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LIMIT OF PHASE ONLY APPROACH IN MICRO-LENS DESIGN

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Abstract. Phase only approach (POA) is generally used to analyze diffractive optical elements (DOEs) such as micro-lenses. We used 3-D finite difference time domain (FDTD) method with perfect matched layer (PML) absorbing boundary conditions to test several micro-lenses that were designed based on phase only approach to evaluate the accuracy of this approach. It is shown that if the focal length is greater than 80λ and 25λ for 2π and 4π phase resets, respectively, the error in the main lobe diffraction efficiency will be less than 10%.

Keywords: Phase only approach (POA); diffractive optical elements (DOEs); micro-lens

1.0 INTRODUCTION

Several methods have been used to design diffractive optical elements (DOEs). Some methods use phase only approach in which the effect of the DOE is considered as a delay element. This approach ignores polarization, internal reflection and resonance phenomena that are important for DOEs with sub-wavelength features. Examples of these methods are the vectorial beam shaping method [1], the optimal rotation angle (ORA) [2], Gerchberg–Saxton method [3], iterative Fourier transform algorithm (IFTA) [4] and iterative angular spectrum approach (IASA) [5].

The above methods are used to design several types of DOEs such as beam-fanners, beam-shapers and micro-lenses. Beam-fanners and beam-shapers deal with various desired parameters, while micro-lenses are only involved with focal length. Therefore, to evaluate the accuracy of phase only approach, we used micro-lens to reduce the complexity of the structure.

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Pommet *et al.* [6] have investigated the limitation of scalar techniques in designing dielectric gratings [5].

In the following section, we design some micro-lenses with IASA and then evaluate their accuracy using FDTD method. The last part of the paper is devoted to conclusions.

2.0 ITERATIVE ANGULAR SPECTRUM APPROACH

The geometry of a 2-D finite aperture DOE is shown in Fig. 1. The input plane that includes the aperture is located in front of the DOE and the observation plane is located at $z=z_{obs}$. It is supposed that a plane wave distributed along the z-axis interacts with the DOE at the input plane and it is expected to produce the desired pattern at the observation plane.

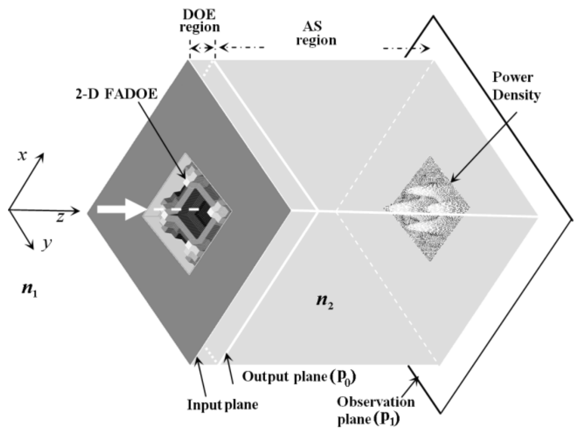


Figure 1 Geometry of 2D finite aperture DOE and the two regions used in the IAS method

The space between the input and the observation plane is divided into two regions: DOE region and AS region. The DOE region extends from the input plane to the output plane (P_0) and includes DOE, while the AS region extends from the output plane located at $z=0$ to the observation plane (P_1). The thickness of DOE region is equal to the maximum etch depth (d_{max}). The refraction index of the dielectric material used is n_2, while Surrounding medium is supposed to be air. ($n_1=1$).

The transmission function of the DOE is

$$t(x,y)=\tau \exp[\,j\phi(x,y)]\Pi(x/L_x, y/L_y) \tag{1}$$

where $\tau=2n_1/(n_1+n_2)$ is the Fresnel transmission coefficient, $\Pi(x/L_x, y/L_y)$ is equal to 1 for any point inside a rectangular aperture of $L_x \times L_y$, and equal to zero for other points. The phase function according to phase only approach is $\phi(x,y)=k_0\Delta n d(x,y)$, where $\Delta n=n_2-n_1$, $k_0=2\pi/\lambda$, λ is the wavelength in free space and $d(x,y)$ is the etch depth. We consider an incident plane wave, $\mathbf{u}_{inc}$, that is distributed normally toward the aperture. The wave at the output plane of the first region is $\mathbf{u}_0=t(x,y)\mathbf{u}_{inc}$. The angular spectrum of $\mathbf{u}_0$, *i.e.*, U_0, is defined as [7].

$$\mathbf{U}_0(f_x, f_y)=\iint_{P_0}\mathbf{u}_0(x,y)\exp[-j2\pi(f_x x+f_y y)]dxdy \tag{2}$$

Using the fast Fourier transform (FFT) technique, $\mathbf{U}_0$ can be computed. Supposing a square aperture, $L_x=L_y=L$, the distance between two adjacent points in the spatial frequency domain is $\delta f=\delta f_x=\delta f_y=1/L$.

