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# Mobile Platform Optical Design

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**ABSTRACT**

Camera modules in mobile devices have become ubiquitous, and the optical design and fabrication technology behind them is underappreciated. We will present a basic summary of the technology and discuss some recent developments that may influence future camera designs.

**Keywords:** Digital cameras, optical design

## 1. INTRODUCTION

Since the beginning of photography, about 170 years ago, camera design has dramatically changed. For most people, large assemblies of wood, leather, brass and glass have made way for the extremely miniaturized modules that are buried within electronic devices.[1] Many millions of them are in mobile phones today, of course. At IODC-2006, Vancouver, Jane Bareau and I gave a similar paper,[2] hoping to describe the issues encountered when designing the optics for such small cameras. Eight years later, there has been significant evolutionary improvement to the "conventional" mobile phone camera, and there are new technologies on the horizon, many based on computational optics, that may change the landscape.

We said in 2006 that, compared with a 35mm film camera, the lens in a miniature camera module (MCM) is roughly an order of magnitude smaller in size and cost. That is probably an understatement today, and of course production quantities are extremely large. Successful products are manufactured by the millions per month.

Now, there are two cameras in typical "smart" phones, and since 2006, camera lens specifications have been evolving:

| Item | 2006 | 2014 primary | 2014 secondary |
|---|---|---|---|
| Pixel size | 2.8 um | 1.1 to 1.4 um | 1.1 to 1.4 um |
| Pixel count | 2 to 3 MP | 5 to 8 MP | 1.3 to 3 MP |
| Autofocus? | Sometimes | yes | no |
| f/number | 2.8 | 2.8-2.4 | 2.4-2.0 |
| Full field of view | ~60° | ~70° | ~75° |

## 2. IMAGE SENSOR DEVELOPMENTS

### 2.1 Pixel Size

The trend to smaller pixels has continued, although perhaps at a slower rate. We can see in Fig.1 how the pixel size has been approaching the wavelength of visible light, and there are sub-micron pixel designs coming in the near future. Developments in the silicon design, such as back side illumination, have improved the sensitivity and reduced directionality of the focal planes. This has allowed the implementation of smaller pixel sensors with acceptable low light performance, and it has somewhat relieved the specification requirement for chief ray angle, which helps the lens design.

What is the motivation for smaller pixels? We believe there are three things driving pixel size down, in descending order of importance:

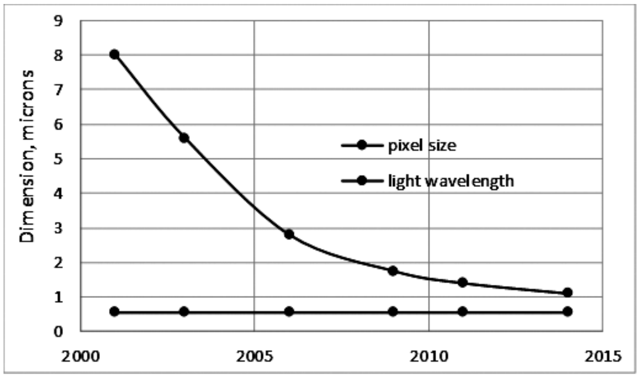



Figure 1. Historically, typical pixel size has been decreasing, getting closer to the wavelength of visible light.

1- Cost. The silicon detector and processor is the highest cost component of the camera module. It can represent nearly half of the cost, while the lens assembly is more like 15% of the camera module cost. Smaller pixels mean a smaller area of silicon, lowering cost.

2- Camera size. If the focal plane is smaller, the lens focal length can be smaller, reducing z-height, which is a critical dimension for achieving thin devices.

3- Resolution. Higher pixel counts appear to be a lower priority, now, although there are cameras being introduced that are pushing beyond 10MP.

