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Design method research of a radiation-resistant zoom lens

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ABSTRACT

In a strong nuclear radiation environment, the life of a traditional zoom lens is extremely short. To improve the life of the zoom lens, a novel method to design the zoom optical system is proposed, in which the front fixed group is all made of Silica lens with stronger irradiation performance. Firstly, the radiation-resistant performance of the glass lens is tested, and the transmittance of the optical system is analyzed. Then, a specific zoom optical system was proposed for the problem of difficult chromatic aberration correction in the front fixed group, and a calculation method of the initial structure parameters is analyzed theoretically. Finally, a 6× radiation-resistant zoom optical system is designed by using only two specific radiation-resistant glass materials. The imaging experiment demonstrates the better imaging performance of the radiation-resistant zoom system, which verifies the feasibility of the design method proposed in this paper.

1. Introduction

With the enrichment of zoom optical system design theory and the continuous improvement of mechanical processing capabilities, the imaging quality of the zoom optical system is basically comparable to that of a fixed focus lens [1,2]. In the zoom optical system, adjusting the cam can continuously change the focal length of the system to make the imaging magnification of the object change continuously, which can not only search the interested target in a large range but also track and observe the object precisely [3,4]. Hence, zoom optical system has been widely used in many fields, such as target tracking, photography, and security monitoring [5–7].

In the process of the zoom optical system design, the imaging quality of the optical system at all focal lengths needs to be considered. Therefore, the aberration correction of the zoom optical system is often difficult, especially the chromatic aberration and spherical aberration at the long focal length [8]. The larger the zoom ratio of the zoom optical system, the more difficult it is to correct the aberrations of the optical system. Therefore, in the process of the zoom optical system design, low-dispersion lenses, aspheric lenses, and diffractive elements are generally used to improve the image quality. Zhang et al. proposed to use the harmonic diffractive lens and new aspheric lens for aberration correction [9]. Using four harmonic diffractive lenses and four new aspheric lenses, and using a multi-component full-motion zoom structure, a 300× visible light zoom optical system was designed; Hou et al. designed a large aperture zoom projection optical system with five-element structure, which used two aspheric lenses [10]; Ma et al. designed a three-step underwater zoom optical system, which used two aspheric lenses for aberration correction [11]. However, all the lenses of these zoom optical systems are made of conventional glass materials, so the life of these zoom lenses is extremely short in the strong radiation environment.

There are few kinds of radiation-resistant glass materials compared with conventional glass materials, which is extremely disadvantageous for the chromatic aberration correction of the zoom optical system. In addition, there are few reports on the design of zoom optical systems with specific two kinds of glass materials. Therefore, in order to increase the life of the zoom lens in the strong radiation environment, this paper proposes a method to design a zoom optical system using specific radiation-resistant materials. Aiming at the difficulty of chromatic aberration correction of the radiation-resistant zoom optical system, this paper analyzes the configuration selection and initial configuration established method of the zoom optical system. A 6× continuous zoom optical system with only two radiation-resistant glass materials Silica and ZF506 is designed by using the design method proposed in this paper. The imaging experiment shows that the system has high imaging quality.

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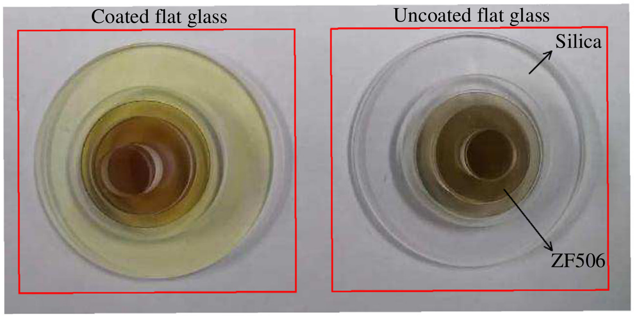


Fig. 1. Radiation-resistant flat glass after high-dose γ-ray irradiation.

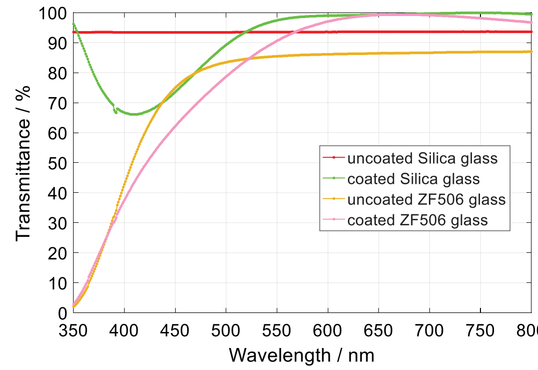


Fig. 2. Transmittance curves of glass materials after irradiation.

2. Glass material selection and radiation resistance test

2.1. Glass material selection

For a conventional zoom lens, after a certain radiation dose of χ or γ-rays, the lens will quickly turn yellow or even black, which will drastically reduce the transmittance of the lens to the imaging light. This situation will result in a very short life span of the lens [12,13]. Therefore, all lenses in the zoom optical system can only use radiation-resistant glass materials to extend the service life of the zoom lens in a high irradiation environment.

