Five beam holographic lithography for simultaneous fabrication of three dimensional photonic crystal templates and line defects using phase tunable diffractive optical element

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Abstract: This paper demonstrates an approach for laser holographic patterning of three-dimensional photonic lattice structures using a single diffractive optical element. The diffractive optical element is fabricated by recording gratings in a photosensitive polymer using a two-beam interference method and has four diffraction gratings oriented with four-fold symmetry around a central opening. Four first-order diffracted beams from the gratings and one non-diffracted central beam overlap and form a three-dimensional interference pattern. The phase of one side beam is delayed by inserting a thin piece of microscope glass slide into the beam. By rotating the glass slide, thus tuning the phase of the side beam, the five beam interference pattern changes from face-center tetragonal symmetry into diamond-like lattice symmetry with an optimal bandgap. Three-dimensional photonic crystal templates are produced in a photoresist and show the phase tuning effect for bandgap optimization. Furthermore, by integrating an amplitude mask in the central opening, line defects are produced within the photonic crystal template. This paper presents the first experimental demonstration on the holographic fabrication approach of three-dimensional photonic crystal templates with functional defects by a single laser exposure using a single optical element.

OCIS codes: (050.1970) Diffractive optics; (050.6875) Three-dimensional fabrication; (260.3160) Interference; (220.4000) Microstructure fabrication; (050.5298) Photonic Crystal

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1. Introduction

Three-dimensional (3D) photonic crystals (PhCs) are periodic microstructures with partial or complete photonic band gaps. Since its introduction in 1987, PhCs have been under intense studies due to their potential applications in low-threshold laser and optical integrated circuits [1,2]. Fabrication of 3D PhCs have been a great challenge in past decades. So far, several techniques have succeeded to a certain degree in fabricating 3D PhCs, such as e-beam lithography for multilayer stacking of woodpile structures [3], colloidal self-assembly [4], multi-photon direct laser writing [5], and holographic lithography [6,7]. Holographic lithography constructs 3D interference patterns using multiple coherent laser beams and records the interference pattern in a photoresist to form 3D structural templates. The structure and symmetry of the interference pattern can be controlled by the beam propagating direction, the number of the interfering beams, the beam intensities, their respective polarizations and relative phases [8,9]. So far holographic lithography has been successful in fabricating large-volume photonic crystal templates at micro/nano-scales [6,7].

Traditional optical setup for multiple-beam holographic lithography is complicated, involving multiple bulk optical elements such as mirrors and beam splitters. In order to simplify the optical setup and improve the fabrication reproducibility, a single optical element such as a refractive optical element (e.g. a flat-top prism [10,11]) or a diffractive optical element (e.g. a phase mask [12–16]) has recently been used for the laser holographic fabrication of photonic crystal structures. A flat-top prism has been used for the fabrication of diamond-like or woodpile photonic crystal templates, using a polarization effect with a configuration consisting of four linearly polarized side beams arranged symmetrically around a circularly polarized central beam [11]. Multi-layer phase masks [13,14] have been demonstrated for the fabrication of diamond-like photonic crystal templates by introducing a phase difference among the diffracted beams by changing the distance between two orthogonally oriented gratings. However the phase difference is not adjustable once the phase

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mask is fabricated [13,14]. Overall the single-beam and single-exposure processes using a single optical element in holographic lithography have drastically reduced the fabrication complexity and produced the complex diamond-like photonic lattice where there is a larger photonic bandgap compared to a simple face-centered-cubic (FCC) structure [13,14]. On the other hand, a significant advance has been achieved on the simultaneous fabrication of functional defects in photonic crystal template. By using a multi-beam phase-controlled one-step holographic lithography, Li *et al.* [17] has fabricated line-defects in a Bragg structure and embedded waveguides in a two-dimensional photonic crystal. They have also proposed a method for fabricating defects into a 3D photonic crystal by one-step method [17].

