Front. Optoelectron. China 2008, 1(1–2): 178–182
DOI 10.1007/s12200-008-0036-y

RESEARCH ARTICLE

Design of objective lens with reflective spherical Fresnel zone plate

Zhenrong ZHENG (✉), Xütao SUN, Peifu GU, Xü LIU

State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China

Abstract An objective lens composed of a spherical Fresnel zone plate mirror and aspheric mirrors is designed. The Fresnel zone plate with a spherical shape is analyzed, and the method to approximately replace the aspherical mirror with spherical Fresnel zone plate is deduced. The objective lens is designed with a single spherical Fresnel zone plate mirror and three aspherical mirrors. Under the condition of 100 × magnification, 2.5 Fresnel number and 120° field angle, the modulation transfer function can reach above 40% at 0.6 line pairs/mm on the magnification side, and the distortion is less than 2.2%. This method can provide a reference for the application of Fresnel zone plate in visible light imaging, and has a bright future with the continuous development of the fabrication technique of Fresnel devices.

Keywords optical design, spherical Fresnel zone plate, objective lens, reflection

1 Introduction

The objective lens is one of the most important parts in an optical system. The performance of the objective lens has great influence on the performance of the system. Since the mid and late 1990s, the development trend of the objective lens has been towards short focus, wide angle of view, large Fresnel number and high definition [1], thus the design and production of the objective lens become more and more difficult. Generally, the objective lens is designed by a refraction lens; however, when the refraction objective lens is used in the condition of short focus and wide field angle, various kinds of aberration are difficult to reduce because of the rapid increase of the chromatic aberration and axial coma aberration owing to the large field of view and Fresnel number. To achieve high performance, it is necessary to optimize the structure of the objective lens. However, the refraction objective lens has its original weak point [2]. At present, the design concept of the reflective objective lens is accepted by more and more lens designers. Many reflective objective lens designs are reported [3–5], for example, Ogawa J has studied the objective lens layout with four aspheric mirrors [6], and the detailed design and manufacture performance were put forward. However, the manufacture and measurement of large aspheric surfaces are difficult.

The Fresnel zone plate has received more and more interest [7–10] for the simplification of the objective lens and reduction of the cost. In this paper, an aspherical mirror is replaced by spherical Fresnel zone plate mirrors. An objective lens which consists of a Fresnel zone plate and three aspherical mirrors is designed. Under the condition of 100 × magnification, 2.5 Fresnel number and 120° field angle, the modulation transfer function can reach above 40% at 0.6 line pairs/mm on the magnification side, with a distortion less than 2.2%.

2 Design of reflective Fresnel zone plate with spherical shape

Figure 1 shows the layout of the objective lens composed of four even aspheric mirrors. The light starts to flux from the object plane, and then it is reflected by four even aspheric mirrors M_1, M_2, M_3, and M_4, projected on the screen. In this design, M_1 and M_3 are concave mirrors; M_2 and M_4 are convex mirrors. The parameters of the four even aspheric surfaces are given in Table 1. Magnification of this design shown in Fig. 1 can reach 100 × when the projection distance is 250 mm.

As shown in Fig. 1, the aspheric mirrors M_3 and M_4 have large areas. Since large-area aspheric mirrors with high precision are hard to be manufactured and measured, the spherical Fresnel zone plate mirror is adopted to replace the aspherical mirror in this paper.

The design idea is to replace the even aspheric mirror by a spherical Fresnel zone plate, and Eq. (1) shows the

Translated from *Acta Optica Sinica*, 2006, 26(10): 1–5 [译自: 光学学报]

