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The Focusing Characteristics on the Binary Phase Sub-wavelength Fresnel Zone Plate

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Abstract In general, the substrate film is included in a practical Fresnel zone plate (FZP). The dependence of focusing characteristics on the incident direction of light illuminating the binary phase sub-wavelength FZP on substrate film are studied by using the finite-different time-domain method. The simulation results show that, in the range of effective etch depth, the intensity and size of FZP's focusing spot in the far-field region are insensitive to the incident direction. However, the focal length for the light illuminating from the etched structure side of the FZP is larger than that from the substrate film side of the FZP. For these two different incident directions, focal length decreases as the increase of etch depth. And for some special value of etch depth, for example, when the value equals to 700 nm, the depth of focus is quite great in the situation of light illuminating from the etched structure side and the reduction of focusing intensity and resolution of spot is within an acceptable range. The simulation results in this paper are useful for the FZP's applications in microscopy and photolithography.

Keywords: *sub-wavelength Fresnel zone plate, focusing, finite-different time-domain method, direction of incidence*

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1. Introduction

Fresnel Zone Plate (FZP) is a kind of important diffractive optical element. It has a wide range of applications and wavelength ranges from visible to X-ray can be accomplished focusing with it [1,2,3]. FZP is divided into three types: phase-only FZP, amplitude-only FZP and phase-amplitude (amplitude and phase hybrid) FZP. Phase FZP has a higher diffraction efficiency than that of amplitude FZP. Many analysis methods, such as rigorous coupled-wave approach [4] and matrix-method [5] are used to study FZP. The scalar diffraction theory is used for calculating the focusing characteristics of long focal length and low NA FZP [6,7,8,9]. For a high-NA or a short focal length FZP, the vector diffraction theory has to be used for analyzing its focusing properties [10-19].

Rayleigh-Sommerfeld vector diffraction theory [20] and plane wave angular spectrum method [21] are effective in calculating the diffraction field distribution of extremely thin amplitude-only FZP [14,15] or phase FZP which focal length is considerably larger than it's etch depth [12,13,16,17,18]. Zhang *et al* [19] consider the scattering effect inside the FZP and calculate the focusing properties of a binary phase FZP with the method of vector diffraction theory. It's found that the results obtained by theory calculation has a good agreement with those obtained by the finite-difference time-domain (FDTD) method within the effective extent of etch depth.

When the feature size of FZP is relatively small, that is for sub-wavelength FZP, no more rigorous and effective theory calculation method exists. If the feature size of FZP is not too great, FDTD method can be used to simulate its focusing properties and this need not to take the amount of time to calculate. Liu et al simulate diffraction properties of four-step phase FZP by using FDTD method [22]. Igor V. Minin et al study the FZP in millimeter wave band [23]. Mote et al study the focusing characteristic of two-step amplitude only FZP and phase thick FZP [24], they found that there is a huge difference between the focal lengths obtained by FDTD method and that obtained by the scalar diffraction theory.

On the other hand, an actual phase FZP is made by a method of photolithography on dielectric optical thin film and the film is generally not etched through. The part that is not etched through we call it the substrate of the phase FZP. In practical application, the incident light can illuminate either from the substrate side of the FZP or from the etch side of the FZP. In the previous analysis and calculation [5-19,21-24], the substrate effect was not taken in account. In this paper, we investigate the correlation of focusing characteristics of the practical binary phase sub-wavelength FZP (with substrate structure) and the illuminating direction of the incident beam.

2. The Focusing Characteristics of FZP

The schematic cross section of a circular binary phase FZP is shown in Figure 1. The FZP pattern is etched on an optical film of glass with diffractive index n and the substrate thickness is w and the etch depth is d.

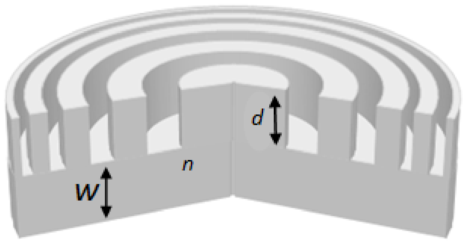

Figure 1. Schematic cross section of a circular binary phase FZP

The dimensions of zone boundaries are obtained from classical equation used in designing conventional FZPs [18], written as

$$r_m = \sqrt{m\lambda f_d + \frac{(m\lambda)^2}{4}},\ m = 1, 2, \cdots, 2N+1 \tag{1}$$

Where N (=1,2, …) is the etched zone number, r_m is the radius of m^{th} zone and f_d is a design parameter which stands for the first order focus of the ideal zone plate (without substrate thin film) it is called the designed focal length in this paper and λ is the operating wavelength. The focusing characteristics of FZP are analyzed by 3-dimensional FDTD. In the following simulation, we assume a phase FZP with $N = 8$ zones etched in the film of glass of n = 1.4574 and its designed focal length is fd = 1.5 μm. The optical thin film thickness of the FZP is (w+d) = 2 μm unchanged, the ambient medium is air, and the width of the outermost zone is 0.52λ smaller than one wavelength. The mesh size is set to 30×30×30nm^3 which ensures that at least 20points per wavelength can be obtained. Linearly x-polarized plane wave with the wavelength λ=633 nm is used for illumination and perfectly matching layer is applied as the boundary condition.

