# 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.

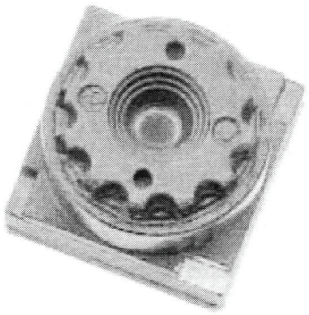

Fig.1: This 3.6um pixel VGA camera module is 6.05 x 6.05 x 4.5 mm.
The most critical dimension is the 4.5 mm axial length.

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

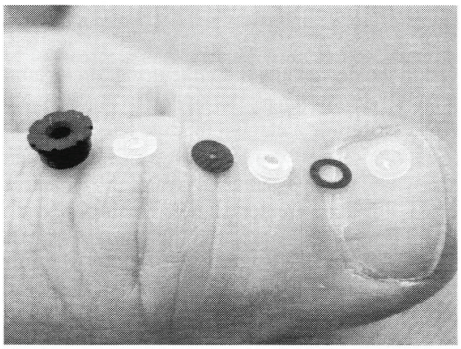


Fig.2: 3-element lens, disassembled. Barrel, three plastic aspheric lenses, thin sheet aperture stop and baffle.

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% |

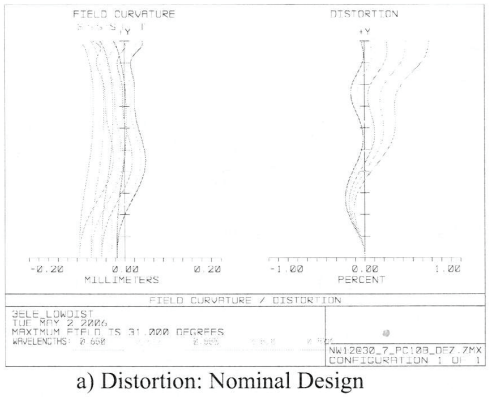
FOV - The field of view for these systems is typically 60 to 66 degrees across the sensor diagonal, but the design must include a slightly larger angle to allow for correction over the image circle.

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.

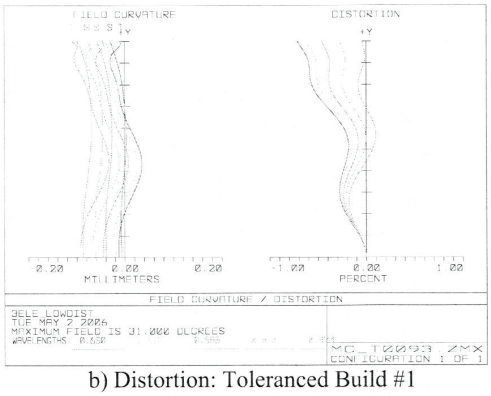
TTL- The total track length is the distance from the front of the barrel to the image plane, this has to be longer than the optical track length by at least 0.050mm in order to protect the front of the lens. This is extremely important to the cell phone designers because of the market pressure to produce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

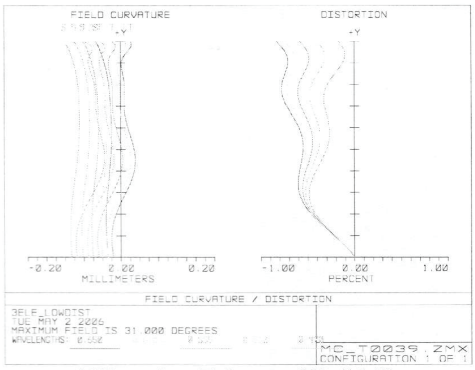
Distortion – The usual distortion requirement is <2% optical distortion or <1% TV distortion. Although this sounds like a much more stringent requirement than the 4% typically allowed in traditional 35mm camera lenses, the distortion curve can vary significantly from assembly to assembly due to build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



