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Design of 13 Million Pixel Camera for Cellphone Applications

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We performed a thickness comparison of current cellphones on the market. On the basis of the results, we developed an optical system with six aspherical lenses, a total optical height of less than 6 mm, and an optical back focus of more than 1.0 mm to analyze and optimize various optical characteristic parameters using a ray tracing simulation program. The software used in this research is the optical simulation program ZEMAX, which is a sequential and nonsequential optical structure design and ray tracing simulation program for simulating the refraction, polarization, diffraction, and reflection of light. In this study, an optical system configuration with six lenses and 12 aspheric surfaces was used. ZEMAX was used to assist in the design of the optical system and aberration analysis, and the optical system was optimized to meet the specifications of the set photosensitive element. The lens was designed using APL5015AL, OKP4HT, and K26R_25 plastic materials, whose parameters are included in the material library of ZEMAX. Sequential ray tracing simulation using these parameters is a way of simulating the movement of light in the imaging optical system, also known as geometric optics. In the simulation of the sequential light, the medium is isotropic and homogeneous, and the light travels in a straight line. The design of the cellphone lens was used in the sequential ray tracing simulation to deal with problems including imaging quality, distortion, relative contrast, and tolerance analysis.

1. Introduction

Many researchers have tried to develop cellphone lenses with high performance. In 2008, Mou proposed the design of a cellphone lens with 3 million pixels and 2.75× optical zoom.[(1)] The design specifications were an aperture value of 2.75–5.13, a field of view (*FOV*) of 60º, a relative illuminance (*RI*) of greater than 65%, an optical distortion of less than 2%, and a traditional television (*TV*) distortion of less than 1%. When the spatial frequency of the modulation transfer function (*MTF*) was set to 80 lp/mm, *MTF* was greater than 45% and the total optical length was

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26 mm. An OV3630 matching sensor, which has a 1/3-inch complementary metal oxide semiconductor (CMOS) structure with 3 million pixels, a pixel size of 2.2 μm, and an imaging circle radius of 2.8 mm, was used. In 2011, Li *et al*. proposed and designed a cellphone lens with 8 million pixels.(2) The design specifications were four lenses, an aperture value of 2.45, *FOV* of 68º, RI of greater than 45%, a distortion of less than 2%, and a traditional *TV* distortion of less than 1%. When *MTF* was set to 100 lp/mm, *MTF* was greater than 50% and the total optical length was 7 mm. An Aptina MT9E013 matching sensor, which has a 1/3.2 inch CMOS structure with 8 million pixels, a pixel size of 1.4 μm, and an imaging circle radius of 2.855 mm, was used. In 2013, Yang proposed the design of a cellphone lens with 10 million pixels.(3) The design specifications were four lenses, an aperture value of 2.8, a relative contrast of 62.6%, *FOV* of 64º, an optical distortion of 0.62%, and a traditional *TV* distortion of 0.55%. When *MTF* was set to 120 lp/mm, *MTF* was greater than 50% and the total optical length was 9.96 mm. An OV10810 matching sensor, which has a 1/2.5 inch CMOS with 10 million pixels, a pixel size of 1.4 μm, and an imaging circle radius of 3.5 mm, was used. Before the CMOS technologies were applied in the optical camera system as the image sensor, it was very difficult to integrate some high-pixel mobile phone lenses in a designed mobile phone, and the total length of the integrated lenses generally exceeded 1 cm. However, with further development of the CMOS structure as the image sensor, the size of the integrated lenses has decreased and the pixel size has decreased from 5 μm to as low as 1.1 μm.

The concept of pixels in the systems of digital cameras has reached the stage of tens of millions of pixels.(4–7) The CMOS sensor used in camera phones can also accommodate tens of millions of pixel units in a smaller volume, so the imaging specifications of cellphone lenses are also increasing. When the number of pixels of the photosensitive element of a cellphone is increased, the imaging range of the lens, *FOV*, the back focus distance, the aberration quality, and other specifications must be improved. At the same time, to comply with the height design of cellphones, the total track length (*TTL*) of the lens has always been limited, making it necessary to use aspherical lenses to reduce the thickness of the lens. The architecture of the cellphone camera module is complicated and is divided into the sensor package architecture, the autofocus motor architecture, and the lens optical system architecture. Among them, the optical system architecture of the lens has the largest impact on the height of the camera module.