### 2.2 Microlenses and focal plane directionality

As in 2006, the CMOS image sensors use an array of microlenses, one for each of the R, B and G pixels. They are intended to image the exit pupil of the camera lens onto the sensitive area of the pixel, which is below the surface of the sensor. It is important for the lens designer to understand that the microlens array is the true image plane of the system, and the microlenses effectively increase the sensitive area of the pixel to nearly 100% of the pixel dimension. (See Fig.2[1])

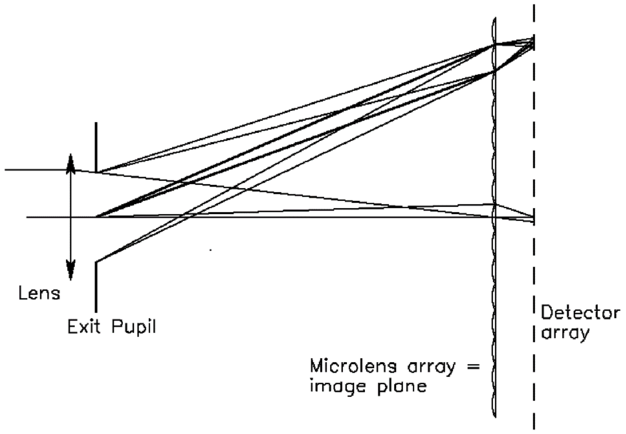



Figure 2. Illustrating the function of the microlens array.

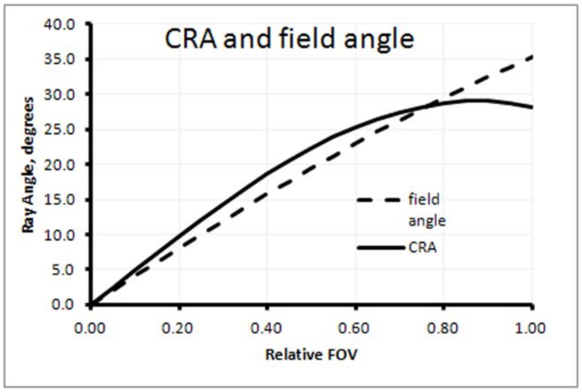



Figure 3. A typical plot of chief ray angle vs field (right).

The incidence angle of the chief ray on the sensor must be limited by the lens design, or else there will be light loss and color crosstalk. The field of view specification has been growing larger since 2006. We believe this is to enable shorter focal length lenses, with shorter z-heights, helping to achieve shorter cameras. Corner to corner FOV's were around 60 degrees in 2006, and they are now often specified at 70 to 75 degrees. At the same time, chief ray angle had been limited to well below 25 degrees in 2006, and it is now nearly 30 degrees. (Fig.3[1])

Relative illumination has been required to be no worse than $\cos^4$, approximately 50% for a 60 degree FOV, and it has recently been relaxing to around 40% as FOV increases – a necessary concession. Vignetting is still not allowed, since the lenses are always used at full aperture, unlike lenses for larger digital still cameras.

## 3. LENS CONSTRUCTION

### 3.1 Basic lens assembly construction

Conventional lens designs are multi-element injection molded plastic lenses assembled in a plastic barrel, as they were in 2006. There is no mechanical shutter or fixed aperture, of course, because the mechanisms would be prohibitively large and expensive.

### 3.2 Plastic optical materials

Optical plastics have improved since 2006. (Fig.4) While optical properties have improved some, the dramatic improvements have been in physical properties. The newer materials (COP, COC and OKP4, for examples) are easier to mold and to coat. Moisture pickup is reduced. Some older materials, like PMMA, would absorb water over time, and refractive index would change significantly. Also, stress birefringence (a problem with PC) is reduced, avoiding unwanted aberrations from the molding process.

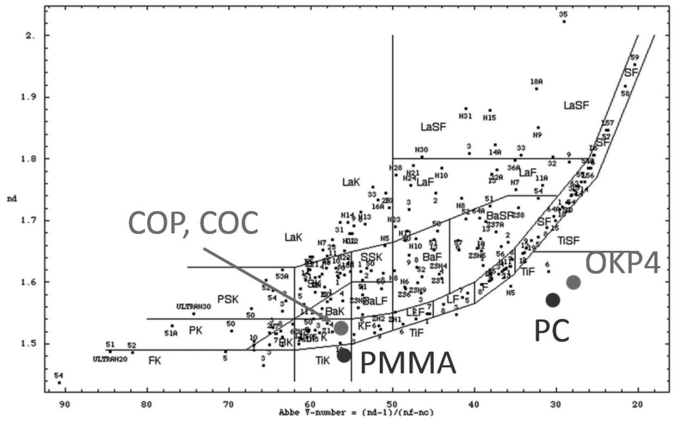



Figure 4. Glass map indicating plastic optical materials.

