastic optical systems, the factors that drive their selection (such as cost and weight) can be additional constraints. One of the functions of the designer is to understand the effects of the various constraints, as well as their interactions, and to determine if they can all simultaneously be met.

In many cases, the customer requesting the design is not familiar with the specification of optical systems. They know what they want but do not necessarily know how to put their desires in the form of a specification. Here the designer must play the role of interpreter, translating the customer's desires into requirements that the design can be evaluated against. For example, in the design of a web camera, the customer may not know the field of view required, but they know that they want to be able to see a person's head and shoulders when using the camera. Using this information, the optical designer can calculate approximately what field of view is needed, and if a specific detector is to be used and what the focal length of the lens needs to be.

In some instances, the customer cannot even be this specific. They may want to be sure to see the person's head and shoulders but cannot decide how much beyond their shoulders they should see. This may result in the need for a trade study, where, for example, different field-of-view systems are designed, and the performance, cost, and other factors compared. The customer may have multiple, competing, and sometimes unachievable desires. In this case, the designer must communicate closely with the customer, explaining what is and what is not achievable. Additionally, the designer must describe the cost, be it monetary, performance, or something else, that is necessary to meet a certain requirement.

Once the basic requirements, desires, and constraints are understood, a basic lens form, or starting point, can be selected. Often, the design that is required is similar to one that already exists; it is difficult to come up with something completely new. In this case, the existing design may be used as a starting point for the new design. Various parameters (such as focal length) can be adjusted in order to meet the requirements of the new design.

One question that often arises is, "Where do I get such an existing design?" In the design of glass optical systems, there are several sources that can provide a wide range of design forms. Multiple books exist that present the design details of various systems, as well as discussions of how they work, and why they look the way that they do.[65,66] Patent databases are another excellent source of potential design starting points. Of course, when using a patented design as a starting point, the designer must ensure that the new design does not infringe on the patents. A third source of starting-point designs is the optical design software program used to perform the design work. Most of the optical design programs come with a database of designs.

In the design of plastic optical systems, it can be more difficult to obtain an existing design to use as a starting point. Many plastic optic manufacturers have a database of designs they have developed over the years, but these are typically not shared with the general public. The patent database can be an excellent place to look for a starting point, although at times it can be difficult to find exactly what is desired. Conference or journal articles can also be good places to look for designs. In many instances, the exact prescription is not available, but the general lens form can be enough to begin with. If comparing glass and plastic solutions, beginning with a glass design and changing the glasses to optical plastics may be one place to begin. If no comparable design can be found to use as a starting point, the designer can always begin by using a single lens and adding lenses as needed.

With a starting point defined, the development of the design can begin. Today, most optical design work is performed on a computer with the assistance of an optical design software program. Readers who are interested in old-school (precomputer) design methods are referred to the book by Conrady.[67] There are multiple design programs available commercially, the best known of which are CodeV,[x] OSLO,[xi] and ZEMAX.[xii] These programs are highly sophisticated and enable the designer to perform a wide range of designs and analyses. The choice of which software program to use is often dependent on a number of variables, such as personal preference and cost. For most plastic optical designs, any of the well-known commercial design codes can perform adequately.

There is currently no closed-loop algorithm to design an optical system. While the same result can be arrived at through different paths, wildly divergent designs may also arise from the same starting point. This is partly due to the large number of variables that are available in the design process. Variables are the parameters, such as radius of curvature, that the design program will vary in an attempt to improve the design. Typically, in a plastic optical design, each lens surface (radius and possibly aspheric coefficients), lens material, and to some extent thickness, as well as lens location, are available as variables. It is the job of the designer to determine what parameters are to be assigned as variables as well as their allowed range.

Once the variables are defined, an algorithm for evaluating the lens is developed. This algorithm is commonly known as the "merit function." The merit function provides a numerical representation of the "goodness" of a design. A small value of the merit function means that a lens is considered better than another lens with a larger value (assuming the same merit function algorithm is used). The optical design codes normally have one or more default merit functions that can be modified by the designer as appropriate. The default merit functions typically use some composite of the performance (such as spot size) at each of the defined field angles to generate the merit function value. In addition to the spot size (or other performance metrics), constraints such as focal length, allowed packaging length, or distortion are also evaluated.

With the variables and constraints defined, the design may now be "optimized." Optimization is usually performed by slightly changing each of the variables and determining which way they should be adjusted to improve the design—that is, lower the merit function value. At the same time, the adjustment

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[x] CodeV is a registered trademark of Optical Research Associates.

[xi] OSLO is a registered trademark of Lambda Research Corporation.

[xii] ZEMAX is a registered trademark of ZEMAX Development Corporation.

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of the variables must be such that the constraints are met. Once the necessary changes are determined, the variables are adjusted (usually by a small amount), the merit function is evaluated, and the cycle is repeated until the improvement in the merit function value is less than some predefined amount. The goal of the optimization is to drive the system to the design form having the lowest value of the merit function. Because the merit function is a function of multiple variables, the solution found may be a local optimum, but not a global one.

Most of the optical design programs feature some type of "global optimization" function. The goal of the global optimization is to find the "best" lens solution given the constraints and variables entered. It must be remembered that "best" is determined solely by the inputs to the computer program. Any constraint that is not included will not necessarily be met. Some constraints (such as cost and manufacturability) are not always easily entered as constraints, although work in this area is ongoing.[68] The global optimizers can be useful for generating different design forms, which may themselves be used for local optimization. In some cases, the global optimization run will result in the preferred solution; in others, an ideal trade amongst the various constraints will not be achieved, and the designer will have to continue to work on the design.

Up to this point, we have discussed the design process as working towards determining the lens form with the lowest merit-function value. One thing to remember is that the merit function typically only evaluates the nominal lens system. In reality, we do not necessarily want to manufacture a lens with the best nominal performance, but a lens that provides the best "as-built" performance, taking into account the tolerances (and cost) that are associated with building it. The evaluation of the performance (and cost) of the various tolerances on the parts and their assembly is known as "tolerancing" the design and is discussed in the next section. The tolerancing of a design is a critical part of the design process. No design should be considered complete until a tolerance analysis has been performed.

Sometimes, the most difficult decision a designer must make during the design process is the determination that a design is finished. This is particularly true for novice designers. With a deadline approaching, this may not be a problem, as the design is done when time has run out. In other cases, when the design schedule is more open ended, it can be difficult to shake the feeling that "just a little more" performance can be squeezed from the system. Experience (or sheer exhaustion) will often allow the designer to recognize the need to bring the design effort to its conclusion.

4.2 Tolerances

There is potentially nothing more frustrating for an experienced optical designer to hear than the statement that "the design is all done, I just need to tolerance it." In reality, nothing could be further from the truth. An optical design is not complete until all necessary tolerances have been assigned. The tolerancing of a design can often take longer than the generation of the nominal optical prescription. Until a design has been toleranced, it is not known if its components can be made accurately enough, or how much it will cost to make the system meet its requirements. In this section, we discuss tolerances that can be achieved on plastic optic elements and consider the basic process of tolerancing a plastic optical design.

While some individuals and vendors in the plastic optics industry do not like to state explicitly what tolerances they can hold (due to part design dependence), we feel that for many typical optical elements there is a fairly standard set of achievable tolerances that a design should initially be evaluated against. Of course, every optical element needs to be individually evaluated, with the assistance of the molder, to assess the chances and/or cost of achieving the desired tolerances. Table 4.1 shows typical tolerances that can be achieved in molded plastic optical elements. The labeling of the columns can be debated as to the accuracy of each term. The terms used are similar to those used in other works discussing tolerances. Coming from a precision plastic optics molding house, the author believes that the tolerances labeled state-of-the-art are actually typical of the tolerances most optics molders hold, and that even slightly tighter tolerances may be able to be achieved. There may, however, be cost savings associated with alternate vendors and looser tolerances, and we suggest that the designer determine what tolerances are actually required to make their system perform adequately, as opposed to what tolerances can be achieved. We now briefly discuss each of the tolerances in the table.

Table 4.1 Typical tolerances for injection-molded optical elements.

	Commercial	**Precision**	**State-of-the-Art**
Radius	± 5%	± 2%	± 0.5%
EFL	± 5%	± 2%	± 1.0%
Thickness (mm)	± 0.13	± 0.05	± 0.020
Diameter (mm)	± 0.13	± 0.05	± 0.020
Surface Figure	< 10f (5λ)	< 6f (3λ)	< 2f (1λ)
Surface Irregularity	< 5f (2.5λ)	< 3f (1.5λ)	< 1f (0.5λ)
Surface Roughness (RMS)	< 100Å	< 50Å	< 20Å
Surface S/D Quality	80/50	60/40	40/20
Wedge (TIR) (mm)	< 0.025	< 0.015	< 0.010
Radial Displacement (mm)	< 0.100	< 0.050	< 0.020
Aspect Ratio[*]	< 8:1	< 6:1	< 4:1
Repeatability[†]	< 2%	< 1%	< 0.5%
DOE[§] **Depth (μm)**	---	± 0.25	± 0.10
DOE Min. Groove (μm)	---	25	10

[*] diameter/thickness ratio [†] part to part in one cavity § diffractive optical element

NOTE: Above tolerances are for 10- to 25-mm-diameter elements.

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< 1f (0.5λ)
< 20Å
40/20
< 0.010
< 0.020
< 4:1
< 0.5%
± 0.10
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The tolerance on the radius of curvature depends on the precision of the optical insert, the injection molding process, and the shape of the surface. Steeper surfaces can typically be held to a tighter tolerance than weak shallow surfaces. This is due to the increased self support that a steeper surface provides. A tighter tolerance on radius may also be achieved through compensation of the optical insert.

The tolerance on the EFL includes within it the tolerances on both surfaces of the element as well as the refractive index of the material. As such, tighter EFL tolerance may require tighter radii tolerances. In some cases, it is the back focal length (BFL), not the effective focal length (EFL), that is of interest. In this case, the tolerance should be called out on the BFL, perhaps with a loosened requirement on EFL.

The thickness of an element is set by adjusting the positions of the optical inserts within the mold. The inserts typically rest on thick, precision-ground spacers. The spacers are often initially built too thick and then are ground to the correct length after the mold processing has been performed. Any change to the optic insert, such as re-turning the surface to remove a scratch or swapping an insert due to damage, may require adjustment to the spacers. In some cases, the accuracy of the thickness measurement sets a lower bound on the thickness adjustment.

The diameter of the element is typically formed by the feature (hole) that is machined into the mold base. This feature size, along with the material shrinkage, sets the final diameter. Improved machining has resulted in diameter features in the mold that are held extremely tightly. However, in some cases the diameter may increase when the part is removed from the mold. Unless the mold has been machined in a "steel safe" condition (with extra material left on), it may not be easy to correct the diameter size.

Glass optical surfaces are typically specified using the terms "power" and "irregularity." The terms come from the test process, where a lens surface is compared against a highly accurate spherical test plate. When putting the test plate and lens together, and using a nearly monochromatic light source, a series of rings (fringes) would be observed from the interference of the light reflected from the two surfaces. If the lens surface was perfectly spherical, but of the wrong radius, the fringes would be perfectly circular and the number of fringes seen would relate to the difference in the radii of the lens surface and test plate. Any departure of the lens surface from true spherical shape would result in changes to the circular shape of the fringes, referred to as irregularity. When dealing with plastic optics and aspheric surfaces in particular, the definitions of surface figure and irregularity are not universally agreed upon.

For our discussion, we consider surface form (figure) to be how closely the surface matches the desired surface, in a symmetric way, while irregularity describes how rotationally asymmetric the surface is. This description is most appropriate for surface testing using a contact profilometer. Sometimes the term cylindrical irregularity is used, which allows the radius to be adjusted between measurements instead of using one radius value for all measurements. For interferometric surface measurement, having only a radius tolerance and a form tolerance is the preferred method. This format can also be used with surface profilers. Whatever specification method is chosen, it is important that the surface description used in the tolerance analysis accurately reflects the specification, and that the designer and vendor agree upon the definitions and test methods.

If we have specified a spherical surface, we would like the surface produced to be spherical as well. However, due to edge break or variation in shrinkage, the surface may end up being slightly aspheric. Provided the asphericity is less than the surface figure tolerance, the surface will conform to its specification. The surface form tolerance is often specified in fringes. Conversion to distance units can be obtained by noting that two fringes correspond to a distance of one wavelength (typically chosen as 632.8 nm).

The surface figure tolerance is typically used in conjunction with the radius tolerance. That is, the radius is first adjusted (up to its allowed tolerance) to minimize the form error, then the form error (surface figure) is evaluated against its tolerance. Surface figure can be adjusted by altering the mold process or by compensating the mold. In some cases, in order to produce a spherical surface, an aspheric optical insert will be used. Surface figure typically gets harder to hold as the size of the part increases. The values in the table are for parts up to about 25 mm in diameter. For symmetric parts up to 75 mm in diameter, Beich[69] suggests that less than two fringes per 25 mm can be achieved.

While the surface figure tolerance sets how well the surface must match the desired surface, the surface irregularity tolerance sets how symmetric the surface must be. As opposed to the terms surface form and irregularity, other authors use the terms irregularity and astigmatism.[22] Plastic optical parts may have some amount of asymmetry in them due to the nonuniform flow of the material during the molding process or due to ejection of the part.

While the surface form and irregularity deal with the surface variation on a larger scale, the surface roughness controls the variation of the surface on a small scale. The main effect of surface roughness is scattering of the light passing through it, which can be particularly troublesome in laser-based systems. In most systems, low enough surface roughness can be achieved to reduce any impact on system performance. In the case of molded plastic optics, the surface roughness largely depends on the surface roughness of the optical insert it is replicated from. Polished stainless steel inserts can achieve excellent surface roughness. The more commonly used nickel-plated inserts, which are diamond turned, also can achieve low-surface roughness values and can be postpolished if necessary.

The surface roughness is called out as a root mean square (rms) value. The actual value of surface roughness reported depends on what spatial frequencies are evaluated in the measurement. There is typically some upper frequency bound set by the wavelengths that the system uses and some lower frequency bound set by the measurement equipment. This is covered in the discussion of testing in a later chapter.

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The scratch-dig specification sets how many and how large the scratches and digs (pits or pit-like defects) on the optical surface can be. The nomenclature of the scratch-dig specification is two numbers separated by a slash. The numbers refer to the allowed size of scratch or dig. For instance, a 40/20 callout means that the maximum allowed scratch width is 40 μm, and the maximum pit diameter is 0.2 mm (200 μm). Scratch-dig inspection is usually performed visually using a calibrated set of reference samples. Scratch-dig specifications are typically referenced to some defining document, such as MIL-SPEC-13830, which gives additional guidance on their interpretation. For small elements, scratch-dig issues can be important, as a dig may take up an appreciable amount of the surface area.

The tolerance on wedge in molded plastic optics is controlled in the production of the mold. Because of the way the molds are made, wedge is usually not a large problem. The wedge specification is often called out as a total indicated run-out (TIR) quantity, which should not be confused with total internal reflection. The total indicated run-out is the full range that a dial indicator moves when held against the part during the measurement.

Radial displacement is another tolerance that is largely controlled by the quality of the mold. As we discussed earlier, molds are typically made up of various inserted pieces. Each inserted piece will have some fit tolerance with the piece it goes into as well as centration of its features to its diameter, for example, the centration of the optic surface to the diameter of the optic pin. These tolerances combine to create the final radial displacement tolerance. In actuality, there are two radial displacements that must be considered. These are the displacement of an individual optic surface to the diameter of the lens and the displacement of the two optic surfaces to each other. These values are regularly held to approximately 20 μm, with surface-to-surface values in the 5-μm range held for small elements in cell phone cameras.

Aspect ratio, or the ratio of the diameter of the lens to its thickness, is not really a tolerance but more of a rule of thumb. As this ratio decreases, the parts look less and less like a standard lens and more "cube-like." If the aspect ratio goes significantly below the values listed, discussion with the molder should take place before proceeding much further with the design.

Repeatability is usually one of the positive characteristics of molded plastic optics. Once the mold has been placed in the injection-molding machine and the process is stable, the parts that are produced from a given cavity will be very much like each other. Part size and shape have some influence on part-to-part repeatability. For instance, a surface with a long radius will tend to vary more than a surface with a short radius, and irregularity on large parts will tend to vary more than irregularity on small ones.

The tolerances on diffractive optical surface features are typically set by the accuracy of the master. With proper mold processing, accurate replication of the master can be achieved. Because of their small feature sizes, shrinkage is usually not a concern. For diamond-turned masters, the depth tolerance is set by the accuracy of the diamond-turning machine, while the minimum groove width is typically set by the diamond tool size. Smaller feature sizes can be obtained through the use of other mastering techniques. As the features grow smaller, attention must be paid to the ratio of the depth to the width of the feature. As the depth-to-width ratio grows larger, the feature becomes more difficult to replicate.

One tolerance that was not listed in the table was variation in the refractive index. Molders do not typically want to set a refractive index tolerance because it is difficult to measure, and more importantly, because it is largely out of their control. While changes in the mold processing can affect the refractive index, the main contributor to index variation is the plastic optical material itself and how well it is controlled by the manufacturer. As we discussed earlier, several of the plastics were not specifically intended for use in optical devices, and the manufacturers do not necessarily attempt to control the refractive index variation. To be on the safe side, an index variation of ±0.002 is often assumed. If a design is highly sensitive to refractive index variation, careful consideration of the design is suggested.

Having discussed the achievable tolerances, we now consider the tolerancing of the design. More detailed discussions of tolerancing can be found in Refs. 60 and 63. There are two main types of tolerancing performed: sensitivity analysis and predicted performance analysis. Sensitivity analysis aims to determine the sensitivity of some system characteristic to each of the individual tolerances. The characteristic may be related to image quality, such as MTF, or it may be some other metric, such as system boresight. Predicted performance analysis (as the name implies) aims to predict the performance of the system or the range of its performance, given a set of tolerances and their distributions. As in the sensitivity analysis, various parameters can be used as representations of the system performance. In each of the tolerance analyses, compensating changes, if they exist, must be specified. For instance, in many optical systems, there will be a final focus adjustment. This may occur by moving the lens barrel with respect to the image plane before it is fixed in place. This adjustment, known as a compensator, should be included in the analysis. Without the compensator, the system performance will appear much more sensitive or much worse than it really is.

To conduct the sensitivity analysis, a small change is made to each system parameter (radii, thickness, etc.) associated with a tolerance, one at a time, and the change in the system characteristic is evaluated. After running through each toleranced parameter, a sensitivity table is displayed. This table tells the designer which parameters the characteristic is most sensitive to. If the system performance is extremely sensitive to a particular parameter, the tolerance on that parameter will need to be tightly controlled, or the design needs to be adjusted to decrease its sensitivity.

To perform the performance prediction analysis, the designer must specify ranges for each of the tolerances as well as the distribution of the tolerances. The distribution of tolerances for a plastic optical system may be different from the distribution of tolerances in a glass system. The reason for this is the difference in manufacturing methods. Consider the thickness of a single element. In a

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plastic optic, the center thickness will be set by adjusting the optic pin locations, as discussed earlier. The adjustment will be made with the attempt to reach the nominal thickness value, but the final thickness may fall anywhere within the allowed range. For a glass optic, often the center thickness will be on the high side. This is because it is safer for the optician to leave on extra material in case additional polishing is required. Once the surfaces meet their requirements and the center thickness is within the tolerance range, work on the lens will usually stop, leaving the center thickness on the high side of nominal. In this case, the predicted distribution of glass lenses would be skewed toward the high side, while the thickness of the plastic lenses would be more symmetrically distributed.

Because of the repeatability of plastic optics, it is often best to assume that their tolerances will take values near the end of their ranges. This is a more conservative approach than assuming a uniform distribution of values, and it will generally predict reduced performance compared to the uniform distribution. The predicted performance analysis can be run with various tolerance probability distributions to see the effect of distribution choice.

Predicted performance analyses are typically conducted in one of two ways: either through the use of statistical analysis or through the use of Monte Carlo techniques. In the statistical analysis method, the tolerance sensitivities are computed, along with their derivatives, and the performance is predicted by statistically combining the tolerance effects. In the Monte Carlo technique, tolerance values are randomly selected from within their distribution, and the lens is evaluated. This procedure is repeated a large number of times until the performance distribution is obtained. The statistical method is far faster than the Monte Carlo method, but it depends upon the underlying statistical assumptions. The Monte Carlo method, if properly set up, may be more representative of the actual built systems. Often it is useful to use the statistical method throughout much of the design cycle, and then perform a Monte Carlo analysis near the end to verify the performance predictions. We will show an example of Monte Carlo analysis and the effect of tolerance probability distribution in the next chapter.

4.3 Plastic Versus Glass

From a pure design viewpoint, standard techniques used in the design of glass optical systems can be utilized in the design of plastic optical systems. Many techniques, such as the balancing of lower- and higher-order spherical aberration, the use of spherochromatism to balance axial color, astigmatic field flattening, and even the use of chromatic distortion to balance lateral color, can be applied to both glass and plastic optical systems. However, in many cases, factors other than optical design may not allow a standard technique to be used, requiring alternate solutions. A number of classic design techniques are discussed in the lens design book by Smith.[70] We follow the general order used in that text in our discussion of the differences in applying these design techniques to plastic and glass.

A common technique used in designing glass optical systems is the "splitting" of an element. Splitting a highly powered element into two (or more) elements, each of approximately equal power, and together having the same total power as the original element, reduces the angles of incidence on each of the surfaces, which results in a reduced amount of aberration. This is true whether the lens is made of glass or plastic. In the design of a plastic lens system, however, there may be a limit on the number of lenses that can be used due, for example, to cost or space constraints. The cost of a plastic optical system increases directly with the number of elements, so a given price point may set the number of elements allowed. An example of a space-constrained system would be a cell phone camera. In this design, a maximum overall length is usually imposed. In theory, increased numbers of elements could be shoved into the available space by decreasing the element thickness and spacing. In reality, there will be a minimum desired thickness such that the lenses can be manufactured. For production using injection molding, the lenses must be thick enough to allow the flow of the injected molten plastic.

A potential alternate solution to splitting the lens would be the use an aspheric surface. Aspheric surfaces are readily manufactured on plastic optics, and the use of an appropriate aspheric surface may eliminate the need for the extra element created by splitting. Aspheric surfaces are discussed in a later section of this chapter.

A second standard technique in the design of glass systems is the use of an achromatic (or intentionally chromatic) doublet, a technique sometimes referred to as compounding an element. We can think of this technique as creating a new glass type, one that doesn't exist on its own, by combining two different glasses. In many cases, the compounded element created is a cemented (as opposed to an air-spaced) doublet. The use of achromatic or partially achromatic doublets helps with the correction of chromatic aberrations as well as control of other aberrations (we have introduced at least one additional potentially cemented surface).

We can take the compounding technique further, in the case of a cemented doublet, by separating the cemented elements. By doing so, we introduce additional degrees of freedom. The shape of each element can now be independently changed, without the requirement of a matching cemented interface surface. Separating the elements may require tighter control of the decentration between them. The refraction at the new glass-air interface will typically be larger than at the previous glass-glass interface, with the possibility of total internal reflection without adjustment of the surfaces. This, however, can be dealt with in the design process and should not hinder separating the cemented elements.

As discussed above, cost or space reasons may not allow the use of sets of achromatic doublets. If doublets are used in a plastic optical system, they are usually not of the cemented variety. Some cemented plastic doublets have been iques to plastic and

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manufactured, but they are not the norm. Instead, air-spaced doublets, or the use of separated elements of varying materials similar to those used in a Cooke triplet, are more likely to be seen. As such, separation of the elements to achieve added performance will already have been used and will not be an additional available technique in the plastic optical system.

Similar to using an aspheric surface instead of splitting a lens, it may be possible in a plastic optical system to use a diffractive surface instead of adding an additional element as required to compound an element. A diffractive surface on a plastic lens, similar to an aspheric surface on a plastic lens, does not increase the cost of producing the element. There is, however, a potential performance cost, in terms of stray light, from using a diffractive surface.

Other standard techniques in the design of glass optical systems, based on material selection, are to raise the index of any positive singlet elements and lower the index of any negative singlet elements, or to raise the refractive indices of all the elements in general. A higher refractive index in a positive element will reduce the amount of Petzval curvature it introduces as well as reduce other aberrations through the use of longer radii surfaces, which typically decreases the angles of incidence on the surfaces. For a negative element, a lower refractive index will increase its (usually correcting) contribution to the Petzval sum. However, it will also result in a reduced radius of curvature, which may have a negative effect on aberrations. The balance of Petzval curvature and aberration correction must be considered when lowering the index of negative singlets. Raising the refractive index of all the elements will again reduce the required curvatures, thus reducing the aberration contribution of the surfaces.

As noted earlier, there are significantly fewer optical plastics to choose from compared to optical glasses. This limits the number of possible material choices available to the designer. In fact, some of the optical plastics, such as polystyrene and polycarbonate, have similar optical properties to each other, effectively reducing the choices even further. Depending on other constraints, such as thermal requirements or spectral band, there may be no higher-index plastic materials that are available. In this case, aspheric surfaces may again be used to provide the aberration reduction that would have been obtained from changing to a higher-index material. In terms of Petzval correction, if alternate materials are not available, it may be that a certain amount of Petzval curvature must be tolerated.

Another design technique in glass systems (which we have already proposed as an alternate solution in plastic systems) is the use of aspheric surfaces. In the design of glass optical systems, the use of an aspheric surface should be carefully considered. While improved manufacturing techniques [such as glass molding, computer-controlled grinding and polishing, and magnetorheological finishing (MRF)[xiii]] have made it possible to produce aspheric glass elements, they still typically cost several times a similar spherical glass element. In some cases, however, the increased cost of a glass asphere is well worth the performance or packaging improvements that it brings. In the case of plastic optical elements, an aspheric surface costs no more than a spherical surface and should be used appropriately as needed.

[xiii] MRF is a registered trademark of QED Technologies.

In addition to the classic design techniques discussed above, there are also some "rules of thumb" used in the design of glass optics that do not apply to plastic optics. Probably the best known of these is the conversion (in a glass lens) of a weakly powered long-radius surface to a planar surface. For instance, in the discussion of lens bending, we showed that the optimum form for minimum spherical aberration (for $n = 1.5$), with an infinite object distance, has a weakly powered rear surface. In moving to a production design, the optician making the lens would commonly ask if the surface could be made planar, which would be easier and less costly to manufacture. In the case of molded plastic optics, just the opposite is true. Instead of turning the weak surface into a planar surface, we would want to add more power to it. The reason for this comes from the molding process. A curved surface will have more structural support (or surface tension) than a planar surface. This will help the surface to be stable while the part is cooling, resulting in less variation in radius as well as less surface irregularity. As discussed in the section on molding, when planar surfaces of high quality are required, it is sometimes necessary to move to an injection-compression molding method.

If the lens is not going to be molded but rather diamond turned, it is not necessary to add power to the weak surface. In fact, it may be easier to make the surface flat, which will allow it to be easily fixtured when diamond turning the curved surface.

Another rule in glass lenses that is often not required in plastic optic elements is symmetry. In the case of glass biconvex or biconcave lens elements that are almost symmetric, the rule of thumb is to force them to be symmetric. This serves several purposes, such as reduced tooling and test plates in the optical shop, and it eliminates the possibility of the lens being installed backwards in the assembly. For plastic optics, the optical inserts are usually formed by independently machined optical inserts. The inserts themselves do not necessarily have the same length or diameter on the two halves of the mold, which reduces the possibility of them being inserted into the wrong side. Also, the flanging on many plastic optical elements is not symmetric (often intentionally so), due to mounting or molding design. The use of automated assembly equipment, with indexed features, should reduce the incorrect insertion of elements. In addition, for manual or automated assembly, orientation marks (such as indentations on the flange) may be molded into the part to provide a visual reference.

4.4 Shape and Thickness

In addition to the rule-of-thumb differences between glass and plastic optics mentioned above, there are also often differences in the preferred shape and

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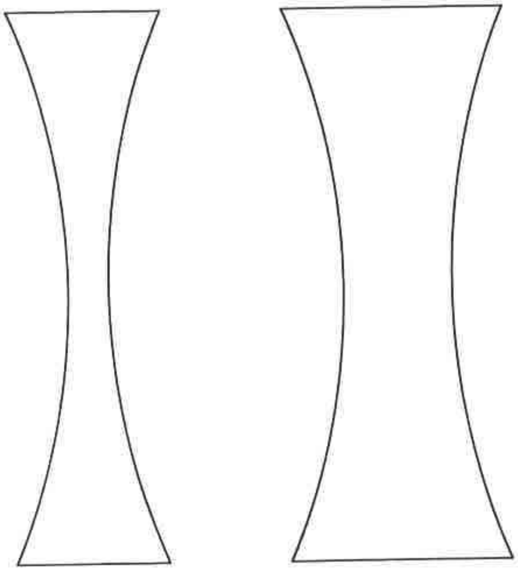

Figure 4.12 Negative lens with thin (left) and with preferred (right) center thickness.

thickness of plastic versus glass optics. These differences are driven by the manufacturing method, in this case injection molding. A fundamental requirement in the molding of plastic optics is sufficient thickness for the molten plastic to flow through. This generally constrains two parameters: the center thickness of the element, particularly for negative lenses, and the edge thickness of the element. Regarding the center thickness, consider the element shown in the left-hand side of Fig. 4.12. This would be a fairly standard glass component, but it is not a preferred plastic element. The reason for this is the flow of plastic during the injection molding process. The gate for injection of the plastic will typically be on the edge of the part. As the plastic enters the mold cavity, it will want to take the path of least resistance, which for this lens will be around the thicker outside portion of the lens. Any flanging added to the part will potentially exacerbate the problem. If the plastic first flows around the periphery of the lens, reaching the center last, the joining of the flow fronts in the central portion of the lens will result in a knit line. In addition to the knit line, the large thickness variation over the part will potentially result in a significant shrinkage variation over the clear aperture, possibly requiring several mold compensation cycles to achieve the desired surfaces.

Increasing the center thickness of the part, as shown in the right-hand side of Fig. 4.12, can eliminate both of these molding problems. With this increased thickness, the mold processor can get the plastic to flow through the center of the part, eliminating the knit line or at least moving it out of the clear aperture. The reduced thickness variation also helps with the variation in shrinkage over the part. Some plastic optics vendors do not like to specify a standard edge-to-center thickness ratio but prefer to look at each part individually. Others will quote a rule of thumb for the edge-to-center thickness ratio to be less than either three or five, depending on the individual asked.

With regard to edge thickness of the lens, the requirement is to provide enough thickness for a suitable gate. The gate size required will depend on the individual part size and shape, but it is always preferable to have room to enlarge the gate if needed. Small parts may be able to use a smaller gate than large parts, but there will generally be some lower limit on minimum gate size. Gates with a width as small as 0.5 mm have been used on small lenses for cell phone cameras.

Edge thickness can be constrained in the optical design program during the optimization process. It is important that the designer understands how the edge thickness value is calculated in the particular software being used. If it is calculated from the sags of the surfaces at the heights of maximum ray intersection, the value calculated may meet the constraint value entered but not the real manufacturing requirement. This is because the clear aperture of the surface will need to be larger than the height of the ray intersections to allow for edge break in the molding process. Molders typically will ask for at least 0.5 to 1 mm of radial distance between the used portion of the optical surface and the transition into the element flange or diameter. If possible, the designer should attempt to provide greater than this amount, particularly on larger parts or parts with large amounts of thickness variation.

In the case of parts with a relatively large center thickness and a small edge thickness, as is sometimes seen on biconvex parts, adequate edge thickness must be allowed so that the gate can be large enough to prevent "jetting." Jetting occurs when the plastic entering the cavity sprays across the open cavity space instead of smoothly flowing through the cavity. It can result in numerous knit lines or unusable parts. Limiting the power of the element, or increasing the center thickness, can generally alleviate the thin edge thickness. Jetting is obviously not a concern for parts that are to be diamond turned.

To be clear in regard to our discussion of edge thickness, it is the minimum cross-sectional area that the molten plastic must flow through that is typically the limiting factor. Occasionally, an engineer will attempt to solve the edge-thickness problem by adding a flange to the lens that is wider than the thickness at the edge of the clear aperture. While adding a flange may enable a wider gate, the plastic still must pass through the smaller thickness area. This is not to say that adding a flange will not help. Having the larger gate available may open the process window for the mold engineer; however, in the case of undersized edges it will not completely solve the flow problem.

Due to variations in shrinkage with thickness, from the viewpoint of a molder, the preferred shape of a molded element is one that has a fairly uniform thickness. In practical designs, in order to obtain sufficient optical power, most optical elements will not have this form. The goal of the optical designer should be to create parts that are as moldable as possible while still meeting the system

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performance requirements. In some cases, there may need to be a trade between the performance and ease of production of the system. Figure 4.13 shows a series of parts, some of which should mold well, and some of which should, if possible, be avoided. Referring to the figure, Lens A would be a fairly typical glass convex-plano lens. For plastic, however, it is not a preferred shape. The edge thickness is fairly thin, which would limit the gate size. In addition, the rear plano surface would not support itself well during the molding process, potentially leading to sink on the surface. A preferred version of the lens is shown as Lens B. The center thickness of the lens has been increased, which allows a better edge thickness. The plano surface has been changed to a fairly low-powered surface, which will provide better support and less variation in radius and irregularity. Lens C shows a typical meniscus lens. This lens should mold well, due to its relatively uniform thickness. Lens D shows a biconvex lens with mounting flanges added. The flanges have been extended far enough to protect the vertices of the surfaces. The flanges are of reasonable length and should not cause problems when molding the lens. Lens E shows a lens where the flange has been extended in order to act as a lens spacer. This is not a preferred lens shape because the long flange will be difficult to fill while maintaining the optical surfaces. It would be better to use a lens similar to Lens D and add a separate spacer if required.

Because of constraints such as cost or packaging, the number of elements a designer is allowed to use may be limited. In this situation, it may be necessary for each element to "work" as hard as it can. This, in addition to the use of aspheric surfaces, may result in lens shapes that are unfamiliar to those used to working with glass lenses. Figure 4.14 shows two examples of such lenses, which while not typically seen in glass designs, would be considered perfectly normal to those familiar with plastic optical design. The lens on the left comes from a web camera design, and the lens on the right comes from a cell phone

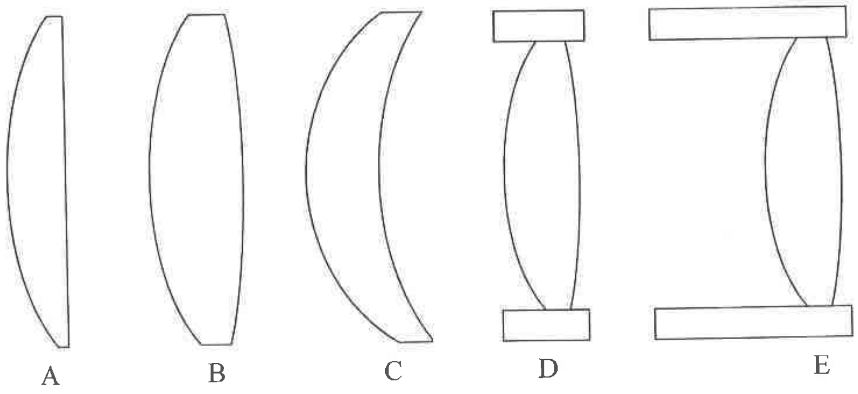

Figure 4.13 Various element shapes, some of which should be avoided (A, E).

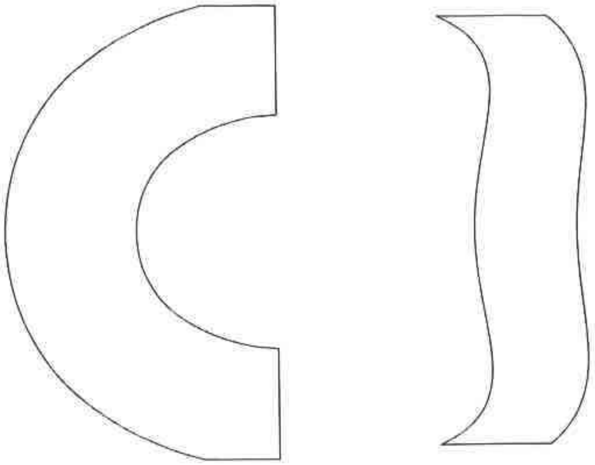

Figure 4.14 Two examples of lens shapes seen in plastic that would be unusual in glass.

camera design. These are not just design study curiosities, as both systems have been put into high-volume production. From a manufacturing standpoint, the lens on the left is considerably easier to produce in plastic than in glass. Manufacturing it in glass requires each lens to be polished individually, as opposed to blocking up a number of lenses on a spindle, which is normally done. In plastic, a multiple-cavity tool produced several copies of the lens with each mold cycle.

Experienced designers of glass optical systems often have familiarity with certain lens shapes as well as an understanding of why systems look the way that they do. They can often get an idea of what the system is doing just by looking at the lenses and comparing it to their knowledge of the "classical" design forms. The same is often true with plastic optical systems. With experience, familiarity with certain plastic lens shapes will develop, and what previously seemed strange will be completely normal.

4.5 Aspheric Surfaces

We have mentioned several times that with plastic optics, unlike glass, creating an aspheric surface costs essentially nothing more than creating a spherical surface. Given this, it makes sense to take advantage of aspheric surfaces in plastic optical designs. An aspheric surface is simply a surface that is not spherical. While a spherical surface can be completely described by defining its radius of curvature, an aspheric surface requires a more complex representation.

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symmetry, of which there are (at least) two well-known forms. The first form is the family of conics. Those who remember their geometry will already know that conics are plane curves that are created by the intersection of a plane and a right circular cone. If the plane is perpendicular to the axis of the cone, the intersection curve is a circle. As the plane is tilted, the intersection curve becomes an ellipse (of course, a circle can be considered a special case of an ellipse). Continuing to tilt the plane, such that one line in the cone is parallel to the plane, the intersection of the two is an open curve, which is a parabola. Continuing to tilt the plane, now two lines in the cone will be parallel to the plane, and the intersecting curve is a hyperbola. When these intersection curves are rotated about their symmetry axis, they form surfaces that are called conic surfaces. As an example, in the case of rotating the plane curve of a parabola, we would generate a parabolic surface or a paraboloid.

Conic surfaces are easily represented in a closed form, as shown in Eq. (4.6):

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}, \tag{4.6}$$

where z is the sag of the surface, which is the distance along the axis of the surface from a vertex plane perpendicular to the axis of the surface; c is the base curvature, the inverse of the radius at the vertex of the surface; k is the conic constant; and r is the radial coordinate, which is the perpendicular distance from the axis. An illustration of the sag of an aspheric surface is shown in Fig. 4.15. The conic constant, along with the base radius, completely describe the conic

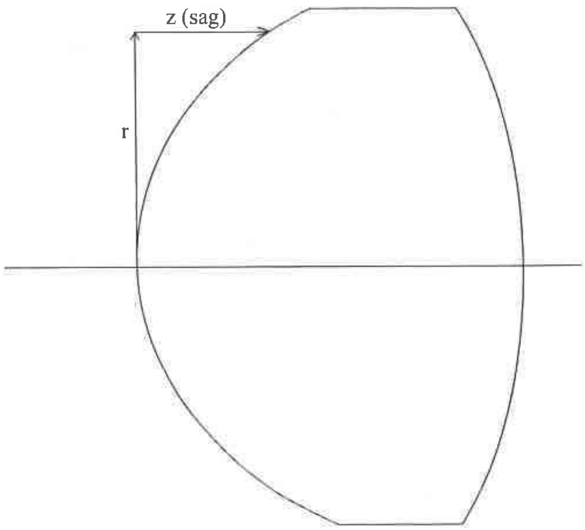

Figure 4.15 Illustration of sag for an aspheric surface.

surface. Using the description in Eq. (4.6), a surface that has a conic constant of 0 is spherical, a surface with a conic constant between 0 and –1 is a (prolate) ellipsoid, a surface with a conic constant equal to –1 is a paraboloid, and a surface with a conic constant less than –1 is a hyperboloid. The conic constant can also be greater than zero, in which case the surface is an oblate ellipsoid.

Conic surfaces have the property of perfect point-to-point reflective imaging for a single pair of points along their axis. For instance, an ellipse provides perfect imaging between its two foci, while a parabola provides perfect imaging of a point at infinity. Thus, a parabolic surface can take a collimated on-axis input beam and focus the beam perfectly at its focal point. As soon as the beam moves off axis, however, there will no longer be perfect imagery.

Conics have long been used in the design of reflecting telescopes. The Ritchey-Chretien telescope form, which consists of hyperbolic primary and secondary mirrors, is an example of this. Conics' property of on-axis point-to-point imaging is useful as a test method in their production. A point source, or input collimated beam in the case of parabolic surfaces, can be used, and the resulting image evaluated. Assuming proper object and focus position, deviation from perfect imagery results from imperfect surface form. Interpretation of the point-source image allows correction of the surface to its proper form.

The second common form of description of aspheric surfaces is a polynomial addition to a sphere or conic, as is shown in Eq. (4.7). This is a fairly standard form used in most optical design software:

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + a_2r^4 + a_3r^6 + a_4r^8 + a_5r^{10} + \cdots, \tag{4.7}$$

where the a_i *terms* are the coefficients of the aspheric terms, and the other variables are the same as in Eq. (4.6).

In Eq. (4.7), the asphere is described using even powers. Sometimes, the absolute value of odd power terms is also used (if the absolute value is not taken, the surface will not be rotationally symmetric). The naming convention of this type of aspheric surface is related to the highest power used. For instance, if the highest order coefficient used is that related to the eighth power, we would say that the surface is an eighth-order polynomial asphere. Obviously, there is an assumption that we are using the standard even-ordered form. To be more specific, we may say we have an eighth-order, even-polynomial asphere.

Polynomial aspheric surfaces do not exhibit the point-to-point imagery of conic surfaces. This means they cannot be tested in the same way. In the past, this often led to conics being selected over polynomial aspheres. Developments in machining and testing have made this much less of a concern, and polynomial aspheric surfaces are frequently used in systems where the surfaces will be produced by diamond turning and/or molding, such as in reflective, infrared, and plastic optical systems.

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In addition to the conic and polynomial representation of aspheric surfaces, there are several other forms. Most optical design programs provide the choice of multiple aspheric surface representations as well as the option for user-defined surfaces. In some cases, the aspheric surface may not have a closed-form solution but may be represented by an array of points, with a suitable interpolation in between.

When required, nonrotationally symmetric aspheric surfaces are also used. In some cases, the surface is simply an off-axis section of a rotationally symmetric surface. Thus, the parent surface is rotationally symmetric, but the used section is not. In other cases, the surface is an extension of the surfaces already described. Instead of describing the surface by a single radial variable, two variables (often the Cartesian coordinates x and y) are used. For instance, a biconic surface may be utilized, which will be described by (possibly) two radii, and two conic constants, k_x and k_y. Similarly, we can change from the radial variable on the polynomial asphere to two Cartesian variables, resulting in an anamorphic asphere. Nonrotationally symmetric aspheres may be used in applications where some system characteristic is nonrotationally symmetric. For instance, laser diodes often emit a noncircular beam that has inherent astigmatism. Nonrotationally symmetric aspheric surfaces may be used to correct this output beam.

In classical optical design, designers are often taught to do as much as possible using spherical surfaces, with an asphere grudgingly used as a last resort in order to meet some performance requirement. As such, the general design form may be well established before the addition of an aspheric surface, with the asphere tweaking up the system performance but not necessarily altering the basic form of the system. This design philosophy is changing somewhat as the use of aspheric surfaces becomes less costly. In the design of plastic optical systems, the decision to use aspheric surfaces is often almost a foregone conclusion, changing the point at which they are inserted into the design process as compared to classical glass systems. This can result in design forms that are distinctly different from those created if the asphere were added near the end of the (local) design optimization. In theory, if global optimization is used (and works as desired), similar solutions should be identified regardless of what starting point design the aspheric surface is added to, provided the necessary variables are available. As the use of aspheric surfaces in optical systems has become more common, there have been increased publications on their use[71] as well as courses on the subject.[72] In addition to these resources, we refer the reader to the chapter by Shannon.[73]

From a simple viewpoint, the location of an aspheric surface determines the effect it has on aberrations. By location, we are referring to the distance of the aspheric surface from the aperture stop (or pupils) of the system. An aspheric surface that is placed at the aperture stop will only affect the spherical aberration produced by the surface, while an aspheric surface that is placed away from the aperture stop will affect spherical aberration, coma, astigmatism, and distortion. One way to think of this is to consider the beam placements on the surface. At the aperture stop, all the beams from the different field angles pass together through the stop. Thus, all fields will see essentially the same effect from the surface, affecting aberrations that do not depend on the field angle, such as spherical aberration. When the aspheric surface is away from the aperture stop (or its images, the pupils), the beams associated with different fields are separated on the surface and will each see a somewhat different effect from the aspheric surface. Thus, multiple aberrations can be affected.

There is no definitive rule for selection of which surface or surfaces on which to use aspheres. From the discussion above, it would make sense to place an asphere near the stop if we are attempting to control spherical aberration, and away from the stop if we are trying to control field-dependent aberrations, such as coma and astigmatism. Of course, in a multielement system, it is the combined aberration content that ultimately determines the image quality. If we place an aspheric surface on one element (for instance, near the stop), the ability to control spherical aberration through this asphere means that the other elements do not need to "worry" about spherical aberration as much, and we can change their shape to work on other aberrations. Thus, the addition of an aspheric surface on one element of the system can not only change that element but also potentially change the other elements. In general, placing an asphere on the surface with the largest beam extent will provide the maximum aspheric leverage.

In the design process of plastic optical systems, it may be useful to make one surface on each of the elements aspheric and allow the optimization of the lens design software to use them as appropriate. It is generally not good practice to make all of the surfaces aspheres from the start. In this case, the optimization algorithm may "beat" the aspheres against each other, introducing a large amount of aberration at one surface that is cancelled by a large negative amount of the same aberration at another surface. This is not a preferred design form because it will tend to be more sensitive to assembly tolerances of the system, such as decenter. If one aspheric surface per lens element is not providing adequate performance, additional aspheric surfaces may be added to determine any performance advantage.

When using aspheric surfaces in a design, a few changes in the setup used for spherical lens design are in order. First, the number of field angles defined should generally be increased. In a design using spherical lenses, it is common to have three or four defined field angles. In designs using multiple aspheric surfaces, it is possible for the lens to be well corrected at these three or four field angles and to perform poorly in between them. This can sometimes be seen by looking at the astigmatic field plots, which may curve repeatedly back and forth, crossing zero at each of the defined fields. By adding additional field angles, we can force the optimization algorithm to work on the performance across the entire image plane. We essentially do not provide the algorithm enough room in the field spacing to allow the performance to "wiggle," as it could with fewer defined fields.

In addition to increasing the number of defined fields, it is also useful to increase the ray density that the optimization algorithm uses. As in the case of too few field angles, if there are too few rays, they may be well corrected, but

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other rays that are not evaluated may not be. This can result in a low merit-function value that suddenly increases when a denser ray grid is used. It is a good practice when using a large number of aspheres to increase the ray density and ensure that there is no significant change in performance.

A final adjustment when designing with aspheric surfaces is to either reduce the minimum improvement value that stops the optimization cycle or to repeatedly run the optimization algorithm. Sometimes, systems with multiple aspheric surfaces will stagnate during the optimization process. However, repeatedly running the optimization algorithm often will continue to drive the merit function value down.

Throughout the design process, or at least near its end, all aspheric surfaces should be evaluated against a "best-fit sphere." A best-fit sphere is a spherical surface with the radius selected such that it has minimal departure from the aspheric surface. In the grinding and polishing of glass aspheres, the use of a best-fit sphere as a starting point minimizes the amount of material that must be removed to create the aspheric surface. In the case of molded parts, if a spherical base surface is used on the optical insert, it may determine how much nickel plating needs to be removed. An important reason to evaluate the asphere against a best-fit sphere is to determine whether the asphere is really necessary. Once aspheric terms are set as variables in the optimization algorithm within the lens design software, they will likely be used, regardless of how small the advantage gained.

If it is determined from comparison to the best-fit sphere that the asphere has a very small departure, then the aspheric surface should be made spherical and the design reoptimized to see if a performance difference results. This may seem at odds with our earlier statements about the cost of aspheres and spheres being the same. In actuality, we are not concerned about cost savings but in creating fewer potential problems by simplifying the system. To put it plainly, there is no need to make the system more complex than it needs to be, just because we can. A sphere, which is defined completely by its radius, is easier to describe than an asphere. This means that fewer terms need to be considered during the manufacture and testing of the surface. This results in less chance for errors due to interchanging digits during any entry of numbers, such as aspheric coefficients. Also, a sphere is easier to test than an asphere, giving more options for the vendor (or customer) to verify the surface.

In addition to comparing the aspheric surfaces to best-fit spheres, the designer should also evaluate the aberration produced by each surface. As mentioned earlier, having too many aspheric surfaces may simply result in them beating against each other. Most optical design codes will provide graphs and/or numerical values of the various aberration contributions of each surface. These can be used to determine if aspheric surfaces are working with or against each other.

While the optical design code can create any shape asphere allowed by the coefficients it can vary, the designer needs to ensure that the aspheric surface can be produced and tested. Most aspheres can be molded, but there are differing levels of complexity. For instance, if the aspheric surface is so steeply curved that it rolls back past a line drawn perpendicular to its axis (that is, it goes beyond a hemisphere) it may not be able to be manufactured in a straight-draw mold. Also, steeply curved surfaces may be difficult to test, making it hard to verify that they have been correctly manufactured.

For the most part, the ability to use aspheric surfaces provides a positive impact on the design of plastic optical systems. However, there can be one particular drawback to using refractive aspheric surfaces (in plastic or glass), which is the chromatic variation of aberrations. Aspheric surfaces do not change the axial or lateral color introduced by a surface. If the asphere is being used to introduce spherical aberration with the intention of offsetting the contributions from other surfaces, it will also introduce spherochromatism, the variation of spherical aberration with wavelength. The amount of spherochromatism introduced will generally be the amount of spherical aberration created by the surface divided by the Abbe number of the lens material. In some cases, spherochromatism can be used to balance the effect of axial color. Other times, however, it may degrade an otherwise monochromatically well-corrected solution. The designer needs to keep in mind the purpose of each aspheric surface and what benefit it brings to the overall design. Aspheric surfaces that do not provide benefit to the design should be removed.

4.6 Diffractive Surfaces

Diffractive surfaces rely upon the wave nature of light to perform their function. They typically consist of some form of microstructure on the optical surface. As a beam of light passes through the diffractive surface, the various microstructure features impart phase delays (usually 2π) to the different portions of the incident beam. As the beam propagates, these different portions interfere with each other, similar to the way that waves in water can combine to form regions of larger or smaller waves. By correctly designing the diffractive microstructures, we can get a desired beam from the surface in a manner similar to designing an aspheric surface to create or eliminate specific aberrations.

Diffractive optical surfaces are used for a variety of purposes, such as fan-out gratings, athermalization, and beam shaping. In many plastic optics imaging systems employing diffractive optics, they are used for color correction, that is, to control chromatic aberration. In this section, a brief overview of their use for this purpose is given. Readers interested in a more thorough discussion of diffractive optics are referred to Ref. 74.

Probably the best-known diffractive surface is the diffraction grating. A diffraction grating normally consists of a substrate with a pattern of parallel-ruled lines on it. Diffraction gratings are often used to separate wavelengths of light, sending each wavelength away from the surface in a different direction. The diffractive surfaces used for color correction are somewhat similar to a diffraction grating, with the difference that instead of a series of parallel-ruled

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lines, the diffractive-color-correction surface (from here forward called a "diffractive") typically consists of a series of concentric rings. Unlike the equal spacing of lines often seen on diffraction gratings, the rings on a color-correcting diffractive surface are not normally equally spaced. The diffractive configuration most often seen has its rings becoming more closely spaced as we move out radially from the center of the surface.

Even though they rely on the wave nature of light, we are usually able to design and analyze diffractive surfaces using rays. This is helpful, as most optical design software specializes in ray tracing. When using a refractive or reflective surface, the path of the rays is determined by the use of Snell's law. When using a diffractive surface, the path of a ray is determined instead by the grating equation, which is shown in Eq. (4.8) for the case of normal incidence:

$$m\lambda = d\sin\theta, \tag{4.8}$$

where m is the order of the diffractive, λ is the wavelength of light, θ is the output angle, and d is the grating spacing. Those familiar with diffraction gratings will recognize this equation. Figure 4.16 shows a ray passing through a diffractive surface with the various parameters labeled.

We see from Eq. (4.8) that there is a parameter m, which defines the order of the diffractive. The fact that the equation can have multiple solutions for different values of m, the order number, means that we could have multiple beams coming

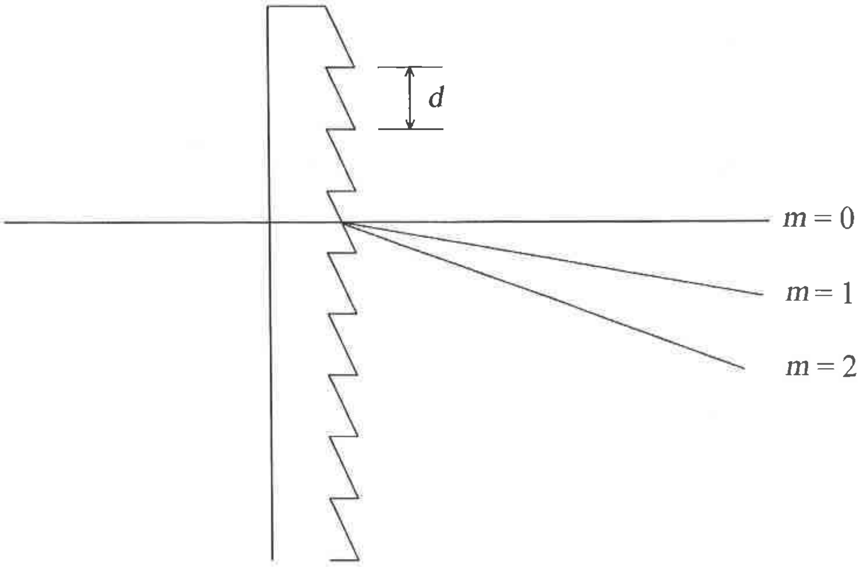

Figure 4.16 Ray passing through a diffractive surface.

from the surface. For instance, we may have one beam associated with the zero order, one beam for the first order, and another beam for the second order, as is shown in Fig. 4.16. The amount of light that is in each order is known as the diffraction efficiency of the order. For color correction in imaging systems, we typically want all of the light in a single order. The preferred diffraction order is known as the design order. In the optical design process, this order is usually taken to be the first order ($m = 1$). The amount of light in each order depends upon the shape and depth of the diffractive groove, as well as on the wavelength of light. The depth of the diffractive groove is usually selected for a wavelength somewhere near the center of the spectral band. For a diffractive surface in air, the depth of the diffractive groove is typically taken as

$$h = \frac{\lambda_0}{n-1}, \tag{4.9}$$

where h is the depth of the groove, λ_0 is the design wavelength, and n is the refractive index of the diffractive substrate for the design wavelength. Because the groove depth is set for one wavelength, the diffractive will not work perfectly for other wavelengths (except in special cases). That is, the diffraction efficiency in the design order will only be 100% (in theory) for a single wavelength. The diffraction efficiency for a given wavelength depends on the ratio of the design wavelength to the wavelength of interest. The efficiency of any wavelength, $\eta(\lambda)$, can be calculated from Eq. (4.10):

$$\eta(\lambda) = \left(\frac{\sin\{\pi[(\lambda_0/\lambda) - m]\}}{\pi[(\lambda_0/\lambda) - m]} \right)^2, \tag{4.10}$$

where λ_0 is the design wavelength, and m is the design order of the diffractive. Figure 4.17 shows a plot of (normalized) diffraction efficiency using this equation for a design wavelength of 550 nm and a design order of one. Imperfect diffraction efficiency (less than 100%) for wavelengths other than the design wavelength results in the transfer of energy, as a function of wavelength, into other diffractive orders. The light in these other orders will continue to propagate through the remainder of the optical system and can end up as stray light or as ghost images.