With the development of camera phones with tens of millions of pixels, people have gradually realized that the pursuit of high resolution does not necessarily result in high-quality photos. The developments of the optical system configuration of a cellphone depend on the desired reliability level of an investigated multilens structure. In this study, an optical system configuration with the structure of six lenses and 12 aspheric surfaces was designed for a 13 million pixel camera, and the optical simulation program ZEMAX was used to simulate the efficacy of the designed cellphone lens module. In addition, the mainstream design of cellphone lenses is a five-lens or six-lens architecture. The main advantage of the five-lens or six-lens architecture is that this number of lenses can increase the resolution and contrast of the lens, and reduce the dispersion, glare, aberration, and so forth. However, having many lenses in a limited space will mean that the lenses must be extremely thin, and too thin lenses will introduce highly technical barriers for mass production. Therefore, the cellphones currently on the market have up to six lenses.

Although an increasing number of lenses are being placed in cellphones and the architecture of camera modules is becoming increasingly complex, the basic design and optimization goals remain the same. Therefore, on the basis of the above discussion, we selected a reasonable initial lens structure and materials to design the camera for a cellphone, and the designed camera had 13 million pixels and a six-plastic-lens configuration.

2. Simulation Process and Parameters

In this study, ZEMAX was used for the design of the cellphone lens. This is a sequential and nonsequential optical structure design and ray tracing program for simulations of light refraction, polarization, diffraction, and reflection. Sequential ray tracing simulation is a way to simulate the movement of light in an imaging optical system, also known as geometric optics.[8] In the sequential optical structure, the medium was isotropic and homogeneous, and the light traveled in a straight line, as shown in Fig. 1.[8] In the design of cellphone lenses, sequential ray tracing simulation is used to solve problems of imaging quality, distortion, relative contrast, tolerance analysis, and so forth. In this research, an Omni Vision OV13853 photosensitive element was used to design the lens. This element has 13 million pixels and can be used to design the structure composed of six plastic aspherical lenses, as used in current cellphones. The specifications of the OV13853 photosensitive element are shown in Table 1.

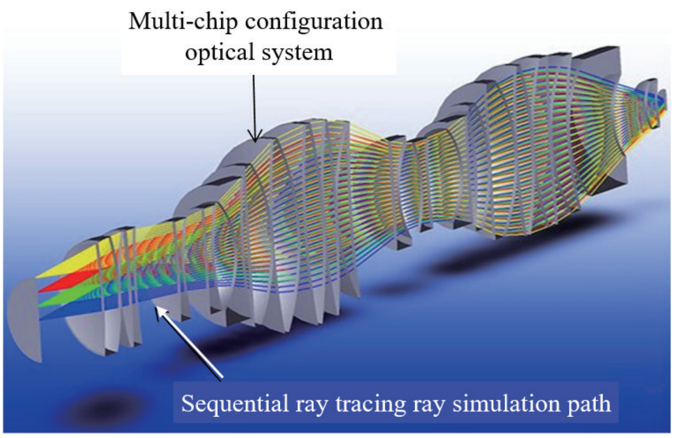


Fig. 1. (Color online) Example of ZEMAX software design.

Table 1
Specifications of OV13853 photosensitive element.

Item	Specification
Sensor lens size	1/3.06 inch
Lens chief ray angle (*CRA*)	32.15°
Sensor pixel size	1.12 μm × 1.12 μm
Image area	4815 μm × 3678.3 μm
Sensor die dimensions	6210 μm × 5517 μm

For the OV13853 photosensitive element, the required imaging circle radius was $\frac{1}{2}\sqrt{4815^2+3678.3^2}=3029$ µm; thus, the conversion unit was 3.029 mm. Therefore, the minimum imaging circle radius of the lens designed with OV13853 was 3.029 mm. Next, we set the size of the aperture (pupil). Because the aperture size mainly controls the amount of light entering the cellphone lens, the larger the aperture value, the less light enters the cellphone lens and the larger the depth of field of the camera. The aperture value is calculated as

$$F = EFL / \Phi, \tag{1}$$

where F is the aperture value, EFL is the effective focal length, and Φ is the entrance pupil diameter of the lens. The aperture value of the cellphone lens in this study was set to 2.2, following the trend of the market of larger apertures.

