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Research Article

Optical design of camera optics for mobile phones

Thomas Steinich and Vladan Blahnik*

Carl Zeiss AG, Carl-Zeiss-Strasse 22, 73447 Oberkochen, Germany

*Corresponding author
e-mail: blahnik@zeiss.de
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Abstract

At present, compact camera modules are included in many mobile electronic devices such as mobile phones, personal digital assistants or tablet computers. They have various uses, from snapshots of everyday situations to capturing barcodes for product information. This paper presents an overview of the key design challenges and some typical solutions. A lens design for a mobile phone camera is compared to a downscaled 35 mm format lens to demonstrate the main differences in optical design. Particular attention is given to scaling effects.

Keywords: aspheric surfaces; mobile phone cameras; optical design.

1. Introduction

In 2011, approximately 1 billion camera mobile phones were sold worldwide. The majority of these compact camera modules (CCMs) have standard resolutions of 0.3 MP (VGA) to 3 MP and cost \$3.00–\$5.00 each. High-resolution CCMs for 5 MP, 8 MP and up to 12 MP still have a rather small market share of approximately 30%. However, this market share will grow significantly within the next few years, even though the cost of \$15.00–\$25.00 is considerably higher. Thus, this is a particularly interesting field for current product development.

It is interesting to note that nearly all CCMs have fixed focal lengths. Mechanical zoom optics plays a very small role in this market primarily because of the increase in size and cost.

2. Design targets

In recent years the optical design of CCM optics has become increasingly challenging. In general, mobile phones are getting thinner and thinner. Consequently, the design space for optical modules within these mobile phones has shrunk with every new product generation. In contrast to this trend, the resolution has increased from 0.3 MP in 2002 to 12 MP at present.

Here is an example of a typical specification for a modern 12 MP mobile phone optical module (Table 1). The pixel pitch of pp=1.4 μm defines the maximum spatial resolution of the sensor according to the Nyquist sampling theorem:

$$V_{Nyquist}=\frac{1}{2\times pp}=357\frac{lp}{mm}$$

The diagonal full field of view 2 w=76° is similar to a 35 mm format lens which corresponds to a maximum image height of y'=21.6 mm and a focal length of f'=28 mm:

$$w=\arctan\left(\frac{y'_{\max}}{f'}\right)=\arctan\left(\frac{3.52\ mm}{4.52\ mm}\right)\approx\arctan\left(\frac{21.6\ mm}{28\ mm}\right)\approx 38°$$

The optical performance of the CCM according to Table 1 is specified in Table 2.

The modulation transfer function (MTF) criteria are related to the Nyquist frequency of the sensor. The complete imaging chain from lens to sensor to image processing can be described by multiplication of individual transfer functions in spatial frequency space. Usually the transfer function towards the Nyquist frequency tends to be zero. Therefore, it is best practice to define 'half Nyquist frequency' as the maximum frequency that is relevant for the complete imaging chain. Table 2.

3. Optical design layouts

In Figure 1 there are three typical optical design solutions for CCMs taken from the patent literature. Their basic system construction is often abbreviated by the number of lenses and their corresponding materials (p=plastic, g=glass).

4. Design task CCM vs. downscaled 35 mm format Biogon lens

To highlight the special tasks in designing optical systems for mobile phones, a 35 mm format Biogon lens (originally invented by Ludwig Bertele) is downscaled and compared to a CCM design with regard to typical design characteristics.

4.1. Scaling effects

A typical layout of a 35 mm format lens is shown in Figure 2 (left side). The lens has the following basic optical characteristics: f'=28 mm, $F\#$=2.8, $DFOV=2\times w=2\times 38°$.

Table 1 Basic optical layout of CCMs.

Basic optical layout		
Sensor size (semi-diameter of image circle)	y' (max)	3.52 mm
Pixel pitch	pp	1.4 µm
Sensor resolution	Number of pixels in x,y	approx. 4000×3000 12 MP
Aperture	$F\#$	2.8
Focal length	f'	4.52 mm
Diagonal full field of view	$DFOV$=2 w	76°
Module size	x×y×z	<1 cm^3
Optical total track from first lens vertex to image plane	s1-img	<7 mm
Filter package thickness in image space (IR-cut, cover glass)	d	0.3 mm
Minimum optical distance for focusing	MOD	100 mm
Maximum chief ray angle upon image plane	CRA	<30°

The system is downscaled by a factor of F=0.161. Thus, all geometrical values such as radii, thicknesses and semi-diameters are multiplied by this factor F. This results in a system having a focal length of f'=28 mm×0.161=4.52 mm. The wavelength λ is not influenced by scaling. Of course, the angular values aperture $F\#$=2.8 and diagonal field of view $DFOV$=2×w=2×38° remain constant after scaling [1].

