Vertically stacked square lattice photonic crystals for Large Angle Optical Beam Steering

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Abstract—In this paper, we reported the fabrication of 2-D square lattice photonic crystals structures targeted at beam steering application using double exposure holographic interference method. Computer simulation gives the electric field distribution patterns and SEM images show the developed photonic crystals on the glass substrate.

I. INTRODUCTION

Nanophotonics promises to have a revolutionary impact on the landscape of photonics technology. Photonic crystal based structures are anticipated to play a significant role in next generation photonic devices[1-4]. There are many different techniques to fabricate 2-D photonic crystals, such as e-beam lithography[5], deep UV lithography[6], holographic interference[7], and so on. E-beam lithography method is a very precise fabrication method with high cost and consumes long time. Holographic method is a low-cost and quick fabrication method which was already proved successful in the fabrication of 3-D photonic crystals structures [8]. In this paper, we carried out the fabrication of 2-D square lattice photonic crystals due to the fact that it provides the best beam steering dynamic range when compared with other photonic crystal structures based on our calculations.

II. EXPERIMENT SETUP AND SIMULATION

Fig.1 (a) shows the experiment optical setup to fabricate 2-D square lattice photonic crystals. A laser beam at 442nm wavelength coming from a He-Cd laser is focused by a UV objective lens onto a pinhole and then collimated by a normal lens to form a parallel wave front. After the laser beam is well collimated, it propagates normally onto the prism and the photo polymer. Figures 1(b) and 1(c) show the first and second exposure to form the needed nanostructure. The incident angle adjustment can be obtained using a coupling prism during the holographic recording. In our experiment, we used a right angle prism with refractive index of around 1.5 to couple recording beams into the recording medium, photo-sensitive polymer. The second exposure was conducted after rotating the prism by 90º along the normal direction of the substrate. The incident beam, which came from the top of the prism, is split and refracted independently. The two refracted beams interfere with each other to generate an interference pattern. Note that there are only two beams in each exposure. The pattern generated by each exposure is a one-dimensional grating structure. The superposition of two identical line gratings

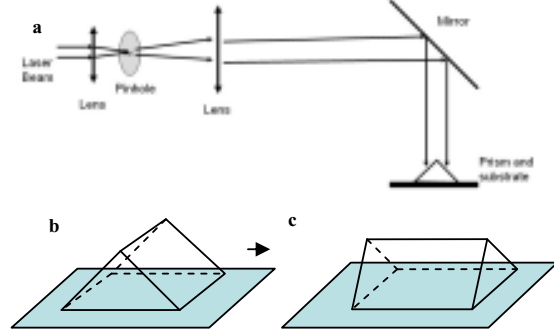perpendicular to each other generates a 2-D square lattice structure.

Fig1. (a) Schematics of the interference set up, (b) the first and (c) the second exposures.

To confirm this, we calculated the electric field distribution inside the photo polymer after a double-exposure process, which is shown in figure 2. The interference pattern is given by the formula [9]:

$$I(r) = \vec{E}_{total}(r,t) \cdot \vec{E}^*_{total}(r,t)$$

$$= \sum_{i=0}^{N-1} E_i^2 + 2\sum_{i=0}^{N-1} E_0 \times E_i \times \vec{e}_0 \cdot \vec{e}_i \times \cos(\vec{K}_i \cdot \vec{r} + \theta_i) + 2\sum_{i>j=1}^{N-1} E_i \times E_j \times \vec{e}_i \cdot \vec{e}_j \times \cos(\vec{K}_{ij} \cdot \vec{r} + \theta_{ij})$$

Where $N = 2, K_i = G_i - G_0, K_{ij} = K_i - K_j, \theta_{ij}$ is the phase difference of the beams. The total number of beams for double exposures is 4. We can clearly observe that the interference pattern is a perfect square lattice structures. The lattice constant is around 0.7um, which is consistent with the formula d=λ/(2sinθ), where λ is the input wavelength and θ is the half angle between two beams (~17º for this case).
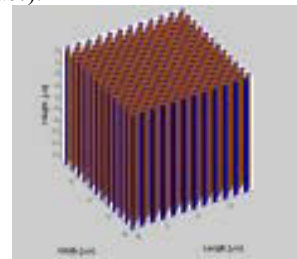

Fig. 2. Simulation of the interference pattern in photo polymer of double-exposure method. Blue and gray colors are for the weak and strong intensity, respectively.

