Fabrication of hetero-binary and honeycomb photonic crystals by one-step holographic lithography

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We report the simulation and fabrication of two-dimensional hetero-binary and honeycomb photonic crystals by one-step holographic lithography. These structures are realized by introducing one or three auxiliary beams into the three basic beams forming a regular hexagonal structure. The size contrast between the center rod and its six neighbors in a hetero-binary structure can be tuned by adjusting the intensity contrast between the auxiliary beam and basic beams. The idea of creating heterogeneity into the interference pattern by auxiliary beams could be easily extended to three-dimensional case by adding more beams in the vertical direction. © 2006 American Institute of Physics. [DOI: 10.1063/1.2181270]

Since its first introduction by Yablonovitch and John, photonic crystal (PhC) has attracted steadily growing interest for the past decades due to the fascinating properties and intriguing application for the miniaturization and integration of optical devices. Photonic crystals also exhibit a variety of new physical phenomena, including the suppression or enhancement of spontaneous emission, low-threshold lasing, and quantum information processing. Fabricating controllable complex micro/nanostructures has been a hot topic in the experimental studies on photonic crystals. Various techniques, such as e-beam lithography, self-assembly and interference lithography have been applied to fabricate PhCs including one-dimensional, two-dimensional (2D) and three-dimensional (3D) structures.

Holographic lithography was first proposed and implemented by Berger, Gauthier-Lafaye, and Costard to fabricate 2D hexagonal patterns in a photosensitive polymer, which subsequently served as an etching mask for transfer to a high-index silicon substrate. This technique was extended by Campbell et al. and Shoji and Kawata by introducing up to two additional laser beams to create 3D structures. As being able to produce defect-free, nanometer-scale structures over large area uniform PhCs in a single step fabrication, this technique is a very economical and powerful tool and might hold the key to volume production of photonic structures.

Much effort has been devoted to develop this method to fabricate 2D and 3D micro/nanostructures. However, most of the work on this topic has been concentrated on fabricating 14 simple Bravais lattices except that by Wang et al. on 2D quasicrystals.

Compared to the regular hexagonal PhC structure, honeycomb lattice of dielectric rods in air exhibits a very large absolute gap that extends over a wide range of filling fractions. Symmetry breaking can lead to an even larger absolute band gap when another rod is placed in the center of the honeycomb cell, which is called hetero-binary PhC structure in this letter. The hetero-binary structure could also provide a profound modulation in the propagation of photons such as defect engineering and filters.

Generally, three laser beams form a 2D interference pattern. In this letter, by introducing one or three auxiliary beams separately, we create 2D hetero-binary and honeycomb PhC microstructures by holographic lithography. To avoid the alignment complexity and inaccuracies due to differences in the optical path length and angles among the interfering beams as well as vibrational instabilities in the optical setup, we applied single refracting prism holographic lithography technique, which was described in our previous work.

The projection of the specially designed prism for this letter, which is a critical component in the optical setup, is schematically shown in Fig. 1. The top and bottom surfaces are hexagonal and surrounded by six symmetrically sepa-

FIG. 1. Projection of the specially designed prism along the optical axis.

B_5

B_2

B_4

B_3

B_6

B_1

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rated side-refracting surfaces. Several types of structures can be obtained by choosing different combinations of the beams. Table I summarizes those used in the present study. Intensity of the independent beams can be controlled by polymer polarizers sitting in front of the refracting prism mounted on the homemade mask.

The samples were fabricated in a standard holographic lithography procedure, as described previously. A Nd:YVO₄ continuous wave laser at 532 nm was used as the irradiation light source to expose the negative photoresist SU-8 (from Shell) film with 2 wt. % Irgacure 261 (from Ciba Co.) as cationic photoinitiator. After being exposed to the interference pattern, the polymerization process was completed by a postbake. Those unpolymerized regions were washed away first by propylene glycol methyl ether acetate and then cleaned with acetone, leaving behind a copy of the interference pattern permanently embedded in the polymer film. Fabricated results were observed by scanning electron microscope (SEM) (JEOL 6300F).

The intensity profile of the holography pattern from interference of N beams is given by

\[ I(r) \propto \left| \sum_{n=1}^{N} E_n e^{i(k_n r - \omega t)} \right|^2 = \sum_{n,m=1}^{N} a_{nm} e^{i(G_m r)} . \]

The differences of the wave vectors for the incident plane waves, \( G_m = k_m - k_n \), can be regarded as the reciprocal lattice vectors. The pattern displays maxima at locations satisfying Bragg diffraction condition: \( G_m \cdot r = 2q \pi \) (q is an integer).

