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Effects of ~~Discrete Levels W~~width ~~E~~errors of discrete levels on ~~the O~~optical ~~P~~performance of binary ~~the D~~diffractive ~~Binary L~~lens

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Abstract: The effects of width errors of discrete levels~~ width error developed by~~during thin-film deposition on the optical performance of a binary diffractive ~~binary ~~germanium lens ~~with four discrete levels ~~are investigated using the nonsequential mode and four discrete levels in the optical design code ZEMAX. The thin-~~-~~film deposition ~~technique ~~errors considered are all metallic mask fabrication errors. The peak value of the ~~P~~point ~~S~~spread ~~F~~function ~~(PSF) was ~~is used as the criterion to show the effects of the width errors of the four discrete levels ~~width error ~~on the optical performance of the ~~four level ~~binary germanium lens.

1. Introduction

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

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

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

Swanson [3] ~~has developed a technique using ~~used the Optical Research Associates~~'~~ (ORA~~'s~~) Code V lens design software [7] to develop a technique for designing DOEs~~diffractive optical elements~~. This ~~is ~~was possible because the code useds direct ray tracinge with a subcode for the holographic optical elements~~ (HOEs)~~, which ~~can be used to ~~allows partial~~ly~~ simulatione of the binary elements. The finite-difference time-domain method ~~was ~~has also been used to simulate subwavelength diffractive lenses [8, 9]. ~~But, for~~Some ~~a few of the ~~optical designers prefer ~~who ~~usinge ~~the optical design code ~~ZEMAX~~,~~ ~~it will be preferable ~~to design the binary

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Should you have any concerns, please feel free to get back to me.
In case you make any revisions to this manuscript, please get them checked by us before you submit to the journal. This will ensure that the manuscript does not receive negative comments on language. You can use our multiple round service to get your paper rechecked by us.
My best wishes for your success with the manuscript.

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Formatted: Font: (Default) Times New Roman, 10 pt diffractive ~~binary~~ lens~~ by it,~~. ~~but~~ However, ~~the optical design code~~ ZEMAX does not allow the direct modeling of~~the~~ wavelength-scale grooves ~~directly~~; ~~.~~ ~~I~~instead, ~~ZEMAX~~ it uses the phase advance or delay represented by the local 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~~ to transfer ~~of their~~ patterns to a substrate sequentially ~~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 with ~~of~~ 2^K phase levels [3]. The development of these masks (photoresist [11] or metallic [12]) is generally not ~~usually~~ error-~~-~~free~~.~~; ~~These~~ such errors are ~~usually~~ known as mask fabrication errors and cause significant deformations ~~of~~ in the resulting binary 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~~ DOE performances and ~~the~~ determination of acceptable fabrication tolerances for each design ~~is~~ are ~~of central~~ important~~ce~~.

Choi et al. ~~and others had~~ used geometrical and Fourier optics theory to simulate the decrease in ~~of~~ the modulation transfer function ~~MTF~~ due to ~~diffractive optical element~~DOE fabrication errors [1]; Glytsis et al. ~~and others~~ [10] ~~had~~ used the b~~B~~oundary-~~E~~element ~~M~~method ~~(BEM)~~ as the basic modeling tool ~~for~~ to analyze~~ing~~ diffractive lenses with fabrication errors. The effects of fabrication errors on the predicted performances of surface-relief phase gratings ~~are~~ were analyzed by Pommet et al. ~~with~~ using a rigorous vector diffraction technique ~~by Pommet et al.~~ [13]. Jabbour ~~had~~ used the ~~method of~~ generalized projection method to study the effects of experimental errors on ~~the diffractive optical element~~ DOE performance [14].

Alshami et al. [12] ~~had~~ used metallic masks ~~in the~~ to develop~~ment of~~ a binary diffractive germanium lens by thin-~~-~~film deposition. ~~; hopefully, this~~ The present ~~paper~~ study shows the effects of ~~discrete levels~~ width errors of discrete levels due to metallic mask fabrication errors on the optical performance ~~using nonsequential mode in ZEMAX to design the~~ of a four-level binary surface of a diffractive germanium lens designed using the nonsequential mode in ZEMAX. In the following sections~~,~~ ~~where the first part presents~~ the design of the~~4~~ four-level~~step binary~~ surface of a binary diffractive germanium lens [12] ~~with nonsequential mode in ZEMAX~~ is presented first, and the ~~second part presents the~~ effects of the ~~discrete levels~~ width errors of discrete levels due to ~~the~~ 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~~step binary~~ surface of ~~the~~ a binary diffractive ~~binary~~ germanium lens [12] by using the nonsequential mode in ZEMAX ~~will be~~ is presented ~~via~~ in the following subsections ~~procedure~~.

