Non-coplanar multi-beam interference produced by one triangular pyramid for fabricating photonic crystals

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Received July 1, 2005

A method for fabricating three-dimensional (3D) photonic crystals (PhCs) easily and simply, by using a visible light (~ 532 nm) to pass one triangular pyramid to form non-coplanar multi-beam interference, named laser interference etching technique, is reported. In the experiment, we exposed a 9-μm-thick photo-resist on the silicon substrate with exposure intensities of 150, 180, and 220 mJ/cm^2, and produced the periodical nanostructures. Through varying a common angle in the triangular pyramid, other interference patterns can be obtained to fabricate various PhCs.

OCIS codes: 220.3740, 220.4000, 260.3160.

Photonic crystals (PhCs), which have complete band gaps, have so promising applications from electronics to photonics that the domestic and overseas researchers have been paying enormous attention to how to fabricate periodic nanostructures in the past decades. The main methods to fabricate three-dimensional (3D) PhCs involve semiconductor micro-fabrication technology[1], self-organization of micro-spheres[2], scanning technique of a tightly focused laser beams[3], and two-photon absorption polymerization technology[4]. Compared with these technologies, the laser interference etching technique has lots of advantages in fabricating PhCs. It has high spatial resolution, and can fabricate PhCs in the visible light range, and change the crystalline structures easily by varying the exposure dosage. The productive process is simple, one-off, and inexpensive, this method is thus adopted extensively[5].

The laser interference etching technique can be explained as follows. Multi-beam interference produces a periodically modulated optical intensity with a period d, which is determined by the colliding angel θ between two light beams and the laser wavelength λ: $d = \lambda/[2\sin(\theta/2)]$. If the periodically modulated optical intensity is transferred to a photo-reactive material (such as photo-resist), a periodical matrix array is obtained after some processing. The interference of two beams creates a one-dimensional (1D) PhC, the interference of three or more beams can create a 3D PhC[6]. In this paper, we report a method for fabricating 3D PhCs using a visible light (~ 532 nm) to form multi-beam interference through one triangular pyramid. It is simpler than the diffractive method, which splits the incident laser beam into several; those beams pass through many reflective mirrors, and produce a face-centered-cubic (fcc) interference pattern.

The experimental setup is shown in Fig. 1. The green light (~ 532 nm) is broadened by a telescopic system that consists of two lenses L_1 and L_2, and is split into four beams, then the four beams pass through a triangular pyramid (see Fig. 2) and interfere, thus the periodically modulated optical intensity is obtained. We put a photo-resist sample on the bottom of the triangular pyramid, choose right exposure time, and then obtain PhCs with periodical nanostructure.

According to interference theory, the interference by four fcc-type laser beams can create 3D periodical structure. Usually, people make one laser beam pass through one grating for creating multiple beams; these beams form fcc-type beams by reflecting many times. In our experimental setup, it was very simple and easy that we can use triangular pyramid to produce the four laser beams.

In Fig. 3, the incident laser beam is covered with the

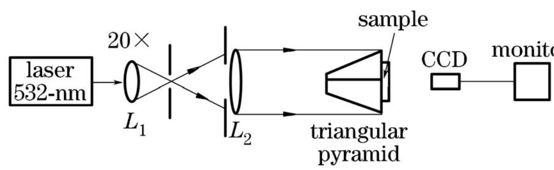

Fig. 1. Experimental layout of the laser interference lithography.

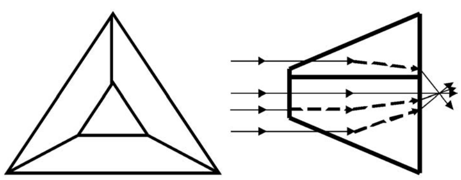

Fig. 2. The structure of pyramid as a prism.

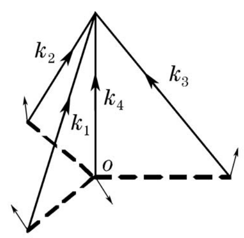

Fig. 3. Formation of the pyramid by four laser beams.

triangular pyramid, the central beam (k_4) is set along the vertical direction while the other three beams (k_i, i = 1, 2, 3) are placed symmetrically around the central one. These four beams will focus on one point beside the bottom of triangular pyramid, and form the interference phenomenon. The incident laser beam used was continuous wave (CW) laser with a long coherent length, and the optical path difference between k_4 and k_i (i = 1, 2, 3) was a constant, and the four beams had the same linear polarization states and frequencies.

In order to produce the fcc-type interference pattern, a common angle $\Phi = 38.94°$ with the vertical must be satisfied. Therefore, it is necessary to set the colliding angle between the side and the base to be 38.94°, as shown in Fig. 4, and the angles between k_i (i = 1, 2, 3) are 120°.