For comparison we choose a 1g3p mobile phone design with identical optical characteristics (Figure 2, right side): f'=4.52 mm, $F\#$=2.8, $DFOV$=2×w=2×38°.

The MTF of an ideal (aberration-free) lens with circular pupils can easily be calculated [2]. The transfer of structural information is limited by the ratio of the numerical aperture of the lens to the wavelength of light and the resolution limit for incoherent imaging is given by:

$$v_{cut\text{-}off}=\frac{2NA'}{\lambda}=\frac{1}{\lambda\times F\#}.$$

Figure 3 shows this ideal MTF of a diffraction-limited lens of aperture $F\#$ =2.8 (solid line) and a wavelength of 656 nm (red light). The blue lines show the MTF specifications at spatial frequencies of Nyquist/2=180 lp/mm and Nyquist/4=90 lp/mm: the difference from diffraction limitation is obviously much smaller compared to a 35 mm lens with corresponding spatial frequencies of approximately 30 lp/mm and 15 lp/mm. The dashed line represents the ideal MTF for $F\#$ =5.6: the specification could not be achieved for this aperture even for an aberration-free lens. Diffraction-limited optical performance of mobile phone optics is merely a necessity of dimension and not an outstanding quality feature.

This has two consequences: first, the relative aperture of a 35 mm format wide-angle lens becomes usually smaller towards the edge of the field (by approx. 1–2 stops) by vignetting at additional fixed stops within the lens. This is not possible for CCM optics as the contrast would severely drop or even fall to zero if the aperture were reduced. The second consequence refers to the behavior when the lens is stopped down: a 35 mm format lens has a variable stop which (in addition to exposure control) facilitates increasing the depths of focus – typically the contrast of a 35 mm format lens increases towards $F\#$ =5.6 or 8 compared to maximum aperture. By contrast, CCM optics would immediately lose contrast when stopped down. Almost all CCMs have a fixed stop.

The actual design MTF data of the scaled Biogon and CCM are shown in Figure 4 for an object positioned at infinity distance: the contrast values are comparable, the scaled Biogon having slightly higher contrast in the center of the field, whereas the CCM has higher contrast towards the edge of the field. The reason for the drop of contrast towards the field corner of the scaled Biogon is vignetting – the aperture decreases approximately 2 stops at the edge of the field.

4.2. Size

Downscaling the Biogon lens leads to an optical total track from the first lens vertex to the image plane of s1-img=10.2 mm. That means the optical total track is 1.7 times longer than

Table 2 Optical performance of CCM.

Optical performance		
Modulation at image center for half Nyquist frequency	MTF (y'=0 mm, 180 lp/mm)	>40%
Modulation at image center for quarter Nyquist frequency	MTF (y'=0 mm, 90 lp/mm)	>70%
Modulation up to 80% image circle for half Nyquist frequency	MTF (y'=2.816 mm, 180 lp/mm)	>30%
Modulation up to 80% image circle for quarter Nyquist frequency	MTF (y'=2.816 mm, 90 lp/mm)	>55%
Relative illumination at the image corner	RI (y' (max))	>35%
Distortion up to full image circle	DIST (y'=0 up to y' (max))	<3%
Lateral color up to full image circle	LACL (y'=0 up to y' (max); all wavelengths referenced to 546.07 nm)	<3 pixel

