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Effects of width errors of discrete levels on optical performance of binary diffractive lens

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Abstract: The effects of width errors of discrete levels during thin-film deposition on the optical performance of a binary diffractive germanium lens are investigated using the nonsequential mode and four discrete levels in the optical design code ZEMAX. The thin-film deposition errors considered are all metallic mask fabrication errors. The peak value of the point spread function is used as the criterion to show the effects of the width errors of the four discrete levels on the optical performance of the binary germanium lens.

1. Introduction

Refractive and diffractive lenses are often combined into a hybrid lens to enhance optical resolution and reduce aberrations [1]. Diffractive lenses are primarily gratings with variable groove spacings across the optical surface, which cause changes in the phases of wavefronts passing through them [2].

A diffractive optical element (DOE) with a continuous surface profile is often referred to as a kinoform, and the ideal theoretical profile of the diffractive surface can be discretely approximated (the sag is approximated in discrete steps) in a manner similar to the digital representation of an analog function [3]. This discrete representation is called a multilevel or binary profile [4]. The design techniques used in binary optics were initially developed by integrated circuit manufacturers by using computer-aided design software [4].

Diffractive surfaces in most optical design codes, such as Oslo [5] and ZEMAX [2], are closer approximations to kinoforms than true binary optics since the phases are continuous everywhere; hence, the optical performance evaluations of such elements are often considered for continuous phase profile cases [6].

Swanson [3] used the Optical Research Associates (ORA) Code V lens design software [7] to develop a technique for designing DOEs. This was possible because the code used direct ray tracing with a subcode for the holographic optical elements, which allows partial simulation of the binary elements. The finite-difference time-domain method has also been used to simulate subwavelength diffractive lenses [8, 9]. Some optical designers prefer using ZEMAX to design the binary diffractive lens. However, ZEMAX does not allow the direct modeling of

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wavelength-scale grooves; instead, it uses the phase advance or delay represented by the local surface to change the direction of propagation of the ray [2].

The fabrication of single-level and multilevel diffractive lenses involves the generation of a set of masks that are used to transfer patterns to a substrate sequentially with photoresist deposition, exposure, and development, as well as an etching procedure, such as reactive-ion etching [10], or thin-film deposition [11, 12]. For example, *K* masks are needed for a lens with 2^K phase levels [3]. The development of these masks (photoresist [11] or metallic [12]) is generally not error-free; such errors are known as mask fabrication errors and cause significant deformations in the resulting binary diffractive lens surface and corresponding deterioration of lens performance. Therefore, analysis of the effects of these errors on the DOE performances and determination of acceptable fabrication tolerances for each design are important.

Choi et al. used geometrical and Fourier optics theory to simulate the decrease in the modulation transfer function due to DOE fabrication errors [1]; Glytsis et al. [10] used the boundary-element method as the basic modeling tool to analyze diffractive lenses with fabrication errors. The effects of fabrication errors on the predicted performances of surface-relief phase gratings were analyzed by Pommet et al. using a rigorous vector diffraction technique [13]. Jabbour used the generalized projection method to study the effects of experimental errors on DOE performance [14].

Alshami et al. [12] used metallic masks to develop a binary diffractive germanium lens by thin-film deposition. The present study shows the effects of width errors of discrete levels due to metallic mask fabrication errors on the optical performance of a four-level binary surface of a diffractive germanium lens designed using the nonsequential mode in ZEMAX. In the following sections, the design of the four-level surface of a binary diffractive germanium lens [12] is presented first, and the effects of the width errors of discrete levels due to mask fabrication on the optical performance are described thereafter using the peak value of the point spread function (PSF) as a criterion.

2. Design of ~~F~~four-~~Step~~level ~~B~~binary ~~S~~surface in ZEMAX

The design of a four-level surface of a binary diffractive germanium lens [12] by using the nonsequential mode in ZEMAX is presented in the following subsections.

2.1 Refractive ~~L~~lens

Table 1 lists the optical design specifications of the refractive germanium (planoconvex) lens illustrated in Fig. 1 for a wavelength band of 8–12 μm, an effective focal length of 75 mm with a 9.09° field of view, and a diameter of 33 mm.

