The Optics of Miniature Digital Camera Modules

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ABSTRACT

Designing lenses for cell phone cameras is different from designing for traditional imaging systems; the format poses unique challenges. Most of the difficulty stems from the scale of the system, which is based on the size of the sensor.

Keywords: Optical design, lens design, digital cameras

1. INTRODUCTION

The scale of cell phone camera systems creates particular challenges for the lens designer that are unique to this format. Both the size and the low-cost requirements have many implications for the design, fabrication and assembly processes.

Fig.1: This 3.6um pixel VGA camera module is 6.05 x 6.05 x 4.5 mm.
The most critical dimension is the 4.5 mm axial length.

For those of us who have been involved in the design and manufacturing of consumer and commercial imaging systems using lens elements with diameters in the 12-40mm range, the switch to much smaller elements with diameters in the 3-5mm range takes some adjustment. When designing a camera module lens, it is not always helpful to begin with a traditional larger-scale imaging lens. Scaling down such a lens will result in a system that is unmanufacturable. If the design includes molded plastic optics, a scaled down system will result in element edge thicknesses shrinking to the point where the flow of plastic is affected. For glass elements, the edge thicknesses will become too thin to be fabricated without chipping. To achieve a successful design we have to modify our lens forms and adjust the proportions of the elements.

Layout drawings can be very misleading. Many times we find ourselves surprised when the mechanical layout of a lens barrel that looked reasonable on paper turns out to be very difficult or impossible to fabricate. Tabs on a barrel that appear substantial in a drawing, are found to be too flimsy to function on the actual part, “sharp” edges on molded stops don’t fill completely because the features are too small. The size of the lenses and mechanical details on the flanges and barrels affect all aspects of the manufacturing process. Diamond tools have to be redesigned to be able to generate large changes in angle over small areas. Handling the lenses becomes difficult even with tweezers, all inspection and screening has to be done with a microscope. Measuring basic dimensions and the surfaces of the lenses becomes very challenging. Center thickness and surface decenter measurements in particular are difficult at the high levels of accuracy required for current designs. The ability to fabricate accurate and robust fixtures for measurement of individual elements has become absolutely critical.

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Another process that has been affected is assembly. Assembly must be done in clean conditions, with visual aids to ensure proper lens orientation and seating. Once an assembly is complete it needs to be tested. Testing assemblies with barrel outer dimensions of 6mm pose similar fixturing challenges as those in the fixturing of individual elements, with the additional requirement that they must be aligned with a test target for MTF or resolution testing. This target or series of targets must provide adequate sampling over an area representing the sensor, to characterize the lens, which could be anywhere from 1/10" diagonal to 1/3" diagonal. Fixturing for both MTF testing and resolution testing must minimize tilt of the lens barrel with respect to the target.

2. CMOS Focal Planes

Development of sensors has been moving steadily towards smaller pixels and higher density formats. The initial cell phone cameras were based around VGA and QVGA modules with 5.6um pixels. Generally formats were between 1/7" and ¼" in size. Next, the sensor manufacturers began offering VGA and SXGA sensors with 3.2-3.8um pixels in 1/6-1/4" formats. Then the sensors moved to 2.8um pixels offered in VGA, 1.3MP and 2MP, 1/8", ¼" and 1/3" formats respectively, a full 50% reduction in pixel size from the original sensors. Today we are designing for 2-3MP sensors in 2.2um pixels, ¼" and 1/3" formats, and there are plans for 5MP sensors with 1.75um(!) pixels coming soon.

Over the past couple of years, pixel areas have been reduced by 75%, then 85%, soon to be 90%, compared with 5.6 micron pixels. Lower pixel count formats (VGA and 1.3mp) have gotten correspondingly smaller, and higher resolution sensors (2mp and 3mp) have been introduced. The higher resolution formats have made the job of the lens designer extremely challenging because, while the basic imaging problem has remained the same, each reduction in pixel size has required an increase in lens performance,, and the overall length of the system is often required to be shorter. VGA systems pose different, but no less daunting problems. VGA sensors have scaled with the pixel size from ¼" with the original 5.6um pixels to the current 1/11" format based on a 2.2um pixel. As the pixels have shrunk, the lenses for VGA systems have become so small that contamination is now a major issue and the scratch/dig requirements for each lens surface are very tight making the lenses very difficult to manufacture.