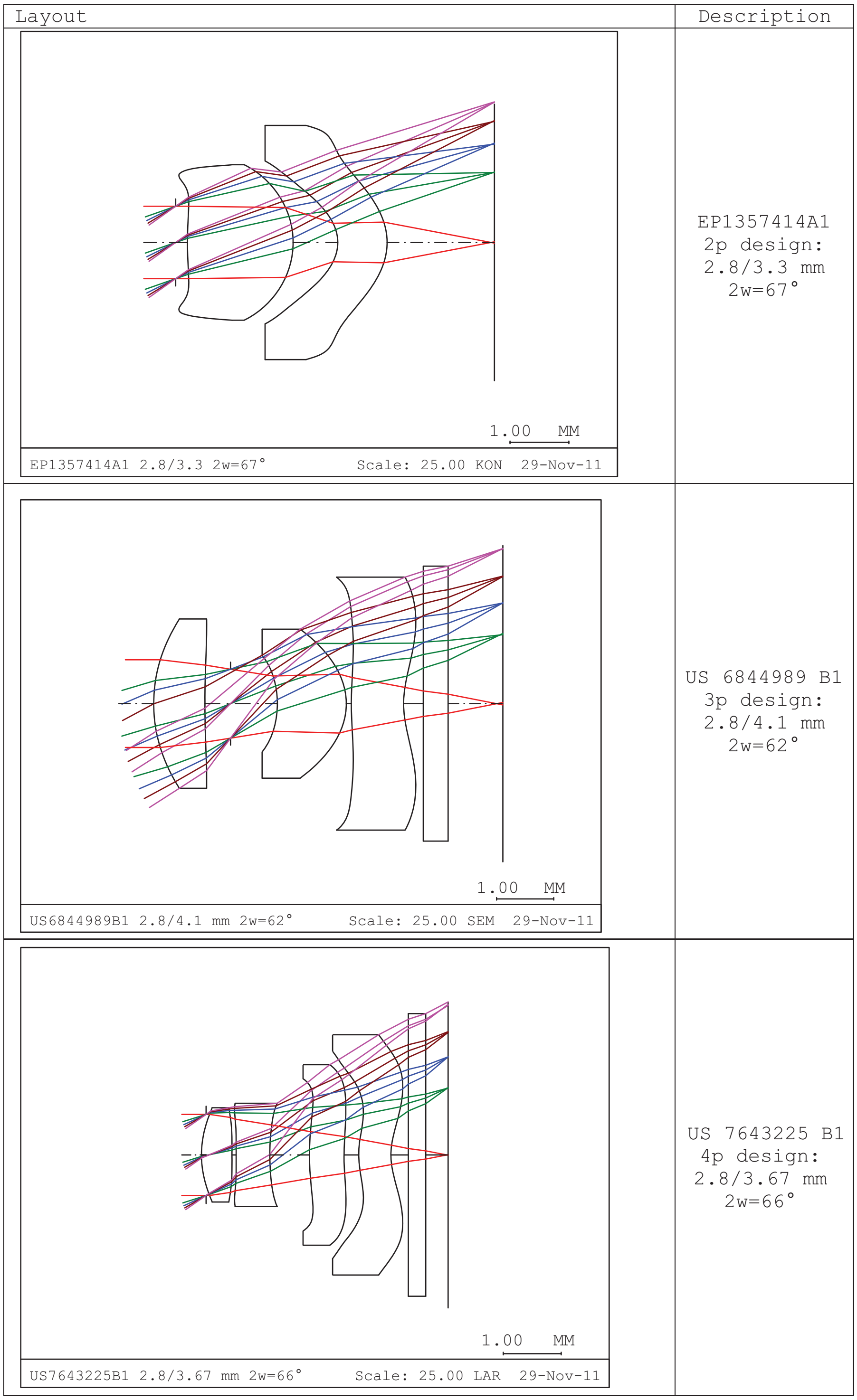

Figure 1 Three typical optical design solutions for CCMs from the patent literature.

the CCM design although the Biogon lens is already a rather compact design (in contrast to retrofocus layouts for SLR cameras).

It becomes clear that size is a very tight requirement and standard lens design solutions are not sufficiently small for CCMs.

4.3. Aberrations

As shown in Figure 2 the basic optical layouts of the two optical systems differ remarkably.

The downscaled Biogon lens represents a rather symmetrical setup with all spherical surfaces. The aperture stop

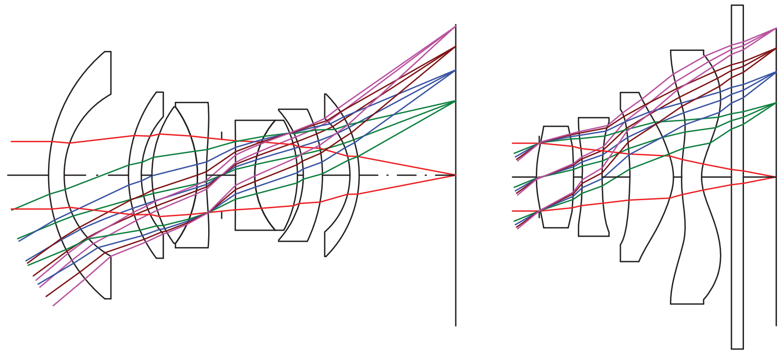

Figure 2 Downscaled Biogon lens (left), CCM (right).

is located between the two doublets. All lenses are made of glass. The general power distribution for the six elements is -/-/(+)/stop/(+)/-/-.