However, there are few types of radiation-resistant glass materials, and even fewer types in stock. Obtaining a certain non-stocked radiation-resistant glass material requires mass forging, which will not only increase research and development (R&D) costs but also extend the R&D cycle. Therefore, focusing on the limitation of the types of radiation-resistant glass materials, and considering the achromatic conditions of the optical system (at least two glass materials are required), we propose to use the two most common radiation-resistant glass materials for zoom optical system design, which are crown glass Silica and flint glass ZF506.

After being irradiated with a certain radiation dose of χ or γ rays, the transmittance of the radiation-resistant glass materials will decrease and vary as different wavelengths. Therefore, in order to obtain the irradiation resistance parameters of Silica and ZF506, the transmittance of the irradiated glass materials needs to be tested. According to the radiation resistance parameters obtained from the experiment, the total transmittance of the optical lens before and after irradiation can be calculated accurately to determine the influence degree of irradiation on the transmittance of the optical lens.

2.2. Irradiation test experiment

After high-dose γ-ray irradiation, the color changes of the radiation-resistant flat glass Silica and ZF506 are shown in Fig. 1, the color of the uncoated flat glass Silica has not changed basically, while the uncoated flat glass ZF506 gradually turns yellow or even black. Compared with uncoated radiation-resistant glass, the color of coated radiation-resistant flat glass is generally yellowish when the material and thickness are the same.

After irradiation, the transmittance of the two kinds of radiation-resistant flat glass was tested. Fig. 2 shows the transmittance curves of flat glass with a thickness of 2 mm. Transmittance of uncoated Silica is basically independent of the wavelength in the visible light range, while the transmittance of Silica after coating changes drastically at shortwaves as shown in Fig. 2. When the wavelength is in the range of 486nm~656 nm, the transmittance of uncoated Silica is almost independent of the wavelength, while the transmittance of coated Silica changes drastically with wavelengths, and the transmittance of coated ZF506 changes much more violently with the wavelengths than that of uncoated ZF506 (shown in Fig. 2). When the optical lens adopts coated lenses, since the transmittance of short-wavelength is significantly lower than that of long-wavelength, the image will become reddish after the optical lens is irradiated, which will affect the imaging quality. Therefore, the optical lenses need to use uncoated lenses to minimize the color deviation of the imaging. The total transmittance of the optical lens is determined by two parts, which are the reflectivity of the front and back optical surfaces of the lens and the light absorption rate of the irradiated lens.

The following is a theoretical calculation of the light absorption rate of the irradiated lens and the total transmittance of the optical system after irradiation. The reflectivity R of the imaging light on the surface of the lens can be expressed as

$$R = \left(\frac{n_0 - n}{n_0 + n}\right)^2 \tag{1}$$

where n_0 is the refractive index of the medium in the space where the lens is located; n is the refractive index of the lens.

When the absorption of the incident light by the lens is not considered, the transmittance of the incident light after passing through a lens is $(1-R)^2$. However, after the irradiation-resistant glass is irradiated, the absorption rate of the incident light by the lens cannot be ignored. At this time, the transmittance of the incident light after passing through an irradiated lens can be expressed as

$$T_g = (1-R)^2 \times \left(1 - T_a\right)^l \tag{2}$$

where T_a is the absorption rate of a 1 mm thick lens to incident light after irradiation, and l is the thickness of the lens.

When an optical system contains only two radiation-resistant glass materials Silica and ZF506, the total transmittance of the lens after a certain radiation dose can be expressed as

$$T_{all} = \left(1 - R_{Si}\right)^m \times \left(1 - R_{ZF}\right)^n \times \left(1 - T_{asi}\right)^p \times \left(1 - T_{azf}\right)^q \tag{3}$$

where R_{Si} is the reflectivity of the optical surface of the Silica lens, R_{ZF} is the reflectivity of the optical surface of the ZF506 lens, m is the total number of the optical surfaces of the Silica lens in the optical system, n is the total number of the optical surfaces of the ZF506 lens in the optical system, T_{asi} and T_{azf} respectively represent the absorption rates of the Silica lens and the ZF506 lens to the incident light after irradiation, p and q represent the total thickness of the Silica lens and ZF506 lens respectively.

By Eq. (1), the reflectivity of the optical surface of the lens can be calculated directly using the refractive index of the lens. When the total transmittance and thickness of a radiation-resistant lens are determined, the light absorption rate of the lens can be calculated by Eq. (2), namely, the light absorption rate of the irradiated lens can be calculated through a transmittance curve.