E-mail: zzr@zju.edu.cn

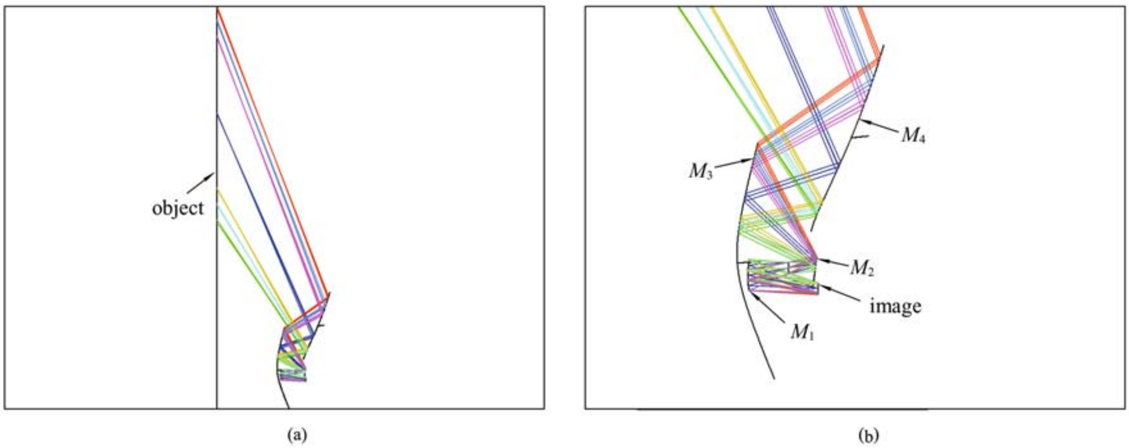

Fig. 1 Layout of objective lens with four even aspheric mirrors

Table 1 Structure data of objective lens with four aspheric mirrors

	type	c	k	a_2	a_3	a_4	a_5
M_1	aspheric	83.902	0.589	-1.387×10^{-7}	7.168×10^{-10}	-1.824×10^{-12}	2.133×10^{-16}
M_2	aspheric	63.585	−10.972	4.000×10^{-8}	-3.060×10^{-9}	2.460×10^{-10}	7.110×10^{-16}
M_3	aspheric	138.041	−0.169	-3.030×10^{-7}	2.166×10^{-11}	-1.384×10^{-15}	4.630×10^{-20}
M_4	aspheric	27.797	−3.423	-8.018×10^{-8}	5.919×10^{-12}	-2.918×10^{-16}	8.936×10^{-21}

expression of the even aspheric:

$$Z(r)=\frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}+a_2r^4+a_3r^6+a_4r^8+a_5r^{10}+\cdots, \tag{1}$$

where, c is the curvature of the reflective surface, k is the conic constant, and a_2, a_3, a_4, a_5, … are the even aspheric coefficients, respectively.

Figure 2 is the schematic diagram in which the reflective even aspheric surface is replaced by the reflective Fresnel zone plate with spherical shape, and Fig. 3 is the enlarged view of a single Fresnel surface shown in Fig. 2. In Fig. 3, there are

$$\begin{cases} t_i=R-\sqrt{R^2-x_i^2}, \\ d_i=\sqrt{R^2-x_i^2}-\sqrt{R^2-(x_i+l_i)^2}, \\ \tan\psi_i=\dfrac{h_i+d_i}{l_i}, \\ \tan 2\psi_i=\dfrac{x_i+(l_i/2)}{f-t_i-[(h_i+d_i)/2]}. \end{cases} \tag{2}$$

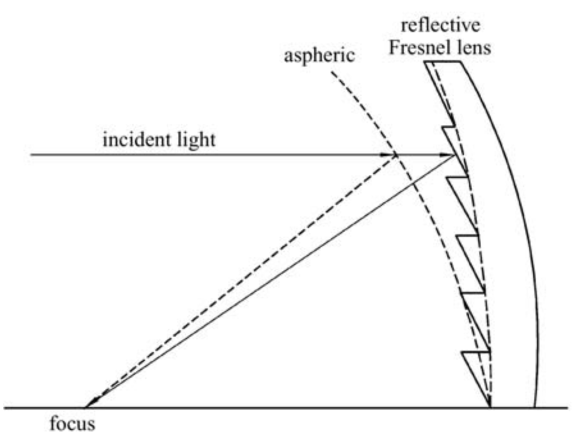

Fig. 2 Reflective Fresnel zone plate with spherical shape

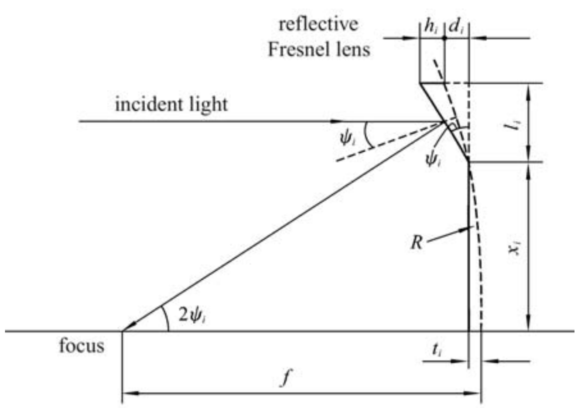

Fig. 3 One of the reflective Fresnel zone plate with spherical shape

The meanings of all the parameters in Eq. (2) are shown in Fig. 3, and Eq. (2) can be solved and obtained as