3. The Problem of Scale

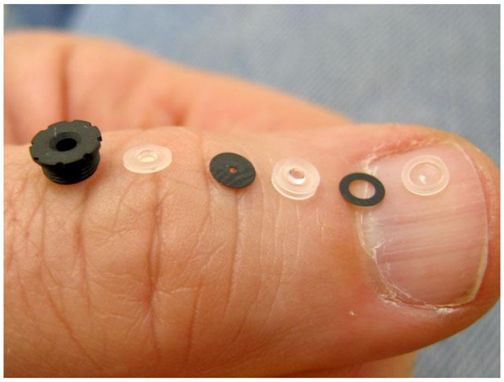


Fig.2: 3-element lens, disassembled. Barrel, three plastic aspheric lenses, thin sheet aperture stop and baffle.

It is interesting to consider the differences between these miniature camera module lenses and lenses for conventional photography, such as the 35 mm format. The goal is the same: Produce pleasing images of snapshot quality. However, the scale of the optical system is reduced by roughly a factor of ten!

	35 mm point and shoot	35 mm single use	¼" CMOS
Film format diagonals:	43 mm	43 mm	4.4 mm
Lens EFL:	37.5 mm	37.5 mm	3.8 mm
f/number:	2.8, variable	11, fixed	2.8, fixed
Entrance pupil diam:	13.4 mm	3.4 mm	1.36 mm
Spatial frequencies:	10 – 40 /mm	10 – 20 /mm	50 – 100 /mm
Cost:	$10 (est.)	$0.50 (est.)	$1 (est.)

If we were able to simply scale the 35 mm lens design by 1/10x, we would encounter a few issues:

1) Smaller entrance pupil: Depth of field will be much greater, but diffraction will limit performance sooner than with larger formats.
2) Surface figure tolerances: Figure tolerances (fringes of irregularity, for example) will be somewhat tighter, because spatial frequencies of interest are higher, but because the surfaces are smaller, they will be easier to achieve in practice.
3) Geometric tolerances: Scaling the system's size requires linear tolerances to scale as well. So center thickness tolerances and surface and element decenter tolerances will be tighter by a factor of ten. This proves to be the greatest challenge of producing these lenses.
4) Angular tolerances: Lens tilt tolerances do not scale down, but small defects on flanges or mounting surfaces will have a larger effect on tilt.
5) Stray light considerations: An aperture or baffle feature that has an acceptably small dimension at the large scale should be scaled down by 1/10. However, some parts cannot be made thin enough, or they may become translucent, so they will cause a larger fraction of the light to scatter from their edges, resulting in flare or veiling glare.
6) Scratch/Dig and Contamination: The smaller system is much more sensitive to defects and contamination causing shadowing on the image. Acceptable defect dimensions scale with the format size, and the situation is often worse in practice, because the back focal distance is very short and defects close to the image are more visible.

4. Specifications

The following are typical lens specifications for a ¼" sensor format:

FOV	60 degrees
Image Circle	4.6 mm diam.
TTL	5.0mm
f/no	f/2.8
Distortion	<2%
Chief Ray Angle	<22 degrees
Relative Illumination	>50%

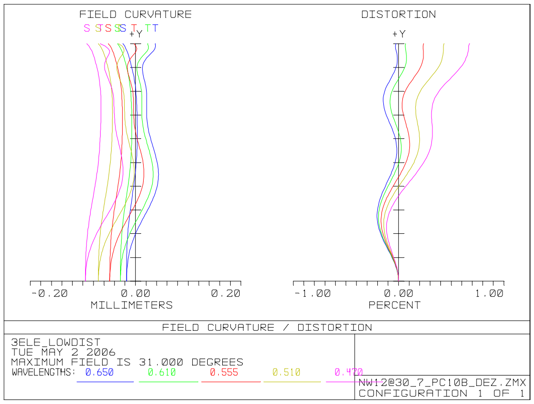
FOV - The field of view for these systems is typically 60 to 66 degrees across the sensor diagonal, but the design must include a slightly larger angle to allow for correction over the image circle.