Eq. (1) is applied to an ideal optical surface, but the roughness of the lens optical surface processing is random, so there will be some errors

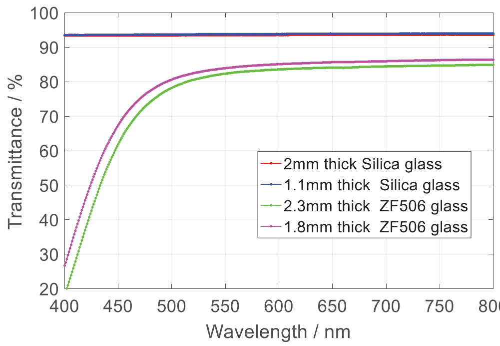


Fig. 3. Transmittance curves of different thickness glass after irradiation.

Table 1
Absorptivity and optical surface reflectivity of the flat glass after irradiation (550 nm).

Material	Reflectivity	Absorptivity (1mm)
Silica	2.9%	0.4%
ZF506	6.5%	2.4%

in the reflectivity calculated by Eq. (1). In order to accurately calculate the reflectivity of the optical surface of the lens and the absorptivity of the lens, we regard the reflectivity and absorptivity as unknown quantities, and the total transmittance of the lens and the thickness of the lens as known quantities, then the unknown quantities are solved by Eq. (2). Therefore, it is necessary to use the transmittance curves of two irradiated lenses with different thicknesses to solve the unknown quantities. The transmittance curves of uncoated radiation-resistant flat glass of different thicknesses after radiation with a certain radiation dose are shown in Fig. 3.

Combining Eq. (2) with the data from Fig. 3, the absorptivity and optical surface reflectivity of the flat glass after irradiation are obtained. The calculation results (shown in Table 1) show that the reflectivity of the optical surface of the lens ZF506 is greater than that of Silica, and the absorptivity of the lens ZF506 is also greater than that of Silica. Therefore, considering to further improve the life of the optical lens, the first few lenses in the optical system need to use Silica material, and the ZF506 material lens should be used as little as possible in the entire system.

3. Design principle of radiation-resistant zoom optical system

3.1. Optical system structure selection

The zoom optical system can be divided into four types: optical compensation zoom optical system, mechanical compensation zoom optical system, dual-group linkage zoom optical system, and full-motion zoom optical system [14–17]. The optical compensation zoom optical system has only a few intermittent focal lengths for stable imaging, so its use range is restricted greatly. The dual-group linkage zoom optical system has at least three components participating in the movement, of which two components are relatively static during the movement, and the relative position of each component is driven by the cam to achieve continuous zooming. There are at least three cam curves in the full-motion zoom optical system, and the complexity of the mechanical structure and the design difficulty of the optical system will be larger with the increase of cam curves. The mechanical compensation zoom optical system is the most widely applied. This type of zoom optical system has only two cam curves (a straight line and a curve), so the mechanical structure is simpler and the cost of research and development is lower. In this paper, the mechanical compensation zoom structure is selected to design the radiation-resistant zoom optical system.

Using two kinds of special radiation-resistant glass materials to design the zoom optical system will greatly increase the difficulty of correcting the chromatic aberration of the optical system. The radiation-resistant performance of the Silica lens is significantly higher than that of the ZF506 lens as seen in Table 1. Therefore, in order to further extend the service life of the zoom lens, all lenses in the front fixed group will use Silica material in the mechanical compensation zoom optical system.

When the compact thin lens group is in the air, the position chromatic aberration of the lens group and the magnification chromatic aberration can be described by Eqs. (4) and (5) respectively as:

$$\sum_{1}^{N} C_{\mathrm{I}} = h^2 \sum_{1}^{N} \frac{\varphi}{\upsilon} \tag{4}$$

$$\sum_{1}^{N} C_{\mathrm{II}} = h h_z \sum_{1}^{N} \frac{\varphi}{\upsilon} \tag{5}$$

where N is the number of thin lenses in the compact thin lens group, φ is the focal power of the thin lens, υ is the Abbe number of the lens, h is the half aperture of the lens, and h_z is the incident height of the main light on the lens surface.

According to Eqs. (4) and (5), when the lens of the front fixed group of the zoom optical system is only Silica material, the greater focal power of the front fixed group, the greater position chromatic aberration and magnification chromatic aberration will be. The chromatic aberrations of the front fixed group can only be compensated by the remaining chromatic aberrations produced by other components. Therefore, when only one glass material is used in the front fixed group, it will further increase the difficulty of chromatic aberration correction of the zoom optical system.

The mechanical compensation zoom optical system can be divided two types: a) negative group compensation zoom optical system (focal power <0); b) positive group compensation zoom optical system (focal power >0). The features of the negative group compensation zoom optical system are large aperture and short length. The larger aperture of the optical system, the greater chromatic aberration can be obtained by Eq. (4), it means the more difficult it is to correct the chromatic aberration. The larger aperture of the zoom optical system also means the larger half aperture h, which cause the greater spherical aberration expressed in Eq. (6) and more difficulty to correct the spherical aberration of the optical system.

$$\sum_{1}^{N} S_{\mathrm{I}} = \sum_{1}^{N} hni \left(i - i'\right) \left(i' - u\right) \tag{6}$$

where h is the incident height of the first paraxial light on the surface of thin lens, n is the refractive index of the lens, i and i' represent the incident angle and exit angle of the light respectively, and u is the aperture angle of the first paraxial light.

