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Controllable fabrication of the micropore shape of two-dimensional photonic crystals using holographic lithography

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In this study, the micropore shape of two-dimensional (2D) photonic crystal structures can be modified and controlled by the intensity ratio of the incident beams of the holographic lithography. By adjusting the intensity ratio of the incident beams, the micropore shape of 2D hexagonal photonic crystal structure could be adjusted from being circular to being elliptical. Hence, we defined and analyzed the ellipticity of the micropore shape on a 2D photonic crystal structure as a function of the intensity ratio of the incident beams. In addition, we set up an optical holographic system by using three incident beams with different intensities to demonstrate the influence of the intensity ratio of the incident beams on the micropore shape. The optical experimental results show that the ellipticity of the micropore shape decreased with increasing the intensity ratio of the incident beams, which is the same trend as with the theoretical analysis. © *2008 American Vacuum Society.* [DOI: 10.1116/1.2905240]

I. INTRODUCTION

Due to the attractive optical properties of photonic crystal structures, they recently became more important and are applied to many areas of interest, such as in waveguides, photonic crystal fibers, the enhancement of the brightness of light emitting diodes, optical devices, and so on.[1–10] There are many techniques to fabricate photonic crystal structures, for example, x-ray lithography, electron-beam lithography, and holographic lithography.[11–15] Among these techniques, the main advantage of holographic lithography is that it can easily generate two-dimensional (2D) and three-dimensional (3D) photonic crystal structures with multiple laser beams in a large area at a single exposure. By fabricating the photonic crystal structure with holographic lithography, the structure and shape of the photonic crystal will depend on the incident angles and intensity ratio of the multiple beams. For the given incident angles of the multiple beams, the period and structure of the photonic crystal are fixed and can be calculated from the parameters of the incident beams. For example, if the three beams are symmetric incident, then we will obtain the 2D hexagonal photonic crystal structure and the period will depend on the included angle between two neighbor incident beams.[16] In general, three laser beams with the same intensity are used to incident and generate the periodic interference pattern, which will produce the circular micropores on the 2D photonic crystal structure. However, if the intensities of the incident beams are not equal, the micropore shape will change and become elliptical. This means that the micropore shape on the photonic crystal structure will be affected by the intensity ratio of the incident beams, and it will modify the optical property of the photonic crystal.

Therefore, we calculated and analyzed the micropore shape on the 2D hexagonal photonic crystal structure as a function of the intensity ratio of the incident beams. By adjusting the intensity ratio of the incident beams, we can control the micropore shape of the 2D photonic crystal. In addition, we set up an optical interference system with three beams to fabricate the 2D hexagonal photonic crystal structure and demonstrate the influence of the intensity ratio of the incident beams on the micropore shape. The experimental results will show a consistent trend with the theoretical analysis.

II. THEORETICAL ANALYSIS

Firstly, we consider a holographic lithography system with three plane waves, which are symmetric incident into the photoresist, as shown in Fig. 1(a). These three beams with the same wavelength and the complex amplitude of each beam can be written as

$$\mathbf{E}_j = \mathbf{e}_j E_j \exp[i(\mathbf{K}_j \cdot \mathbf{r} + \delta_j)], \quad j = 1,2,3, \tag{1}$$

where E_j is the amplitude of the jth incident beam, and $\mathbf{r} = x\hat{x} + y\hat{y} + z\hat{z}$ is the position vector (where $\hat{x},\hat{y},\hat{z}$ are the orthogonal unit vectors). δ_j represents the initial phase of the jth incident beam, and $\mathbf{e}_j$ is the unit vector of the polarization direction. $\mathbf{K}_j$ is the wave vector of the jth incident beam and can be expressed using the spherical coordinate system as follows:

$$\mathbf{K}_j = \frac{2\pi}{\lambda}(\cos\phi_j \sin\theta_j, \sin\phi_j \sin\theta_j, \cos\theta_j), \tag{2}$$

where λ represents the wavelength of the incident wave. As Fig. 1(a) shows, θ_j is the included angle of the jth incident beam and the z axis, and ϕ_j is the included angle between the projection of the jth incident angle on the xy plane and the x

