Sensors and Materials, Vol. 34, No. 9 (2022) 3637–3647
MYU Tokyo

S & M 3066

Use of Six Plastic Lenses to Design Lens Module with 13 Million Pixels for Application in Cellphone Camera Module

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(Received July 4, 2022; accepted August 29, 2022)

Keywords: plastic lenses, cellphone phones, optical simulation program, aspheric surface

The Zemax optical simulation program was used to design a multilens configuration and further optimize the design of a lens module using six plastic lenses and 12 aspheric surfaces. The lens module with 13 million pixels was designed for application in a cellphone camera module. The basic specifications of the design with six plastic lenses were established and matched with those of an OV13853 complementary metal oxide semiconductor (CMOS) chip, and the minimum imaging circle radius of the designed optical lens module based on OV13853 was 3.029 mm. The optimized mirror aspheric coefficients of surfaces #1–#12 of the designed lens module and the aspheric coefficients of each mirror surface were increased to the 18th order. The optimal parameters for the designed lens module, including the radiuses, thicknesses, conics, and materials used, are presented in this paper. The modulation transfer function (MTF) curves, the ranges of field curvature, the maximum horizontal chromatic aberration, and the maximum range of Seidel aberration were also found.

1. Introduction

Owing to the popularity of camera phones in the communication and consumer electronic markets, various cellphone manufacturers have begun to invest heavily in the technical development of camera cellphones, and the camera modules of cellphones have also entered a state of rapid development. In 2005, Sony Ericsson Ltd. launched the K750i cellphone with a camera having two million camera pixels that was also equipped with autofocus and a xenon flash to enhance the clarity of images. In 2007, cellphone manufacturers competed to launch cellphones with high-resolution cameras. A representative cellphone from that era was Nokia N95, which had a camera equipped with a lens module of five megapixels and autofocus. This cellphone could also support the communication systems of the 3.5G network and the Global

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https://doi.org/10.18494/SAM.2018.4026

ISSN 0914-4935 © MYU K.K.
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Positioning System (GPS). This cellphone was also the prototype silhouette of a smart camera cellphone. After 2007, the number of pixels of camera cellphones grew explosively. With the addition of applications on the iOS and Android platforms, cellphone users developed the habit of taking pictures at any time and sharing them on the internet. This situation further increased the universality of the camera functions of smart cellphones, making the resolution (i.e., the number of pixels) of the camera one of the main specifications of cellphones.(1,2)

Simulation is a very good method for designing optical components. Its main advantages when designing a lens module are that it can reduce the design time by rapidly solving problems with optical components, acquiring the optimized design parameters, and determining the optimized optical components. In this study, we use the Zemax optical simulation program to design a lens module. Zemax is a sequential and non-sequential optical structure design software program and a ray tracing simulation program that can simulate the reflection, diffraction, polarization, and refraction of rays. The number of pixels in digital cameras has reached tens of millions, and the complementary metal oxide semiconductor (CMOS) sensors used in camera phones can also accommodate tens of millions of pixels in a small volume. To meet the high requirements of cellphones designed to be thin and light, there are strong limitations on the optical total track length (TTL) of lens modules, making it necessary to use modules with aspheric lenses to reduce the width of smart cellphones. The architectures of cellphone camera modules are complicated and are divided into the sensor package architecture, the autofocus motor architecture, and the lens optical system architecture. Among them, the optical system structures of the lens modules are the most important factor affecting the overall heights of cellphone camera modules.(3)

In addition, the mainstream designs of cellphone lens modules have five or six lenses. The main advantages for lens modules with such a number of lenses are improved resolution and contrast and reduced problems with dispersion, glare, aberration, and so forth. However, in the limited space of a cellphone camera module, too many lenses will necessitate extremely thin lens modules, introducing technical problems in the mass production of the designed lenses. Because the height of the entire camera module must be less than 6 mm and the back focal length (BFL) must be greater than 1 mm, current cellphone lens modules on the market have a design structure of up to six lenses. The novelty of this work is that we study the configuration of six plastic lenses and then use them to design lens modules with 13 million pixels for use in smart cellphones.(4–6) The basic specifications of the six plastic lenses can be matched with those of an OV13853 CMOS chip to enable the design of cellphone lens modules with 13 million pixels. In this study, we use the Zemax optical simulation program and the multilens configuration to further explore the optimized design of a cellphone camera module using six plastic lenses and 12 aspheric surfaces.(7,8) The important finding of this study is that it is necessary to reduce the size of the lens modules to increase the module loading.