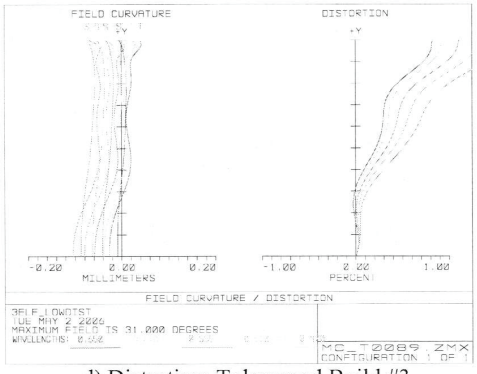

a) Distortion: Nominal Design




b) Distortion: Toleranced Build #1



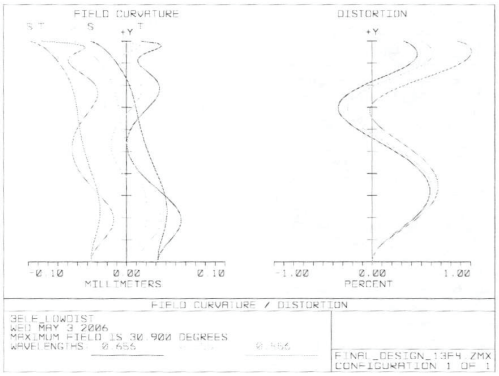

c) Distortion: Toleranced Build #2



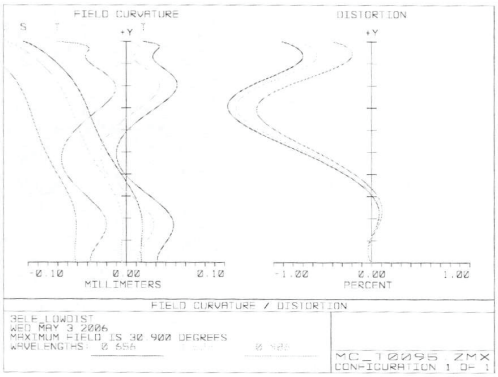

d) Distortion: Toleranced Build #3

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.

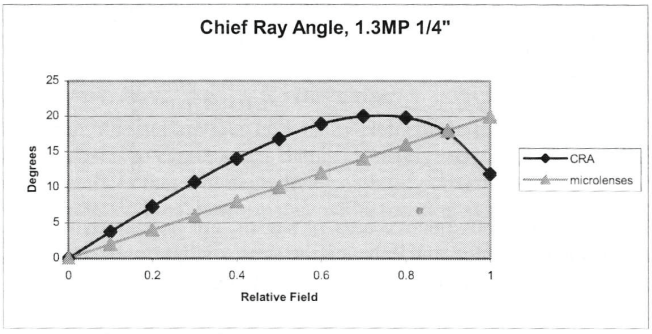



Fig.5: Chief Ray Angle and Microlens Optimum Acceptance Angle as a Function of Relative Field

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:

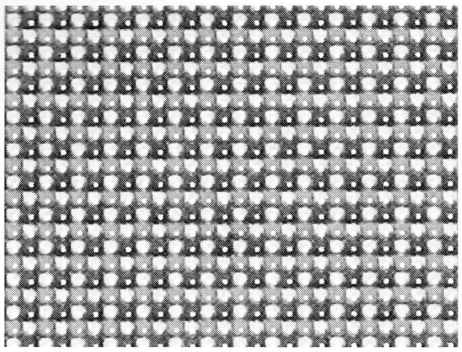


Fig.6: Photomicrograph of a portion of a Bayer pattern sensor. 2.8um pixels.
Note the specular highlights from microlens surfaces.

The surface of the detectors is not uniformly sensitive, though. Circuitry integrated with the sensor reduces the active area significantly. To improve sensitivity, an array of microlenses is applied to the top of the sensor:

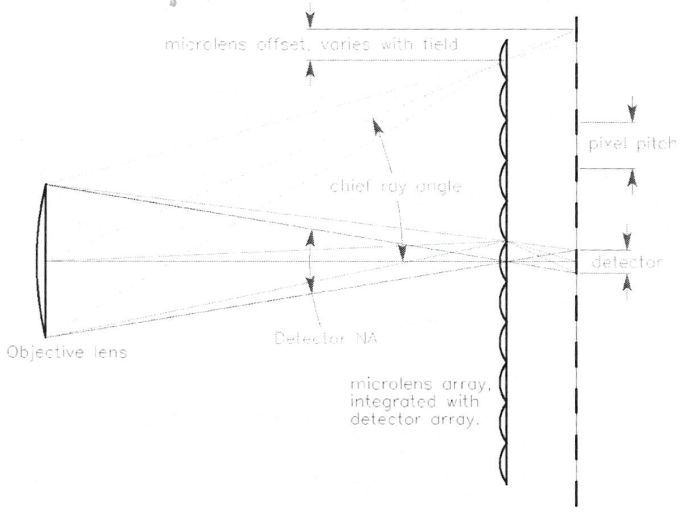



Fig.7: Microlenses located above active area of sensor, are positioned relative to pixel location based on expected incident angle and enhance the sensor's light collecting ability by magnifying the effective area of each pixel. [Highly schematic drawing, not to scale.]

These lenses act as condensors, relaying the sensor image to the exit pupil of the lens. This increases the apparent size of the detectors, improving sensitivity, because the diameter of the microlens becomes the apparent size of the detectors. The plane of microlenses is effectively the image plane of the system. The microlensed detectors now have limited angular response; if the exit pupil of the taking lens is increased beyond the size of the detector image, system sensitivity does NOT increase. In practice, the microlenses are not perfectly formed, so their imaging is crude, but they do improve performance.

The CRA curve illustrated in fig.5 represents a lens designed for a maximum CRA value of 20 degrees. The purpose of the CRA constraint is to maximize the light collection efficiency of the microlenses. Instead of centering each microlens on its pixel, the sensor manufacturers have offset the center of each microlens in order to compensate for the incidence angle of chief rays. Ideally the microlens distribution would exactly match the CRA variation of the lens it was to be used with, but this is not generally seen in practice. Typically the microlens offsets vary linearly with radial position from the center of the sensor, and are designed to minimize CRA/microlens mismatch based on expected lens CRA

curves. The effect of mismatch is a drop in light collection efficiency or decreased relative illumination at the image, or cross-talk between microlenses and adjacent pixels, resulting in false coloration.

Today, maximum CRA specifications for different sensor formats are readily available in the <12 degree to <26 degree range, with the larger CRA allowances corresponding to smaller VGA formats (2.2um, 3.6um). The demand for shorter TTL's is putting pressure on sensor manufacturers to increase their maximum allowable CRA values. Added constraints and fewer elements are lessening the lens designer's ability to deliver good image quality performance and low CRA's.

Relative Illumination – The relative illumination is the level of light energy incident at the image plane for a given field point relative to that at the center of the image.

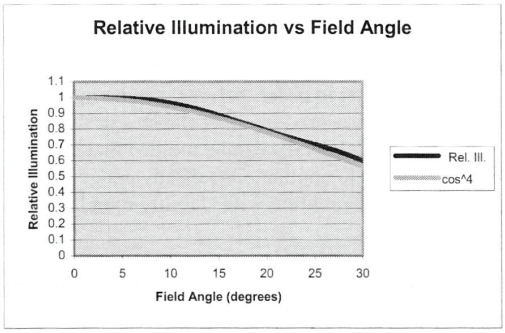



Fig.8: Relative Illumination and Cos^4 as a Function of Field Angle

The blue curve in fig.8 is a typical relative illumination plot. Lens specifications usually require a value greater than 50% at the edge of the field. This corresponds roughly to cos^4, so there is rarely enough corner illumination to allow vignetting for aberration control. If relative illumination meets the requirements, the final image is corrected electronically. Also, it's important that the drop in the relative illumination curve is not precipitous towards full field, or a slight decenter of the sensor relative to the optical axis will cause one corner of an image to appear noticeably dark.

## 5. Designing

When first beginning a lens design, it is not obvious how many elements to use or which materials. The biggest challenge in designing these systems is to create a lens that is insensitive to tolerances and will perform well when built. Each additional element adds tolerances that will degrade the as-built performance. But each element also adds variables that can be used to increase nominal performance while meeting system and manufacturing constraints.

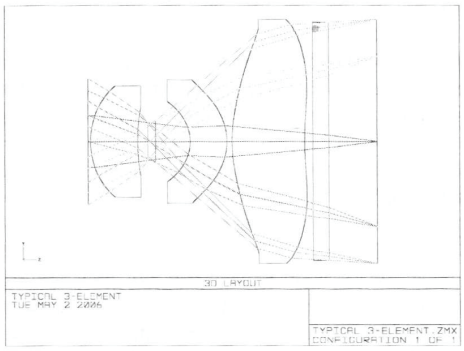



Fig.9: A typical 3-plastic element (3p) imaging system.