$$[x_i-(l_i/2)]\tan^2\psi_i+2(f-t_i)\tan\psi_i-[x_i+(l_i/2)]=0. \quad (3)$$

Thus, the parameters of a single reflective Fresnel surface can be obtained as

$$\begin{cases}\tan\psi_i=\dfrac{-2(f-t_i)+\sqrt{4(f-t_i)^2+4x_i^2-l_i^2}}{2x_i-l_i},\\ h_i=l_i\cdot\tan\psi_i-d_i,\end{cases} \quad (4)$$

and the parameters of initial structure are

$$x_1=0,\ t_1=0,\ x_{i+1}=x_i+l_i. \quad (5)$$

If the radius of the reference spherical surface is set, the structure parameters of the reflective Fresnel surface can be obtained according to Eqs. (2), (4) and (5) with different l_i, and the reflective Fresnel surface can be designed to have the same focal power with aspheric surface.

The set of R and l_i should make the aberration of the reflective Fresnel surface close to that of the replaced aspheric surface. The spot diagram of the aspheric surface at a specified location can be obtained by ray tracing, and the spot diagram of the reflective Fresnel zone plate with spherical surface can be calculated by amplitude transmittance.

According to the optical path difference (OPD) of rays reflected by the Fresnel zone plate, the phase shift between pre and post of the reflective Fresnel zone plate can be expressed as

$$\gamma(x)=2k[h_i(x)+d_i(x)+t_i(x)], \quad (6)$$

where $k=2\pi/\lambda$, and the function of the amplitude transmittance for reflective Fresnel surface can be expressed as

$$T(x)=\sum_{i=-N}^{N}\exp\{-\mathrm{j}2k[h_i(x)+d_i(x)+t_i(x)]\}. \quad (7)$$

According to Eqs. (2) and (4),

$$h_i(x)+d_i(x)=\begin{cases}\tan\psi_i(x-x_i), & x_i<x\leqslant x_i+l_i,\\ 0, & \text{other},\end{cases} \quad (8)$$

where $x_i=\sum_{k=0}^{i-1}l_k$, Eq. (7) can be expressed as

$$T(x)=\sum_{i=-N}^{N}\left\{\mathrm{rect}\left\{\left[x-\sum_{k=0}^{i-1}l_k-(l_i/2)\right]\Big/l_i\right\}\cdot\exp\left[-\mathrm{j}2kl_i\tan\psi_i\cdot\left(x-\sum_{k=0}^{i-1}l_k\right)\right]\cdot\exp[-\mathrm{j}2kt_i(x)]\right\}. \quad (9)$$

The light intensity distribution on the focus plane can be obtained by Fourier transformation for the function of amplitude transmittance:

$$\begin{aligned}\mathcal{F}[T(x)]&=\mathcal{F}\left\{\sum_{i=-N}^{N}\left\{\mathrm{rect}\left\{\left[x-\sum_{k=0}^{i-1}l_k-(l_i/2)\right]\Big/l_i\right\}\cdot\exp\left[-\mathrm{j}2kl_i\tan\psi_i\cdot\left(x-\sum_{k=0}^{i-1}l_k\right)\right]\cdot\exp[-\mathrm{j}2kt_i(x)]\right\}\right\}\\&=\sum_{i=-N}^{N}\mathcal{F}\left\{\mathrm{rect}\left\{\left[x-\sum_{k=0}^{i-1}l_k-(l_i/2)\right]\Big/l_i\right\}\cdot\exp\left[-\mathrm{j}2kl_i\tan\psi_i\cdot\left(x-\sum_{k=0}^{i-1}l_k\right)\right]\cdot\exp[-\mathrm{j}2kt_i(x)]\right\}.\end{aligned}$$

Therefore, the distribution on the Z offset plane against focus plane can be acquired by Fresnel diffraction as

$$U(Z)=\frac{1}{\mathrm{j}\lambda Z}\exp(\mathrm{j}kZ)F\{T(x)\exp[\mathrm{j}kx^2/(2Z)]\}. \quad (10)$$

The light intensity distribution of the ray spots reflected by the Fresnel zone plate with spherical surface can be obtained by Eq. (10), according to the known parameters R and l_i. The reflective Fresnel surface can achieve the same focal power as the replaced aspheric surface by continuous correction for parameters R and l_i.

3 Design of new objective lens

In the reflective objective lens shown in Fig. 1, the major function of the aspheric mirror M_3 is to correct the astigmatism and distortion. The focus value of M_3 is −79.8 mm and the dimension is 80 mm × 60 mm. If M_3 is replaced by the reflective Fresnel zone plate with a spherical shape, the radius of the reference spherical surface R can be assumed as 150 mm and 0.02 mm for the reference pitch. According to Eqs. (4) and (5), the structure parameters which will satisfy the requirement of the focal power can be calculated. The structure of the reflective Fresnel mirror is shown in Fig. 4. Meanwhile, the reflective surface of the basic structure will be corrected by being divided into surface unit by n ($n=8$–12). The light intensity of the reflective Fresnel zone plate with spherical shape can be calculated by amplitude transmittance, and the reference pitch and angle of the reflecting surface should be modified to have the similar aberration as the aspheric mirror. Figure 5 is the comparison diagram of the spot distribution of the reflective Fresnel zone plate and the aspheric mirror at the center of the imaging plane.