For positive group compensation zoom optical system, the main characteristics are small diameter and long length. Therefore, compared with the negative group compensation zoom optical system, the positive group compensation zoom optical system has stronger correction ability for chromatic aberration and spherical aberration. Based on the above analyzes, it is obviously that the positive compensation structure is more suitable for the design of the radiation-resistant zoom optical system.

The focal power of the front fixed group is usually positive, and the focal power of the rear fixed group can be positive or negative. When the focal power of the rear fixed group is positive, the focal power of the front fixed group will be smaller to meet the focal power distribution equation. From Eqs. (4) and (5), the smaller focal power of the front fixed group causes the smaller position chromatic aberration and magnification chromatic aberration. Consequently, the positive group compensation zoom optical system with positive focal power of the rear fixed group is more conducive to chromatic aberration correction.

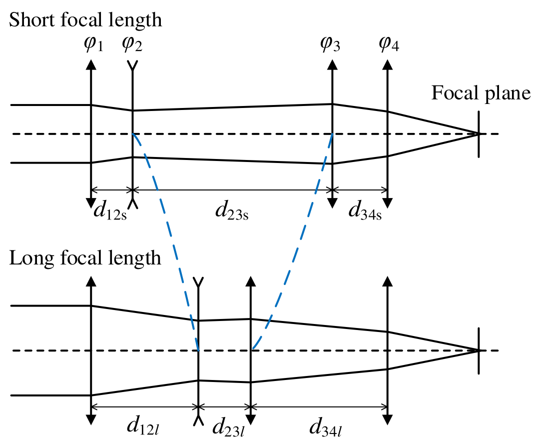


Fig. 4. Movement principle diagram of the positive group compensation zoom optical system.

It follows that when the optical power distribution of the front fixed group, zoom group, compensation group and rear fixed group of mechanical compensation zoom optical system is "+, −, +, +" respectively, the aberration correction ability of the radiation-resistant zoom optical system is best.

3.2. Calculation method of initial structure parameters

The zoom principle of the positive compensation optical system is shown in Fig. 4. The zoom optical system has four components: the front fixed group, the zoom group, the compensation group, and the rear fixed group corresponding focal powers φ_1, φ_2, φ_3 and φ_4 respectively. When the zoom optical system is in the short focal length, the zoom group will be close to the front fixed group, and the compensation group will be close to the rear fixed group. When the zoom optical system gradually changes from short focal length to long focal length, the zoom group will gradually move away from the front fixed group to the right and the compensation group away from the rear fixed group to the left. Finally, the distance between the zoom group and the compensation group reaches the minimum value, and the focal length of the optical system is the longest.

When calculating the initial structure of zoom optical system, there must be enough space between adjacent components to avoid the collision of adjacent components during the movement. Gaussian optics are applied to calculate the initial structure of the zoom optical system as following [18].

In the zoom optical system, it is assumed that the normalized focal lengths of the zoom group and the compensation group are f_2' and f_3' respectively, according to the normalized magnification m_{2l} and m_{3l} of the zoom group and the compensation group at long focal length, the distance between the zoom group and the compensation group can be obtained as follows:

$$d_{23l} = f_2'\left(1 - m_{2l}\right) + f_3' - \frac{f_3'}{m_{3l}} \tag{7}$$

The total moving distance of the zoom group from long focal length to short focal length is:

$$q = d_{12l} - d_{12s} \tag{8}$$

When the focal length is short, the magnification of the zoom group is as follows:

$$m_{2s} = \frac{1}{1/m_{2l} + q/f_2'} \tag{9}$$

According to differential equation of the zoom optical system, the magnification of the compensation group is m_{3s} in the short focal length.

$$m_{3s} = \frac{b \pm \sqrt{b^2 - 4}}{2} \tag{10}$$

$$b = -\frac{f_2'}{f_3'}\left(\frac{1}{m_{2s}} - \frac{1}{m_{2l}} + m_{2s} - m_{2l}\right) + \left(\frac{1}{m_{3l}} + m_{3l}\right) \tag{11}$$

The total moving distance of the compensation group from long focal length to short focal length is:

$$\Delta = f_3'\left(m_{3s} - m_{3l}\right) \tag{12}$$

The total zoom ratio of the zoom optical system can be expressed as:

$$\Gamma = \frac{m_{2l} m_{3l}}{m_{2s} m_{3s}} \tag{13}$$

When the zoom optical system is in short focus, the distance between the front fixed group and the zoom group is d_{12s}, the distance between the compensation group and the rear fixed group is d_{34s}, and the ratio of the rear fixed group is m_{4s}, the focal length of the front fixed group can be obtained as:

$$f_1' = d_{12s} + \frac{f_2'\left(1 - m_{2s}\right)}{m_{2s}} \tag{14}$$

$$\frac{1}{m_{4s}\left(l_{3s}' - d_{34s}\right)} - \frac{1}{l_{3s}' - d_{34s}} = \frac{1}{f_4'} \tag{15}$$

where l_{3s}' is the imaging distance of the compensation group of the optical system at short focal length.