Image Circle - This is the diameter of the image over which the lens has to be well corrected to allow for lateral displacement of the sensor relative to the optical axis. Lens to sensor centration errors are caused mostly by uncertainty in the placement of the sensor on its circuit board. To allow for those errors, the lens image circle is increased by at least 0.2 mm. As sensors get smaller sensor placement accuracy must improve.

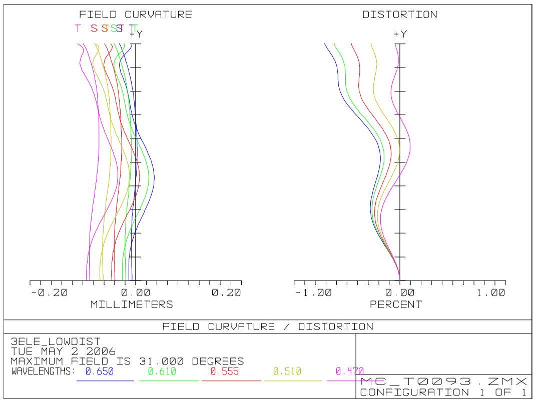
TTL- The total track length is the distance from the front of the barrel to the image plane, this has to be longer than the optical track length by at least 0.050mm in order to protect the front of the lens. This is extremely important to the cell phone designers because of the market pressure to produce thinner phones.

f/number – Although most camera module customers specify f/2.8, it is not uncommon to see lenses at f/3.0 and f/3.3 when the increased fno has a significant effect on performance or manufacturability. However, smaller pixel sensors have less light gathering capability and will suffer at slower f/numbers.

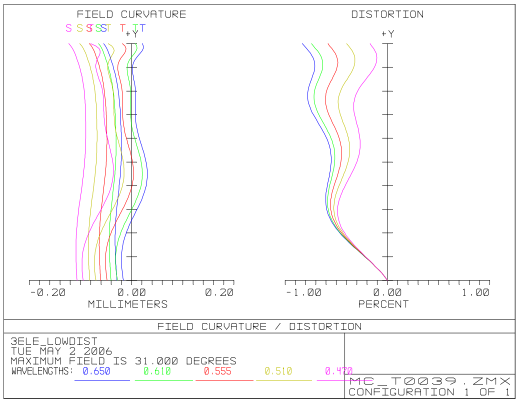
Distortion – The usual distortion requirement is <2% optical distortion or <1% TV distortion. Although this sounds like a much more stringent requirement than the 4% typically allowed in traditional 35mm camera lenses, the distortion curve can vary significantly from assembly to assembly due to build tolerances. In fact the approximate effect of tolerances is to add positive or negative slope to the nominal distortion curve.