Technically, it is relatively easy to produce single-layer phase masks such as gratings on a substrate. Divliansky *et al.* [18] has fabricated a phase mask with three diffraction gratings surrounding a central opening for the fabrication of a 3D photonic crystal based on four-beam interference. However, this method can only produce simple FCC or face-center-tetragonal (FCT) photonic lattice structure because the phase control of the interfering beams can only translate the photonic lattice [19].

In this paper, we present a phase tunable holographic fabrication method to produce 3D photonic crystals based on a single diffractive optical element. A simple approach is demonstrated for the tuning and optimization of photonic structural symmetry from FCT to a desired diamond-like structure. Furthermore, this paper presents the first experimental demonstration on the holographic fabrication approach of three-dimensional photonic crystal templates with functional defect by a single laser exposure using a single optical element.

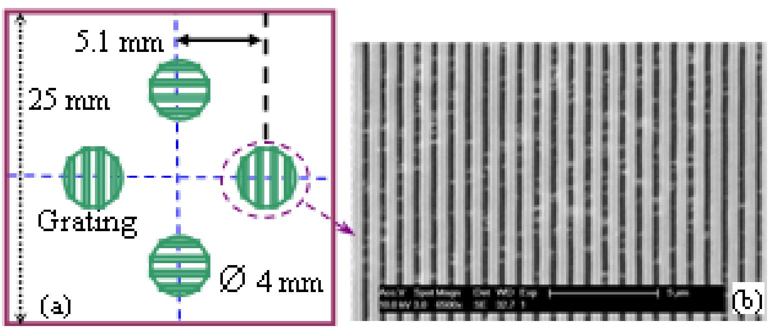

Fig. 1. (a) Scheme of single diffractive optical element consisting of four gratings. (b) SEM of fabricated grating in a polymer.

2. Fabrication of single diffractive optical element

The single diffractive optical element is produced by recording gratings in a photosensitive photoresist mixture. In order to obtain right grating depth and grating cycle for a high diffraction efficiency, low power laser is used so that laser exposure time is extended and used as a control of exposure condition. Thus Coherent Compass laser (532 nm, 60 mW) is used for the exposure of the photoresist mixture. One laser beam was expanded to a size of 4 mm and separated into two by using a 50:50 beam-splitter. Parallel fringes are formed when two laser beams overlap. The laser polarization is set in parallel with fringes. The photoresist mixture has dipentaerythritol penta/hexaacrylate (DPHPA) monomer (Aldrich, 88.45%), photo initiator rose bengal (0.21%), co-initiator N-phenyl glycine (NPG, 0.81%) and chain extender N-vinyl pyrrolidinone (NVP, 10.53%). The mixture is spin-coated on a glass slide (25 mm x 25 mm) with a speed of 3000 rpm for 2 minutes. The glass slide is mounted on a rotation stage combined with a linear motion stage (Thorlabs). The location of the glass slide is initially adjusted with two beams overlapped in the rotational center, then moved away from the center by 5.1 mm. After the photoresist mixture receives the first exposure, the glass slide is rotated by 90 degree for the second exposure. Total four gratings are produced for the entire grating writing process as shown in Fig. 1(a). The exposure time is 2 seconds for each

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exposure. After exposure, the photoresist mixture is developed directly in propylene glycol methyl ether acetate (PGMEA) for 20s, followed by rinsing in isopropanol for 10s and air drying. Figure 1(b) shows scanning electron microscope (SEM) of fabricated gratings in the thin polymer on the glass slide. The period of the grating is approximately 0.78 μm. Thus the fabricated diffractive optical element consists of the central opening surrounded by four diffraction gratings orientated four-fold symmetrically with size of 4 mm in diameter and period of 0.78 μm.