In conclusion, we can calculate f_1', f_2', f_3', f_4' and the distance between them by joint Eqs. (7)–(15).

4. Design example of radiation-resistant zoom lens

4.1. Design index

The zoom lens designed in this paper is mainly used in the environment with strong radiation, and it needs to monitor different spatial ranges in real time and identify objects of interest at different distances. Combining the user's requirements, and taking into account the volume, weight and design difficulty of the zoom optical system, the design index of the radiation-resistant zoom optical system is finally determined as shown in Table 2. The weights of the working spectral are all set to 1, and the design temperature of the radiation-resistant zoom optical system is 20 °C.

Table 2
Design index of zoom lens.

Parameter	Value
Focal length	14~84 mm
F number	4
Working spectrum	486~656 nm
Full field of view	5.6°~34°
Distortion	≤2%
MTF (100lp/mm)	≥0.3
Glass material	Silica&ZF506

4.2. Optical system design

Gauss optics are used to determine the initial structure parameters of the radiation-resistant zoom optical system. In the calculation process, we minimize the focal power of the front fixed group, and finally get the focal length of each component in the zoom optical system, as shown in Table 3.

The data (in Table 3) is substituted into the optical design software for lens replacement. The front fixed group consists of two Silica lenses with the best radiation resistance. First use the combination of Silica and ZF506 lens to achromatize the zoom group, compensation group and rear fixed group respectively, and then use their residual

Table 3
Focal length of each component.

Components	Front fixed group	Zoom group	Compensation group	Rear fixed group
Focal length/mm	132	−36	47	90

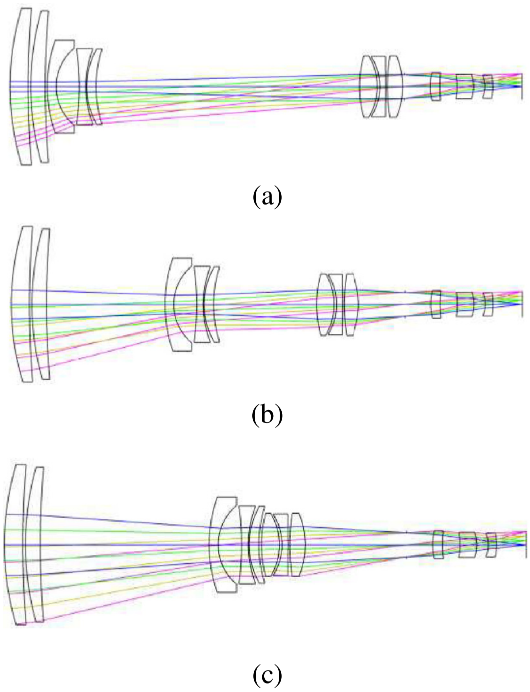


Fig. 5. Structure diagram of the zoom optical system. (a) f = 14 mm, (b) f = 40 mm, (c) f = 84 mm.

chromatic aberration to compensate the chromatic aberration produced by the front fixed group to eliminate the chromatic aberration of the entire optical system. The structures of the resulting radiation-resistant zoom optical system are shown in Fig. 5. In order to improve the service life of the radiation-resistant zoom lens, we do not add infrared filter.

Taking the data (in Table 1) into Eq. (3), the transmittance of the zoom lens before irradiation is 38.7%, the transmittance after irradiation is 27.5%. The transmittance of the zoom lens after irradiation is 71.1% of that before irradiation. These show that the radiation has little effect on the transmittance of the optical system, and the design requirements for radiation resistance are achieved.

4.3. Imaging performance evaluation

Modulation transfer function (MTF), spot diagram, and distortion are important indicators for evaluating the image quality of an optical system. The MTF represents the modulation variation law of optical system imaging, and the imaging performance of the optical system can be more comprehensively evaluated through the MTF curve. Fig. 6 is the MTF curves of the radiation-resistant zoom optical system, MTF of short, medium and long focal length at Nyquist frequency of 100lp/mm are all greater than 0.3.

Each point in the spot diagram corresponds to a ray, and the size of the diffuse spot completely depends on the position of each ray on the image plane, so it can accurately judge the diffusion of the imaging ray of the optical system. The smaller the radius of the root mean square (RMS) diffuse spot, the better the imaging quality of the optical system. Fig. 7 are spot diagram of the zoom optical system at short, medium and long focal length.

Table 4
Tolerance distribution table of the radiation-resistant zoom system.

