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Vol 18 No 1, January 2009
1674-1056/2009/18(01)/0183-06

Chinese Physics B

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(Received 18 April 2008; revised manuscript received 15 August 2008)

A novel diffractive optical element, named phase zone photon sieve (PZPS), is presented. There are three kinds of phase plates in PZPSs: PZPS1, PZPS2, and PZPS3. Each of the PZPSs has its own structure and is made on quartz substrate by etching. The three PZPSs have stronger diffraction peak intensity than a photon sieve (PS) when the margin pinhole and zone line width are kept the same. The PZPS3 can produce a smaller central diffractive spot than the ordinary PS with the same number of zones on the Fresnel zone plate. We have given the design method for and the simulation of PZPS and PS. PZPS has potential applications in optical maskless lithography.

Keywords: photon sieve, Fresnel zone plate, diffractive optics
PACC: 4225, 4280B, 4280K

1. Introduction

Photon sieves, proposed by Kipp *et al*,[1] are a new kind of diffractive optical element, developed for focusing and imaging soft x rays with high resolution. A conventional photon sieve (PS) is essentially a Fresnel zone plate with the clear zones replaced by a great number of non-overlapping holes of different sizes. Cao and Jahns[2,3] proposed the individual far-field model and the non-paraxial model for focusing high numerical aperture PS to analyse the diffractive field of it. Andersen[4] demonstrated the feasibility of using a PS as the primary element in an optical telescope. Menon *et al*[5] first used high numerical aperture PSs as focusing elements in a scanning-optical-beam-lithograph system. Fernando *et al*[6] proposed the fractal PS, which is a novel focusing structure with a better performance than the common PS. Pepler *et al*[7] described the binary phase Fresnel zone plate arrays for high-power laser beam smoothing. Furthermore, Anderson and Tullson[8] discussed the extension of PS to 'odd' zones.

Beam shaping can generally be regarded as converting an incident wave front into a desired one in the output plane, and this is required in many laser applications, for instance, laser processing and laser fusion.[9] Diffractive optical elements stand out as an ideal candidate for laser beam shaping because of their compact configuration, good performance, low cost of production, and ease of replication. In particular, a diffractive phase element is often used for its high efficiency, coaxial transformation features, and good optical functionality.[10,11]

The PS, shown in Fig.1(a), is composed of pinholes arranged in the radial direction such that their centre locations correspond to the open zones of a zone plate. This arrangement ensures that a portion of the light diffracted from the pinholes interferes constructively at the focal point.

2. Design and computational methods

We have designed a new kind of PS. This new PS consists not only of traditional pinholes, but also the phase zone, instead of the opaque part in the PS. The new PS, which we call a phase zone photon sieve (PZPS), is the combination of the PS and a phase Fresnel zone plate (FZP). There are three kinds of phase plates for PZPSs, that is, the PZPS1, PZPS2, and PZPS3. In a PZPS, the phase in the pinhole is zero and the phase in the phase zone is π. The pinhole and phase zone are etched on a substrate such as quartz. Since the parts other than the pinhole and phase zone are opaque, the light enters through the

*Project supported by the National Key Basic Research Special Foundation of China (Grant No 2007CB935302) and the National Natural Science Foundation of China (Grant No 60825403).
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phase zone and pinholes. The position and number of the pinhole in PZPS are the same as those in the PS, except for the phase zone.

Figure 1(a) presents the PS based on 50 FZPs and the ratio of the radius of the pinhole to the width of the FZP zone is 1.5 ($k_1 = d/w$=1.5).[1] In the pinhole of every even zone the phase is zero, and the transmission coefficient (TC) of light in this part is 1, while that of the other part is 0, that is, it is opaque. Figure 1(b) gives the profile of PZPS1 based on 50 FZPs, but the ratio of the radius of the pinhole to the width of the FZP zone is 1.0 (k_1=1.0). However, the phase in the pinhole of the even zone is still zero while the odd zone is a phase zone with its phase being π. So the TC of the light in this zone is also 1.