### 3.3 Wafer level optics

An unconventional alternative has been produced, called "wafer level optics," WLO. Lenses are made in large wafers, perhaps thousands at once, and the wafers are stacked, with spacers and baffles, to create arrays of lens assemblies. The silicon wafer that contains the image sensors can be included in the assembly. This has the potential of reducing cost dramatically, but it also imposes constraints on the lens design. WLO designs have been produced, but they have been limited to the smaller, simpler cameras, so far.

### 3.4 Lens construction and assembly tolerances

In 2006, we emphasized the difficulty of controlling centering tolerances, and that is still an important issue today. The extremely small scale of these lenses means that centering tolerances must be proportionately small. Centering requirements vary with design, but can easily be below 5 microns decenter of individual surfaces and some lens elements. This is not easy to achieve, considering the molding process, where two halves of a large multi-cavity mold must maintain centration. Manufacturers control the effects of tolerances in several ways, from design through manufacture:

1- Design for tolerance insensitivity. For example, multi-configuration optimization allows the designer to include the effects of tolerances in the design merit function.
2- Element manufacture. Careful design and construction of manufacturing tools and processes is essential.
3- Assembly strategies. Determination of the best combinations of cavities and assembly orientation. Also, sometimes active alignment is useful, for example, for tilting the lens above the sensor to correct field tilt.

## 4. OPTICAL DESIGN

The designs of these MCM lenses are very different than those we are used to seeing for larger cameras. Why?

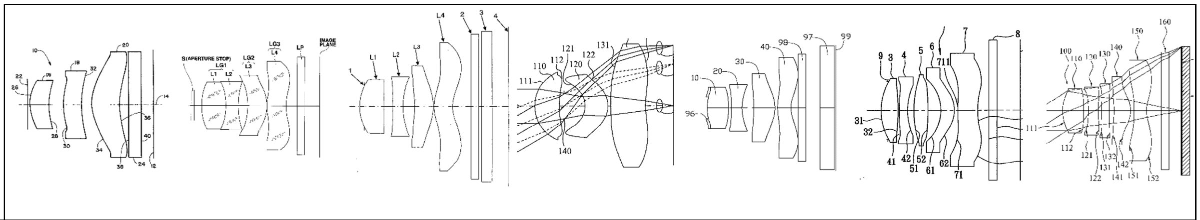
1- Product requirements. Shortest possible length. Chief ray angle and relative illumination requirements.
2- Plastic materials. For cost, and to allow the aspheric surfaces necessary for performance.
3- Small scale. Designs are influenced by tolerance requirements, and lens elements will be relatively thicker and larger, when compared with the size of the image.

### 4.1 Historical look at patented designs

Looking at the patent record can give us an idea of the history and variety of these miniature digital camera lens designs. There are several characteristics that separate this class of lenses from more traditional wide-angle camera lens designs:

1- Telephoto ratio is usually less than 1.3.
2- Aperture stop is close to the front of the lens.
3- f/number is between f/3 and f/2, and corner to corner FOV is 60 to 75 degrees.
4- Extensive use of aspherics, including a large final surface, which is concave in the center and turning back before the edge of the surface.

We might refer to them as "wide angle-aspheric field flattened" (WA-AFF) designs. This collection of patented designs is not exhaustive, but it does illustrate the variety of designs and give us some idea of the historical record.