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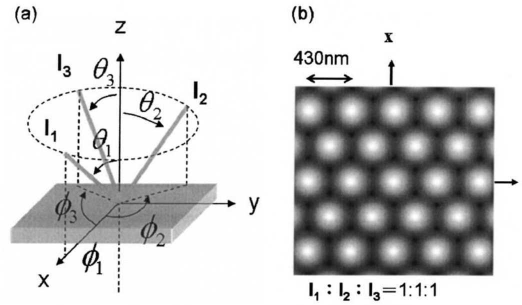

FIG. 1. (a) Schematic diagram of the optical interference system. (b) Computer simulated result of the interference pattern by using the three beam interference system.

axis. To simplify the calculation, we assume that the initial phase of each incident beam is equal to zero, i.e., $\delta_j=0$, and the polarization directions of the incident beams with the linear polarization are the same, i.e., $\mathbf{e}_j=1$.

These three beams are incident and form the interference pattern on the photoresist. The distribution of the interference pattern can be derived by the superposition principle and can be written as

$$I=|\mathbf{E}_1|^2+|\mathbf{E}_2|^2+|\mathbf{E}_3|^2+2\{\mathbf{E}_1\cdot\mathbf{E}_2\cos[(\mathbf{K}_1-\mathbf{K}_2)\cdot\mathbf{r}] + \mathbf{E}_1\cdot\mathbf{E}_3\cos[(\mathbf{K}_1-\mathbf{K}_3)\cdot\mathbf{r}]+\mathbf{E}_2\cdot\mathbf{E}_3\cos[(\mathbf{K}_2 - \mathbf{K}_3)\cdot\mathbf{r}]\}, \tag{3}$$

According to Eq. (3), when these three beams with the same intensity are symmetric incident in Fig. 1(a), i.e., $\theta_1=\theta_2=\theta_3=\theta$ and $\phi_1=0°$, $\phi_2=120°$, and $\phi_3=-120°$, the distribution of the interference pattern on the xy plane is periodic and has hexagonal structure, which is shown in Fig. 1(b). The period d of the interference pattern depends on the incident angle θ and the wavelength λ of the incident beams, which can be written as

$$d=\frac{2\lambda}{3\sin\theta}. \tag{4}$$

From Eq. (4), the period increases with the wavelength and decreases with the incident angle θ from 0° to 90°. For example, if the wavelength of the incident beam is assumed to be 355 nm and the incident angle θ is 33.4°, then the period of the interference pattern can be calculated as 430 nm by Eq. (4). Hence, in Fig. 1(b), the brightness region represents the high intensity distribution, and the dark region represents the low intensity distribution. When the intensities of the three incident beams are equal, the shape of the brightness region on the interference pattern is circular, as we can see in Fig. 1(b). If we use the positive photoresist to fabricate this interference pattern, then we can obtain the 2D hexagonal photonic crystal structure with the circular micropore, which is generated by the brightness region of the interference pattern. However, if the intensity ratio of these three beams is not equal, then the shape of the brightness region on the interference pattern will change. The computer simulated results of the interference pattern with different incident intensity ratios are shown in Fig. 2. Here, we only change the intensity of the first beam I_1 and fix the intensities of the other two incident beams, i.e., $I_2=I_3$. The intensity ratio of the three beams is changed and increased from $I_1:I_2:I_3=1:1:1$ to $I_1:I_2:I_3=15:1:1$. As we can see in Fig. 2, the shape of the brightness region modified from being circular to being elliptical with increasing the intensity ratio.

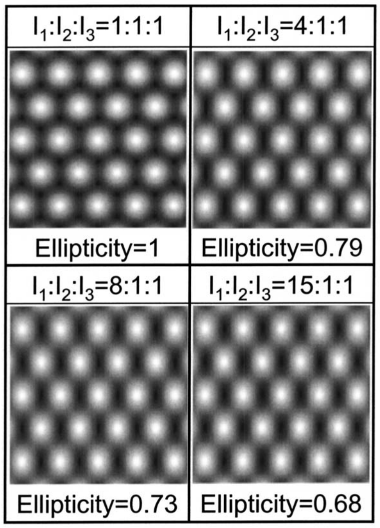

FIG. 2. Computer simulated results of the interference pattern with different intensity ratios of the three incident beams.