To improve the resolution in the frequency domain we can compute the FFT on an area larger than the DOE area. This is particularly useful if the desired intensity profile in the observation plane extends to a larger area than the DOE area.

The field distribution at the observation plane, $\mathbf{u}_1$, can be obtained by the inverse fast Fourier transform (IFFT):

$$\mathbf{u}_1=\mathrm{IFFT}\,(\mathrm{H}\mathbf{U}_0) \tag{3}$$

Where

$$\mathrm{H}(f_x, f_y)=\exp[jk_2\, z_{obs}\sqrt{1-(\lambda_2 f_x)^2-(\lambda_2 f_y)^2}\,] \tag{4}$$

is the angular spectrum transfer function, $k_2=n_2k_0$ and $\lambda_2=\lambda/n_2$ are the wave-number and wavelength in the AS region, respectively.

If the intensity at the observation plane satisfies the desired specification, the process is stopped and the obtained DOE is used. Otherwise, the amplitude (not phase) of the field at the observation plane, $\mathbf{u}_1$, is modified in a way that the difference between the obtained amplitude and the desired amplitude is reduced. The modified field distribution is then distributed backward to find the corresponding field distribution at the DOE output plane. Also, using the phase of the back going field, the DOE structure is modified to satisfy the new field distribution. This modified DOE is quantized and used to repeat the above procedure.

We used this method to design several micro-lenses with different focal lengths form 2λ to 300λ in a 10λ×10λ square aperture silicon (n_2=3.4). The wave length, λ, is assumed to be 5μm.

3.0 EVALUATION OF MICRO-LENSES

To analyze the designed micro-lenses, we used a 3-D FDTD algorithm with unsplit step PML absorbing boundary condition. The analyzed region is divided to the total field and the scattered filed regions, as shown in Fig. 2. We have used the technique introduced by Sullivan for implementing the PML [8].

The mesh size for the FDTD simulation was chosen equal for all three directions, *i.e.*, $\delta_x=\delta_y=\delta_z=\delta$. Also, $\delta t=\delta/(2c)$, where c is the velocity of light in free space, was used as the time step. The depths of PML and scattered field were set to 7δ.

The incident field was assumed to be a TEM wave with a sharp Gaussian time varying amplitude, $E_{xinc}=\exp\{-(t-t_d)^2/(2w_t^2)\}$, where t_d and w_t are the time delay and the spread parameters of the Gaussian pulse, respectively. Using the FDTD method, the distributions of the electric and magnetic fields were obtained for 200 time steps.

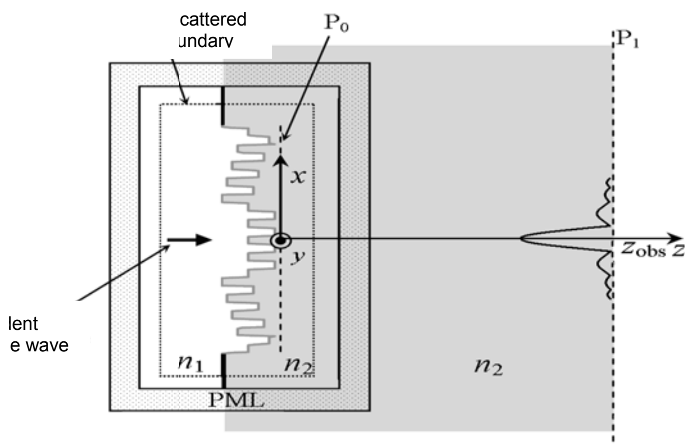


Figure 2 Cross section of the analyzed region.

After the fields were found at P_0 plane by the FDTD method, the angular spectrum technique was used to obtain the fields at the observation plane, *i.e.*, P_1. The distribution of light intensity at P_1 is then calculated using

$$\mathrm{I}(x,y)=\frac{1}{2}\mathrm{Real}\{\mathbf{E}\times\mathbf{H}^{*}\}.\hat{\mathbf{a}}_z\ , \tag{5}$$

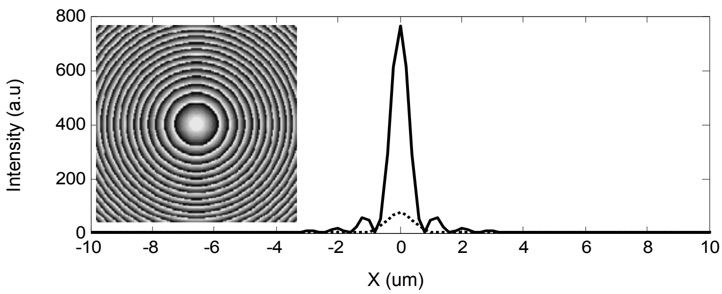
Where **E** and **H** are the complex amplitudes of the electric and magnetic fields intensities, respectively, * represents the complex conjugate, and $\hat{\mathbf{a}}_z$ is the unit vector along the *z*-axis. Next, the diffraction efficiency defined as

$$\mathrm{DE}=\frac{\iint_{W}\mathrm{I}(x,y)dxdy}{\iint_{P_1}\mathrm{I}(x,y)dxdy} \tag{6}$$