There are 14 radii, eight glass thicknesses, six air spaces within the lens and eight glasses. This makes a total of 36 parameters that can vary during optimization.

The CCM layout is an asymmetrical front stop system. All surfaces are aspherics mathematically described by the following polynomial [3]:

$$z=\frac{c\times r^2}{1+\sqrt{1-(1+k)c^2r^2}}+A3\times r^3+A4\times r^4+\cdots+A10\times r^{10}$$

where z=sag of the surface parallel to the z-axis, c=curvature at the vertex of the surface, k=conic constant, r=radial distance and A3 to A10=polynomial coefficients.

The first lens is made of glass and the other three lenses are made of three different types of plastics.

The power distribution is stop/+/-/+/-. There are eight radii, 72 polynomial coefficients including conic constants, four glass thicknesses, four air spaces within the lens and four lens materials. This makes a total of 92 parameters that can vary during optimization.

Obviously there is an abundance of variables for designing mobile phone optics with regard to the surface shape. Looking at the different types of aberrations present in rotationally symmetric optical systems, not all of them can be controlled by surface shape variables.

4.3.1. Longitudinal aberrations of the on-axis field

Figure 5 shows that the correction of spherical aberration is better for the all-spherical Biogon lens. In general, the use of aspheres for 35 mm format lenses is carefully considered as aspheres of these diameters are a significant cost driver. For example, they are specifically introduced close to the pupil planes to correct primarily spherical aberration [4]. In the CCM design the large number of aspheres is necessary to correct all types of aberrations.

Another aspect is the more rippled curve for the CCM example. Higher spatial frequencies in the surface shapes lead to higher order ripples in the wavefront during the optimization process. Therefore, it is essential for the optical designer to sufficiently sample the pupil to control these higher order effects.

Another issue in this context is longitudinal color. The left diagram in Figure 5 shows that all wavelengths have almost

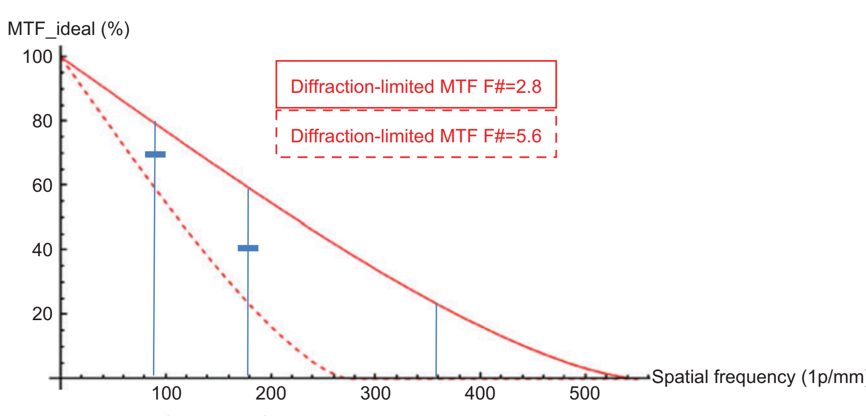

Figure 3 MTF of diffraction-limited lens at $F\#$=2.8 (solid line) and $F\#$=5.6 (dashed line) compared to the contrast requirements at the center of field of >70% at 90 lp/mm (Nyquist/4) and >40% at 180 lp/mm (Nyquist/2).