2. Simulation Process and Parameters

The selected tool used to design and simulate the lens module with 13 million pixels was the Zemax optical program, which is a simulation program that can be used to simulate the reflection, diffraction, polarization, and refraction of rays and perform sequential and non-sequential simulations of optical structure designs and ray tracing with various styles. In this study, an optical system configuration with six lenses and 12 aspheric surfaces was used to design a lens module. Zemax was used to assist the optical ray design and aberration analysis of the designed lens module, and the designed lens module was optimized to meet the specifications of the set photosensitive element (CMOS). The procedure for designing a lens module is described as follows:

(a) The brand and model of the selected sensors are confirmed. (b) The required optical specifications for the selected photosensitive sensors are set. (c) The optical specifications of the lens module are set. (d) The designed optical system is set up. (e) The required optical specifications are optimized. (f) The optical specifications are examined to confirm that they can meet the requirements of the designed lens module. (g) Aberration and image analyses of the designed lens module are performed to confirm that the required specifications are met. (h) Finally, the design of the optical lens module is completed.

In this study, we used the Omni Vision OV13853 CMOS photosensitive chip to design the optical lens module. This photosensitive chip has 13 million pixels and can be used to design the structure composed of six plastic lenses and 12 aspheric surfaces for use in current smart cellphones. Table 1 shows the specifications of the OV13853 photosensitive chip.

When the OV13853 photosensitive chip was used as the photosensitive element, the required imaging circle radius of the optical lens module was calculated as $\frac{1}{2}\sqrt{4815^2+3678.3^2} = 3029$ µm, which is equal to 3.029 mm. Therefore, the minimum imaging circle radius of the designed optical lens module based on the OV13853 photosensitive chip was 3.029 mm. Next, the size of the aperture of the designed optical lens module was set. The amount of light entering the designed optical lens module is mainly controlled by the aperture size, because when the aperture value is larger, less light enters the optical lens module of a cellphone and the depth of field of the camera is larger.

A cellphone has front and rear lens modules with different specifications. The front lens module mainly captures video images according to the distance from the images at which the cellphone is held. The field of view (FOV) is used to define the ability of each sensor or pixel to detect tiny objects, the size of which determines the detail of the image and the observable distance of the object. Therefore, the front lens module of the cellphone is mainly used for short-range scenes and the FOV angle is large. However, the whole lens module designed in this study is based on the rear lens module of the cellphone as the main axis. Because the camera range of

Table 1
Specifications of OV13853 photosensitive chip.

Item	Specification
Lens size (dimension of sensor chip)	0.327 (1/3.06) inch
Pixel size of sensor	1.12×1.12 µm^2
Die dimensions of sensor	6210×5517 µm^2
Chief ray angle of lens	32.15°
Effective image area	4815×3678.3 µm^2

the rear lens module is mainly designed for medium- and long-range scenes, the FOV angle is designed to be more than 60° in accordance with the mainstream market specifications, and we set the FOV to be larger than 60°, as shown in Fig. 1.(9)

The back focal distances of cellphone lens modules are divided into the back focal length (BFL) and flange focal length (FFL), as respectively shown in Figs. 2(a) and 2(b). A current cellphone lens module with 10 million pixels must be equipped with an autofocus motor to provide the module with the autofocus function. However, the total length of focus movement of the autofocus motor and the package height of the photosensitive chip must exceed the FFL in the lens module. The FFL setting is one of the main factors affecting the selection of lenses by camera module factories for the fabrication of lens modules used in smart cellphones. Therefore, the BFL of the cellphone lens module in this study must be maximized to increase the design margin of the FFL mechanism; thus, the BFL is set to a value greater than or equal to 1 mm.

