Research Article

Effect of Discrete Levels Width Error on the Optical Performance of the Diffractive Binary Lens

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The effects of discrete levels width error developed by thin film deposition on the optical performance of diffractive binary germanium lens with four discrete levels are investigated using nonsequential mode in the optical design code ZEMAX. The thin film deposition technique errors considered are metallic mask fabrication errors. The peak value of the Point Spread Function (PSF) was used as criterion to show the effect of discrete levels width error on the optical performance of the four-level binary germanium lens.

1. Introduction

To enhance optical resolution and reduce aberrations, refractive and diffractive lenses are often combined as a hybrid lens [1]. Diffractive lenses are essentially gratings with variable groove spacing across the optical surface, which impart a change in phase of the wavefront passing through it [2].

A diffractive optical element (DOE), with continuous surface profile, is often referred to as kinoform, and the theoretical ideal profile of the diffractive surface can be approximated in a discrete fashion (the sag is approximated by discrete steps), 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 for binary optics were initially developed by integrated circuit (IC) manufacturers, by using the CAD software [4].

Diffractive surfaces in most of the optical design codes, such as Oslo [5] and ZEMAX [2], are closer approximation to kinoforms than true binary optics, since the phase is continuous everywhere, so the evaluation of the optical performance of that elements will be done for continuous phase profile case [6].

Swanson [3] has developed a technique using Optical Research Associates' (ORA's) Code V lens design software [7] to design diffractive optical elements. This is possible because the code uses direct ray trace with a subcode for holographic optical elements (HOEs), which can be used to partially

simulate binary elements. The finite-difference time-domain method was used to simulate subwavelength diffractive lenses [8, 9]. But, for a few of the optical designers who use the optical design code ZEMAX, it will be preferable to design diffractive binary lens by it, but the optical design code ZEMAX does not model the wavelength-scale grooves directly. Instead, ZEMAX uses the phase advance or delay represented by the surface locally to change the direction of propagation of the ray [2].

The fabrication of the single-level and multilevel diffractive lenses involves the generation of a set of masks that are used sequentially for the transfer of their pattern to a substrate in conjunction with photoresist deposition, exposure, and development, as well as an etching procedure such as reactive-ion etching [10], or with thin film deposition [11, 12].

For example, K masks are needed for a lens of 2^K phase levels [3]. The development of these masks (photoresist [11] or metallic [12]) is not usually error-free. These errors are usually known as mask fabrication errors and cause significant deformations of the resulting diffractive binary lens surface and corresponding deterioration of the lens performance. Therefore, the analysis of the effects of these errors on the performance of diffractive optical elements and the determination of acceptable fabrication tolerances for each design is of central importance.

Choi and others had used geometrical and Fourier optics theory to simulate the decrease of MTF due to diffractive

TABLE 1: Specifications of the refractive 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

optical element fabrication error [1]; Glytis and others [10] had used the Boundary-Element Method (BEM) as basic modeling tool for analyzing diffractive lenses with fabrication errors. The effects of fabrication errors on the predicted performance of surface-relief phase gratings are analyzed with a rigorous vector diffraction technique by Pommet et al. [13]. Jabbour had used the method of generalized projection to study the effect of experimental errors on the diffractive optical element performance [14].

Alshami et al. [12] had used metallic masks in the development of binary diffractive germanium lens by thin film deposition; hopefully, this paper shows the effect of discrete levels width error due to metallic mask fabrication errors on the optical performance using nonsequential mode in ZEMAX to design the four-level binary surface of a diffractive germanium lens, where the first part presents the design of 4-step binary surface of a diffractive germanium lens [12] with nonsequential mode in ZEMAX and the second part presents the effect of discrete levels width error due to the mask fabrication on the optical performance using the peak value of PSF as criterion.

2. Design of Four-Step Binary Surface in ZEMAX

The design of four-step binary surface of the diffractive binary germanium lens [12] by nonsequential mode in ZEMAX will be presented via the following procedure.

2.1. Refractive Lens. Table 1 shows the optical design specifications of refractive germanium (planoconvex) lens, as shown in Figure 1, for the wavelength band (8)–(12) μm , effective focal length of 75 mm with a 9.09-degree field of view, and diameter 33 mm.