the same smooth curve and are separated by <25 µm. In contrast to this, the graphs in the right diagram differ remarkably: the Biogon basically shows secondary color, whereas the CCM has primary color in the center of the pupil. For the CCM the deviations in between the wavelengths are 50 µm at the center of the pupil and approximately 20 µm at the edge of the pupil. This is longitudinal color and spherochromatism. Color corrections of mobile phone optics are typically worse compared to all glass lenses on the corresponding pixel pitch scale. Aspheric surfaces do not provide any reasonable degree of freedom to correct longitudinal color. This color aberration is primarily influenced by material selection and power distribution. Mobile phone optics are predominantly made of plastics manufactured by injection molding (see section 3). Plastics cost little for high volume production and lenses can be produced in surface shapes with strong gradients. Disadvantages include reduced transmission and strong environmental dependencies [5]. There are only a few plastics available and they are all positioned in the lower right corner of the Abbe diagram (see Figure 6). For the correction of longitudinal color aberration it is beneficial to use materials with large differences in the Abbe number to correct the primary spectrum and similar partial dispersion for secondary spectrum reduction. Both requirements are strongly limited with the currently available plastics.

One possibility to overcome this limitation is to use one glass lens, preferably close to the stop position. This glass lens can be used to introduce material characteristics into the optical design which are not available with plastics. In particular, high Abbe numbers and anomalous partial dispersions from glass lenses help to further reduce longitudinal color and spherochromatism.