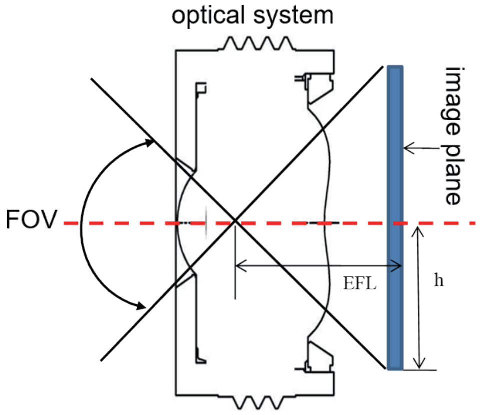
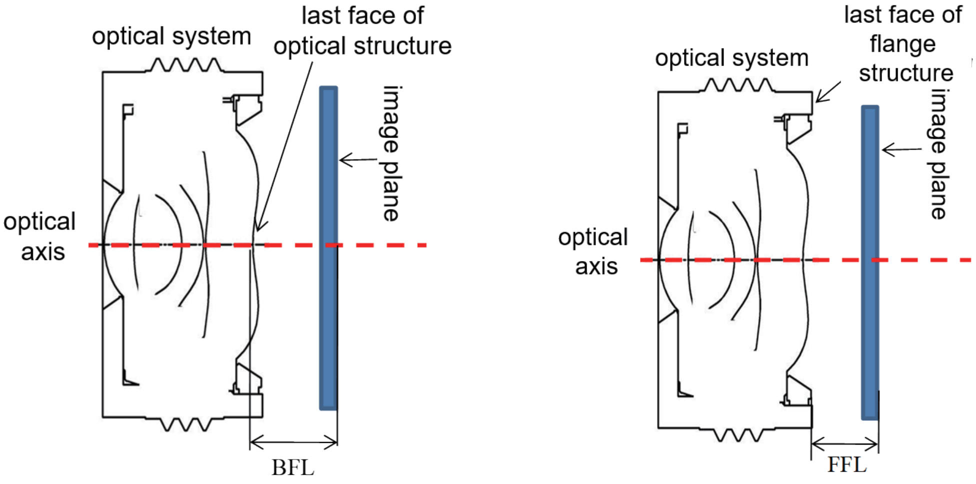


Fig. 1. (Color online) Schematic diagram of FOV of lens.



(a) (b)

Fig. 2. (Color online) Schematic diagrams of (a) BFL and (b) FFL of optical lens module.

3. Simulation Results and Discussion

The relative illuminance (RI) is defined as the ratio of the illuminance at the center of a screen or image to that at the edge. When the RI is low, the center region is brighter, whereas the corners are darker, which is commonly known as the vignetting of a screen or image. As shown in Fig. 3, when the RI is low, vignetting is readily observed at the corners of a screen. In addition, when the relative contrast is low, color distortion occurs.(3,4)

The RI is proportional to(10)

$$\cos^4\left(\frac{1}{2}FOV\right). \tag{1}$$

This suggests that the FOV has a large effect on the RI. When a semi-FOV (1/2FOV) of 25° is substituted into Eq. (1), the theoretical RI is found to be smaller than 67%; when the semi-FOV is 35°, the theoretical RI is smaller than 45%. When the RI is smaller than 45%, the human eye can clearly detect vignetting at the corners of a screen; thus, the RI is set to be greater than or equal to 45%. In this design, seven monitoring points are used for the FOV to increase the density of monitoring points and improve the image resolution.

The aspheric coefficients of each mirror surface are increased to the 18th order rather than to the 14th order used previously, as shown in Tables 2 and 3.(5) As compared with our previously designed lens nodule, the problems of the thinness of the lens module and the aberration have been mitigated. The optical back focal distance is reduced to 1.355 mm to optimize each optical characteristic and balance each item. In this design, the radius of the imaging circle is 3.23 mm, which increases the assembly tolerance margins of the lens packages of the photosensitive sensors and reduces the accuracy required for lens packages. Our designed optical lens module is a combination of six plastic lenses, which have a 12-sided aspheric structure and are fabricated using the injection method. Tables 2 and 3 show the relative coefficients of the surfaces of the lenses. Figure 4 shows the configuration of the optical lenses for the designed lens module with

Fig. 3. (Color online) Low RI, resulting in vignetting at corners of screen.

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

Order	Surface #1	Surface #2	Surface #3	Surface #4	Surface #5	Surface #6
4th	−7.0772826E−03	−3.3661005E−02	−3.7308640E−02	1.2461547E−02	−4.8895531E−02	3.1833159E−02
6th	2.0600358E−02	−4.5263122E−03	1.5725969E−02	−1.5846668E−02	1.2076645E−01	5.9826343E−02
8th	−8.6975004E−02	−4.7606239E−03	−1.0675866E−01	8.4152480E−02	−2.3740349E−01	−4.6631584E−02
10th	1.7013308E−01	6.3380861E−02	3.1916759E−01	−4.0164010E−01	2.5957808E−01	−1.3455560E−02
12th	−1.8561403E−01	−1.0309637E−01	−4.5070308E−01	7.6101892E−01	−1.5520892E−01	1.0393069E−01
14th	1.0430018E−01	8.1238943E−02	3.3621559E−01	−6.4286820E−01	5.6666106E−02	−8.0337807E−02
16th	−2.3605199E−02	−2.5672101E−02	−1.0559216E−01	1.9881887E−01	−2.1489196E−02	1.3919517E−02
18th	3.2748925E−06	−3.9364453E−06	−1.1311022E−05	−6.1307970E−05	−2.7278362E−06	−4.6144739E−04