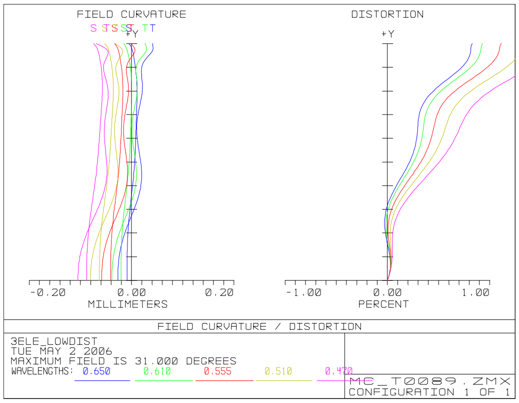
a) Distortion: Nominal Design



b) Distortion: Toleranced Build #1



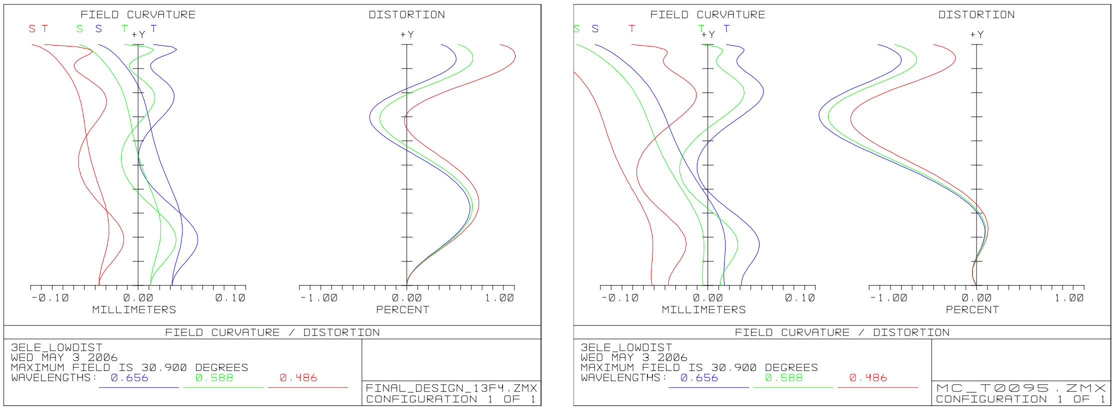
c) Distortion: Toleranced Build #2



d) Distortion: Toleranced Build #3

Fig.3: a) Nominal design distortion curve, b) Distortion curve for a simulated toleranced build, displaying moderate tilt, c) Another sample of a simulated build with induced tilt in the distortion curve, d) Distortion curve representing the simulated build with the maximum amount of tilt generated for this design.

As demonstrated in fig.3, a nominal design with distortion < 0.3% can easily generate distortion >1% when fabricated. An even more critical factor in ensuring good performance is to limit the slope and rate of change of slope of the distortion curve. The added tilt due to tolerances applied to a fast changing distortion curve can result in extremely steep slopes that are objectionable in an image.



a) Distortion: Nominal Design b) Distortion: Toleranced Build

Fig.4: a) Nominal design distortion is low in magnitude but fast changing over the field, b) Distortion curve for simulated build displaying unacceptable tilt and variation in slope as a result of build tolerances.

Even though absolute distortion values may be low, large changes in slope over a small area will be noticeable in an image. For this reason it is important to control both the shape and the magnitude of the distortion curve.

Chief Ray Angle (CRA)– The CRA is the incidence angle of the chief ray at the image plane for any field point. The CRA is usually specified as a maximum value that cannot be exceeded anywhere in the field. Most camera module lens CRA curves increase monotonically with field to a maximum value and then drop off at the edge of the image, because of pupil aberrations. See fig.5.

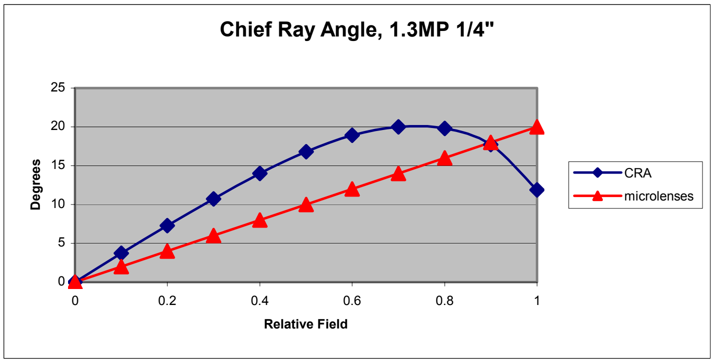


Fig.5: Chief Ray Angle and Microlens Optimum Acceptance Angle as a Function of Relative Field

To better illustrate the source of this requirement, let's first take a closer look at the structure of the focal plane. The CMOS sensor array is an array of sensors with color filters integrated, to produce the standard Bayer pattern of red, green and blue detectors:

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