FOV of the phone lens was set. The lens in this study was designed with the rear lens of the cellphone as the main axis. Because the main range of the rear lens in the camera comprises long- and middle-distance scenes, *FOV* is above 60° in most market specifications, and we also set *FOV* to above 60°. The back focus distance of the cellphone lens can be divided into the back focal length (*BFL*) and flange focal length (*FFL*). *BFL* is the distance from the surface of the final lens of the optical system to the imaging surface and *FFL* is the distance from the surface of the final mechanism of the lens to the imaging surface. It was necessary to maximize *BFL* of the cellphone lens in this study to increase the margin in the *FFL* mechanism design; thus, *BFL* was set to ≥1 mm. Because the height of the camera module package is limited by the thickness of the cellphone product, the total height of the lens (*TTL*) required for the camera module is different for different products. *TTL* of the cellphone lens in this study was based on the thickness of cellphones in the market and was set to <6 mm.

3. Simulation Results and Discussion

The refraction of glass produces different refractive indexes due to the different wavelengths of light. For example, the refractive index of glass becomes higher for a shorter wavelength of light. Therefore, when the entire range of wavelengths of light enters an optical system and is focused on the image plane, a focus does not appear and bands of different colors are displayed. Because the wavelengths of light in different sections are different owing to different refractive indexes, the light with different wavelengths in different sections cannot be overlapped on the image plane, a phenomenon known as chromatic aberration. Generally, the wavelength of blue light is about 450–495 nm and the wavelength of red light is about 620–750 nm, both of which are used as benchmarks. There are two types of chromatic aberration. The axial chromatic aberration is the distance from the focus of the red light wavelength to the focus of the blue light wavelength on the optical axis, as shown in Fig. 2. The vertical axis chromatic aberration is the distance from the focus of the red light wavelength to the focus of the blue light wavelength on the image plane.

MTF is the most important test data for evaluating imaging lenses. *MTF* is used to evaluate the contrast and resolution of imaging at different spatial frequencies to determine the imaging

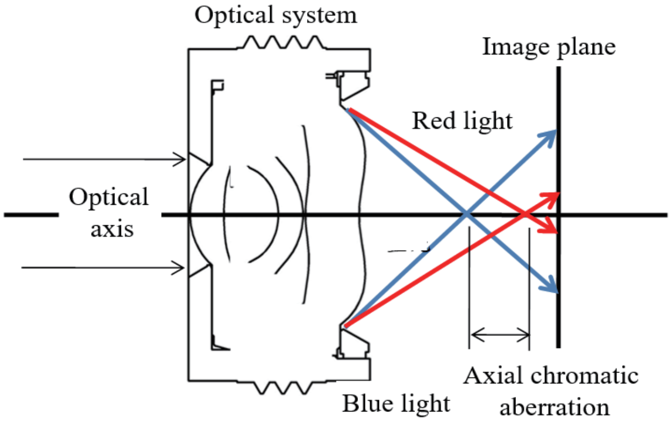


Fig. 2. (Color online) Axial chromatic aberration.

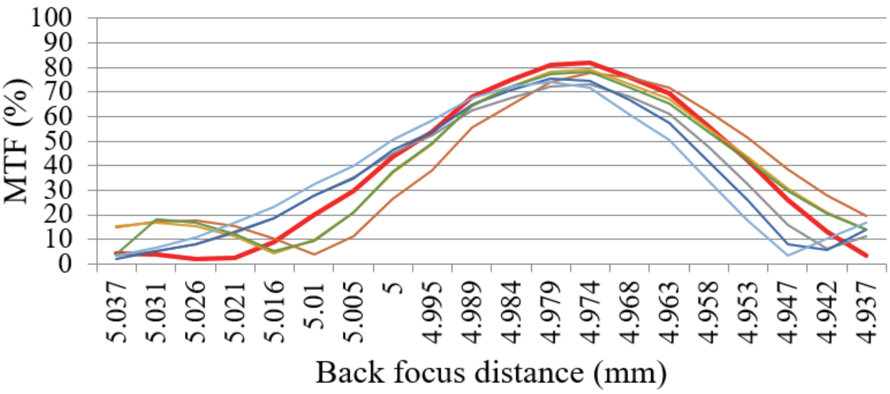


Fig. 3. (Color online) *MTF* detection curve with fixed spatial frequency.