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

Order	Surface #7	Surface #8	Surface #9	Surface #10	Surface #11	Surface #12
4th	−7.4233894E−02	−3.3661005E−02	−3.7308640E−02	1.2461547E−02	−4.8895531E−02	3.1833159E−02
6th	2.0600358E−02	−4.5263122E−03	1.5725969E−02	−1.5846668E−02	1.2076645E−01	5.9826343E−02
8th	−8.6975004E−02	−4.7606239E−03	−1.0675866E−01	8.4152480E−02	−2.3740349E−01	−4.6631584E−02
10th	1.7013308E−01	6.3380861E−02	3.1916759E−01	−4.0164010E−01	2.5957808E−01	−1.3455560E−02
12th	−1.8561403E−01	−1.0309637E−01	−4.5070308E−01	7.6101892E−01	−1.5520892E−01	1.0393069E−01
14th	1.0430018E−01	8.1238943E−02	3.3621559E−01	−6.4286820E−01	5.6666106E−02	−8.0337807E−02
16th	−2.3605199E−02	−2.5672101E−02	−1.0559216E−01	1.9881887E−01	−2.1489196E−02	1.3919517E−02
18th	3.2748925E−06	−3.9364453E−06	−1.1311022E−05	−6.1307970E−05	−2.7278362E−06	−4.6144739E−04

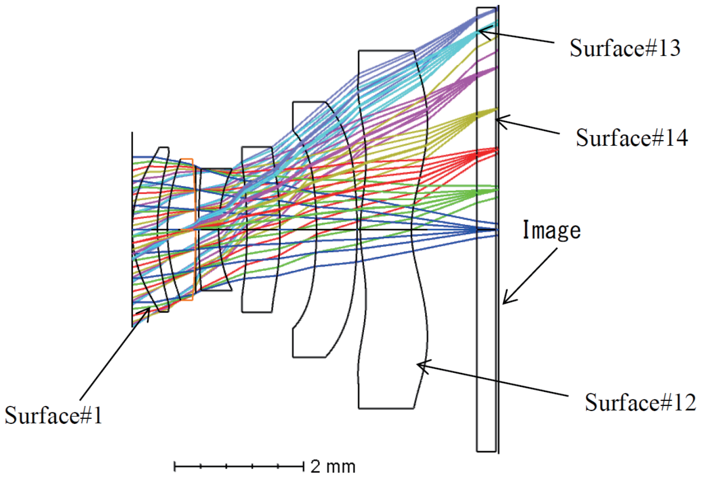


Fig. 4. (Color online) Optimized configuration of designed cellphone lens module (surface # is numbered sequentially from left to right).

the optimal parameters. In the figure, the six lenses and the numbers assigned to the 12-sided faces of the designed lens module increase from left to right. As compared with our previously designed lens module, the thicknesses of the optimized lenses have increased and the mirrors have less complicated shapes, which can improve the feasibility of producing the designed lens module.(5) As shown in Table 4, in the designed lens module, the thickness of the thinnest lens is 0.3106 mm and that of the thickest lens is 0.7911 mm, and both thicknesses meet the requirements for molding production.

Table 4
Optimized values of structural parameters of designed lens module.