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| SOURCE: | US 6,441,971 | US 6,476,982 | US 7,277,238 | US 7,477,461 | US 7,408,723 | US 8,072,695 | US 8,605,367 |
| inventor/ assignee | Ning/Ning | Kawakami/Casio | Noda/Largan | Bareau/Flextronics | Lin/Hon Hai | Lee/Genius | Tsai/Largan |
| priority year | 1999 | 2001 | 2005 | 2006 | 2007 | 2010 | 2011 |
| SPECS: pixels | 0.3 MP | 1.3 MP | 2 MP* | 1.3 MP | 3 to 5 MP* | 8 MP* | 8 MP* |
| | f/2.8 | f/2.85 | f/2.83 | f/2.97 | f/2.83 | f/2.4* | f/2.45 |
| full FOV | 64 deg | 61.4 deg | 69.6 deg | 62 deg | 64.3 deg | 60 deg | 66.2 deg |
| DESIGN: | 1G-2P | 2G-2P | 4P* | 3P | 4P | 5P | 5P |
| materials | SK16-PMMA-PMMA | LASF3-SF63-PMMA-PMMA | 407.704-PC-COP-COP | COP-PC-COP | COP-OKP4-COP-COP | COC-OKP4-COC-COC-COP | COC-OKP4-OKP4-COC-COC |
| tele ratio | 1.26x | 1.29x | 1.13x | 1.37x | 1.28x | 1.25x | 1.22x |
| aspheres? | S-S / A10-C / C-A10 | S-S-S / A6-A10 / A10-A10 | S-S / A10-A10 / A10-A10 / A10-A10 | A10-A10 / A10-A10 / A10-A10 | A10-A10 / A10-A10 / A10-A10 / A10-A10 | A10-A10 / A10-A10 / A10-A10 / A10-A10 / A10-A10 | A12-A12 / A12-A12 / A12-A12 / A14-A16 / A16-A16 |

* not certain from patent information

The earliest patented WA-AFF design that we found was from 1999. (It would be interesting to learn about earlier ones, if they exist.) In the chronological progression above, we see materials shifting completely to the newer types, and the use of high-order aspherics becoming more uninhibited. (We describe the aspheres by the highest order non-zero coefficient listed in the patent, with S for sphere and C for pure conic.) Glass elements were used in early designs to reduce Petzval sum and sometimes to correct longitudinal chromatic aberration. All of the designs are stop in front, except the fourth example (3P designs are frequently not stop in front.)

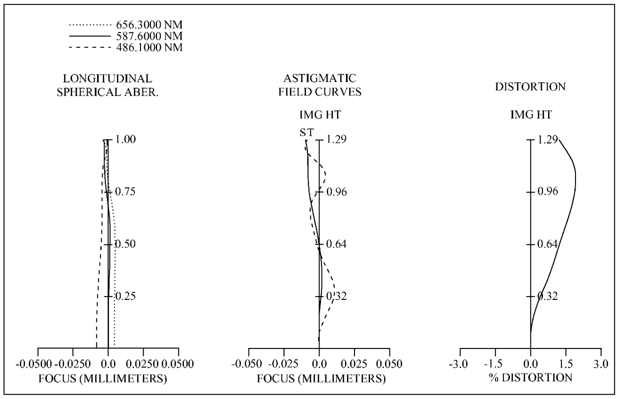



Figure 5. Field aberrations, USP 8,605,367.

### 4.2 Is it possible to understand how these designs work?

If we consider small field angles, third-order aberrations make sense. For example, the negative last surface reduces Petzval sum, controlling field curvature. It cannot continue, though, because the chief ray angle would become much too large. At higher field angles, the aspheres become dominant.

Lateral chromatic aberration, distortion, field curvature, and astigmatism, in particular, are corrected by the interaction of multiple high-order aspheric surfaces, see Figs. 5 and 6. This is remarkable, because the front stop designs get no help from stop symmetry in the correction of distortion and lateral chromatic aberration, and the plastic material choices are limited. This observer cannot come up with a simple explanation for it. [J. Sasian discusses the use of aspheres to correct field curvature in another paper at this conference, though.] We would expect that the very strong aspherics and high ray incidence angles increase alignment tolerance sensitivities, making the practical success of these lenses even more impressive.

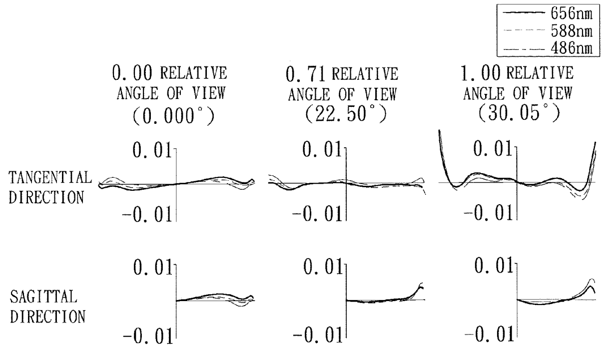



Figure 6. Transverse ray aberrations, USP 8,072,695.

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