level of the lens. The spatial frequency of *MTF* refers to how many pairs of black and white lines can be clearly distinguished at a width of 1 mm. The *MTF* curve graph mainly has two different representations. The first is the fixed spatial frequency, which indicates the relationship between *MTF* and the focal distance, and the second is the fixed focal distance, which indicates the relationship between *MTF* and the spatial frequency. The pixel size of the OV13853 photosensitive element used in this study was 1.12 µm, and the full frequency of *MTF* was calculated to be 1000 / (2 × 1.12) = 446 lp/mm. When the spatial frequency of OV13853 reached the upper limit (full frequency), the identifiable black and white line width was 1 / (2 × 446) = 0.00112 mm. This result indicates that it is very difficult to make a projection film of the *MTF* detection equipment with a line width of 1.12 µm, which increases the instability of the detection data of the *MTF* equipment. Therefore, the space frequency in this study was about one-third of the full frequency of OV13583; thus, we set the space frequency as 150 lp/mm. *MTF* needed to be greater than or equal to 45% in this study. Figure 3 shows the variation of the *MTF* values detected with a fixed spatial frequency.

The optical system of our design is a combination of six plastic injection lenses with a 12-sided aspheric structure, and the coefficients of the surfaces are shown in Tables 2 and 3. The final piece of flat glass was set to the thickness of the flat glass used to protect the sensor package, which is 0.3 mm. The aperture value of the lens parameters of the design was set as F# = 2.2, the optical back focus was set as 1.64 mm, and the imaging circle radius was set as 3.029 mm. The results of analysis using these values showed that, with zero *FOV* (F) defined as the center, the lengths of 0.5 *FOV*, 0.8 *FOV*, and 1.0 *FOV* were 1.5, 2.423, and 3.029 mm, respectively. The values for different monitored points of the lenses used and the optimized structural parameters of the design camera are shown in Table 4, which also includes the set thickness and lens spacing and the lens material used. A schematic diagram of the total optical length, back focus, and *EFL* of the design is shown in Fig. 4.

When *MTF* was at a spatial frequency of 150 lp/mm and *FOV* was 2.423 mm, the astigmatism value of the sagittal ray (S) and meridional ray (T) *MTF*s was 18.2% and the value of the meridional ray *MTF* was 44.9%. However, when *FOV* was 3.029 mm, the astigmatism value of the sagittal ray and meridional ray *MTF*s was 29.7% and the value of the meridional ray *MTF* was 30.5%. Detailed results are shown in Table 5. Figure 5 presents the optimized *MTF* curves of *FOV* for each point of the designed cellphone lens module. It can be seen that the *MTF* levels of the four fields of view were not in full compliance because not all *MTF* levels meet the specification of *MTF* > 45%.

Because of the different spectral wavelengths of light in the external *FOV*, the imaging positions and magnifications are different. Therefore, the imaging positions of the red light (longest wavelength) and blue light (shortest wavelength) on the same image plane are different, which is called lateral chromatic aberration. If the design error of the lateral chromatic aberration is smaller than the size of a single pixel, no color shift will occur on the sensor and fewer

Table 2
Optimized mirror aspheric coefficients of surfaces #1–#6 of the designed cellphone lens module.

	Surface #1	Surface #2	Surface #3	Surface #4	Surface #5	Surface #6
4th order	−1.2530627E−02	−2.9250254E−02	−4.5025023E−02	6.4175446E−03	−4.8273137E−02	2.8751256E−02
6th order	1.5100345E−02	1.9168992E−04	1.5350468E−02	−1.7456455E−02	1.2811947E−01	4.7749362E−02
8th order	−8.7872430E−02	−6.3280172E−03	−1.0744704E−01	8.7882758E−02	−2.3921553E−01	−5.1621456E−02
10th order	1.8292549E−01	5.4245729E−02	3.0061743E−01	−4.0172690E−01	2.6753419E−01	−3.6325608E−02
12th order	−1.9471239E−01	−1.0940544E−01	−4.4407863E−01	7.2020758E−01	−1.4692397E−01	1.4195374E−01
14th order	7.3522576E−02	5.6534210E−02	3.3029141E−01	−5.7113646E−01	1.6917428E−02	−1.0184977E−01
16th order	0	0	−9.3152339E−02	1.6818932E−01	0	0

Table 3
Optimized mirror aspheric coefficients of surfaces #7–#12 of the designed cellphone lens module.