The three-element form is very common (fig.9), and a good place to start. Just about every camera module lens manufacturer has a lens of this form in their offerings. Designs tend not to be stop-symmetric. The aperture stop is usually towards the front of the lens, often before the first element, which helps CRA and TTL. The majority of these lenses are all-plastic although some incorporate one glass element (usually the front element) for the advantages of high-index refraction and color correction. Plastic elements are almost always bi-aspheric, and frequently the aspheres are not subtle! The shape of the last lens surface in the design above is typical. Four element systems provide high performance, but are only viable when the TTL is relatively large (>6.0mm), otherwise the performance degradation due to tolerances cancels out the nominal gain. Four element systems are mostly found in cameras with ¼" sensor formats or larger, though they are becoming less common. Likewise, the effectiveness of a 3-element approach decreases to the point that a 2-element system becomes more practical when the TTL is less than 4 mm.

Part of the selection process, when considering materials, is the cost of satisfying the manufacturing constraints. Plastic injection molded optics have minimum edge thicknesses, minimum center thickness and a range of acceptability for their center to edge thickness ratio that must be met in order that they can be molded. Additionally, the maximum slope that can be diamond-turned in mold inserts and measured in either the lens or the mold is around 45 degrees. One big advantage of plastic is that flanges with mechanical details can be molded that eliminate the need for spacers and allow for mechanically driven centering of one element to another. One disadvantage is that there are very few plastic materials that lend themselves to precision optical molding with stability over large ranges of temperature and humidity, so the choices are limited.

Traditional glass lenses have similar types of requirements but with different values, based on their own manufacturing processes. The inability of lens manufacturers to accurately center the outer dimension of these elements on the optical axis, makes precise mounting very difficult. The benefits of traditional glass is reduced as the TTL requirements become shorter.

Another option becoming more readily available is molded glass, allowing the advantages of both high index and aspheric correction. Some current issues with molded glass are the small number of flint-type glasses available for molding, surfaces with inflections can only be used under very limited circumstances and flanges can only be formed in a restricted range of shapes, no sharp corners or abrupt changes in slope are allowed. Cost and manufacturing capacity also limit the use of molded glass elements today. Nevertheless molded glass can be the lens type of choice when the goal is stability over extreme ranges of conditions, or great lengths of time.

## 6. Performance Requirements

Lens performance for digital sensors is commonly expressed in terms of MTF at spatial frequencies between Nyquist/2 (Ny/2), and Nyquist/4 (Ny/4). The Nyquist frequency is 1/(2*(pixel size)), so for 5.6um pixels Ny/2 is 45 lp/mm and Ny/4 is 22.5 lp/mm; for 1.75 pixels Ny/2 is 143 lp/mm, Ny/4 is 71.4 lp/mm.

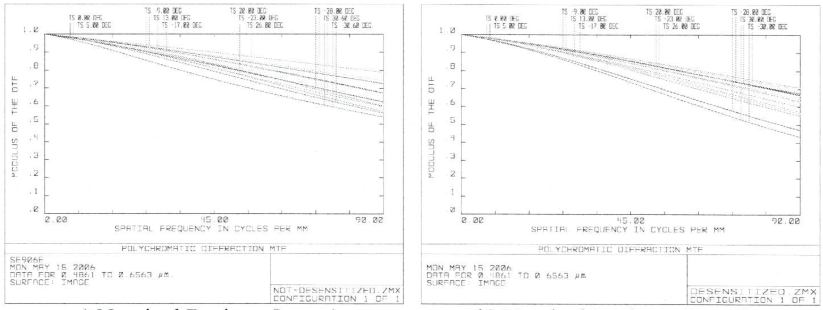
Initially, when pixel sizes were relatively large (5.6um), cell phone manufacturers would specify MTF performance for Ny/2 and even Ny. This was because Ny/2 was still a relatively low frequency, so the requirements were possible to meet. As pixels became smaller (3.6-2.8um), the specifications gravitated to significant response at Ny/4 and Ny/2. These requirements were more challenging, but the size was allowed to grow to help satisfy the MTF requirements. At the same time the tooling capability of manufacturers was increasing so that build tolerances could be decreased, improving performance. The combination of these factors allowed delivery of high performance camera modules. And then the drive to reduce TTL began.