2.1 Refractive ~~L~~lens

Table 1 lists~~shows~~ the optical design specifications of the refractive germanium (planoconvex) lens~~,~~ ~~as shown~~ illustrated in Fig.~~ure~~ 1~~,~~ for a~~the~~ wavelength band of ~~(~~8~~)~~–~~(~~12~~)~~ μ~~μ~~m, an effective focal length of 75 mm with a 9.09°~~ degree~~ 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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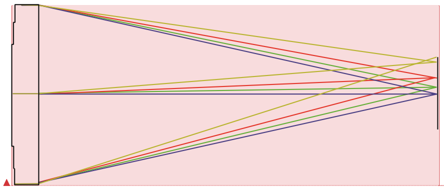

Fig.~~ure~~ 1.~~:~~ Layout of the refractive lens.

2.2 Diffractive ~~L~~lens

Table 2 lists~~shows~~ the optical design specifications of the diffractive germanium lens~~,~~ with the same specifications ~~conditions~~ as the refractive lens ~~one~~, ~~and~~ with the plane surface chosen as the ~~b~~Binary 2 surface (1), as shown in Fig.~~ure~~ 2.~~:~~

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

Table 2~~:~~. Specifications of the ~~d~~Diffractive ~~l~~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		

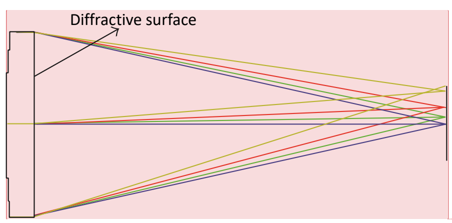

Fig.~~ure~~ 2.~~:~~ Layout of the diffractive lens.

2.3 Switching from ~~K~~kinoform to ~~B~~binary ~~S~~surface

In the optical design of the ~~considered~~ proposed lens [12], the diffractive surface contained one diffractive zone, and the ideal diffractive phase profile to be approximated in a binary ~~fashion~~ manner (~~4~~ four steps or ~~4~~ phase levels) is given by (1). The diameters of the ~~each~~ discrete phase levels or binary steps (equivalent to phase values $\pi/2$, π, $3\pi/2$, and 2π) and the sag~~'s~~ thicknesses equivalent to the ~~each~~ phase values are provided~~shown~~ in Table 3 and Fig.~~ure~~ 3 [12].

Table 3~~:~~. Diameters and ~~t~~Thickness of each ~~b~~Binary ~~z~~Zone

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

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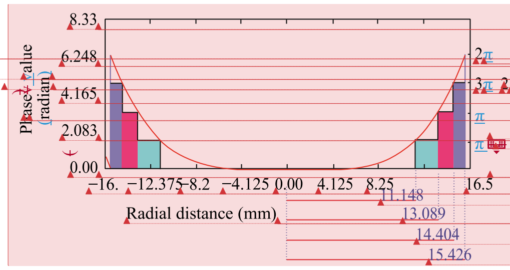
4	2π	15.426	30.851	3.333



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~~step binary~~ surface of the binary diffractive germanium lens by ~~by~~ using the nonsequential mode in ZEMAX is presented in Tables 4 and 5. ~~, and it was done by using t~~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 ~~is~~ 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~~ure~~. 4. For ~~the~~ optical design in the nonsequential mode, we ~~need to~~ define the *x*, *y*, and *z* positions of each object.

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		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 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

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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

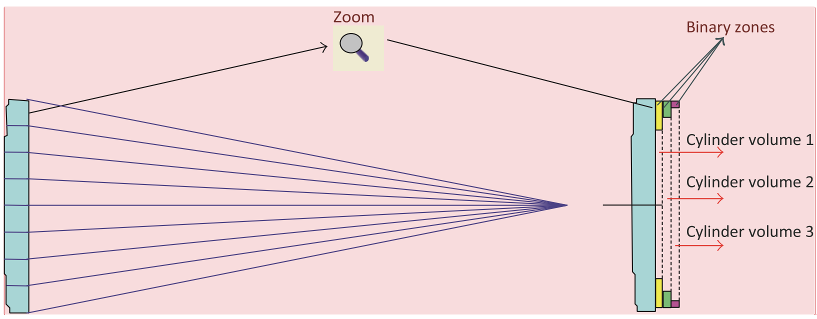

Fig.~~ure~~ 4.~~:~~ ~~The b~~Binary diffractive lens with discrete phase levels.