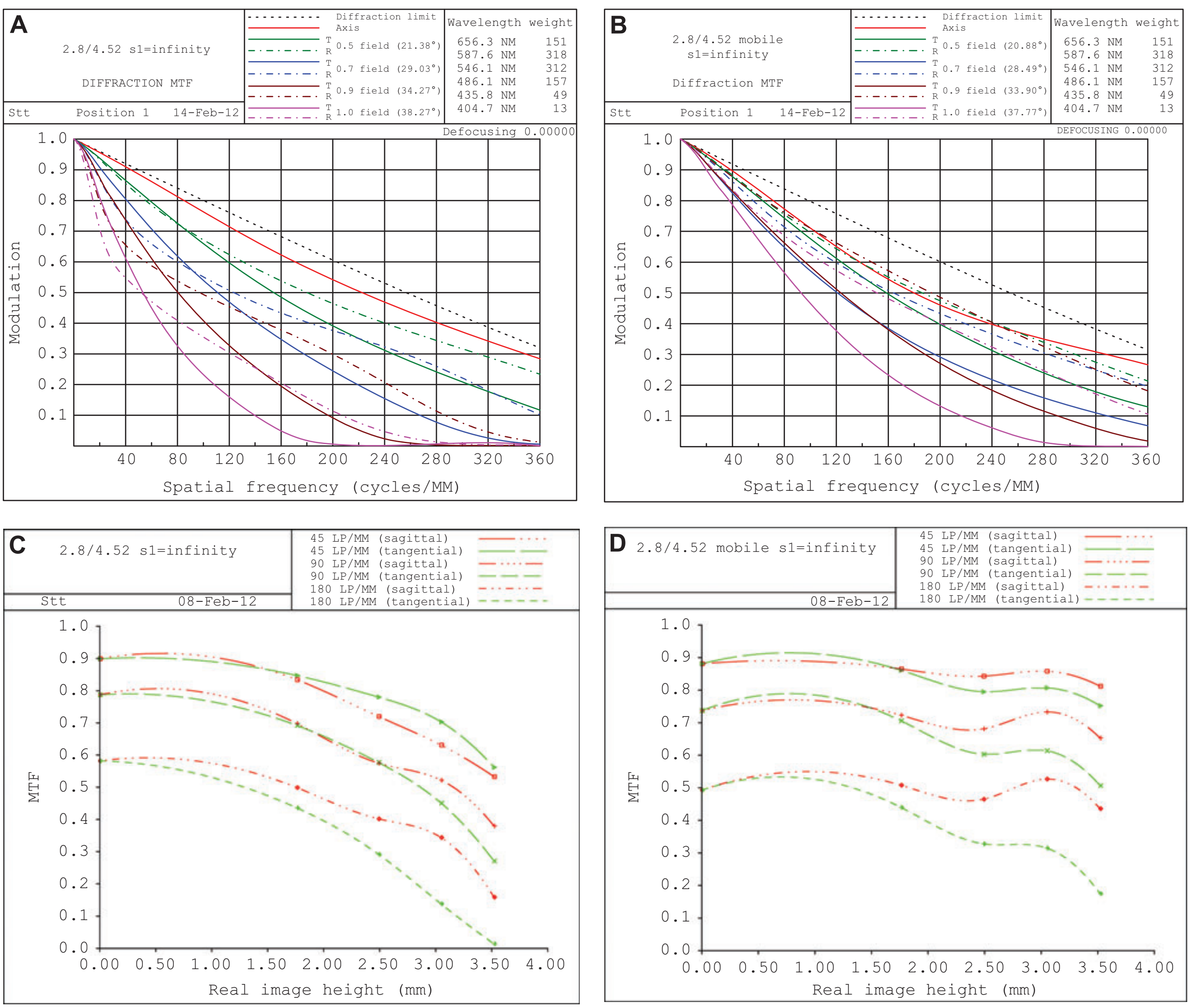

Figure 4 MTF design data (relative wavelength weights 656.28 nm–151; 587.56 nm–318; 546.07 nm–312; 486.13 nm–157; 435.84 nm–49; 404.66 nm–13) of (A) scaled Biogon vs. spatial frequency at different relative field positions, (B) CCM contrast vs. spatial frequency, (C) scaled Biogon contrast vs. field and (D) CCM contrast vs. field.

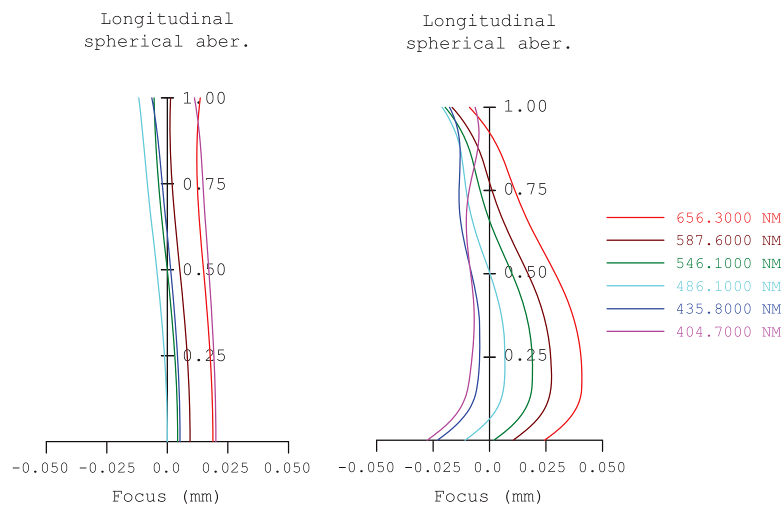

Figure 5 Focus deviation (x-axis) with regard to the normalized pupil (y-axis) for different wavelengths; downscaled Biogon lens (left), CCM (right).

4.3.2. Distortion In Figure 7, the difference in distortion correction calculated with the paraxial image coordinates obtained for an object at infinity can be seen. The distortion for the downscaled Biogon lens increases constantly with image height. The maximal distortion is -1.1% at the corner of the sensor. In general, distortion vanishes completely for symmetrical lens setups at the magnification β'=-1. Therefore, the almost symmetrical lens setup (see Figure 2) helps to correct this aberration.

For the CCM, distortion varies strongly over image height. The maximal distortion is +2.0% at 1.8 mm image height.

In general, spherical front stop lenses introduce negative distortion. However, owing to the aspheric surfaces (especially those closer to the image surface), distortion is controlled selectively for many image heights during optimization and even shifted to positive values. Therefore, it is important for the optical designer to sufficiently sample the field coordinate during optimization of this CCM lens. The strong aspheres can introduce strong gradients in distortion which are to be avoided because they result in unwanted inclination angles for horizontal and vertical lines [7].

4.4. Ray incidence angle on image plane

Sensors for CCMs normally use microlens arrays to increase their sensitivity. This helps in taking pictures in low-light situations. Steep incidence angles of the rays at the edge of the field of view can cause crosstalk to neighboring pixels on the sensor. This crosstalk can create unwanted additional color fringing especially at the corner of the image. To reduce this problem the ray angles need to be limited.