Tolerance items	Value
Radius (fringe)	≤3
Thickness (mm)	±0.02
Surface decenter (mm)	±0.02
Element tilt (°)	±0.02
Element decenter (mm)	±0.02
Surface irregularity (fringe)	≤0.3
Refractive index	±0.001
Abbe number (%)	±0.5

The distortion of the optical system will not cause the image to be blurred, but will make the image of the object deformed, the distortion of the zoom optical system is less than 2% as shown in Fig. 8.

4.4. Tolerance analysis

Tolerance analysis is one of the most important steps before the production of optical lens. Using the tolerance analysis function in the optical design software, the manufacturing difficulty of the lens can be evaluated. Considering the tolerance sensitivity of each optical element of the zoom optical system at long, medium and short focal length, the tolerance distribution of the zoom optical system is shown in Table 4. According to Monte Carlo analysis, the distribution law of the MTF of the optical system at 100lp/mm is shown in Fig. 9. In the Monte Carlo analysis, 90% of the optical systems have a MTF greater than 0.2 in the full focal range.

4.5. Cam curve design

In the mechanical zoom optical system, the design of the cam curve is related to whether there will be stuck in the zoom process, so the design of the cam curve is very critical [19]. In addition, the imaging quality of the zoom optical system is also related to the fitting accuracy and processing accuracy of the cam curve. In the process of cam curve fitting of the zoom optical system, the cam with a straight line and a curve only needs high-order curve fitting once, while the cam with two curves needs high-order curve fitting twice. Therefore, a straight line and a curve of the zoom cam will be less difficult to process, and the processing cost will be lower.

The zoom optical system designed in this paper adopts the linear motion of the zoom group and the nonlinear motion of the compensation group for continuous zooming. When the cam diameter of the zoom lens is 74 mm and the cam rotation angle is 218.7°, the cam curve of the radiation-resistant zoom lens is shown in Fig. 10. The nonlinear motion curve of the compensation group is fitted by quartic polynomial. At this time, the pressure angle of the zoom group is 20°, the maximum pressure angle of the compensation group is 28°. From the above analyzes, the pressure angle of the cam is relatively small, and the radiation-resistant zoom lens can zoom smoothly without jamming.

The cam curve is used to fit in Fig. 10, the three-dimensional structure of the cam is simulated by the mechanical design software, and the three-dimensional structure of the zoom lens' cam (as shown in Fig. 11) is obtained after simulation.

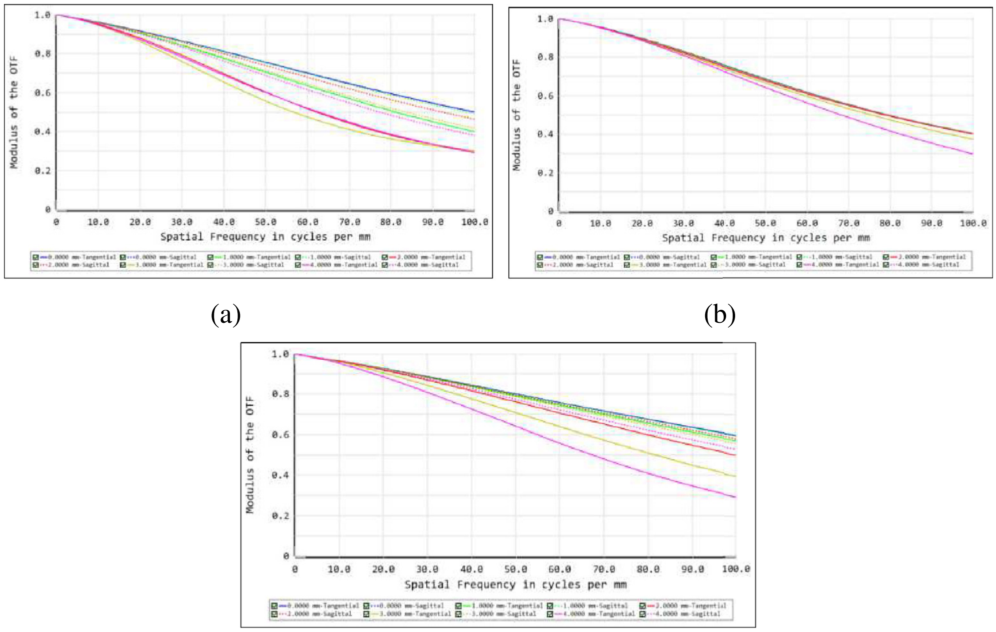


Fig. 6. MTF curves of the zoom optical system. (a) $f = 14$ mm, (b) $f = 40$ mm, (c) $f = 84$ mm.