Table 1~~:~~. Specifications of the ~~r~~Refractive ~~l~~Lens (mm)~~.~~

Surface	Type	Radius	Thickness	Glass	Diameter
OBJ	Standard	Infinity	Infinity		0.000
STO	Standard	225.371	5.000	Germanium	33.097
2	Standard	Infinity	72.849		32.787
IMA	Standard	Infinity			13.435

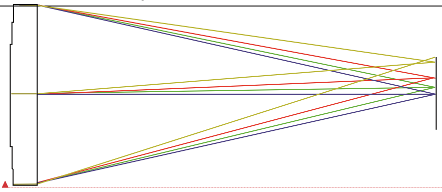

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Fig. 1. Layout of the refractive lens.

2.2 Diffractive lens

Table 2 lists the optical design specifications of the diffractive germanium lens with the same specifications as the refractive lens, with the plane surface chosen as the Binary 2 surface (1), as shown in Fig. 2.

$$Ø = -0.65554\rho^2 + 8.97589\rho^4. \quad (1)$$

Table 2. Specifications of the Diffractive Lens (mm)

Surface	Type	Radius	Thickness	Glass	Diameter	Coeff. on ρ^2	Coeff. on ρ^4
OBJ	Standard	Infinity	Infinity		0.000		
STO	Standard	225.371	5.000	Germanium	33.097		
2	Binary 2	Infinity	73.339		32.787	−0.65554	8.97588
IMA	Standard	Infinity			13.323		

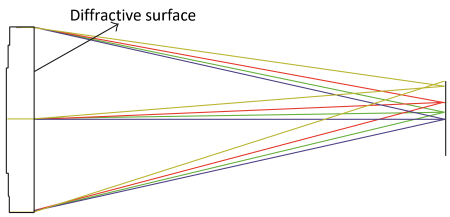

Fig. 2. Layout of the diffractive lens.

2.3 Switching from kinoform to binary surface

In the optical design of the proposed lens [12], the diffractive surface contained one diffractive zone, and the ideal diffractive phase profile to be approximated in a binary manner (four steps or phase levels) is given by (1). The diameters of the discrete phase levels or binary steps (equivalent to phase values $\pi/2$, π, $3\pi/2$, and 2π) and the sag thicknesses equivalent to the phase values are provided in Table 3 and Fig. 3 [12].

Table 3. Diameters and Thickness of each Binary Zone

Binary zone number	Equivalent phase value Equivalent sag thickness (radian)	Radius of each binary zone (mm)	Diameter of each binary zone (mm)	(μm)
1	$\pi/2$	11.148	22.295	0.833
2	π	13.089	26.177	1.667
3	$3\pi/2$	14.404	28.807	2.498
4	2π	15.426	30.851	3.333

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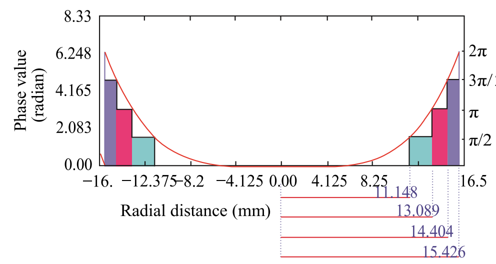

Fig.~~ure~~ 3.~~:~~ Phase curve versus aperture of the diffractive surface slic~~ing~~ed into 2π layers and ~~the~~ discrete phase levels.

2.4 Design of ~~F~~four-~~Step~~level ~~Binary S~~surface of a binary ~~D~~diffractive ~~G~~germanium ~~L~~lens

The design of the four-layer surface of the binary diffractive germanium lens by using the nonsequential mode in ZEMAX is presented in Tables 4 and 5. The object *cylinder volume*, which is a rotationally symmetric volume, was used to design each step of the germanium material, wherein the diameters of the front and rear faces of each cylinder are the same as their equivalent binary steps, and the length along the local *z*-axis of each cylinder is the thickness of the equivalent binary step, as shown in Fig. 4. For optical design in the nonsequential mode, we define the *x*, *y*, and *z* positions of each object.