To describe the elliptic shape of the brightness region for the interference pattern in Fig. 2, the ellipticity of the brightness region can be defined as the ratio of the major axis m_x to the minor axis m_y. Here, the minor axis is along the vertical direction, which is the y axis, and the major axis is along the horizontal direction, which is the x axis. Thus, the ellipticity can be calculated as m_x/m_y. When the intensity ratio of the three incident beams is $I_1:I_2:I_3=1:1:1$, the ellipticity will be 1 and the shape of the brightness region will be circular. However, when we increase the intensity of the first beam, I_1, and the intensity ratio is $I_1:I_2:I_3=4:1:1$, the shape of the brightness region becomes elliptical and the value of m_y increases. According to the definition of the ellipticity, the ellipticity should become smaller and can be calculated as 0.79. With increasing the intensity ratio, the ellipticity decreases. The shape of the brightness region becomes more elliptic at $I_1:I_2:I_3=15:1:1$. In addition, the curve of the ellipticity as a function of the incident intensity ratio can be calculated and is plotted as the dotted line in Fig. 3. As we can see in Fig. 3, the ellipticity will decrease with increasing the intensity of the first beam, I_1. Therefore, we can adjust the intensity ratio of the incident beams to modify the shape of the brightness region on the interference pattern. This means that the micropore shape of the 2D photonic crystal structure can be controlled and modified by adjusting the intensity ratio of the incident beams for the holographic lithography.

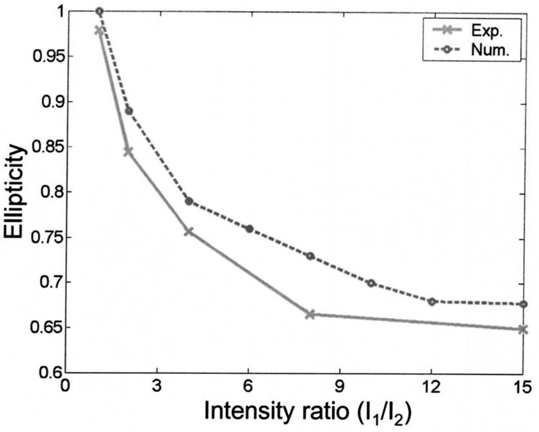

FIG. 3. Curves of the ellipticity as a function of the incident intensity ratio.

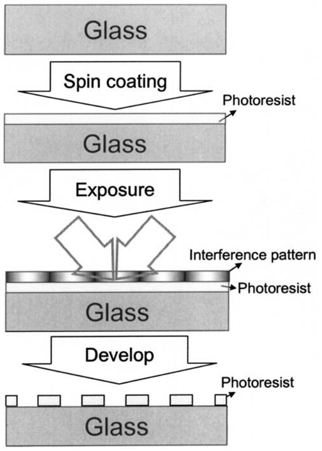

FIG. 5. Flowchart of the procedure for the holographic lithography.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In the optical experiment, we set up an interference system with three incident beams and fabricate the 2D hexagonal photonic crystal structure on a glass covered by a photoresist S-1805 by using a single exposure. Figure 4 shows the optical system to generate the 2D hexagonal interference pattern. The Innova 70C series ion laser with wavelength of 355 nm is used in this optical system. The expanded laser beam is split into three beams by using two beam splitters, BS1 and BS2. One beam is reflected by BS1 and mirror M1 and then incident to the sample. The second beam is passed through BS1 and reflected by BS2 and M2 and then incident into the sample. The last beam is passed through BS1 and BS2 and reflected by mirrors M3 and M4 to the sample. These three beams are interfering and generate the 2D hexagonal interference pattern on the sample.