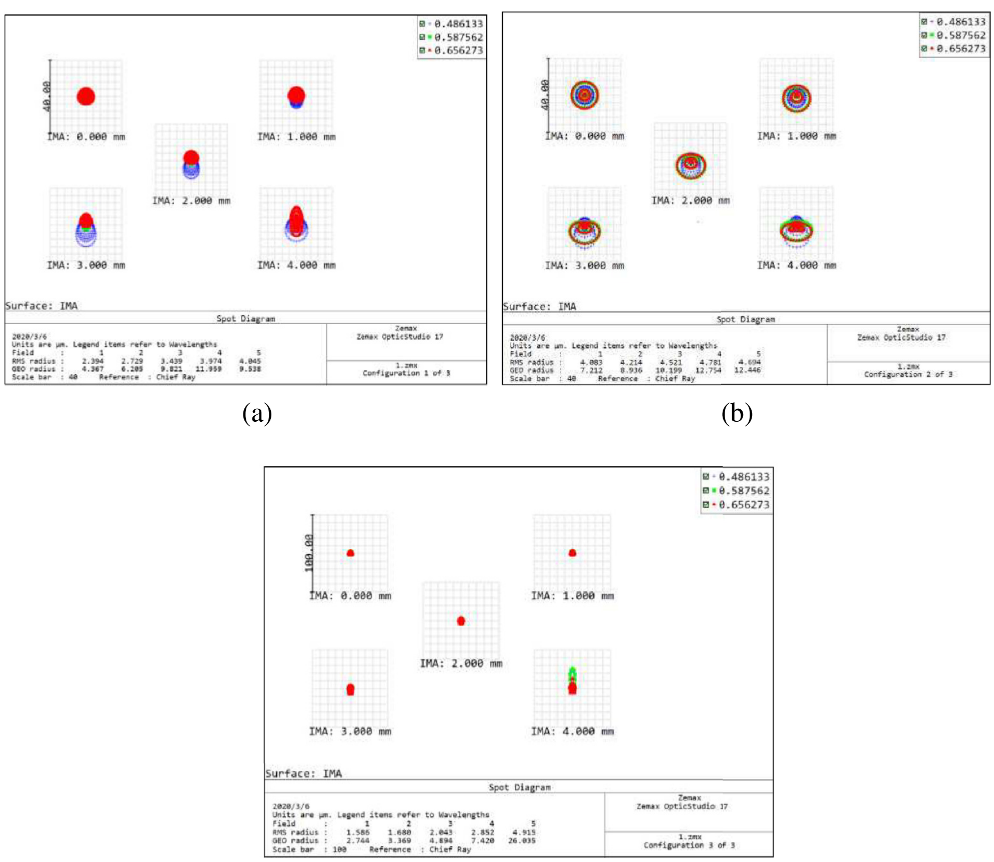


Fig. 7. Spot diagram of the zoom optical system. (a) $f = 14$ mm, (b) $f = 40$ mm, (c) $f = 84$ mm.

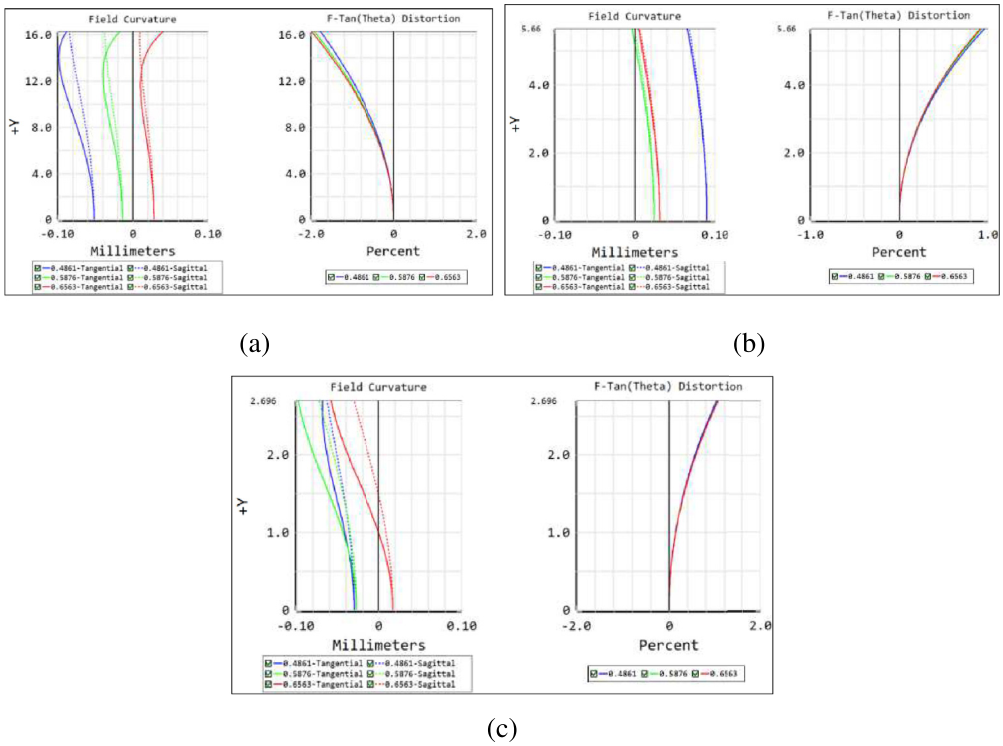


Fig. 8. Field curves and distortion curves. (a) $f = 14$ mm, (b) $f = 40$ mm, (c) $f = 84$ mm.