	Surface #7	Surface #8	Surface #9	Surface #10	Surface #11	Surface #12
4th order	−7.5654216E−02	−4.3258159E−02	4.0535157E−02	5.6956157E−02	−7.1292036E−02	−5.9176363E−02
6th order	1.9126825E−02	−1.0650415E−02	−7.6662814E−02	−4.7602562E−02	3.7051274E−02	2.3378055E−02
8th order	1.5130627E−01	1.2629422E−01	6.1397712E−02	2.5320748E−02	−1.3165134E−02	−6.1414526E−03
10th order	−2.2133930E−01	−1.2526327E−01	−2.4134130E−02	−8.3430601E−03	3.0983543E−03	1.0520832E−03
12th order	1.5580038E−01	6.7155610E−02	4.5109940E−03	1.5576148E−03	−6.6699066E−04	−1.5122033E−04
14th order	−4.4100181E−02	−1.5622589E−02	−0.000340609	−1.3553963E−04	6.5036437E−05	1.0066931E−05

Table 4
Optimized structural parameters of the designed cellphone lens module.

F#2.2, optical back focus = 1.64 mm, radius of imaging circle = 3.029 mm, 0 *FOV* = central field, 0.5 *FOV* = 1.5 mm, 0.8 *FOV* = 2.423 mm, 1.0 *FOV* = 3.029 mm				
Surface	Radius	Thickness	Conic	Material
#1 (lens 1)	2.331422	0.2267	−1.09832	APL5015AL
#2	4.581613	0.3730	−3.49941	
#3 (lens 2)	3.624936	0.4160	−1.04955	APL5015AL
#4	−4.80158	0.0803	1.860823	
Aperture Stop	Infinity	0.1533	0	
#5 (lens 3)	9.523596	0.1267	56.55783	OKP4HT
#6	1.864182	0.5619	−6.4876	
#7 (lens 4)	−13.5213	0.2728	−140.89	OKP4HT
#8	−6.05759	0.5358	1.095904	
#9 (lens 5)	−2.96357	0.5412	−71.6057	OKP4HT
#10	−4.69479	0.1187	3.349182	
#11 (lens 6)	1.218883	0.6443	−5.26495	K26R_25
#12	1.292657	1.3	−4.77827	
#13 (package glass)	Infinity	0.3	0	BK7
#14 (package gap)	Infinity	0.04	0	
Image	Infinity			

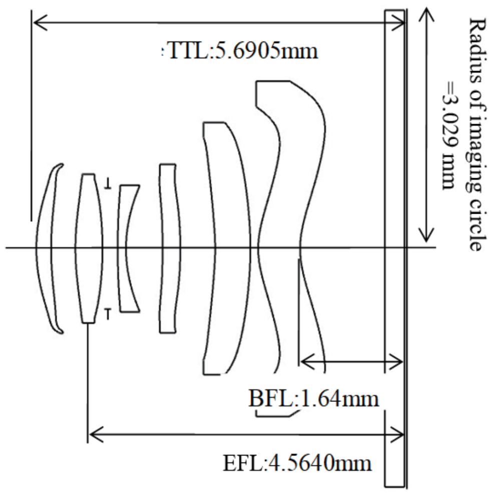


Fig. 4. Schematic diagram of *TTL*, *BFL*, and *EFL* of the designed cellphone lens module.

Table 5
Optimized *MTF* data of each *FOV* at a frequency of 150 lp/mm for the designed cellphone lens module.

FOV (mm)	0	1.5	2.423	3.029
Meridional ray (T)-*MTF*	0.737	0.586	0.449	0.305
Sagittal ray (S)-*MTF*	0.737	0.634	0.631	0.602
Astigmatism (S-T)	0	0.048	0.182	0.297

abnormal color lines will appear at the edge of the image. Therefore, the lateral chromatic aberration was set to ≤1.12 μm for our design. When light is focused into the sensor, the chief ray angle (*CRA*) is related to the angle of each pixel and its position. The degree of the focus light at