Surface	Radius	Thickness	Conic	Material
#1 (lens 1)	1.831972	0.3921	−0.466996	APL5015AL
#2	3.081636	0.1551	−0.462562	
#3 (lens 2)	2.63916	0.4359	1.202992	APL5015AL
#4	−12.77473	0	−19.18539	
Aperture stop	Infinity	0.0482	0	—
#5 (lens 3)	9.192868	0.3106	56.72615	OKP4HT
#6	2.178839	0.4374	−6.910704	
#7 (lens 4)	−9.575147	0.5137	−275.6127	OKP4HT
#8	−6.269648	0.5670	−35.29518	
#9 (lens 5)	−4.56981 5	0.6307	−84.20788	OKP4HT
#10	−6.367179	0.0486	5.680484	
#11 (lens 6)	2.378639	0.7911	−12.48286	K26R_25
#12	1.682813	1.015	−6.63361	
#13 (package glass)	Infinity	0.3	0	BK7
#14 (package gap)	Infinity	0.04	0	
Image	Infinity	—	—	—

F#2.2; optical back focus is 1.355 mm and radius of imaging circle is 3.23 mm

The values for different monitoring points of the lenses used and the optimized structural parameters of the designed camera are shown in Table 4, which also includes the designed radiuses, thicknesses, and conics, and the material used for each lens in the designed lens module. The final glass piece is set to a thickness of 0.3 mm and used to protect the package of the photosensitive chip. The aperture value of the design lens module is set to F#=2.2, the optical back focus to 1.355 mm, and the radius of the imaging circle to 3.23 mm.

The modulation transfer function (MTF) is the most important test data for evaluating imaging lens modules. It evaluates the contrast and resolution of images formatted in different spatial frequencies to determine the imaging level of designed lens modules. The so-called spatial frequency of the MTF refers to how many pairs of black and white lines can be clearly distinguished in a width of 1 mm.(11) In this study, the dimension of a photosensitive pixel of the OV13853 chip is selected to be 1.12 μm, and the full frequency of the calculated MTF is 1000/(2 × 1.12) = 446 lp/mm. Therefore, when the spatial frequency of the OV13853 chip reaches the upper limit (full frequency), the recognizable black and white line width is 1/(2 × 446) = 0.00112 mm. It is very difficult to form a line with a width of 1.12 μm for the light-emitting film of MTF detection equipment, which increases the instability of the detection data of the MTF testing equipment.

Figure 5 shows the relationship between the MTF and the spatial frequency when the BFL is fixed for different monitoring points. The MTF decreases with increasing spatial frequency at all monitoring points. Therefore, the spatial frequency of the OV13583 photosensitive chip is selected to be about one-third of the full frequency, which means that when a spatial frequency of 150 lp/mm is set, the MTF is greater than or equal to 45%. It can be seen that an FOV below 2.423 mm results in a concentrated MTF curve, small astigmatism, and uniform resolution. When the external FOV is larger than 3.029 mm and the MTF is close to 0.5, the lens module has

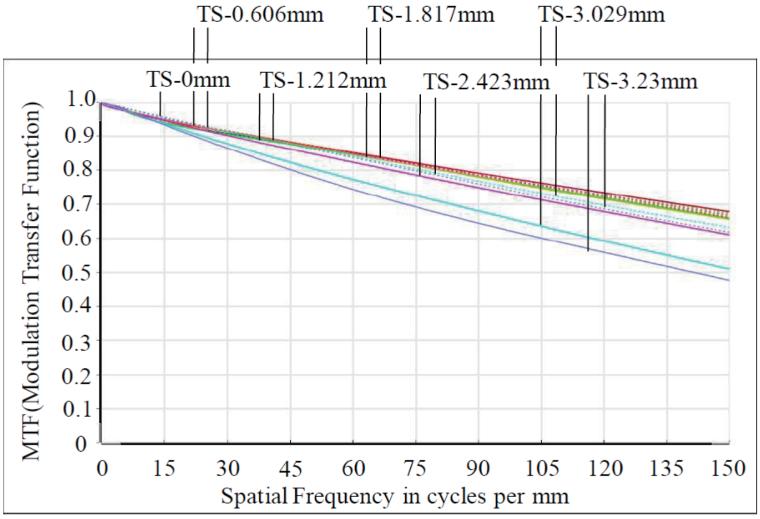


Fig. 5. (Color online) Optimized MTF curves of FOV for each point.

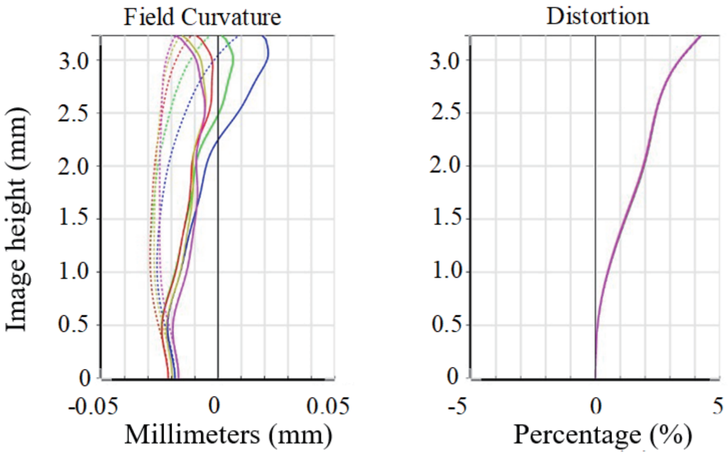


Fig. 6. (Color online) Optimized field curvature and distortion of designed lens module.