As an optical element, diffractive surfaces have the interesting property of possessing a negative Abbe number, which we have not seen to this point. For the visible wavelength range, the Abbe number of a diffractive surface is –3.45. We discussed earlier that the Abbe number describes how much the refractive index of a material changes with wavelength, and that lower Abbe numbers mean that the material is more dispersive. A more dispersive material results in a larger difference in direction between two colors, for instance red and blue. We also

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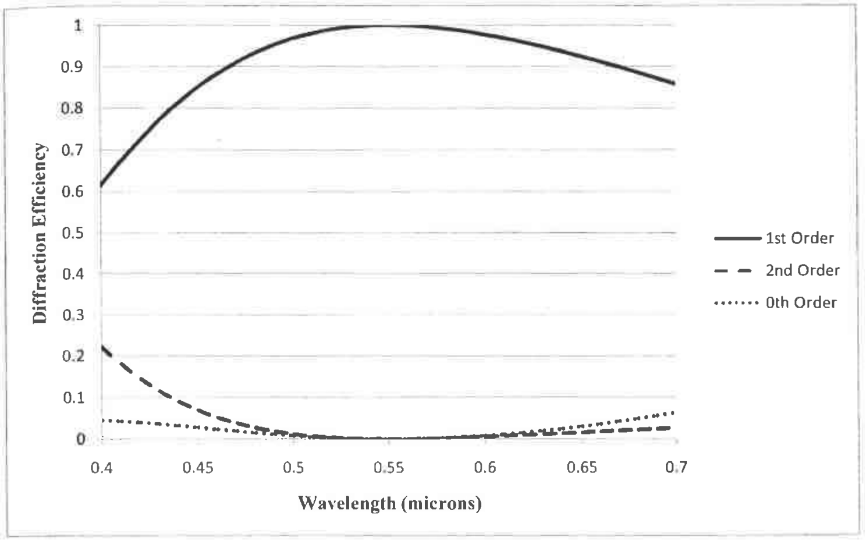

Figure 4.17 Plot of diffraction efficiency versus wavelength for a first-order diffractive design.

saw earlier that in a typical positive lens, the blue light would focus closer to the lens than the red light. For a (positive-powered) diffractive surface, the opposite is true: the red light will focus closer to the surface than the blue light. This is what is meant by the negative sign of the diffractive Abbe number. The red light focuses nearer to the surface than the blue because the light paths for a diffractive are determined by the grating equation instead of by Snell's law.

Knowing this, it is a logical step to consider combining a refractive and diffractive surface to get the red and blue light to focus together, eliminating axial color. Just as we can combine lenses of two different glasses to form an achromatic doublet, we can combine a diffractive surface with a refractive lens to form what is usually called a "hybrid lens." Also similar to a standard doublet, we do not necessarily need to fully correct the chromatic aberration of the combination. In this way, we are essentially creating a new glass, one that has the desired chromatic properties; Stone and George published a study on this subject.[75] Using a diffractive surface, we can do this without having to add an additional lens element. This is particularly useful for plastic optical systems because there are a limited number of materials to choose from, and constraints often limit the number of lens elements allowed in a system.

The design of diffractive surfaces using optical design software is fairly straightforward. The diffractive surface can be described in several ways; the most common of which is by using a polynomial description, similar to the one used for even-polynomial aspheric surfaces. It should be noted that the coefficients for the diffractive surfaces usually start at the second order, as opposed to the fourth order often seen on polynomial aspheres. This is an important distinction, as the second-order coefficient is used to provide optical power, while the higher-order coefficients provide aberration correction. The use of the second-order diffractive term is typically all that is needed to control chromatic aberration. The use of the higher-order diffractive coefficients is generally not recommended unless they bring significant improvement to the design. Some vendors are unfamiliar with diffractives using higher-order coefficients, which can lead to confusion in their manufacture. If higher-order diffractive terms are used, extra attention to detail is warranted.

Similar to the effect of location of an aspheric surface, the position of a diffractive surface with the system will determine its effect on chromatic aberration. If the diffractive is positioned at the stop (or at a pupil of the system), it will only affect the axial color. If it is positioned away from the stop, it will affect both axial and lateral color. Because of this, engineers sometimes design systems with multiple diffractive surfaces, similar to using multiple aspheric surfaces. This is generally not a wise design practice. We have already discussed how using a diffractive element will result in losses due to diffraction efficiency. Using multiple diffractive surfaces will only compound this effect.

Also similar to designing with aspheric surfaces, it is easy to let the optimization algorithm run wild with the polynomial coefficients when using a diffractive in a design. Many a designer has had the sinking feeling that comes from seeing what looks like a great design solution turn out to be essentially worthless, due to the unrealistic groove spacings on the diffractive. In most design codes, minimum diffractive groove spacing can be set as a constraint on the optimization. The designer needs to keep an eye on the groove spacing as the design progresses to verify that it is not becoming too small. Most design codes have commands to plot the diffractive feature size as a function of radial location.

On the other hand, the designer also needs to ensure that the diffractive spacing does not become too large, at least in comparison with the beam size on the surface. Because the diffractive works by the interference of beams from different portions of the microstructured surface, it is important that the beam associated with each field angle covers several diffractive grooves. In most plastic optical systems this is not a concern; having too small a groove spacing is more common. However, unless told to do so, the design code will not be concerned with groove spacing. It relies on the polynomial coefficient representation of the surface and is not concerned with the effect of turning it into a surface relief pattern.

To convert from the polynomial description to an actual microstructured surface, the sag of the diffractive surface is first computed. Then, in a manner similar to producing a Fresnel lens, the surface is "collapsed" with a step occurring each time the sag reaches a multiple of the diffractive step height, which is typically the value shown in Eq. (4.9).

When calling out diffractive surfaces on a drawing, it is good practice to show a profile of the diffractive surface, often with the groove depth exaggerated,

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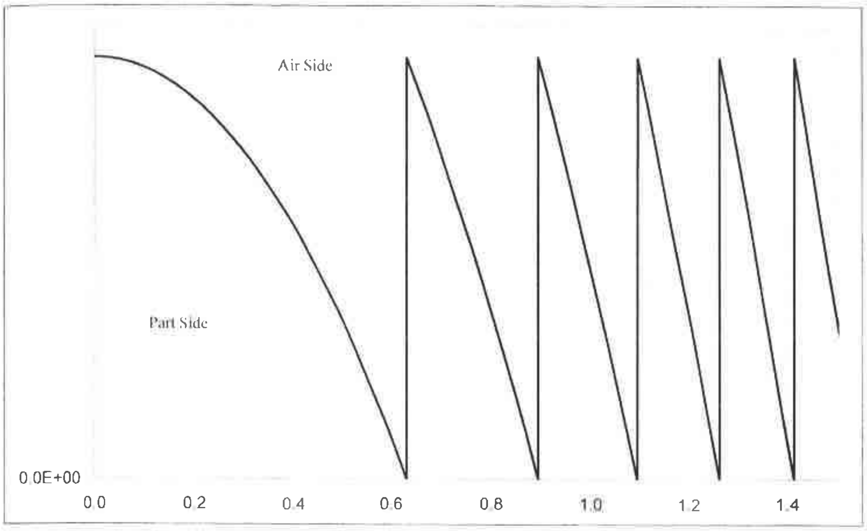

Figure 4.18 Example of diffractive profile showing step orientation.

and with labeling indicating the "part side" and the "air side." This can prevent confusion as to the correct orientation of the diffractive steps. An example of this is shown in Fig. 4.18.

Diffractives, or the microstructures that form them, can be manufactured on planar, spherical, or aspheric base surfaces. The optical design codes support each of these surface types. The decision as to what type of base surface to use will depend in part on how the diffractive master is made. If the master is to be made by diamond turning, which is most often the case for the molded chromatic-controlling diffractives discussed here, the surface can be any form that can be diamond turned. For other types of diffractive functions, such as fan-out gratings, the master may be created through a lithographic process that typically works best with planar surfaces.

We mentioned earlier in this section that the first order is normally selected as the design order. However, there are cases where a larger design order is intentionally selected. These types of diffractives, known as multiorder diffractives (MODs) or harmonic diffractive lenses (HDLs), will be discussed in one of the design examples.

4.7 Athermalization

We discussed earlier that one potential downside to the use of plastic optics is that a focus shift may occur over temperature due to the thermal properties of the materials. Plastic optical materials have a coefficient of thermal expansion (CTE) and a change in refractive index with temperature (*dn*/*dt*) that are much larger than that of glass optical materials. These properties make it more difficult to design a system that does not significantly change performance over temperature.

From the selfish viewpoint of the optical designer, the easiest way to deal with a potential focus shift due to temperature changes is to make it someone else's problem by requiring the use of a manual focus adjustment or an autofocus system. Of course, if the optical designer is also the optomechanical designer, the feeling of happiness at having shifted the problem may be short lived. While the use of manual or autofocus systems can greatly reduce the demands on the optical design over temperature, in many systems using plastic optics these are not viable solutions due to cost constraints, packaging issues, or customer desires. In this case, the designer needs to work towards developing an optical system that can work over temperature without relying on focus adjustment, that is, one that is athermalized.

Several methods are commonly used to athermalize systems that incorporate plastic optical elements. One popular method is to combine elements made of glass with elements made of plastic. This is sometimes referred to as a "hybrid" lens or as a plastic-glass design. This method can be thought of as trying to use "the best of both worlds." We know from our earlier discussions that glass lenses have a much smaller thermal focus shift than plastic lenses do. We also know that it is much easier and more cost effective to create aspheric surfaces on a plastic element. Thus, we can use a conventional (spherical) glass element to provide most of the optical power, which limits the focus shift, and use low-power aspheric plastic lenses to provide aberration correction.

Another method, which due to terminology can be confused with the method above, is the use of a diffractive surface to athermalize a design. Lenses with diffractive surfaces are also sometimes referred to as hybrid lenses. Unlike the previously discussed use of a diffractive to correct chromatic aberration, the diffractive in this case changes power over temperature to compensate the power change in the base refractive lens. Similar to equations that can be used in the first-order design of an achromatic doublet, a set of equations can be developed for the first-order design of a temperature-corrected refractive/diffractive lens, often referred to as an athermat.[76] Because of the chromatic dependence of the diffractive element, singlet athermats are typically used with narrow wavebands or in laser-based systems. It is possible to extend the waveband by using the diffractive surface in combination with a doublet. The reader is cautioned that several patents exist that utilize this athermalization method.[77,78]

The use of plastic mirrors is another method of athermalization. It should be noted that an all-reflective system made of a single material is inherently athermal because a temperature change simply scales the entire system up or down for this type of design. It is as if the entire system was put into a 3D copy machine, and a slight scale factor applied. It is also possible to combine reflective and refractive elements, which is known as a catadioptric system. Since reflective elements do not rely on the refractive index of the base material, the large change in index associated with optical plastics does not affect the power of the mirror, only the coefficient of thermal expansion does this.

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Another athermalization method, when using all plastic elements, is to balance the power changes amongst the elements such that they (partially or completely) compensate for each other over temperature. This method is similar to what is performed on many glass element systems. It is important to remember that when the temperature of the optical system changes, not only are the lenses affected, but also any associated spacers or mounting structures. This may cause the spacing of the lenses to change as well as the location of the detector or film that will capture the image. What is usually important is not that the image stay in the same location over temperature, but that the image remain focused on the detector over temperature.

Understanding that the image may move, with a corresponding motion of the detector, allows for the athermalization of optical systems through the appropriate selection of materials. For instance, returning to the acrylic lens discussed in Chapter 2, we found that for a 50 °C temperature increase, the focus position of the lens shifted by 0.681 mm. If we were able to have the detector move by the same amount, the image would remain in focus over the temperature change. In that case, the image plane was originally 47.3 mm behind the rear surface of the lens. To achieve a 0.681-mm-length increase from a 47.3 mm length (over a 50 °C temperature change) would require a material with a CTE of about 288×10^{-6} per °C. This CTE is much higher than what is seen in most materials, so there may be no direct solution in this case. However, if we were to use multiple lenses and reduce the amount of focus shift, a suitable (and available) material could potentially be found.

If the desired CTE falls between that of two available materials, it is possible to combine different lengths of the two materials to achieve an effective CTE matching the desired value. Putting an optical spin on this, it is similar to combining two glasses in a doublet to create an effective glass with the desired chromatic characteristics. In addition to material selection and combination, mounting configuration can also be used to control thermal performance.[79] The use of proper optomechanical material selection and mount design, combined with the use of appropriate lens powers and optical materials, is the most frequently used method of athermalizing systems using plastic optical elements.

Regardless of which athermalization method is selected, the design and analysis of the system over temperature must be performed. This is typically conducted through a first-order analysis and/or by using optical design software. A first-order analysis is usually concerned with the lens power and image location and not with the image quality. In the case of singlet athermats, the first-order analysis would entail using the athermat equations to determine the necessary powers of the refractive and diffractive surfaces. For the method of balancing the power changes of the various refractive elements, similar equations can be developed. In some cases it may be useful to have a spreadsheet that calculates the power change of each element as well as the power change of the entire system and the image location, as a function of temperature. After the initial analysis, optical design software may be used to further develop the design.[80]

For many systems, there is a requirement for both ambient image quality as well as (possibly reduced) image quality over temperature. We discussed some design techniques for controlling aberrations, which may limit image quality, earlier in this chapter. Having a requirement for performance over temperature can be thought of as an additional constraint on our image quality requirement. Thus, one way that we can attempt to fulfill both requirements during the design process is to add the thermal performance as a constraint in our optical design software model. This is typically done through the use of a multiconfiguration or "zoom" model. These models are normally used in the design of zoom lenses, which work over a range of focal lengths and object distances. In our thermal case, instead of having the system zoomed over focal length, we zoom it over temperature.

A fairly standard technique to do this is to create three zoom positions, also called a three-configuration model. The first zoom position models the lens system at ambient temperature, while the second position represents the lens system at an elevated (hot) temperature, and the third zoom position represents the lens system at a lower (cold) temperature. The various element parameters are linked across the zoom positions, such that their values are those associated with the position's temperature. For instance, if we consider the radius on a surface in the first zoom position, the same surface in the second zoom position will have a slightly larger radius value. Similarly, the surface in the third zoom position will have a slightly smaller radius value, due to the change that would occur from the lens material's CTE value in conjunction with the temperature difference between the respective zoom positions.

Linking the various parameters across the zoom positions in this way is known as "picking up" the parameter. As a linked parameter (for instance, a radius in zoom position one) is varied by the optimization algorithm, the radius values in zoom positions two and three will change accordingly, keeping the correct scale factor with respect to the value in zoom position one. The merit function of the lens should consider the image quality across all three zoom positions. If there is a performance relaxation at the temperature extremes, the zoom positions representing these temperatures can have a reduced weight in the merit function. While the radius scale factor depends on the material CTE and temperature, the scale factor for the refractive index, which also must be adjusted across the zoom positions, would depend on the *dn*/*dt* of the material and the temperature.

When using aspheric and diffractive surfaces, care must be taken with the scaling of the aspheric and diffractive coefficients. Aspheric coefficients typically scale with a power of one less than the term the coefficient is associated with, while diffractive coefficients (depending on the representation used in the program) may scale with a power one less than that of the associated term or with a power equal to that of the associated term. Simple tests should be run to verify that the appropriate scaling is taking place. It should also be noted that conic constants do not scale with temperature but remain at a constant value. As such,

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The temperatures for the zoom positions are usually taken at the extremes of the temperature range the system must operate over, though they need not be. Some material properties can vary with temperature, so different CTEs, *dn*/*dt*s, etc. may be associated with different zoom positions. In this case, depending on the complexity of the system, or the size of the temperature range, three zoom positions may not be adequate, requiring additional positions to be added. Similar to our discussion of the need to add extra field angles when using aspheric surfaces, before completing the design, the designer should evaluate temperatures in between the zoom positions to verify performance throughout the entire temperature range.

In addition to material properties, attention must be paid to the mounting features of the elements. Most optical design codes consider thickness based on the distance between the vertices of adjacent optical surfaces. However, this thickness may not be the appropriate distance to use in the calculation of lens position shift due to thermal expansion, as the lens is not normally attached to the barrel by its vertex. Consider the case of the lens shown in Fig. 4.19. The lens barrel length is different from the thickness between the lens vertex and the end of the barrel. In this case, the expansion of the lens barrel material, as well as that of the lens material, must be taken into account. This is often performed in the lens design program by adding "dummy" surfaces, which take the mounting features into account.

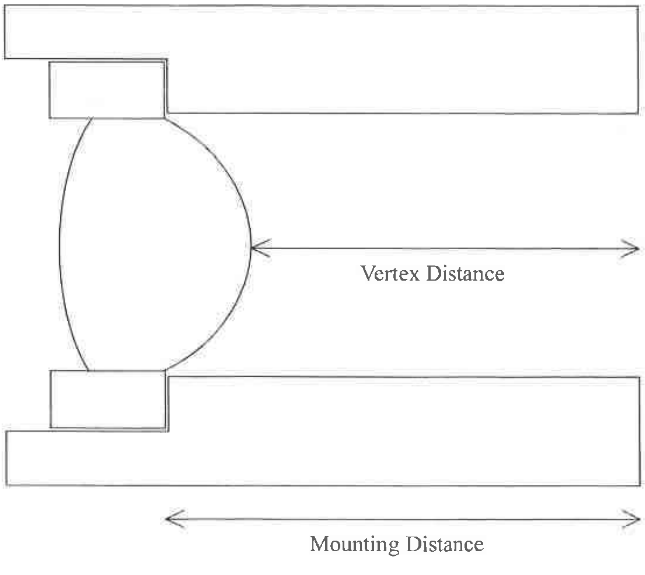

Figure 4.19 Difference in mounting distance versus vertex distance, which must be accounted for in athermalization optimization.

Once the multiconfiguration model has been created, optimization occurs in a way similar to that of a single-configuration system. Because of the additional thermal performance constraints, the design process may take more designer intervention than usual. The designer may need to change the lens or spacer materials or add additional elements to provide more variables for the optimization algorithm. Again, the software should not just be "left to its own devices;" the designer must remain involved in the design process.

Although not explicitly stated, the discussion on athermalization in this section has been based on the assumption of a thermal soak, which means that all of the system is at a uniform temperature. In reality, this may not be the case, as temperature gradients may exist throughout the system. This is most likely to be seen in systems subjected to rapid temperature changes, such as military hardware. In many cases, due to variations and permutations of operating conditions, no single thermal gradient model may cover the entire spectrum of thermal gradients that may be seen. The design and analysis of systems under the influence of temperature gradients is more complex than systems assumed to be under thermal soak, and we do not discuss them here. However, once an understanding of thermal soak design and analysis is obtained, the extension to thermal gradients, though they require more complex models, is a fairly straightforward and logical one.

4.8 Coatings

Coatings on plastic optics are typically used for one of two purposes: either to perform an optical function, such as reducing the surface reflectance, or to improve the mechanical or chemical properties of the surface. In some cases, multiple coatings are applied to achieve both purposes. Most of the development of coatings for plastic optics has occurred in the last 30 years, with increased improvements made in the last decade or so. The early development of coatings for plastic optics was driven by the ophthalmic market. The increased use of polycarbonate eyeglass lenses in the 1980s created demand for antireflection coatings that would work with that material. In addition, coatings to improve the scratch resistance of the lenses were also desired. As a result of this early demand, as well as the increased use of polycarbonate in the automotive market, coatings for polycarbonate are probably the most developed.

With the introduction of new materials, such as the cyclic olefins, and the increased use of plastic optics in general, there has been a renewed push for the development of coatings for plastic optics. The main issue with the development of optical coatings for plastic elements is the plastic materials themselves. As we mentioned previously, plastic materials have lower deflection and melting temperatures than optical glasses. As a result of this, standard processes used in the application of optical coatings to glass lenses cannot be employed with plastic lenses.

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When applying optical coatings to glass elements, the process normally takes place at an elevated temperature. This temperature activates the surface the coating will be applied to, producing coatings that have stable optical and mechanical properties. The temperature required to properly activate the surface is higher than the deflection temperature of most of the optical plastics. This would result in deformation of the plastic optic if this standard coating process were applied.

There are three main coating deposition methods for use with plastic optics. These are physical vapor deposition, chemical vapor deposition, and wet processes (spin or dip coating). The first two methods are most commonly used. Since elevated temperatures cannot be used to activate the surfaces of optical plastics, alternate methods of surface activation have been developed, such as the use of ion guns and plasmas.

A commonly used coating for plastic optics is an antireflection (AR) coating. We saw in our earlier discussion of material properties that uncoated plastic optics have transmissions in the low 90% range. This is due to the reflection loss at each of the surfaces of the element. For an uncoated surface, the amount of reflection at an air/plastic interface, for normal incidence, is given by

$$R = \frac{(n-1)^2}{(n+1)^2}, \tag{4.11}$$

where n is the refractive index of the material. Using an index of 1.492, that of acrylic, results in a single surface reflectance loss of 0.039 or 3.9%. If we had a three-element lens system (six surfaces), the transmission after only taking the surface reflection losses into account would be 78.8%. This transmission value can be increased by using AR surfaces on some or all of the lenses.

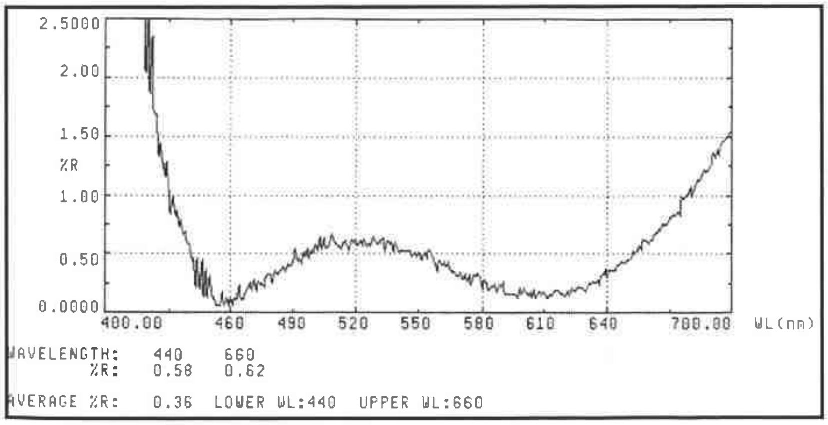

Figure 4.20 Measured performance of a typical multilayer AR coating. (Figure courtesy of Alan Symmons.)

Most coaters have a catalog of coatings to choose from, depending on the required performance.[81] The rule of thumb for AR coatings (and most coatings in general) is that the wider the waveband desired, and the better the performance desired, the more complex the coating. Figure 4.20 shows the measured performance of a typical multilayer AR coating for the visible waveband. In addition to AR coatings, other optical coatings are also available, such as bandpass filters, infrared blocking filters, and reflective coatings.

The use of reflective coatings in the production of plastic mirrors is quite common in a number of applications, such as medical devices and the automotive industry. The material used for the reflective coating depends on the waveband of interest. Aluminum and silver are used for the visible waveband, while gold is often used for the infrared.

In addition to these optical functions, coatings on plastic optics can be used for other purposes. Because of the lower scratch resistance of optical plastics compared to optical glasses, hardcoats can be applied to the plastics to improve their handling performance. In cases where the optical components or housing surround sensitive electronics, conductive coatings can be applied to prevent the buildup of static as well as to reduce electromagnetic interference. Coatings can also be applied in order to reduce absorption of water by the plastic substrate.

Coatings for plastic optics can be specified in the same manner as coatings for optical glasses. The coatings are often called out to meet the adhesion, moderate abrasion, and humidity requirements of MIL-PRF-13830. One particular problem with coatings on plastic optical elements can be crazing due to thermal cycling, where crazing is the development of a network of fine cracks. As noted previously, plastic optical materials have a larger coefficient of thermal expansion than optical glasses. This results in a greater expansion over temperature, which the coating must be able to deal with. As part of the coating specification, a temperature range as well as the maximum temperature ramp (change rate of temperature) should be included. A thermal cycling test can also be included.

Proof of coating conformance is often obtained through the use of witness samples, small disks, or wedges that are coated together with the parts. The transmission or reflectance tests as well as the adhesion, abrasion, humidity, and temperature testing are typically performed on the witness samples. Of course, it is the performance of the coating on the optical parts that ultimately matters. In order to get the best correlation between part and witness sample, the witness samples should be made of the identical material as the parts and processed in the same manner as the parts.

Most producers of plastic optics either have coating equipment and capability themselves or work closely with a local company that has it. In general, it is preferred that the producer of the parts be held responsible for their coating, as opposed to the producer shipping the parts to the customer, who then sends them out for coating. This reduces the potential for contamination of the parts before coating and reduces finger pointing in the event of an unsuccessful coating run.

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The primary downside to the use of coatings is their cost. When using plastic optics to reduce cost, the need for coatings can limit the cost savings. The application of coatings on plastic optics can increase their price anywhere from 10% to 100%. Coating runs, regardless of the number of parts coated, have a somewhat fixed price due to the need to pull a vacuum on the coating chamber. In order to reduce cost, as many pieces as possible should be coated in a single run. If there is considerable risk in the coating run, the parts may be divided into two runs in order to improve the odds of at least one batch of parts yielding.

For the reader interested in additional information on coatings for plastic optics, a thorough review, with extensive references, can be found in the chapter by Schulz.[82] More recent articles can also be found in journals and in conference proceedings.[83,84]

In addition to surface coatings, changes in spectral performance of plastic optics can also be achieved through the use of dyes, which can be mixed in with the plastic pellets during the injection molding process. A well-known example of this is the purplish windows seen on TV remote controls. The purplish color results from the absorbing dye in the material. In this case, the dye is used to block the visible band while allowing the near infrared (NIR) band to be transmitted. The complementary dye is sometimes used in optical systems employing complementary metal-oxide semiconductor (CMOS) sensors, such as Webcams, which are sensitive out to the NIR band. In this case, the near infrared is blocked and the visible spectrum is passed.

The main concern with these dyes is the sharpness of their spectral characteristics. The dyes tend not to have sharp cutoffs and cut-ons. Instead, these features tend to be more of a rolling change. This may be a problem in systems that require a well-defined transition between transmission and absorption/reflection. The dyes can also sometimes be sensitive to the thermal environment of the molding machine and may change property if the residence time is too long. However, the use of these dyes, in combination with the surface coatings above, may result in a cost savings by reducing the complexity of the coating required.

4.9 Optomechanical Design

The goal of the optomechanical designer is to adequately maintain the position (and shape) of the optical elements in a system over the various environments the system is subjected to. By "adequately," we mean that the positions and shapes of the elements can change but only by an amount that ensures the system performance requirements are still met. The characteristics of plastic optics, such as molded-in flanges and integral mounting features, can provide the optomechanical designer with freedom and room for creativity in his optomechanical design.

The optomechanical designer should be involved early in the design process. Too many times, the optical engineer performs their design work, then "throws the design over the wall" to the optomechanical designer. Working in this fashion often produces a nonoptimal design. The best overall system designs typically result from having the optical, optomechanical, and manufacturing engineers (potentially the molder) all working collaboratively throughout the design process. Other disciplines, such as system or electrical engineering, should be included as well.

In some areas, the optomechanical design and analysis of plastic optical systems is similar to that of glass optical systems. However, there are some significant differences that must be taken into account. The main differences between optomechanical design for glass and plastic optical elements are the material properties of the elements themselves and the manufacturing methods used to produce them. Plastics tend to have higher fracture resistance than glass but a lower hardness. Plastics have a higher coefficient of thermal expansion than glass, which must be taken into account when considering the temperature range the system must operate over. Plastics also have lower service temperatures than glass, which can lead to permanent deformation of the optics under certain conditions. Additionally, plastic materials will usually have some amount of outgassing (that new car smell) that must be considered.

Most glass optical elements are still produced by grinding and polishing, although the use of glass molding is increasing. These manufacturing methods tend to limit the optomechanical features that can be incorporated in the glass elements. Plastic optics, on the other hand, can be produced by several methods, with molding being the most popular. This allows the integration of a variety of optomechanical features into the parts.

We begin by discussing typical optomechanical features and concerns with plastic optic elements. If the parts are to be injection molded, there are two main considerations. First, there must be a gate to allow the plastic to be injected into the mold cavity forming the part. For most plastic optical parts, the gate is positioned on or near the diameter of the part. From the optomechanical designer's viewpoint, the gate on a plastic optic part usually results either in a protrusion from the diameter or necessitates a cutout on the diameter of the part. As discussed earlier, as the part comes out of the mold, it is usually attached to a runner system by the gate. The part is then degated, with residual material (known as gate vestige) remaining. This gate vestige is the reason that gate flat cutouts are often used on molded parts. The flat should be set low enough to provide room for the expected gate vestige. The amount of vestige may depend upon the degating method used. Some of the different methods are the use of a pair of side-cut dikes, a hot knife, ultrasonics, or laser systems. If a gate cutout is not desired, the gate protrusion from the part can be used as an alignment or antirotation feature for the element. If neither flat nor protrusion is desired, the gate can be milled off, leaving a fairly clean diameter. It should be kept in mind that the preferred location for a gate is directly above the optical element, as opposed to being positioned out on the end of a flange being used as a spacer. The molder will normally want to fill the optical areas first and then fill any other features.

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The second consideration for molded parts is the potential need for draft on the part to enable it to be ejected from the mold. Draft, as discussed earlier, is the angling of surfaces oriented in the direction of the mold-opening motion. The amount of draft required can depend on the size of the part, the length of the surfaces parallel to the mold draw direction, and the plastic material that is used. In some cases, the optomechanical designer may not want draft on the outer diameter of the part, especially if the outer diameter is being used as a centration feature. However, the molder may feel he cannot produce the part without some draft. One way to achieve a compromise in this area is to use a relatively small no-draft zone on the outer diameter. The no-draft zone, which can be used as the diametral locating feature, can be situated on the part between two drafted zones. In this way, most of the diameter of the part is drafted, making the molder happy, and a defined diameter is available to the optomechanical designer. Of course, a small no-draft zone typically won't be able to control tilt of the optical element, which must be taken into consideration in the overall design.

Another guideline for optomechanical design is to avoid sharp corners. For instance, if an eyepiece lens for a microdisplay is being designed, the lens may be made rectangular, instead of circular, to reduce its volume and weight. The corners on the rectangular piece should be designed as rounded as opposed to sharp. This will help with stress and shrinkage in the part.

Flanges are often incorporated into plastic optical elements. These flanges may be used to set the spacing between adjacent elements or between elements and apertures or other features. It is good practice, when possible, to have the flange on a plastic optical element extend past the highest point, which may or may not be the vertex, on an optical surface. By doing so, the flange can protect the surface from damage when set in a tray or during assembly. In some cases, it may not be possible to extend the flange beyond both optical surfaces. If the flange on at least one side of the element can be extended past the highest point on the surface, it will increase the ability to safely handle the part.

The use of flanging to set spacing between elements is common, but it must be tempered by the realities of the production process. Long, thin flanges can be difficult to fill out during the molding process and can affect the quality of the optical surfaces. In cases where the spacing between elements becomes significant, alternate mounting methods (such as the use of opaque molded spacers) should be considered.

The design of the individual components should be conducted with an understanding of the overall system approach as well as the required positional tolerances of the elements. There are several methods commonly used for assembling multielement plastic optical systems. One method is to use a clamshell design. In this design, the barrel is made of two halves that are often identical. The two halves are formed by dividing the cylindrical barrel by a plane containing the axis of the barrel. The optical elements can be loaded into the lower half of the barrel, and the top half is brought down to seal the assembly. The two halves can be connected in a number of ways, such as screws, bonding, or with an external sleeve. Features can be integrated into the barrel halves to locate the optical elements, or separate spacers may be used.

Another common method of assembling a multielement system is the use of a single-piece stepped barrel. An example of this is shown in Figs. 4.21 and 4.22, with the first figure showing an exploded view, and the second showing a cross-sectional view. A single-piece barrel assembly has several attractive features. By using a rotationally symmetric barrel, the concentricity of the steps that the lenses mount on can be held quite tightly. This is because the inner barrel features can be formed using a single pin, which is fabricated by diamond turning or precision grinding. Both of these methods, performed on high-precision spindles, produce highly concentric features. The limitation of the concentricity of the features in the molded part will be due to the molding process (such as its ejection), not by the fabrication of the tool.

There is often a debate as to whether the outer diameter of the elements, the inner diameter of the part that holds it (in this case the barrel), or both need to be a specific size. In some instances, the lens mold is machined and the diameter of the lenses that are produced from it is measured, and the complementary part (such as a barrel) is adjusted to the lens. In many cases, this may be the preferred method. It may be easier, in the precision grinding of the holes that form the lens diameters for a multicavity tool, to get repeatable size as opposed to a specific size. With multiple-element systems, multiple molds are typically built, whereas a single barrel tool will often suffice. The manufacturing method of the barrel insert also lends itself to precise finishing.

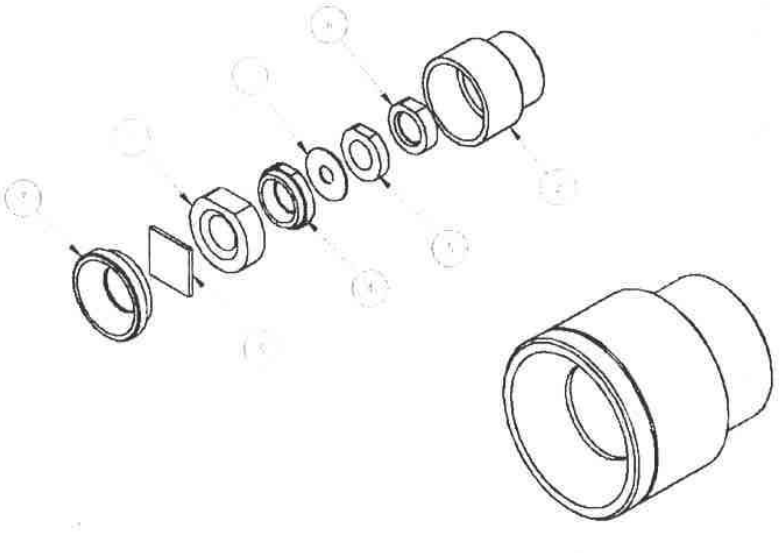

Figure 4.21 Exploded view of a single-piece barrel lens assembly. (Figure courtesy of Paul Merems.)

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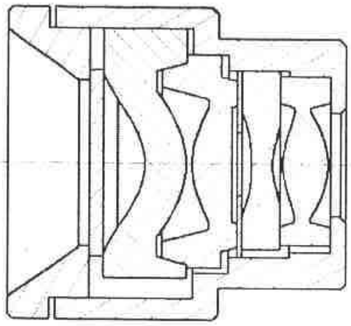

Figure 4.22 Cross-sectional view of a single-piece barrel lens assembly. (Figure courtesy of Paul Merems.)

The use of a single-piece barrel also allows for easy automated or manual assembly, allowing the lenses to be stacked upon each other, along with any apertures, spacers, or stray light baffles. As can be seen in Fig. 4.22, the flanges of the lenses can be designed to interface with each other (for example, through the use of tapers). Using tapers to provide centration between two elements can be a useful technique. It must be remembered that tapers, while providing centration, do not provide accurate spacing at the same time.

In the design of a part that requires features to be accurately aligned to one another, it is best to keep all of the features on one side of the mold parting line. For instance, in the case of the single-piece barrel discussed above, all of the lens steps, where the lenses are mounted, would be in a single side of the tool. Similar conditions exist for lenses. If a taper is to precisely align the lens relative to a specific optical surface, it will be best to have the taper and surface on the same side of the mold.

The optomechanical analyses that are performed on plastic optical systems are similar to those performed on glass optical systems. Evaluation of the distortion of the elements under temperature is a typical analysis. The distortion due to thermal expansion (which again is larger than glass), with the constraints of the mounting structure, must be considered. Distortion plots or coefficients can be provided to the optical designer, who can assess the impact on the optical performance. Deflection under vibration is another standard analysis. Bending of the structure can result in changes in the line of sight of the system. In certain cases, stress-induced birefringence must also be considered.

The final considerations for optomechanical design are configuration control and agreement between models. In developing the optomechanical model, the designer typically receives a listing of the optical model (the prescription) as well as an Initial Graphics Exchange Specification (IGES) file of the system. For plastic optical systems, particularly those using aspheric surfaces, importing the

IGES file into the CAD model will not adequately represent the optical surfaces. These should be modeled in the CAD program using the prescription provided.

Optical design codes usually carry many more significant digits than CAD programs. Often, the optomechanical designer will round off values to three or four digits, which may be adequate for mechanical parts, but not for optical ones. The optomechanical designer should provide his prescription of the system back to the optical engineer, who should modify (a copy of) his optical model using the specific values called out in the CAD model or drawings. This can be particularly important when using higher-order aspheric surfaces. If a performance change is seen due to the reduced number of digits, the optical and optomechanical designer must agree upon the number of significant digits required.

Once the final optomechanical design has been completed, the optical designer should create a final optical model from it, verify the performance, and archive the model. It is good practice for the optomechanical model to reference this corresponding optical model. If any changes occur in either the optical or optomechanical model, similar changes need to be made in the corresponding model, and the new models archived.

4.10 Stray Light

Stray light is unwanted light that degrades the performance of a system. In general, there are two types of stray light: that due to in-field sources and that due to out-of-field sources. An example of out-of-field stray light would be the flares often seen in pictures taken with consumer imaging systems, such as digital cameras, due to the sun being just outside the field of view. An example of in-field stray light, again considering digital cameras, would be the halos sometimes seen around street lamps in a picture taken at night. In addition to imaging systems, stray light can also degrade the performance of nonimaging or illumination systems. For instance, an automotive headlamp reflector that projects light in the wrong direction may blind other drivers, creating a safety hazard.

Plastic optical systems have at least the same susceptibility to stray light as do glass optical systems. In some cases, due to their special characteristics, plastic optics may be more susceptible to stray light than glass optics. Consider, for instance, the use of integrated mounting flanges on lenses. Because the flange is made of the same material as the lens, it will also transmit light. In contrast, a glass lens will generally not have an integrated flange and will most likely rest on an opaque spacer or lens cell, which will not allow light to pass. This is not to say that we should not take advantage of integrated flanges in plastic optics; we just need to be mindful about doing so.

Consideration and analysis of stray light issues should be conducted during the optical and optomechanical design phase of system development. Frequently, stray light and stray-light analysis are an afterthought, left as something to be

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dealt with once the rest of the design is complete. This mindset can be severely detrimental to a project. Finding a stray light issue after the rest of the design work has been completed, with prototypes and/or injection molds built or being built, can result in a significant cost in terms of both money and schedule. In many cases, simple up-front design changes could have eliminated the stray light problem.

Stray light can result from a number of mechanisms, alone or in combination with each other. There are several techniques to reduce or eliminate stray light from each of the mechanisms. Depending on the particular application, design form, cost, and other constraints, it may not be possible to utilize a particular technique. In this case, alternate techniques, redesign, or simply living with the stray light may be required. We now discuss several stray light mechanisms and mitigation techniques.

The first stray-light mechanism is straightforward reflection from optical surfaces, an example of which is shown in Fig. 4.23. We can see in this simple example that light reflects from the rear surface of the lens, heads back towards the front lens surface, reflects again, and then passes through the second surface, arriving at the image plane. This type of stray light is referred to as a "ghost." For a point object, there will be an illuminated spot of stray light on the image plane in addition to the direct image of the point object. In this case, the size of the ghost image will depend on how far from the image plane the stray light focuses. In this example, the stray light is focused near the primary image plane. The irradiance of the ghost image (how bright it is, usually in W/cm^2) will also depend on how far from focus it is as well as the amount of energy reflected from the surfaces. Depending on the light source and sensor geometry, the ghost may be laterally offset from the primary image, in which case it could appear that there are two objects of different intensity. Alternately, the ghost may fall on top of the primary image, most likely resulting in the appearance of a halo.

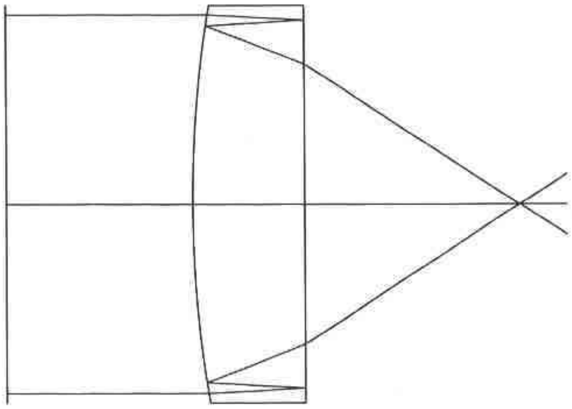

Figure 4.23 Stray light due to ghost reflection.

There are two main techniques for reducing or eliminating ghost images. The first technique is to design the optical surfaces such that any ghost images are well out of focus. In this way, the energy from the ghost will be spread out over a large area and appear only as a small background change. The first-order analysis of ghost images can be performed by the designer during the optical design process. Most optical design programs have built in features (or at least macroprogramming capability) to analyze ghosts due to two reflections, as was shown in Fig 4.23. The analysis is performed by considering the image location of each pair of potentially reflecting surfaces within the system, with the appropriate refraction at each of the intervening and subsequent surfaces. For simple systems, this analysis can be performed manually by converting refracting surfaces to reflecting surfaces and performing the appropriate ray tracing. The number of possible surface pairs rises rapidly as the complexity of the system grows, which is why the automated method of the programs is preferred.

In addition to reflection off the surfaces of lenses, reflections can also come from any filters between (in multielement systems), in front of, or behind the lenses, or from the surfaces of the window covering the detector, and/or the detector surface itself. Because of this, it is generally good practice to avoid having the final optical surface concentric to the detector (concentric to the detector meaning that the detector is at the center of curvature of the surface). If the surface is concentric to the detector, or close to being concentric, reflections from the detector surface will be directly reimaged, resulting in a sharply focused ghost.

Besides controlling the focus position of the ghost image, we can also try to control the amount of energy it contains. This is performed through the use of AR coatings, which were discussed previously. Antireflection coatings become more important as the number of elements in the system increases, not just for ghost image reasons but for overall system transmission as well. In addition to coating the optical elements, AR coatings on the detector window and detector surface can help to control the amount of energy in a ghost image.

In addition to reflection from optical surfaces, stray light can also result due to reflections from nonoptical surfaces. In most systems, there are a number of nonoptical surfaces that stray light reflections can come from. These include any housings, baffles or sun shields, spacers, lens flanges, barrel walls or openings, and even the aperture stop of the system. Each surface must be evaluated for possible reflection paths that end on or near the detector surface. Most of these surfaces are generated during the optomechanical design, so it is useful for the stray light analyst and the optomechanical designer (if they are not the same person) to be in close collaboration.

Stray light due to reflection from a nonoptical surface is usually handled using one or more of three methods. The first method is to prevent the reflection from reaching the image plane through the use of baffling. The second method of handling reflections is to alter the shape, location, or orientation of the surface that is causing the stray-light reflection. For example, consider a two-element system with an opaque spacer between the lenses. In this system, it is possible for

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a reflection off of the inner diameter of the lens spacer to go directly to the image plane. By altering the spacer geometry from a cylindrical section to a conical section, a given reflection can be shifted from going to the detector to going into the rear flanging of the barrel where it is blocked. Of course, the entire range of possible input angles must be evaluated. It may be that due to the range of input angles, there is not a suitable angle for the spacer such that reflections for all input angles are dealt with. If so, it may require multiple techniques to prevent unwanted reflections from reaching the image plane. For instance, a "sunshade" may be necessary at the front of the system to limit the angular range of input rays. The sunshade, in combination with selection of the appropriate spacer angle, may solve the stray light problem.

The third method of dealing with reflections from nonoptical surfaces is to alter the reflective nature of the offending surface, which can be accomplished in several ways. One way would be to apply an absorptive coating to the surface, such as paint or black ink. Ink can sometimes be applied using a fairly straightforward pad printing process. In this process, the surface is pressed against an ink pad, similar to those used with rubber stamps, transferring ink onto it. While absorptive coating techniques can be effective, they are generally not the preferred approach. The reason they are not preferred is because they require an additional process to the part, which will tend to increase its cost. If we have elected to use plastic optics because of their relatively low cost, we do not want to add processes that will increase their price.

An alternate technique is to change the part reflectance by texturing the surface. Texturing or roughening of plastic parts is quite common. It is possible to mold parts with a wide range of surface textures, as can be seen from observing plastic parts such as keyboards, televisions, or other electronic equipment. In nonoptical applications, texturing is often used for styling purposes, to improve the ability to grip an item, or to hide fingerprints or other contamination. In our optical application, the amount and type of texturing will determine how the light is spread after striking the surface. The spread or scattering of the light will depend on the type of plastic material, the roughness of the surface, the angle of incidence of the light, and to a certain extent, the wavelength of light used.

For purposes of stray-light analysis and modeling, we would like to know the distribution of light reflected from the surface as a function of the angle of incidence of light on the surface. This distribution is known as the Bidirectional scatter distribution function (BSDF). Knowledge of the BSDF is typically acquired by directly measuring parts using equipment known as a scatterometer. This type of equipment is commercially available,[85] although many designers will not have sufficient need to justify its purchase. BSDF information may also be obtained from various scatter databases, though in many cases they are considered proprietary. If scatter measurements are desired but the designer does not own a scatterometer or have access to a scatter database, the measurement can be performed on a contract basis, often from the equipment manufacturers. However, many times the parts are not available upfront or there is limited funding to allow directly obtaining the BSDF. In these cases, it is possible to use approximations or analytic models to perform the stray-light analysis. For example, the assumption may be used that the surface will have a Lambertian scatter distribution, where the radiance of light scattered at a given angle from the normal to the surface is constant.

In many cases of roughening parts, a scatter model is assumed for the analysis, the parts are made as rough as reasonably possible, and the stray light performance is tested when the system becomes available. Most molders have a three-ring binder full of plaques that show a range of possible surface textures. The customer, often in consultation with the vendor, can then select the appropriate surface texture. It can be important to include the vendor in the selection, as the texture may introduce difficulty in molding the part. If the texturing causes the part to stick in the mold, this can cause trouble during its ejection, which may result in warping the part or potential mold damage.

One example of a troublesome reflection from a nonoptical surface is that from the rear aperture of a lens barrel. Consider the following example, where a molded plastic barrel was used to house a multielement lens system. The rear of the barrel had an opening smaller than its diameter. The size of the opening was set sufficiently large to pass the cones of light going to the image plane, but small enough to provide a ledge on the barrel on which the final element of the system rested, as is illustrated in Fig. 4.24. The barrel was molded using a single through pin to allow precise control of the inner-stepped diameters where the lenses were mounted. The barrel material was Acrylonitrile Butadiene Styrene (ABS), which can be molded to achieve a high-gloss finish, inadvertently in this case. This resulted in a shiny cylindrical aperture in the rear of the barrel. When mated to a detector, a brightly illuminated ring was seen in the image. The ring resulted from reflection off the cylindrical surface by rays that would otherwise fall outside the detector.

Resolution of this stray light issue was achieved by altering the offending reflecting surface in two ways. First, the length of the surface parallel to the optical axis was shortened by adding a chamfer, and second, the surface was roughened to diffuse the light striking it. Because the roughening of the surface created problems molding and ejecting the part, the surface eventually was roughened using a secondary manual process. This secondary roughening could have been eliminated had a more thorough stray-light analysis been performed early in the design process. One solution would have been to shorten the length of the reflecting surface (as was done) as well as to move it to a larger diameter where the reflections from it would not have reached the used portion of the detector. Regrettably, by the time the problem was found, the lens mold was already being manufactured, and the lens-mounting flange structure could not easily be changed. In hindsight, this type of design error is readily apparent; however, it is easily overlooked during the rush to get a design completed and systems built. This example shows the potential benefits of making the effort, and taking the time, to perform stray-light analysis early in the design cycle.

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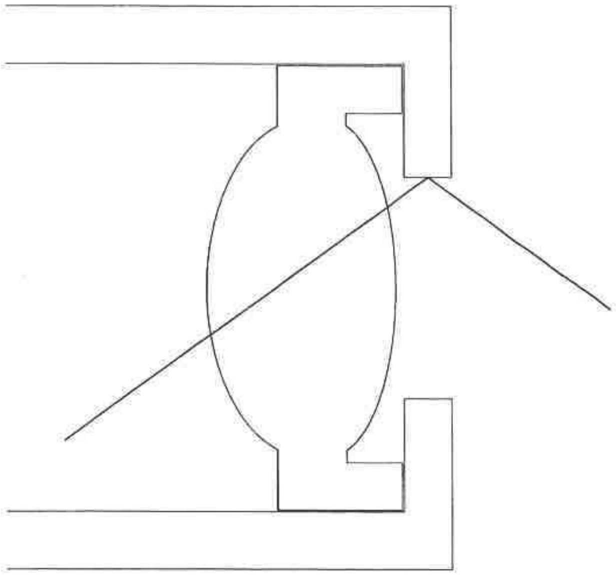

Figure 4.24 Stray light due to reflection off of the rear-lens-barrel aperture.

Another type of reflection that can cause stray light issues is total internal reflection (TIR), which occurs when light is incident on the boundary of two media, going from a higher to a lower-index material, at an angle larger than the critical angle. In this case, the light is totally internally reflected: totally, in that the amount of light reflected is (theoretically) 100%, and internally, since it was attempting to go from a higher-index material to a lower-index material. Total internal reflection can occur on lens surfaces, typically from out-of-field rays. The total internal reflection of any in-field rays should be seen during the design process if the range of field angles is sufficiently represented. Total internal reflection of out-of-field rays is most likely found during the stray-light analysis. In addition to the lens surfaces, TIR can also occur in lens flanges or in the transition region between the optical surface and the flange of the lens.

Like other stray light due to reflections, TIR reflections can be controlled by surface position, orientation, and texture. Since total internal reflection occurs when rays strike an interface beyond the critical angle, it should be a goal to limit the ray angles to less than this angle. Achieving this may require adjusting the slope of a flange surface or limiting the input ray angles with a baffle or sunshade.

Stray light due to TIR can be particularly severe due to the amount of energy in the reflected beam. Unlike reflection from an AR-coated lens surface, which may be 1% or less, a beam that totally internally reflects will carry the entire amount of energy incident on the interface. While a detriment in certain situations, total internal reflection, with its ability to reflect all the incident energy, is often used in the design of illumination systems. For example, LEDs are often encapsulated with or inserted into a part designed to totally internally reflect the light emitted at large angles, thus directing it in forward angles.

In addition to being caused by reflections, stray-light issues can also arise from scattering. Probably the most familiar example of this is looking through a dirty car windshield. The light from the sun, or from cars' headlights at night, is scattered by the contamination on the windshield, which creates a large amount of glare. The amount of scattered light can be enough to essentially blind the driver, washing out all useful visual information. A similar effect can happen from rough surfaces within an optical system. The scattered light that reaches the detector can increase the background light level, reducing the contrast of the image.

We previously mentioned roughening surfaces as a stray-light mitigation technique in order to diffuse light striking them. In some instances, a smooth (rather than rough) surface is desired. This can be the case when a surface is oriented such that all reflections from it are blocked from reaching the detector. On the other hand, if the surface is rough, the scatter would spread the light over a larger angular range, possibly resulting in stray-light paths to the detector. The effect of surface finish of all elements in and around the imaging path should be considered. In some instances, such as a long cylindrical section that is being injection molded, it may not be possible to mold the part with a rough surface, as this will cause it to stick in the mold.

In addition to reflections and scattered stray light, there can also be stray light that results from direct paths. While not typically seen with inline refractive glass optical systems, it is sometimes seen with inline refractive plastic optical systems. An example of this is shown in Fig. 4.25, where the direct path travels

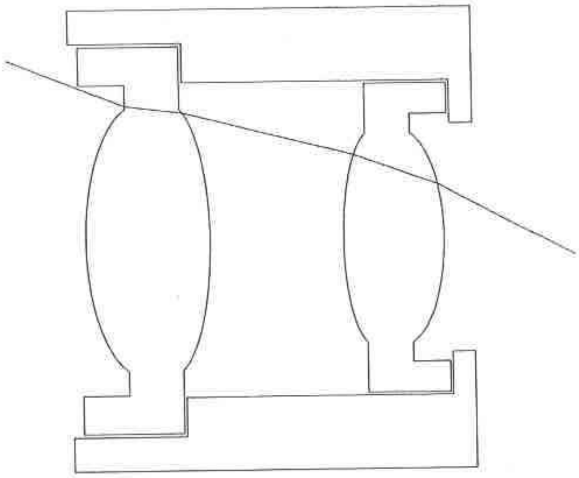

Figure 4.25 Stray-light path through lens transition zone on first element.