As cell phone manufacturers began demanding smaller and smaller camera modules to be able to offer extremely thin cell phones, image quality became secondary to size. Today most cell phone manufacturers understand that imposing severe size restrictions will significantly compromise image quality, and they are willing to accept worse performance based on Ny/2 and Ny/4 MTF response than with previous camera modules. This means that the image quality of 2MP camera modules are not all alike; as the pixels get smaller the image quality will be worse, and even newer, thinner

versions of cameras based on the same sensor will have worse performance. The opposing requirements of good image quality and short TTLs coupled with the shrinking size of pixels are rapidly running into the limitations of physics.

## 7. Tolerance-limited Design

The lens designer must consider manufacturing tolerances at the optimization stage, compromising nominal performance to achieve improved as-built performance. Nevertheless, manufacturing processes are not always available to achieve the necessary tolerances. One of the most challenging aspects of designing lenses for camera modules is desensitizing the system. If sensitivity to manufacturing tolerances is not built into the merit function, then the lens will not be manufacturable.




a) Nominal Design - Lens A b) Nominal Design - Lens B

c) 50th Percentile Build - Lens A d) 50th Percentile Build - Lens B

Fig.10: a) and b) Nominal MTF curves for two lens designs, lens B has been desensitized to the effects of manufacturing tolerances, lens A has not; c) and d) 50th percentile MTF curves representing a typical manufactured lens, based on simulated builds. The manufacturable MTF performance of lens A is greatly deteriorated from the nominal, the performance of lens B holds up much better when manufacturing tolerances are applied.

Fig.10 illustrates the impact of including desensitization in the optimization process. As the MTF curves clearly illustrate, a desensitized lens generally has slightly lower performance than a lens that has not been desensitized, but the benefit in the performance stability of manufactured systems more than offsets this difference, improving the overall performance of the manufactured lens population.

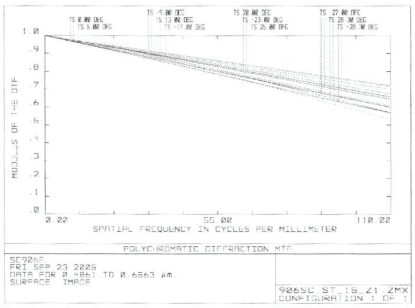
Due to the significant risk that an unfortunate combination of build tolerances will produce a lens with unacceptable performance, most lenses for miniature camera modules are 100% tested for image quality, usually with commercially available test systems that measure through-focus MTF. Performance is judged at representative points across the field, usually at one or two spatial frequencies. Evaluating MTF in two defocused planes can quickly expose field tilt or curvature problems.

The vast majority of systems are built in threaded barrels and focused at assembly, with no other alignments performed. Accurate, tight threads are difficult to produce, and they present measurement and contamination problems. Alternatives that allow alignments for lens to sensor centration and tilt are being implemented. As pixel counts get higher and sensor dimensions get smaller, these alignments are becoming more critical.

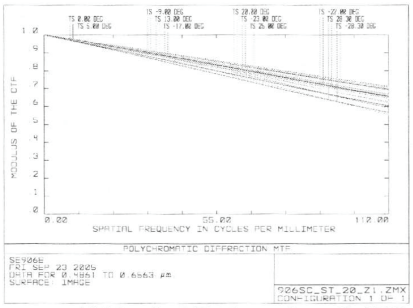
The problem of communication of quality between lens manufacturers and their customers is important. Manufacturers usually produce their own designs, and they are unwilling to share design data with customers. Also, actual manufacturing tolerance capability is not usually available, so it is not possible to verify the manufacturability of a new design. Standard methods of predicting production quality are needed to avoid unpleasant surprises during volume manufacturing.