Theoretical analysis demonstrated that the fcc-type four beams' interference could form many kinds of Bravais crystal lattices. Which kind of crystal lattice would be formed depended on the maximum value point in the interference field and satisfied

$$I = \sum_{j=1}^{4} E_j^2 + 2\sum_{i<j} E_i E_j e_{ij} \cos\left[(K_i - K_j)\, r + \delta_{ij}\right], \quad (1)$$

$$\cos\left[(K_1 - K_2)\, r\right] = \cos\left[(K_1 - K_3)\, r\right] = \cos\left[(K_1 - K_4)\, r\right] = 1. \quad (2)$$

We could use the beams' direction cosine to match the above two conditions, and also could get the difference of direction cosines by solving the equations set, and then obtain various crystal lattices. In our experiment, we produced different 3D PhCs through turning the sample on the bottom of triangular pyramid slightly.

In this experiment, the laser wavelength was 532 nm, so the raw materials used for interference etching were photo-resist SU8 (Epon-SU8), solvent γ butyrolactone, and cationic photo-initiator Irgacure 261. We coated the photo-resist SU8 on the silicon substrate, the thickness of the thin film was set by the dimensions we wanted. If the dimensions were three, thin film was about 8—10 μm, and would be heated at 90 °C for two hours. During the pattern etching, the exposure duration was varied along with the power of the laser beam, the sensitivity and concentration of the photo-initiator. The duration value ought to be decided after doing a lot of tries. At last, the exposed thin film needed to be heated for about one hour.

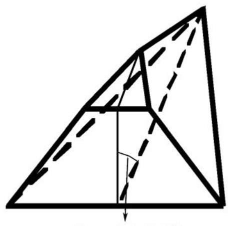

Fig. 4. Angle between the base and the side of the prism is 38.94°.

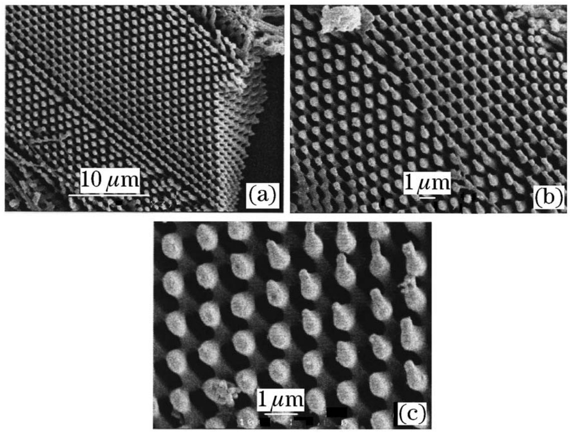

Fig. 5. SEM images of the 3D PhCs. (a), (b) and (c) correspond to exposure intensities of 220, 180, and 150 mJ/cm^2.

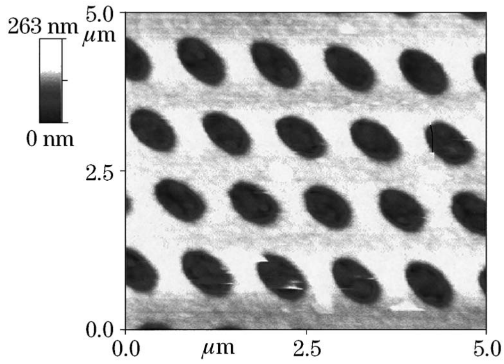

Fig. 6. AFM image of 2D PhCs made by non-coplanar three-beam lithography.

In the experiment, the thickness of the thin film is 9 μm. The exposure dosage had one threshold based on different laser powers. The part below the threshold would be removed at last. We carried out experimental study particularly for condition 1: same exposure durations and different laser powers; and for condition 2: different exposure durations and same laser powers. Some valuable results were obtained.

Figure 5 shows the scanning electron microscopy (SEM) images of the 3D PhCs. Figures 5(a), (b), and (c) show the SEM images of the porous structures fabricated with laser powers of 220, 180, and 150 mJ/cm^2, respectively.

Figure 6 shows an atomic force microscopy (AFM) image of the two-dimensional (2D) PhCs. It is a 2D-square PhC structural pattern fabricated by the interference of three non-coplanar laser beams, which was formed by removing the central beam from the triangular pyramid.

In conclusion, we reported a method for fabricating 3D PhCs by using a visible light ($\sim$ 532 nm) to form fcc-type multi-beam interference through one triangular pyramid. It is simple and practical. If other interference patterns were needed, the common angle Φ must be varied, in other words, the shape of the pyramid lens needs to be re-designed.

The authors thank Department of Physics, Hong Kong University of Science and Technology for support. W. Xiang's e-mail address is whxiang@tju.edu.cn.

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