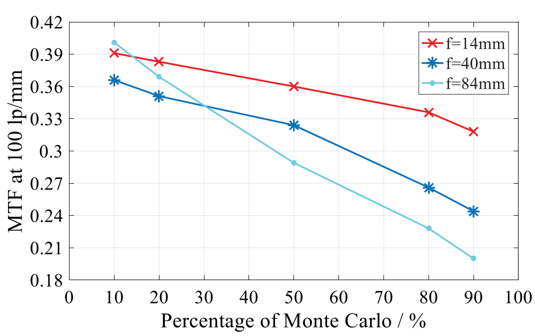


Fig. 9. Probability diagram of Monte Carlo analysis.

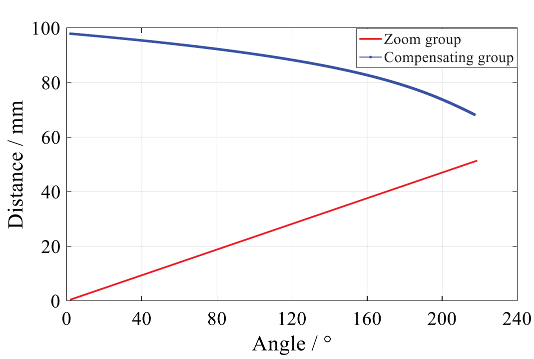


Fig. 10. Cam curve fitting diagram.

Fig. 11. Three-dimensional structure diagram of the cam.

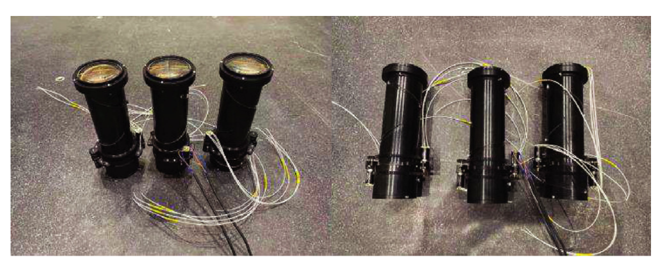
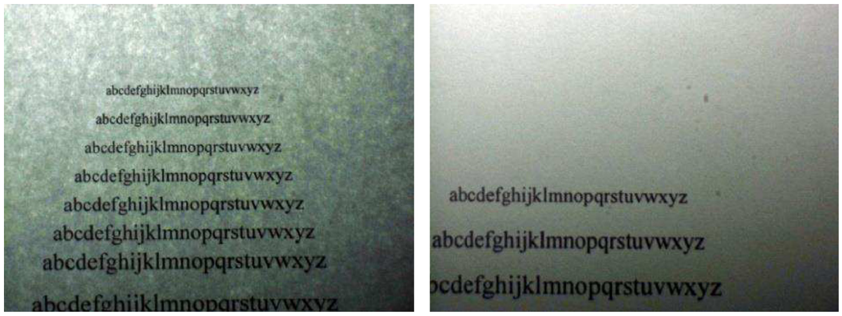


Fig. 12. Material object of the radiation-resistant zoom lens.

5. Experiment

The material object of the radiation-resistant continuous zoom lens is shown in Fig. 12. The zoom lens uses two motors, one motor drives the cam to rotate for continuous zooming, and the other motor is used to adjust the focal length of the zoom lens.

So as to evaluate the imaging quality of the radiation-resistant zoom system, the imaging experiment was carried out on the letters with a height of 1 mm. When the focal length of the zoom system is about 74 mm, the letters at different object distances are imaged, and the images obtained are shown in Fig. 13. The true height of the top line of the letters is 1 mm and the letters with a height of 1 mm can be clearly distinguished at different object distances, so the imaging quality is better. The chromatic aberration and uneven illumination of the images are caused by the lighting method, and are not related to the zoom lens.



(a) (b)

Fig. 13. Images at different object distances. (a) Object distance 1 m, (b) Object distance 0.6 m.

6. Conclusion

The traditional zoom lens cannot be used in a high irradiation environment for a long time. Therefore, in order to increase the working life of the zoom lens in a strong irradiation environment, this paper proposes a design method of the zoom optical system using only two specific radiation-resistant glass materials. Firstly, the radiation-resistant performance of two specific glass materials is tested, and the transmittance of the optical system is analyzed. Then, the aberration correction ability of the positive compensation zoom optical system is analyzed theoretically, and it is concluded that the positive compensation zoom optical system has stronger chromatic aberration and spherical aberration correction capabilities. Finally, a radiation-resistant zoom optical system is designed by using positive compensation structure and using Silica and ZF506 glass materials. Imaging experiments show that the zoom lens has good imaging quality.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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