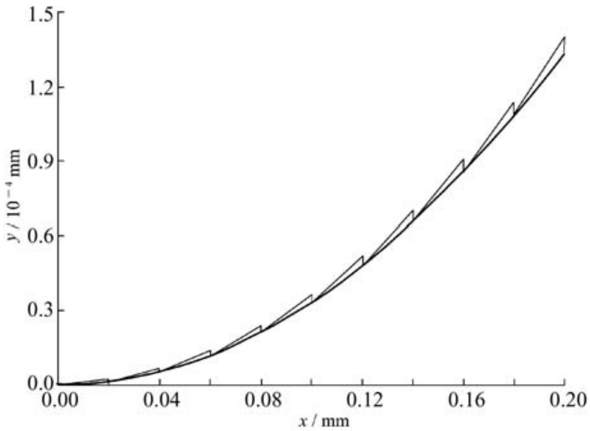

Fig. 4 Structure of reflective Fresnel mirror

Figure 5(a) is the spot diagram for the aspheric mirror at the centre of the imaging plane and Fig. 5(b) for the spheric Fresnel mirror. Figure 5 shows the difference in aberration between these two types of mirrors. Table 2 shows the structure parameters of the final design. Compared with Table 1, it can be inferred that the residual aberrations which cannot be corrected by using spheric Fresnel mirror has to be corrected by other aspheric mirrors.

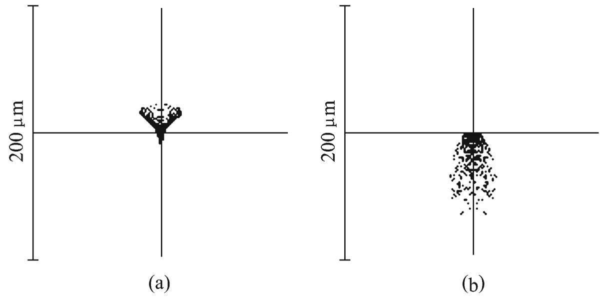

Fig. 5 Spot diagram for aspheric mirror (a) and spheric Fresnel mirror (b)

Figure 6 is the layout and modulation transfer function (MTF) results of the objective lens, which are calculated by the ZEMAX software. Figure 6(a) is the structure layout with three aspheric mirrors and a piece of spheric Fresnel mirror, under the condition of magnification of 100 ×, Fresnel number of 2.5, projection distance of 250 mm and field angle of 120°, and the MTF reaches above 40% at 0.6 line pairs/mm on the magnification side shown in Fig. 6(b). MTF of the other side can reach above 60 line pairs/mm, considering the magnification 100 × of the objective lens, which will satisfy the definition requirement of the objective lens.

Table 2 Structure data of objective lens with Fresnel mirror and three aspheric mirrors

	type	c	k	a_1	a_2	a_3	a_4
M_1	aspheric	83.902	0.589	-1.387×10^{-7}	7.168×10^{-10}	-1.824×10^{-12}	2.133×10^{-15}
M_2	aspheric	65.373	−9.232	4.000×10^{-8}	-1.828×10^{-8}	1.398×10^{-10}	6.311×10^{-16}
M_3	Fresnel	Fresnel mirror: $R = 150$ mm, $l_i = 0.02$ mm					
M_4	aspheric	27.797	−3.837	-6.302×10^{-8}	7.523×10^{-12}	-3.549×10^{-16}	8.835×10^{-21}