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first through the transition zone between the optical surface and the lens flange on the first element, then through the optical surfaces of the second lens. This direct path could be dealt with in several ways. One solution would be to place a baffle or blocking structure in front of the first element in order to prevent the light from reaching the transition region of the lens. If the lenses are being stacked into a barrel and are loaded from the front, a retaining ring used to hold the lenses in place could serve the dual purpose of preventing the direct stray-light path.

If a blocking structure cannot be placed in front of the element, the direct path could also be blocked behind the lens. There are several options for the blocking element, which again may serve a dual purpose. One option would be to use a molded spacer, which sets the distance between the two lenses as well as blocks the direct path. However, it must be considered that the axial length of the spacer may create an additional stray-light path. A way of limiting the axial length of the blocking element is to use a thin disk of material, such as a Mylar or metal washer. These washers can be stamped from sheets of material of various thicknesses. The thickness should be thin enough to limit potential reflections from the inner diameter of the washer but thick enough to allow for handling. The thickness tolerance of the washer material selected must be kept in mind, as the addition of a spacer or washer may increase the overall lens spacing variation. This additional tolerance stack-up must be accounted for in the system tolerance analysis.

Another potential solution to eliminate the direct path would be to reduce or move the transition zone. Provided there is suitable edge thickness, it may be possible to carry the optical surface out to a larger diameter. Of course, the effect of the increased aperture on the system must be considered as well as any implications on the lens mold or other components that interface with the altered lens.

One other potential source of stray light, as discussed earlier, is diffractive surfaces. The efficiency of standard (as opposed to MOD) diffractive surfaces is optimum for one wavelength—the design wavelength. As we move away from this optimum value, the diffraction efficiency decreases, and light appears in other orders. These other orders may reach the image plane, resulting in stray light images. Any stray-light analysis on a system containing diffractive surfaces should consider diffraction-efficiency effects.

Stray-light analysis, like optical design, is a specialty that is learned partially through study but mostly through practice and experience. There are a number of consultants and companies that specialize in stray-light analysis. Several of these companies also have commercially available software programs, which are often used for illumination design as well as for stray-light work. The most well known of these programs (listed alphabetically) are ASAP,[xiv] FRED,[xv] and TracePro.[xvi]

[xiv] ASAP is a registered trademark of Breault Research Organization.

[xv] FRED is a registered trademark of Photon Engineering LLC.

[xvi] TracePro is a registered trademark of Lambda Research Corporation.

Some level of illumination and stray-light analysis can also be performed in the optical design programs mentioned earlier, but it can be argued that they are not as well suited as the programs listed here, which are written for these particular purposes.

One of the most important aspects of performing a successful stray-light analysis is to have the optical system accurately represented in the analysis software. As with many other software programs, the output will only be as good as the input it is created from. This representation is referred to as a "stray-light model." The model can be entered into the software in a number of ways and most often requires a combination of methods.

The most basic time-consuming way is to create the model from scratch, using the geometric elements available in the software. This is sometimes done when there is a need for an independent model to verify previous work or when no computer-aided design (CAD) or electronic models exist. Today, the optical and optomechanical design work will most likely be performed using software programs that have the ability to export various file types. In this case, optical and CAD files are generated, which are then imported into the stray-light analysis program. Typical CAD file types that the stray-light programs can handle are IGES and standard for the exchange of product (STEP) model data.

Once the files have been imported, properties must be applied to all elements and surfaces. These properties include the reflectance and transmittance of surfaces, their scatter distributions (BSDFs), any polarization effects, and the refractive indices and dispersions of the various materials. Antireflection or other optical coatings (such as band-pass filters) can also be applied. Some of these characteristics may be automatically assigned when importing the optical files. In general, however, some amount of time must be spent manually assigning and verifying the correct surface and element properties.

One problem that frequently arises during the construction of a stray-light model is that the optical and optomechanical files it is constructed from do not themselves accurately represent the actual parts produced. For instance, in many optical programs, the designer sets a clear aperture radius or diameter value that is used to determine which rays pass through a surface and which rays are blocked. In molded plastic parts, as discussed above, it is desirable to provide a region outside the optical clear aperture to allow for edge break. This additional area outside the clear aperture needs to be properly represented in the stray-light model. If the stray-light analyst simply enters the aperture sizes in the optical model, regardless of the optical surface dimensions of the actual part, the model will be incorrect. This may result in an existing stray-light path that is not shown in the stray-light model.

Another frequent flaw in stray-light-model development of plastic optical systems is missing transition radii. Sometimes, either in order to simplify the optomechanical model or because of a lack of understanding of most molded parts, the optomechanical designer will leave cusps in their model instead of including transition radii. An example of this is shown in Fig. 4.26, which shows

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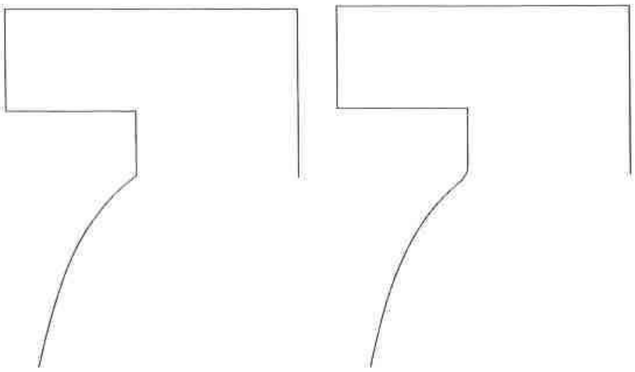

Figure 4.26 Unrealistic versus realistic transition radius.

the difference between a theoretical part (on the left-hand side) and the more realistic molded part (on the right-hand side). The transition radius in the molded part can act as a small negatively powered annulus, which may spread out light that would, in the incorrect model, refract as through a plane surface. All corners, which are shown in the figure as sharp, would in reality also have some minimum radius value.

Another often-overlooked feature in molded parts is the gate flat, which (as discussed earlier) is often used to provide space for any gate vestige during the degating process. With gate flats, the part is no longer circularly symmetric, which may have been the way it was modeled. In multielement systems, the gate flats are sometimes aligned during assembly by choice, and other times they are randomly oriented. This can complicate the stray-light analysis if the gate flats are creating stray-light paths, for instance, if rays totally internally reflect off them.

One difficulty with getting an accurate stray-light model of the system is the tolerances on the actual parts. In the case of a transition radius, there will normally be some allowed range of radius value. As an example, the radius may be called out with a maximum radius of 0.5 mm, which means the transition radius can vary from 0 to 500 μm. Because of the large number of rays that are traced during a stray-light analysis, and the time it can take to trace them, tolerances and perturbations to the system are usually not extensively evaluated. In this case, it is probably best to select a representative value for the transition radius and determine if it plays a role in significant stray-light paths. If it is found to play a large role, further perturbation analysis may be necessary.

Another problem with the stray-light model can occur due to uncommunicated changes to the system components. What appears to be a small change to one engineer may have a considerable effect on the stray-light analyst. For instance, consider the effect of a small change in the draft on a lens flange. To the mechanical engineer or lens designer, this may have no apparent effect, since it did not significantly change the structural stability of the system or alter the aberrations of the lens. To the stray-light analyst, however, this change in angle could move a reflection that was previously not reaching the detector into the image region. To prevent this kind of mishap, there must be ongoing discussion between all parties involved with changes to the baseline design. This includes both internal and external parties, such as vendors.

We now consider the process of performing a basic stray-light analysis. As with some other processes described in the text, we do not have space to provide a complete description; however, most providers of stray-light software offer training on this type of analysis. Once the model has been entered and all appropriate properties applied, the first task is to perform a simple in-field ray trace. This is similar to generating a spot diagram in an optical design program. The purpose of this initial ray trace is to compare the output of the stray-light model with that of the optical design model in order to verify that the optical portion of the model has been entered correctly. This is particularly important when the system contains diffractive or highly aspheric surfaces.

Once the optical performance of the model has been verified, the next step is to run a "backwards ray trace." This is performed by considering the detector surface as a light source that is illuminating back through the system. It may at first seem counterintuitive to perform a backwards ray trace, but there is a simple reason to do so. By considering the image plane as a source, emitting into (at least) a full hemisphere, we are tracing all possible ray paths to the detector. From the backwards ray trace, a list of all surfaces that rays reach is generated. The surfaces on this list are known as "critical surfaces."

A forward ray trace is next performed, where rays are sent into the front of the system from all angles. A list of surfaces that the rays hit is again generated, with these surfaces known as "illuminated surfaces."

The critical and illuminated surfaces are compared, with the surfaces that appear on both lists being determined. Surfaces on both lists are the ones that can generate a stray-light path because they can be illuminated by external sources, and the detector can see them.

With the various stray-light paths identified, forward ray tracing can be performed on any particular path to determine its effect on system performance as well as to evaluate the mechanisms involved in its creation. With this knowledge, appropriate mitigation strategies can be developed. The proposed solution may need to be a compromise between the optical, optomechanical, and production teams. Changes that eliminate one stray-light path may possibly create other unintended paths. As such, it may take an iterative design approach to eliminate or reduce stray-light effects.

4.11 Special Considerations for Small and Large Parts

Certain applications (such as mobile phone cameras, telecommunication components, and fiber optic couplers) often have severe packaging constraints,

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resulting in the use of small-diameter lenses. It is not unusual for these applications to use lenses that have diameters ranging from 2 to 5 mm. These small-diameter lenses require special consideration during both their design and fabrication.

From the optical design standpoint, adequate performance of these systems often requires tight tolerances on the tilt and decentration between elements as well as between the surfaces on each individual lens. This results in a need to precisely register the elements during assembly, which can be achieved through interlocking features or through control of the element diameter or mounting features. In general, the tilt of the individual optical surfaces should be well controlled by the mold build process. For example, the holes for the optical inserts may be machined through both mold half plates at the same time, which all but guarantees they are parallel. Even if not machined this way, the angle of the insert hole with respect to the mold face will be tightly controlled. The inserts themselves should also run true, if proper set up on the diamond-turning machine is performed.

Proper control of the decentration of the two surfaces of a lens with respect to each other can be a challenging task. In these types of designs, the optical designer will often ask that the centers of the two surfaces be aligned to each other within 5 μm. For those who prefer units of inches, this would be two ten-thousandths of an inch (0.0002 in.). Achieving this tight decenter tolerance requires precision in all steps of the mold build process. To the credit of various plastic optic molders, these values can and are being achieved.

Even on a small lens, some room around the clear aperture surface is required for edge break in the injection molding process. This can use a significant portion of the lens area, possibly resulting in the need for a larger diameter. If this is not acceptable, trades should be discussed with the molder as to the minimum extra surface area required. Alternately, the designer may be able to put up with a small amount of error around the edge of the element or stop the system down slightly to eliminate rays from this portion of the lens.

Because of the small clear apertures of these lenses, digs or contamination on the optical surface can block a large portion of the beams passing through them. Digs are usually controlled by caring for and inspecting the optical inserts that form the surfaces. Contamination can be controlled through good housekeeping practices, proper packaging, and the use of air guns and deionizers. Care must be taken not to generate large amounts of debris during the degating process.

We previously mentioned that diamond turning of parts or optic inserts leaves a small mark at the center of the optical surface. If the diamond-turning setup is not performed well, this mark can become an appreciable area on a small lens. In general, centration requirements of the optical surface will force the diamond-turning mark to be small.

We discussed earlier the ejection of parts from the mold. Small parts are often optically ejected because of the limited area around the optic surface. Optical ejection, however, requires that the optic pin on the moving half of the mold slide back and forth in its receiver. This necessitates additional diametrical clearance from what is required for simply inserting the pin. If this additional clearance is considered too large, ejector pins or sleeves may be utilized. Of course, the small available area for ejection requires thin ejection sleeves or pins, which are more fragile and susceptible to bending. The ejection method is often selected by the molder, based on his or her experience of what works best for a particular part type.

Another consideration for small parts, particularly for those with convex optical surfaces, is having a small annular ring around the optic surface. This annulus results from the desire not to have a "knife edge" on the concave optic pin that forms the surface. A concave optic pin with a sharp edge is more likely to be damaged during handing or insertion into the mold base. This annular region may lead to stray-light problems, as mentioned earlier, but also may be useful in testing, as we shall discuss later. Convex optic pins, which form concave part surfaces, do not require this annular flat.

Another concern for small optical parts is the size of the gate region relative to the size of the part. In order to adequately fill the part during molding, the gate needs to be some minimum size. This size can often be a significant portion of the edge of the element. Sufficient room must be left for degating the part and for any gate vestige that remains. Handling small parts during degating and other processes can be difficult. Element-specific tooling can be useful to assist in handling the elements, as can using the runner system as a support structure. In addition, special racks or trays may be needed for coating as well as for storing or shipping the elements.

We discussed stray light in the previous section; however, we mention the topic again as it applies to small elements. Systems using small elements can be particularly susceptible to stray light. This is because the packaging constraints that drive their use often do not allow length for stray-light suppression features, such as sunshades. Performance requirements often impose the need for multiple elements, which, when constrained to a short overall length, results in closely spaced lenses. Many times, this does not allow the use of molded opaque spacers. Given this, the use of inked surfaces or stamped apertures may become more important. In the case of stamped apertures, they may interfere with lens centration features, such as molded-in tapers. The use of multiple apertures with overlapping blocking regions and cutouts for alignment features has been attempted, as has stamped apertures with conforming tapers. The additional tolerance stack-up due to using stamped apertures must not be overlooked. Figure 4.27 shows a schematic of a small lens and optical insert, reiterating some of the special considerations for small elements.

At the other end of the range, large parts also need certain considerations. The definition of what constitutes a large part is somewhat arbitrary. For our purposes, we will consider large parts to be those over 50 mm in diameter. Some vendors specialize in very large parts, such as Fresnel lenses, while others will only work up to a given size, since manufacturing larger parts normally requires larger molding machines.

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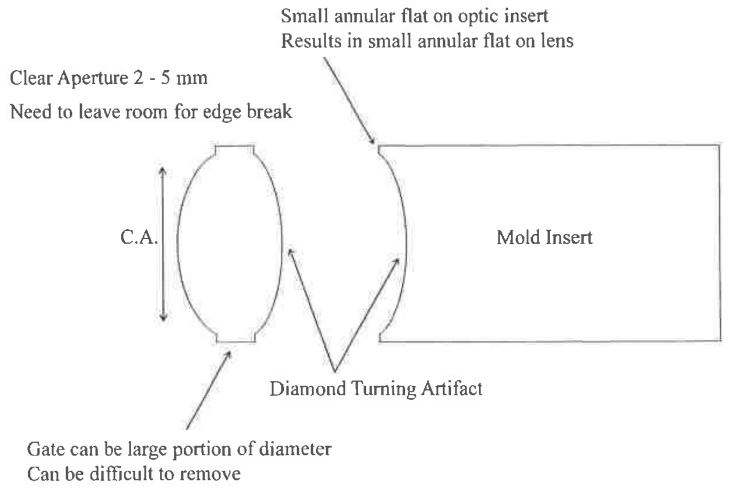
Small annular flat on optic insert
Results in small annular flat on lens
Clear Aperture 2 - 5 mm
Need to leave room for edge break
C.A.
Mold Insert
Diamond Turning Artifact
Gate can be large portion of diameter
Can be difficult to remove

Figure 4.27 Considerations for small elements.

The primary consideration for large parts, when they are molded, is a realistic view of the tolerances that can be achieved. As parts grow larger, the accuracy that the surfaces can be held to decreases. In our discussion of tolerances, we stated that irregularity can be held to about one fringe on up to a 25-mm-diameter part. Beich[69] states that one fringe of irregularity per 25 mm can be held on up to 75-mm-diameter parts, which would mean that a 75-mm-diameter part has three fringes of irregularity. Ning,[55] on the other hand, suggests one fringe for the first 8 mm of diameter, and three fringes per each additional 10 mm, which would give about 20 fringes of irregularity on a 75-mm-diameter part. Obviously, there is a significant difference between these two values. This may be explained in part by differences in the level of effort and cost associated with larger parts and what is considered the baseline level. The use of standard injection molding or injection compression molding can also make a difference. Requirements for large parts should be discussed with potential vendors to ensure that the tolerances required can be met at a reasonable cost. Overly optimistic expectations can quickly leave the designer looking for alternate solutions.

As we discussed earlier, cost is typically proportional to cycle time. Higher irregularity tolerances are obviously easier to achieve and will require fewer mold compensations and shorter cycle times. Larger parts, because of their larger mass, will require a longer cycle time than smaller parts to achieve a given quality level. This will result in an increased cost compared to smaller parts. In addition, as parts become larger, the impact of material selection may also have a larger influence on their cost. Depending on the size and shape of the large part, alternate manufacturing techniques to injection molding (such as injection-compression, straight compression molding, or machining) may need to be considered.

4.12 Drawings

Drawings for plastic optical elements are similar in many ways to drawings for glass elements. The drawing should specify all the necessary information to correctly produce the part. Because of the special characteristics and manufacturing methods of plastic optics, the drawings may require additional callouts not seen on glass optical elements. It should be noted that several drawings may need to be produced during the product development. For instance, an initial drawing for diamond-turned prototype parts may be used, followed by a production drawing, which includes features for a molded part, such as draft and a gate flat. Figure 4.28 and Fig. 4.29 show the two sheets of a production plastic lens drawing. We do not claim this drawing to be error free or that it should be used as a template. It does, however, contain most of the features that a plastic optic drawing should contain. We discuss this drawing, working our way through the notes and pointing out relevant features.

Notes 1 and 2 indicate that statistical process control (SPC) features and critical characteristics (CC) have been called out on the drawing. Because of the repeatability of the injection-molding process, as well as the desire for lower cost, most plastic optic elements are not individually inspected. Instead, samples are selected at some frequency, and certain characteristics are measured. These measurements are tracked and analyzed using statistical process methods, which are well known in high-volume production environments and are used more frequently in general manufacturing. We do not elaborate on these SPC methods, except to say that they can be used to track a process and predict when it is going out of control, so that adjustments can be made before nonconforming parts are produced. This is done through the use of control limits, which are not the same as, and are normally smaller than, the tolerance on the SPC feature.

For this part, the overall flange thickness has been selected as the SPC feature. Selection of the individual SPC features is often done in consultation with the vendor, based on an understanding of their molding process. The critical characteristics are features of the part that are considered to be critical to the fit or function of the part or to the system it goes into. For this part, the flange thickness, center thickness, the stack of surface S1 (the distance from the vertex of the surface to the flange), and the diameter have been called out as critical characteristics. Critical characteristics are usually determined by the part and system designers, often the optical and optomechanical designers, who understand the effect of each dimension on the part or system performance.

Note 3 on the drawing calls out the requirements for surface roughness and scratch-dig on the optical surfaces. For surface roughness, it is best to supply a frequency range that the roughness should be measured over. This, as well as the subject of scratch-dig, will be discussed in the section on testing.

Notes 4 and 5 specify the forms of the two optical surfaces. For this part, both of the surfaces are aspheric; in particular, they are conics. On this drawing, the surfaces are specified using the standard polynomial aspheric form, with the

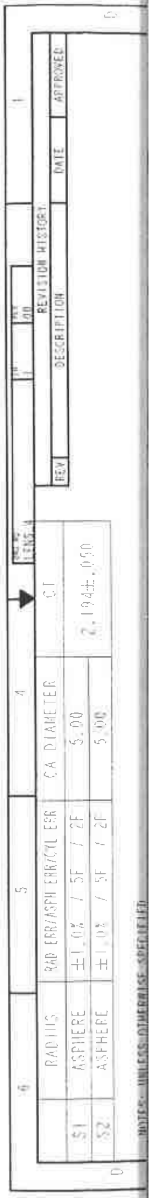

Figure 4.28

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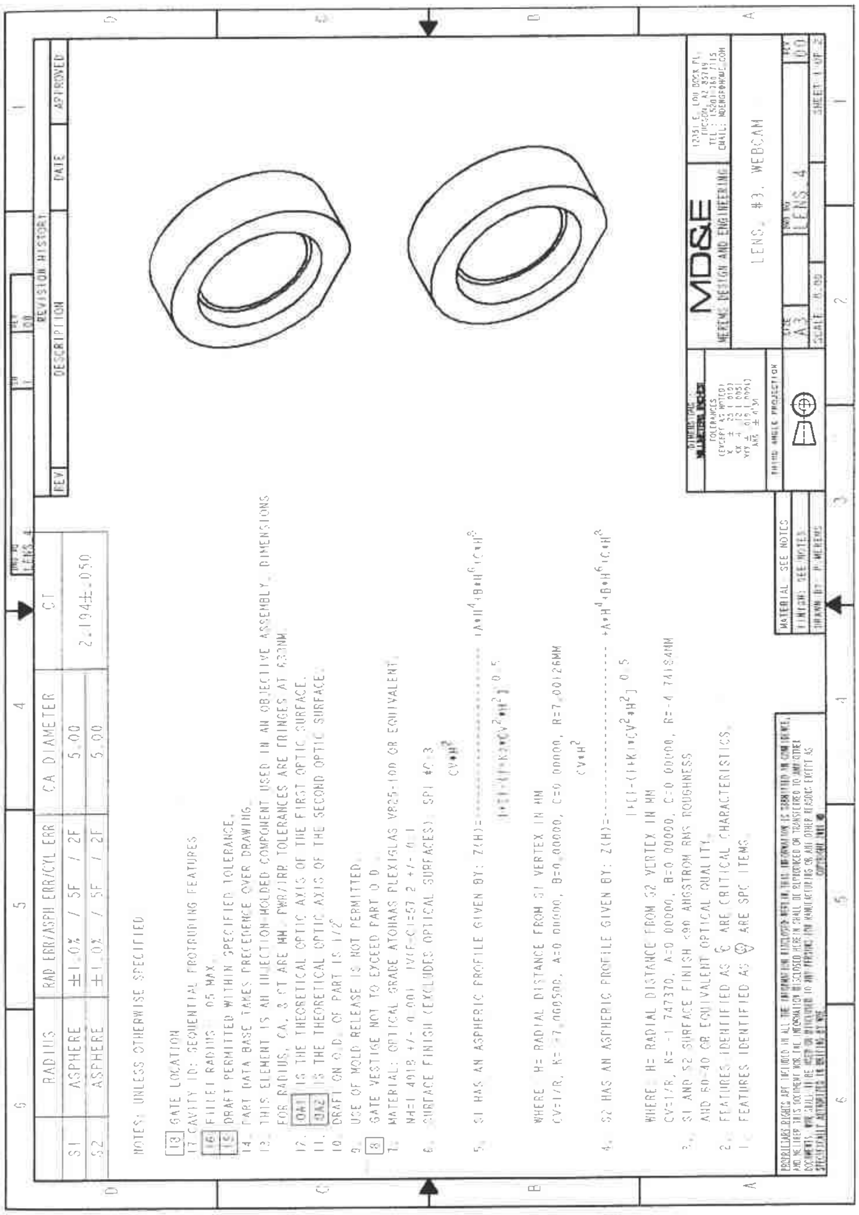


RADIUS | RAD ERR/ASPH ERR/CYL ERR | CA DIAMETER | CT
S1 ASPHERE ±1.0% / 5F / 2F 5.00 2.194±.050
S2 ASPHERE ±1.0% / 5F / 2F 5.00
NOTES: UNLESS OTHERWISE SPECIFIED
13 GATE LOCATION
17 CAVITY ID: SEQUENTIAL PROTRUDING FEATURES
16 FILLET RADIUS .05 MAX
15 DRAFT PERMITTED WITHIN SPECIFIED TOLERANCE
14. PART DATA BASE TAKES PRECEDENCE OVER DRAWING
13. THIS ELEMENT IS AN INJECTION-MOLDED COMPONENT USED IN AN OBJECTIVE ASSEMBLY. DIMENSIONS FOR RADIUS, CA, & CT ARE MM. PWR/IRR TOLERANCES ARE FRINGES AT 633NM
12. OA1 IS THE THEORETICAL OPTIC AXIS OF THE FIRST OPTIC SURFACE.
11. OA2 IS THE THEORETICAL OPTIC AXIS OF THE SECOND OPTIC SURFACE.
10. DRAFT ON O.D. OF PART IS 1/2°
9. USE OF MOLD RELEASE IS NOT PERMITTED.
8 GATE VESTIGE NOT TO EXCEED PART O.D.
7. MATERIAL: OPTICAL GRADE ATOHAAS PLEXIGLAS V825-100 OR EQUIVALENT.
Nd=1.4918 +/- 0.001 (Vd=57.2 +/- 0.1)
6. SURFACE FINISH (EXCLUDES OPTICAL SURFACES): SPI #C-3
5. S1 HAS AN ASPHERIC PROFILE GIVEN BY: Z(H)=
WHERE: H= RADIAL DISTANCE FROM S1 VERTEX IN MM
CV=1/R, K= -7.060500, A=0.00000, B=0.00000, C=0.00000, R=7.00126MM
4. S2 HAS AN ASPHERIC PROFILE GIVEN BY: Z(H)=
WHERE: H= RADIAL DISTANCE FROM S2 VERTEX IN MM
CV=1/R, K= -1.747370, A=0.00000, B=0.00000, C=0.00000, R=-4.74184MM
3. S1 AND S2 SURFACE FINISH <90 ANGSTROM RMS ROUGHNESS AND 60-40 OR EQUIVALENT OPTICAL QUALITY.
2. FEATURES IDENTIFIED AS C ARE CRITICAL CHARACTERISTICS.
1. FEATURES IDENTIFIED AS ARE SPC ITEMS.
REV DESCRIPTION DATE APPROVED
REVISION HISTORY
MD&E
MEREMS DESIGN AND ENGINEERING
LENS, #3, WEBCAM
LENS 4
THIRD ANGLE PROJECTION
MATERIAL: SEE NOTES
FINISH: SEE NOTES
DRAWN BY: P. MEREMS
SCALE
SHEET 1 OF 2

Figure 4.28 Sheet 1 of a plastic lens drawing. (Figure courtesy of Paul Merems.)

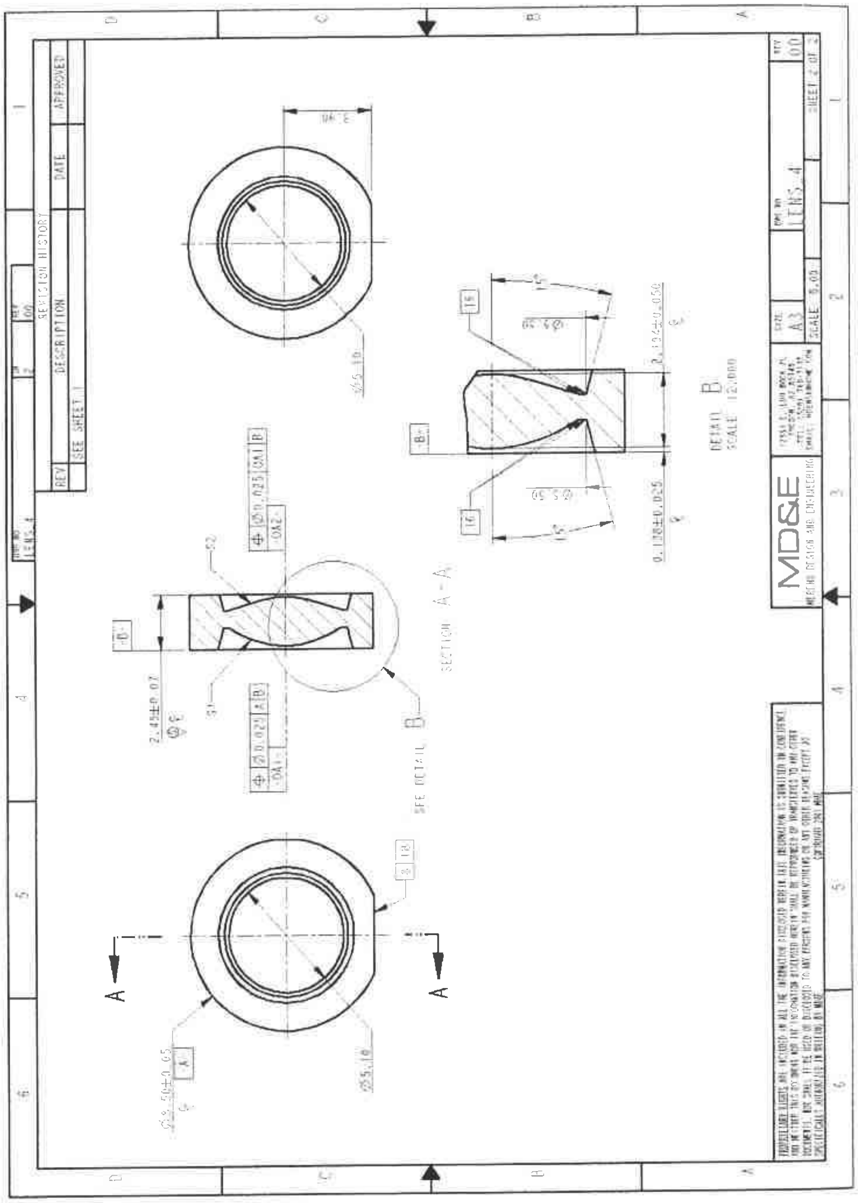
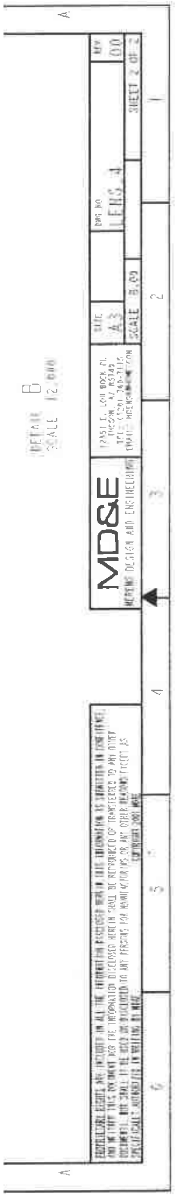

SECTION A-A
SEE DETAIL B
DETAIL B
SCALE 12.000
A
A
MD&E
LENS 4
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
SEE SHEET 1
A3
SCALE 5.00
SHEET 2 OF 2
-B-
-A-
2.45±0.07
15°

Figure 4.29 Sheet 2 of a plastic lens drawing. (Figure courtesy of Paul Merems.)



f Paul Merems.)

radii and conic constant values supplied, and the polynomial terms all set to zero. This form was used, even though the polynomial terms are zero, because the drawing is created from a template in the CAD software. Using standard drawing forms can be a good practice if the template is properly set up to ensure that all necessary data will be included on the drawing.

Note 6 specifies the surface finish on the nonoptical surfaces of the part. It is useful to specify a surface finish for these areas so that the parts will match the input to the stray-light model. It is especially important when a desired amount of texturing is required.

Note 7 calls out the optical plastic material of the part. In this case, the material specified is acrylic, one brand name of which is Plexiglas. A specific supplier and grade of material have been listed, with the possible use of an equivalent material. As noted earlier, it is wise to call out the specific grade of material to be used. There are usually multiple grades of each plastic optical material, with each grade having different additives and/or characteristics. If the designer is going to allow or consider alternate or equivalent materials to be used, it is best to require notification by the vendor of this material change before it is implemented. This can be dictated by a statement such as, "Substitution of the primary material called out by an alternate or equivalent material must be approved in writing by the customer prior to substitution taking place." Such a statement reduces the possibility of errors due to doubt about the definition of "equivalent." This statement may be placed on the drawing itself, or it may be included in the purchase order, depending on the drawing philosophy of the customer.

It is also generally wise to include a note that precludes the use of reground or recycled material. Most optical parts are not manufactured using regrind material, and most vendors themselves believe this to be appropriate. However, this is a case where it is better to be safe than sorry. A note dictating no regrind may be written along the lines of "Virgin material only—no recycle, remelt, or regrind material is allowed."

Note 8 on the drawing specifies that the gate vestige must be below the outer diameter of the part. As we recall, gate vestige is material remaining on the gate flat after the part has been separated from the runner system (degated). This is a fairly standard callout, particularly for lenses that will be inserted into a cylindrical barrel.

Note 9 prohibits the use of mold release. Mold release is often used in standard plastic molding. The mold release may be contained within the plastic itself (another reason to specify the material grade), or it may be added to the plastic or to the mold. Mold release is a lubricant that allows the parts to come out of the mold more easily. Most optical elements are produced without the use of mold release, which may contaminate the optics, outgas, or make them difficult to coat.

Note 10 calls out the amount of draft allowed on the diameter of the part. We discussed earlier that draft is the angling of surfaces that would be otherwise parallel to the draw direction of the mold. Draft helps parts release from the cavities, both when the parts are pulled with the B mold half as well as upon ejection. In this case, the designer is allowing up to one-half degree of draft. Many times, when the diameter of the lens is used for centration control, a small no-draft section will be included on the part, as was discussed in the optomechanical design section.

Notes 11 and 12 reference the optic axes of the two optical surfaces. The optic axes are geometrically toleranced to control the position of the optic surfaces to the relevant part features.

Note 13 states that the part is an injection-molded element and that the dimensions are in units of millimeters. This dimensional statement may also be called out in the block near the drawing name. This, again, is fundamentally a drawing philosophy issue. More importantly, the note also calls out that power and irregularity tolerances are specified in fringes, at a wavelength of 633 nm. This is a fairly standard callout on optical drawings. Having it explicitly stated prevents any confusion as to whether the tolerances are in fringes or waves, which would result in a factor of two differences in tolerance size. The wavelength of 633 nm is that of a helium-neon (HeNe) laser, which is the red laser commonly seen in laboratory interferometers. Sometimes optics are specified using the mercury green line of 546.1 nm. This applies more to parts that are to be checked using test plates (under a mercury lamp). Since most plastic optics will not be tested using test plates, we recommend using the HeNe wavelength.

Note 14 sets the precedence of the various descriptions of the part. In this case, the note specifies that the electronic CAD model of the part takes precedence over the drawing. This may seem a bit unusual given that we are reviewing the part drawing; however, the fact is that, as a result of the advances in CAD software and computer-controlled machining, many vendors prefer to work from the electronic model of the part rather than the drawing. It is much easier for the molder to design the injection mold starting with the CAD model of the part, supplied by the part designer, than to receive a drawing and have to create a CAD model from it. Electronic models can also be used to program automated test equipment, such as coordinate measuring machines. The CAD models of the parts can (and should) be placed under configuration control, just as the drawing should be.

Another advantage of using an electronic model is that the molder can suggest and implement (if permitted) changes to the model that will make the part more producible. These changes may include adjustment of the gate region or the addition of desired draft. This type of concurrent engineering with the molder can improve the design from a cost and producibility standpoint.

Note 15 reiterates the allowed draft on the part, though no callout block associated with the note is shown on the drawing.

Note 16 calls out the allowed fillet radii on the transition between the optical surface and the flat annular region surrounding it, and the transition between the flat annular region and the flange of the part. We have mentioned previously that sharp corners or cusps are generally not preferred, and they are not typically

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achieved without extra effort. Calling out the maximum fillet radius sets an upper bound on the part geometry in the transition regions. Since sharp corners are not preferred, a minimum radius callout may be added as well. As we discussed in the section on stray light, the effect of these fillet radii, which can act as negatively powered annular zones, must be considered.

Note 17 calls out that the parts will have a cavity ID molded on them. In multicavity molds, this is a common practice. Molding a cavity ID on or into the part will allow the determination of which mold cavity it was produced from. This can be useful in linking system performance to component performance. For instance, if it is found that low-performing systems all contain a lens molded from cavity 5, the cavity 5 lenses can be pulled from the assembly line and stock area and be segregated and analyzed to determine the root cause of the low system performance. In some cases, it may be determined that system yield is maximized when certain cavity combinations are assembled together. For example, consider a two-element lens system, with each lens molded in its own four-cavity mold. It may be that the lens 1 from mold cavities 1 and 3, when combined with lens 2 from cavities 1 and 2 (of the lens 2 mold), provide high performance systems, but not when combined with the lens 2 from cavities 3 and 4. This is obviously not the preferred situation; we would like all lens and cavity combinations to work equally well together. However, we may find that we need to assemble the systems according to certain lens cavity combinations. Having cavity IDs on the parts will allow for easy separation and verification of which cavities the lenses are from and an orderly flow of the appropriate parts to the assembly floor.

Cavity IDs can be produced in a number of forms. Most commonly, numbers (1, 2, 3,...) or letters (A, B, C,...) represent the cavities. In other cases, symbols (such as dots) may be used. For larger parts, some molds also have an adjustable date stamp, which marks the part with the date it was produced. The cavity ID feature can either be proud of or below the surface. It is best to call out where on the part the cavity ID should be located, a maximum and minimum size, and if the ID is to be proud of or below the surface. Simply calling out the need for a cavity ID may result in a feature in an undesirable location. If possible, it is best not to put the cavity ID on an area that will be used as a mounting surface.

The final note on the drawing, Note 18, specifies the location of the gate. Appropriately, this is indicated on the gate flat feature. Sometimes a callout is made that the part must be single gated or that multiple gates are allowed, provided certain restrictions (such as "no knit lines within the clear aperture") are met. Gate size and location issues should preferably be discussed with the molder before the final part design is set.

In addition to the notes, there are a number of dimensions and tolerances on the part. The blocks on the upper left of sheet 1 call out the tolerances on radius error, aspheric error, and cylindrical error as well as the minimum clear aperture diameter, the center thickness, and its tolerance. Radius tolerances are often called out as either a percentage or as a number of fringes of power. For glass optics, test plates are often used, which provide a measurement of radius error in fringes. For plastic optics, radius measurement techniques other than test plates are most often used. In these cases, a percentage tolerance is easier for the molder to work with than a fringe tolerance, due to the measurement technique. If the drawing calls out the radius tolerance in fringes, it may just be converted to a percentage for the vendor's internal measurement. On this drawing, the tolerance on both radii is given as ±1.0%.

There are several ways to specify the tolerances on an aspheric surface. Providing a bounding zone for the aspheric surface is one way; a bounding zone combined with a slope error specification is another. The surface can also be specified not directly by its form but by the parameters of a particular wavefront after passing through it (typically the wavefront after passing through the entire element). Yet another method is to specify the surface required with respect to a defined null configuration. However the surface is specified, the designer should verify that the vendor has the capability to measure it in the desired manner. If the vendor does not have certain types of equipment, an alternate or equivalent tolerance specification may be required.

On this drawing, the aspheric form is called out using an aspheric error term, specified as five fringes (F). This tolerance callout sets a bounding zone around the desired aspheric form. That is, the asphere may depart by up to five fringes from the desired form. There is some ambiguity in this tolerance callout, as it is not completely clear if the tolerance is five fringes departure peak to valley or a departure of plus or minus five fringes, which would potentially double the allowed tolerance. This ambiguity can be removed by stating the appropriate interpretation either in the drawing notes or in the tolerance box itself. There is also an unstated assumption that the radius may be varied within its allowed tolerance range to minimize the aspheric error, before the aspheric error is calculated.

The cylinder error called out allows variation in the surface form in two orthogonal directions. From the molding standpoint, cylindrical error may arise from asymmetric shrinkage, often in directions with and opposite the gate, or it may result from imperfect ejection.

The clear aperture diameter callouts indicate the diameters over which the surface specifications must be met. It is assumed that the clear aperture is centered on the theoretical optical axis of the surface. We emphasize once more the need for the optical surface to be sufficiently larger than the clear aperture diameter in order to account for "edge break" or shrinkage at the edge of the optical surface on molded parts. On this part, the clear aperture diameters are called out as 5.00 mm, while the optical surface itself is 5.10 mm. This is less room for edge break than most molders usually would want. When specifying the clear aperture and the optic surface diameter, it is important to take the transition zone fillet radius into account. If the clear aperture, optic surface, and fillet radii are not considered together, it can result in conflicting dimensions on the drawing.

On this drawing, center thickness and its tolerance are included in the tolerance block as well as being listed on sheet 2. This again comes from the use

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of a standard drawing template. The specification for this lens is a center thickness tolerance of ±0.050 mm, which is ±50 μm, a tolerance that should easily be met.

Finally, on sheet 1 in the lower left corner is a proprietary statement block. This type of statement has become fairly standard on drawings. Most vendors will sign nondisclosure agreements in order to handle proprietary drawings and will control the information accordingly. Nevertheless, it is good practice to declare any and all information that is considered to be proprietary.

Moving to sheet 2, there are a number of different dimensional and tolerancing callouts. The diameter of the lens is specified as the primary datum, with a given value and tolerance, while the front face of the lens flange is called out as the secondary datum. In addition to the center thickness (the "stack" of S1), the distance from the vertex of S1 to the front face of the flange is called out. Typically, one surface stack is called out, and the other surface stack floats within the given tolerances for the stack (CT) and overall flange thickness. From an optical design standpoint in a multielement lens system, this may put a tighter surface-to-surface spacing (between adjacent elements) on one side of the lens than on the other. If one side's spacing is more critical than the other, putting the stack callout on the critical side may help with the tolerancing. On the other hand, if the center thickness is less sensitive, it may be more appropriate to call out both surface stacks and let the center thickness float. Whatever choice is made, it is important that the tolerance analysis accurately reflect the way the parts will be built and assembled. The drawing callouts should reflect the desires of the designer, as opposed to choosing which stack to tolerance by chance or convention.

With regard to centration of the two lens surfaces, on this drawing the first lens surface S1 is referenced to the diameter of the lens, while the second surface S2 is referenced to the first surface. In some cases, both surfaces are referenced to the diameter. The choice of how to dimension the two surfaces should again depend on the sensitivities of the design, in this case the sensitivity of the two surfaces to each other versus the sensitivity of the two surfaces to the diameter.

This drawing does not call out any coatings for the lens. If any coatings [such as antireflection (AR) coatings] are required, they should be called out in the drawing notes. In some cases, the element may have multiple or different coatings on the different surfaces. For instance, the rear surface may have an AR coating, while the front surface may have an AR coating, a scratch-resistant coating, or both. Any coatings should be fully specified without any ambiguity. For instance, if a transmission is specified, it should be clear if the specification is for the surface or for the entire element. The note should include the required coating properties, such as allowed reflectance over spectral band and angular range as well as any adhesion, abrasion, and environmental requirements. In addition, if coating properties are to be tested using witness samples, appropriate control of the witness samples should be specified.

The drawing shown and discussed in this section details most characteristics of a typical plastic optical element. Plastic optics of different forms and for different applications may require alternate or additional callouts and/or dimensioning schemes. The ultimate goal of the drawing is to document the part that has been designed and to allow it to be produced and compared against measureable characteristics. If there are doubts about the correct way to specify a particular part characteristic, discussion with the vendor is recommended.

4.13 Vendors and Vendor Interaction

The best time to begin discussions with plastic optic vendors is at the beginning of the project. This is particularly true if the designers are unfamiliar or relatively inexperienced in the design of plastic optical systems. Discussions with the vendor can help avoid potentially costly missteps in the early stages of the design. The best overall system designs result from collaborative engineering between the designers and the vendor. The designers should understand the product they are designing, which requirements are firm, and which can be traded for cost, performance, or producibility. The vendor should be able to provide input on the trades that can be made, such as those that will help them produce the parts more easily, or what the effect of not making certain changes to the part design will be. In addition, based on their experience, they may be able to offer alternate suggestions with regard to mounting, assembly, or test procedures. In the article by Beich, there is an excellent case study on concurrent engineering and the use of multiple prototype and mold methods to transition from the prototype design to production. In it, he provides a guide for use upon starting a program using plastic optics.[69]

Most vendors are willing to sign nondisclosure agreements (NDAs), which allow and protect the transfer of customer proprietary information to the vendor (and potentially vice versa). The designer should clearly specify the proprietary nature of any information that is passed to the vendor, while the vendor should also specify any information they consider proprietary, such as tooling techniques. Careful labeling of documentation and the secure transfer of data, through methods such as encryption, should be considered.

Most companies have a procurement and/or supply chain person or group who deal with the contractual details associated with working with a vendor. These individuals should be contacted when beginning vendor discussions. In some cases, the vendor may not be on an "approved supplier list," which may require the need for a site inspection before any orders can be placed. The designer should verify if their company has any history with a vendor, or if any special requirements (such as signed NDAs) need to be fulfilled before they can speak to them.

The selection of a plastic optics vendor can be driven by several considerations. In some cases, geography or nationality may be a factor. For instance, in the defense sector, selection of a manufacturer may be limited to domestic suppliers or those owned by allied countries. For medical devices, the associated need for certification of facilities may limit the supplier base. In the

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case of consumer electronics, it may be required that subassemblies (such as optical systems) be manufactured in close proximity to the location of the final assembly facility. This can also sometimes be true in the automotive industry.

Cost can be a significant factor in the selection of a vendor. We mentioned earlier the movement of manufacturing towards lower-cost regions, a trend which will likely continue. When considering vendor selection based on cost, it is important to include not just piece price but also the cost of any required engineering support, travel, and on-site supervision.

Reputation and relationships can be another factor in selecting vendors. Having worked with the designer to develop a product through the prototype phase, the vendor that was used should have the best knowledge of both the elements and product. This may give them an advantage in understanding the needs and cost of making the parts. Basic trust can also be an issue, particularly with companies not known for the highest standards of business ethics. One of my colleagues experienced the interesting situation of walking into the "wrong" stockroom, only to find additional assemblies of our product labeled as the manufacturer's own. While rare, these types of situations do exist and are best mitigated through supervision and vendor inspection.

Quality control and testing can be additional vendor selection criteria. Different industries and companies have various quality requirements, such as International Organization Standardization (ISO) certification. Most vendors have some kind of established quality control system, with appropriate procedures and documentation. Modern molding machines, computers, and e-mail allow the relatively easy collection, analysis, and transfer of quality control or SPC data, and most vendors have adequate storage for any necessary part retention. Available test equipment can sometimes play a role in selection of a particular vendor. For instance, a vendor may have an interferometer but not an MTF test station. If the specification on the system is a required MTF value, it must be determined if the use of an interferometer (instead of an MTF test) is adequate.

When placing an order, either for a prototype or for production quantities, clearly defined goals, schedules, and costs should be in place. For instance, if purchasing an injection mold, any nonrecurring engineering (NRE) costs, expedite fees, process development costs, mold compensation limits, required secondary process tooling, or guaranteed production should be understood by both parties. The process of qualifying the mold should also be known, whether based on a full first-article inspection (FAI) or some other method. If a pull-ahead mold is used, with a limited number of cavities initially used, the method of qualifying the additional later cavities should be agreed upon.

There are a fairly limited number of high-quality plastic optics vendors in any country or region of the world. Designers who will be developing plastic optics should make an effort to contact these potential suppliers and begin building a relationship with them. Most suppliers have one or more individuals that spend much of their time providing customer support and product development. These individuals are more than happy to be contacted and begin discussions on a project. They can often be contacted at the exhibitions at various conferences or through the information on their websites.

We cannot overemphasize the advantage of working with vendors at the beginning of a project; it is in the best interest of both the designer and the vendor. Vendors themselves often state that they wish they would be contacted earlier. If nothing else is gained from reading this tutorial text, remember this: begin discussions with vendors at the start of a project.

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Chapter 5

Design Examples

Having discussed materials, manufacturing methods, and design guidelines in the previous chapters, we now present several design examples. The examples are intended to show several different design considerations, such as using a diffractive surface for color correction, the trade between number of lenses and performance, and the effect of the selection of probability distributions of tolerances. We also consider a more unusual system: a higher-order diffractive.

5.1 Singlet Lens

Probably the simplest example of a plastic optical system is one that uses only a single lens. In this section, we consider the design of a singlet plastic lens and compare its performance to that of a cemented glass doublet. To compare the two systems, we will use a 100-mm EFL *f*/4 lens, with a full field of 2 deg. This combination of EFL and *f*/# means that the lens will have an entrance pupil diameter of 25 mm. For the wavelengths, we use the d, f, and c lines (587.6 nm, 486.1 nm, and 656.3 nm, respectively), equally weighted.

We begin the comparison by designing a cemented achromatic glass doublet. We select two glasses, one crown and one flint. For the crown, we select N-SK5, which has a glass code of 589.613. For the flint, we select N-F2, which has a glass code of 620.364. We initially set the thickness of each element equal to 3 mm, about one-tenth of the diameter. We allow all three radii (we assume the cemented radii are equal) to be varied by the optimization algorithm. In reality, we may want the cemented radii to be slightly different so that they do not make contact at the center of the surfaces, but we do not concern ourselves with that now. We use the default (rms wavefront) merit function, with the additional constraint of requiring a 100-mm EFL. We initially set the radius of the first surface to be 100 mm and the second surface to be –100 mm, so that we have a positive-powered doublet as our starting point.

Running the optimization algorithm, we obtain the doublet shown in Fig. 5.1. We can see from the figure that the edge thickness of the front lens (lens 1) is not sufficient. In fact, the front and rear surfaces of the lens have "crossed over." This is due to the initial thickness that was set as well as the fact that no edge thickness constraint was applied. Some optical design software has default settings that will prevent this from happening, while others do not impose such a constraint. This is mainly a result of the philosophy of the software developers. In order to get a realistic edge thickness, we increase the center thickness of the front lens to 6 mm and rerun the optimization algorithm. With the increased center thickness, the lens 1 surfaces no longer cross over, and a reasonable edge thickness is obtained. The optimized system is shown in Fig. 5.2.

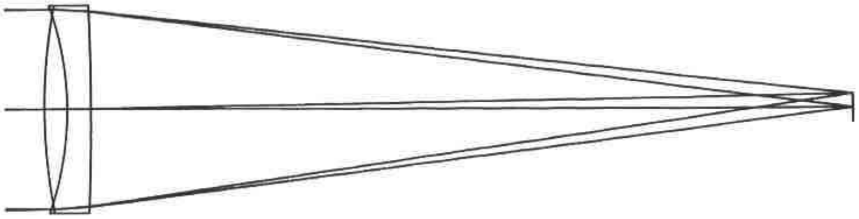


Figure 5.1 Cemented doublet after initial optimization run.

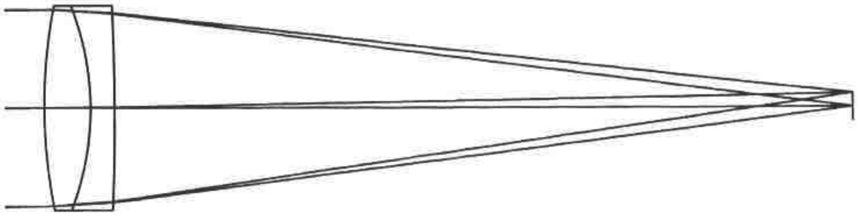


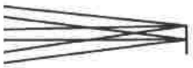
Figure 5.2 Cemented doublet after increasing lens 1 center thickness and reoptimizing.

As a metric to compare the doublet and the plastic lens, we calculate the modulation transfer function (MTF) of the systems. The MTF is a widely used performance metric in optical systems that tells us how well the details of an object will be imaged. The MTF of an optical system is simply the ratio of the contrast of the image of a sine wave to the contrast of the input sine wave object, where the contrast m is defined as

$$m = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \tag{5.1}$$

where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensity values of each sinusoid. An example is shown in Fig. 5.3, where at the top of the figure we have the input object sinusoid, and at the bottom of the figure we have its image after passing through the optical system.

The object sinusoid has a period of 2 mm, while the image sinusoid has a period of 1 mm. This is due to the magnification of the optical system, in this case a magnification of 0.5. MTF values are usually quoted at the image plane for a given sinusoidal frequency. Because the image sinusoid has a period of 1 mm, we would say that it has a spatial frequency of 1 cycle/mm, which is the inverse of the period. If the period had been 0.2 mm, it would have a spatial frequency of 5 cycles/mm.



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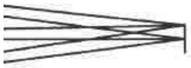

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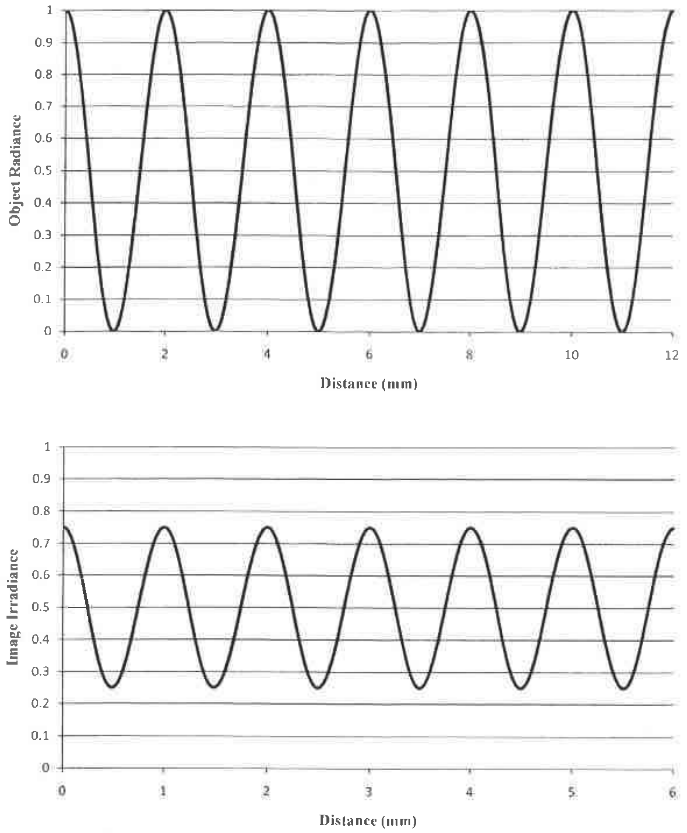

Figure 5.3 Input and output sinusoids used in the calculation of MTF.

We now calculate the MTF value of this system at 1 cycle/mm. The contrast of the input sinusoid is equal to (1 – 0)/(1 + 0) = 1. The contrast of the image sinusoid (at 1 cycle/mm) is (0.75 – 0.25)/(0.75 + 0.25) = 0.5. Thus, the MTF of the system at 1 cycle/mm is (0.5/1) or 0.5. We could perform similar calculations for a range of sinusoidal frequencies and generate an MTF curve for the system.

The reason we use sinusoids is that a generic object can be considered to be made up of a sum of sinusoidal intensity distributions, with each sinusoid having an appropriate contribution. When forming an image, the optical system transfers each of the constituent object sinusoids to the image plane. In doing so, the contrast of each sinusoid is reduced by the MTF value of the system at that particular spatial frequency. The image we see is the sum of the transferred sinusoids. Because the MTF values are less than one, the contrast in the image will not be as high as the contrast in the object, resulting in loss of detail in the image. Higher spatial frequencies correspond to finer details in the object, so in order to see a given level of detail, we would like to have a reasonable MTF value at the corresponding spatial frequency. In general, it is best to have a highly valued, smoothly varying MTF curve. Readers interested in a more thorough review of the modulation transfer function are referred Refs. 86, 87, and 88.