Table 4.~~:~~ Optical ~~d~~Design of the ~~b~~Binary ~~g~~Germanium ~~l~~Lens in ~~n~~Nonsequential ~~m~~Mode~~.~~

Surface	Type	Radius	Thickness	Glass	Diameter	Exit lock *Z*
OBJ	Standard	Infinity	Infinity		Infinity	
STO	Standard	225.371	5.000	Germanium	33.097	
2	Standard	Infinity	0.000		32.787	
3	Nonsequential	Infinity			32.787	73.368
IMA	Standard	Infinity			13.342	

Table 5.~~:~~ Data in the ~~n~~Nonsequential ~~c~~Component ~~e~~Editor

Object number	Object 1	Object 2	Object 3	Object 4	Object 5	Object 6
Object type	Standard lens	Cylinder volume	Standard lens	Cylinder volume	Standard lens	Cylinder volume
Z position (mm)	0.000	0.000	0.000833	0.000833	0.001667	0.001667
Material	Germanium		Germanium		Germanium	
Front *R* (mm)	0.000	11.148	0.000	13.089	0.000	14.404
Z length (mm)	0.000	0.000833	0.000	0.000833	0.000	0.000833
Back *R* (mm)	16.500	11.148	16.500	13.089	16.500	14.404
Edge 1 (mm)	16.500	Not used	16.500	not used	16.500	Not used

Thickness (mm)	0.000833	Not used	0.000833	not used	0.000833	Not used
Clear 2 (mm)	16.500	Not used	16.500	not used	16.500	Not used
Edge 2 (mm)	16.500	Not used	16.500	not used	16.500	Not used

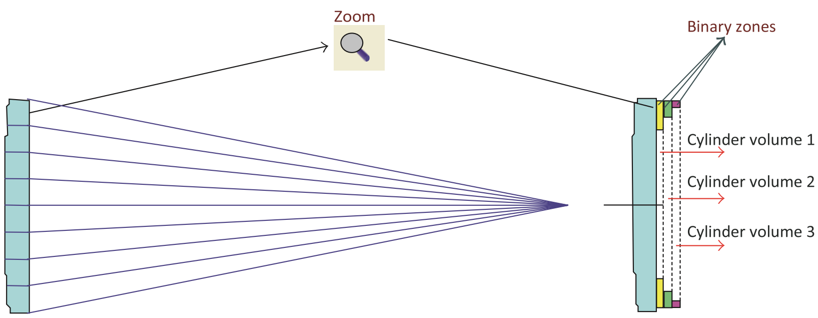

Fig.~~ure~~ 4.~~:~~ ~~The b~~Binary diffractive lens with discrete phase levels.

Fig. 5 shows the differences in the fast Fourier transform (FFT) PSF cross-sectional curves among the refractive, diffractive, and designed four-level binary germanium lens.

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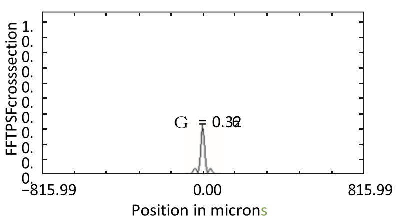
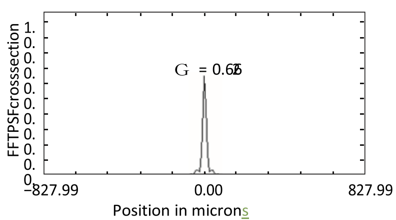


(a)



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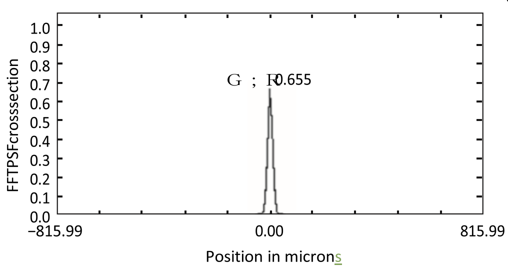

(c)

Fig.~~ure~~ 5.~~:~~ FFT PSF cross sections of (a) refractive~~ lens~~, (b) diffractive~~ lens~~, and (c) designed binary lenses.

3. Effects of width errors of ~~D~~discrete ~~L~~levels ~~Width Error~~ on performance of DOE~~the Diffractive Optical Element Performance~~

Imprecisions in the metallic mask fabrication process can cause the widths of the discrete levels to differ from their theoretical target values; consequently, this can have adverse effects on the optical performance. To understand how this effect degrades performance and to obtain the tolerances for fabrication errors, we studied the changes in the peak values of the PSFs of the designed lens as functions of the discrete levels or zone width variations. The variable Δw was introduced to specify the differences between the final and intended positions of the boundaries for each binary zone (an expected error is obtained for the width of each binary zone owing to the metallic mask fabrication accuracy of 0.1 mm of the laser machine), as shown in Fig. 6 [12]; the width of each binary zone was then changed by $2\Delta w$ ($2\Delta w$ = 0.2 mm). Δw can be either positive or negative, corresponding to wider or narrower zones, respectively. In this study, it was assumed that Δw was equal for all zones and independent of their widths.