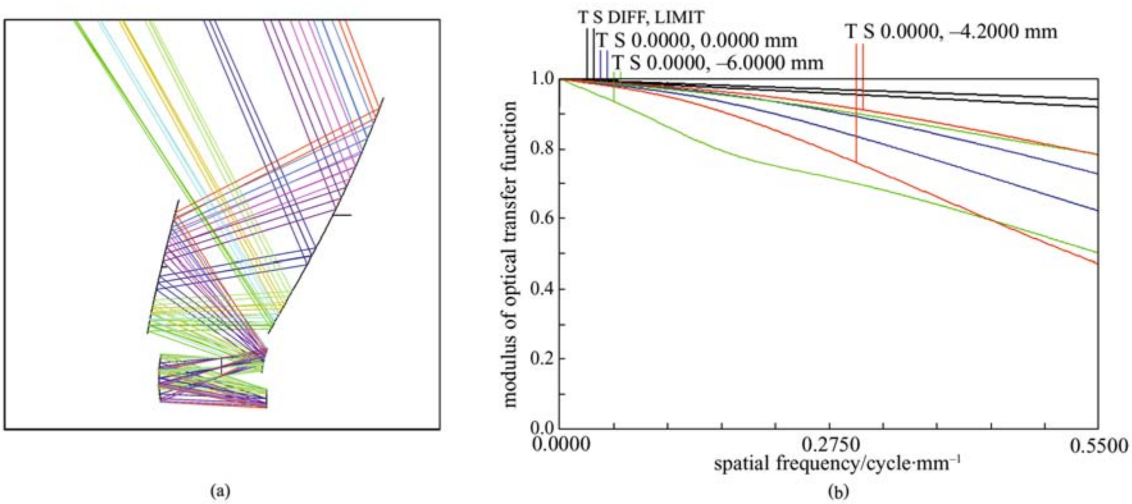

Fig. 6 Structure (a) and MTF of the 3-aspheric and 1-reflective Fresnel lens (b)

Figure 7 shows the field curvature and distortion results. It can be seen that the distortion is less than 2.2% in field and the design can satisfy the imaging requirement within a narrow band of 550 to 600 nm.

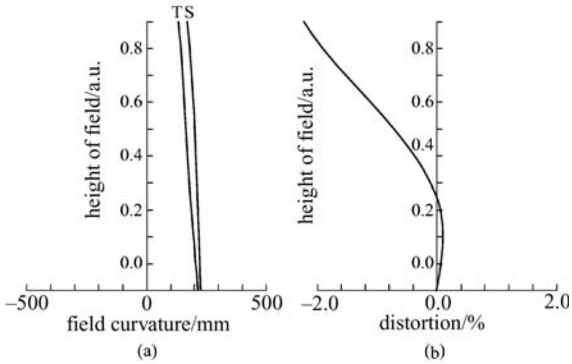

Fig. 7 Field curvature (a) and distortion (b) of lens

4 Conclusion

In this paper, a new method using a reflective Fresnel zone plate with spherical shape to replace the aspheric mirror is put forward. An objective lens with a spheric Fresnel mirror is designed. The Fresnel zone plate is concerned due to its light structure and low replication cost; however, the application of the Fresnel zone plate is restricted by current technological condition. The Fresnel zone plate manufactured now has low diffraction efficiency with harmful interference grade, meanwhile, the chromatic aberration is hard to correct owning to the diffraction grade of the Fresnel zone plate. The objective lens proposed in this paper can only perform within a narrow band (500–600 nm) of the invisible light, so there is still certain difficulty for this kind of reflective Fresnel zone plate working at a broader band in imaging design.

Acknowledgements This work was supported by the National Defense Fund of China.

References

1. Schuster N, Schonheit T. Telecentric large field lenses using Fresnel optics. Proceedings of SPIE, 2002, 4567: 190–198
2. Korsch D. Reflective Optics. London: Academic Press, 1991, 5–12
3. Jin C S, Ma Y Y, Pei S, et al. Study of the integration of EUVL experimental tool. Acta Optica Sinica, 2002, 22(7): 852–857 (in Chinese)
4. Li Y Q. Optical performance of extreme-ultraviolet lithography for 50 nm generation. Acta Optica Sinica, 2004, 24(7): 865–868 (in Chinese)
5. Shikama S, et al. Optical system of Ultra-thin rear projection equipped with refractive reflective projection optics. In: SID. Boston. 2002, 46(2): 1250–1253
6. Ogawa J, Agata K, Sakamoto M, et al. Super-short focus front projector with aspheric mirror projection optical system. In: SID Digest, San Diego. 2004, 170–173
7. Erismann F. Design of a plastic aspheric fresnel lens with a spherical shape. Optical Engineering, 1997, 36(4): 988–991
8. Schmitz M, Bryngdahl O. Rigorous analysis and design of diffractive cylindrical lenses with high numerical and large geometrical apertures. Optics Communications, 1998, 153(1–3): 118–124
9. Roder H, Ehrke H J, Gerhard-Multhaupt R, et al. Full-colour diffraction-based optical system for light-valve projection displays. Displays, 1995, 16(1): 27–33
10. Fukuda H, Terasawa T. Design and analysis of diffraction mirror optics for EUV projection lithography. Microelectronic Engineering, 1995, 27(1–4): 239–242