The MTF of the glass doublet is shown in Fig. 5.4. As with most optical systems, the value of the MTF (which is normalized at the origin) decreases as a function of increasing spatial frequency. We have plotted the MTF at the image plane out to its value at a spatial frequency of 100 cycles/mm. The line on the plot labeled "diff. limit" shows the largest value of MTF that could be obtained at any spatial frequency given our system's *f*/# and wavelength range; that is, the diffraction limit curve shows the MTF performance of a perfect system. As we mentioned previously, diffraction sets a lower limit on how small the image of a point object can be, which is equivalent to setting a limit on how high the MTF can be at a given spatial frequency. The difference between the diffraction limit and the performance of the doublet is due to the aberrations that exist in the design. Given the number of (spherical) surfaces in the design, we cannot completely correct all the aberrations (both geometrical and chromatic), which results in performance below the diffraction limit. Improving the performance of the system would require separating the two elements or the use of additional of elements.

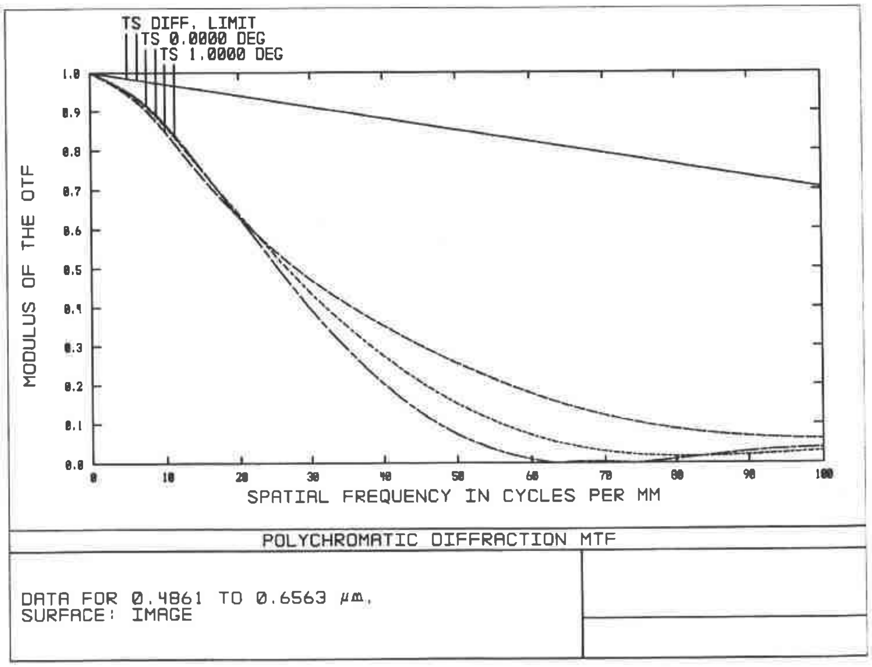

Figure 5.4 MTF of the glass doublet.

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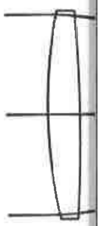

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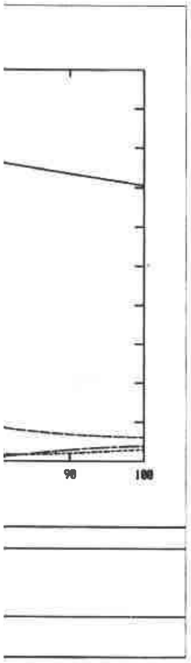


We now consider the design of the plastic singlet. We select acrylic as the lens material and want the same EFL and *f*/# as the glass doublet. We set the center thickness of the lens at 4 mm and allow the front surface of the lens to be aspheric (conic). After running the optimization algorithm, the lens obtained is shown in Fig. 5.5. We can see that there is an acceptable edge thickness for a gate if the part is to be molded. The performance of this lens is poorer than that of the doublet, as can be seen from the MTF plot in Fig. 5.6. The MTF curve for

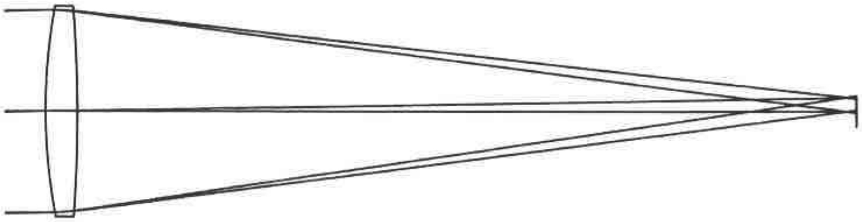


Figure 5.5 Plastic refractive singlet.

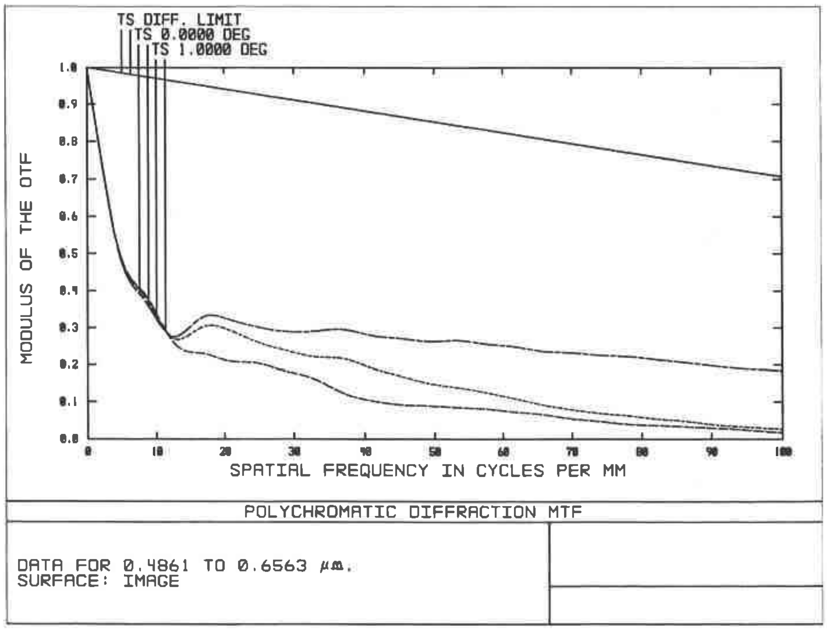


Figure 5.6 MTF of the plastic refractive singlet.

the plastic element drops off more rapidly than that for the doublet and is less smooth. Even though the plastic element has an aspheric surface, its performance is poorer than the spherically surfaced doublet. This is due to the fact that the plastic refractive element is not color corrected. As we discussed earlier, the variation in the refractive index with wavelength results in a variation in focus for different wavelengths for a singlet lens. In the glass doublet, the two elements (with their different dispersions and powers) compensate for this, while in the singlet there is no such compensation. The aspheric surface, while able to correct for spherical aberration, does not change the basic chromatic aberration of the singlet. Of course, we could always add a second element, similar to the design of the glass doublet, but this will increase the system cost.

As discussed in the last chapter, one way of correcting color without adding another element is to use a diffractive surface. We now add a diffractive surface to the rear of the singlet lens in order to help control the chromatic aberration. The diffractive surface in this case is represented by an even-order polynomial. We select the design order as the first diffraction order ($m = 1$) and allow the coefficient on the second-order polynomial term to vary in the optimization. The other variables—the radii on the two surfaces and the conic on the first surface—are allowed to vary as well. The lens resulting from running the optimization algorithm is almost a convex-plano form, with a very weak rear surface. As discussed earlier, it is often best to introduce some power into such a surface to improve its molding characteristics. The radius of the rear surface was therefore fixed at 200 mm, and the optimization was rerun. The lens that results is shown in Fig. 5.7, and its MTF plot is shown in Fig. 5.8. Comparing the MTF plot for the plastic diffractive singlet to that of the glass doublet in Fig. 5.4, we see that they are approximately the same. The diffractive surface has provided the color correction in the singlet that the combination of lenses provides in the doublet.

We discussed in the design guidelines that the designer should check two things when using aspheric and diffractive surfaces: if any aspheric surfaces are truly needed and the minimum ring spacing on the diffractive. Checking the value of an aspheric surface is easy in this design. If we remove it and rerun the optimization, we find a definite decrease in the MTF performance; thus, the aspheric surface is providing a benefit that justifies its use. For the diffractive surface, we run an analysis option within the program that calculates the radial position of each diffractive ring and provides the minimum ring spacing.

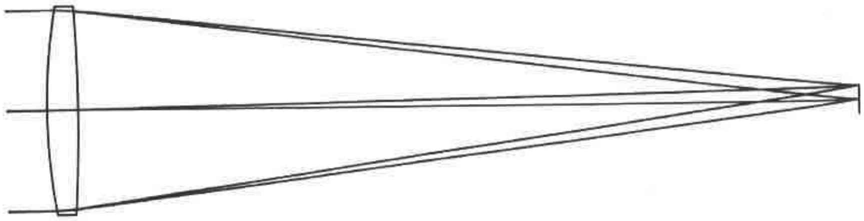
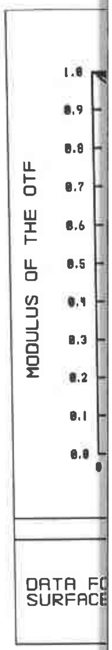
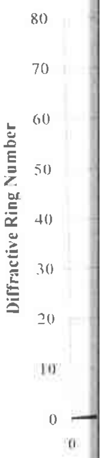


Figure 5.7 Plastic hybrid (refractive with diffractive) lens.





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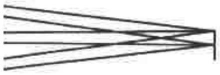

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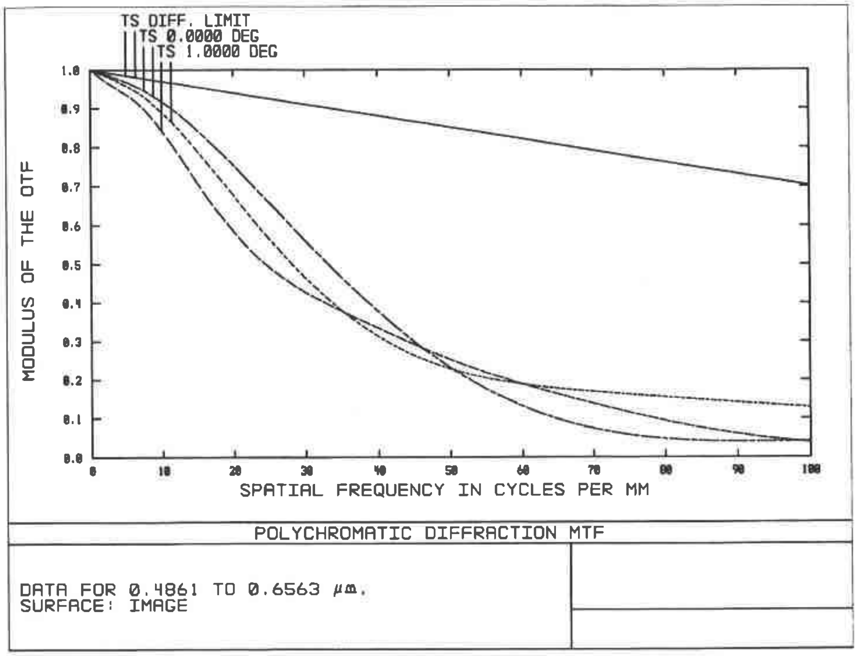

Figure 5.8 MTF of the plastic hybrid lens.

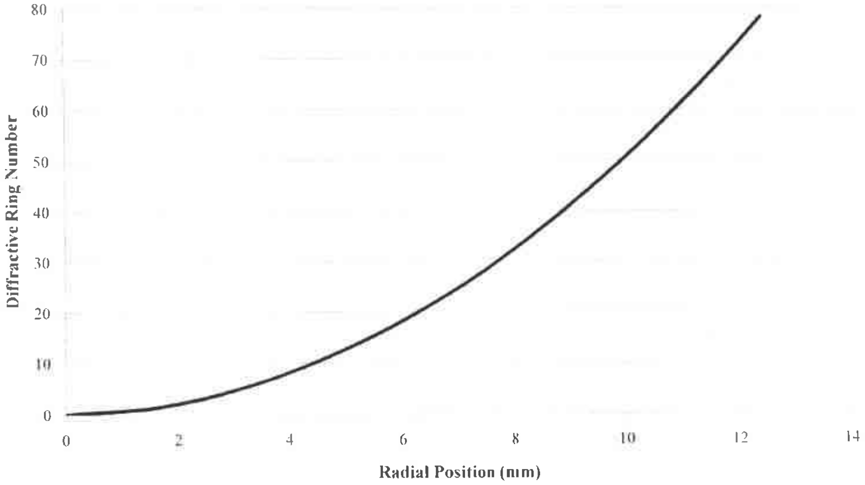

Figure 5.9 Plot of diffractive ring number versus radial position.

For this lens, there are 78 diffractive rings with a minimum ring spacing of approximately 80 μm. This ring spacing is well above the minimum spacing limit for diamond turning the lens or an optic insert to produce it. Figure 5.9 shows a plot of the ring number as a function of radial position. We can see from the slope of the curve that the rings get increasingly smaller as we move out from the center of the lens.

Although a relatively simple system, single-element plastic lenses are used in a variety of applications. We discussed their use as intraocular lenses in Chapter 1. They are also used in CD/DVD (and other data storage systems), simple microscopes, in safety beam break devices, and as eyepieces for microdisplays. The decision whether to use a diffractive surface in each application will depend upon the need for color correction, the waveband of interest, and any issues associated with diffraction efficiency.

In general, the use of a diffractive does not come without some performance cost due to its diffraction efficiency. As was shown in Fig. 4.17, the efficiency of the diffractive is only optimal for one wavelength. In reality, the diffraction efficiency will be less than 100% even for the design wavelength, due to manufacturing limitations. Some percentage of light will be transferred from the design order to other orders coming from the diffractive surface. These other orders will typically be out of focus, compared to the design order. This is shown in Fig. 5.10, where we can see the light from the second diffractive order coming to focus in front of the light from the design (first) order. Light from the zero order, which is not shown, would focus behind the design order focus. The amount of light in these other orders will depend on the width of the waveband relative to the design wavelength, as evident from Eq. (4.10).

A particularly dramatic effect of this nondesign order light can be seen in Fig. 5.11. This figure shows the effect of looking at a high-contrast object on a microdisplay through a singlet eyepiece. In this application, the customer did not want to pay for a second plastic lens, so a single element with a diffractive

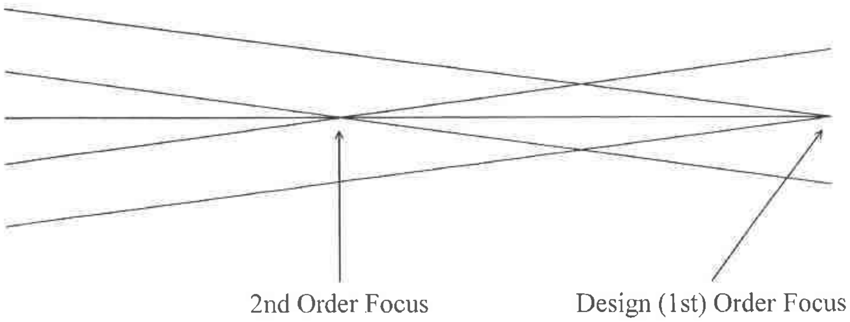

Figure 5.10 Variation in focus for different diffractive orders.

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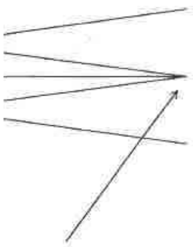

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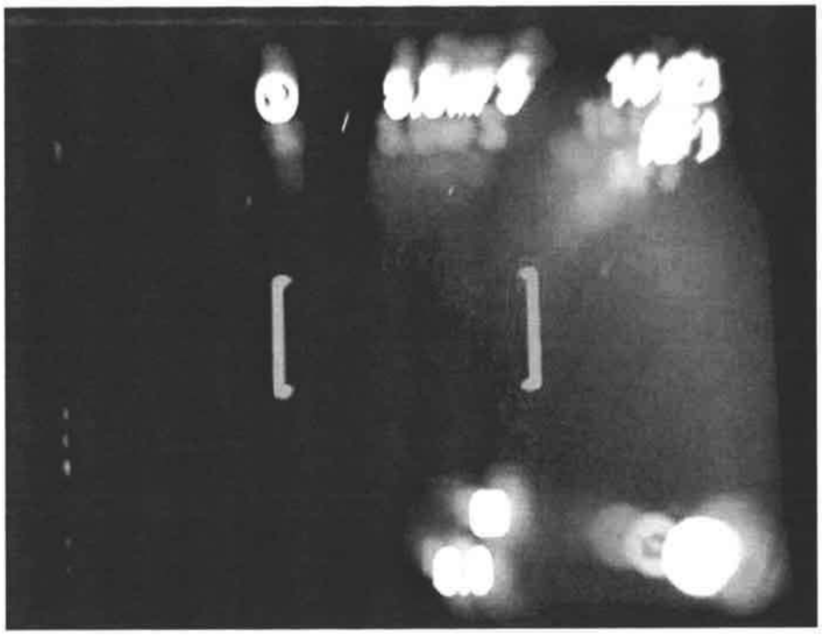


Figure 5.11 Multiple images resulting from light in various diffractive orders. (Photograph courtesy of Alan Symmons.)

surface was used instead. For most of the microdisplay images observed, the diffractive worked adequately. However, under the condition of viewing high-contrast text, as is shown in the figure above, secondary images due to imperfect diffraction efficiency were clearly evident. This was unacceptable to the customer, who in the end chose a single-element lens (without a diffractive) for cost and packaging purposes and lived with the reduced image quality due to uncorrected chromatic aberration. The case shown is worst than most, with the picture saturated to emphasize the secondary images.

The consideration of such diffraction-efficiency effects must be taken into account during the design process. It may be possible to model the effect in software, but the manufacture of a prototype is often the best way to evaluate the effects.

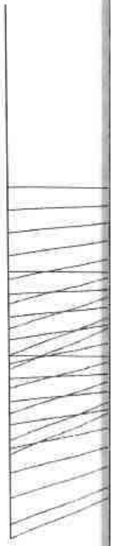
5.2 Webcams

Web cameras (or webcams, as they are commonly referred to) have become increasingly popular. Mounted on a computer monitor and connected to the Internet, they allow real-time visual and audio contact between parties that may be on different sides of the world. A decade ago, due to data transfer rates, video from a webcam was often slow to update, resulting in jerky and annoying images. Today, improved speeds have made the use of a webcam a more enjoyable experience. Several commercial companies provide free webcam data transfer, which can reduce or eliminate long-distance phone charges, and many companies are using video conferencing as a way to reduce travel costs. Even though they provide reduced phone and travel costs, webcams are still expected to be relatively inexpensive, which has led to their use of plastic optical lenses. In many cases, the cameras are a free accessory with the purchase of a computer, thus limiting the number of elements that can be used in their optical design. In this section, we consider the design of a two-element webcam lens. We then compare its performance to that of a single-element and a three-element system in order to show the trade between complexity and performance.

In this example, the design process was fairly well structured by the desires of the customer. Based on previous cost-versus-performance trades, it was specified that a two-element system be developed. Because of concerns about stray-light artifacts, diffractive surfaces were not preferred. The desired lens was to have a focal length of 3 mm, operate at *f*/2.4, and have a maximum image height of 1.7 mm, which yields a semidiagonal field of 29.5 deg. The system was to work over the visible region (from 420 to 740 nm), with the central portion of the waveband more heavily weighted than either edge. The lens was to be used with a CMOS sensor, which required the inclusion of an IR-blocking filter in the optical system. The image performance goal was to have relatively uniform image quality across the field. Some distortion was acceptable (up to about 5%), with the goal of it being smoothly varying. The relative illumination, which is the ratio of the irradiance in the corner of the image to that in the center of the image, was to be greater than 60%. Finally, due to the fact that the detector had a microlens array over it, the angle of incidence of the chief ray (the center ray of each field bundle) on the image plane was to be held to less than 15 deg.

Based on the customer requirements, optical design basics, and prior experience, a starting point lens form was selected, which is shown in Fig. 5.12. In reality, a more developed starting point was available (from a design database), but the starting point shown will work for anyone without access to such a database. The starting point consists of a front negative lens and a rear positive lens. This form is common for a two-element system and can be thought of as a variation on an achromatic doublet. Having a negative and a positive lens will help with the Petzval curvature of the system and allow for some chromatic correction. We would like the negative element to be a (high-dispersion) flint material, while for the positive lens we would like a (low-dispersion) crown material. The plastics selected were polystyrene for the negative element and acrylic for the positive one.

In between the two lenses is an IR-blocking filter, which consists of a multilayer coating on a flat glass plate. This will prevent the detector from receiving light of wavelengths above 740 nm, which it is sensitive to. If the IR filter were not in the system, the image would have reduced contrast due to these additional uncorrected wavelengths. The location of the filter plate was driven



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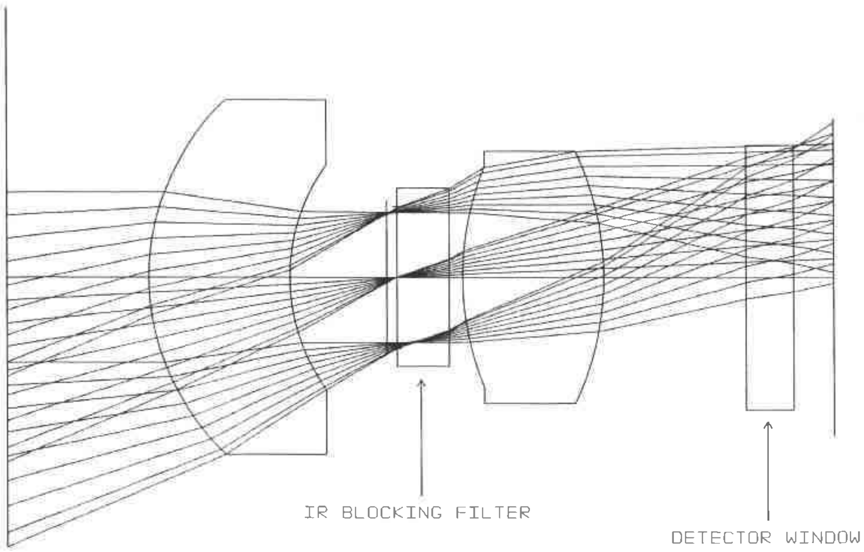

Figure 5.12 Starting point for web camera design.

not by optical design considerations but by concerns over patent infringement. Because of existing patents on similar systems, legal counsel (insert your favorite lawyer joke here) determined that the filter needed to be between the lenses, as opposed to in front of or behind the system. From an aberration correction standpoint, having the glass between the lenses was not significant. It can matter, however, for the performance of the filter, due to the potentially large range of angles of incidence at this position. In this case, the angular range was not a significant problem, and having the filter between the lenses actually was somewhat beneficial, as this position required the smallest filter area, which was the lowest cost option. In addition to the IR filter, another glass plate (the detector window) can also be seen.

A large number of fields (nine) were input to the system in order to provide closely spaced coverage of the image plane. For the initial optimization, the full field of 1.7 mm was not used; it was reduced to 1.5 mm. This allowed the optimization program to avoid having to deal with untraceable rays. Wavelengths spanning the 740- to 420-nm waveband were input, with wavelength weights dropping off when moving from center to edge. Initially, the first surface of lens 1 and the second surface of lens 2 were allowed to be aspheric, while the other two lens surfaces were spherical.

The merit function used was the default merit function, with several additional constraints. These constraints were the desired value of the EFL, control on the allowed distortion values, and limits on the chief ray angles of incidence on the detector. The distortion, if unconstrained, can take on large values (over 20%) in order to achieve better image quality. The chief ray angle constraint, although required by the design, did not strongly influence the optimization. After an initial optimization run, the lens was evaluated by examining the ray fans. Due to the presence of spherical aberration, the first surface on lens 2 was allowed to be aspheric, and the optimization algorithm was run again.

With the design now under control, the fields were adjusted to bring them up to the full field height of 1.7 mm, and the lens was reoptimized. For tolerance considerations (such as detector decenter), the field heights should actually be slightly larger than the required field. The general form of the lens did not change, but there was a decrease in performance. This is due to adding larger field angles, which require additional geometric aberration control. In addition, increasing the field angles resulted in larger distortion, which also needed to be controlled. To help with the reduced performance, the final spherical surface (the second surface of lens 1) was allowed to become aspheric. After again running the optimization, the performance improved, while the lens form did not significantly change. The resulting lens is shown in Fig. 5.13.

At this point, the optical performance of the system was adequate, and the initial design work could theoretically be stopped. In reality, several changes could be made to improve the producibility of the design. Reviewing the design with the optomechanical designer and the mold processor resulted in several desired modifications. Looking again at Fig. 5.13, we can see that the surfaces of lens 1 are both approaching hemispheres, and the rays are quite close to their

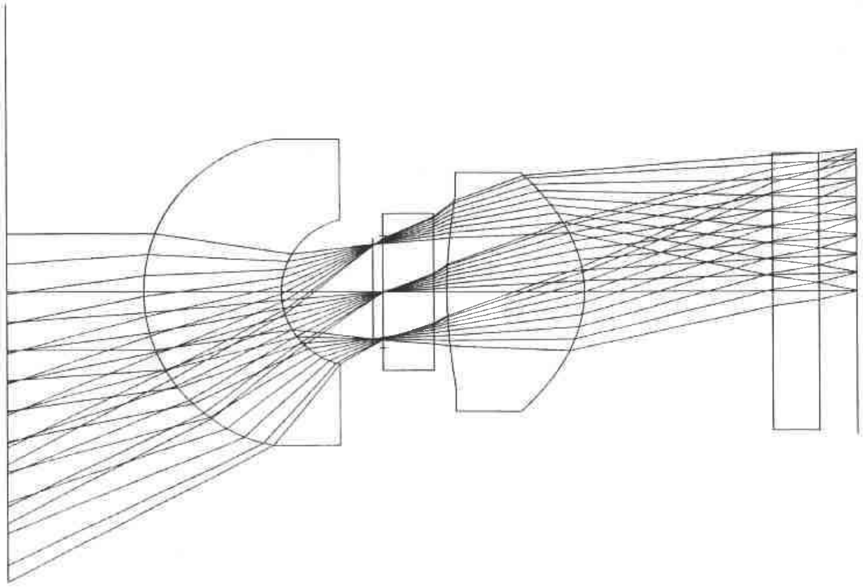

Figure 5.13 Two-element web camera after optimization.

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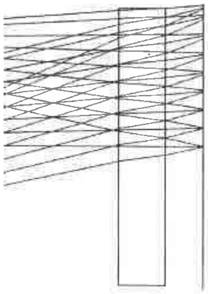

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edges. From the processor's standpoint, flattening the surfaces and providing more ray clearance on the surfaces would improve the design by making the surfaces easier to mold. The additional clearance would also allow more room on the edge of the part for the gate. On lens 2, edge thickness and edge break were also concerns; carrying the second surface out farther to provide room for edge break would allow for easier molding.

With these changes in mind, additional design work was performed. The center thickness of lens 2 was increased to improve its edge thickness, and a constraint was placed on the radius of the first surface of lens 1. This constraint forced the radius to be above a certain value, which was arrived at through several attempts. The thickness of the first element was also allowed to vary. At first, no constraint was applied to the thickness, and the optimization algorithm made the lens unnecessarily thick. After an upper-limit thickness constraint was applied, a much more reasonable lens was obtained, which is shown in Fig. 5.14. For the larger fields, some rays are drawn that would actually be clipped by the aperture stop. The MTF performance of the lens is shown in Fig. 5.15, and the astigmatic field plot and distortion are shown in Fig. 5.16. The distortion reaches its peak of 5% at about three-quarters of the full field. Tighter control of the distortion can be traded for image quality. The relative illumination of the lens, when the proper clipping of rays is accounted for, is over 60%, as is shown in Fig. 5.17.

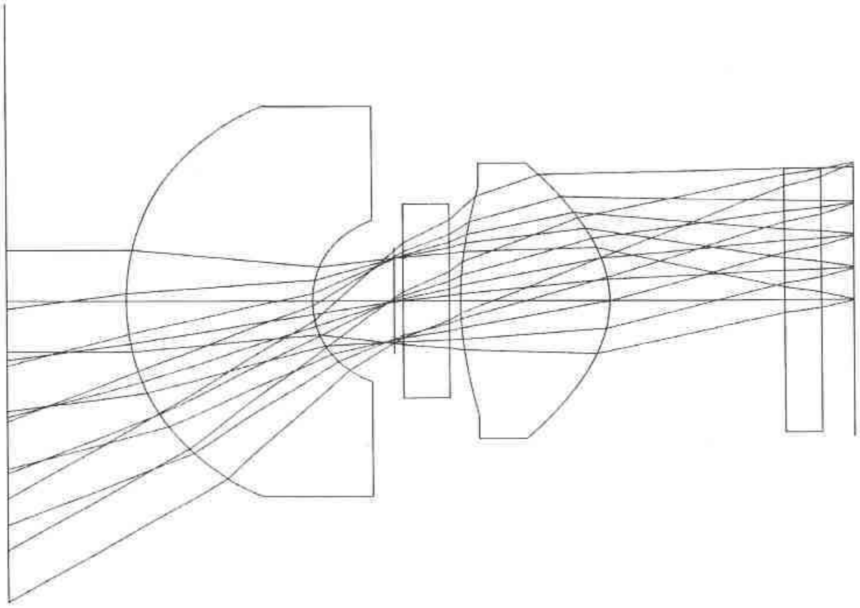


Figure 5.14 Final optical design of a two-element web camera.

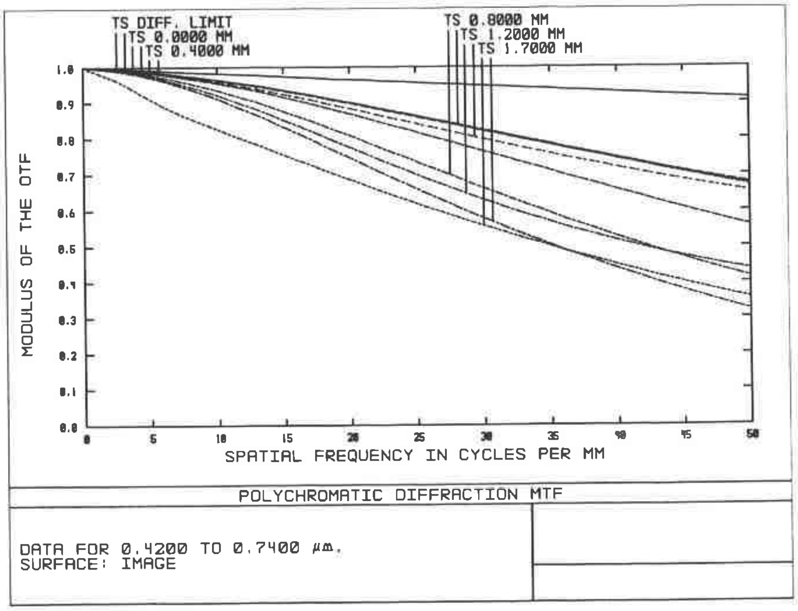


Figure 5.15 MTF performance of a two-element web camera.

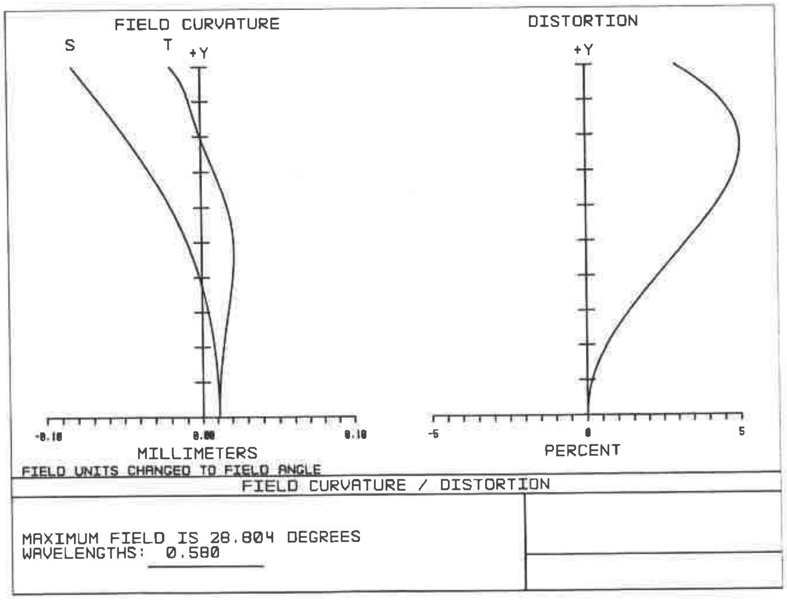
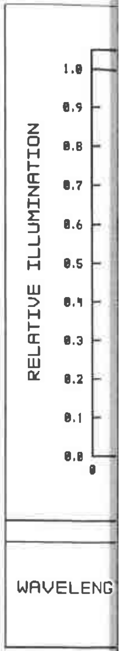


Figure 5.16 Astigmatic field plots and distortion of a two-element web camera.



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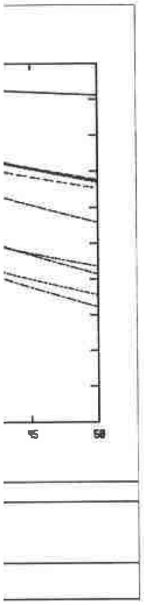

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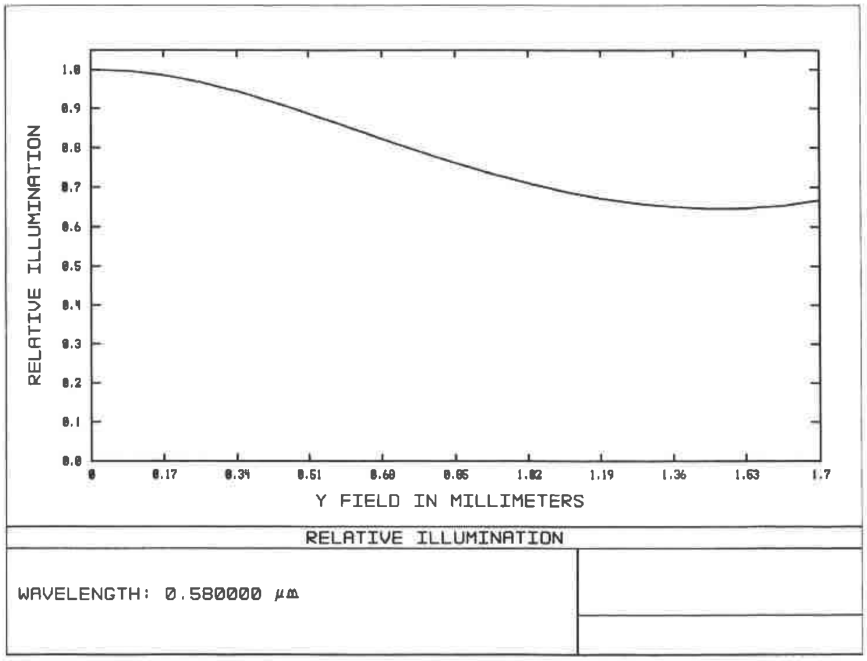


Figure 5.17 Relative illumination of a two-element web camera.

As noted before, a tolerance analysis must be performed before the design is truly complete. By performing a sensitivity analysis, it was found that the primary tolerance drivers for the MTF performance were the surface and element decentrations. For the predicted performance analysis, radial surface centration and element decenter values of 20 µm were used. Radii tolerances were set at 0.5% to 1%, and thickness tolerances were set at 25 µm. The result of the tolerance analysis was a predicted (two sigma) drop of 10% in the MTF value at 35 cycles/mm. The predicted drop was quite uniform across the field.

In the section on aspheric surfaces, we mentioned the importance of increasing the number of fields during the design optimization. This is also true during the tolerance analysis. It is possible for designs such as this to have a particularly sensitive image zone, often somewhere in the range of half to three-quarters of the full field height. If this zone is not adequately represented in the tolerance analysis, an annular region of poor image quality may be seen in the associated prototype lens. It is well worth the small extra computing time to ensure this effect is not present in a design.

A schematic of the final optomechanical design is shown in Fig. 5.18. A multipurpose molded opaque part was incorporated into the system. It contained the hole for the aperture stop, a square recessed area to hold the IR filter, and had the appropriate thickness to set the spacing of the two lenses. The IR filter was

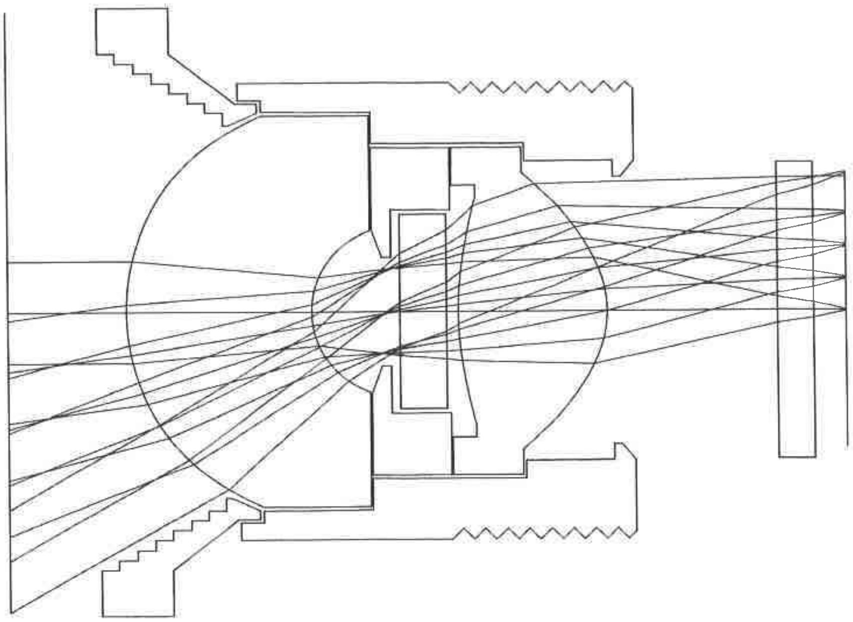
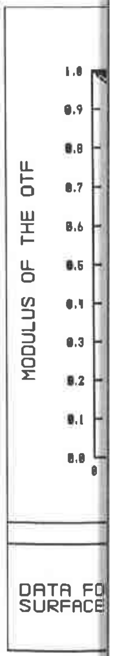


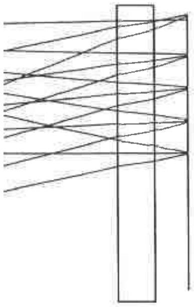
Figure 5.18 Schematic of the final optomechanical design of the two-element web camera.

held in the aperture stop piece through the use of UV cure cement. The lenses and aperture stop/filter combination were assembled into a molded, threaded barrel. The threaded barrel allowed a manual focus adjustment on the web camera. Lens 2, the aperture/filter assembly, and then lens 1 were stacked in the barrel and retained using a molded plastic sunshade. The sunshade could be attached either with UV-cure cement or through ultrasonic staking.

We now compare the performance of this two-element lens with systems having one more or one less element. Figure 5.19 shows a single-element system that was designed to have the same system parameters as the two-element lens just designed. A plot of the singlet's MTF performance is shown in Fig. 5.20. Comparing this to Fig. 5.15, we see that the performance of the singlet is worse than that of the two-element lens, particularly for the larger field angles. This is not a surprising result. As mentioned earlier, the addition of a second lens allows greater control over the chromatic aberration, a reduction in the Petzval curvature, as well as additional variables for aberration control.

Figure 5.21 shows a three-element design. This design was produced by taking an existing longer focal length system and scaling it to the same focal length as the two-element lens. In this system, there is a diffractive surface on the third lens element. The MTF for this lens is shown in Fig. 5.22. Comparing this MTF to that of Fig. 5.15, we see that the addition of another lens again improves





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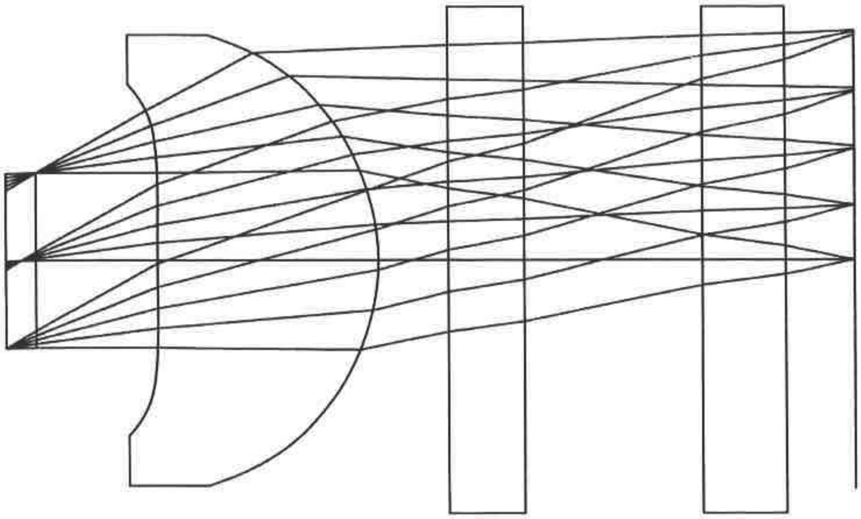

Figure 5.19 Single-element web camera design.

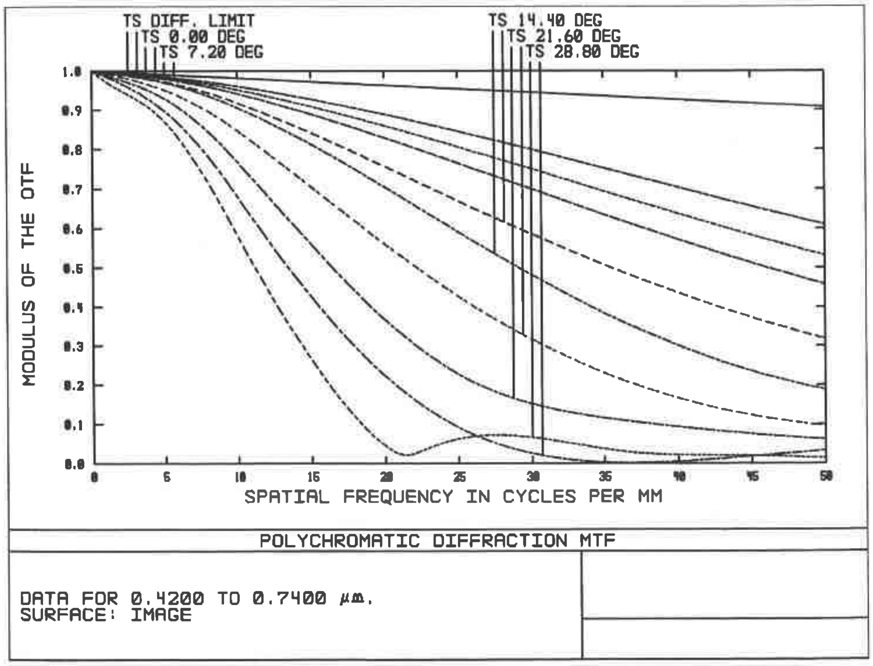

Figure 5.20 MTF of the single-element web camera design.

the lens systems performance. The addition of a diffractive surface improves the MTF beyond that which would be achieved with three refractive elements alone. A similar design exists where instead of using a diffractive surface, the rear lens is compounded into a doublet.

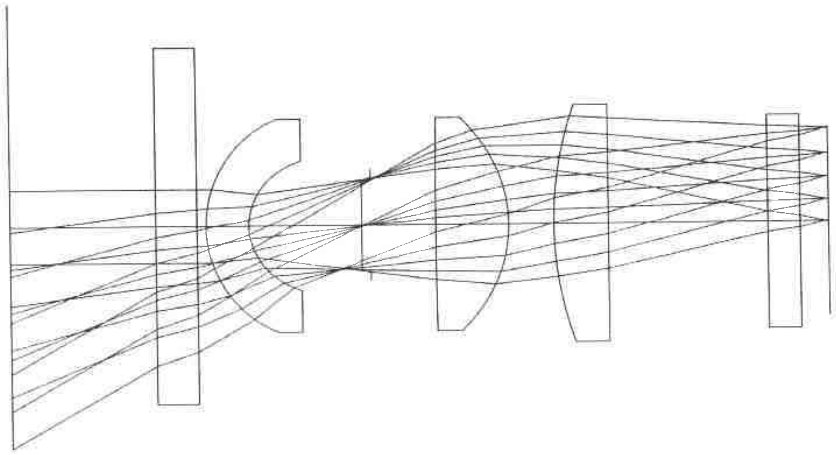

Figure 5.21 Three-element web camera design.

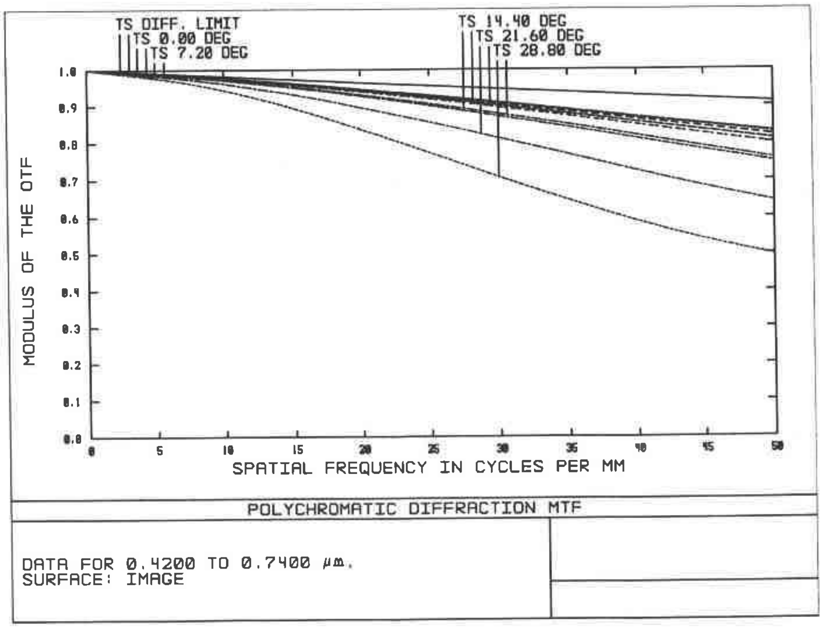

Figure 5.22 MTF of the three-element web camera design.

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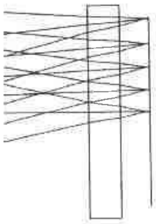

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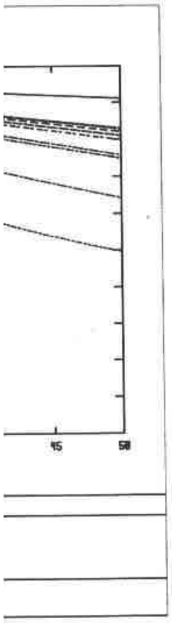


design.

While looking at MTF curves may be meaningful to a trained optical engineer, it may be difficult for most people (such as customers) to understand how the curves relate to the actual image. Since we know that the MTF value, especially at higher frequencies, is related to detail in the image (from the object), we would expect that the three-element system would provide a more detailed image than the two-element system, which would in turn provide more detail than the singlet. With the continuing improvements in computing and optical design codes, it is now possible to get an idea of what the image from a system will really look like. This can be achieved by using the image simulation features in the optical design programs.

In my opinion, the addition of image simulation to the optical design codes is one of the greatest improvements that have been made to them. Instead of showing a customer an MTF curve and trying to explain its meaning, the customer can be presented with simulated images showing what improvement they can expect for the cost of an additional element. Since the input to the simulation algorithm is a picture (such as a jpeg file or bitmap), the customer can provide input objects that are representative of their application. For instance, a microdisplay manufacture may provide text files, diagrams, or checkerboard patterns, while a web camera company may want to see how a typical office scene will appear.

Examples of using an image simulation feature are shown in Figs. 5.23 through 5.26. These were generated using the lenses above, with a jpeg image of the model (Shadow) as the input file. Figure 5.23 shows an example with a "perfect" lens. In this case, there are no aberrations; the spot size formed by the lens is only limited by diffraction. This is the "best" picture that could be obtained with a *f*/2.4 lens. Figure 5.24 shows the simulated image for the single-element system. The decrease in image quality for the larger fields is obvious. This is in agreement with our understanding of the MTF curve of the lens, which showed low values for the larger fields. Figure 5.25 shows the simulated image for the two-element system we designed in this section. As expected, there is a definite improvement in detail over the single-element system; notice how the larger field angles are less blurry than the previous image. Finally, Fig. 5.26 shows the simulated image for the three-element system. The image quality of this system is better still. This lens has better relative illumination than the two-element system, resulting in brighter corners. In addition, the sign of the distortion for this lens is negative as opposed to the positive distortion of the two-element system. This can be seen by comparing the location of objects at larger field angles.

These images were all simulated using the nominal performance of the systems. A further exercise could be conducted where lenses representing the average (or lower bound) on the toleranced system performance are used. Such representative lenses can be obtained from those created during a Monte Carlo tolerance analysis. Although more time consuming than the automated design code feature, visual representations of sensitivity analyses can also be performed.

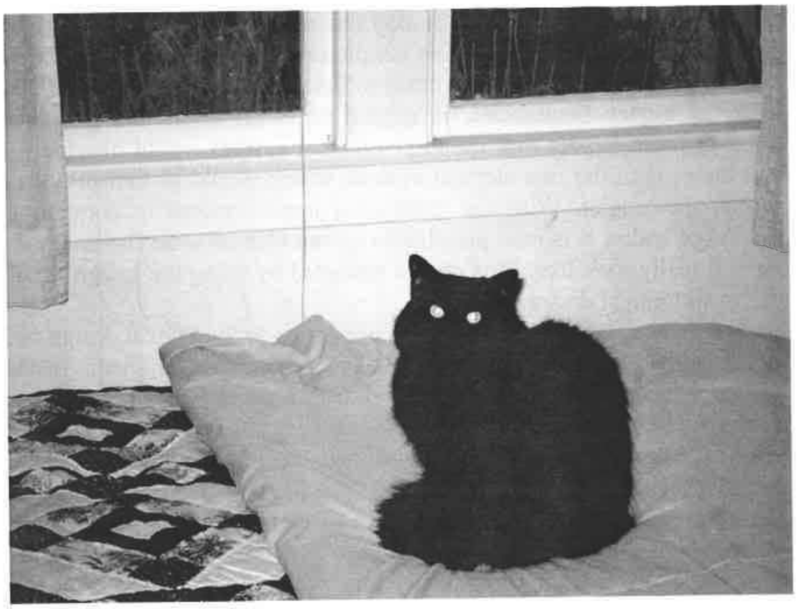


Figure 5.23 Simulated image of Shadow using a perfect lens. (Input image courtesy of Elsa Nunes Schaub.)

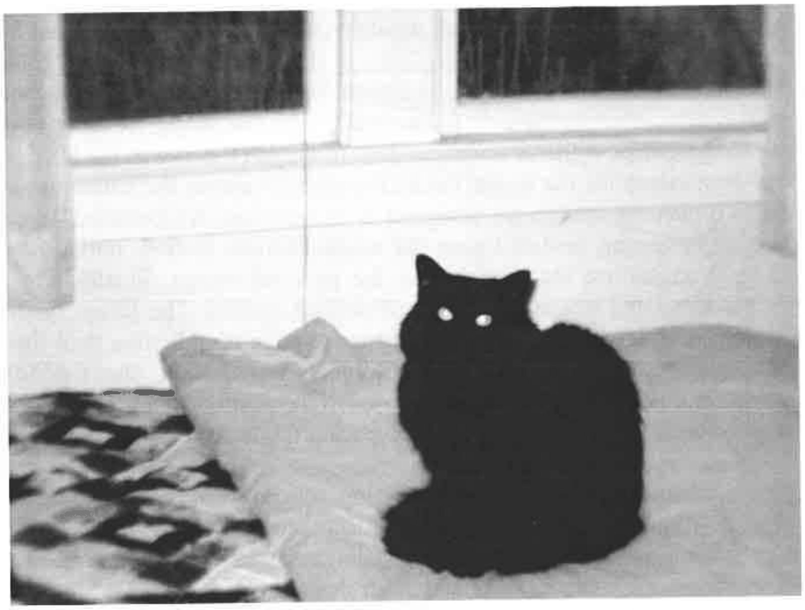
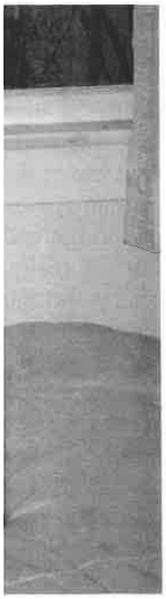


Figure 5.24 Simulated image of Shadow using the single-element design. (Input image courtesy of Elsa Nunes Schaub.)



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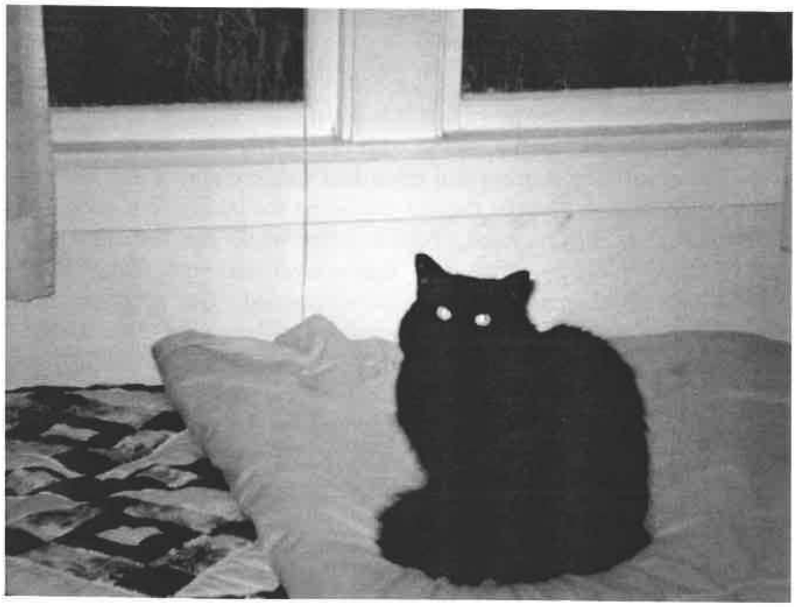

Figure 5.25 Simulated image of Shadow using the two-element design. (Input image courtesy of Elsa Nunes Schaub.)