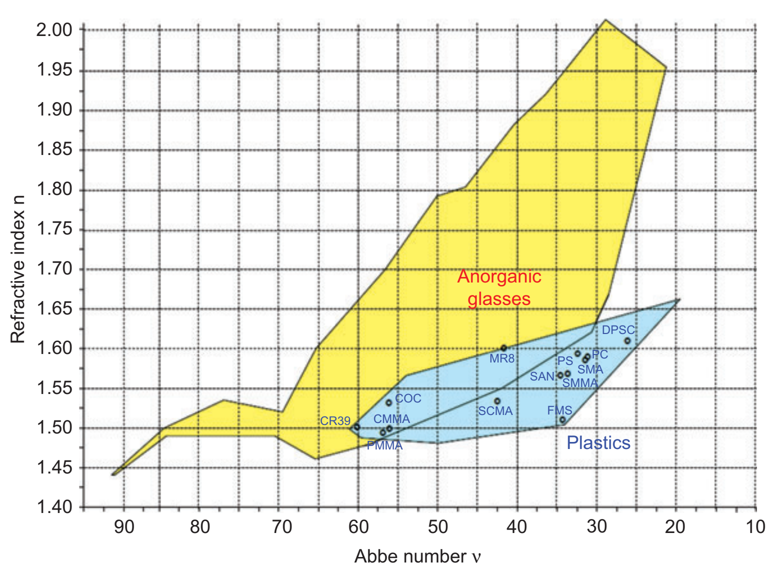

Figure 6 Abbe diagram of plastics compared to glasses [6]. Distortion over image height for λ=587.6 nm.

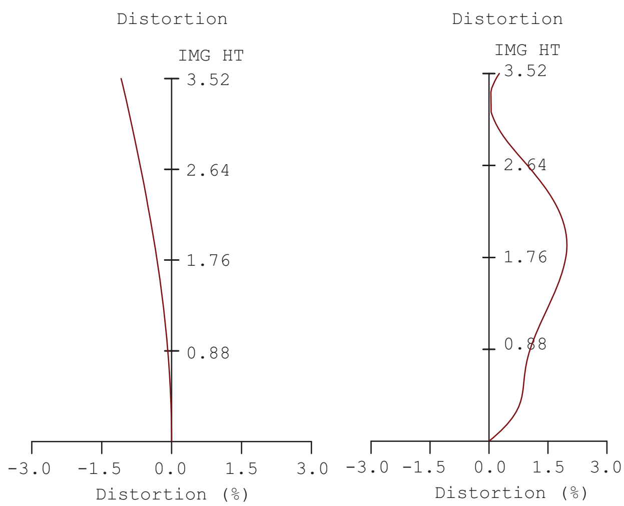

Figure 7 Distortion (x-axis) with regard to the image height (y-axis) at λ=587.6 nm; downscaled Biogon lens (left), CCM (right).

Normally, the chief ray angle upon the image plane is taken as the reference ray and limited to <30° (depending upon the sensor; see Table 1) during optimization.

Typically, the last lens closest to the image plane in a CCM design has a characteristic form to support this angle reduction (see Figure 2 and Section 3). In the outermost parts of the diagonal field of view the rays are strongly bent towards the z-axis. In Figure 8, the reduced incident angle from 80% to 100% field coordinate in the CCM design can be seen. By contrast, the downscaled Biogon lens shows a constantly increasing angle of incidence towards the maximum field coordinate.

4.5. Sensitivity

For high-volume optics, production yield is one of the key performance metrics. Therefore, the tolerance analysis is an essential and integral part of the optical design process. Sensitivity analysis is especially important for CCM designs because the individual tolerances are at the technological limit [8]. In addition, compensators such as lens longitudinal or lateral displacement to increase overall performance in a separate adjustment step are often not implemented, primarily due to production cost.

To compare the sensitivity regarding the lateral misalignment of both optical designs according to Figure 2, a tolerance analysis with the following input data is evaluated:

- All lenses are displaced 1 µm in x- and y-direction.
- The performance is measured as MTF at 90 lp/mm over the full field of view.
- The drop in MTF performance for all fields and tolerances is calculated and listed.

Displacing lens 1 next to the stop surface in the CCM design (see Figure 2) by 1 µm leads to a drop in MTF performance at 90 lp/mm (Nyquist/4) and for 70% relative field coordinate of -7.2% (see Table 3). The downscaled Biogon lens is less sensitive to this lateral misalignment by a factor of approximately 9 for the worst individual offender. The increased decentration sensitivity is primarily caused by the strong aspheric surface

Table 3 Ten worst individual offenders in MTF drop for the downscaled Biogon lens and CCM.