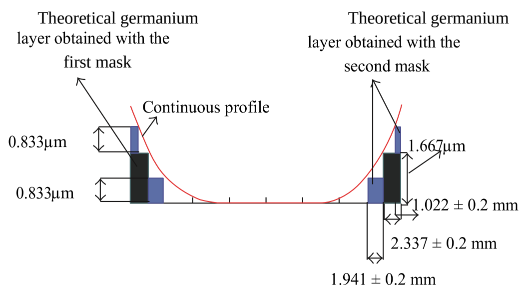

Fig.~~ure~~ 6.~~:~~ Germanium layers (binary zones) and ~~the~~ expected errors in their widths.

4. Results and ~~D~~discussion

Table 6 and Fig. 7 show the variations in peak values of the PSFs as functions of $2\Delta w$. The observed changes in $2\Delta w$ were limited to 200 µm (Δw = 100 µm, i.e., metallic mask fabrication error of the laser machine). A change of 200 µm for $2\Delta w$ has the effect of lowering the PSF peak value (Table 6) by 5%, thus lowering the diffraction efficiency by 5% [15].

Fig. 8 shows the FFT PSF cross section of the proposed lens for the extreme error values and without any errors. It can be seen from the figure that for the proposed binary diffractive lens, the axial resolution increases with increasing zone widths, but this results in decreasing PSF peak values. The metallic mask can be replaced with masks of similar dimensions that are produced using three-dimensional printers (rapid prototype) with an accuracy of 35 µm such that the width errors of the discrete levels change from −70 µm to 70 µm, which cause lowering in PSF peak value less than 2% then lowering in diffraction efficiency less than 2%; in this case, within the 70 µm change in $2\Delta w$, the performance of the considered lens is still acceptable.

Table 6~~:~~. Peak ~~v~~Values of the PSFs as ~~a f~~Functions of $2\Delta w$~~.~~

$2\Delta w$ (µ~~µ~~m)	−200	−150	−100	−50	0.00	50	100	150	200
Peak value of PSF	0.667	0.6684	0.6681	0.662	0.655	0.648	0.642	0.634	0.626

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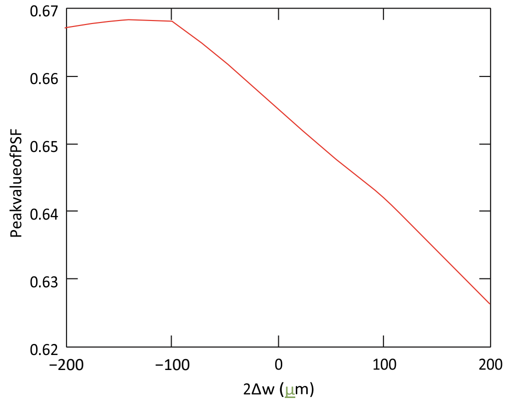

Fig. 7. Peak value of PSF as a function of variation in zone width error.

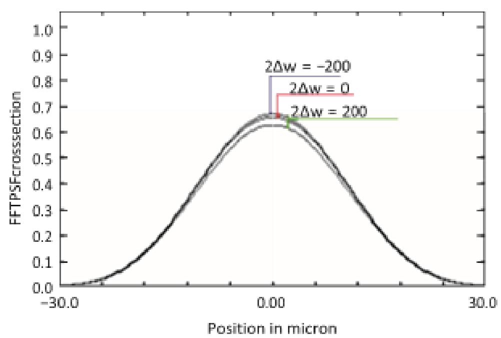

Fig. 8. FFT PSF cross section.

5. Conclusion

The effects of width errors of discrete levels fabricated by thin-film deposition on the optical performance of a four-level binary diffractive germanium lens were analyzed using the nonsequential mode in the optical design code ZEMAX. The primary errors in the thin-film deposition technique considered in this study were metallic mask fabrication errors. The peak values of the PSFs of the metallic mask fabrication errors (laser machine accuracy of 100 μm) were found to have considerable effects on the performance of the designed four-level binary germanium lens. To reduce such effects, it may be preferable to use masks fabricated by alternative techniques, such as 3D printing, which allow better accuracy (~35 μm).

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Competing interests. The authors declare that they have no competing interests.

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