Figure 1(c) shows the profile of PZPS2 based on 50 FZPs, and the ratio of the radius of the pinhole to the width of the FZP zone is also 1.0 (k_1=1.0). The phase in the pinhole of the even zone is still zero, while the odd zone is also composed of the pinholes. In the even zone the number and position of the pinholes are the same as the ordinary PS. But the position of the pinhole in the odd zone is situated at the middle point of the odd zone and its radius is equal to the width of the odd zone. The phase of the pinhole in the odd zone is π, thus the TC of the pinhole in the odd and even zones is 1.

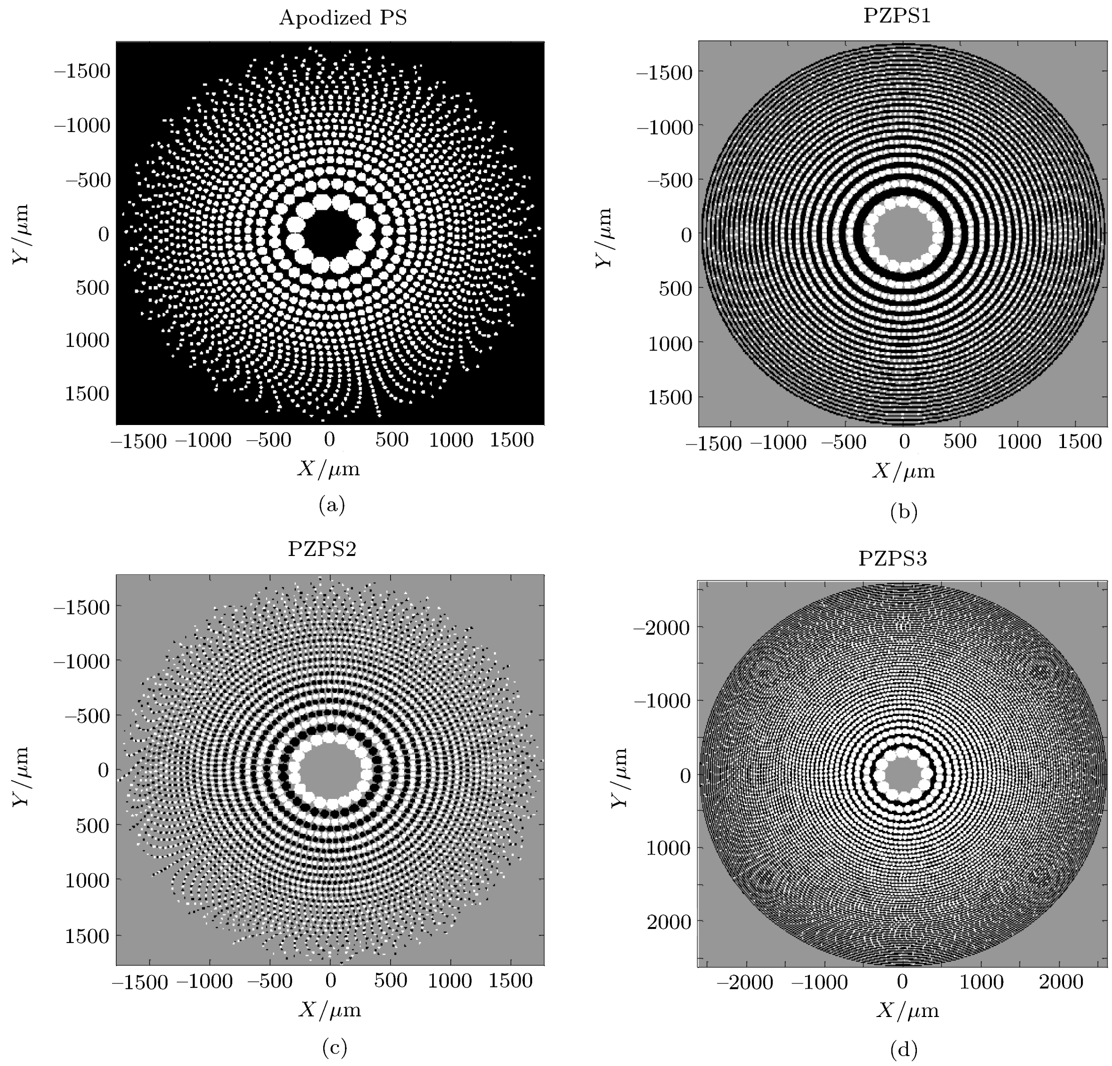

Fig.1. (a) The profile of PS based on 50 FZPs, (b) that of PZPS1 based on 50 FZPs, (c) that of PZPS2 based on 50 FZPs,(d) that of PZPS3 based on 108 FZPs.

Figure 1(d) illustrates the profile of PZPS3 based on 108 FZPs, but the ratio of the radius of the pinhole to the width of the FZP zone is 1.5 (k_1=1.5). In the pinhole in the even zone the phase is still zero, but the phase of the odd zone is π. Since the radius and position of the pinhole in the even zone are the same as the ordinary PS, the difference between PZPS1 and PZPS3 is that of the radii between the pinholes in the even zones. The radius of the pinhole in PZPS1 is equal to the width of the even zone in the FZP, while the radius of the pinhole in PZPS3 is 1.5 times the width of the even zone in the FZP. Thus, the phase of the odd zone, except that part occupied by the pinhole in the even zone, is π. The TC of the light in the odd zone and the other part in the even zone is 1.

For a clearer description of the profile and structure of PS and PZPS, the PS, PZPS1, PZPS2, and PZPS3 based on 10 FZPs are shown in Figs.2(a)–2(d), respectively. The phase in the white area in Fig.2(a) is zero and that in the black area is opaque, while the phase in the white area in Figs.2(b)–2(d) is zero and that in the black area is π, while the grey area is opaque.