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

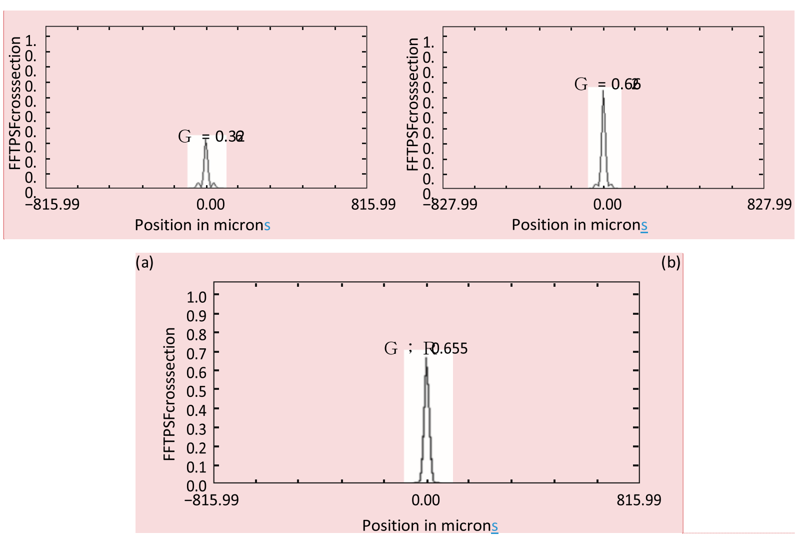

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Fig.~~ure~~ 5.~~:~~ FFT PSF cross sections of (a) refractive~~ lens~~, (b) diffractive~~ lens~~, and (c) designed binary lenses.

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

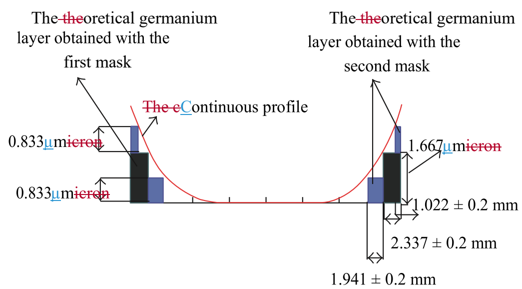

Fig.~~ure~~ 6.~~:~~ Germanium layers (binary zones) and ~~the~~ expected errors in their widths.

4. Results and dDiscussion

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

Fig.~~ure~~ 8 shows the FFT PSF cross section of the ~~considered~~ proposed lens for the extreme error values and without any errors. It can be seen from the figure ~~Figure 8~~ that~~,~~ for ~~this~~ the proposed ~~particular~~ binary diffractive ~~binary~~ lens, the axial resolution increases with increasing zone widths, but this ~~occurs at the expense of~~ results in decreasing ~~the~~ PSF peak values. The metallic mask can be replaced with masks of similar dimensions ~~masks which can be~~ that are produced ~~by~~ using three-dimensional printers (rapid prototype) with an accuracy of 35 µm ~~so~~ such that the width errors of the discrete levels ~~width error will~~ 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 $2\Delta w$~~.~~

$2\Delta w$ (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

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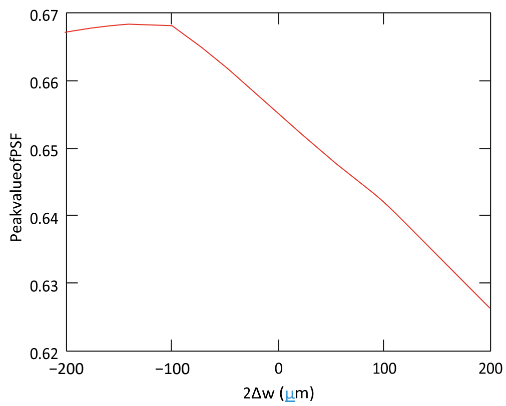
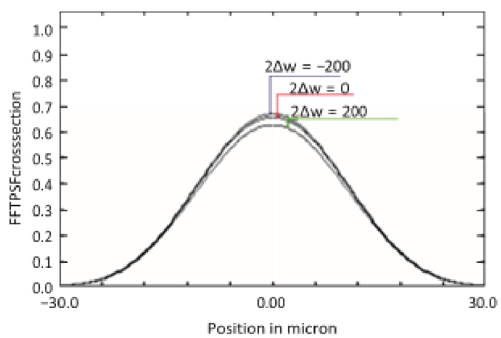


Fig~~ure~~ 7~~:~~. Peak value of PSF as a function of variation in zone width error.



Fig~~ure~~ 8~~:~~. FFT PSF cross section.

5. Conclusion

The effects of width errors of discrete levels ~~width error developed~~ fabricated by thin-~~-~~film deposition on the optical performance of a four-level binary diffractive ~~binary~~ germanium lens ~~with four discrete levels have been~~ were analyzed using the nonsequential mode in the optical design code ZEMAX. The primary errors in the thin-~~-~~film deposition technique ~~errors~~ considered in this study were ~~are~~ metallic mask fabrication errors. ~~It was found by using the~~ The peak values of the PSFs ~~as criterion that~~ of the metallic mask fabrication errors (~~100 μm~~ laser machine accuracy of 100 μm) were found to have ~~a significant~~ considerable effects on the performance of the designed four-level binary germanium lens~~ performance~~.~~,~~ ~~and t~~To reduce ~~this~~ such effects, it ~~will~~ may be preferable to use masks fabricated by alternative ~~another~~ techniques~~ to fabricate the desired mask~~, such as 3D printing, which ~~with~~ allow ~~more~~ better ~~fabrication~~ accuracy~~ like, for example, by three-dimensional printer~~ (~35 μ~~μ~~m~~ is its accuracy~~).

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

Acknowledgments. This work was ~~totally~~ fully supported by ~~HIAST (~~the Higher Institute for Applied Sciences and Technology (HIAST).

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