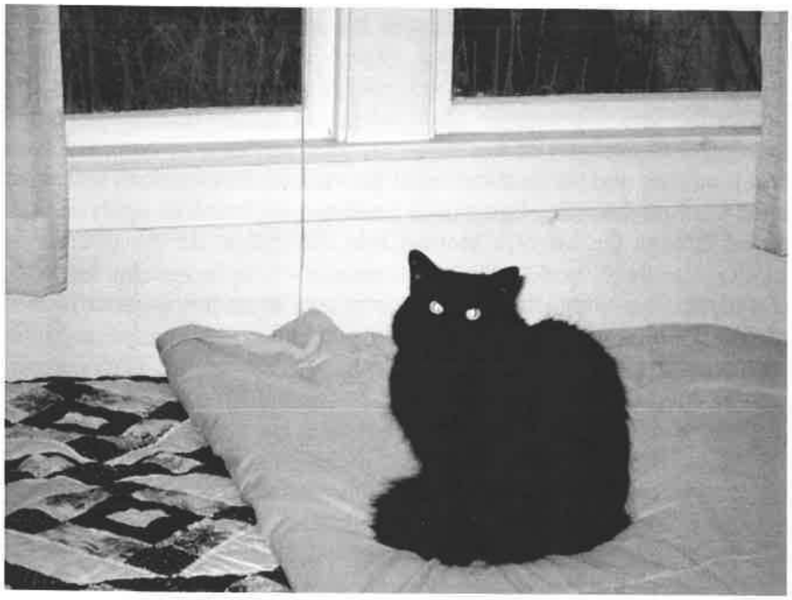

Figure 5.26 Simulated image of Shadow using the three-element design. (Input image courtesy of Elsa Nunes Schaub.)

5.3 Cell Phone Camera

The next design example we discuss is a cell phone camera. These systems have become quite popular, to the point that it is often more difficult to purchase a cell phone without a camera than a phone with one. Early cell phone cameras used relatively low-resolution sensors and often had single-element lens designs. The original use model was that the camera would be for taking "bar shots;" that is, people would be taking pictures of each other while out socializing. As the cameras became more popular and the convenience of using them was understood, increased image quality was demanded. The detector resolution steadily increased to the point that megapixel sensors are used today. This increase in sensor resolution and size drove complexity into the optical designs. Instead of single-element designs, two, three, and even four elements are used. In fact, the newest generation of cell phone cameras will have autofocus and zoom capability.

Figure 5.27 shows an example of a three-element cell phone camera design. These types of designs are usually heavily constrained, with overall length being a driving factor. This often results in thin, tightly spaced elements. During the design process, the edge and center thickness of the elements must be constrained to manufacturable sizes. Additionally, sensors containing microlens arrays may limit the chief ray angle of incidence on the image plane. This can result in unusual-looking (for glass) rear elements, which bend the ray bundles over to meet the angle of incidence constraint.

In this example, we will not focus on the actual design of such systems but instead concern ourselves with one aspect of their tolerance analysis. In particular, we compare the predicted performance for two different surface decenter probability distributions. Most cell phone camera lens designs tend to be quite sensitive to decenter of the elements, their surfaces, or both. As such, the maximum amount and the distribution of the various decentrations will affect the predicted performance. To show this, a predicted performance analysis was run, conducted through the use of a Monte Carlo simulation. As described before, a Monte Carlo analysis models the production of multiple systems by randomly varying parameters within their tolerance ranges according to a defined set of probability distributions. In this case, the probability distribution used for the surface decenter tolerance was varied.

First, a Monte Carlo simulation was performed for a surface decentration with a uniform distribution. This means that the surface decenter is equally likely to be anywhere within its tolerance range. Next, an endpoint distribution for the surface decenter was used. This means that the surface will always be decentered by the maximum amount allowed, with a rotational orientation of the decentration that is random. For instance, on one system, surface 1 on lens 1 may be decentered upward, while surface 2 on lens 1 is decentered to the left. In another instance, both may be decentered upward, which is similar to the entire lens shifting upward.

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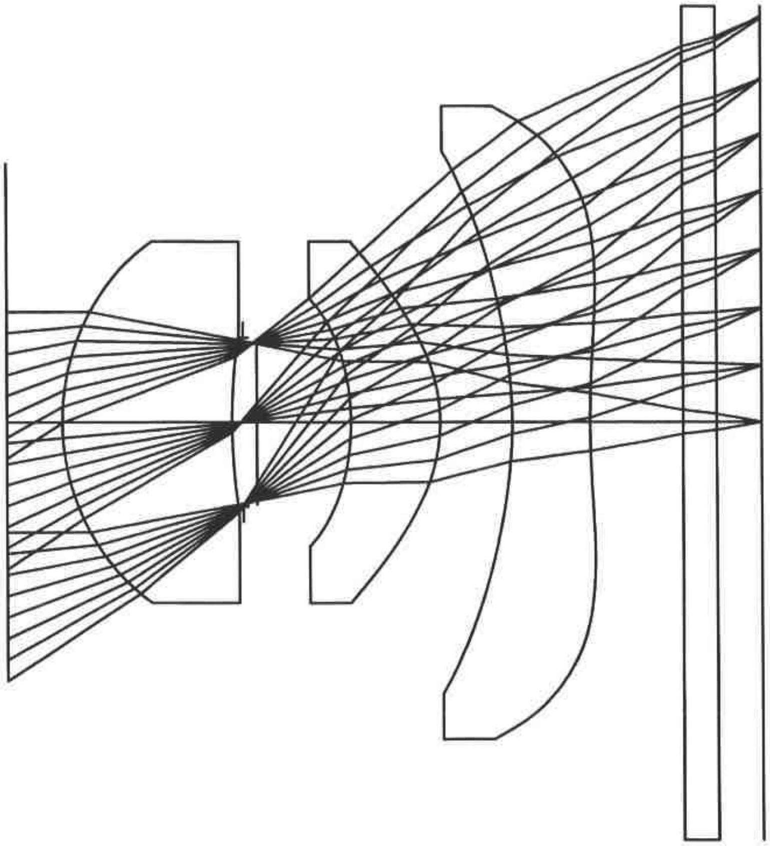

Figure 5.27 Three-element cell phone camera design.

All other tolerances used the same set of probability distributions (uniform) for both Monte Carlo runs. A total of 25,000 lenses were created in each Monte Carlo run, and the MTF data at several field points was collected. The tangential and sagittal MTF values for one off-axis field were averaged, and a histogram was generated from the data, which is shown in Fig. 5.28.

We can see from the histograms that the choice of probability distribution for surface decentration has an effect on the predicted performance distribution of the system. The uniform distribution, shown as the dashed line, has its peak at an MTF value at 50 cycles/mm of 0.465. The endpoint distribution, shown as the solid line, has its peak at an MTF value of 50 cycles/mm of 0.450. The effect of using the endpoint distribution is a general skewing to the left of the predicted performance distribution curve. This can be more clearly seen by plotting the normalized number of systems above a certain MTF value, which is shown in Fig. 5.29.

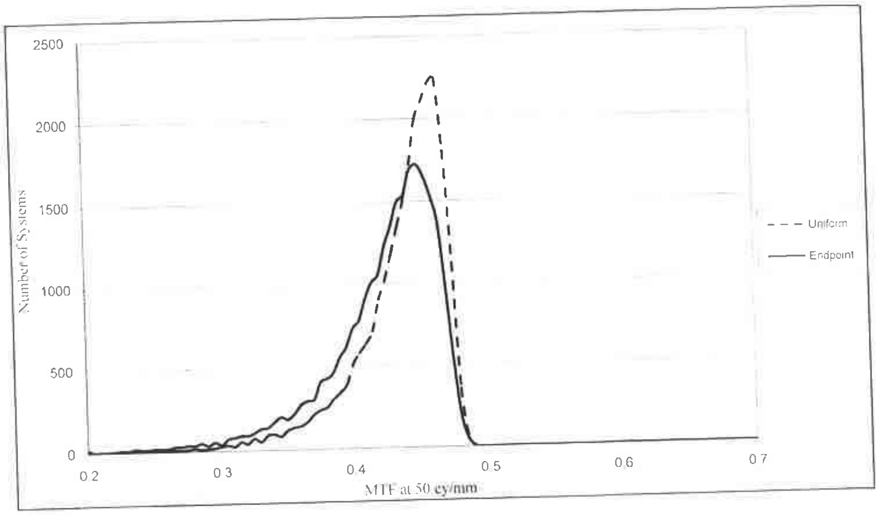

Figure 5.28 Histogram of data collected from Monte Carlo runs.

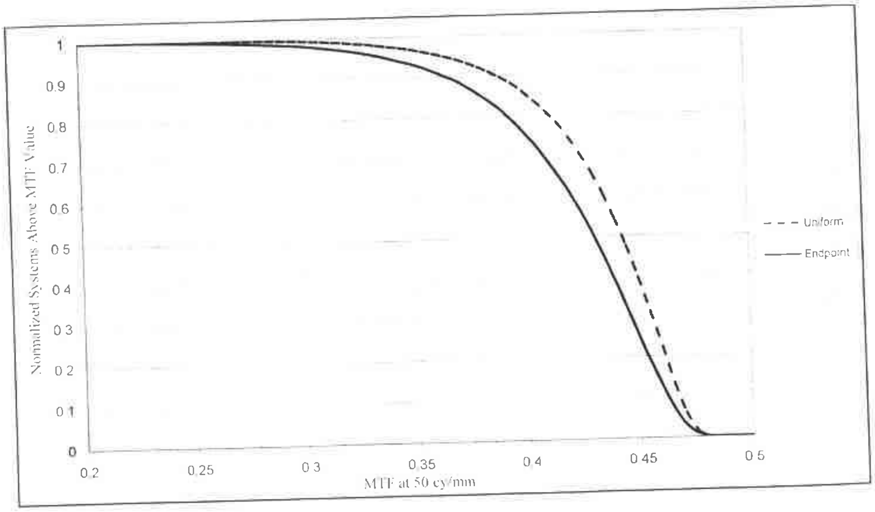

Figure 5.29 Normalized number of systems above a certain MTF value.

If we take the difference between the two curves, as is shown in Fig. 5.30, we can see the percentage difference in systems above a certain MTF value (at 50 cycles/mm) for the two distributions. For instance, consider the number of systems for the uniform distribution that have an MTF value at 50 cycles/mm above 0.35. This value turns out to be just under 97%. So if our system MTF specification were set at 0.35 (and we only considered this field), we would

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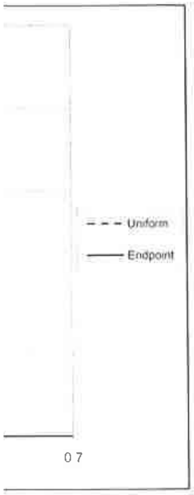

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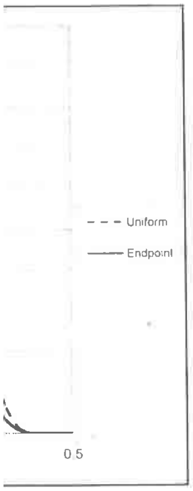

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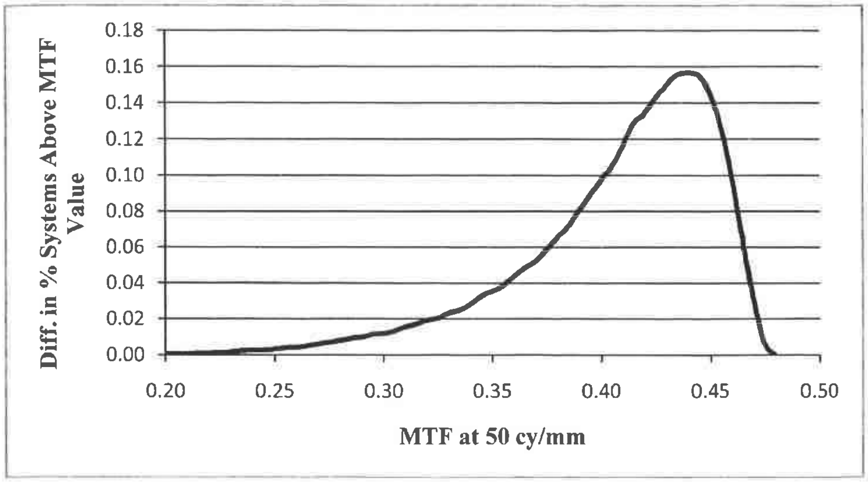

Figure 5.30 Difference in percentage of systems above a certain MTF value (for 50 cycles/mm).

expect a 3% yield loss during production. For the endpoint distribution, the percentage of the system that would meet this criterion is just over 93%. Thus, if the distribution of surface decentration had an endpoint distribution instead of a uniform distribution, we would see an additional 3.5% yield loss or double our uniform distribution prediction.

While 3.5% may not seem like a large value, it can have a significant impact on production, particularly when many thousands or millions of systems are being produced each month. A large amount of wasted material, time, and energy would go into producing and testing these systems. In this analysis, an endpoint distribution was used, which is a conservative selection. A parabolic distribution, which may be considered a compromise between endpoint and uniform distributions, may be more appropriate. Nevertheless, the fact that we saw a potential doubling in yield loss (for only a single field) should serve as a warning to the designer to carefully consider the choice of tolerance probability distributions in their analyses.

5.4 Infrared Multiorder or Harmonic Diffractive Lens

A question that frequently comes up with regard to plastic optics is why they are not seen more often in military or civilian IR systems. These systems, typically operating in the 3- to 5- or 8- to 12-μm region, often use lenses made from germanium, silicon, zinc sulfide, or other expensive materials. Since plastic optics are generally less costly, why not use them for these regions? The answer to this question is transmission. Currently available optical plastics do not transmit or, more correctly, do not transmit well in these regions. Published transmission measurements[35] show poor transmission in these bands, particularly for material thickness on the order of 5 mm, which is in the general range for molded plastic parts.

It has been a dream of plastic optic designers, and probably material scientists as well, to have a plastic optical material that transmits well in the mid- and long-wave infrared. Whoever invents such a material will likely become famous (at least amongst the optics community) and, quite possibly, rich. The cost savings that could be achieved using such a material are significant, even with a material cost multiple times that of existing optical plastics. For the moment, however, such a material does not exist, and the only reasonable way to use optical plastics in the IR is to make very thin elements. An example of this is the type of Fresnel lenses used on security or convenience lighting systems. These systems detect the change in the infrared scene when a person enters the field of view of the sensor. Transmission spectra for a number of materials for thicknesses of 0.38 mm (0.015 in.) can be found at the websites of manufacturers of Fresnel lenses.[89] In addition to Fresnel lenses, diffractive microlenses can also be used.[90]

Another option exists as an alternative to Fresnel lenses and microlenses (refractive and diffractive) to create thin, powered optical elements. This option is a diffractive surface, though not a first-order diffractive, as is usually used for color correction; instead, the lens is designed to operate at a higher diffraction order. Such a lens [known as a multiorder diffractive (MOD) or a harmonic diffractive lens (HDL)] was independently developed by two groups in 1994.[91,92] Additional improvements and applications were shown the following year.[93,94] Whereas a standard (first-order) diffractive has a step height that is designed to impart a phase shift of 2π, the multiorder diffractives have step heights that impart a phase shift of $2m\pi$, where m is the (higher) design order. These higher-order diffractive lenses rely upon several characteristics of diffractive surfaces, particularly the dependence of their focal lengths on wavelength and diffraction order, the narrowing of the diffraction efficiency curve with order, and the appearance of harmonic wavelengths. We first discuss the focal length dependence, then the change in diffraction efficiency with order, and finally consider the effect of wavelengths becoming harmonic.

The focal length of a purely diffractive (no refractive power) surface depends inversely upon the diffraction order. Thus, light in the first order will have a focal length that is twice as long as that in the second order. This can be seen by referring back to Fig. 4.16, which shows rays for multiple orders. When using first-order color-correcting diffractives, as seen in the first design example, we do not usually notice this large change in focal length with order. This is typically because the power of the diffractive surface in these cases is much less than the refractive power, resulting in only a small focus change with diffractive order. In the case of a completely diffractive surface, the change in focal length with order for a given wavelength can be significant.

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The Design of Plastic Optical Systems

Michael P. Schaub

Many items we use in our daily lives—traffic signals, motion sensors, fingerprint readers, cell phone cameras, bar code scanners, and DVD players—rely upon plastic optical systems to perform. Consequently, there is a growing need for individuals who are knowledgeable in the design, development, and production of such systems.

This book provides an overview of the design of plastic optical systems and is structured along the lines of a typical development project. Following a brief background discussion, the advantages and disadvantages of plastic optics are considered. Next, the available materials and their properties are described, as well as the issues of material selection and specification. Various manufacturing methods are reviewed, followed by a chapter on design guidelines, leading into several design examples. Following the examples, the prototyping and testing of a design are covered. Finally, bringing the design to production is discussed.

Several groups will benefit from the material presented, including optical engineers, technical managers, and engineers of other disciplines who need to design and develop plastic optical systems but lack the knowledge or training to do so.

With the help of this book, readers should understand the benefits and limitations of plastic optical systems and be able to determine if this technology is appropriate for their applications. They will have the basic knowledge to undertake the design of these systems, should they choose to do so themselves, or they will be able to have the appropriate conversations with the individuals or companies they ask to perform the work.

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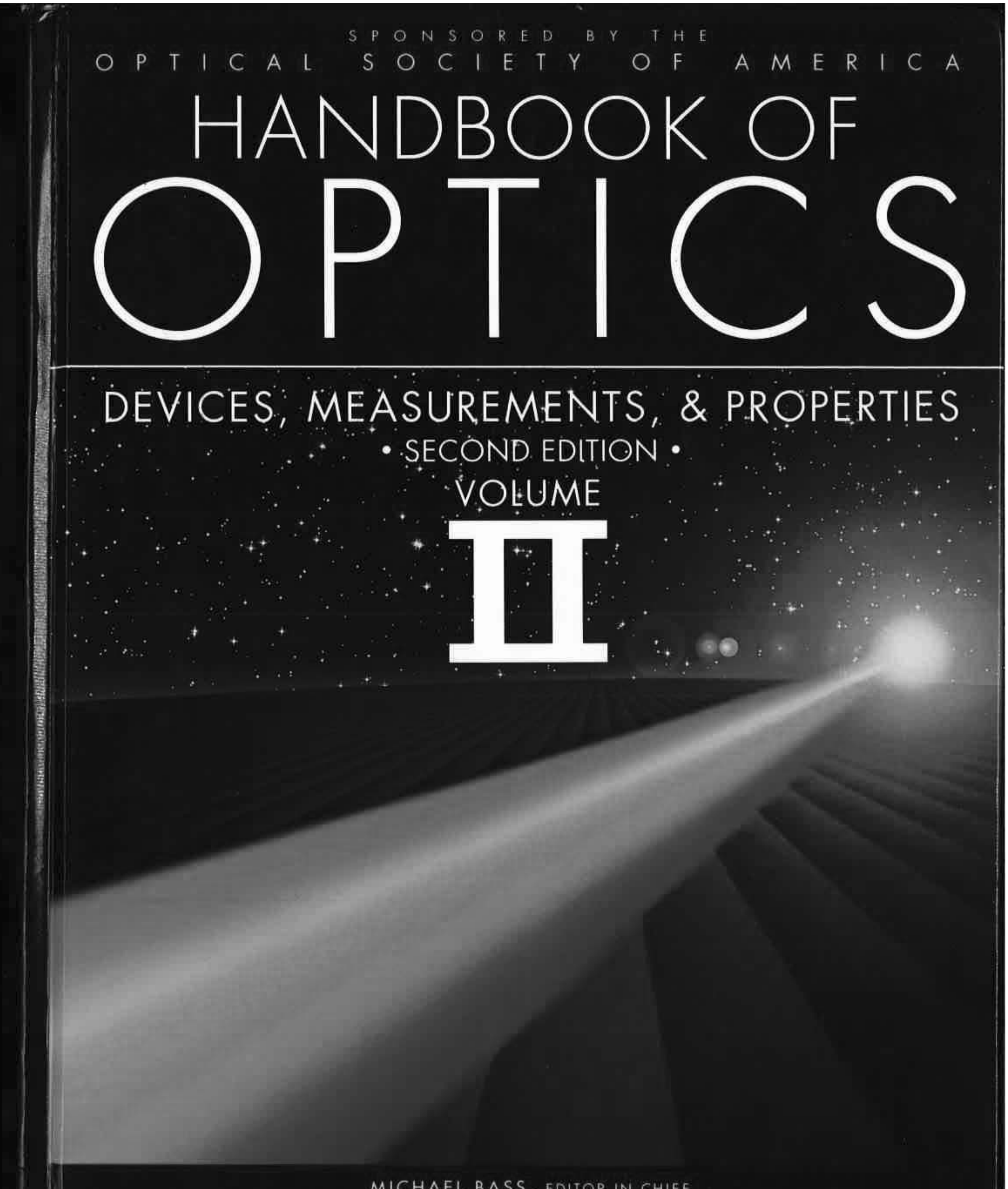

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PREFACE

The *Handbook of Optics,* Second Edition, is designed to serve as a general purpose desktop reference for the field of Optics yet stay within the confines of two books of finite length. Our purpose is to cover as much of optics as possible in a manner enabling the reader to deal with both basic and applied problems. To this end, we present articles about basic concepts, techniques, devices, instruments, measurements, and optical properties. In selecting subjects to include, we also had to select which subjects to leave out. The criteria we applied when excluding a subject were: (1) was it a specific application of optics rather than a core science or technology and (2) was it a subject in which the role of optics was peripheral to the central issue addressed. Thus, such topics as medical optics, laser surgery, and laser materials processing were not included. The resulting *Handbook of Optics,* Second Edition, serves the long-term information needs of those working in optics rather than presenting highly specific papers of current interest.

The authors were asked to prepare archival, tutorial articles which contain not only useful data but also descriptive material and references. Such articles were designed to enable the reader to understand a topic sufficiently well to get started using that knowledge. They also supply guidance as to where to find more in-depth material. Most include cross references to related articles within the Handbook. While applications of optics are mentioned, there is not space in the Handbook to include articles devoted to all of the myriad uses of optics in today's world. If we had, the Handbook would have been many volumes long and would have been too soon outdated.

The *Handbook of Optics,* Second Edition, contains 83 chapters organized into 17 broad categories or parts. The categorization enables the reader to find articles on a specific subject, say Vision, more easily and to find related articles within the Handbook. Within the categories the articles are grouped to make it simpler to find related material.

Volume I presents tutorial articles in the categories of Geometric Optics, Physical Optics, Quantum Optics, Optical Sources, Optical Detectors, Imaging Detectors, Vision, Optical Information and Image Processing, Optical Design Techniques, Optical Fabrication, Optical Properties of Films and Coatings, and Terrestrial Optics. This material is, for the most part, in a form which could serve to teach the underlying concepts of optics and its implementation. In fact, by careful selection of what to present and how to present it, the contents of Volume I could be used as a text for a comprehensive course in Optics.

The subjects covered in Volume II are Optical Elements, Optical Instruments, Optical Measurements, Optical and Physical Properties of Materials, and Nonlinear and Photorefractive Optics. As can be seen from these titles, Volume II concerns the specific devices, instruments, and techniques which are needed to employ optics in a wide variety of problems. It also provides data and discussion to assist one in the choice of optical materials.

The *Handbook of Optics*, Second Edition, would not have been possible without the support of the staff of the Optical Society of America and in particular Mr. Alan N. Tourtlotte and Ms. Kelly Furr.

For his pivotal roles in the development of the Optical Society of America, in the development of the profession of Optics, and for his encouragement to us in the task of preparing this Handbook, the editors dedicate this edition to Dr. Jarus Quinn.

Michael Bass, Editor-in-Chief
Eric W. Van Stryland, Associate Editor
David R. Williams, Associate Editor
William L. Wolfe, Associate Editor

GLOSSARY AND FUNDAMENTAL CONSTANTS

Introduction

This glossary of the terms used in the Handbook represents to a large extent the language of optics. The symbols are representations of numbers, variables, and concepts. Although the basic list was compiled by the author of this section, all the editors have contributed and agreed to this set of symbols and definitions. Every attempt has been made to use the same symbols for the same concepts throughout the entire handbook, although there are exceptions. Some symbols seem to be used for many concepts. The symbol α is a prime example, as it is used for absorptivity, absorption coefficient, coefficient of linear thermal expansion, and more. Although we have tried to limit this kind of redundancy, we have also bowed deeply to custom.

Units

The abbreviations for the most common units are given first. They are consistent with most of the established lists of symbols, such as given by the International Standards Organization ISO[1] and the International Union of Pure and Applied Physics, IUPAP.[2]

Prefixes

Similarly, a list of the numerical prefixes[1] that are most frequently used is given, along with both the common names (where they exist) and the multiples of ten that they represent.

Fundamental Constants

The values of the fundamental constants[3] are listed following the sections on SI units.

Symbols

The most commonly used symbols are then given. Most chapters of the Handbook also have a glossary of the terms and symbols specific to them for the convenience of the reader. In the following list, the symbol is given, its meaning is next, and the most customary unit of measure for the quantity is presented in brackets. A bracket with a dash in it indicates that the quantity is unitless. Note that there is a difference between units and dimensions. An angle has units of degrees or radians and a solid angle square degrees or steradians, but both are pure ratios and are dimensionless. The unit symbols as recommended in the SI system are used, but decimal multiples of some of the dimensions are sometimes given. The symbols chosen, with some cited exceptions are also those of the first two references.

RATIONALE FOR SOME DISPUTED SYMBOLS

The choice of symbols is a personal decision, but commonality improves communication. This section explains why the editors have chosen the preferred symbols for the Handbook. We hope that this will encourage more agreement.

Fundamental Constants

It is encouraging that there is almost universal agreement for the symbols for the fundamental constants. We have taken one small exception by adding a subscript B to the k for Boltzmann's constant.

Mathematics

We have chosen i as the imaginary almost arbitrarily. IUPAP lists both i and j, while ISO does not report on these.

Spectral Variables

These include expressions for the wavelength, λ, frequency, ν, wave number, σ, ω for circular or radian frequency, k for circular or radian wave number and dimensionless frequency x. Although some use f for frequency, it can be easily confused with electronic or spatial frequency. Some use $\tilde{\nu}$ for wave number, but, because of typography problems and agreement with ISO and IUPAP, we have chosen σ; it should not be confused with the Stephan Boltzmann constant. For spatial frequencies we have chosen ξ and η, although f_x and f_y are sometimes used. ISO and IUPAP do not report on these.

Radiometry

Radiometric terms are contentious. The most recent set of recommendations by ISO and IUPAP are L for radiance [$\mathrm{Wcm}^{-2}\,\mathrm{sr}^{-1}$], M for radiant emittance or exitance [Wcm^{-2}], E for irradiance or incidance [Wcm^{-2}], and I for intensity [Wsr^{-2}]. The previous terms, W, H, N and J respectively, are still in many texts, notably Smith and Lloyd[4] but we have used the revised set, although there are still shortcomings. We have tried to deal with the vexatious term *intensity* by using *specific intensity* when the units are $\mathrm{Wcm}^{-2}\,\mathrm{sr}^{-1}$, *field intensity* when they are Wcm^{-2}, and *radiometric intensity* when they are Wsr^{-1}.

There are two sets of terms for these radiometric quantities, that arise in part from the terms for different types of reflection, transmission, absorption, and emission. It has been proposed that the *ion* ending indicate a process, that the *ance* ending indicate a value associated with a particular sample, and that the *ivity* ending indicate a generic value for a "pure" substance. Then one also has reflectance, transmittance, absorptance, and emittance as well as reflectivity, transmissibity, absorptivity, and emissivity. There are now two different uses of the word emissivity. Thus the words *exitance, incidance*, and *sterance* were coined to be used in place of emittance, irradiance, and radiance. It is interesting that ISO uses radiance, exitance, and irradiance whereas IUPAP uses radiance, excitance [*sic*] and irradiance. We have chosen to use them both, i.e., emittance, irradiance, and radiance will be followed in square brackets by exitance, incidance, and sterance (or vice versa). Individual authors will use the different endings for transmission, reflection, absorption, and emission as they see fit.

We are still troubled by the use of the symbol E for irradiance, as it is so close in meaning to electric field, but we have maintained that accepted use. The spectral concentrations of these quantities, indicated by a wavelength, wave number, or frequency subscript (e.g., L_λ) represent partial differentiations; a subscript q represents a photon quantity; and a subscript v indicates a quantity normalized to the response of the eye. Thereby, L_v is luminance, E_v illuminance, and M_v and I_v luminous emittance and luminous intensity. The symbols we have chosen are consistent with ISO and IUPAP.

The refractive index may be considered a radiometric quantity. It is generally complex and is indicated by $\tilde{n} = n - ik$. The real part is the relative refractive index and k is the extinction coefficient. These are consistent with ISO and IUPAP, but they do not address the complex index or extinction coefficient.

Optical Design

For the most part ISO and IUPAP do not address the symbols that are important in this area.

There were at least 20 different ways to indicate focal ratio; we have chosen FN as symmetrical with NA; we chose f and efl to indicate the effective focal length. Object and image distance, although given many different symbols, were finally called s_o and s_i since s is an almost universal symbol for distance. Field angles are θ and ϕ; angles that measure the slope of a ray to the optical axis are u; u can also be $\sin u$. Wave aberrations are indicated by W_{ijk}, while third order ray aberrations are indicated by σ_i and more mnemonic symbols.

Electromagnetic Fields

There is no argument about **E** and **H** for the electric and magnetic field strengths, Q for quantity of charge, ρ for volume charge density, σ for surface charge density, etc. There is no guidance from References 1 and 2 on polarization indication. We chose $\perp$ and $\parallel$ rather than p and s, partly because s is sometimes also used to indicate scattered light.

There are several sets of symbols used for reflection, transmission, and (sometimes) absorption, each with good logic. The versions of these quantities dealing with field amplitudes are usually specified with lower case symbols: r, t, and a. The versions dealing with power are alternately given by the uppercase symbols or the corresponding Greek symbols: R and T vs ρ and τ. We have chosen to use the Greek, mainly because these quantities are also closely associated with Kirchhoff's law that is usually stated symbolically as $\alpha = \epsilon$. The law of conservation of energy for light on a surface is also usually written as $\alpha + \rho + \tau = 1$.

Base SI Quantities

length	m	meter
time	s	second
mass	kg	kilogram
electric current	A	ampere
Temperature	K	kelvin
Amount of substance	mol	mole
Luminous intensity	cd	candela

Derived SI Quantities

energy	J	joule
electric charge	C	coulomb
electric potential	V	volt
electric capacitance	F	farad
electric resistance	Ω	ohm
electric conductance	S	siemens

magnetic flux	Wb	weber
inductance	H	henry
pressure	Pa	pascal
magnetic flux density	T	tesla
frequency	Hz	hertz
power	W	watt
force	N	newton
angle	rad	radian
angle	sr	steradian

Prefixes

Symbol	Name	Common name	Exponent of ten
E	exa		18
P	peta		15
T	tera	trillion	12
G	giga	billion	9
M	mega	million	6
k	kilo	thousand	3
h	hecto	hundred	2
da	deca	ten	1
d	deci	tenth	−1
c	centi	hundredth	−2
m	milli	thousandth	−3
μ	micro	millionth	−6
n	nano	billionth	−9
p	pico	trillionth	−12
f	femto		−15
a	atto		−18

Constants

c	speed of light in vacuo [299792458 $\mathrm{ms^{-1}}$]
c_1	first radiation constant = $2\pi c^2 h = 3.7417749 \times 10^{-16}$ [$\mathrm{Wm^2}$]
c_2	second radiation constant = $hc/k = 0.01438769$ [mK]
e	elementary charge [$1.60217733 \times 10^{-19}$C]
g_n	free fall constant [9.80665 $\mathrm{ms^{-2}}$]
h	Planck's constant [$6.6260755 \times 10^{-34}$ Ws]
k_B	Boltzmann constant [1.380658×10^{-23} $\mathrm{JK^{-1}}$]
m_e	mass of the electron [$9.1093897 \times 10^{-31}$ kg]
N_A	Avogadro constant [6.0221367×10^{23} $\mathrm{mol^{-1}}$]
R_∞	Rydberg constant [10973731.534 $\mathrm{m^{-1}}$]
ϵ_o	vacuum permittivity [$\mu_o^{-1} c^{-2}$]
σ	Stefan Boltzmann constant [5.67051×10^{-8} $\mathrm{Wm^{-1} K^{-4}}$]
μ_o	vacuum permeability [$4\pi \times 10^{-7}$ $\mathrm{NA^{-2}}$]
μ_B	Bohr magneton [$9.2740154 \times 10^{-24}$ $\mathrm{JT^{-1}}$]

General

$\mathbf{B}$	magnetic induction [$\mathrm{Wbm^{-2}, kgs^{-1} C^{-1}}$]
C	capacitance [f, $\mathrm{C^2 s^2 m^{-2} kg^{-1}}$]
C	curvature [$\mathrm{m^{-1}}$]

c	speed of light in vacuo [ms^{-1}]
c_1	first radiation constant [Wm^2]
c_2	second radiation constant [mK]
$\mathbf{D}$	electric displacement [Cm^{-2}]
E	incidance [irradiance] [Wm^{-2}]
e	electronic charge [coulomb]
E_v	illuminance [lux, lmm^{-2}]
$\mathbf{E}$	electrical field strength [Vm^{-1}]
E	transition energy [J]
E_g	band-gap energy [eV]
f	focal length [m]
f_c	Fermi occupation function, conduction band
f_v	Fermi occupation function, valence band
FN	focal ratio (f/number) [—]
g	gain per unit length [m^{-1}]
g_{th}	gain threshold per unit length [m^1]
$\mathbf{H}$	magnetic field strength [Am^{-1}, Cs^{-1} m^{-1}]
h	height [m]
I	irradiance (see also E) [Wm^{-2}]
I	radiant intensity [Wsr^{-1}]
I	nuclear spin quantum number [—]
I	current [A]
i	$\sqrt{-1}$
Im()	Imaginary part of
J	current density [Am^{-2}]
$\mathbf{j}$	total angular momentum [kg m^2 sec^{-1}]
$J_1()$	Bessel function of the first kind [—]
k	radian wave number $= 2\pi/\lambda$ [rad cm^{-1}]
$\mathbf{k}$	wave vector [rad cm^{-1}]
k	extinction coefficient [—]
L	sterance [radiance] [Wm^{-2} sr^{-1}]
L_v	luminance [cdm^{-2}]
L	inductance [h, m^{2}kgC^{-2}]
L	laser cavity length
L, M, N	direction cosines [—]
M	angular magnification [—]
M	radiant exitance [radiant emittance] [Wm^{-2}]
m	linear magnification [—]
m	effective mass [kg]
MTF	modulation transfer function [—]
N	photon flux [s^{-1}]
N	carrier (number) density [m^{-3}]
n	real part of the relative refractive index [—]
$\tilde{n}$	complex index of refraction [—]
NA	numerical aperture [—]
OPD	optical path difference [m]
P	macroscopic polarization [C m^{-2}]
Re()	real part of [—]
R	resistance [Ω]
$\mathbf{r}$	position vector [m]
r	(amplitude) reflectivity
S	Seebeck coefficient [VK^{-1}]
s	spin quantum number [—]
s	path length [m]

s_o	object distance [m]
s_i	image distance [m]
T	temperature [K, C]
t	time [s]
t	thickness [m]
u	slope of ray with the optical axis [rad]
V	Abbé reciprocal dispersion [—]
V	voltage [V, m^2 kgs^{-2} C^{-1}]
x, y, z	rectangular coordinates [m]
Z	atomic number [—]

Greek Symbols

α	absorption coefficient [cm^{-1}]
α	(power) absorptance (absorptivity)
ϵ	dielectric coefficient (constant) [—]
ϵ	emittance (emissivity) [—]
ϵ	eccentricity [—]
ϵ_1	Re (ϵ)
ϵ_2	Im (ϵ)
τ	(power) transmittance (transmissivity) [—]
ν	radiation frequency [Hz]
ω	circular frequency $= 2\pi\nu$ [rads^{-1}]
ω_p	plasma frequency [H_2]
λ	wavelength [μm, nm]
σ	wave number $= 1/\lambda$ [cm^{-1}]
σ	Stefan Boltzmann constant [Wm^{-2} K^{-1}]
ρ	reflectance (reflectivity) [—]
θ, ϕ	angular coordinates [rad, °]
ξ, η	rectangular spatial frequencies [m^{-1}, r^{-1}]
ϕ	phase [rad, °]
ϕ	lens power [m^{-1}]
Φ	flux [W]
χ	electric susceptibility tensor [—]
Ω	solid angle [sr]

Other

$\mathfrak{R}$	responsivity
$\exp(x)$	e^x
$\log_a(x)$	log to the base a of x
$\ln(x)$	natural log of x
$\log(x)$	standard log of x: $\log_{10}(x)$
Σ	summation
Π	product
Δ	finite difference
δx	variation in x
dx	total differential
∂x	partial derivative of x
$\delta(x)$	Dirac delta function of x
δ_{ij}	Kronecker delta

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CHAPTER 1

LENSES

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1.1 GLOSSARY

AChr	axial chromatic aberration
AST	astigmatism
b	factor
bfl	back focal length
C_o	scaling factor
c	curvature
C_1	scaling factor
C_2	scaling factor
CC	conic constant
CMA_s	sagittal coma
CMA_t	tangential coma
D_{ep}	diameter of entrance pupil
d_o	distance from object to loupe
d_e	distance from loupe to the eye
E	irradiance
efl	effective focal length
ep	eyepiece
FN	F-number
f	focal length
h	height above axis
H_i	height of ray intercept in image plane

$\mathcal{H}$	shape factor
i	image
$J_1()$	Bessel function of the first kind
k	$2\pi/\lambda$
L	length
MP	magnifying power [cf. linear lateral longitudinal magnification]
m	linear, lateral magnification
$\bar{m}$	linear, longitudinal, magnification
n	refractive index
$\mathcal{M}$	factor
MTF	modulation transfer function
NA	numerical aperture
a,b	first and second lenses
o	object
obj	objective
P	partial dispersion
P_i	principal points
p	$= d/f_a$
$\bar{\mathcal{R}}$	peak normalized spectral weighting function
$\mathcal{S}$	object to image distance
SA3	third-order spherical aberration
SAC	secondary angular spectrum
s_i	image distance
s_{ot}	optical tube length
s_o	object distance
TPAC	transverse primary chromatic aberration
t	thickness
u	slope
V	Abbe number or reciprocal dispersion
v	ϕ-normalized reciprocal object distance $1/s_o\phi$
x, y, z	cartesian coordinates
β	angular blur diameter
δ	depth of focus
ζ	sag
$\Delta\theta$	angular blur tolerance

θ	field of view
λ	wavelength
ν	spatial frequency
ϕ	lens power
ρ	radius
σ	standard deviation of the irradiance distribution
τ	transmission
Ω	normalized spatial frequency

1.2 INTRODUCTION

This section provides a basic understanding of using lenses for image formation and manipulation. The principles of image formation are reviewed first. The effects of lens shape, index of refraction, magnification, and F-number on the image quality of a singlet lens are discussed in some detail. Achromatic doublets and more complex lens systems are covered next. A representative variety of lenses is analyzed and discussed. Performance that may be expected of each class of lens is presented. The section concludes with several techniques for rapid estimation of the performance of lenses. Refer to Chap. 1 "Geometric Optics" in Vol. I, for further discussion of geometrical optics and aberrations.

1.3 BASICS

Figure 1 illustrates an image being formed by a simple lens. The object height is h_o and the image height is h_i, with u_o and u_i being the corresponding slope angles. It follows from the Lagrange invariant that the *lateral magnification* is defined to be

$$\begin{aligned} m &\equiv \frac{h_i}{h_o} \\ &= \frac{(nu)_o}{(nu)_i} \end{aligned} \tag{1}$$

where n_o and n_i are the refractive indices of the medium in which the object and image lie, respectively. By convention, a height is positive if above the optical axis and a ray angle is positive if its slope angle is positive. Distances are positive if the ray propagates left to right. Since the Lagrange invariant is applicable for paraxial rays, the angle nu

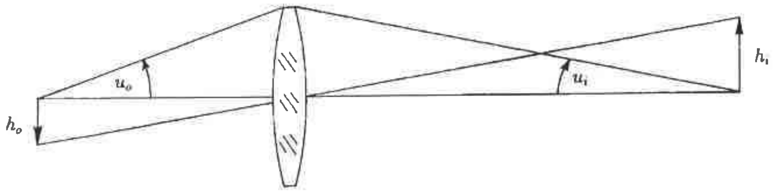

FIGURE 1 Imaging by a simple lens.

should be understood to mean $n \tan u$. This interpretation applies to all paraxial computations. For an *aplanatic* lens, which is free of spherical aberration and linear coma, the magnification can be shown by the *optical sine theorem* to be given by

$$\begin{aligned} m &\equiv \frac{h_i}{h_o} \\ &= \frac{n_o \sin u_o}{n_i \sin u_i} \end{aligned} \tag{2}$$

If the object is moved a small distance ∂s_o longitudinally, the corresponding displacement of the image ∂s_i can be found by the differential form of the basic imaging equation and leads to an equation analogous to the Lagrange invariant. The *longitudinal magnification* is then defined as

$$\begin{aligned} \bar{m} &\equiv \frac{\partial s_i}{\partial s_o} \\ &= \frac{(nu^2)_o}{(nu^2)_i} \\ &= m^2 \left[\frac{n_i}{n_o}\right] \end{aligned} \tag{3}$$

The following example will illustrate one application of m and $\bar{m}$. Consider that a spherical object of radius r_o is to be imaged as shown in Fig. 2. The equation of the object is $r_o^2 = y_o^2 + z^2$, where z is measured along the optical axis and is zero at the object's center of curvature. Letting the surface sag as measured from the vertex plane of the object be denoted as ζ_o, the equation of the object becomes $r_o^2 = (r_o - \zeta_o)^2 + y_o^2$ since $z = r_o - \zeta_o$. In the region near the optical axis, $\zeta_o^2 \ll r_o^2$, which implies that $r_o \approx y_o^2/2\zeta_o$. The image of the object is expressed in the transverse or lateral direction by $y_i = my_o$ and in the longitudinal or axial direction by $\zeta_i = \bar{m}\zeta_o = \zeta_o m^2(n_i/n_o)$. In a like manner, the image of the spherical object is expressed as $r_i \approx (y_i)^2/2\zeta_i$. By substitution, the sag of the image is expressed by

$$\begin{aligned} r_i &\equiv \frac{n_o y_o^2}{2n_i\zeta_o} \\ &= r_o\left[\frac{n_o}{n_i}\right] \end{aligned} \tag{4}$$

Hence, in the paraxial region about the optical axis, the radius of the image of a spherical

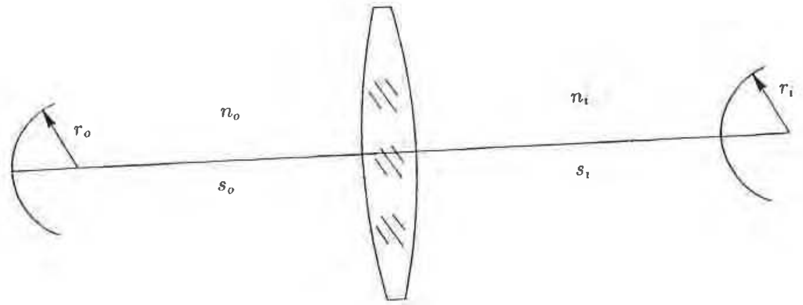

FIGURE 2 Imaging of a spherical object by a lens.

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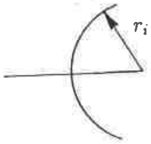

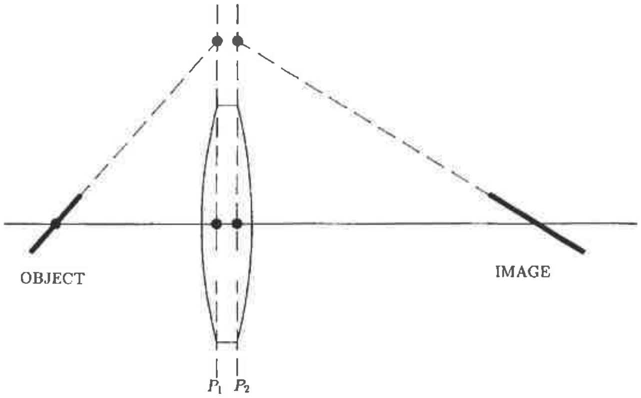

FIGURE 3 Imaging of a tilted object illustrating the Scheimpflug condition.

object is independent of the magnification and depends only on the ratio of the refractive indices of the object and image spaces.

When an optical system as shown in Fig. 3 images a tilted object, the image will also be tilted. By employing the concept of lateral and longitudinal magnification, it can be easily shown that the intersection height of the object plane with the first principal plane P_1 of the lens must be the same as the intersection height of the image plane with the second principal plane P_2 of the lens. This principle is known as the *Scheimpflug condition.*

The object-image relationship of a lens system is often described with respect to its *cardinal points,* which are as follows:

- *Principal points*: the axial intersection point of conjugate planes related by unit lateral magnification
- *Nodal points*: conjugate points related by unit angular magnification $(m = u_i/u_0)$
- *Focal points*: front (f_1) and rear (f_2)

The focal length of a lens is related to the power of the lens by

$$\phi = \frac{n_o}{f_o} = \frac{n_i}{f_i} \tag{5}$$

This relationship is important in such optical systems as underwater cameras, cameras in space, etc. For example, it is evident that the field of view is decreased for a camera in water.

The *lens law* can be expressed in several forms. If s_o and s_i are the distance from the object to the first principal point and the distance from the second principal point to the image, then the relationship between the object and the image is given by

$$\phi = \frac{n_i}{s_i} + \frac{n_o}{s_o} \tag{6}$$

Should the distances be measured with respect to the nodal points, the imaging equation becomes

$$\phi = \frac{n_o}{s_i} + \frac{n_i}{s_o} \tag{7}$$

When the distances are measured from the focal points, the image relationship, known as the *Newtonian imaging equation*, is given by

$$f_1 f_2 = s_o s_i \tag{8}$$

The power of a spherical refracting surface, with curvature c and n being the refractive index following the surface, is given by

$$\phi = c(n - n_o) \tag{9}$$

It can be shown that the power of a single thick lens in air is

$$\phi_{\text{thick}} = \phi_1 + \phi_2 - \phi_1 \phi_2 \frac{t}{n} \tag{10}$$

where t is the thickness of the lens. The distance from the first principal plane to the first surface is $-(t/n)\phi_2 f_1$ and the distance from the second principal point to the rear surface is $(-t/n)\phi_1 f_2$. The power of a thin lens ($t \rightarrow 0$) in air is given by

$$\phi_{\text{thin}} = (n-1)(c_1 - c_2) \tag{11}$$

1.4 STOPS AND PUPILS

The *aperture stop* or *stop* of a lens is the limiting aperture associated with the lens that determines how large an axial beam may pass through the lens. The stop is also called an *iris*. The *marginal ray* is the extreme ray from the axial point of the object through the edge of the stop. The *entrance pupil* is the image of the stop formed by all lenses preceding it when viewed from object space. The *exit pupil* is the image of the stop formed by all lenses following it when viewed from image space. These pupils and the stop are all images of one another. The *principal ray* is defined as the ray emanating from an off-axis object point that passes through the center of the stop. In the absence of pupil aberrations, the principal ray also passes through the center of the entrance and exit pupils.

As the obliquity angle of the principal ray increases, the defining apertures of the components comprising the lens may limit the passage of some of the rays in the entering beam thereby causing the stop not to be filled with rays. The failure of an off-axis beam to fill the aperture stop is called *vignetting*. The ray centered between the upper and lower rays defining the oblique beam is called the *chief ray*. When the object moves to large off-axis locations, the entrance pupil often has a highly distorted shape, may be tilted, and/or displaced longitudinally and transversely. Due to the vignetting and pupil aberrations, the chief and principal rays may become displaced from one another. In some cases, the principal ray is vignetted.

The *field stop* is an aperture that limits the passage of principal rays beyond a certain field angle. The image of the field stop when viewed from object space is called the *entrance window* and is called the *exit window* when viewed from image space. The field stop effectively controls the field of view of the lens system. Should the field stop be coincident with an image formed within or by the lens system, the entrance and exit windows will be located at the object and/or image(s).

A *telecentric stop* is an aperture located such that the entrance and/or exit pupils are located at infinity. This is accomplished by placing the aperture in the focal plane. Consider a stop placed at the front focal plane of a lens. The image is located at infinity and the principal ray exits the lens parallel to the optical axis. This feature is often used in metrology since the measurement error is reduced when compared to conventional lens systems because the centroid of the blur remains at the same height from the optical axis even as the focus is varied.

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1.5 F-NUMBER AND NUMERICAL APERTURE

The focal ratio or F-number (FN) of a lens is defined as the effective focal length divided by the entrance pupil diameter D_{ep}. When the object is not located at infinity, the effective FN is given by

$$\mathrm{FN}_{eff} = \mathrm{FN}_{\infty}(1 - m) \tag{12}$$

where m is the magnification. For example, for a simple positive lens being used at unity magnification ($m = -1$), the $\mathrm{FN}_{eff} = 2\mathrm{FN}_{\infty}$. The *numerical aperture* of a lens is defined as

$$\mathrm{NA} = n_i \sin U_i \tag{13}$$

where n_i is the refractive index in which the image lies and U_i is the slope angle of the marginal ray exiting the lens. If the lens is aplanatic, then

$$\mathrm{FN}_{eff} = \frac{1}{2\mathrm{NA}} \tag{14}$$

1.6 MAGNIFIER OR EYE LOUPE

The typical magnifying glass, or *loupe,* comprises a singlet lens and is used to produce an erect but virtual magnified image of an object. The magnifying power of the loupe is stated to be the ratio of the angular size of the image when viewed through the magnifier to the angular size without the magnifier. By using the thin-lens model of the human eye, the magnifying power (MP) can be shown to be given by

$$\mathrm{MP} = \frac{25\text{ cm}}{d_e + d_o - \phi d_e d_o} \tag{15}$$

where d_o is the distance from the object to the loupe, d_e is the separation of the loupe from the eye, and $\phi = 1/f$ is the power of the magnifier. When d_o is set to the focal length of the lens, the virtual image is placed at infinity and the magnifying power reduces to

$$\mathrm{MP} = \frac{25\text{ cm}}{f} \tag{16}$$

Should the virtual image be located at the near viewing distance of the eye (about 25 cm), then

$$\mathrm{MP} = \frac{25\text{ cm}}{f} + 1 \tag{17}$$

Typically simple magnifiers are difficult to make with magnifying powers greater than about 10×.

1.7 COMPOUND MICROSCOPES

For magnifying power greater than that of a simple magnifier, a compound microscope, which comprises an objective lens and an eyepiece, may be used. The objective forms an aerial image of the object at a distance s_{oi} from the rear focal point of the objective. The distance s_{ot} is called the *optical tube length* and is typically 160 mm. The objective magnification is

$$\mathrm{MP}_{obj} = \frac{s_{ot}}{f_{obj}} \tag{18}$$

The image formed is further magnified by the eyepiece which has a $\mathrm{MP}_{ep} = 250\ \mathrm{mm}/f_{ep}$. The total magnifying power of the compound microscope is given by

$$\begin{aligned} \mathrm{MP} &= \mathrm{MP}_{obj}\mathrm{MP}_{ep} \\ &= \frac{160}{f_{obj}} \cdot \frac{250}{f_{ep}} \end{aligned} \tag{19}$$

Typically, $f_{ep} = 25$ mm, so its MP = 10. Should the objective have a focal length of 10 mm, the total magnifying power of the microscope is 16× times 10×, or 160×.

1.8 FIELD AND RELAY LENSES

Field lenses are placed at (or near) an image location for the purpose of optically relocating the pupil or to increase the field of view of the optical system. For example, a field lens may be used at the image plane of an astronomical telescope such that the field lens images the objective lens onto the eyepiece. In general, the field lens does not contribute to the aberrations of the system except for distortion and field curvature. Since the field lens must be positive, it adds inward curving Petzval. For systems having a small detector requiring an apparent increase in size, the field lens is a possible solution. The detector is located beyond the image plane such that it subtends the same angle as the objective lens when viewed from the image point. The field lens images the objective lens onto the detector.

Relay lenses are used to transfer an image from one location to another such as in a submarine periscope or borescope. It is also used as a means to erect an image in many types of telescopes and other such instruments. Often relay lenses are made using two lens groups spaced about a stop, or an image of the system stop, in order to take advantage of the principle of symmetry, thereby minimizing the comatic aberrations and lateral color. The relayed image is frequently magnified.

1.9 APLANATIC SURFACES AND IMMERSION LENSES

Abbe called a lens an aplanat that has an equivalent refractive surface which is a portion of a sphere with a radius r centered about the focal point. Such a lens satisfies the Abbe sine condition and implies that the lens is free of spherical and coma near the optical axis. Consequently, the maximum possible numerical aperture (NA) of an aplanat is unity, or an FN = 0.5. In practice, an FN less than 0.6 is difficult to achieve. For an aplanat,

$$\mathrm{FN} = \frac{1}{2 \cdot \mathrm{NA}} \tag{20}$$

It can be shown that three cases exist where the spherical aberration is zero for a spherical surface. These are: (1) the trivial case where the object and image are located at the surface, (2) the object and image are located at the center of curvature of the surface, and (3) the object is located at the aplanatic point. The third case is of primary interest. If

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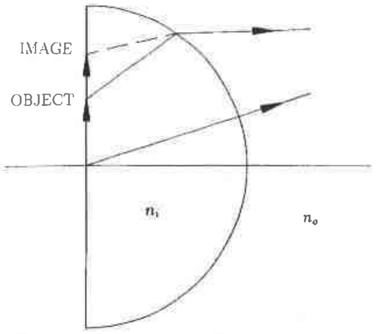

FIGURE 4 Aplanatic hemispherical magnifier with the object and image located at the center of curvature of the spherical surface. This type of magnifier has a magnification of n_i/n_o which can be used as a contact magnifier or as an immersion lens.