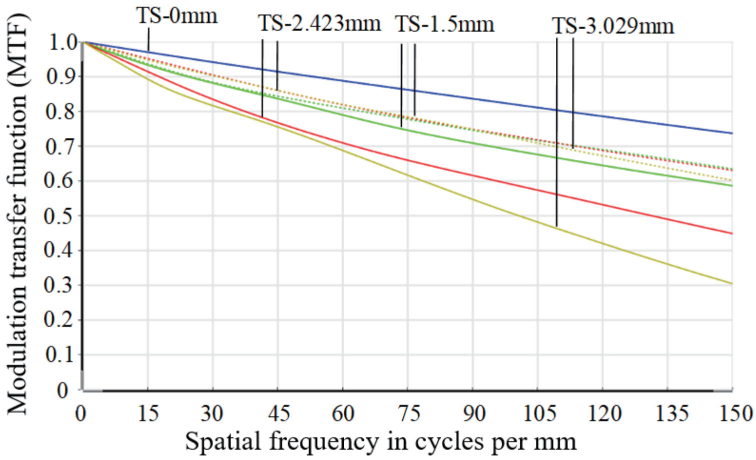


Fig. 5. (Color online) Optimized *MTF* curves of *FOV* for each point of the designed cellphone lens module.

the central axis of the lens required for the light to enter the pixel approached zero. With increasing distance of the pixel from the central axis, the focus angle required for the light to enter the pixel also increases.

CRA of the OV13853 photosensitive element is 34.15 ± 2° according to the Omni Vision official website. *RI* is defined as the ratio of the center illuminance to the edge illuminance. When *RI* is low, the center of the image is brighter and the edge corners are darker, which is commonly known as vignetting. In addition, a low relative contrast causes color distortion. When *RI* is less than 45%, the human eye can clearly perceive the vignetting phenomenon at the corners of the screen; thus, *RI* is set to greater than or equal to 45%. After we surveyed the design range set in the previous section, we set the values of the optical design as shown in Table 6.

Table 6
Specifications of the designed cellphone lens module.

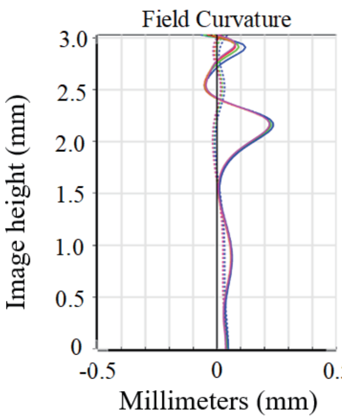
Design specification	Set value	Remark
Image range	≥3.029 mm	1/2 diagonal of OV13853
F value of lens	2.2	
FOV of lens	>60°	
TTL	<6 mm	
BFL	>1 mm	
Traditional view distortion	≤1%	1/distortion of SMIA-T
Optical distortion	≤2%	
RI	≥45%	
CRA	32.15 ± 2°	
MTF	≥45%	Frequency: 150 lp/mm
Astigmatism	≤10%	
Lateral chromatic aberration	<1.12 μm	
No. of lenses in optical system	6	

Figure 6 shows the field curvatures and distortion curves of the design as a function of image height. As shown on the right-hand side of Fig. 6, the farther the *FOV* was from the center, the greater the distortion, and the maximum distortion value was 13.96%. The left-hand side of Fig. 6 shows the field curvature graph, where the *Y*-axis is the image height (mm) and the *X*-axis is the field curvature. This figure shows that the field curvature of the external *FOV* had a large range of fluctuations, as also shown in Table 7.

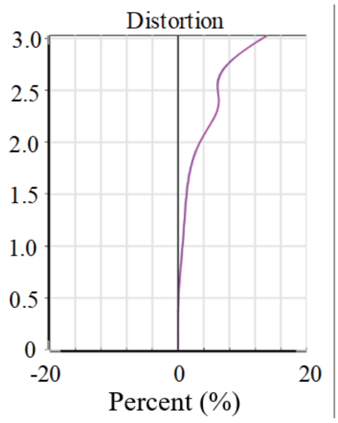
Figure 7 shows *RI* of the design as a function of image height, where the *X*-axis is the image height (mm) and the *Y*-axis is *RI*, which ranges from 0 to 1. With increasing *RI*, the difference between the illuminance and the center illuminance of each *FOV* decreases. Figure 7 shows that the larger the *FOV*, the smaller the *RI*. A small *RI* will result in insufficient illuminance in the external *FOV*, leading to dark corners in the image. The optimized *RI* values of the designed cellphone lens module are shown in Table 8.