Table 5
Optimized distortion values of designed lens module.

FOV (mm)	0	0.606	1.212	1.817	2.423	3.029	3.23
Distortion (%)	0	0.16	0.81	1.75	2.37	3.53	4.25

good performance, but the maximum astigmatism is 0.141, which exceeds the specification of 0.1 and must be further improved in the future.

Figure 6 shows the field curvature and distortion curves of the designed lens module. In our previous research, the maximum distortion was 13.96% at an FOV of 3.029 mm.(5) The right image of Fig. 6 shows that as the FOV was increased from the center, the distortion also increased. However, the maximum distortion value decreased to 4.25%, even when the FOV was 3.23 mm, as shown in Table 5. The right image of Fig. 6 shows that the field curvature of the external FOV has a small fluctuation range, as also shown in Table 5, and the fluctuation range of the field curvature is reduced to ± 0.03 mm. As compared with our previous research, both the field curvature and the distortion of the designed lens module have been greatly reduced.

The RI of the designed lens module as a function of the image height between image heights of 0 and 3.23 mm is shown in Fig. 7 and Table 6. With decreasing RI, the difference between the center illuminance and the illuminance of each FOV increases. Figure 7 and Table 6 show that the RI decreases with increasing FOV. However, a small RI results in insufficient illuminance in the external FOV, causing the image to have dark corners.

The horizontal chromatic aberration of the optimum lens module as a function of the image height is shown in Fig. 8, where the horizontal chromatic aberration is shown on the X-axis (μm)

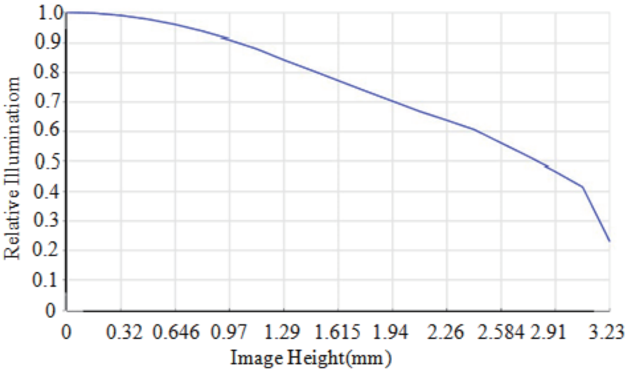


Fig. 7. (Color online) RI of design lens module as a function of image height.

Table 6
Relationship between FOV and *RI* of designed lens module.

FOV (mm)	0	0.606	1.212	1.817	2.423	3.029	3.23
RI	1	0.959	0.843	0.703	0.606	0.415	0.230

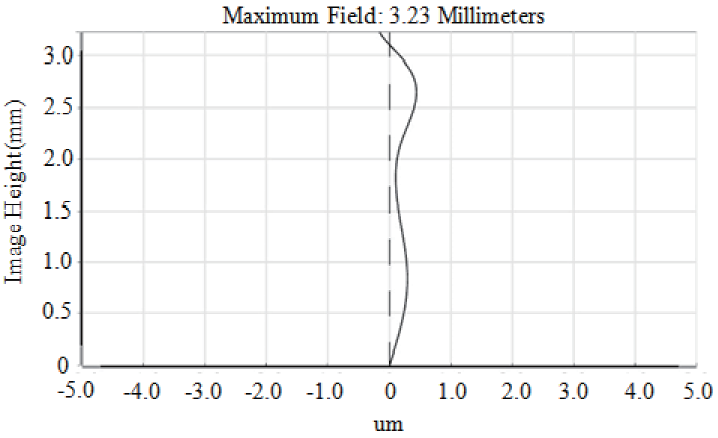


Fig. 8. Relationship between horizontal chromatic aberration and image height of designed lens module.

and the image height is shown on the *Y*-axis (mm). This designed lens module was based on the OV13853 photosensitive chip; therefore, the horizontal chromatic aberration of the designed lens module should be smaller than 1.12 µm. The figure shows that when the image height was in the range of 0–3.23 mm, the horizontal chromatic aberration varied in the range of 0–0.48 µm. The relationship between the horizontal chromatic aberration and the image height of the designed lens module is also shown in Table 7. It can be clearly seen in the figure that the horizontal chromatic aberration in each FOV does not exceed 0.5 µm, showing that the designed lens module has good optical properties because of its small horizontal chromatic aberration.