2.2. Diffractive Lens. Table 2 shows the optical design specifications of diffractive germanium lens, with the same conditions as refractive one, and the plane surface chosen as the binary 2 surface (1), as shown in Figure 2:

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

2.3. Switch from Kinoform to Binary Surface. In the optical design of the considered lens [12], the diffractive surface contained one diffractive zone, and the ideal diffractive phase profile to be approximated in a binary fashion (4 steps or 4 phase levels) is (1). The diameter of each discrete phase level or binary step (equivalent to phase value $\pi/2, \pi, 3\pi/2, 2\pi$) and the sag's thickness equivalent to each phase value are shown in Table 3 and Figure 3 [12].

FIGURE 1: Layout of the refractive lens.

FIGURE 2: Layout of the diffractive lens.

FIGURE 3: Phase curve versus aperture of the diffractive surface slicing into 2π layers and the discrete phase levels.

2.4. Design of Four-Step Binary Surface of a Diffractive Germanium Lens. The design of four-step binary surface of diffractive germanium lens by nonsequential mode in ZEMAX is presented in Tables 4 and 5, and it was done by using the *object cylinder volume* which is a rotationally symmetric volume to design each step of germanium, where the diameter of the front and rear face of each cylinder is the same as the equivalent binary step and the length along the local z -axis of each cylinder is the thickness of the equivalent binary step, as shown in Figure 4. For the optical design in nonsequential mode, we need to define x, y, z position of each object.

Figure 5 shows the difference in FFT PSF cross-sectional curves between the refractive, diffractive, and the designed four-step binary germanium lens.

3. Effect of Discrete Levels Width Error on the Diffractive Optical Element Performance

Imprecision in the metallic mask fabrication process can cause the width of the discrete levels to differ from the theoretical target. This can have an adverse effect on the optical performance. To understand how this effect degrades

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		

TABLE 3: Diameters and thickness of each binary zone.

Binary zone's number	Equivalent phase value (radian)	Radius of each binary zone (mm)	Diameter of each binary zone (mm)	Equivalent sag's thickness (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

FIGURE 4: The binary diffractive lens with discrete phase levels.

FIGURE 5: FFT PSF cross section of (a) refractive lens, (b) diffractive lens, and (c) designed binary lens.

TABLE 4: Optical design of the binary germanium lens in nonsequential mode.

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

TABLE 5: Data in the nonsequential component 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

FIGURE 6: Germanium layers (binary zones) and the expected error in their width.

performance and thus obtain a tolerance for fabrication errors, we studied how the peak value of the PSF of the designed lens changes as a function of discrete level or zone width variation. The variable Δw is introduced to specify the difference between the final and intended position of the boundaries of each binary zone (an expected error in the width of each binary zone will result due to the metallic masks fabrication accuracy 0.1 mm of the laser machine), as in Figure 6 [12]; the width of each binary zone is then changed by $2\Delta w$ ($2\Delta w = 0.2$ mm). The sign of Δw can be positive or negative corresponding to wider and narrower zones, respectively. In this study, it is assumed that Δw is equal for all zones, independent of their width.

4. Results and Discussion

Table 6 and Figure 7 show the variation in peak value of PSF as a function of $2\Delta w$. The change in $2\Delta w$ studied was limited to

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

200 μm ($\Delta w = 100$ μm , the metallic masks fabrication error caused by laser machine). The change 200 μm in $2\Delta w$ has the effect of lowering the PSF peak value (Table 6) by 5%, lowering the diffraction efficiency by 5% [15].

Figure 8 shows the FFT PSF cross section of the considered lens for the extreme error values and without error. It can be seen from Figure 8 that, for this particular diffractive binary lens, the axial resolution increases with increasing zone width, but this occurs at the expense of decreasing the PSF peak value. The metallic mask can be replaced with similar dimension masks which can be produced by three-dimensional printer (rapid prototype) with accuracy of 35 μm so the discrete levels width error will change from -70 μm to

TABLE 6: Peak value of PSF as a function of $2\Delta w$.

$2\Delta w$ (μm)	-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

FIGURE 8: FFT PSF cross section.

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.

5. Conclusion

The effects of discrete levels width error developed by thin film deposition on the optical performance of diffractive binary germanium lens with four discrete levels have been analyzed using nonsequential mode in the optical design code ZEMAX. The thin film deposition technique errors considered are metallic mask fabrication errors. It was found by using the peak value of PSF as criterion that the metallic mask fabrication errors (100 μm laser machine accuracy) have a significant effect on the designed four-level binary germanium lens performance, and to reduce this effect it will be preferable to use another technique to fabricate the desired mask with more fabrication accuracy like, for example, by three-dimensional printer (35 μm is its accuracy).

Competing Interests

The authors declare that they have no competing interests.

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