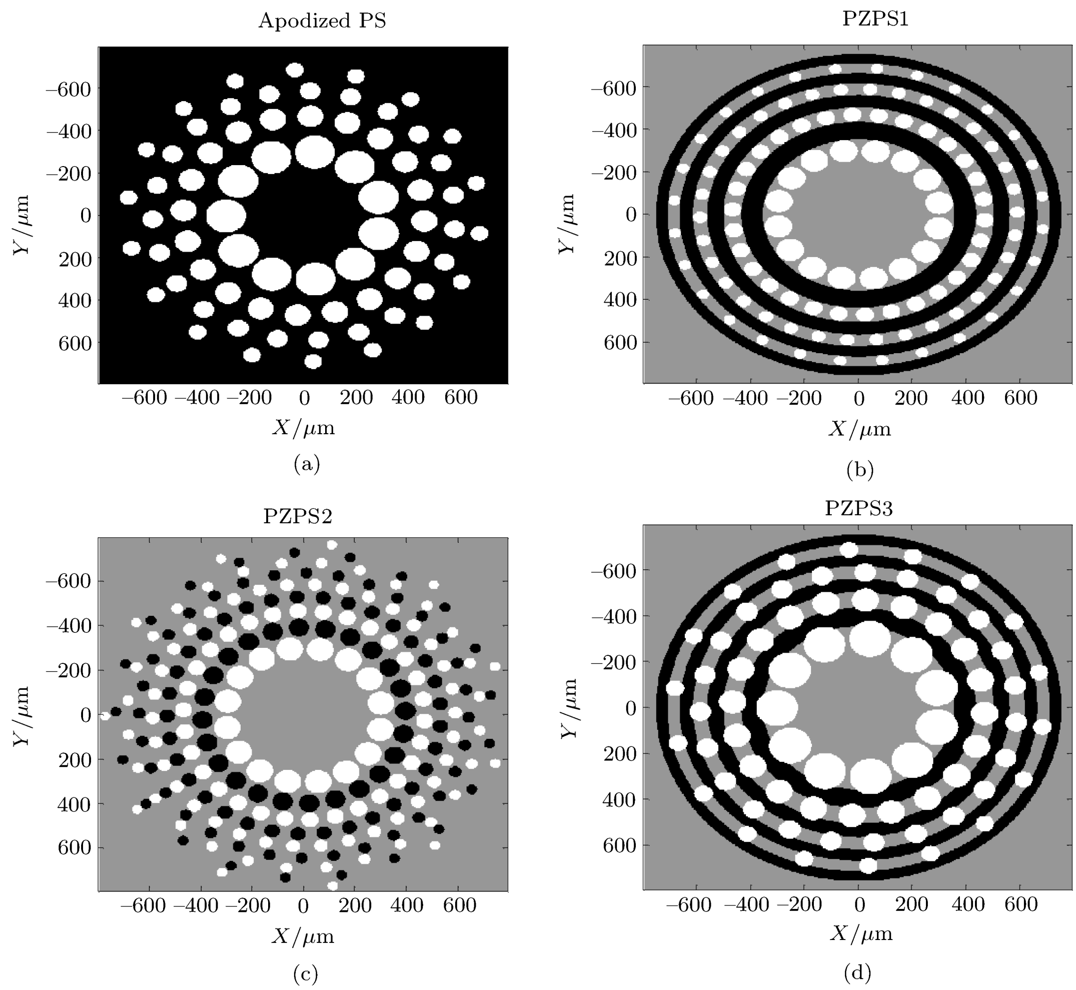

Fig.2. (a) The profile of PS, (b) that of PZPS1, (c) that of PZPS2, (d) that of PZPS3, all based on 10 FZPs. The phase in the white area in (a) is 0 and that in black area is opaque while the phase in the white area in (b)–(d) is 0, that in the black area is π, and the grey area is opaque.

The PZPS performs better than PS, although the latter can focus the incident light into a very small spot and suppress the high diffractive orders of the light. Our results show that all the PZPS can allow of much more transparent light than the PS with the phase plate. The PZPS3 can suppress the centre diffractive spot and realize a smaller diffractive spot than a PS with the same margin pinhole or zone line width. The smaller diffractive spot and the higher intensity at the same incident light have potential applications in laser direct lithography for microelectronics fabrications.

Various compression parameters, such as the Strehl ratio (S) and the first zero (G), have been defined to describe the compression effect on a centre diffractive spot.[12−14] In this paper, we propose to use the centre spot intensity ratio (CSI ratio) and the first zero to describe the centre spot compression effect to make a comparison of PZPS with PS. The CSI ratio is defined as the ratio between the intensity of the centre main spot and that of