Figure 8 shows the lateral chromatic aberration of the design as a function of image height, where the *Y*-axis is the image height (mm) and the *X*-axis is the lateral chromatic aberration. Because this design was based on the OV13853 sensor, the lateral chromatic aberration should be less than 1.12 μm. From Fig. 8, it can be seen that when the image height was larger than 2.2 mm, the lateral chromatic aberration was greater than 1.12 μm. The optimized values of horizontal chromatic aberration of the designed cellphone lens module are shown in Table 9.

Figure 9 shows a histogram of the five major aberrations and the lateral and axial chromatic aberration coefficients of each aspheric surface in the design. It can be seen that surfaces #9, #10, #11, and #12 are the main factors contributing to the distortion and that surfaces #9, #11, and #12 are the main factors contributing to the astigmatism.



(a)



(b)

Fig. 6. (Color online) (a) Optimized field curvatures and (b) distortion curves of the designed cellphone lens module.

Table 7
Optimized values for the distortion of the designed cellphone lens module.

FOV (mm)	0	0.576	1.09	1.515	2.09	2.514	3.029
Distortion (%)	0	0.13	0.79	1.33	4.22	6.15	13.96

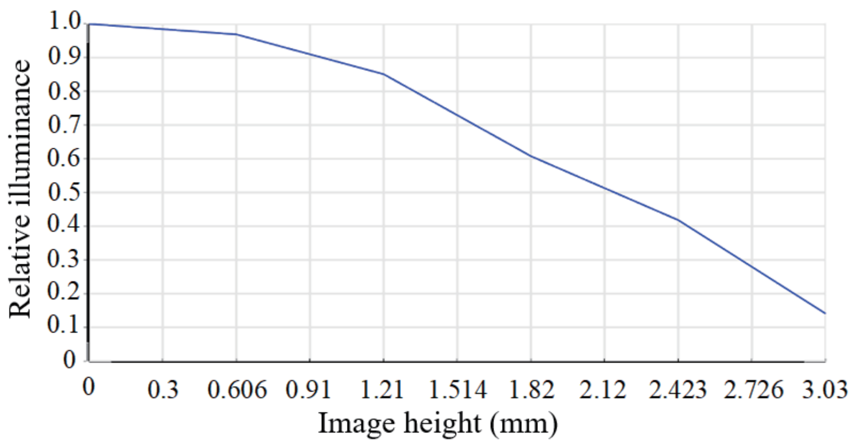


Fig. 7. (Color online) *RI* of the designed cellphone lens module.

Table 8
Optimized *RI* values of the designed cellphone lens module.

FOV (mm)	0	0.606	1.212	1.817	2.423	3.029
RI	1	0.969	0.851	0.608	0.418	0.141

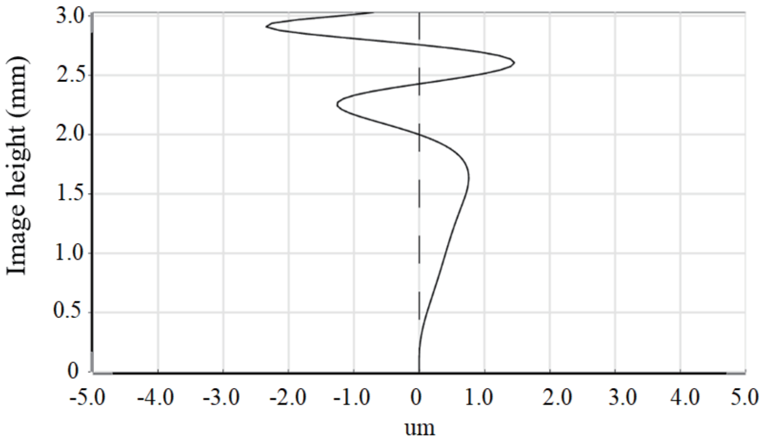


Fig. 8. Optimized values of the lateral chromatic aberration of the designed cellphone lens module.

Table 9
Optimized values of horizontal chromatic aberration of the designed cellphone lens module.