We define the substrate incidence and structure incidence respectively as shown in Figure 2(a) and Figure 2(b).

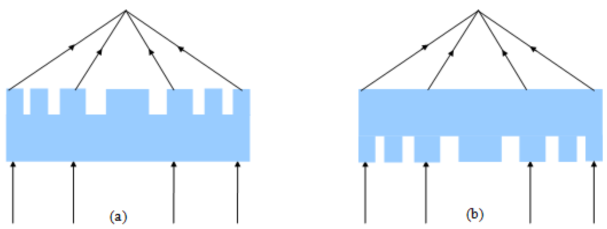

Figure 2. Incident direction of light. (a) incidence from the substrate side of the FZP, (b) incidence from the structure side of the FZP

Figure 3 gives the intensity distribution of the diffraction field in x-y plane and y-z plane for different etch depths of 200, 400 and 600 nm, where (a) and (b) show the cases of incident light from the substrate side and structure side, respectively. The value of f obtained by FDTD simulation is actual focal length, w is the substrate thickness of the FZP and the white waveform represents the outline of FZP. We define the actual focal length f as the distance between the exit pupil and the place at which the maximum focusing intensity occurs. It's seen from Figure 3 that when keeping the direction of incident light invariable, the value of actual focal length f decreases with the value of etch depth increasing. Comparing these two pictures Figure 3(a) and Figure 3(b), it's found that when the value of etch depth remains unchanged, the focal length f obtained by the incident light illuminating from the structure side of the FZP is larger than that from the substrate side of the FZP. This phenomenon can be explained according to scalar diffraction theory. It's well known that when light propagates in a homogeneous medium, in scalar diffraction theory approximation, the focal length can be estimated by following formula [7,8]:

$$f = r_1^2 / \lambda_n \tag{2}$$

where λ_n is the wavelength of light in the medium and r_1 is the radius of the first zone of FZP. The wavelength of the light propagating in the solid material is larger than that propagating in the air. When the incident light illuminating from the structure side of the FZP, diffraction light will propagate forward several nanometers more. Therefore, the actual focal length is larger than that obtained from the substrate side of the FZP.

For the different incident direction, Figure 4(a) describes the intensity distribution along x direction in the focal plane and Figure 4(b) shows the intensity distribution along the optical z-axis, where the etch depth of 400 nm is kept invariable. As shown in Figure 4(a), the value of peak intensity and FWHM of focusing spot are not sensitive to the direction of incident light (When the incident light illuminating from the structure side, the value of focusing intensity is 212 and FWHM is 0.43 μm. While the value of focusing intensity is 189 and FWHM is 0.46 μm for substrate side incidence). However, the value of focal length is sensitive to the direction of incident light. And the value of focal length is 2.42 μm for structure side incidence, which is larger than 1.51 μm, the focal length obtained from the incident light illuminating from substrate side. The reason can be explained from formula (2).

Generally speaking, the focusing characteristic of FZP is often relevant to its etch depth. Figure 5 describes the focusing intensity (I_m), spot size (FWHM) along the x direction in the focal plane, depth of focus (DoF), and focal length (f) as a function of the etch depth. In application of microscopy imaging, the large focusing intensity and high resolutions spot are desired to obtain. If we regard the FZP with which maximum focusing intensity can be obtained as the FZP of optimal structure, it is seen from Figure 5(a) that the optimal etch depth value of FZP occurs at 0.6 μm and it is irrelevant to the direction of incident light. Besides, it is found from Figure 5(a) and Figure 5(b), when d=0.6 μm and the incident light illuminating from the substrate side, the resolution is 0.45 μm which is a little higher than 0.47 μm obtained from the case that the incident light illuminates from structure side, while the former's focusing intensity is slightly smaller than the latter's. Overall, when the incident light illuminates from different directions, their focusing intensity almost equals each other during the range of etch depth 0.4~0.6 μm and so are the resolution. Likewise, the depth of focus (DoF) has tiny difference in these two cases during the range of 0.4~0.6 μm as shown in Figure 5(c). Furthermore, when the etch depth *d* increases to 0.7 μm, for the incident direction illuminating from structure side the value of DoF becomes 1.6 μm, which is 2.3 times larger than that obtained substrate from the side. This large depth of focus is useful for deep etched grating. In the production procession of deep etched grating, larger depth of focus is expected to get and a slight decrease of focusing intensity or a slight increase of spot size is allowed [25,26].