all diffractive fields in a PZPS pattern or a PS pattern. The first zero is defined as the first zero position of the intensity in a PZPS pattern, or a PS pattern, from the centre point in the diffractive field.

We use the angular spectrum method to calculate the intensity of the diffractive field. The ideal plane wave incident on PS at the position of z=0 has the transparent function as follows:

$$E(x,y,0)=\begin{cases}1 \;\; (x-x_{ij})^2+(y-y_{ij})^2 \le r_i^2; \\ 0 \qquad\qquad \text{otherwise.}\end{cases} \tag{1}$$

Here x_{ij} and y_{ij} are the centre coordinates of the pinholes in PS, with $i=1,2\ldots,n$, (n is the number of the circular zones in the zone plate) and $j=1,2,\ldots,m$ (m is the number of the pinholes in each zone). Using a 2D discrete Fourier transformation, $E(x,y,0)$ can be changed into the angular spectrum F_0 (f_x, f_y, 0) in the incident light plane:

$$E(f_x,f_y,0)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}E(x,y,0) \times \exp\left[-\mathrm{j}2\pi(f_x x+f_y y)\right]\mathrm{d}x\mathrm{d}y, \tag{2}$$

where f_x and f_y are the space frequencies, with $f_x=\alpha/\lambda$ and $f_y=\beta/\lambda$ (α and β are the angles made by $\boldsymbol{k}$ with x and y coordinates, respectively). The incident light spreads along the z-axis after reaching the PS. At $Z=z$, the spectrum of the space frequency $E(f_x,\ f_y,\ z)$ is