\( N = 3 \) is sufficient to create a 2D lattice. For example, \( \mathbf{k}_1 = (2\pi/\lambda)(1,0,0) \), \( \mathbf{k}_2 = (2\pi/\lambda)(\cos(2\pi/3), \sin(2\pi/3), 0) \), and \( \mathbf{k}_3 = (2\pi/\lambda)(\cos(4\pi/3), \sin(4\pi/3), 0) \) form a regular hexagonal lattice with \( \{ \mathbf{G}_1 = [(2\pi/\lambda)(3/2, \sqrt{3}/2, 0)], \mathbf{G}_2 = [(2\pi/\lambda)(\sqrt{3}, 0, 0)] \} \) as the reciprocal basis vectors. The beam layout is illustrated in the inset between Figs. 2(a) and 2(b). This beam configuration can be realized by choosing three of the refracted beams (\( B_1, B_2, B_3 \)) from the prism in Fig. 1, which are the basic beams for all the beam arrangements in this letter. The calculated intensity distribution and SEM image for the fabricated structure are demonstrated in Figs. 2(a) and 2(b), respectively.

By introducing an auxiliary beam, \( \mathbf{k}_4 = (2\pi/\lambda) \times (\cos(\pi/3), \sin(\pi/3), 0) \) into the above basic beam arrangement, as shown in the inset between Figs. 2(c) and 2(d), the size of the center rod in the hexagonal lattice is able to be modulated. From Fig. 2(c), it can be seen that there is a size contrast, i.e., the size difference between the rod in the center of the hexagonal structure and its six closest neighbors, which is called hetero-binary structure here. This structure has been realized by picking up four refracted beams (\( B_1, B_2, B_3, B_4 \)) in Fig. 1. The fabricated result is illustrated in Fig. 2(d), where the rod in the center is smaller than its six closest neighbors, being consistent with the simulation result. In Figs. 2(b) and 2(d), some remaining resist bridges between neighbor rods are visible, which were explained as from a kind of chemical self-assembling process due to surface tension occurring at the sample drying stage.

The size contrast between the central rod and its six neighbors can be tuned by the intensity contrast between the auxiliary beam and three basic beams. As exhibited in Fig. 2(c), when the intensity contrast \( I_{B1}/I_{B0} = 52\% \) (in this letter, three basic beams, denoted as \( I_{B0} \), are intensity equivalent during the fabrication, i.e., \( I_{B1} = I_{B2} = I_{B3} \)), the size contrast is very obvious. By decreasing the intensity contrast to 26%, the size contrast is reduced, i.e., the size of the center rod is closer to that of its neighbors, as shown in Fig. 2(e). The fabricated result in Fig. 2(f) matches with that from the simulation.

Auxiliary beams can be chosen more flexibly. By adding three auxiliary beams, \( \mathbf{k}_4 = (2\pi/\lambda)(\cos(3\pi/3), \sin(3\pi/3), 0), \mathbf{k}_5 = (2\pi/\lambda)(\cos(5\pi/3), \sin(3\pi/3), 0), \mathbf{k}_6 = (2\pi/\lambda)(\cos(5\pi/3), \sin(5\pi/3), 0) \) with same intensity, the honeycomb structure can be created. Six beams, \( B_1 + B_2 + B_3 + B_4 + B_5 + B_6 \), were used to yield this structure. Beam configuration is shown in the inset of Fig. 3. The honeycomb structures are clearly exhibited in Fig. 3, both from simulation and fabrication.

All the above beam configurations are based on the fact that three basic beams have equal intensity, thus the rod shape is nearly round. In fact, the shape of the rod is tunable.

**TABLE I. Selection of laser beams for various structures.**

<table>
<thead>
<tr>
<th>Name of structures</th>
<th>Selected beams</th>
</tr>
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<tbody>
<tr>
<td>Hexagonal structure</td>
<td>( B_1 + B_2 + B_3 )</td>
</tr>
<tr>
<td>Hetero-binary structure</td>
<td>( B_1 + B_2 + B_3 + B_4 )</td>
</tr>
<tr>
<td>Honeycomb structure</td>
<td>( B_1 + B_2 + B_3 + B_4 + B_5 + B_6 )</td>
</tr>
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</table>
in the same lattice structure by adjusting the intensity ratio of these three basic beams. Also by modifying the phase and polarization of the independent beams, different hetero-binary or hetero-ternary structures are obtainable. Furthermore, by controlling the exposure intensity, very different configurations such as holes and rods can be switched (these are not shown here). Therefore, by introducing auxiliary beams, holographic lithography could become a very flexible and useful technique to obtain heterostructures or compound structures other than 14 Bravias structures. This method is also possible to be extended to fabricate 3D heterostructures by adding more beams in the vertical direction, which is very difficult by other techniques such as e-beam lithography or self-assembly.

To summarize, by introducing one or three auxiliary beams separately, we have obtained hetero-binary and honeycomb PhC structures with a specially designed prism having six side-refracting surfaces. The size contrast between the central rod and its six closest neighbors can be tuned by adjusting the intensity contrast between the auxiliary beam and basic beams. More hetero-microstructures could be realized by designing the beam configuration, phase, polarization and intensity ratio between different beams properly.

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