III. RESULTS AND DISCUSSION

In the experiment, we use a right vertex angle prism. In order to make the index match and reduce the unwanted reflections, we filled silicone oil, which has a refractive index of from 1.45 to

1.50 at 25°C, at the interfaces between prism and PR, glass and the holder. The photo polymer we used in the fabrication is AZ P4620. First, we spin coated a film of 10μm PR on the glass after coating the adhesion promoter, then baked the substrate, expose under 442nm laser beam for 15s for the first exposure. Then, we rotate the prism 90° along the z-axis direction and do the second exposure. At the end the sample was developed. Fig.3 and Fig.4 show the top view and side view of the 2-dimensional square lattice we have achieved. The left and right panel of the pictures shows the small and large magnification of photonic crystals structures, respectively.
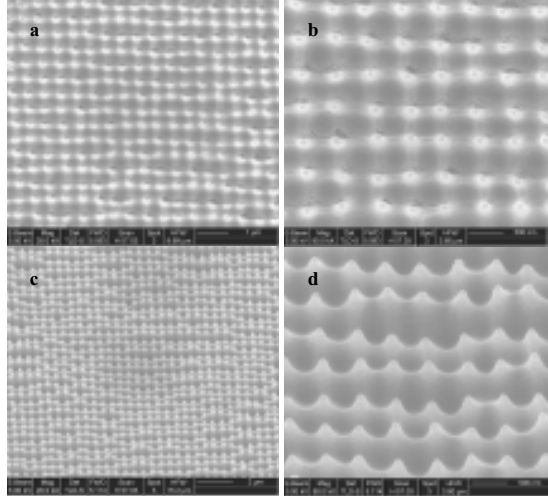

Fig.3 SEM images of top view with lower(a) and higher(b) magnification and side view with lower(c) and higher(d) magnification of the square lattice structure made by AZ P4620.

Because we conducted the exposure with the prism on the surface of the substrate, the photonic crystal pillars are formed which were standing on the substrate. In SEM pictures, the period of the pillars is around 0.6um, which is consistent with the simulation results. The period shows a fluctuation due to the gravity and some other factors in the experiment process, such as tiny vibrations of the sample holder during exposure. To avoid the photonic crystal being collapse, we can have a post bake or hard bake after developing to make the photonic crystals more stable. For the negative photo polymer, such as SU8, the developed square lattice is the hole structure through this double exposure method. To achieve photonic crystals with different lattice constants, we can use prism with different angles or use laser beam with different wavelengths.

Fig. 4 shows the theoretical analysis of the beam steering process for the square lattice photonic crystals. We calculate the 3D band structure of the square lattice photonic crystals that have the equifrequency contour with a crossing line of certain frequency plane of the 3D band structure. The laser beam firstly enters the photonic crystals surface from the air or medium. After two negative refractions, the laser beam enters the air or medium again. In Figure 4, k_{in} is the input wavevector, k_{pc} is the wavevector inside photonic crystals, s_{pc} is the group velocity inside photonic crystals. k_{out} is the output wavevector after the 2nd interface. k_{in} and k_{pc} have equal k_z component due to the momentum conservation at the 1st interface. k_{pc} and k_{out} have equal k_x component due to the momentum conservation at the 2nd interface.
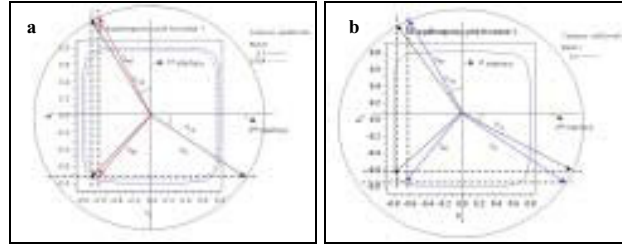

Fig.4 Equifrequency Contour (EFC) analysis of the beam steering process (a) the process with changing the incident angle (b) the process with changing the incident wavelength.

Momentum conservation is indicated by the dashed line in the figure. s_{pc} is in the opposite direction with respect to k_{pc} is because s vector is in the direction where frequency is increased with the wavevector k. When the input angle or wavelength is changed, the corresponding wavevector k_{in} will also be changed. k_{pc} and s_{pc} also will be changed correspondingly. k_{out} will be also migrated according to the momentum conservation. Based on the calculations, this results in a very large beam steering as indicated.

In summary, we reported the fabrication of 2-D square lattice photonic crystals through holographic interference method. A right angle prism was used in the double exposure process. Computer simulations of the interference patterns and SEM pictures of the 2-D photonic crystals were shown as well. The beam steering principle of the square lattice photonic crystal is also discussed through Equifrequency Contour analysis. This research is supported by AFRL. Helpful discussion with Dr. Rob Nelson is acknowledged.

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