## 8. TTL and Desensitization

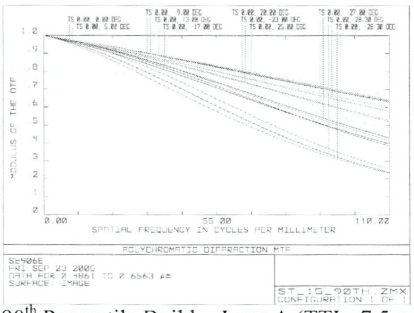
The ability of the designer to desensitize a lens is directly tied to the TTL and, for shorter forms, the BFL constraints. For instance, the 2MP 2.8um sensor required a lens with good performance over a large format. We were able to produce a lens that consistently delivers good image quality only because the TTL for this system was allowed to increase to as large as 7.8mm. The longer the TTL, the more modest the refraction needed at each surface, the weaker each lens can be and the less sensitive the performance of the system is to build tolerances. The more constrained the lens system in length, the more refractive power is needed at each surface, and the more sensitive the lens becomes to tolerance-induced image degradation.



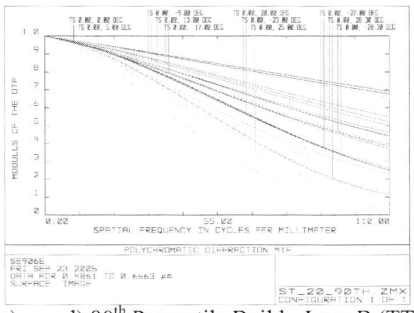

a) Nominal Design - Lens A (TTL=7.5 mm)




b) Nominal Design - Lens B (TTL=6.5 mm)




c) 90th Percentile Build - Lens A (TTL=7.5 mm)




d) 90th Percentile Build - Lens B (TTL=6.5 mm)

Fig.11: a) and b) Nominal MTF curves for two 4-element lens designs constrained by different TTLs, the performance is essentially identical; c) and d) MTF curves representing 90th percentile performance based on simulated builds. The longer TTL results in more consistently high performance.

The MTF curves in fig.11 illustrate the effect of TTL on desensitization. The additional constraint of conforming to a shorter TTL increases the difficulty of designing a manufacturable lens with acceptable performance and reasonable yields. Although this exercise was performed using a relatively long TTL lens (an older design), the same concept applies to today's shorter TTL designs for systems with three elements or more.

Two-element systems often naturally adopt forms with short TTL's, but desensitization to tolerances can require a relatively short BFL. Positioning the IR filter in such a system can be challenging. It is important for the back surface of the filter to be as far as possible from the sensor to ensure small surface defects and contamination are adequately out of focus. The closer to the sensor, the more restrictive the acceptability requirements on defect size. An IR filter positioned too close to the sensor could require such a tight scratch dig specification as to make it prohibitively costly or unmanufacturable.

The primary focus in recent camera module development has shifted from image quality to size and lens designers are being pressured to design lenses with shorter and shorter TTLs. Recent lenses for ¼" formats are being held to TTLs<5.0mm and there are plans for new lenses for the same format to be even shorter. Of course the pixels are smaller, so Ny/2 is higher (113.6 lp/mmfor 2.2um pixels, 142.9 lp/mm for 1.75um pixels) making the problem even more difficult.

## 9. Future Prospects

We believe that the race for smaller pixels is slowing, because Moore's law cannot shorten the wavelength of visible light, or increase the brightness of photographic subjects. Pixels whose dimensions are under 2 um have limited light-collection ability, and much faster f/number lenses are unlikely to be developed. The continuing pressure to design with very short TTL's both for packaging and cost considerations suggests that in the near term the customer can expect worse image quality from camera modules using sensors with these very small pixels. Perhaps the market will split, to allow a choice between low cost/very small/modest quality cameras, and more costly/larger cameras that can rival today's digital still cameras.

The path to sharpness improvement most likely involves a hybrid solution incorporating a desensitized lens design combined with improved build tolerances, active alignment at lens and camera assembly, image processing for improved depth of field, or all three. There are companies currently developing image processing methods to improve image quality and depth of field in digital images. These methods may allow us to build simplified, desensitized lens systems whose performance is corrected by digital image processing. There are, of course, tradeoffs to be made between sharpness, noise levels and electronic complexity. In each case there will be added costs; it will interesting to see what cost/image quality balance cell phone manufacturers finally select to offer their customers in the next generation of cell phone cameras products.