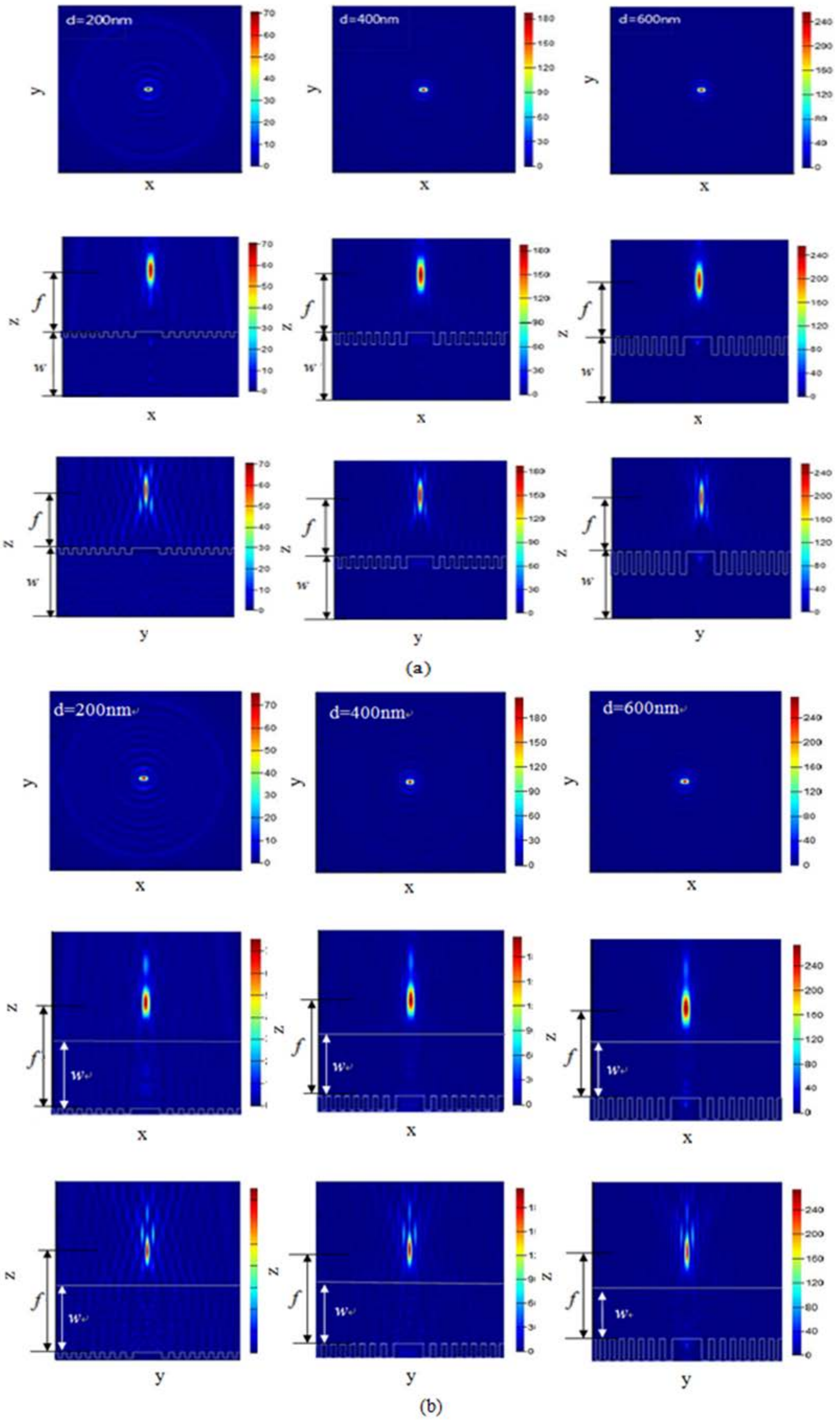

Figure 3. The intensity distribution of the diffraction field in x-y plane and y-z plane for different etch depths of 200, 400 and 600 nm, where (a) and (b) show the cases of incident light from the substrate and FZP's structure sides, respectively