The horizontal and axial chromatic aberration coefficients of each aspheric surface and a histogram of the five major aberrations of the designed lens module are shown in Fig. 9. According to our results, the maximum aberration range of the designed lens module after optimization is reduced to 2 mm. Figure 9 also shows that in this designed lens module, surfaces #9, #11, and #12 are the main factors causing the astigmatism and that surfaces #9, #10, #11, and #12 are the main factors causing the distortion.

Table 7
Relationship between horizontal chromatic aberration and image height of designed lens module.

Field (mm)	0	0.606	1.212	1.817	2.423	3.029	3.23
Horizontal chromatic aberration (µm)	0	0.264	0.225	0.099	0.355	0.105	−0.162

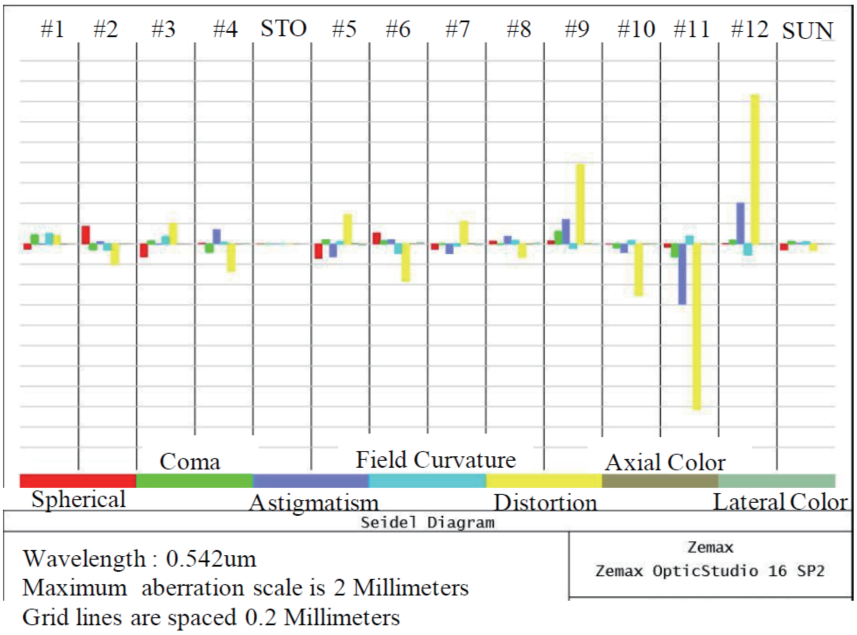


Fig. 9. (Color online) Seidel aberration results for each mirror of designed lens module.

4. Conclusions

In this study, Zemax software and K26R_25, OKP4HT, and APL5015AL plastic materials were successfully used to design a cellphone lens module with the following advantages:

I. The minimum thickness of the lens module in this study was 0.3106 mm, which allows mass production by injection molding, reduces the difficulty in production, and stabilizes the molding quality.
II. According to the MTF curves, each FOV meets the requirement that the MTF value must be greater than 45%.
III. According to the graph of the simulated field curvature and distortion, the range of the field curvature is reduced to ±0.03 mm.
IV. According to the graph of the horizontal chromatic aberration, the maximum horizontal chromatic aberration is reduced to 0.355 μm.
V. The maximum range of Seidel aberration is reduced to 2 mm.

However, the designed cellphone lens module has the following shortcomings: (a) The maximum astigmatism in the external FOV was 14.1%, which did not meet the specification requirement of less than 10%; (b) the distortion was 4.25%, which exceeded the specification requirement of less than 2%; and (c) the RI of the external FOV was 0.23, which did not meet the specification requirement of greater than 0.45. In the future, we will perform simulations to further optimize the parameters of the designed cellphone lens module.

Acknowledgments

This work was supported by projects under Nos. MOST 110–2622-E-390–002 and MOST 110–2221-E-390–020.

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