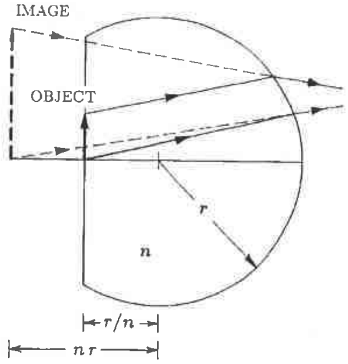

FIGURE 5 Aplanatic hyperhemispherical magnifier or Amici lens has the object located at the aplanatic point. The lateral magnification is $(n_i/n_0)^2$.

the refractive index preceding the surface is n_o and following the surface is n_i, then the object is located a distance s_o from the surface as expressed by

$$s_o = \frac{r(n_o + n_i)}{n_o} \tag{21}$$

and the image is located at

$$s_i = \frac{r(n_o + n_i)}{n_i} \tag{22}$$

An immersion lens or contact lens can be formed from an aplanatic surface and a plano surface. Figure 4 illustrates a hemispherical magnifier that employs the second aplanatic case. The resultant magnification is n_i if in air or n_i/n_o otherwise. A similar magnifier can be constructed by using a hyperhemispherical surface and a plano surface as depicted in Fig. 5. The lateral magnification is n_i^2. This lens, called an *Amici lens,* is based upon the third aplanatic case. The image is free of all orders of spherical aberration, third-order coma, and third-order astigmatism. Axial color is also absent from the hemispherical magnifier. These magnifiers are often used as a means to make a detector appear larger and as the first component in microscope objectives.

1.10 SINGLE ELEMENT LENS

It is well known that the spherical aberration of a lens is a function of its shape factor or bending. Although several definitions for the shape factor have been suggested, a useful formulation is

$$\mathcal{K} = \frac{c_1}{c_1 - c_2} \tag{23}$$

where c_1 and c_2 are the curvatures of the lens with the first surface facing the object. By adjusting the lens bending, the spherical aberration can be seen to have a minimum value.

The power of a thin lens or the reciprocal of its focal length is given by

$$\phi = \frac{(n-1)c_1}{\mathcal{K}} \tag{24}$$

When the object is located at infinity, the shape factor for minimum spherical aberration can be represented by

$$\mathcal{K} = \frac{n(2n+1)}{2(n+2)} \tag{25}$$

The resultant third-order spherical aberration of the marginal ray in angular units is

$$\mathrm{SA3} = \frac{n^2 - (2n+1)\mathcal{K} + (1 + 2/n)\mathcal{K}^2}{16(n-1)^2(\mathrm{FN})^3} \tag{26}$$

or after some algebraic manipulations,

$$\mathrm{SA3} = \frac{n(4n-1)}{64(n+2)(n-1)^2(\mathrm{FN})^3} \tag{27}$$

where, for a thin lens, the FN is the focal length f divided by the lens diameter, which in this case is the same as entrance pupil diameter D_{ep}. Inspection of this equation illustrates that smaller values of spherical aberration are obtained as the refractive index increases.

When the object is located at a finite distance s_o, the equations for the shape factor and residual spherical aberration are more complex. Recalling that the magnification m is the ratio of the object distance to the image distance and that the object distance is negative if the object lies to the left of the lens, the relationship between the object distance and the magnification is

$$\frac{1}{s_o\phi} = \frac{m}{1-m} \tag{28}$$

where m is negative if the object distance and the lens power have opposite signs. The term $1/s_o\phi$ represents the reduced or ϕ-normalized reciprocal object distance v, i.e., s_o is measured in units of focal length ϕ^{-1}. The shape factor for minimum spherical aberration is given by

$$\mathcal{K} = \frac{n(2n+1)}{2(n+2)} + \frac{2(n^2-1)}{n+2}\left(\frac{m}{1-m}\right) \tag{29}$$

and the resultant third-order spherical aberration of the marginal ray in angular units is

$$\begin{aligned} \mathrm{SA3} = \frac{1}{16(n-1)^2(\mathrm{FN})^3}\Bigg[& n^2 - (2n+1)\mathcal{K} + \frac{n+2}{n}\mathcal{K}^2 + (3n+1)(n-1)\left(\frac{m}{1-m}\right) \\ & - \frac{4(n^2-1)}{n}\left(\frac{m}{1-m}\right)\mathcal{K} + \frac{(3n+2)(n-1)^2}{n}\left(\frac{m}{1-m}\right)^2\Bigg] \end{aligned} \tag{30}$$

where FN is the effective focal length of the lens f divided by its entrance pupil diameter. When the object is located at infinity, the magnification becomes zero and the above two equations reduce to those previously given.

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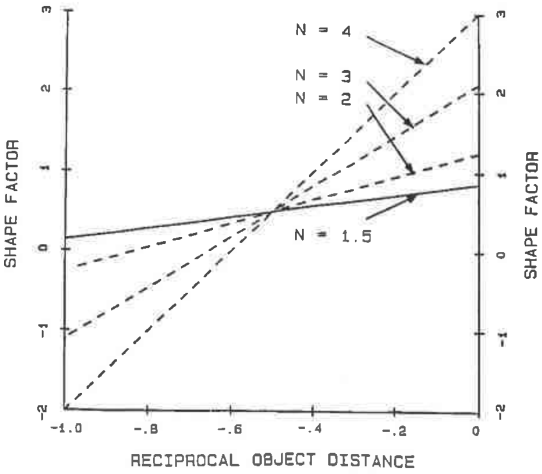

FIGURE 6 The shape factor for a single lens is shown for several refractive indexes as a function of reciprocal object distance v where the distance is measured in units of focal length.

Figure 6 illustrates the variation in shape factor as a function of v for refractive indices of 1.5–4 for an $\mathrm{FN} = 1$. As can be seen from the figure, lenses have a shape factor of 0.5 regardless of the refractive index when the magnification is -1 or $v = -0.5$. For this shape factor, all lenses have biconvex surfaces with equal radii. When the object is at infinity and the refractive index is 4, lenses have a meniscus shape towards the image. For a lens with a refractive index of 1.5, the shape is somewhat biconvex, with the second surface having a radius about 6 times greater than the first surface radius.

Since the minimum-spherical lens shape is selected for a specific magnification, the spherical aberration will vary as the object-image conjugates are adjusted. For example, a lens having a refractive index of 1.5 and configured for $m = 0$ exhibits a substantial increase in spherical aberration when the lens is used at a magnification of -1. Figure 7 illustrates the variation in the angular spherical aberration as both a function of refractive index and reciprocal object distance v when the lens bending is for minimum spherical aberration with the object located at infinity. As can be observed from Fig. 7, the ratio of the spherical aberration, when $m = -0.5$ and $m = 0$, increases as n increases. Figure 8 shows the variation in angular spherical aberration when the lens bending is for minimum spherical aberration at a magnification of -1. In a like manner, Fig. 9 presents the variation in angular spherical aberration for a convex-plano lens with the plano side facing the image. The figure can also be used when the lens is reversed by simply replacing the object distance with the image distance.

Figures 7–9 may provide useful guidance in setting up experiments when the three forms of lenses are available. The so-called "off-the-shelf" lenses that are readily available from a number of vendors often have the convex-plano, equal-radii biconvex, and minimum spherical shapes.

Figure 10 shows the relationship between the third-order spherical aberration and coma, and the shape factor for a thin lens with a refractive index of 1.5, stop in contact, and the object at infinity. The coma is near zero at the minimum spherical aberration shape. The shape of the lens as a function of shape factor is shown at the top of the figure.

For certain cases, it is desirable to have a single lens with no spherical aberration. A

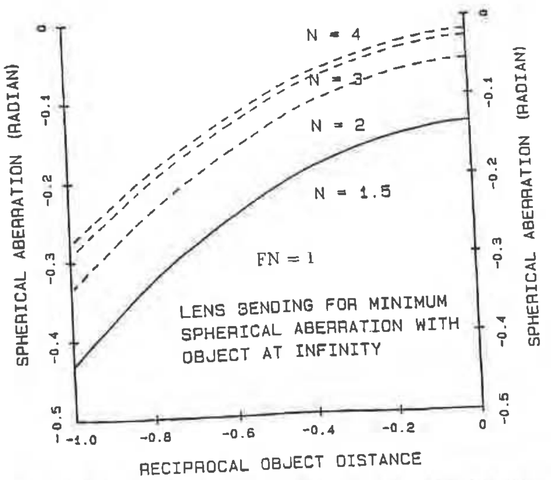

FIGURE 7 Variation of angular spherical aberration as a function of reciprocal object distance v for various refractive indices when the lens is shaped for minimum spherical aberration with the object at infinity. Spherical aberration for a specific FN is determined by dividing the aberration value shown by $(FN)^3$.

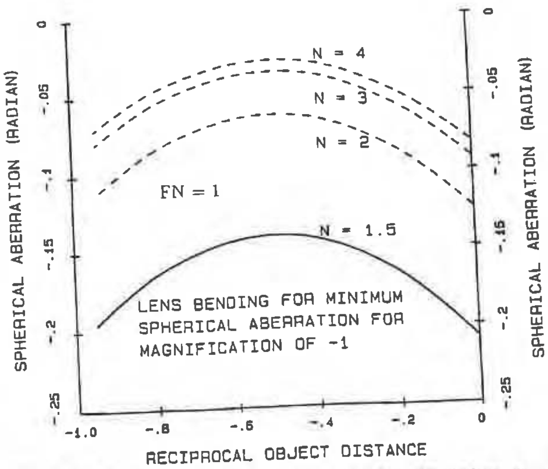

FIGURE 8 Variation of angular spherical aberration as a function of reciprocal object distance v for various refractive indices when the lens is shaped for minimum spherical aberration for a magnification of −1. Spherical aberration for a specific FN is determined by dividing the aberration value shown by $(FN)^3$.

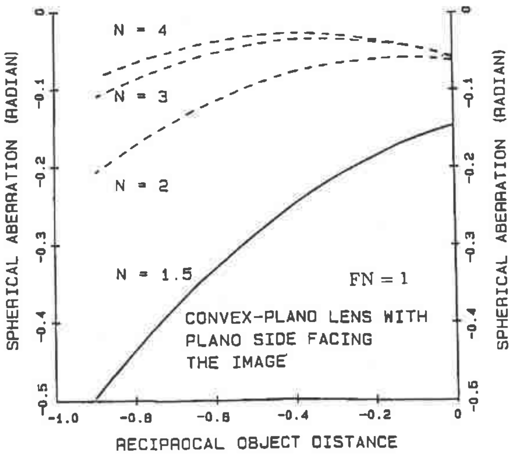

FIGURE 9 Variation of angular spherical aberration as a function of reciprocal object distance v for various refractive indices when the lens has a convex-plano shape with the plano side facing the object. Spherical aberration for a specific FN is determined by dividing the aberration value shown by $(FN)^3$.

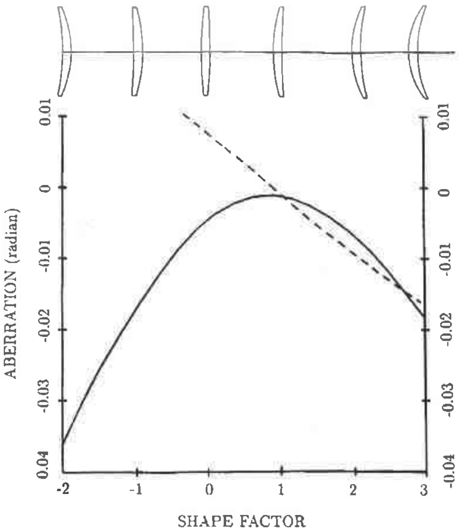

FIGURE 10 Variation of spherical aberration (solid curve) and coma (dashed line) as a function of shape factor for a thin lens with a refractive index of 1.5, stop in contact with the lens, and the object at infinity. The shape of the lens as the shape factor changes is shown at the top of the figure.

useful form is the plano-convex, with the plano side facing the object, if the convex side is figured as a conic surface with a conic constant of $-n^2$. Caution should be exercised when using this lens form at other than infinite object distances; however, imaging at finite conjugates can be accomplished by using two lenses with their plano surfaces facing one another and the magnification being determined by the ratio of the focal lengths. It should be noted that for this lens form, the actual thickness of the lenses is not important and that the inclusion of the conic surface does not alter the focal length.

The off-axis performance of a lens shaped for minimum spherical aberration with the object at infinity can be estimated by using the following equations. Assuming that the stop is in contact with the lens, the third-order angular sagittal coma is given by

$$\mathrm{CMA}_s = \frac{\theta}{16(n+2)(\mathrm{FN})^2} \tag{31}$$

where the field angle θ is expressed in radians. The tangential coma is three times the sagittal coma or $\mathrm{CMA}_t = 3 \cdot \mathrm{CMA}_s$. The diameter of the angular astigmatic blur formed at best focus is expressed by

$$\mathrm{AST} = \frac{\theta^2}{\mathrm{FN}} \tag{32}$$

The best focus location lies midway between the sagittal and tangential foci. An estimate of the axial angular chromatic aberration is given by

$$\mathrm{AChr} = \frac{1}{2V(\mathrm{FN})} \tag{33}$$

where V is the Abbe number of the glass and $V = (n_2 - 1)/(n_3 - n_1)$, with $n_1 < n_2 < n_3$.

If a singlet is made with a conic or fourth-order surface, the spherical aberration is corrected by the aspheric surface, and the bending can be used to remove the coma. With the stop in contact with the lens, the residual astigmatism and chromatic errors remain as expressed by the preceding equations. Figure 11 depicts the shapes of such singlets for

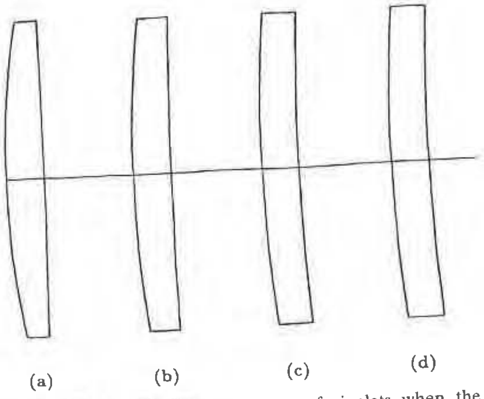

FIGURE 11 Variation of shape of singlets when the spherical aberration is corrected by the conic constant and the coma by the bending.

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TABLE 1. Prescription of Singlets Corrected for Both Spherical Aberration and Coma

Lens	R_1	Thickness	R_2	Index	CC_2
a	0.55143	0.025	−5.27966	1.5	−673.543
b	0.74715	0.025	2.90553	2.0	23.2435
c	0.88729	0.025	1.56487	3.0	0.86904
d	0.93648	0.025	1.33421	4.0	0.24340

refractive indices of 1.5, 2, 3, and 4. Each lens has a unity focal length and an FN of 10. Table 1 presents the prescription of each lens where CC_2 is the conic constant of the second surface.

1.11 LANDSCAPE LENSES AND THE INFLUENCE OF STOP POSITION

The first lens used for photography was designed in 1812 by the English scientist W. H. Wollaston about a quarter of a century before the invention of photography. He discovered that a meniscus lens with its concave surface towards the object could produce a much flatter image field than the simple biconvex lens commonly used at that time in the camera obscuras. This lens became known as the landscape lens and is illustrated in Fig. 12. Wollaston realized that if the stop was placed an appropriate amount in front of the lens and the F-number was made to be modest, the image quality would be improved significantly over the biconvex lens.

The rationale for this can be readily seen by considering the influence on the residual aberrations of the lens by movement of the stop. Functionally, the stop allows certain rays in the oblique beam to pass through it while rejecting the rest. By simple inspection, it is clear that the movement of the stop (assuming a constant FN is maintained) will not affect the axial aberrations, while the oblique aberrations will be changed. In order to understand the influence of stop movement on the image quality, a graphical method was devised by

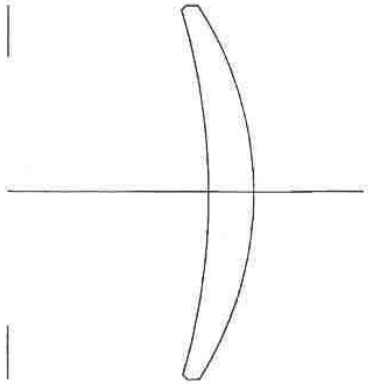

FIGURE 12 Landscape lens with the aperture stop located to the left of the lens.

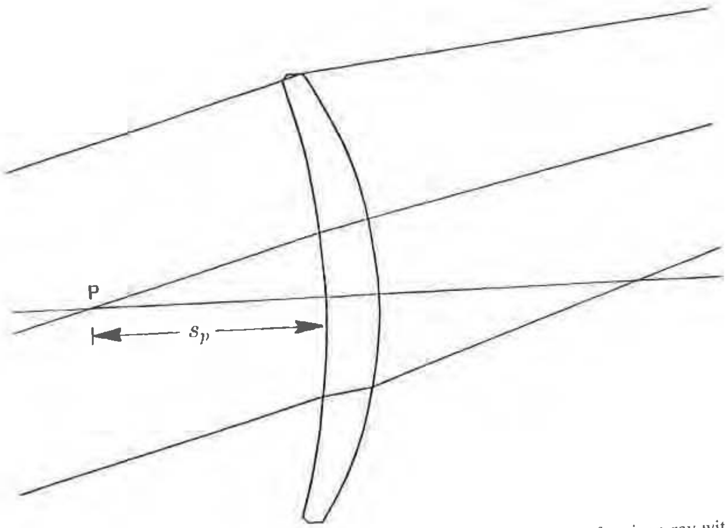

FIGURE 13 Rays traced at a given obliquity where the intersection of a given ray with the optical axis is P, located a distance s_p from the front surface of the lens.

R. Kingslake in which he traced a number of rays in the meridional plane at a given obliquity angle as illustrated in Fig. 13. A plot is generated that relates the intercept height of each real ray at the image plane H_i to the distance s_p from the intersection of the ray with optical axis P to the front surface of the lens. Each ray can be viewed as the principal ray when the stop is located at the intersection point P. This $H_i - s_p$ plot provides significant insight into the effect upon image quality incurred by placement of the stop. The shape of the curve provides information about the spherical aberration, coma, tangential field curvature, and distortion. Spherical aberration is indicated by an S-shaped curve, while the curvature at the principal ray point is a gauge of the coma. The coma is zero at inflection points. When the curve is a straight line, both coma and spherical aberration are essentially absent. The slope of the curve at the principal ray point is a measure of the tangential field curvature or the sag of the tangential field, i.e., astigmatism. The difference in height of the real and Gaussian principal rays in the image plane is distortion. For situations where the curve does not exhibit spherical aberration, it is impossible to correct the coma by shifting the stop.

Since a simple meniscus lens has stop position and lens bending as degrees of freedom, only two aberrations can be corrected. Typically, coma and tangential field curvature are chosen to be corrected, while axial aberrations are controlled by adjusting the FN of the lens. The $H_i - s_p$ plot for the lens shown in Fig. 13 is presented in Fig. 14, where the field angle is 10° and the image height is expressed as a percent of the Gaussian image height. The lens has a unity focal length, and the lens diameter is 0.275. Table 2 contains the prescription of the lens. Examination of this graph indicates that the best selection for stop location is when the stop is located at $s_p = -0.1505$ (left of the lens). For this selection, the coma and tangential astigmatism will be zero since the slope of the curve is zero and an inflection point is located at this stop position. Figure 15 shows the astigmatic field curves which clearly demonstrate the flat tangential image field for all field angles. Other aberrations cannot be controlled and must consequently be tolerated. When this lens is used at F/11, the angular blur diameter is less than 300 μradians. It should be noted that this condition is generally valid for only the evaluated field-angle obliquity and will likely

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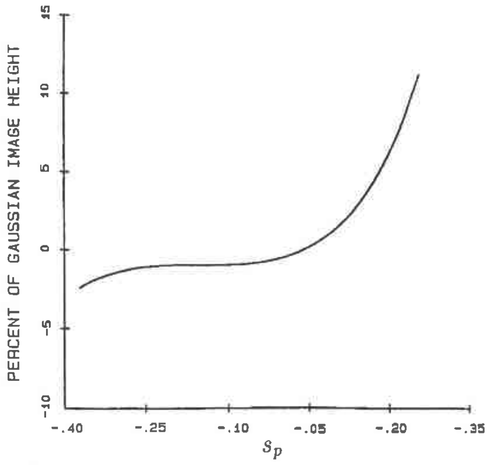

FIGURE 14 The image height H_i of each ray traced in Fig. 13 is plotted against the intersection length s_p to form the $H_i - s_p$ plot. H_i is expressed as a percent of the Gaussian image height as a direct measure of distortion.

TABLE 2. Prescription of Landscape Lens Shown in Fig. 13

Surface no.	Radius	Thickness	Index	Comment
1	Infinite	0.15050	1.0	Stop
2	−0.45759	0.03419	1.51680	BK7
3	−0.24887	0.99843	1.0	
4	Infinite			Image

be different at other field angles. Nevertheless, the performance of this lens is often acceptable for many applications.

An alternate configuration can be used where the lens is in front of the stop. Such configuration is used to conserve space since the stop would be located between the lens and the image. The optical performance is typically poorer due to greater residual spherical aberration.

The principle demonstrated by the $H_i - s_p$ plot can be applied to lenses of any complexity as a means to locate the proper stop position. It should be noted that movement of the stop will not affect the coma if spherical aberration is absent nor will astigmatism be affected if both spherical aberration and coma have been eliminated.

1.12 TWO-LENS SYSTEMS

Figure 16 illustrates the general imaging problem where an image is formed of an object by two lenses at a specified magnification and object-to-image distance. Most imaging

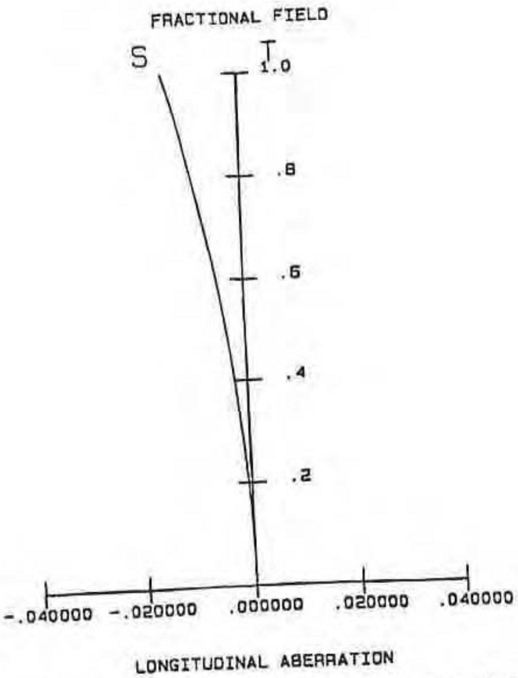

FIGURE 15 Astigmatic field curves for the landscape lens having the stop located at the zero slope location on the $H_i - s_p$ plot in Fig. 14, which is the flat tangential field position. S represents the sagittal astigmatic focus while T indicates the tangential astigmatic focus.

problems can be solved by using two *equivalent* lens elements. An equivalent lens can comprise one lens or multiple lenses and may be represented by the principal planes and power of a single thick lens. All distances are measured from the principal points of each equivalent lens element. For simplicity, the lenses shown in Fig. 16 are thin lenses. If the magnification m, object-image distance $\mathcal{S}$, and lens powers ϕ_a and ϕ_b are known, then the

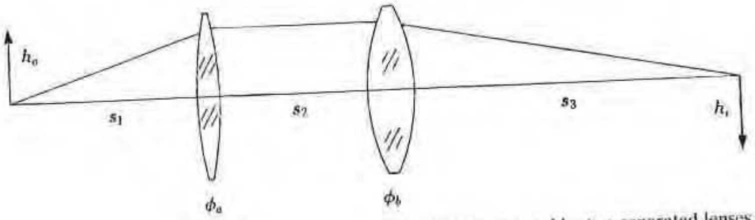

FIGURE 16 General imaging problem where the image is formed by two separated lenses.

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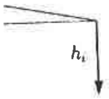

arated lenses.

equations for s_1, s_2, and s_3 are given by

$$s_1 = \frac{\phi_b(\mathcal{S} - s_2) - 1 + m}{m\phi_a + \phi_b}$$

$$s_2 = \frac{\mathcal{S}}{2}\left[1 \pm \sqrt{1 - \frac{4[\mathcal{S}_m(\phi_a + \phi_b) + (m-1)^2]}{\mathcal{S}^2 m\phi_a\phi_b}}\right]$$

$$s_3 = \mathcal{S} - s_1 - s_2 \tag{34}$$

The equation for s_2 indicates that zero, one, or two solutions may exist.

If the magnification and the distances are known, then the lens powers can be determined by

$$\phi_a = \frac{\mathcal{S} + (s_1 + s_2)(m - 1)}{ms_1s_2}$$

and (35)

$$\phi_b = \frac{\mathcal{S} + s_1(m - 1)}{s_2(\mathcal{S} - s_1 - s_2)}$$

It can be shown that only certain pairs of lens powers can satisfy the magnification and separation requirements. Commonly, only the magnification and object-image distance are specified with the selection of the lens powers and locations to be determined. By utilizing the preceding equations, a plot of regions of all possible lens power pairs can be generated. Such a plot is shown as the shaded region in Fig. 17 where $\mathcal{S} = 1$ and $m = -0.2$.

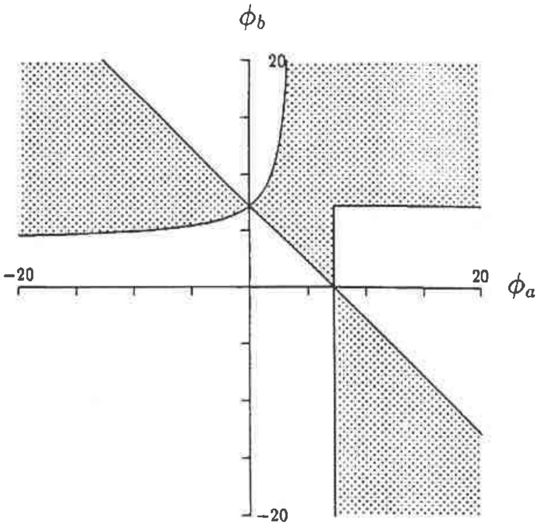

FIGURE 17 Shaded regions indicate all possible power pairs for the two lenses used for imaging. The solution space may be limited by physical considerations such as maximum aperture.

Examination of this plot can assist in the selection of lenses that may likely produce better performance by, for example, selecting the minimum power lenses. The potential solution space may be limited by placing various physical constraints on the lens system. For example, the allowable lens diameters can dictate the maximum powers that are reasonable. Lines of maximum power can then be plotted to show the solution space.

When s_1 becomes very large compared to the effective focal length *efl* of the lens combination, the optical power of the combination of these lenses is expressed by

$$\phi_{ab} = \phi_a + \phi_b - s_2\phi_a\phi_b \tag{36}$$

The effective focal length is ϕ_{ab}^{-1} or

$$f_{ab} = \frac{f_a f_b}{f_a + f_b - s_2} \tag{37}$$

and the back focal length is given by

$$bfl = f_{ab}\left(\frac{f_a - s_2}{f_a}\right) \tag{38}$$

The separation between lenses is expressed by

$$s_2 = f_a + f_b - \frac{f_a f_b}{f_{ab}} \tag{39}$$

Figure 18 illustrates the two-lens configuration when thick lenses are used. The principal points for the lens combination are denoted by P_1 and P_2, P_{a1} and P_{a2} for lens a, and P_{b1} and P_{b2} for lens b. With the exception of the back focal length, all distances are measured from the principal points of each lens element or the combined lens system as shown in

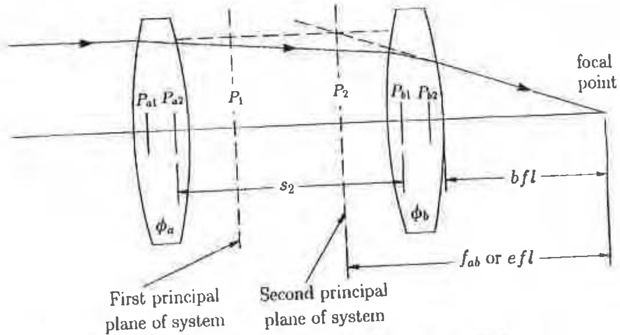

FIGURE 18 Combination of two thick lenses illustrating the principal points of each lens and the system, the f_{ab} or *efl*, and the *bfl*. Distances are measured from the principal points with the exception of the *bfl*.

the figure. For example, s_2 is the distance from P_{a2} to P_{b1}. The *bfl* is measured from the final surface vertex of the lens system to the focal point.

1.13 ACHROMATIC DOUBLETS

The singlet lens suffers from axial chromatic aberration, which is determined by the Abbe number V of the lens material and its FN. A widely used lens form that corrects this aberration is the achromatic doublet as illustrated in Fig. 19. An achromatic lens has equal focal lengths in *c* and *f* light. This lens comprises two lens elements where one element with a high V-number (crown glass) has the same power sign as the doublet and the other element has a low V-number (flint glass) with opposite power sign. Three basic configurations are used. These are the cemented doublet, broken contact doublet, and the widely airspaced doublet (dialyte). The degrees of freedom are two lens powers, glasses, and shape of each lens.

The resultant power of two thin lenses in close proximity, $s_2 \rightarrow 0$, is $\phi_{ab} = \phi_a + \phi_b$ and the transverse primary chromatic aberration TPAC is

$$\mathrm{TPAC} = -yf_{ab}\left[\frac{\phi_a}{V_a} + \frac{\phi_b}{V_b}\right] \tag{40}$$

where y is the marginal ray height. Setting TPAC = 0 and solving for the powers of the lenses yields

$$\phi_a = \frac{V_a}{f_{ab}(V_a - V_b)} \tag{41}$$

and

$$\phi_b = \frac{-V_b\phi_a}{V_a} \tag{42}$$

The bending or shape of a lens is expressed by $c = c_1 - c_2$ and affects the aberrations of the lens. The bending of each lens is related to its power by $c_a = \phi_a/(n_a - 1)$ and $c_b = \phi_b(n_b - 1)$. Since the two bendings can be used to correct the third-order spherical and coma, the equations for these aberrations can be combined to form a quadratic equation in terms of the curvature of the first surface c_1. Solving for c_1 will yield zero, one, or two solutions for the first lens. A linear equation relates c_1 to c_2 of the second lens.

While maintaining the achromatic correction of a doublet, the spherical aberration as a function of its shape (c_1) is described by a parabolic curve. Depending upon the choices of

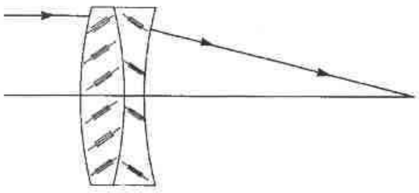

FIGURE 19 Typical achromatic doublet lens.

glasses, the peak of the curve may be above, below, or at the zero spherical aberration value. When the peak lies in the positive spherical aberration region, two solutions with zero spherical aberration exist in which the solution with the smaller value of c_1 is called the left-hand solution (Fraunhofer or Steinheil forms) and the other is called the right-hand solution (Gaussian form). Two additional solutions are possible by reversal of the glasses. These two classes of designs are denoted as crown-in-front and flint-in-front designs. Depending upon the particular design requirements, one should examine all four configurations to select the most appropriate. The spherical aberration curve can be raised or lowered by the selection of the V difference or the n difference. Specifically, the curve will be lowered as the V difference is increased or if the n difference is reduced. As for the thin singlet lens, the coma will be zero for the configuration corresponding to the peak of the spherical aberration curve.

Although the primary chromatic aberration may be corrected, a residual chromatic error often remains and is called the secondary spectrum, which is the difference between the ray intercepts in d and c. Figure 20*a* illustrates an F/5 airspaced doublet that exhibits well-corrected spherical light and primary chromatic aberrations and has notable secondary color. The angular secondary spectrum for an achromatic thin-lens doublet is given by

$$\text{SAC} = \frac{-(P_a - P_b)}{2(\text{FN})(V_a - V_b)} \tag{43}$$

where $P = (n_\lambda - n_F)/(n_f - n_c)$ is the partial dispersion of a lens material. In general, the ratio $(P_a - P_b)/(V_a - V_b)$ is nearly a constant which means little can be done to correct the SAC. A few glasses exist that allow $P_a - P_b \approx 0$, but the $V_a - V_b$ is often small, which results in lens element powers of rather excessive strength in order to achieve achromatism. Figure 20*b* shows an F/5 airspaced doublet using a relatively new pair of glasses that have a small $P_a - P_b$ and a more typical $V_a - V_b$. Both the primary and secondary chromatic aberration are well corrected. Due to the relatively low refractive index of the crown glass, the higher power of the elements results in spherical aberration through the seventh order. Almost no spherochromatism (variation of spherical aberration with wavelength) is

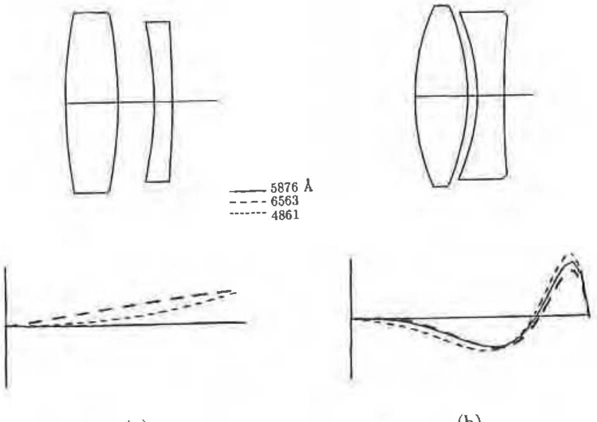

FIGURE 20 An F/5 airspaced doublet using conventional glasses is shown in *a* and exhibits residual secondary chromatic aberration. A similar lens is shown in *b* that uses a new glass to effectively eliminate the secondary color.

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TABLE 3. Prescriptions for Achromatic Doublets Shown in Fig. 20

Achromatic doublet—1

Surface no.	Radius	Thickness	Glass
1	49.331	6.000	BK7 517:642
2	−52.351	4.044	Air
3	−43.888	2.000	SF1 717:295
4	−141.706		Air

Achromatic doublet—2

Surface no.	Radius	Thickness	Glass
1	23.457	6.000	FK03 439:950
2	−24.822	1.059	Air
3	−22.516	3.000	BK7 517:642
4	94.310		Air

observed. The 80 percent blur diameter is almost the same for both lenses and is 0.007. Table 3 contains the prescriptions for these lenses.

When the separation between the lens elements is made a finite value, the resultant lens is known as a *dialyte* and is illustrated in Fig. 21. As the lenses are separated by a distance s_d, the power of the flint or negative lens increases rapidly. The distance s_d may be expressed as a fraction of the crown-lens focal length by $p = s_d/f_a$. Requiring the chromatic aberration to be zero implies that

$$\frac{y_a^2}{f_a V_a} + \frac{y_b^2}{f_b V_b} = 0 \tag{44}$$

By inspection of the figure and the definition of p, it is evident that $y_b = y_a(1-p)$ from which it follows that

$$f_b V_b = -f_a V_a (1-p)^2 \tag{45}$$

The total power of the dialyte is

$$\phi = \phi_a + \phi_b(1-p) \tag{46}$$

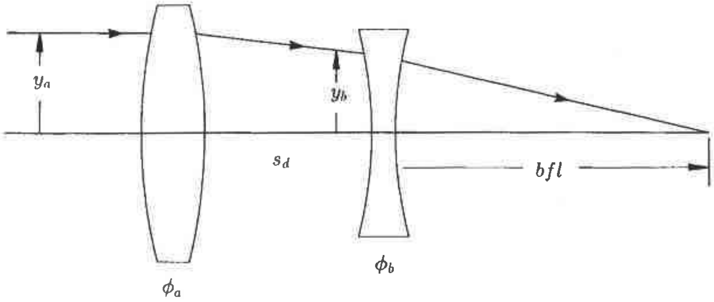

FIGURE 21 Widely separated achromatic doublet known as the dialyte lens.

Solving for the focal lengths of the lenses yields

$$f_a = f_{ab}\left[1 - \frac{V_b}{V_a(1-p)}\right] \tag{47}$$

and

$$f_b = f_{ab}(1-p)\left[1 - \frac{V_a(1-p)}{V_b}\right] \tag{48}$$

The power of both lenses increases as p increases.

The typical dialyte lens suffers from residual secondary spectrum; however, it is possible to design an airspaced achromatic doublet with only one glass type that has significantly reduced secondary spectrum. Letting $V_a = V_b$ results in the former equations becoming

$$f_a = \frac{pf_{ab}}{p-1} \qquad f_b = -pf_{ab}(p-1) \qquad s_d = pf_a \qquad bfl = -f_{ab}(p-1) \tag{49}$$

When $f_{ab} > 0$, then p must be greater than unity, which means that the lens is quite long. The focal point lies between the two lenses, which reduces its general usefulness. This type of lens is known as the Schupmann lens, based upon his research in the late 1890s. Several significant telescopes, as well as eyepieces, have employed this configuraton. For $f_{ab} < 0$, the lens can be made rather compact and is sometimes used as the rear component of some telephoto lenses.

1.14 TRIPLET LENSES

In 1893, a new type of triplet lens for photographic applications was invented by the English designer H. Dennis Taylor. He realized that the power of two lenses in contact of equal, but opposite, power is zero, as is its Petzval sum. As the lenses are separated, the system power becomes positive since the negative lens contributes less power. The Petzval sum remains zero, since it does not depend upon the marginal ray height. In order to overcome the large aberrations of such a configuration, Taylor split the positive lens into two positive lenses and placed one on each side of the negative lens. A stop is often located between the negative and rear-positive lenses. Figure 22 illustrates a typical triplet lens. The triplet can be used at reasonably large apertures (>F/4) and moderately large fields of view (>±25°).

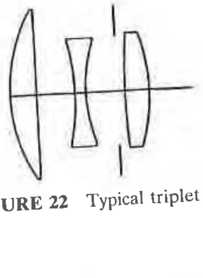

FIGURE 22 Typical triplet lens.

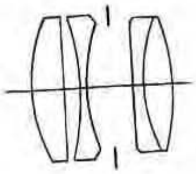

FIGURE 23 Typical Tessar lens.

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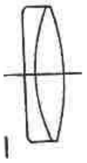

ical Tessar lens.

The triplet has eight degrees of freedom which are the three powers, two airspaces, and three lens bendings. The lens powers and airspaces are used to control the axial and lateral chromatic aberrations, the Petzval sum, the focal length, and the ratio of the airspaces. Spherical aberration, coma, and astigmatism are corrected by the lens bendings. Distortion is usually controlled by the airspace ratio or the choice of glasses. Consequently, the triplet has exactly the number of degrees of freedom to allow correction of the basic aberrations and maintain the focal length.

The design of a triplet is somewhat difficult since a change of any surface affects every aberration. The choice of glass is important and impacts the relative aperture, field of view, and overall length. For example, a large ΔV produces a long system. It should be noted that a triplet corrected for third-order aberrations by using the degrees of freedom almost always leads to a lens with poor performance. A designer normally leaves a certain amount of residual third-order aberrations to balance the higher-order terms. The process for thin-lens predesign is beyond the scope of this handbook; however, it may be found in various references comprising the bibliography.

A few years later, Paul Rudolph of Zeiss developed the Tessar, which resembles the triplet, with the rear lens replaced by an achromatic doublet. The Tessar shown in Fig. 23 was an evolution of Rudolph's anastigmats which were achromatic lenses located about a central stop. The advantage of the achromatic rear component is that it allows reduction of the zonal spherical aberration and the oblique spherical aberration, and reduces the separation of the astigmatic foci at other than the design maximum field angle. Performance of the Tessar is quite good and has generally larger relative apertures at equivalent field angles than the triplet. A variety of lenses were derived from the triplet and the Tessar in which the component lenses were made into doublets or cemented triplets.

1.15 SYMMETRICAL LENSES

In the early 1840s, it was recognized that lenses that exhibit symmetry afford various benefits to the lens designer. The first aberration acknowledged to be corrected by the symmetry principle was distortion. It can also be shown that coma and lateral color are necessarily corrected by a symmetrical lens construction. Although the principle of symmetry implies that the lens be operated at a magnification of −1, the degree to which the aberrations are upset by utilizing the lens at other conjugates is remarkably small. This principle forms the basis of most wide-field-of-view lenses.

One of the earliest symmetrical lenses was the Periscopic (Periskop) lens invented by C. A. Steinheil in 1865. Figure 24 shows an F/11 Periscopic lens constructed from the landscape lens discussed previously. Symmetry corrects for coma and distortion, while the

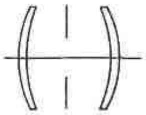

FIGURE 24 The periscopic lens illustrates the earliest form of symmetrical lenses. It is formed by placing two landscape lenses about a central stop. Symmetry removes the aberrations of coma, distortion, and lateral color.

spacing of the lenses and their shapes are selected to produce a flat tangential astigmatic field. Since the stop position for the landscape lens was chosen to yield a flat tangential astigmatic field, essentially no change in the lens separation is necessary even though the Periscopic lens is being used at infinite conjugates. No correction for spherical aberration can be made. When used at other than unit magnification, some optical improvement can be achieved by making the stop slightly asymmetrical and/or having a different shape for the front or rear lens. This lens has continued to find application throughout this century.

By 1966, Dallmeyer in England and Steinheil and von Seidel in Germany both invented the Rapid Rectilinear lens that could be used at apertures of up to F/6. The lens has two cemented achromats about a central stop. Use of the doublet allows correction of the axial chromatic and spherical aberrations. Glass selection is of importance in the design. Typically, the Δn between the glasses should be large while the ΔV should be relatively small. The positive lens is located nearest the stop and has the lower refractive index. A notable characteristic of the lens is that the aberrations are reasonably stable over a broad range of object distances.

It should be noted that vignetting is often used in these and other lens types to control the higher-order aberrations that are often observed at large field angles. Although a loss in illumination occurs, the gain in resolution is often worthwhile.

The airspaced dialyte lens comprises four lenses symmetrically arranged about a central stop. The rear portion of the lens is an achromatic doublet that has five degrees of freedom (an air space, two powers, and two bendings) which may be used to control the focal length, spherical aberration, axial chromatic aberration, astigmatism, and the Petzval sum. With a like pair of lenses mounted in front of the stop, the symmetry corrects the coma, distortion, and lateral color. When used at infinite conjugates, the resultant residuals of the aberrations can be controlled by deviating somewhat from perfect symmetry of the air spaces about the stop. Lenses of this type can provide useful performance with apertures approaching F/4 and fields of view of about ±20° or so.

1.16 DOUBLE-GAUSS LENSES

In the early 1800s, Gauss described a telescope objective comprising a pair of meniscus lenses with one having positive power and the other negative power. An interesting aspect of his lens is that the spherochromatism is essentially constant. Although this lens found little acceptance, in 1888, Alvan Clark of Massachusetts placed a pair of the Gauss lenses around a central stop to create a high-aperture, wide-field-of-view lens. This lens form is known as the Double-Gauss lens and is the basis of almost every high-aperture lens developed to date. An example of this lens was patented by Richter in 1933 and can cover a field of view of ±45° at F/6.

In 1896, Paul Rudolph of Zeiss developed the Planar which reduces the often serious oblique spherical aberration and the separation of the astigmatic foci at intermediate field angles. Rudolph placed a buried surface into the thick negative elements to control the chromatic aberration. A buried surface is defined as the interface between two glasses that have the same refractive index n_d at the central wavelength, but have significantly different Abbe numbers. Such a surface has no effect upon the monochromatic aberrations or the lens system power, but does allow the inclusion of a wide range of chromatic aberration to compensate for that caused by the rest of the lens.

Many Double-Gauss lenses are symmetrical; however, it was discovered that if the lens was made unsymmetrical, then an improvement in performance could be realized. This lens form is often called the Biotar. A large portion of 35-mm camera lenses are based

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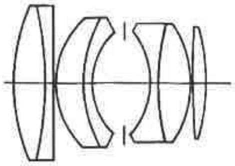

FIGURE 25 Unsymmetrical Double-Gauss or Biotar lens introduced as the Leica Summitar in 1939.

upon this design form or some modification thereof. Figure 25 shows the configuration of the Leica Summitar introduced in 1939.

It is the general nature of meniscus lens systems of this type to exhibit little coma, distortion, or lateral color; however, oblique spherical aberration is often observed to increase to significant levels as the field angle increases. Oblique spherical aberration can be recognized in transverse ray plots as the S shape of spherical aberration, but with the S becoming increasingly stronger as the field angle increases. As the aperture is increased beyond about F/8, the outer negative elements must be thickened dramatically and achromatic surfaces must necessarily be included.

1.17 PETZVAL LENSES

In 1839, Petzval designed a new type of lens that comprises a front objective with an achromatic, airspaced doublet as the rear elements. The Petzval lens has found great application in projectors and as a portrait lens. Both spherical aberration and coma can be well-corrected, but the lens configuration causes the Petzval sum to be undercorrected, which results in the field of view being limited by the astigmatism. The Petzval field curves inward and may be corrected by including a *field flattener lens* in close proximity to the image plane. A typical example of a Petzval lens is shown in Fig. 26.

1.18 TELEPHOTO LENSES

A telephoto lens provides an effective focal length *efl* that is longer than its overall length s_{ol} as measured from the front of the lens to the image plane. The telephoto ratio is defined as s_{ol}/efl, thus a lens with a ratio less than one is a telephoto lens. The basic concept of a telephoto lens is illustrated by the dialyte lens configuration in which a negative lens is inserted between the objective lens and the image plane. This concept goes back to Kepler, but Peter Barlow developed the idea in the early 1800s by including a negative achromat

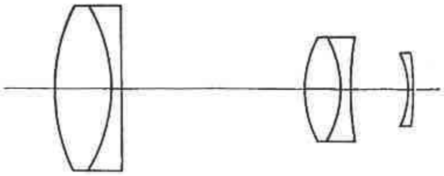

FIGURE 26 Typical Petzval lens.

in telescopes to increase their magnification. Barlow type lenses are widely used today. As the telephoto ratio is made smaller, the design of the lens becomes more difficult, primarily due to the Petzval sum increasing.

When most telephoto lenses are used to view objects that are relatively close, the image quality degrades rapidly due to the typical unsymmetrical lens configuration. Some modern telephoto lenses include one or more elements that move as the lens is focused for the purpose of aberration correction.

1.19 INVERTED OR REVERSE TELEPHOTO LENSES

A reverse telephoto lens has a telephoto ratio greater than unity and exhibits a shorter focal length than its overall length, a larger *bfl* than is provided by normal lenses of the same *efl*, lenses with generally large apertures and wide fields of view, and lens elements of physically larger size that allow easier manufacture and handling. The basic configuration has a large negative lens located in front of a positive objective lens. Since the negative lens makes the object appear closer to the objective lens, the resultant image moves beyond the focal point, thereby making the *bfl* greater than the *efl*.

An extreme form of the reverse telephoto lens is the fish-eye or sky lens. Such lenses have a total field of view of 180° or more. The image formed by these lenses has very large barrel distortion. Recalling that the image height for a distortionless lens on a flat image surface is $f \tan \theta$, the reverse telephoto lens has mapping relationships such as $f\theta$ and $f \sin \theta$. When the barrel distortion is given by $f \sin \theta$, the illumination across the image will be constant if such effects as vignetting and stop distortion are absent. Barrel distortion has the effect of compressing the outer portions of the image towards the central portion, thereby increasing the flux density appropriately.

After World War II, the Russian designer M. M. Roosinov patented a double-ended reverse-telephoto lens that was nearly symmetrical with large negative lenses surrounding a pair of positive lenses with a central stop. Although the back focal length is quite short, it provides relatively large aperture with a wide field of view and essentially no distortion. Lenses of this type have found significant use in aerial photography and photogrammetry.

1.20 PERFORMANCE OF REPRESENTATIVE LENSES

Figures 27–38 present the performance of lenses, selected generally from the patent literature, representing a variety of lens types. The measures of performance provided in each figure have been selected for utilization purposes. Diffraction effects have not been included.

Each figure is divided into four sections *a–d*. Section *a* is a drawing of the lens showing the aperture stop. Section *b* contains two set of plots. The *solid* line is for the distortion versus field of view (θ) in degrees while the *dashed* lines show the transmission of the lens versus field of view for three F-numbers. Transmission in this case is *one minus the fractional vignetting*. No loss for coatings, surface reflection, absorption, etc., is included. The rms diameter of the geometric point source image versus field of view for three F-numbers is presented in section *c*. The spot sizes are in angular units and were calculated for the central wavelength only, i.e., monochromatic values. Note that the ordinate is logarithmic. The final section, *d*, contains angular transverse ray plots in all three colors for both the on-axis and near-extreme field angles with y_{ep} being measured in the entrance pupil. The lower right plot shows the axial aberrations while the upper left plot represents the tangential/meridional aberrations and the upper right plot presents the sagittal

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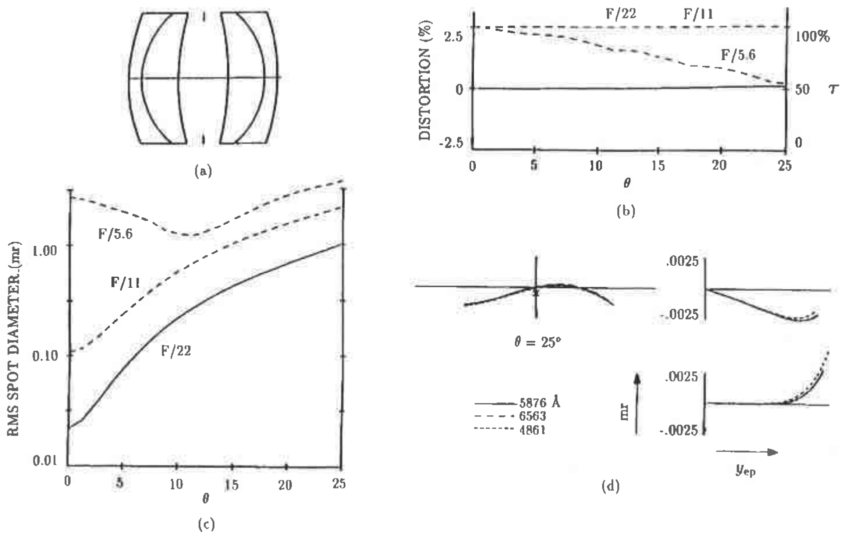

FIGURE 27 Rapid Rectlinear: This lens is an aplanat which is symmetrical with the rear half corrected for spherical aberration and flat tangential field. A compact configuration is realized by having a large amount of coma in each half. Symmetry removes the lens system coma, distortion, and lateral color. This type of lens is one of the most popular camera lenses ever made.