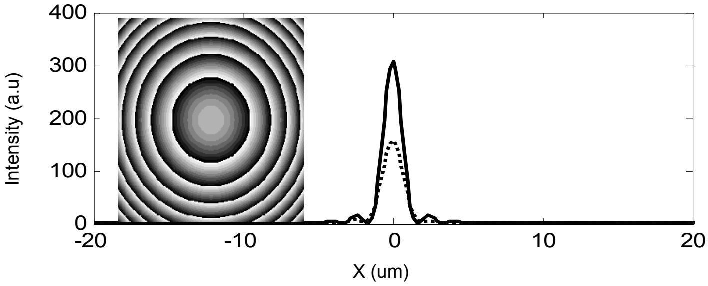
is computed, where W is the detector window which is a circular area that covers the main lobe. Fig. 3 shows three micro-lenses with different focal lengths. The corresponding cross sections of the intensity profiles are also depicted on the figure. It can be seen that the intensity profile calculated by POA gets closer to the exact intensity profile as the focal length is increased.

Figure.4 shows the variation of diffraction efficiencies for several designed micro-lenses. It can be seen that for 2π phase resets and focal lengths less than 80λ, the POA-based method is not accurate enough to provide designs with less than 10% error. By increasing phase resets from 2π to 4π (as shown in Fig. 5) and so increasing the maximum each depth, the diffraction efficiency is increased about 5.5%. In this condition the 10% error occurs at $z_{obs}=25\lambda$.

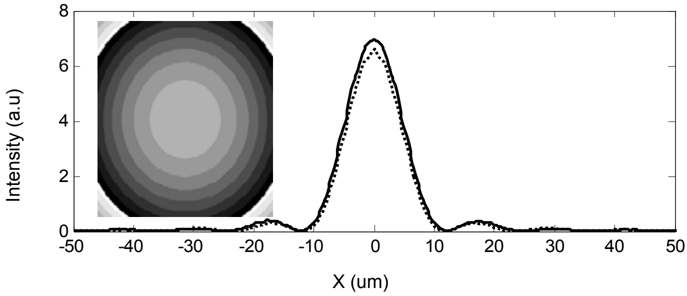
Choosing 5μm as the wavelength of incident wave and using silicon as the material are just for calculation and the results are not affected by these assumptions.



(a)



(b)



(c)

Figure 3 Micro-lens and its cross section of intensity profile for focal length (a) 2λ, (b) 10λ and (c) 80λ, calculated by POA (—) and FDTD method for 2π phase reset (┈)

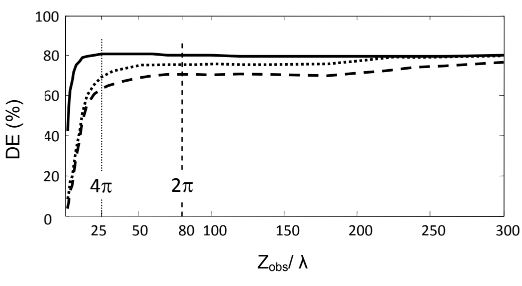


Figure 4 The diffraction efficiencies of designed micro-lenses for POA (—) and FDTD method for 2π (---) and 4π (┈) phase resets

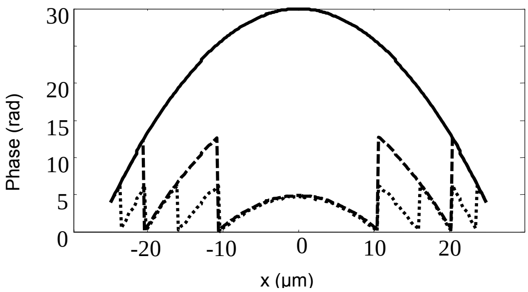


Figure 5 Cross section of a DOE phase profile without reset (—), and with 4π (---) and 2π (····) phase resets

4.0 CONCLUSIONS

We evaluated the accuracy of phase-only approach by using the finite difference time domain method. The results show that in the micro-lens design, when the focal length is greater than 80λ, the POA provides acceptable results with less than 10% error. By switching phase resets from 2π to 4π radians and so increasing the maximum etch depth; we obtain 10% error at 25λ.

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