Ranking	MTF drop at 90 lp/mm for individual tolerances downscaled Biogon lens	MTF drop at 90 lp/mm for individual tolerances CCM
1	-0.8%	-7.2%
2	-0.7%	-6.7%
3	-0.7%	-5.6%
4	-0.7%	-4.2%
5	-0.7%	-4.0%
6	-0.6%	-3.8%
7	-0.5%	-3.1%
8	-0.5%	-3.0%
9	-0.5%	-2.1%
10	-0.5%	-2.0%

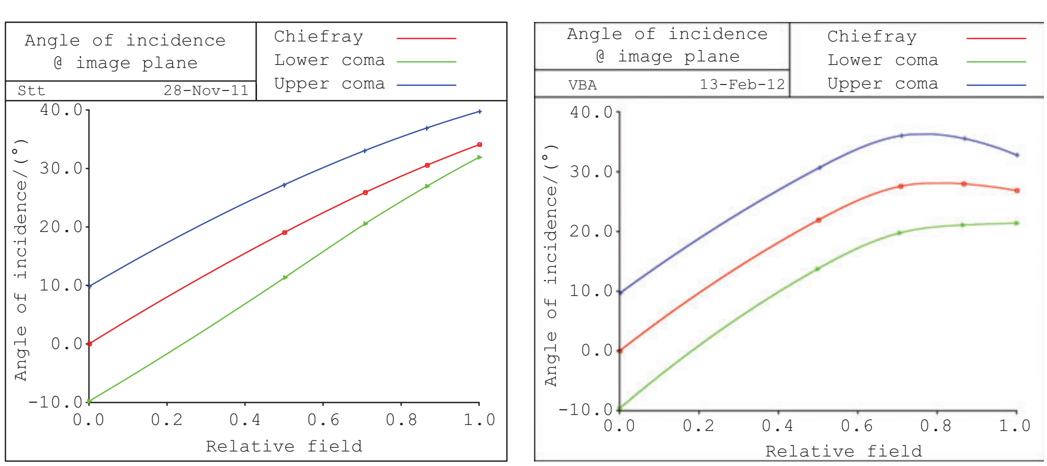

Figure 8 Angle of incidence at the image plane (x-axis) for three different reference rays with regard to the normalized image height (y-axis); downscaled Biogon lens (left), CCM (right).

shapes in the CCM design. As mentioned in Section 4.3, the footprints of every single field point are precisely located on the aspheric surfaces to minimize aberrations. Lateral misalignment shifts the individual locations of the footprints for every field point. Owing to the higher gradients in surface shape compared to the all-spherical Biogon lens, even small lateral shifts lead to remarkable performance drops.

5. Conclusions

The nominal optical performance of mobile phone optics is in the range of corresponding 35 mm format lenses. The design strategy and available degrees of freedom are very different. CCM designs are primarily driven by high aspheric aberration correction to achieve size and cost restrictions. Proper sampling in pupil and field coordinates is therefore necessary to control higher order aberration contributions.

The nominal MTF performance of CCMs is shifted close to the diffraction limit because of the small dimensions, whereas the MTF performance of 35 mm format lenses at maximum aperture is dominated by aberrations.

The large number of highly aspheric surfaces lead to an increase in misalignment sensitivities for CCMs. Thus, technological requirements are correspondingly demanding.

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Thomas Steinich was born on 4 March, 1980 in Stollberg, Germany. He studied Applied Physics and Optical System Engineering at the University of Applied Sciences in Weingarten including one semester abroad at the Swinburne University of Technology in Melbourne, Australia. In 2006 he received a Master of Science in Optical System Engineering on wavefront analysis in optical lithography. From 2006 to 2011 he was an Optical Designer in the R&D department for Jos. Schneider Optische Werke GmbH, Bad Kreuznach. Since 2011, he has been an Optical Designer in the Camera Lens Division of Carl Zeiss, Oberkochen.

Vladan Blahnik was born on 25 October, 1971 in Wolfsburg, Germany. He studied Physics at the Technical University in Braunschweig with a stay at the Optical Sciences Center in Tucson, AZ, USA. He received a PhD in 2002 on non-isoplanatic partially coherent imaging theory. Since 2001, he has been at Carl Zeiss Semiconductor Manufacturing Technologies in Oberkochen, Germany as a Project Leader in System Engineering focussing projection optics and illumination systems for optical lithography. Since 2008, he has been Head of the Optical Design Department in the Camera Lens Division of Carl Zeiss.