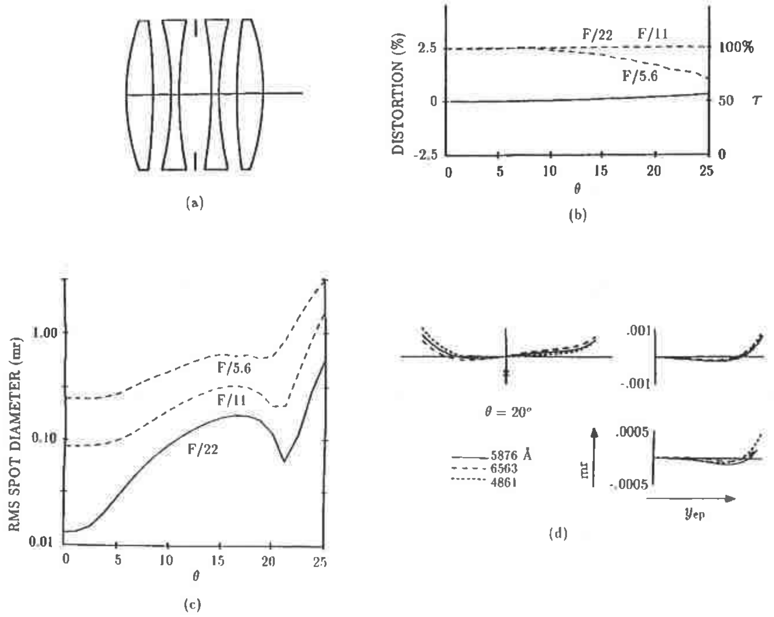

FIGURE 28 Celor: F/5.6 with 50° total field of view. Also known as an airspaced dialyte lens. *After R. Kingslake,* Lens Design Fundamentals, *Academic Press, New York, 1978, p. 243.*

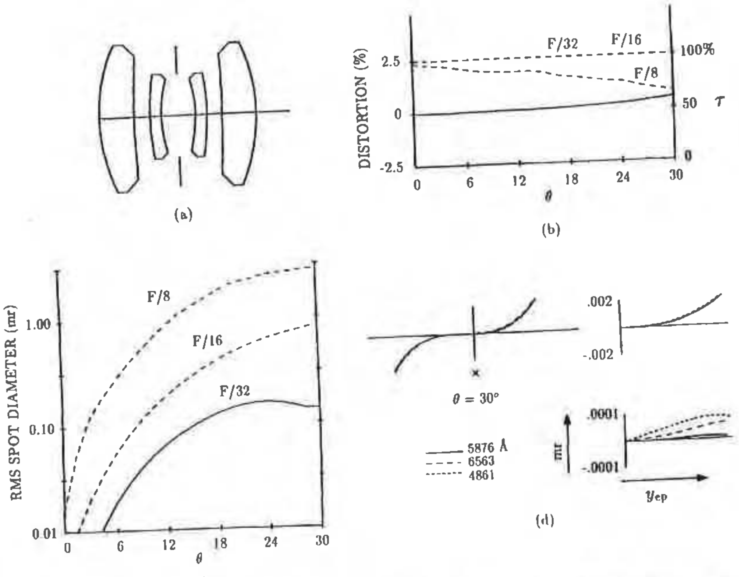

FIGURE 29 Symmetrical double anastigmat or Gauss homocentric objective: basic form of Double-Gauss lens using a pair of Gauss telescope objectives. First patented by Alvan Clark in 1888, USP 399,499. After *R. Kingslake*, Lens Design Fundamentals, *Academic Press, New York, 1978, pp. 244–250.*

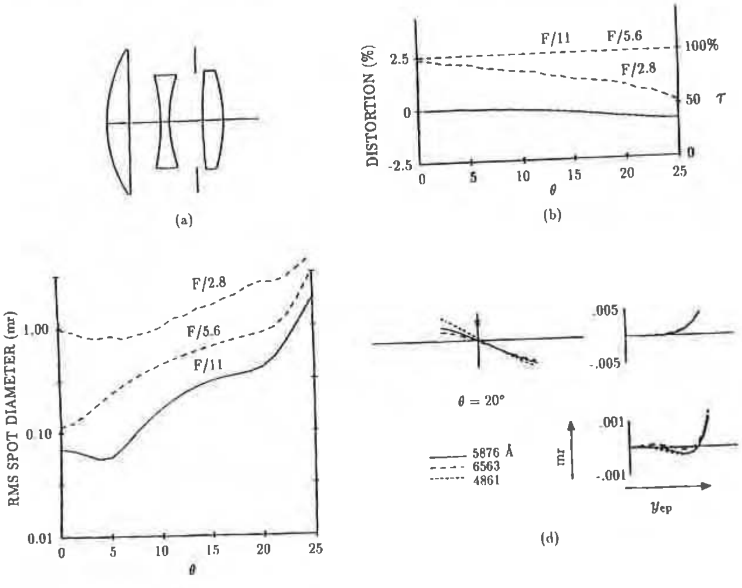

FIGURE 30 Triplet: F/2.8 with 50° total field of view. (*Tronnier, USP 3,176,582.)*

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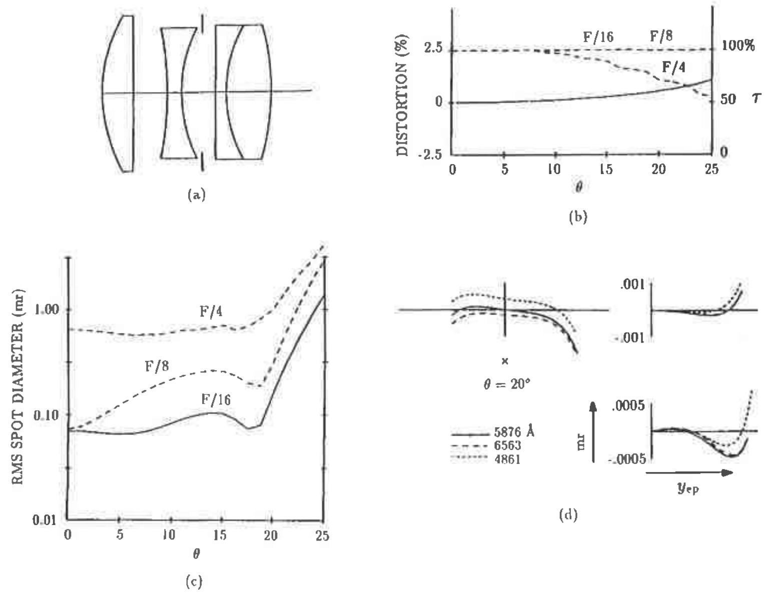

FIGURE 31 Tessar: F/4 with 50° total field of view. (*Tronnier, USP 2,084,714, 1937.*)

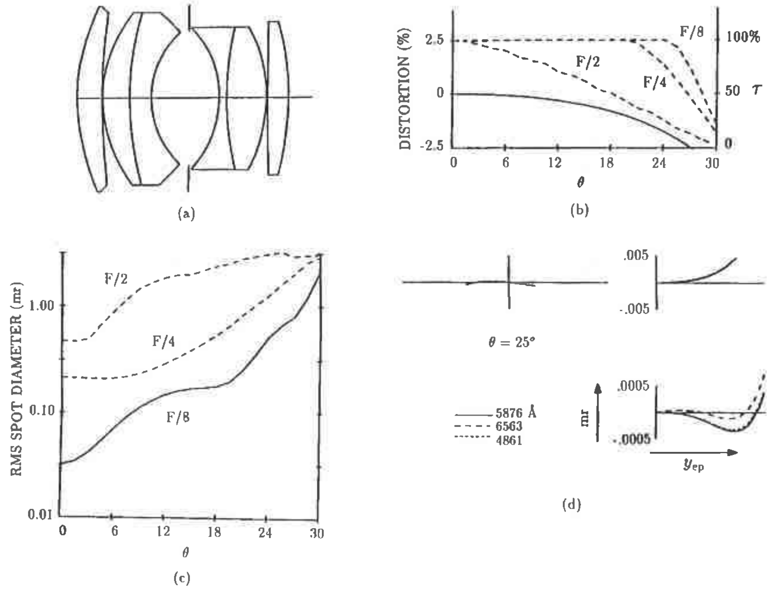

FIGURE 32 Unsymmetrical Double-Gauss: This lens was designed in 1933 for Leitz and was called the Summar. F/2 with 60° total field of view. This lens was replaced by the Leitz Summitar in 1939, due to rapidly degrading off-axis resolution and vignetting. Compare this lens with the lens shown in Fig. 33. (*Tronnier, USP 2,673,491.*)

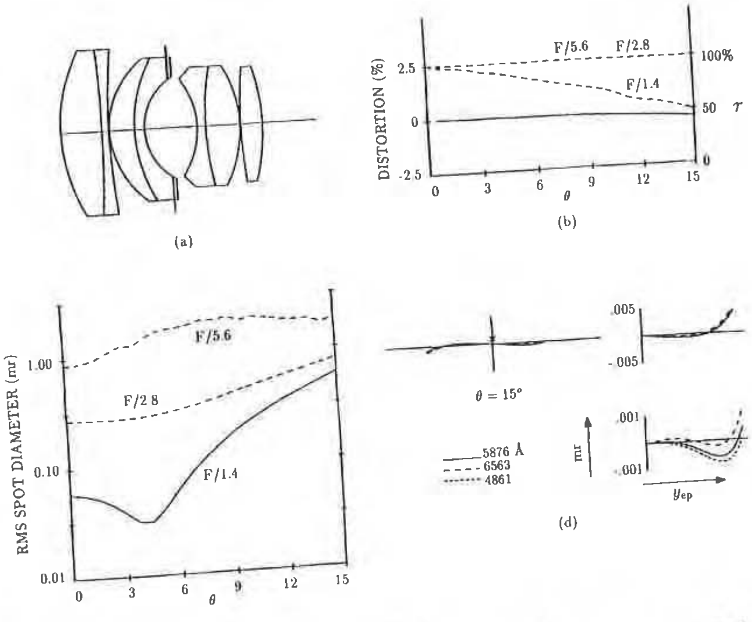

FIGURE 33 Unsymmetrical Double-Gauss: This lens type was designed in 1939 for Leitz and was called the F/2 Summitar. Kodak had a similar lens called the F/1.9 Ektar. A later example of this design form is shown and operates at F/1.4 with 30° total field of view. (*Klemp, USP 3,005,379.*)

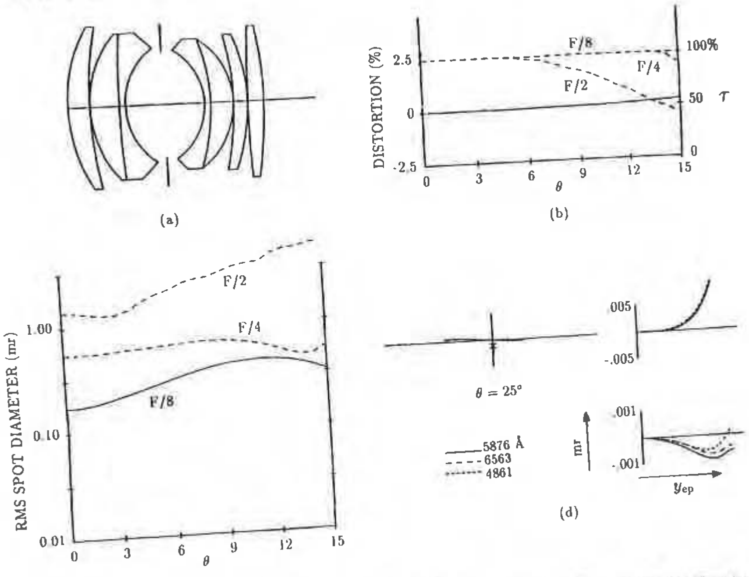

FIGURE 34 Unsymmetrical Double-Gauss: F/1.75 with 50° total field of view. Similar to the 1949 Leitz F/1.5 Summarit. This lens has a split rear element which produces improved resolution of the field of view and less vignetting than the earlier Summar type lens. (*Cook, USP 2,959,102.*)

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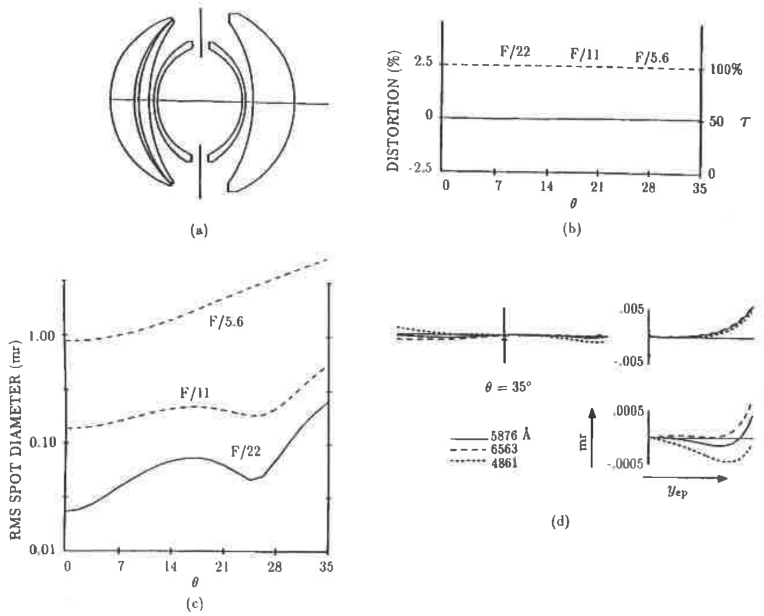

FIGURE 35 Unsymmetrical Double-Gauss: F/5.6 with 70° field of view. This lens is a variant of the 1933 Zeiss F/6.3 Topogon (*USP 2,031,792*) and is the Bausch & Lomb Metrogon. The principal difference is the splitting of the front element. (*Rayton, USP 2,325,275.*)

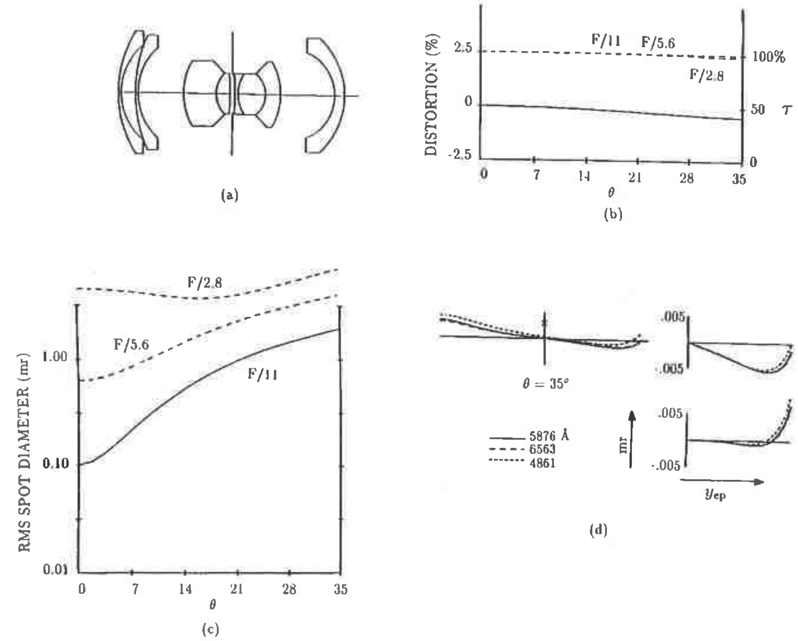

FIGURE 36 Reverse Telephoto: This lens was developed by Zeiss in 1951 and is known as the Biogon. It operates at F/2.8 with 70° field of view. This lens comprises two reverse-telephoto objectives about a central stop. (*Bertele, USP 2,721,499.*)

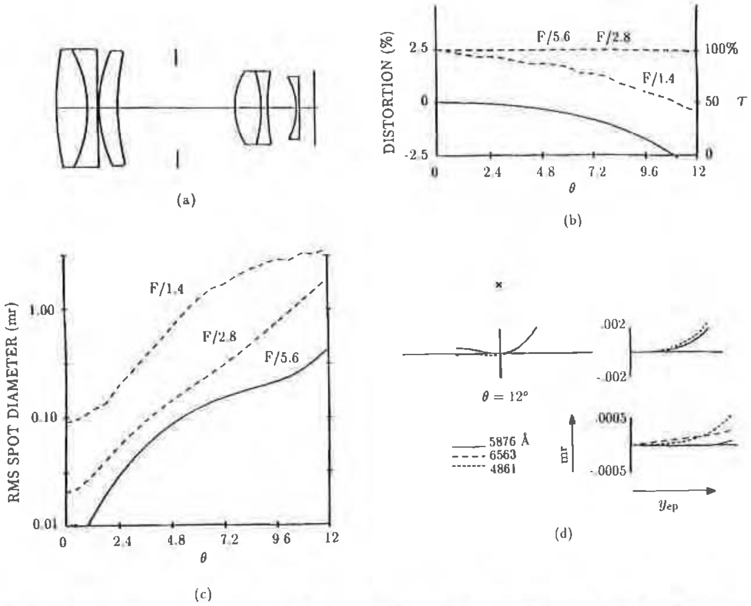

FIGURE 37 Petzval: Example of Kodak projector lens operating at F/1.4 with 24° total field of view. The front lens group has its power shared between a cemented doublet and a singlet for aberration correction. Note that the aperture stop is located between the front and rear groups rather than the more common location at the front group. Resolution in the region near the optical axis is very good although it falls off roughly exponentially. The limiting aberrations are oblique spherical and cubic coma. (*Schade, USP 2,541,484.*)

aberrations. The X included on some of the tangential plots represents the location of the paraxial principal ray. The legend indicating the relationship between line type and wavelength is included.

The linear spot size is computed by multiplying the *efl* by the angular spot size. This value can be compared against the diffraction-limited spot size given by $2.44(\lambda/D_{ep})$. If the geometric spot is several times *smaller* than the diffraction-limited spot, then the lens may be considered to be diffraction-limited for most purposes. If the geometric spot is several times *larger,* then the lens performance is controlled by the geometric spot size for most applications.

1.21 RAPID ESTIMATION OF LENS PERFORMANCE

Singlet

Figure 39 is a nomogram that allows quick estimation of the performance of a single refracting lens, with the stop at the lens, as a function of refractive index *N*, dispersion *V*, F-number, and field of view *θ*. Chart A estimates the angular blur diameter *β* resulting

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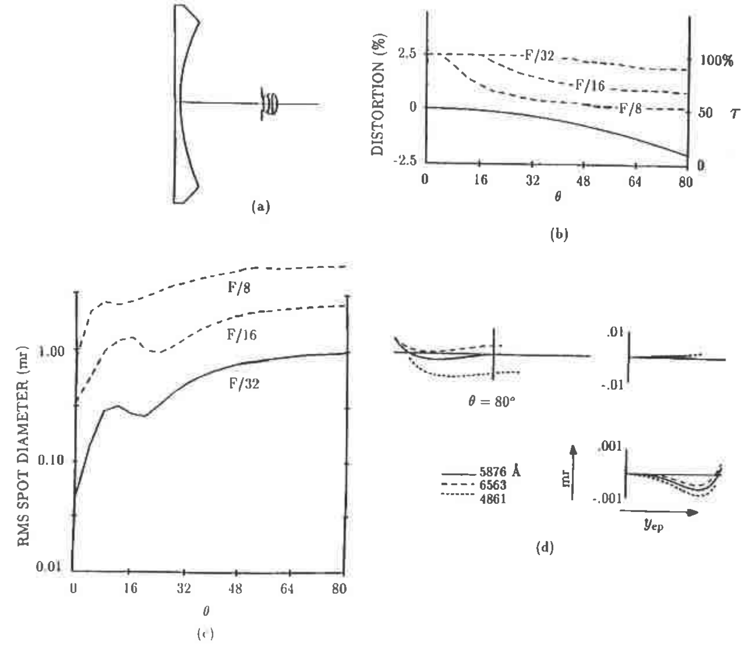

FIGURE 38 Fish-eye: The Hill Sky lens was manufactured by Beck of London in 1924. The lens has moderate resolution and enormous distortion characteristic of this type of lens. (*Merte, USP 2,126,126.*)

from a singlet with bending for minimum spherical aberration. The angular chromatic blur diameter is given by Chart B. The three rows of FN values below the chart represent the angular blur diameter that contains the indicated percentage of the total energy. Chart C shows the blur diameter due to astigmatism. Coma for a singlet bent for minimum spherical aberration with the stop at the lens is approximately

$$\frac{\theta}{16 \cdot (N+2) \cdot (\mathrm{FN})^2} \tag{50}$$

Depth of Focus

The *depth of focus* of an optical system is expressed as the axial displacement that the image may experience before the resultant image blur becomes excessive. Figure 40 shows the geometric relationship of the angular blur tolerance $\Delta\theta$ to the depth of focus $\delta_{\pm}$. If the entrance pupil diameter is D_{ep} and the image distance is s_i, then the depth of focus is

$$\delta_{\pm} = \frac{s_i^2 \, \Delta\theta}{D_{ep} \pm s_i \, \Delta\theta} \tag{51}$$

or when $\delta \ll s_i$, the depth of focus becomes

$$\delta = \frac{s_i^2 \, \Delta\theta}{D_{ep}} \tag{52}$$

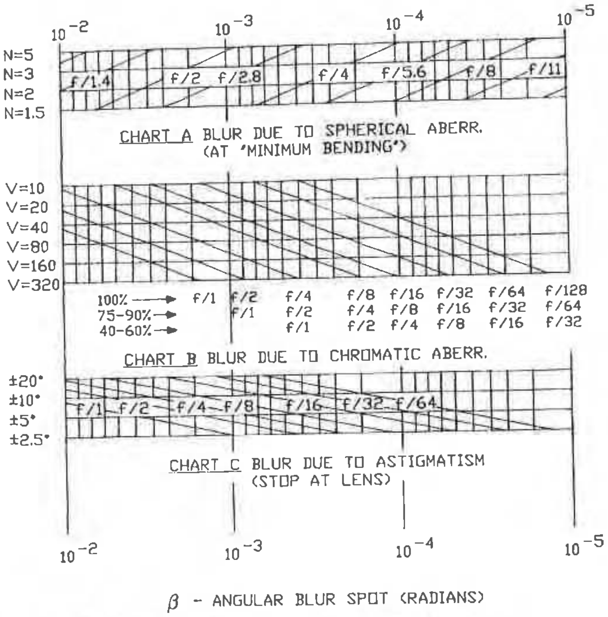

FIGURE 39 Estimation of single lens spot size as a function of refractive index, dispersion, F-number, and field of view. (*Smith*, Modern Optical Engineering, *McGraw-Hill, New York, 1990, p. 458.*)

When $s_i = f$, then

$$\delta = f\,\Delta\theta\,\mathrm{FN} \tag{53}$$

The *depth of field* is distance that the object may be moved without causing excessive image blur with a fixed image location. The distance at which a lens may be focused such that the depth of field extends to infinity is $s_o = D_{ep}/\Delta\theta$ and is called the hyperfocal distance.

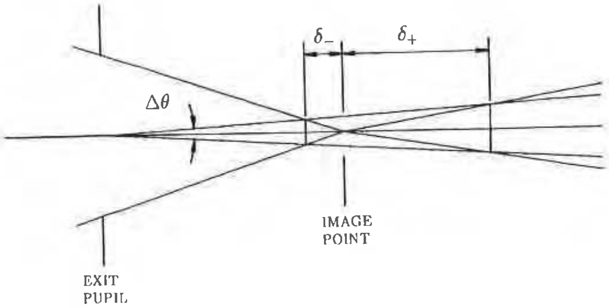

FIGURE 40 Geometric relationships for determining the geometric depth of focus of a lens.

If the lens system is diffraction-limited, then the depth of focus according to the Rayleigh criterion is given by

$$\delta = \pm \frac{\lambda}{2n_i \sin^2 u_i} \tag{54}$$

Diffraction-Limited Lenses

It is well known that the shape of the image irradiance of an incoherent, monochromatic point-source formed by an aberration-free, circularly-symmetric lens system is described by the Airy function

$$E(r) = C_0 \left[\frac{2J_1(kD_{ep}r/2)}{kD_{ep}r} \right]^2 \tag{55}$$

where J_1 is the first order Bessel function of the first kind, D_{ep} is the diameter of the entrance pupil, k is $2\pi/\lambda$, r is the radial distance from the center of the image to the

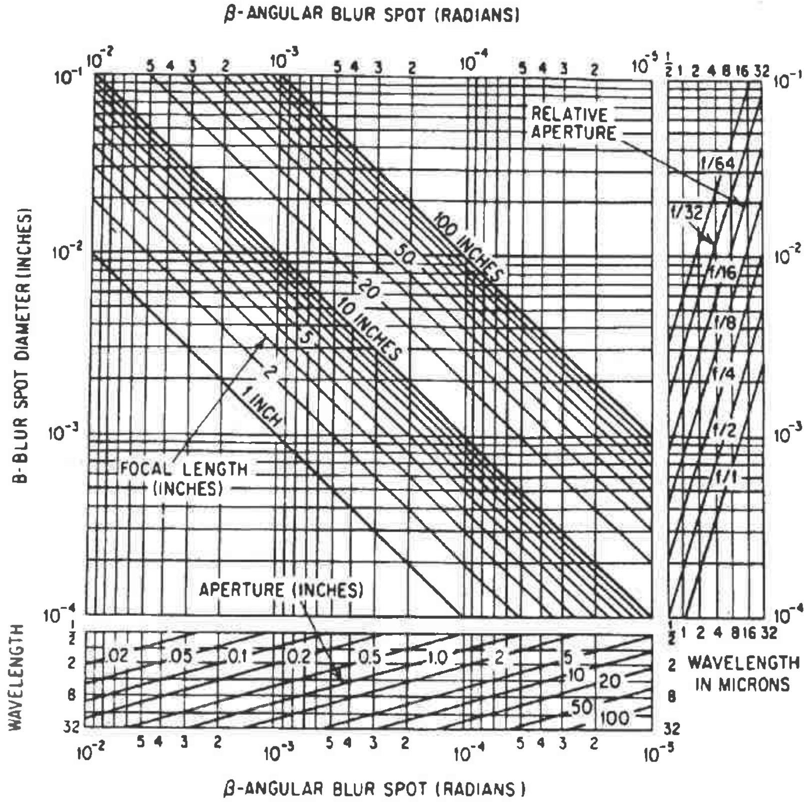

FIGURE 41 Estimation of the spot diameter for a diffraction-limited lens system. The diameter is that of the first dark ring of the Airy disk. (*Smith,* Modern Optical Engineering, *McGraw-Hill, New York, 1990, p. 458.*)

observation point, and C_0 is a scaling factor. The angular radius β_{DL} of the first dark ring of the image is $1.22(\lambda/D_{ep})$. A common measure for the resolution is Lord Rayleigh's criterion that asserts that two point sources are just resolvable when the maximum of one Airy pattern coincides with the first dark ring of the second Airy pattern, i.e., an angular separation of β_{DL}. Figure 41 presents a nomogram that can be used to make a rapid estimate of the diameter of angular or linear blur for a diffraction-limited system.

The modulation transfer function (MTF) *at a specific wavelength* λ for a circular entrance pupil can be computed by

$$\mathrm{MTF}_\lambda(\Omega) = \frac{2}{\pi}\left[\arccos \Omega - \Omega\sqrt{1-\Omega^2}\right] \quad \text{for} \quad 0 \le \Omega \le 1 \tag{56}$$

where Ω is the normalized spatial frequency (ν/ν_{co}) with the maximum or cut-off frequency ν_{co} being given by $1/\lambda_o$ FN.

Should the source be polychromatic and the lens system be aberration-free, then the perfect-image irradiance distribution of a point source can be written as

$$E(r) = C_1 \int_0^\infty \tilde{\mathfrak{R}}(\lambda) \left[\frac{2J_1(kD_{ep}r/2)}{kD_{ep}r}\right]^2 d\lambda \tag{57}$$

where $\tilde{\mathfrak{R}}(\lambda)$ is the peak normalized spectral weighting factor and C_1 is a scaling factor.

A quick estimation of this ideal irradiance distribution can be made by invoking the central limit theorem to approximate this distribution by a Gaussian function, i.e.,

$$E(r) \approx C_2 e^{-(r^2/2\sigma^2)} \tag{58}$$

where C_2 is a scaling constant and σ^2 is the estimated variance of the irradiance distribution. When $\tilde{\mathfrak{R}}(\lambda) = 1$ in the spectral interval λ_S to λ_L and zero otherwise with $\lambda_s < \lambda_L$, an estimate of σ can be written as

$$\sigma = \frac{\mathcal{M}\lambda_L}{\pi D_{ep}} \tag{59}$$

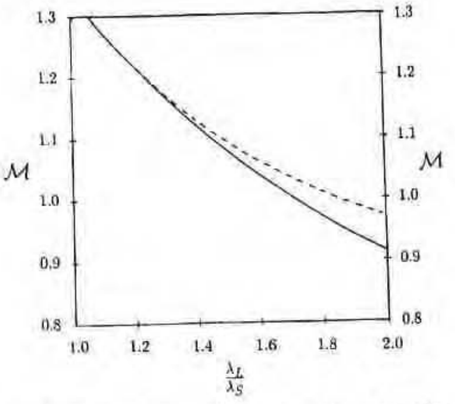

FIGURE 42 Variation of $\mathcal{M}$ with λ_L/λ_S or $b+1$ for $\tilde{\mathfrak{R}}(\lambda) = 1$ as the solid curve and $\tilde{\mathfrak{R}}(\lambda) = \lambda/\lambda_S$ as the dashed curve.

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where $\mathcal{M} = 1.335 - 0.625b + 0.25b^2 - 0.0465b^3$ with $b = (\lambda_L/\lambda_S) - 1$. Should $\tilde{\mathfrak{R}}(\lambda) = \lambda/\lambda_L$ in the spectral interval λ_S to λ_L and zero otherwise, which approximates the behavior of a quantum detector, $\mathcal{M} = 1.335 - 0.65b + 0.385b^2 - 0.099b^3$. The Gaussian estimate residual error is less than a few percent for $b = 0.5$ and remains useful even as $b \to 0$. Figure 42 contains plots of $\mathcal{M}$ for both cases of $\tilde{\mathfrak{R}}(\lambda)$, where the abscissa is λ_L/λ_S.

A useful estimation of the modulation transfer function for this *polychromatic* lens system is given by

$$\mathrm{MTF}(v) \approx e^{-2(\pi\sigma v)^2} \tag{60}$$

where v is the spatial frequency. This approximation overestimates the MTF somewhat at lower spatial frequencies, while being rather a close fit at medium and higher spatial frequencies. The reason for this is that the central portion of the irradiance distribution is closely matched by the Gaussian approximation, while the irradiance estimation beyond several Airy radii begins to degrade, therefore impacting the lower spatial frequencies. Nevertheless, this approximation can provide useful insight into expected performance limits.

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CHAPTER 34
POLYMERIC OPTICS

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34.1 GLOSSARY

A_{H_2O}	water absorption
K	thermal conductivity
T_s	maximum service temperature
α	thermal expansion coefficient
ρ	density

34.2 INTRODUCTION

A small number of carbon-based polymeric materials possesses some of those qualities which have made glass an attractive optical material. Most of these polymeric materials do exhibit certain physical deficiencies compared to glass. But, despite the fact that "plastic optics" has acquired an image as a low-end technology, it may nonetheless be a better choice, or even the best choice, in certain applications.

Selection Factors

Virtually all of the polymers having useful optical properties are much less dense than any of the optical glasses, making them worthy of consideration in applications where weight-saving is of paramount importance. Many of them exhibit impact resistance properties which exceed those of any silicate glass, rendering them well-suited to military applications (wherein high "g" loads may be encountered), or ideal for some consumer products in which safety may be a critical consideration.

Though the physical properties of the polymers may make them better matched to certain design requirements than glass, by far the most important advantage of polymeric optics is the considerable creative freedom they make available to the optical and mechanical design effort.[1] While the design constraints and guidelines governing glass optics design and fabrication are fairly well defined, the various replication processes which may be put to use in polymer optics fabrication make available unique opportunities for the creation of novel optical components and systems which would be unthinkable or unworkable in glass. Oftentimes, the differences in the engineering approach, or in the production processes themselves, may make possible very significant cost reductions in high-volume situations.[2]

34.3 FORMS

Thermoset Resins

Optical polymers fall into basically two categories—the *thermoset* resins and the *thermoplastic* resins. The thermoset resin group consists of chemistries in which the polymerization reaction takes place during the creation of the part, which may be produced by casting, or by transfer replication. The part which has been created at completion of the reaction may then be postprocessed, if desired, by machining. In general, the thermoset resins cannot be melted and reformed.

The most commonly encountered thermoset optical resin is that used to produce ophthalmic lenses for eyewear.[3] The monomer, which is stored in liquid form at reduced temperature, is introduced into a mold, where the polymerization reaction takes place, forming a part which assumes the shape of the cavity containing it. Alternatively, epoxy-based chemistries have been used with some success to form replicated reflecting surface shapes by a transfer process, and to produce aspheric figuring (at relatively modest expense) upon spherical refractive or reflective substrates.

Thermoplastic Resins

With the possible exception of eyewear, most polymeric optics are executed in thermoplastic materials which are supplied in already-polymerized form.[4] These materials are normally purchased in bulk as small pellets. These pellets are heated to a temperature beyond the softening point, so that they flow to become a single viscous mass. This mass is then formed to assume the shape desired in the final part.

Parts may be created by the injection molding process, in which the heated polymer is squirted into a mold at high pressure and allowed to cool in the shape of the desired component. Or the pellets may be directly heated between the two halves of a compression mold, and the mold closed to effect formation of the part. Hybrid molding technologies combining these two processes are recently experiencing increasing popularity in optical molding applications, and have produced optical surface figures of very high quality.

The capability of modern molding technology to produce optics having very good surface-figure quality has made possible the creation of polymeric optical components for a wide variety of applications. Among these are medical disposables, intraocular lenses, a host of consumer products, military optics, and a number of articles in which optical, mechanical, and electrical functions are combined in a single part.[5]

34.4 PHYSICAL PROPERTIES

Density

Optical glass types number in the hundreds (if all manufacturers worldwide are counted). The glass types available from the catalogs cover a wide range of optical, physical, thermal, and chemical properties. The density of these materials varies from about 2.3 g/cm^3 to about 6.3 g/cm^3. The heaviest optically viable polymer possesses a density of only about 1.4 g/cm^3, whereas the lightest of these materials will readily float in water, having a density of 0.83 g/cm^3.[6] All other things being equal, the total element count in an optical system may often be reduced (at modest cost penalty) by the inclusion of nonspherical surfaces. All things considered, then, polymeric optical systems may be made much less massive than their glass counterparts, especially if aspheric technology is applied to the polymer optical trains.

Hardness

Although cosmetic blemishes rarely impact final image quality (except in the cases of field lenses or reticles), optical surfaces are customarily expected to be relatively free of scratches, pits, and the like. Ordinary usage, especially cleaning procedures, are likely to result in some scratching with the passage of time. Most common optical glasses possess sufficient hardness that they are relatively immune to damage, if some modest amount of care is exercised.

The polymeric optical materials, on the other hand, are often so soft that a determined thumbnail will permanently indent them. The hardness of polymeric optics is difficult to quantify (in comparison to glass), since this parameter is not only material-dependent, but also dependent upon the processing. Suffice it to say that handling procedures which would result in little or no damage to a glass element may produce considerable evidence of abrasion in a polymeric surface, particularly in a thermoplastic. In fact, the compressibility of most thermoplastic polymers is such that the support for hard surface coatings is sufficiently low that protection provides immunity against only superficial abrasion. These deficiencies are of no particular consequence, however, if the questionable surfaces are internal, and thereby inaccessible.

Rigidity

A property closely related to hardness is the elastic modulus, or Young's modulus. This quantity, and the elongation factor at yield, are determinants of the impact resistance, a performance parameter in which the polymers outshine the glasses. These properties are, again, dependent upon the specified polymeric alloy, any additives which may be present, and processing history of the polymer, and cannot be dependably quoted.[7,8] The reader is referred to any of several comprehensive references listed herein for mechanical properties data. Those properties which create good impact resistance become liabilities if an optical part is subjected to some torsion or compressive stress. Since optical surface profiles must often be maintained to subwavelength accuracy, improper choice of the thickness/diameter ratio, or excessive compression by retaining rings, may produce unacceptable optical figure deformations.

Polymer chemistry is a complex subject probably best avoided in a discussion of polymer optics. Carbon-based polymers have been synthesized to include an extensive variety of chemical subgroups, however. Unfortunately, relatively few of these materials are actually in regular production, and only a handful of those possess useful optical properties for imaging purposes.

Service Temperature

Any decision involving a glass/plastic tradeoff should include some consideration of the anticipated thermal environment. While the optical glasses may exhibit upper service temperature limits of from 400 to 700°C, many of the glass types having the most interesting optical properties are quite fragile, and prone to failure if cooled too quickly. These failures are mostly attributable to cooling-induced shrinkage of the skin layer, which shatters because the insulating properties of the material prevent cooling (and shrinkage) of the bulk material at the same rate.

The polymeric materials, on the other hand, have much lower service temperature limits, in some cases no higher than about 60°C.[9] The limit may approach 250°C for some of the fluoropolymers. The thermal conductivity of many of these polymers may be as much as an order of magnitude lower than for the glasses and the thermal expansion coefficients

TABLE 1 Physical Properties

Material	ρ	α	T_s	K	A_{H_2O}
P-methylmethacrylate	1.18	6.0	85	4–6	0.3
P-styrene	1.05	6.4–6.7	80	2.4–3.3	0.03
NAS	1.13	5.6	85	4.5	0.15
Styrene acrylonitrile (SAN)	1.07	6.4	75	2.8	0.28
P-carbonate	1.25	6.7	120	4.7	0.2–0.3
P-methyl pentene	0.835	11.7	115	4.0	0.01
P-amide (Nylon)	1.185	8.2	80	5.1–5.8	1.5–3.0
P-arylate	1.21	6.3		7.1	0.26
P-sulfone	1.24	2.5	160	2.8	0.1–0.6
P-styrene co-butadiene	1.01	7.8–12			0.08
P-cyclohexyl methacrylate	1.11				
P-allyl diglycol carbonate	1.32		100	4.9	
Cellulose acetate butyrate	1.20			4.0–8.0	
P-ethersulfone	1.37	5.5	200	3.2–4.4	
P-chloro-trifluoroethelyne	2.2	4.7	200	6.2	0.003
P-vinylidene fluoride	1.78	7.4–13	150		0.05
P-etherimide	1.27	5.6	170		0.25

characterizing the polymers are often an order of magnitude larger than those associated with optical glasses. Consequently, subjecting any polymeric optical element to a significant thermal transient is likely to create more severe thermal gradients in the material, and result in significant thermally-induced optical figure errors.[10] Again, it is suggested that the interested reader consult the plastic handbooks and manufacturer's literature for a complete listing of this behavior, as additives and variation in molecular weight distribution may significantly affect all of these properties. Some of the most important physical properties of the more readily available optical polymers are tabulated in Table 1.

Conductivity (Thermal, Electrical)

Most materials which exhibit poor thermal conductivity are also poor electrical conductors. Since many unfilled polymers are very effective electrical insulators, they acquire static surface charge fairly easily, and dissipate it very slowly. Not surprisingly, these areas of surface charge quickly attract oppositely charged contaminants, most of which are harder than the plastic. Attempts to clear the accumulated particles from the surfaces by cleaning can, and usually do, result in superficial damage. Application of inorganic coatings to these surfaces may do double duty by providing a more conductive surface (less likely to attract contaminants), while improving the abrasion resistance.

Outgassing

In contrast to glass optical parts, which normally have very low vapor pressure when properly cleaned, most polymers contain lubricants, colorants, stabilizers, and so on, which may outgas throughout the life of the part. This behavior disqualifies most plastic optical elements from serving in space-borne instrumentation, since the gaseous products, once lost, surround the spacecraft, depositing upon solar panels and other critical surfaces. Some, but few, thermoset resins may be clean enough for space applications if their reaction stoichiometry is very carefully controlled in the creation of the part.

Water Absorption

Most polymers, particularly the thermoplastics, are hygroscopic. They absorb and retain water, which must, in most cases, be driven off by heating prior to processing. Following processing, the water will be reabsorbed if the surfaces are not treated to inhibit absorption. Whereas only a very small amount of water will normally attach to the surfaces of a glass optical element, the polymer materials used for optics may absorb from about 0.003 to about 2 percent water by weight. Needless to say, the trapped water may produce dimensional changes, as well as some minor alterations of the spectral transmission. Physical properties of some of the more familiar optical polymers are listed in Table 1. Density = ρ (g/cm^3); thermal expansion coefficient = α (cm/cm °C $\times 10^{-5}$); max. service temperature = T_s (°C); thermal conductivity = K (cal/sec cm °C $\times 10^4$); and water absorption (24 hr) = A_{H_2O} (%). Values are to be considered approximate, and may vary with supplier and processing variations.

Additives

Polymers are normally available in a variety of "melt flow" grades—each of which possesses viscosity properties best suited to use in parts having specific form factors. A number of additives are commonly present in these materials. Such additives may, or may not, be appropriate in an optical application. Additives for such things as flame retardancy, lubricants, lubrication, and mold release are best avoided if not included to address a specific requirement. Frequently, colorants are added for the purpose of neutralizing the naturally occurring coloration of the material. These additives create an artificial, but "clear," appearance. The colorants must, of course, absorb energy to accomplish this, resulting in a net reduction in total spectral transmission.

Radiation Resistance

Most of the optical polymers will be seen to exhibit some amount of fluorescence if irradiated by sufficiently intense high-energy radiation.[11] High-energy radiation of the ultraviolet and ionizing varieties will, in addition, produce varying amounts of polymer chain crosslinking, depending upon the specific polymer chemistry. Crosslinking typically results in discoloration of the material, and some amount of nonuniform energy absorption. Inhibitors may be added to the polymeric material to retard crosslinking, although, oddly enough, the polymers most susceptible to UV-induced discoloration are generally the least likely to be affected by ionizing radiation, and vice versa.

Documentation

Although polymeric materials suffer some shortcomings in comparison to glass (for optical applications), distinct advantages do exist. The major obstacle to the use of polymers, however, is the spotty and imprecise documentation of many of those properties required for good engineering and design. In general, the resin producers supply these materials in large quantity to markets wherein a knowledge of the optical properties is of little or no importance. With luck, the documentation of optical properties may consist of a statement that the material is "clear". In the rare case where refractive index is documented, the accuracy may be only two decimal places. In these circumstances, the optical designer or molder is left to investigate these properties independently—a complex task, since the processing itself may affect those properties to a substantial degree.

Unfortunately, optical applications may represent only a small fraction of a percent of the total market for a given resin formulation, and since these materials are sold at prices ranging from less than two dollars to a few dollars per pound, the market opportunity represented by optical applications seems minuscule to most polymer vendors.

34.5 OPTICAL PROPERTIES

Variations

It is only a fortuitous accident that some of the polymers exhibit useful optical behavior, since most all of these materials were originally developed for other end uses. The possible exceptions are the materials used for eyeglass applications (poly-diallylglycol), and the materials for optical information storage (specially formulated polycarbonate). Citation of optical properties for any polymeric material must be done with some caution and qualification, as different melt flow grades (having different molecular weight distribution) may exhibit slightly different refractive index properties. Additives to regulate lubricity, color, and so on can also produce subtle alterations in the spectral transmission properties.

Spectral Transmission

In general, the carbon-based optical polymers are visible-wavelength materials, absorbing fairly strongly in the ultraviolet and throughout the infrared.[12,13,14] This is not readily apparent from the absorption spectra published in numerous references, though. Such data are normally generated by spectroscopists for the purpose of identifying chemical structure, and are representative of very thin samples. One can easily develop the impression from this information that the polymers transmit well over a wide spectral range. Parenthetically, most of these polymers, while they have been characterized in the laboratory, are not commercially available. What is needed for optical design purposes is transmission data (for available polymers) taken from samples having sufficient thickness to be useful for imaging purposes.

Some specially formulated variants of poly-methylmethacrylate have useful transmission down to 300 nm.[15] Most optical polymers, however, begin to absorb in the blue portion of the visible spectrum, and have additional absorption regions at about 900 nm, 1150 nm, 1350 nm, finally becoming totally opaque at about 2100 nm. The chemical structure which results in these absorption regions is common to almost all carbon-based polymers, thus the internal transmittance characteristics of these materials are remarkably similar, with the possible exception of the blue and near-UV regions. A scant few polymers do exhibit some spotty narrowband transmission leakage in the far-infrared portion of the spectrum, but in thicknesses suitable only for use in filter applications.

Refractive Index

The chemistry of carbon-based polymers is markedly different from that of silicate glasses and inorganic crystals in common use as optical materials. Consequently, the refractive properties differ significantly. In general, the refractive indices are lower, extending to about 1.73 on the high end, and down to a lower limit of about 1.3. In practice, those materials which are readily available for purchase exhibit a more limited index range—from about 1.42 to 1.65. The Abbe values for these materials vary considerably, though, from about 100 to something less than 20. Refractive index data for a few of these polymers, compiled from a number of sources, is displayed in Table 2. In the chart,

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TABLE 2 Refractive Index of Some Optical Polymers

Line ID	Wavl., nm	PMMA	P-styr	P-carb	SAN	PEI	PCHMA
	1014.0	1.4831	1.5726	1.5672	1.5519		
s	852.1	1.4850	1.5762	1.5710	1.5551		
r	706.5	1.4878	1.5820	1.5768	1.5601		
C	656.3	1.4892	1.5849	1.5799	1.5627		1.502
C′	643.9	1.4896	1.5858	1.5807	1.5634	1.651	
D	589.3	1.4917	1.5903	1.5853	1.5673		
d	587.6	1.4918	1.5905	1.5855	1.5674	1.660	1.505
e	546.1	1.4938	1.5950	1.5901	1.5713	1.668	
F	486.1	1.4978	1.6041	1.5994	1.5790		1.511
F′	480.0	1.4983	1.6052	1.6007	1.5800	1.687	
g	435.8	1.5026	1.6154	1.6115	1.5886		
h	404.7	1.5066	1.6253	1.6224	1.5971		
i	365.0	1.5136	1.6431	1.6432	1.6125		
Abbe number		57.4	30.9	29.9	34.8	18.3	56.1
$dn/dT \times 10^{-4}/°C$		−1.05	−1.4	−1.07	−1.1		

PMMA signifies polymethylmethacrylate; P = styr, polystyrene; p = care, polycarbonate; san, styrene acrylonitrile; PEI, polyetherimide; PCHMA, polycyclohexylmethacrylate. The thermo-optic coefficients at room temperature (change in refractive index with temperature) are also listed. Note that these materials, unlike most glasses, experience a reduction in refractive index with increasing temperature. Figure 1, a simplified rendition

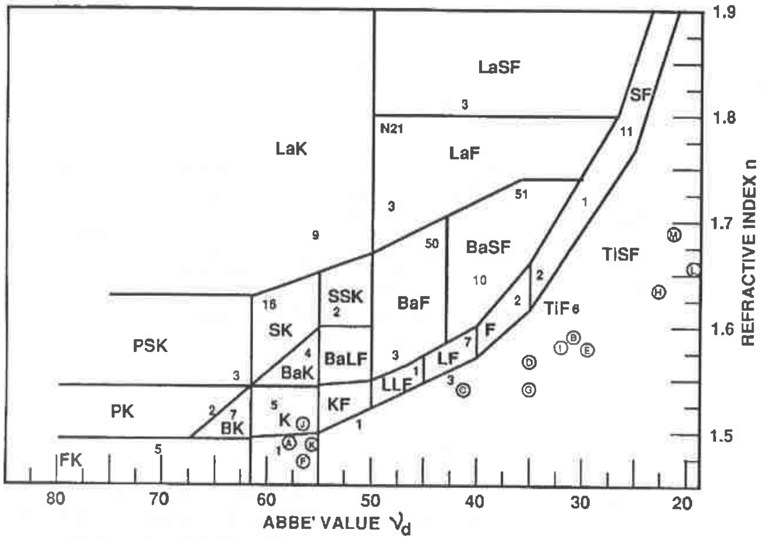

FIGURE 1 Optical glasses and polymers: (*a*) polymethylmethacrylate; (*b*) polystyrene; (*c*) NAS; (*d*) styrene acrylonitrile; (*e*) polycarbonate; (*f*) polymethyl pentene; (*g*) acrylonitrile-butadiene styrene (ABS); (*h*) polysulfone; (*i*) polystyrene co-maleic anhydride; (*j*) polycyclohexylmethacrylate (PCHMA); (*k*) polyallyl diglycol carbonte; (*l*) polyetherimide (PEI); (*m*) polyvinyl naphthalene.

of the familiar glass map (n vs. v), shows the locations of some of the more familiar polymers. Note that these materials all occupy the lower and right-hand regions of the map. In the Schott classification system, the polymers populate mostly the FK, TiK, and TiF regions of the map.[16]

Homogeneity

It must be kept constantly in mind that polymeric optics are molded and not mechanically shaped. The exact optical properties of a piece cannot, therefore, be quantified prior to manufacture of the element. In fact, the precise optical properties of the bulk material in an optical element are virtually certain to be a function of both the material itself, and of the process which produced the part. Some materials, notably styrene and butyrate resins, are crystalline to some degree, and therefore inherently birefringent. Birefringence may develop in amorphous materials, though, if the injection mold and process parameters are not optimized to prevent this occurrence. Likewise, the bulk scatter properties of a molded optical element are a function of the inherent properties of the material, but are also strongly related to the cleanliness of the processing and the heat history of the finished part.

34.6 OPTICAL DESIGN

Design Strategy

Virtually all optical design techniques which have evolved for use with glass materials work well with polymer optics. Ray-tracing formulary, optimization approaches, and fundamental optical construction principals are equally suitable for glass or plastic. The generalized approach to optical design with polymeric materials should be strongly medium-oriented, though. That is, every effort must be made to capitalize upon the design flexibility which the materials and manufacturing processes afford. Integration of form and function should be relentlessly pursued, since mechanical features may be molded integral with the optics to reduce the metal part count and assembly labor content in many systems.

Aberration Control

The basic optical design task normally entails the simultaneous satisfaction of several first-order constraints, the correction of the monochromatic aberrations, and the control of the chromatic variation of both first-order quantities and higher-order aberrations. It is well known that management of the Petzval sum, while maintaining control of the chromatic defects, may be the most difficult aspect of this effort.[17,18] It is also widely recognized that the choice of optical materials is key to success. While the available polymer choices cover a wide range of Abbe values, insuring that achromatization may be accomplished in an all-polymer system, the refractive index values for these materials are not well-positioned on the "glass" map to permit low Petzval sums to be easily achieved.

Material Selection

Simultaneous correction of the Petzval sum and the first-order chromatic aberration may, however, be nicely accomplished if the materials employed possess similar ratios of Abbe number to central refractive index. This implies that the *best* material combinations (involving polymers) should probably include an optical glass. Also implied is the fact that these hybrid material combinations may be inherently superior (in this respect) to all-glass combinations. Ideally, the chosen materials should be well-separated (in Abbe value) on the glass map, so that the component powers required for achromatization do not become unduly high. This condition is satisfied most completely with polymers which lie in the TiF sector of the glass map, coupled with glasses of the LaK, LaF, and LaSF families.

Most lens designers would prefer to utilize high-refractive-index materials almost exclusively in their work. Optical power must be generated in order to form images, and because the combination of optical surface curvature and refractive index creates this refractive power, these two variables may be traded in the lens design process. Since it is well known that curvature generates aberration more readily than does a refractive index discontinuity, one generally prefers to achieve a specified amount of refractive power through the use of low curvature and high refractive index. From this perspective, the polymers are at a distinct disadvantage, most of them being low-index materials.

Aspheric Surfaces

An offsetting consideration in the use of polymeric optical materials is the freedom to employ nonspherical surfaces. While these may be awkward (and very expensive) to produce in glass, the replication processes which create plastic optical parts do not differentiate between spherical and nonspherical surfaces.

As any lens designer can attest, the flexibility that aspheric surfaces make available is quite remarkable.[19,20] Spherical surfaces, while convenient to manufacture by grinding and polishing, may generate substantial amounts of high-order aberration if used in any optical geometry which departs significantly from the aplanatic condition. These high-order aberrations are often somewhat insensitive to substantial changes in the optical prescription. Thus, profound configurational alterations may be necessary to effect a reduction in these image defects.

On the other hand, the ability to utilize surface shapes which are more complex than simple spheres permits these high-order aberration components to be moderated at their point of origin, which may in turn reduce the amount of "transferred aberration" imparted to surfaces downstream in the optical train. In a multielement optical system, especially one employing cascaded aspheric surfaces, the required imagery performance may be achieved using fewer total elements. And due to the fact that the surface aberration contributions are diminished, the sensitivity to positioning errors may also be reduced, with the result that an aspheric optical system may actually be more forgiving to manufacture than its spherical counterpart.

In practice, the use of aspheric surfaces in polymer optical elements appears to more than compensate for the handicap imposed by low refractive index values. Using aspheric surfaces, it is possible to bend, if not break, many of the rules which limit design with spherical surfaces. Aspherics create extra leverage to deal with the monochromatic aberrations, and with the chromatic variation of these image defects. A designer experienced with aspherics, given a capable set of software tools, can frequently create optical constructions which deliver high performance, despite the fact that they appear odd to those accustomed to the more "classical" spherical surface configurations. Quite often, unfavorable design constraints such as an inconvenient aperture stop location, may be handled with less difficulty using aspherics.

Athermalization

The thermal behavior of the polymers, mentioned previously, may cast a shadow upon some applications where the temperature is expected to vary over a significant range, but the focal surface location must be fixed in space. In such cases, the variation of refractive index usually accounts for the largest share of the variation, with the dimensional changes playing a secondary role. In such situations, the thermally induced excursions of the focal surface may be compensated by modeling these functions and designing mechanical spacers of the proper material to stabilize the detector/image location.

Alternatively, the optical system may be designed to exhibit inherently athermal behavior over the operational temperature range.[21] Unfortunately, this is not strictly possible using only polymeric materials, as the thermo-optic coefficients display so little variation among themselves that the component powers would be absurdly high.

In combination with one or more glass elements, however, very nicely athermalized design solutions may be obtained with polymer elements.[22] Athermal designs may be generated by modeling the optical system in multiconfiguration mode in the lens design software, much as one would develop a zoom lens. The parameters to be "zoomed" in this case are the refractive indices at two or more temperatures within the operating range. The resulting designs frequently concentrate most of the refractive power in the glass elements, with the polymer elements functioning to achieve achromatism and control of the monochromatic aberrations. See also Vol. I, Chap. 39 of this Handbook.

Processing Considerations

In much the same manner that optical design with polymer materials is different from optical design with glass, the treatment of the fabrication and assembly issues are also quite different matters. The major issues requiring examination are those related to the materials themselves. While it is possible to characterize the glass for an optical system with complete certainty prior to performing any fabrication operations, with polymers, one's knowledge of the starting materials is only a rough indication of the properties of the finished optical parts.

When optical properties data are offered by the polymer supplier, it should be realized that these numbers apply *only* to measurement samples which have been predried to specification, have experienced a specified residence time in the extrusion barrel under specific temperature conditions, have been injected into the mold cavity at specific rates and pressures, and so on. Consequently, it is unlikely that the refractive properties of a polymer element will conform closely to catalog values (if such values are indeed supplied). Moreover, homogeneity, bubble content, scatter properties, and so on, are all process-dependent. So while the melt sheets may fix the optical properties of glass materials very precisely, the uncertainty associated with the polymers demands that

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refractive variations be allocated a significant portion of the fabrication and assembly error budget.

Manufacturing Error Budget

Other constructional parameters, conversely, may be implemented with great precision and repeatability in plastic. The molding process, executed by means of modern equipment, can be exceedingly stable. Vertex thickness, curvature, and wedge may often be maintained to a greater level of precision, with greater economy than is possible with glass fabrication technology. It is not unusual to see part-to-part variations in vertex thickness of less than 0.01 to 0.02 mm over a run of thousands of parts from a single cavity.

Multiple Cavities

The economic appeal of injection molding is the ability to create several parts in one molding cycle. In a multicavity scenario, the parts from different cavities may exhibit some small dimensional differences, depending upon the level of sophistication of the tool design and the quality of its construction. Cavity variations in axial thickness, fortunately, may be permanently minimized by implementing small tooling adjustments after the mold has been exercised. Consequently, part thickness variation rarely consumes a significant fraction of the constructional error budget.

Dimensional Variations

Surface radii, like axial thickness, may be replicated with great repeatability *if* the molding process is adjusted to a stable optimum. Radius errors, if they are present, are usually attributable to incorrect predictions of shrinkage, and may be biased out by correcting the radii of the mold inserts. Thus, the consistency of surface radii achievable with glass may often be equaled in plastic. Thus, radius errors, as well as axial thickness errors, frequently constitute a small portion of the polymer optics manufacturing error budget.

Element wedge, like axial thickness, may be minimized by careful attention to precision in the tool design and construction. It is quite possible to achieve edge-to-edge thickness variations of less than 0.01 mm in molded plastic lenses. With polymer lenses, the azimuthal location of the part gate may be used, if necessary, to define rotational orientation of the element in the optical train. Consequently, rotational alignment of plastic optical parts may be easily indexed.