Then, we prepare the glass as the substrate and spin coat the positive photoresist S-1805 on the substrate. The thickness of the positive photoresist is 450 nm. Then, we put the substrate on the position of the sample in Fig. 4 and use the interference pattern to illuminate the positive photoresist. The flowchart of the exposure and development procedures are illustrated in Fig. 5. After the exposure and development procedures, the photoresist is removed at the brightness region of the interference pattern, and the interference pattern is transferred to the photoresist. Thus, we can obtain a periodic pattern on the photoresist that is the same interference pattern that is generated by the three beams. This technique is the so-called holographic lithography or the interference lithography.

After the lithographic procedure in Fig. 5, the interference pattern is transferred to the photoresist and the photoresist on the brightness region of the interference pattern is removed and becomes a micropore. This means that the micropore shape on the photoresist depends on the shape of the brightness region. However, according to the theoretical analysis, the shape of the brightness region on the interference pattern depends on the intensity ratio of the incident beams. Thus, we can fabricate the 2D hexagonal photonic crystal structure on the photoresist and control the micropore shape with the different incident intensity ratios of the incident beams. The experimental results are shown in Fig. 6. When the intensities of the three incident beams are equal, i.e., $I_1:I_2:I_3 = 1:1:1$, then the micropore shape is circular. As we can see in Fig. 6, the micropore shape becomes elliptical with in-

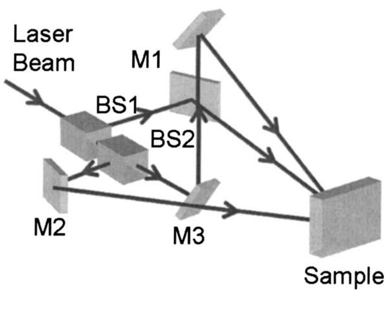

FIG. 4. Architecture of the optical experimental system.

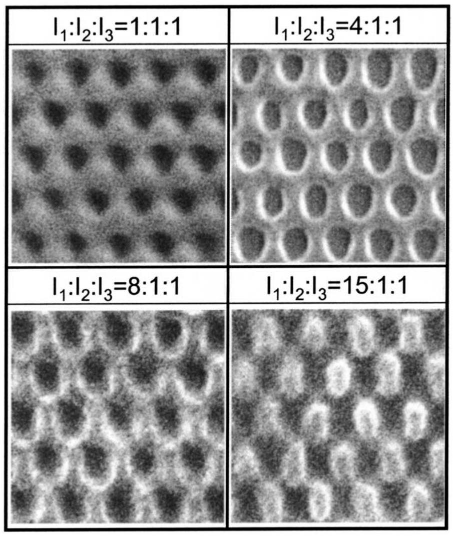

FIG. 6. SEM pictures of the experimental results with different incident intensity ratios.

creasing the intensity ratio. In addition, we can calculate the ellipticity of the micropore shape from the scanning electron microscopy (SEM) pictures in Fig. 6 and plot the experimental curve of the ellipticity for the micropore shape on the 2D hexagonal photonic crystal structure as a function of the incident intensity ratio, (solid line in Fig. 3). It can be clearly seen that the experimental curve shows the same trend as the simulated curve in Fig. 3. However, there is still some difference between the experimental and theoretical results. The main reason for this error is that the sample is not exactly located along the *xy* plane, which means that there is a titled angle between the sample and the *xy* plane. The small tilted angle will cause the micropore shape to become more elliptic. This shows that the ellipticity of the micropore will decrease with the small tilted angle.

IV. CONCLUSION

In this article, we propose and describe a method to modify and control the micropore shape for a 2D hexagonal photonic crystal structure by adjusting the intensity ratio of three incident beams. In theoretical analysis, the ellipticity of the micropore shape has been defined and we calculated the curve of the ellipticity as a function of the incident intensity ratio. The ellipticity will decrease with increasing the incident intensity ratio. In addition, we have set up an optical experimental system and fabricate the 2D hexagonal photonic crystal structure on the photoresist with the glass substrate. By adjusting the incident intensity ratio, a micropore shape with different ellipticity will be obtained and is controllable. The experimental results are consistent with the theoretical analysis. Finally, the holographic lithography can also generate 3D photonic crystal structures and this means that the micropore of 3D photonic crystal structures can be analyzed and controlled by adjusting the intensity ratio of incident beams.

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