$$E(f_x,f_y,z)=E(f_x,f_y,0) \times \exp\left(\mathrm{j}2\pi z\sqrt{\frac{1}{\lambda^2}-f_x^2-f_y^2}\right), \tag{3}$$

where f_x and f_y satisfy $(f_x^2+f_y^2)\le 1/\lambda^2$, so the effect of the light spread is only to change the phase of the angular spectrum. When $(f_x^2+f_y^2)>1/\lambda^2$, the spectrum of the space frequency $E(f_x,\ f_y,z)$ is

$$E(f_x,f_y,z)=E(f_x,f_y,0)\exp(-\mu z), \tag{4}$$

where $\mu=\dfrac{2\pi}{\lambda}\sqrt{\left(\dfrac{x}{z}\right)^2+\left(\dfrac{y}{z}\right)^2-1}$.
When μ is a positive real number, this part of the wave will attenuate quickly in a large distance. Using inverted Fourier transformation, Eq.(3) can be transformed to obtain the amplitude of the diffractive field $E(x,y,z)$

$$E(x,y,z)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}E(f_x,f_y,0) \exp(\mathrm{j}2\pi z\sqrt{\frac{1}{\lambda^2}-f_x^2-f_y^2}) \exp[\mathrm{j}2\pi(f_x x+f_y y)]\mathrm{d}f_x\mathrm{d}f_y. \tag{5}$$

3. Results and discussion

We have simulated the CSI ratio and the first zero of the PZPS and PS, the result is shown in Table 1, where F denotes the zone numbers on the FZP base. For k_1=1.5 in the PS and PZPS3 and k_1=1.0 in the PZPS1, PZPS2, we choose F=108 in the PS and PZPS3 and F=50 in the PZPS1 and PZPS2. Thus, the outermost pinhole and zone have the same diameter (the same marginal pinhole or zone line width), which is the limitation of the line width in microelectronic technology. In this case, the diameter for the outermost pinhole and zone is about 18.2 μm. The wavelength of the incident light is 632.8 nm while the focal length of the PS and PZPS is 100 mm. Since the CSI ratio can denote the light concentration in the diffractive field, a greater CSI means that more light can be concentrated into the centre diffraction spot. Table 1 gives the CSIs of the PS, PZPS1, PZPS2, and PZPS3, which are 0.9592, 0.9698, 0.9713 and 0.9802, respectively. The numbers of pinholes in PS, PZPS1, PZPS2, and PZPS3 are 8222, 2673, 5361, and 8222, respectively. Since the first zero denotes the width of the centre diffractive spot, a smaller first zero means a smaller centre diffractive spot. The first zeros of the PS, PZPS1, PZPS2, and PZPS3 are 9, 14, 17, and 7, respectively. The unit is 1.7131 μm in simulation. Table 1 demonstrates that PZPS3 has a smaller first zero than PS.

Table 1. F (zone numbers on FZP), CSI, first zero position, the number of pinholes for PS, PZPS1, PZPS2, PZPS3.

	F	CSI	first zero position (unit in 1.7371 μm)	number of pinholes
PS	108	0.9592	9	8222
PZPS1	50	0.9698	14	2673
PZPS2	50	0.9713	17	5361
PZPS3	108	0.9802	7	8222

We also simulated the diffractive field intensity for the PZPS and PS, as shown in Fig.3. This figure indicates that the peak intensity of the centre diffractive spot of the PZPS is much larger than that of the PS. In particular, the peak intensity of the centre diffractive spot of PZPS3 is larger than that of PZPS1, and the latter is larger than that of PZPS2. In order to denote the position of first zero clearly, we present the normalized diffractive field intensity in Fig.4. Arrows 1, 2, 3, 4 denote the first zero positions of PZPS3, PS, PZPS1, and PZPS2, respectively. Under the condition that the limitations for the line width of all the PS and PZPS, in microelectronic technology are the same, we find that PZPS3 can compress the centre diffraction spot and has a much higher diffractive peak intensity (approximately 8 times higher) than the PS. PZPS1 and PZPS2 cannot realize a smaller centre diffraction spot than the PS, but the peak diffractive intensity of the PZPS1 is higher (about 2 times) than the PS. PZPS2 has a similar higher peak intensity than the PS.