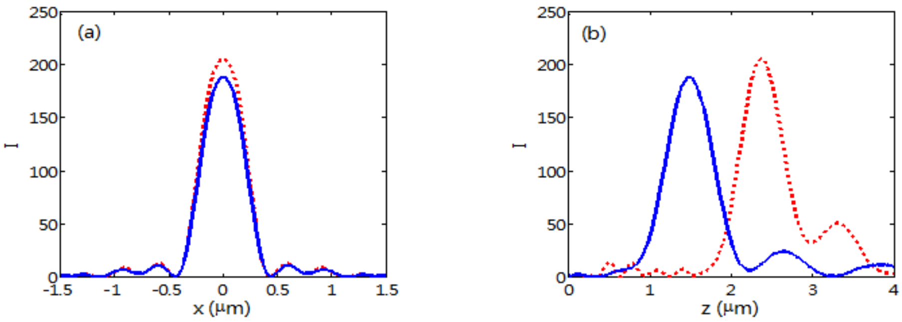

Figure 4. The intensity distribution along x direction in the focal plane (a) and along the optical z-axis (b), where the etch depth of 400 nm is kept invariable. The solid and dot curves respond to the cases of light incident from the FZP's substrate and structure sides, respectively, and all intensity normalized to the intensity of the incident light

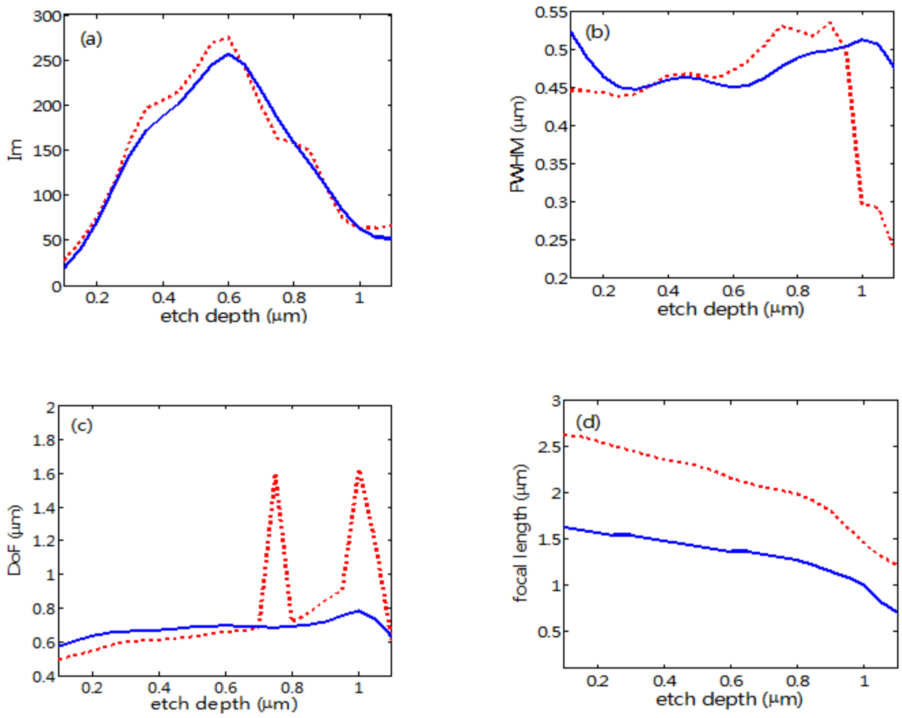

Figure 5. Dependence of focusing intensity (I_m), spot size (FWHM) along the x direction in the focal plane, depth of focus (DoF), and focal length (f) on the etch depth. The solid and dot curves respond to the cases of light incident from the FZP's substrate and structure sides, respectively

3. Conclusion

Above all, this paper investigates the correlation of focusing characteristics of a binary phase sub-wavelength FZP with a substrate film and the incident direction of light illuminating by using the finite-different time-domain method. The results show that the far field focusing intensity and size of FZP's focusing spot are insensitive to the incident direction. That is, in the range of effective etch depth, whether light is incident onto the FZP from the substrate side or from the structure side, the focusing intensity is nearly equality and so are the size of focusing spots. However, the focal length of the incident beam from the structure side of the FZP is larger than that from the substrate side of the FZP. For these two different incident directions, focal length decreases as the increase of etch depth. If it is admitted to appropriately decrease the focusing spot quality, the large depth of focus will be obtained in the case of incident light illuminating from the structure side and the value of the etching depth of the FZP keeping at 0.7 μm. Meanwhile, the reduction of focusing intensity and resolution of spot is within an acceptable range. The result (large depth of focus) is useful for deep etched grating. Besides, that the incident light illuminating from the structure side and propagating through the substrate thin film (which refractive index is larger than that of imaging space) to achieve focus is a common phenomenon. Such as, both the oil immersion lens used in microscopical of biological samples [27] and the solid immersion lens in the integrated circuit testing [28] need incident light to accomplish focusing after propagating through the material of high refractive index. Therefore, the results of this paper are useful for the FZP's applications in some special conditions.

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