Field (mm)	0	0.76	1.51	2.6	2.91	3.029
Lateral chromatic aberration (μm)	0	0.27	0.72	1.46	−2.35	−0.69

The design has many evaluation items that do not have ideal target values. According to the lens configuration diagram of the design, some lenses have a thickness of less than 0.3 mm, making them difficult to fabricate by injection molding. In addition to the dispersion of the *MTF* curve of each *FOV*, *MTF* of the external *FOV* does not meet the required specification of being

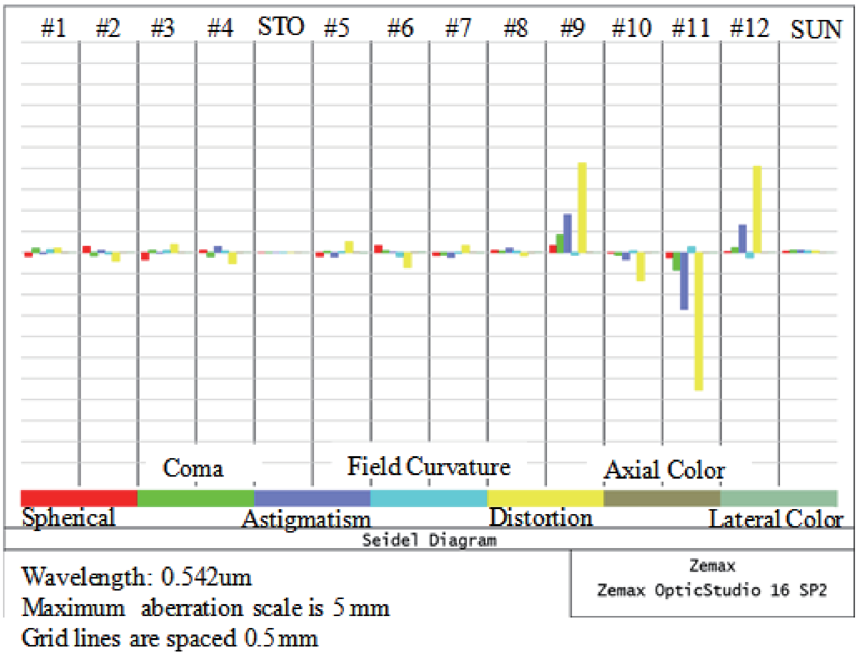


Fig. 9. (Color online) Seidel aberration results for each mirror of the designed cellphone lens module.

greater than or equal to 45%, the distortion is as high as 13.96%, *RI* is only 14.1%, the lateral chromatic aberration exceeds the 1.12 μm specification, and so forth. Thus, in the future, we will focus on simulating and optimizing the parameters of the designed cellphone lens module.

4. Conclusions

In this study, ZEMAX software and APL5015AL, OKP4HT, and K26R_25 plastic materials were successfully used to design an optical system with six aspherical lenses for a cellphone having the following advantages:

I. The designed cellphone lens module used the 14th-order aspheric coefficient as a principle to improve the accuracy of the aspheric surface and shorten the labor required for ultraprecision processing.

II. The lens materials had good molding fluidity and release properties, which help to stabilize the molding quality and reduce the production cost.

III. The optical *BFL* of the designed cellphone lens module was 1.64 mm, and there was a large space to cover the height of the sensor package.

IV. *TTL* of the designed cellphone lens module was 5.6907 mm, which is suitable for cellphone thicknesses above 6 mm.

However, *MTF* of the external *FOV* of the designed cellphone lens module did not meet the required specification of greater than or equal to 45%, the distortion was as high as 13.96%, *RI* was only 14.1%, and the lateral chromatic aberration exceeded the 1.12 μm specification. Thus, in the future, we will focus on simulating and optimizing the parameters of the designed cellphone lens module.

Acknowledgments

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References

1 Y. Mou: The design of 3 million pixel 2.75x optical zoom mobile phone lens, Master's thesis of the Institute of Optoelectronics, Central University (2008) (in Chinese).
2 G. Li, J. Wang, and Y. Zhang: J. Appl. Opt. (2011) (in Chinese).
3 Q. Yang: The design of 10 million pixel mobile phone lens, Master's Thesis of the Department of Optoelectronics Science and Engineering, National Central University (2013) (in Chinese).
4 T. Steinich and V. Blahnik: Adv. Opt. Technol. **1** (2012) 51.
5 W. S. Sun, C. L. Tien, J. W. Pan, K. C. Huang, and P. Y. Chu: Appl. Opt. **54** (2015) E203.
6 P. D. Lin and R. B. Johnson: Opt. Express **27** (2019) 19712.
7 F. Yilmazturk and A. E. Gurbak: Inter. J. Opt. **2019** (2019) Article ID 8561380.
8 Zemax, an Arrays Company: https://www.zemax.com/pages/opticstudio (accessed March, 2020).