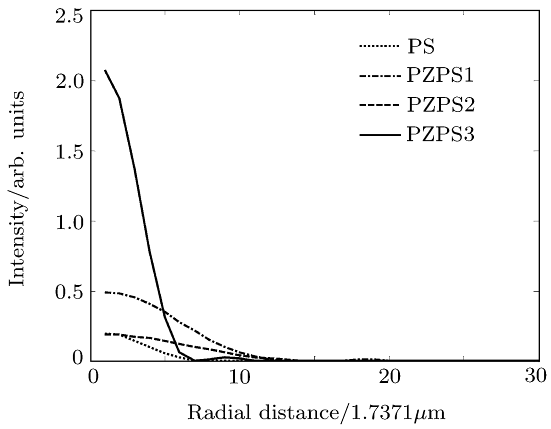

Fig.3. The relationships between the diffractive field intensity and the radial distance for PZPS, PS.

We can explain the simulation result by the intrinsic character of the phase plate of PZPS. The diffractive field of a FZP is the sum of the light amplitudes of the intermission zones. And PS only allows of light through its pinholes in the even zones, while the other parts are opaque. But the PZPS allows of light not only through the pinholes in the even zones but also through the pinholes in odd zones (PZPS2) and the zones in odd zones(PZPS1, 3). So the diffractive intensity peak of a PZPS is higher than that of the PS. The PZPS demonstrates an improved diffractive effectiveness over the PS.

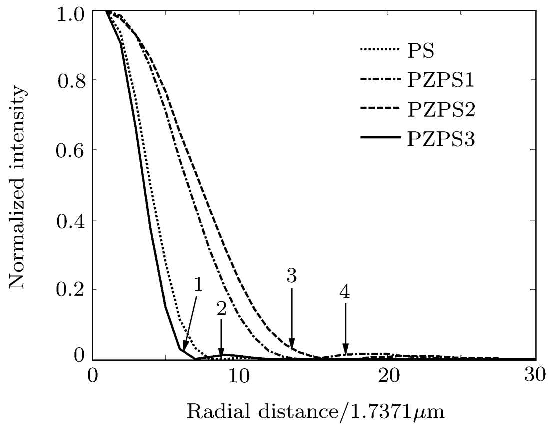

Fig.4. The relationship between normalized diffractive field intensity and radial distance of the PZPS, PS. Arrows 1, 2, 3, 4 indicate the first zero positions of PZPS3, PS, PZPS1, PZPS2, respectively.

4. Summary

In conclusion, we have presented a novel diffractive optical element, a PZPS. In Ref.[5], a similar device was also presented without giving details. Reference [5] described a conception similar to the PZPS1 or PZPS2 in no more than 120 words, and gave no detailed design method and simulation. Our PZPS3 can produce a smaller central diffractive spot than an ordinary PS. There are different types of PS. Kipp, Cao, Gimenez, and Anderson all have suggested slight modifications of PS. In this paper, we compare the PZPS with the PS with the same margin pinholes and zone line width under the same limitation of the microelectronic technology. We use the ordinary PS presented by Kipp. The design method and diffractive simulation of PZPS and PS are also presented. PZPSs (especially, PZPS3) have applications in optical maskless lithography due to their smaller diffractive centre spot and higher peak diffraction intensity. A large array of PZPSs focus the incident light into a diffraction-limited on-axis nano-scale spot on the substrate coated with photo-resist in the laser maskless lithography. Patterns of arbitrary geometry are exposed in a dot matrix fashion while the substrate on a stepping stage is precisely driven in two dimensions according to the computer program. The PZPSs (especially PZPS3) show better performance than the ordinary PS with the same margin pinholes. Future work will focus on the fabrication of the PZPS.

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