Optical Figure Variations

Control of optical figure quality is obviously key to the successful execution of a good optical design. In glass, achievement of subfringe figure conformance is accomplished routinely, albeit at some cost penalty. In polymeric optics, the nonlinear shrinkage, surface tension, and other processing-related effects cause surface figure errors to scale with part size, sometimes at a rate proportional to some exponent of diameter. This limits the practical size range for polymeric optics, although capable optics molders may routinely produce elements in the 10-mm-diameter range to subfringe accuracy.[23]

On one hand, it can probably be stated that processing-induced variations in properties, and a dearth of dependable optical data, preclude any serious discussions of such things as apochromatic polymeric optics, or of large polymeric optics operating at the diffraction limit. On the other hand, the consistency with which some dimensional parameters may be reproduced in quantity, and the design freedom and flexibility afforded by molded asph erics, make possible the satisfaction of some design requirements which would be out of range for conventional glass optics.[24,25]

Specification

Given the fact that the guidelines and restrictions for design and implementation are very different for glass and polymeric optics, it is not surprising that the approach to specification of polymer optical parts and systems should be tailored to the materials and processes of polymer optics. Attempts to convert a glass optics concept to plastic are frequently unsuccessful if the translation overlooks the fundamental themes of the molding and tooling technologies involved. Much as optimum tube and solid-state electrical circuit topologies should be significantly different, so must the execution of a conceptual optical system, depending upon whether glass or polymer material is the medium.

It follows naturally that manufacturing drawings for polymer optics may contain annotations which seem unfamiliar to those versed in glass optics manufacture. Furthermore, some specifications which are universally present on all glass optics drawings may be conspicuously absent from a polymer optics print.

For example, thermal and cosmetic damage considerations preclude the use of the familiar test glasses in the certification of polymeric optics. Figure conformance, then, need only be specified in "irregularity" or asphericity terms, since the alternative method, use of a noncontacting interferometer, implies that the focus error (*fringe power* in test plate language) will be automatically removed in the adjustment of the test setup.

References to ground surfaces may be omitted from polymer optics drawings, since no such operation takes place. Discussions of "chips" inside the clear aperture, staining, and the like are also superfluous. Beauty defect specifications do apply, although such imperfections are almost always present in every sample from a specific cavity, probably implying the need to rework a master surface.

In general, the lexicon of optics, and that of the molding industry, do not overlap to a great extent. Molding terms like *flash* and *splay* are meaningless to most optical engineers. Those endeavoring to create a sophisticated polymeric optical system, anticipating a successful outcome, are advised to devote some time to the study of molding, and to discussions with the few experts in the arcane field of optics molding, before releasing a drawing package which may be unintelligible to or misunderstood by the vendor.

34.7 PROCESSING

Casting

As mentioned above, polymeric optics may be produced by any of several processes. These include fabrication, transfer replication, casting, compression molding, injection molding, and some combinations of the aforementioned.[26] The earliest polymeric optical parts were probably produced by fabrication or precipitation from solution. Large military tank prisms have been made by both processes. In the latter case, the polymer (typically PMMA) was dissolved, and the solvent then evaporated to produce a residue of polymer material in the shape of the mold—a very inefficient technique indeed.

Many of the polymers may be fabricated by cutting, grinding, and polishing, much as one would deal with glass materials. The thermoset resin tradenamed CR-39 (polydiallylglycol) was formulated specifically to be processed using the same techniques and materials as those used to fabricate glass optics. And this material does indeed produce good results when processed in this manner. It is used extensively in the ophthalmic industry to produce spectacle lenses. The processing, in fact, usually involves casting the thermoset resin to create a lens blank which emerges from the mold with the optical surfaces polished to final form. More conventional fabrication techniques may then be utilized to edge the lens, or perhaps to add a bifocal portion.

Abrasive Forming

Unfortunately, the softness of most of the polymers, coupled with their poor thermal conductivity, complicates the achievement of a truly high quality polish using conventional methods. Even in the case of CR-39, which is relatively hard for a polymer material, some amount of "orange peel" in the polished surface seems unavoidable. Many thermoplastics, most of them softer than CR-39, may be conventionally ground and polished to give the appearance of an acceptable optical surface. Closer examination, however, reveals surface microstructure which probably does not fall within the standards normally associated with precision optics. Nonetheless, fabrication of optical elements from large slabs of plastic is often the only viable approach to the creation of large, lightweight refractive lenses, especially if cost is an issue.

In general, the harder, more brittle polymers produce better optical surfaces when ground and polished. PMMA and others seem to fare better than, say, polycarbonate, which is quite soft, exhibits considerable elongation at the mechanical yield point, but is in great demand due to its impact resistance.

Single-point Turning

An alternative approach to fabrication, one that is especially useful for the production of aspheric surfaces, is the computer numerical control (CNC) lathe turning of the bulk material using a carefully shaped and polished tool bit of single-crystal diamond or cubic boron nitride. See also Vol. I, Chap. 41, this Handbook. The lathe required to produce a good result is an exceedingly high precision tool, having vibration isolation, temperature control, hydrostatic or air bearings, and so on. On the best substrate materials (PMMA is again a good candidate), very good microroughness qualities may be achieved. With other materials, a somewhat gummy character (once more, polycarbonate comes to mind) may result in microscopic tearing of the surface, and the expected scatter of the incident radiation.

The diamond-turning process is often applied in conjunction with other techniques in order to speed progress and reduce cost. Parts which would be too large or too thick for economical stand-alone injection molding are frequently produced more efficiently by diamond-turning injection molded, stress-relieved preforms, which require minimal material removal and lathe time for finishing. Postpolishing, asymmetric edging, and other postoperations may be performed as necessary to create the finished part. Optics for illumination and TV projection applications are often produced by some combination of these techniques. Given the fact that the technology in most widespread use for the production of plastic optics involves some form of molding (a front-loaded process, where cost is concerned), diamond-turning is often the preferred production method for short production runs and prototype quantities.

Compression Molding

Most high-volume polymeric optics programs employ a manufacturing technology involving some form of molding to produce the optical surfaces, if not the entire finished part.[27] Of the two most widely used approaches, compression molding is best suited to the creation of large parts having a thin cross section. In general, any optical surface possessing relief structure having high spatial frequency is not amenable to injection molding, due to the difficulty of forcing the material through the cavity, and due to the fact that the relief structure in the mold disrupts the flow of the polymer. In addition, the relief structure in the master surfaces may be quite delicate, and prone to damage at the high pressures often present in the mold cavity.

The compression molding process is capable of producing results at considerably lower surface pressure than injection molding, and as long as the amount of material to be formed is small, this molding technology can replicate fine structure and sharp edge contours with amazing fidelity. Since the platens of a compression molding press are normally heated using steam or electrical heaters, most compression molded parts are designed to be executed in polymers having a relatively low temperature softening point, and materials like polyethersulfone are rarely utilized.

Injection Molding

Optical parts having somewhat smaller dimensions may be better suited to production by the injection molding process.[28] This is probably the preferred polymer manufacturing technology for optical elements having a diameter smaller than 0.1 m and a thickness not greater than 3 cm. Not only do the economics favor this approach in high production volume, but if properly applied, superior optical surfaces may be produced.[29]

It should be kept firmly in mind that the basic injection molded process (as it is known to most practitioners) requires a great deal of refinement and enhancement in order to produce credible optical parts.[30] Unfortunately, very few molders possess either the molding know-how, or the testing and measurement sophistication to do the job correctly. Given a supply of quality polymer material, the molding machine itself must be properly configured and qualified. Relatively new machinery is a must. The platens to which the mold halves are mounted must be very rigid and properly aligned. And this alignment must be maintainable on a shot-to-shot basis for long periods. The screw and barrel must be kept scrupulously clean, and must be carefully cleaned and purged when switching materials. The shot capacity, in ideal circumstances, should be more carefully matched to the part volume than for non-optical parts. The process control computer must be an inordinately flexible and accurate device, able to profile and servo a number of operational functions that might be of little importance if the molded part were not optical in nature.[31]

Since much of the heating of the injected polymer resin occurs as a result of physical shear and compression (due to a variable pitch screw), the selection of these machine characteristics is critical to success. In addition, the energy supplied to the machine barrel by external electric heaters must be controlled with more care than in standard industrial applications. A failure of a single heater, or a failure of one of the thermal measurement devices which close that servo loop, may result in many defective parts.

Vendor Selection

The injection mold itself requires special attention in both design and execution in order to produce state-of-the-art molded lenses. A number of closely held "trade tricks" normally characterize a mold designed to produce optical parts, and these subtle variations must be implemented with considerably greater accuracy than is normally necessary in ordinary molding. The mold and molding machine are often designed to operate more symbiotically than would be the case in producing non-optical parts. Control of the mold temperature and temperature gradients is extremely critical, as is the control bandwidth of those temperatures and the temperature of the molding room itself. The most important conclusion to be drawn from the preceding paragraphs is that *the molding vendor for polymer optical parts must be selected with great care.* A molding shop, no matter how sophisticated and experienced with medical parts, precision parts for electronics, and so on, will probably consume much time and many dollars before conceding defeat with optical parts.

Although success in molding optical elements is a strong function of equipment, process control, and engineering acumen, *attention to detail in the optical and mechanical design phases will consistently reduce the overall difficulty of manufacturing these items.* An awareness of the basic principles of injection molding procedures and materials is very helpful here, but it is necessary to be aware that, in the optical domain, we are dealing with micrometer-scale deformations in the optical surfaces. Thus, errors or oversights in design and/or molding technique which would totally escape notice in conventional parts can easily create scrap optics.

Geometry Considerations

The lens design effort, for best results, must be guided by an awareness of the basic physics of creating an injection molded part, and of the impact of part cross section, edge configuration, asymmetry, and so on. In general, any lens having refractive power will possess a varying thickness across its diameter. Unfortunately, meniscus-shaped elements may mold best due to the more uniform nature of the heat transfer from the bulk.[32] Positive-powered lens elements will naturally shrink toward their center of mass as they cool, and it may be difficult to fill the mold cavity efficiently if the edge cross section is only a small fraction of the center thickness.

Negative lenses, on the other hand, tend to fill in the outer zones more readily, since the thinner portion of the section (the center) tends to obstruct flow directly across the piece from the part gate. In extreme circumstances, it is possible that the outer zones of the lens element will be first to fill, trapping gases in the center, forming an obvious *sink* in molding terminology. Parts designed with molded-in bores may exhibit the '*weld-line*' phenomenon, which is a visible line in the part where the flow front of the molten plastic is divided by the mold cavity obstruction forming the bore. In the case of both negative and positive lens elements, it is good policy to avoid element forms wherein the center-to-edge thickness ratio exceeds three for positive elements, or is smaller than 0.3 for negative elements.

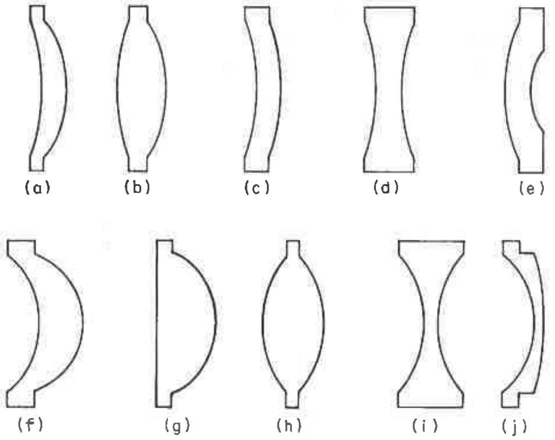

FIGURE 2 Some polymer lens element cross-sectional configurations.

Shrinkage

Surface-tension effects may play a significant role in the accuracy to which a precision optical surface may be molded.[33,34] Particularly in areas of the part where the ratio of surface area/volume is locally high (corners, edges), surface tension may create nonuniform shrinkage which propagates inward into the clear aperture, resulting in an edge rollback condition similar to that which is familiar to glass opticians. Surface tension and volumetric shrinkage may, however, actually aid in the production of accurate surfaces. Strongly curved surfaces are frequently easier to mold to interferometric tolerances than those having little or no curvature. These phenomena provide motivation to oversize optical elements, if possible, to a dimension considerably beyond the clear apertures. A buffer region, or an integrally molded flange provides the additional benefit of harmlessly absorbing optical inhomogeneities which typically form near the injection gate. Figure 2 depicts several optical element forms exhibiting favorable (*a–e*) and unfavorable (*f–j*) molding geometries. In some cases, a process combining injection and compression molding may be used to improve optical figure quality. Several variants of this hybrid process are in use worldwide, with some injection molding presses being specifically fitted at the factory to implement this procedure.[35]

Mechanical Assembly

In order to appreciate fully the design flexibility and cost-saving potential of polymer optics, it is necessary to modify one's approach to both optical and mechanical design. A fully optimized polymeric optical system not only makes use of aspheric technology and integrally molded features in the optical elements, but embodies an extension of this design philosophy into the lens housing concept and assembly strategy. These issues should ideally be considered in concert from the very beginning, so that design progress in one aspect does not preclude parallel innovation in other facets of the development process.

It is important to resist the urge to emulate glass-based optomechanical design approaches, since the polymer technology permits design features to be implemented which would be prohibitively expensive (or even impossible) in metal and glass. Spacers

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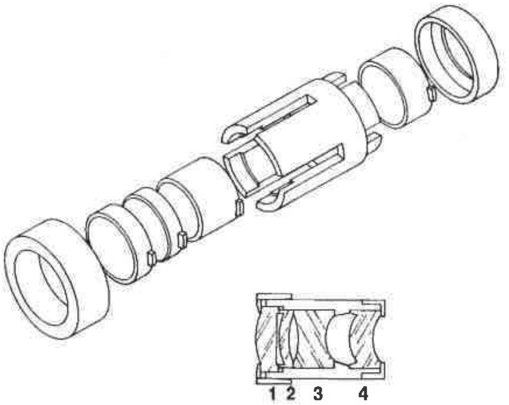

FIGURE 3 Collet-type lens housing. Joining by ultrasound eliminates the possibility of pinching lens elements.

required to separate elements may be molded as part of the elements (Fig. 2), reducing the metal part total, and simplifying assembly operations. See also Vol. I, Chap. 37, of this Handbook. Housings may be configurations which would be either improbable or unmanufacturable using machine tool technology. The collet-and-cap design shown in Fig. 3 is one such example. Joining might be accomplished by ultrasonic bonding. The clamshell concept shown in Fig. 4 may be designed so that the two halves of the housing are actually the same part, aligned by molded-in locating pins. Joining might be performed by a simple slip-on C ring.

Whereas lens assemblies in glass and metal are normally completed by seating threaded retaining rings, their plastic counterparts may be joined by snap-together pieces, ultrasonic bonding, ultraviolet-curing epoxies, expansion C rings, or even solvent bonding.[36] Solvent bonding is dangerous, however, since the errant vapors may actually attack the polymer optical surfaces.

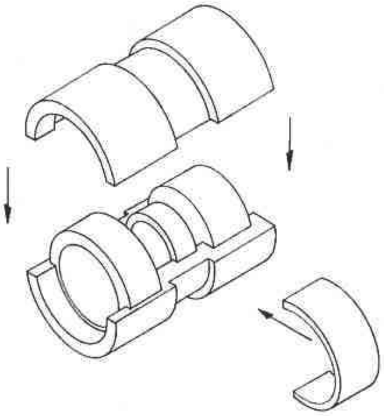

FIGURE 4 Clamshell lens housing. Possibility of lens jamming during assembly is minimized.

Following the basic polymeric optics philosophy, the lens element containment and assembly approach should probably not even consider the disassembly option in the event of a problem. In order to maximize assembly precision, and minimize unit cost, the design of the lens cell should evolve alongside that of the optical system, and this cell should be visualized as an extension of a fixture conceived to minimize the labor content of the assembly.

An in-depth treatment of optical mold design and tooling technology is obviously beyond the scope of this discussion. Many of the methods and procedures parallel those in use in the molding industry at large. However, a number of subtle and very important detail differences do exist, and these are not extensively documented in the literature. Issues having to do with metallurgy, heat treatment, chemical passivation, metal polishing, and so on, have little to do with the actual design and engineering of a polymeric optical system. In a modern tool design exercise, though, the flow behavior of the polymer material in the mold, and the thermal behavior of that mold, are carefully modeled in multinode fashion, so that part quality may be maximized, and cycle time minimized.[37] A nodding awareness of these methods, and the underlying physics, may be helpful to the person responsible for the engineering of the polymer optical system.

Testing and Qualification

In the process of implementing any optical system design, the matters of testing and certification become key issues. In molded optics, the master surfaces, whose shapes are ultimately transferred to the polymer optical parts, must be measured and documented. A convenient testing procedure for the optical elements replicated from these surfaces must likewise be contrived, in order to optimize the molding process and insure that the finished assembly will perform to specification. The performance of that assembly must itself be verified, and any disparities from specification diagnosed.

In general, mechanical dimensions of the polymer parts may be verified by common inspection tools and techniques used in the glass optics realm. The possibility of inflicting surface damage, however, dictates that noncontact interferometric techniques be used in lieu of test glasses for optical figure diagnosis. This is a straightforward matter in the case of spherical surfaces, but requires some extra effort in the case of aspherics. See also Vol. II, Chap. 30, of this Handbook.

Obviously, aspheric master surfaces must be scrupulously checked and documented, lest the molder struggle in vain to replicate a contour which is inherently incorrect. The verification of the aspheric masters and their molded counterparts may be accomplished in a variety of ways. Mechanical gauging, if properly implemented, works well, but provides reliable information through only one azimuthal section of the part. Measurement at a sufficient number of points to detect astigmatism is awkward, very time consuming, and expensive. And this is not exactly consistent with the spirit of polymer optics.

Null Optics

An optical *null corrector* permits the aspheric surface to be viewed in its entirety by the interferometer as if it were a simple spherical surface.[38,39] This is a rapid and convenient procedure. The null optics consist of very accurately manufactured (and precisely aligned) spherical glass elements designed to introduce aberration in an amount equal to, but of opposite sign from, that of the tested aspheric. Thus, interspersing this device permits aspherics to be viewed as if they were spherical. Since there exists no simple independent test of the null compensator, one must depend heavily upon the computed predictions of correction and upon the skill of the fabricator of the corrective optics. See also Vol. II, Chap. 31, of this Handbook.

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The concept of greatest importance regarding the use of aspheric surfaces is that *successful production of the total system is cast into considerable doubt if a surface is present which is not amenable to convenient testing.* While some aspheric optics may be nulled fairly easily, those which appear in polymer optical systems are frequently strong, exhibiting significant high-order derivatives. If the base curves are strong, especially strongly convex, there may exist no practical geometry in which to create a nulling optical system. And if a favorable geometry does exist, several optical elements may be necessary to effect adequate correction. One can easily approach a practical limit in this situation, since the manufacturing and assembly tolerances of the cascaded spherical elements may themselves (in superposition) exceed the theoretical correction requirement. The bottom line is that one should not proceed with cell design, or any other hardware design and construction, until the aspheric testing issues have been completely resolved.

34.8 COATINGS

Reflective Coatings

Given the fact that optical polymers exhibit specular properties similar to those of glass, it is not surprising that optical coatings are often necessary in polymeric optical systems. The coatings deposited upon polymer substrates fall mostly into four general categories. These include coatings to improve reflectivity, to suppress specular reflection, to improve abrasion resistance, and to retard accumulation of electrostatic charge.

Reflective coatings may be applied by solution plating, or by vacuum-deposition. These are most often metallic coatings, usually aluminum if vacuum-deposited, and normally chromium if applied by plating. The abrasion resistance and general durability of such coatings is rather poor, and susceptibility to oxidation quite high, if no protective coating is applied over the metal film. In some applications, especially involving vacuum deposition, the overcoat may be a thin dielectric layer, deposited during the same process which applies the metal film. If the reflective coating has been applied by plating, the overcoat may be an organic material, perhaps lacquer, and may be deposited separately by spraying or dipping. Not surprisingly, the quality of a surface so treated will be poor by optical standards, and probably suitable only for toy or similar applications.

Antireflection Coatings

Antireflection coatings are frequently utilized on polymer substrates, and may consist of a single layer or a rudimentary multilayer stack yielding better reflection-suppression performance. Due to the stringent requirements for control of the layer thicknesses, such coating formulations may be successfully deposited only in high-vacuum conditions, and only if temperatures in the chamber remain well below the service temperature of the substrate material. Elevated temperatures, necessary for baking the coatings to achieve good adhesion and abrasion resistance, may drive off plasticizing agents, limiting the "hardness" of the chamber vacuum. Such temperatures can ultimately soften the optical elements, so that their optical figure qualities are compromised. Relatively recent developments in the area of ion beam-assisted deposition have made possible improvements in the durability of coatings on polymer materials without having to resort to significantly elevated chamber temperatures.[40] See also Vol. I, Chap. 42, of this Handbook.

Antiabrasion Coatings

In general, many polymeric optical systems which could benefit from application of coatings are left uncoated. This happens because the expense incurred in cleaning, loading, coating, unloading, and inspecting the optical elements may often exceed that of molding the part itself. Some optics, particularly those intended for ophthalmic applications, are constantly exposed to abuse by abrasion, and must be protected, cost notwithstanding. Antiabrasion coatings intended to provide immunity to scratching may be of inorganic materials (normally vacuum-deposited), or may be organic formulations.[41]

Inorganic antiabrasion coatings may be similar to those used for simple antireflection requirements, except that they may be deposited in thicknesses which amount to several quarter-wavelengths. The practical thickness is usually limited by internal stress buildup, and by differential thermal expansion between coating and substrate. In general, the inorganic coatings derive their effectiveness by virtue of their hardness, and provide protection only superficially, since sufficient pressure will collapse the underlying substrate, allowing the coating to fracture.

Organic coatings for abrasion resistance normally derive their effectiveness from reduction of the surface frictional coefficient, thereby minimizing the opportunity for a hard contaminant to gain the purchase required to initiate a scratch. These coatings are often applied by dipping, spraying, or spinning. Coatings thus deposited usually destroy the smoothness which is required if the piece is to be qualified as a precision optical element.

Antistatic Coatings

Coatings applied for the purpose of immunization against abrasion, or suppression of specular reflection, often provide a secondary benefit. They may improve the electrical conductivity of the host surface, thus promoting the dissipation of surface static charge, and the accumulation of oppositely charged contaminants. In circumstances where antireflection or antiabrasion coating costs cannot be justified, chemical treatments may be applied which increase conductivity. These materials typically leave a residue sufficiently thin that they are undetectable, even in interferometric testing.

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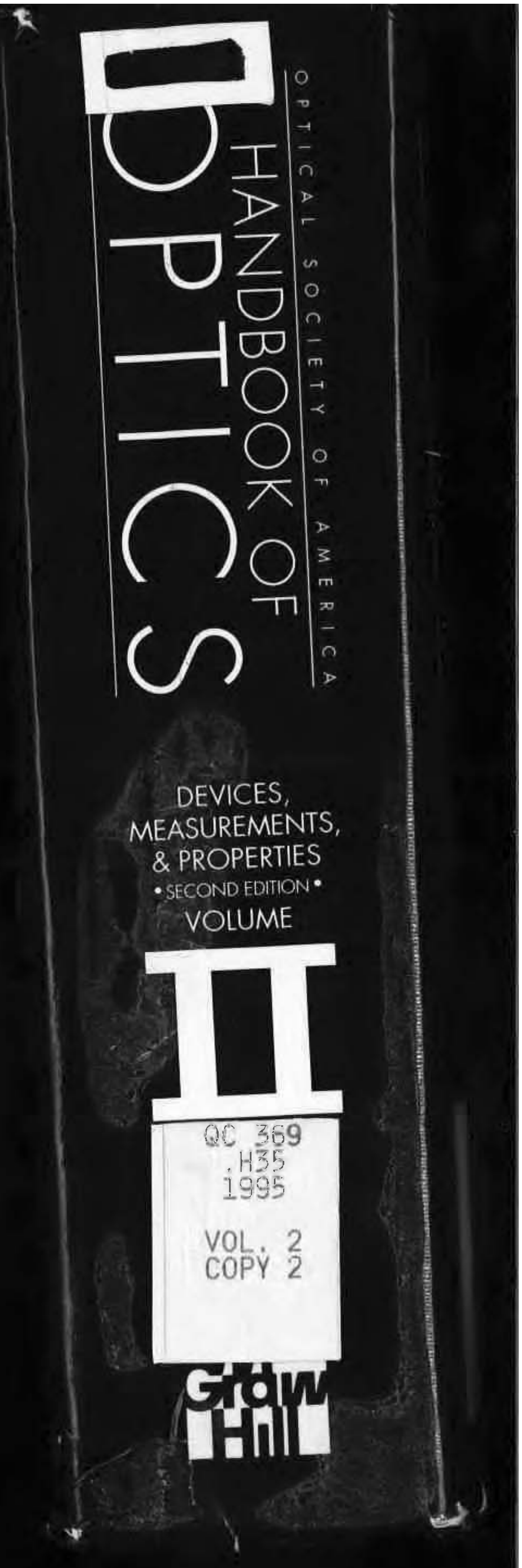

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David H. Krevor, SolFocus, Inc. (United States)

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Introduction

These proceedings represent the second symposium on polymer optics since the topic was reinstated by SPIE.

Polymer optics is a maturing field, as exemplified by more than a billion cellphone and camera lenses produced annually from polymeric materials. The relative markets and niches for optical plastics and glasses continue to evolve, usually according to the cost of mass production. As some applications for plastic optics wax and wane, such as the diminishing use of optical storage media in CDs and DVDs, other applications emerge, such as mass produced Fresnel lenses for concentrated photovoltaic (CPV) systems and, potentially, automotive windscreens.

The papers presented represent both industry and academia, ranging from micro-electronics to macro-applications, form replication to the predominant injection molding. The authors represent three continents and seven countries, indicating the global nature of both the industry and academic research. In recent years, the excellent monographs by Michael Schaub and Stefan Baumer have significantly advanced the understanding and sophistication of plastic optics. These symposia and proceedings are a progression of that knowledge.

I thank all of the authors for their fine presentations and papers. I thank my co-chair, Will Beich, and SPIE for their assistance and support.

Our next symposium is August 2012 in San Diego. We invite your participation.

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Polymer Optics: A manufacturer's perspective on the factors that contribute to successful programs

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ABSTRACT

Precision polymer optics is a key enabling technology allowing the deployment of sophisticated devices with increasingly complex optics on a cost competitive basis. This is possible because of the incredible versatility that polymer optics offers the designer. The unique nature of injection molding demands a very disciplined approach during the component design and development phase. All too often this process is poorly understood. We will discuss best practices when working with a polymer optics manufacturer. This will be done through an examination of the process of creating state-of-the-art polymer optics and a review of the cost tradeoffs between design tolerances, production volumes, and mold cavitation.

Keywords: Optical fabrication, injection molding optics, polymer optics, plastic optics, optical systems design

1. INTRODUCTION

Polymer optics is a key optical technology enabling a wide array of sophisticated devices. Because these types of optics are made of plastic and through the process of injection molding many options exists for providing customized solutions to unique engineering and product problems. However, the tremendous flexibility available to the designer is at once a bonus and a burden. It's a bonus because of the potential for creative problem solving. The burden comes from not understanding how the optics are made, how they're toleranced, and how alternative solutions may accomplish the goal-albeit with a different design.

While many options are available the challenge for designers is to understand the manufacturing process behind these solutions so that they can design their programs to leverage the technology. Without this level of understanding the designer may not achieve an optimal solution. Or, as is sometimes the case, the design team may go away thinking that a polymer optic is not an appropriate solution after all. We call this not knowing what you don't know. From a manufacturer's perspective many times we have encountered programs where we were given a small glimpse of what the engineering team was trying to achieve. This is often presented as a set of disembodied specifications for a particular optic. Frequently this comes in the form of a request to substitute the existing expensive glass substrate for a 'cheaper' plastic one. It's not unusual to hear something like, "the specs are on the drawing, just substitute the word acrylic for the word BK-7."

While this approach sometimes works, more often than not the challenges in making polymer optics a commercial success are completely ignored. The glass-appropriate specifications, which are completely wrong for plastic, result in either a no bid or an optic that works but could have been customized for plastic to work even better.

It is our belief that given the challenges and opportunities, designers are well served by getting the manufacturer involved early on in program discussions, since it is the optimal time to insert manufacturability expertise. To that end we will discuss the polymer optics manufacturing process and examine the best practices to use when working with a polymer optics manufacturer.

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2. WHAT ARE POLYMER OPTICS

Polymer optics are precision optics that are made of thermoplastics. Materials such as acrylic, styrene, Topas, Zeonex, and Ultem are examples of thermoplastics. In most instances they are made by a process called injection molding.

There are some exceptions to this. For example, some large area plastic optics, such as Fresnel lenses, are often made using compression molding. We will confine our discussion to optics made using the injection molding process. The technology was pioneered by companies such as Eastman Kodak, Polaroid, and U.S Precision Lens.

Today, in addition to being manufactured in the United States, polymer optics are made in Europe and in Asia, by companies such as Jenoptik in Germany and Nalux in Japan.

2.1 Where are they used, why would you want to use them

The number of devices and instruments that use these types of optics continues to grow. In short, any application that calls for an optical component, be it for imaging, scanning, detection, or illumination is a candidate for using a polymer optic. Some limitations on use will be discussed below.

A partial listing of devices that are in the market place today employing polymer optics would include: barcode scanners (both linear-1D laser scanners and matrix- 2D bar code imagers), biometric security systems, medical devices, document scanners, printers, light curtains, light guides, cameras and mobile imaging, smoke detector optics, automated sanitary valve systems, and laboratory equipment such as spectrometers and particle counters. All of these and more have benefited from using precision polymer optics. Polymer optics are also found in certain telecommunication products and commonly used to replicate micro structured surfaces such as microlens arrays, Fresnel lenses, refractive-diffractive optics, and some types of gratings. They are increasingly being used in LED illumination applications.

2.2 How are they made: the manufacturing technology

Polymer optics are manufactured by injection molding thermoplastics into optical forms. The key ingredients for production are molding resins, the molds, and injection molding machines.

2.2.1 Thermoplastics

As noted above, the principle molding thermoplastics are acrylic, styrene, polycarbonate, cyclic-olefins polymers (such as Zeonex and Zeonor, manufactured by Zeon Chemicals), Cyclic-olefin co-polymers (Topas, manufactured by Topas Advanced Polymers), and other specialty resins such as Ultem., Radel, and Udel. All of these materials are thermoplastics, which means they are plastics that can be heated and cooled repeatedly. This category of polymer is different from the optical grade thermoset plastics, which, once cured, are not able to become molten again. The manufacturers of these materials publish data related to their mechanical, thermal, and optical properties. Optical designers need to understand how these materials behave so that they can arrive at appropriate solutions.

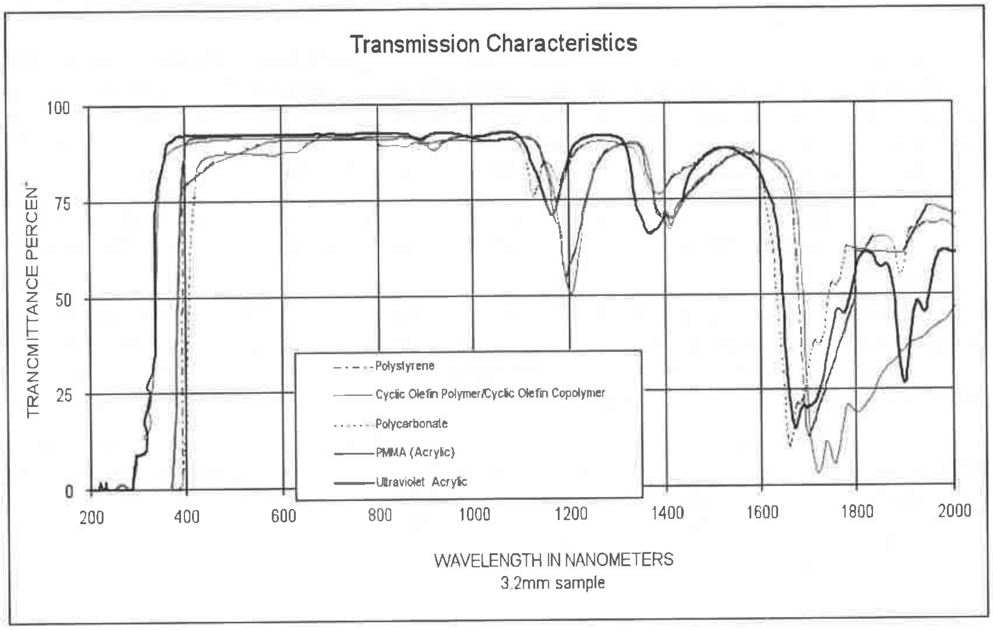
SPECIFICATIONS OF OPTICAL GRADE PLASTICS

Properties	Acrylic (PMMA)	Polycarbonate (PC)	Polystyrene (PS)	Cyclic Olefin Copolymer	Cyclic Olefin Polymer	Ultem 1010 (PEI)
Refractive Index N_F (486.1nm) N_D (589.3nm) N_C (656.3nm)	 1.497 1.491 1.489	 1.599 1.585 1.579	 1.604 1.590 1.584	 1.540 1.530 1.526	 1.537 1.530 1.527	 1.689 1.682 1.653
Abbe Value	57.2	34.0	30.8	58.0	55.8	18.94
Transmission % Visible Spectrum 3.174mm thickness	92	85-91	87-92	92	92	36-82
Deflection Temp 3.6°F/min @ 66psi 3.6°F/min @ 264psi	 214°F/101°C 198°F/92°C	 295°F/146°C 288°F/142°C	 230°F/110°C 180°F/82°C	 266°F/130°C 253°F/123°C	 266°F/130°C 263°F/123°C	 410°F/210°C 394°F/201°C
Max Continuous Service Temperature	198°F 92°C	255°F 124°C	180°F 82°C	266°F 130°C	266°F 130°C	338°F 170°C
Water Absorption % (in water, 73°F for 24 hrs)	0.3	0.15	0.2	<0.01	<0.01	0.25
Specific Gravity	1.19	1.20	1.06	1.03	1.01	1.27
Hardness	M97	M70	M90	M89	M89	M109
Haze (%)	1 to 2	1 to 2	2 to 3	1 to 2	1 to 2	-
Coeff of Linear Exp cm X 10-5/cm/°C	6.74	6.6-7.0	6.0-8.0	6.0-7.0	6.0-7.0	4.7-5.6
dN/dT X 10-5/°C	-8.5	-11.8 to -14.3	-12.0	-10.1	-8.0	-
Impact Strength (ft-lb/in) (Izod notch)	0.3-0.5	12-17	0.35	0.5	0.5	0.60
Key Advantages	Scratch Resistance Chemical Resistance High Abbe Low Dispersion	Impact Strength Temperature Resistance	Clarity Lowest Cost	High moisture barrier High Modulus Good Electrical Properties	Low Birefringence Chemical Resistance Completely Amorphous	Impact Resistance Thermal & Chemical Resistance High Index

Table 1. A brief summary of some of the key characteristics of the most important optical thermoplastics.

2.2.1.1 Light Transmission

Most optical plastics have high clarity in the broad band visible portion of the spectrum. For example, acrylic and some grades of Zeonex have transmission properties of about 92%. Materials such as polycarbonate have lower transmission, but higher impact resistance. The table below summarizes the transmission characteristics of the most commonly used optical polymers.



Graph 1. Transmission characteristics of optical polymers.

2.2.1.2 Index of Refraction and abbe value

The range of available indices of refraction is quite narrow when compared to that available for glass. Acrylics and COP materials behave more like crown glass types (having abbe values in the mid 50s) with an index of refraction of about 1.49 and 1.53 respectively. On the other hand styrene and polycarbonate behave more like flints (with abbe values in the low to mid-30s) and having an index of refraction of about 1.59.

2.2.1.3 Transition Temperature, Coefficient of Thermal Expansion, H2O uptake, and dn/dt

When compared to glass, plastics have a much lower transition temperature (it's not unusual to see maximum continuous service temperatures of under 130-degrees C.) They also have a much higher coefficient of linear expansion (about an order of magnitude higher). Plastics will exhibit a change in index of refraction relative to temperature; the thermoplastic dn/dt is fairly large (about 20 times that of glass) and negative[1]. Most thermoplastics (with the exception of COP and COC materials) will absorb water, which will cause the lens shape to change dimensionally. For example, acrylic will absorb approximately 0.3% water over a 24-hr period. During the same period, a COP or COC material may absorb only 0.01%.

Plastic generally is lighter in weight than glass, so depending on the glass type alternative, using a polymer optic can significantly reduce the weight in a system. Finally, it should be noted that polymers are not nearly as hard as glass. Many different scales are used to measure hardness. One scale that is readily grasped is Moh's ordinal scale of mineral hardness. With talc at the softest (1) and diamond at the top of the scale (10), most plastics come in at around 2 (absolute hardness of about 3), equal to gypsum. It is clear that polymer optics must be protected in whatever system they are used.

2.2.2 Molds

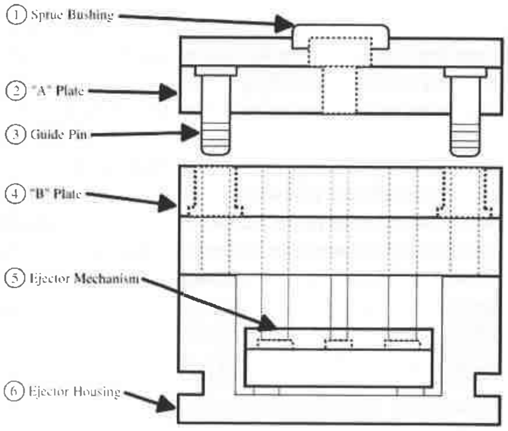
The mold used to manufacture polymer optics can be thought of as a sophisticated three dimensional steel puzzle that has two main features: (1) the cavity details along with the core pins (also known as optical inserts or nubbins), and (2) the frame (sometimes called the base) that houses the cavities and inserts. The figures below illustrate the basic concept of the mold. The complexity of the mold is a function of the complexity of the element being molded. One of the key advantages of using polymer optics is the ability to combine optical and mechanical features into one platform. So, depending upon the nature of the mechanical features being considered the mold itself can take on additional complexity.

The mold is mounted into the molding press. One side of the mold is mounted to the fixed side of the press; the other side is mounted onto the moveable platen within the press. During the molding process, the two mold halves are clamped together under high pressure. The molten resin is injected into the mold by the press and the melt moves through the channels in the tool to the cavities. The cavities fill with the resin and take on the shape of the cavity detail. Once the plastic has cooled to an appropriate temperature, the mold opens and the optics are removed.

The mold is built to the negative of the final part. Thus if the final optic has a convex surface the optical insert will be concave. The mechanical features of the part have to be drafted (tapered) so that they will not be trapped in the mold after the resin has solidified.

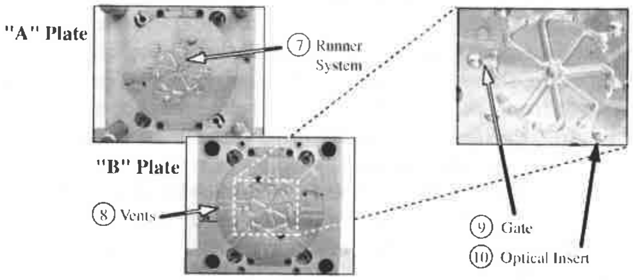
All thermoplastics shrink as they cool. In general, the shrinkage is approximately 0.5% to 0.6%. It is important that the shrinkage be taken into consideration when determining the final dimensions of the mold. If the mold is made to the final drawing specifications the part will be too small. One needs to make the mold wrong, if you will, to make the part right. Usually molds are built steel-safe, which allows mold adjustments to be done by removing steel.

With the advent of sophisticated CNC lathes most optical inserts are diamond turned from nickel-plated steel. This method makes it possible to create on and off axis aspheric surfaces and allows the optical molder the flexibility of adjusting the inserts for shrinkage after initial molding trials have be done.



① Sprue Bushing
② "A" Plate
③ Guide Pin
④ "B" Plate
⑤ Ejector Mechanism
⑥ Ejector Housing

Figure 1. Mold Cross Section



"A" Plate
⑦ Runner System
"B" Plate
⑧ Vents
⑨ Gate
⑩ Optical Insert

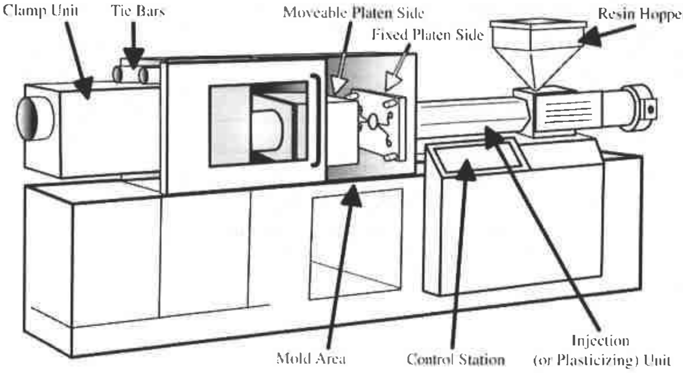
Figure 2. Mold-parting line photos

The following is a brief list of some of the key features generally found in molds along with a brief description of their intended function[2].

1. Sprue Bushing. Provides means of entry into the mold interior.
2. Top (A-side) plate. Portion of the mold mounted on the stationary side of the press.
3. Guide Pins. Maintains proper alignment of the two halves of the mold.
4. Bottom (B-side) plate. Side opposite the "A" side, sits on the moveable platen of the molding press.
5. Ejector Mechanism System. Used to eject rigid molded elements from the cavities.
6. Ejector Housing. Houses the ejector system.
7. Runner System. System of channels in the mold face used to convey molten plastic from the sprue to the cavities.
8. Vents. Structures that allows trapped gas to escape.
9. Gates Region of the mold that controls the flow of molten material into the cavities.
10. Optical inserts (sometimes referred to as nubbins). Pins within the mold that have been deterministically ground and polished against which the optical surface forms during the molding process. These surfaces can be steel or a non-ferrous alloy.

2.2.3 Molding Machines

Molding machines are used to hold the mold and to melt and inject the plastic into the mold. The figure below shows the basic features of a molding machine.



Clamp Unit
Tie Bars
Moveable Platen Side
Fixed Platen Side
Resin Hopper
Mold Area
Control Station
Injection (or Plasticizing) Unit

Figure 3. Schematic of a molding press.

The molding press has a clamp unit on one end and the injection unit on the other. The mold is hung in the middle region as shown. The clamp unit is used to keep the two mold halves together as the molten resin is being injected. The molding cycle begins. The moveable platen closes against the fixed platen (closing the mold). An appropriate amount of force is used to hold the mold closed during the injection cycle. The injection unit, consisting of a feed hopper, reciprocating screw, and barrel, picks up an amount of pelletized resin from the hopper. It is the job of the injection unit to melt the resin and to push it into the mold through the sprue bushing. The reciprocating screw turns within the barrel. It is fluted allowing it to trap the material between the heated chamber wall and the screw. The chamber wall is the bearing surface where sheer is applied to the resin as it is being advanced towards the mold. Once the molten material accumulates at the end of the screw it is injected at an appropriate speed and pressure into the mold. This causes the material to flow into the mold to fill the cavities. The molding machine provides complete control over this process, governing the size of the shot, injection speed, injection pressure, backpressure, cushion, and other critical variables that will determine the final outcome of the optic. After an appropriate cooling time, the moveable platen moves away from the fixed platen, and the mold opens. This allows the optics (still attached to the runner system) to be removed. After the shot is removed, the cycle starts over again.

Other equipment is often found along side the molding machine. For parts that require a large amount of material, auto loading hoppers are used to feed material into the machine. Also, the thermoplastics must be dried before being fed into the injection unit. It is common to see desiccating equipment located near the press for this purpose. Once the molding cycle is completed it is desirable to promptly remove the shot so that the entire molding process may be repeated with regularity. To aide in this, a robotic arm is frequently used to ensure that the removal is done on time. This enables the entire process to go into a steady state. Depending on the nature of the program, additional automation or end of arm tooling may be required to remove of the parts from the press, degate them from the runner, and package them into trays for final shipment. Degating is the process whereby the optical elements themselves are removed from the runner system.

3. TYING IT ALL TOGETHER

As noted above, it is important that the designer has a basic understanding of the manufacturing process and of the limits of size and tolerances that might be expected of the finished optics. In general terms, overall shape and tolerances of the optic will drive cost and manufacturability. There are some general guidelines: thicker parts take longer to mold than thinner parts. Optics with extremely thick centers and thin edges are very challenging to mold. Negative optics (thin centers with heavy edges) are difficult to mold. Optics with very tight tolerances may not be manufacturable at all in a one cavity mold, much less in a mold with more than one cavity. There are some other general tolerances that can describe the limits of fabrication in an ideally designed optic.

Attribute	**Rules of Thumb Tolerances**
Radius of Curvature	± 0.50%
EFL	± 1.0%
Center Thickness	± 0.020mm
Diameter	± 0.020mm
Wedge (TIR) in the Element	< 0.010mm
S1 to S2 Displacement (across the parting line)	< 0.020mm
Surface Figure Error	≤ 2 fringes per 25.4mm (2 fringes = 1 wave @ 632nm)
Surface Irregularity	≤ 1 fringes per 25.4mm (2 fringes = 1 wave @ 632nm)
Scratch-Dig Specification	40-20
Surface Roughness (RMS)	≤ 100 Å
Diameter to Center Thickness Ratio	< 4:1
Center Thickness to Edge Thickness Ratio	< 3:1
Part to Part Repeatability (in a one cavity mold)	< 0.50%

Table 2. Rules of thumb.

Two things should be observed here. (1) Even with the rules of thumb, it is very difficult for the experienced optical molder to communicate all of the things that the designer should look out for. There are simply too many variables to consider without expert guidance. In this regard we might say it is not unlike consulting with a doctor on a medical issue or with a lawyer on a legal matter. One might have a general idea of the issues from one's own reading or researching on the internet; however, expert assistance is needed to answer deeper questions. And (2), what is not discussed here is how the rules of thumb interact with one another or how a change in one area will impact another. Rules of thumb are quick generalizations. They are useful for initial discussions, but the rules can quickly break down as the limits of size, shape, thickness, materials, and tolerances are encountered. It is impossible to publish an exhaustive list of possible interactions between all of these variables. The main reason for consulting with the optical molder is that a good optical molder will bring years of experience to the table.

What is the best way for the designer to work with an optical molder? Perhaps the best way is to proceed from a systems design perspective. Instead of communicating with the optical molder at arms length with a drawing and tolerances hoping for the right solution, instead, why not communicate the big picture to the molder so that they can help address questions that may not even be in view at the component drawing level. Perhaps the best way to grasp this is to consider an example.

3.1 Example 1. The effect of design on cycle time and total cost of acquisition

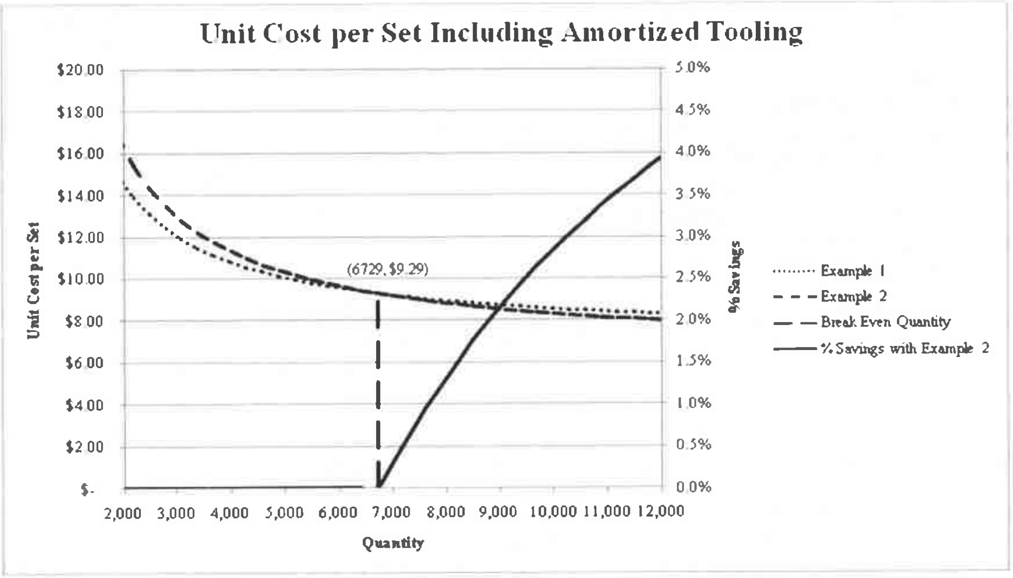
The optical molder received the following request for quotation. The element is acrylic, bi-convex, aspheric on both surfaces, 75mm in diameter ± 0.050mm, with a 12mm center thickness and a 2mm edge thickness, both toleranced at ± 0.020mm. The clear aperture extends to within 2 mm of the edge. Power and irregularity are specified at 5 fringes and 10 fringes respectively. The lens has a S1 to S2 displacement tolerance of ± 0.020mm. The drawing has no provisions for a gate location. Volumes are 10,000 pieces per year. Please quote.

A lens with this description is going to be very expensive. If we use an overhead rate of \$120/hr[3], and an estimated cycle time of 6 minutes, we would have a lens that costs about \$12.00. The tight tolerances would likely increase scrap, so accounting for yield loss would push the price higher to around \$14.00. To mitigate this increase, a typical tactic would be to build a higher cavitation tool, but because of the tight tolerances, this lens could never be run in a multi-cavity mold. Cavity to cavity variation would increase the power and irregularity errors to a point where not every cavity would meet the specification. There is no way to achieve the economies of scale that can be realized by going to higher cavitation. If we say that the mold for this lens would cost about \$15,000, the total cost of acquisition for the first year production would be about \$15.50/lens.

3.2 Example 2. How a manufacturable design can reduce the total cost of acquisition

An alternative approach to example 1 is to look at the system design with guidance from an optical molder, who may ask the question: can this thick optic be split into two thinner optics? If the system design were flexible enough to allow a two lens solution, then we might see an alternative scenario where two lenses with 3 minute cycle times can reduce the total cost of ownership through yield improvements (assuming the two separate lenses have more achievable tolerances, which is very likely).

The tooling cost for the two-lens solution, which would involve building one mold with two cavities that can be run independently, would be about \$20,000 – a \$5,000 increase over example 1. The graph below, which plots the unit cost of examples 1 and 2 (a set of two parts) including amortized tooling, shows that the improvement in yield gained through a more manufacturable design results in a breakeven point of around 6,700 pieces. From a cost perspective, if more than 6,700 pieces are required, it becomes cheaper to have a two lens solution. This savings could increase if the cycle time for either lens is less than 3 minutes (which is likely).



Graph 2. Unit cost per set with tooling amortized.

The economics work out, but the hidden cost of the risk between examples 1 and 2 is not captured. On paper example 1 is more challenging to manufacture and may lead to unexpected manufacturability issues. A competent optical molder would identify those issues as potential red flags so that contingencies can be determined upfront. For example, the power and irregularity tolerances are very difficult, and the parts may only barely meet the specification. What is the impact to the system if these values exceed the spec? Will it degrade performance? What if the tolerance analysis is incorrect and the specs need to be tighter, but that is only discovered after parts have been molded and tested? These are a few of the questions an optical molder must consider. Example 2 is expected to have looser tolerances, so many of the above concerns are inherently less risky.

The inquiry in example one called for an annual volume of 10,000 pieces. If the company has success selling the product, the volumes may go up and create a capacity constraint or lower cost requirement. A mold can only produce a certain number of pieces per year (around 35,000 pieces for one shift in example 1), and the cost is primarily cycle time driven. Since multi-cavity tools help to address both concerns, it is important to consider at the beginning if the lens can be made in a mold that has more than one-cavity. In example one above, the answer is no. The tolerances are too tight. In contrast example two has the benefit of looser tolerances and thinner optics, both of which bode well for the ability to expand to multiple cavities. The need to act on higher cavitation tooling may be delayed due to the higher production capacity of the 1-cavity molds (due to shorter cycle times), but having flexibility in the decision making process is often beneficial.

In much the same way that future expectations of multi-cavity molds must be considered upfront, the need for and method of prototyping must be mindful of future production methods and requirements. Prototypes are often used to provide functional devices to evaluate customer demand and market opportunities, but sometimes they are produced to prove that the system will work. Diamond turning is the most direct way of producing prototypes, and the achieved tolerances are typically much less than the specification limits. This is both a blessing and a curse, since the end result of the prototyping process may verify that a design is functional without testing the tolerance limits. Understanding the differences between what is achievable with prototypes (via diamond turning or prototype molding) versus volume production is crucial to making sure a design is production capable. The experienced optical molder can help a designer navigate through these potential pitfalls.

Other system design factors come into play as well. The temptation is to consider these as mundane non-optical issues, however, if not addressed correctly these issues can add considerably to the total cost of acquisition. For example, where will the lens be gated? Can the mating part be adjusted so that a longer gate vestige can be accommodated? How will the part be packaged? How will the part be handled? Does the optic need some kind of keying feature to help with down the road assembly? The answers to these questions can add additional and sometimes significant cost to the final component.

There are other things to consider: As the design deviates from a conventional on-axis rotationally symmetric optic, measuring the part to verify conformance can become a limiting factor. Interferometers are typically used to measure flat and spherical surfaces, and contact profilometers are proficient at measuring aspheres. For bi-conic, freeform, or off-axis surfaces, a combination of profilometry and CMM (contour measuring machine) inspection can answer many inspection questions. There are instances, though, where the design requires an optic be inspected to a level beyond which these tools are capable. Functional testers and customized inspection setups can often close the gap, but identifying that a gap exists early on in the design process is critical for finding a solution.

The point here is that the lens designer may not be thinking of these things when presenting a drawing for bid. He may not even be aware that there are larger issues like this to consider. He is probably concentrating on how the lens needs to perform in the system and rightly so. But the lens does not exist in isolation. The rest of the system, along with the commercial aspects of future production needs, should be addressed up front so that the appropriate tooling set can be accounted for. These are the things that the layman may not know that he doesn't know.

Finally, similar to how it is impossible for a designer to work from an exhaustive list of optical molding rules, there are other critical to success aspects of the manufacturing process that the molder does not know either. This is where the molder's supplier network comes into play. The tooling supplier identifies risks and makes suggestions about the mold in a back and forth process similar to how the molder works with the designer/customer. The same is true about coating, diamond turning, or other processes that are needed to make or support the production of the part. As an extension of this, it is beneficial for the molder to know many of these things first hand so that as many requirements can be determined in the one-on-one discussions with the customer. Finding a molder that has internal capability for diamond turning, coating, automation, fixturing, and so forth, will help to streamline the process, manage cost, and improve quality.

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