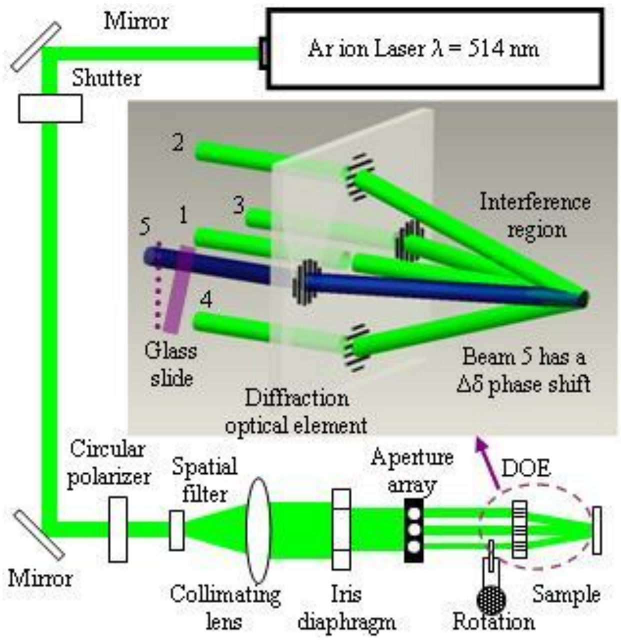

Fig. 2. Experimental setup of the five-beam holographic fabrication using the single diffractive element with one beam phase-delayed by a glass slide.

3. Fabrication of photonic crystal templates using the diffractive optical element

Figure 2 shows the optical setup for the holographic fabrication of 3D photonic crystal template. For the five beam holographic lithography, a high power laser is needed. Thus a 514.5nm laser beam from a Sabre Ar ion laser (Coherent Inc.) is circularly polarized, cleaned, expanded, and collimated by spatial filter and collimating lens. Five beams are selected by an aperture array from one incoming beam. When the beams go through the single diffraction element, four first-order diffracted beams overlap with the central beam passing through the central opening (labeled as beam 1 in Fig. 2). The four beams are arranged symmetrically around the central one and tilted at the same angle. The first-order diffraction efficiency of the gratings is approximately between 24% and 28% of the incident beams 2, 3 and 4. The diffraction efficiency of the grating for beam 5 is 30%. The phase of the beam 5 is delayed by inserting a thin microscope glass cover slide with a uniform thickness (BK7 glass, d = 130μm, n = 1.52). By rotating the glass slide through a rotation stage, the phase delay of beam 5 can be adjusted continuously and precisely.

When five beams overlap, an interference pattern is formed. The intensity profile of the five-beam interference pattern can be calculated as,

$$I = \left\langle \sum_{i=1}^{5} E_i^2 \right\rangle + \sum_{i<j}^{4} E_i \cdot E_j \cos\left[\; k_i - k_j \;\; r + \Delta\delta_{ij} \right] + \sum_{i=1}^{5} E_i \cdot E_5 \cos\left[\; k_i - k_5 \;\; r + \Delta\delta_{5i} \right] \quad (1)$$

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with E_i as an electric field strength and k_i as a wave number. The last term is related to the phase delay by the insertion of the glass slide in beam 5. The phase difference $\Delta\delta_{5i}$ is a function of the glass slide rotation angle θ and can be described as,

$$\Delta\delta_{5i}(\theta) = \frac{2\pi}{\lambda}\left\{\frac{d}{\cos\alpha}\left[n_{glass} - n_{air}\cos(\theta-\alpha)\right]\right\} \tag{2}$$

where $\alpha = \arcsin(\sin\theta / n_{glass})$ and λ is the incident wavelength.

The insertion of the glass cover slide introduces a large phase delay for beam 5. However the interference pattern with a phase delay of $\Delta\delta_{5i}$ is the same as the one with a phase delay of $\Delta\delta_{5i} + 2n\pi$ (n is an integral) because of the periodicity of the cosine function. A phase delay of $\pi + \Delta\delta_{5i}$ produces the same pattern with a phase delay of $\pi\text{-}\Delta\delta_{5i}$. Thus we can simulate the five beam interference pattern related to the phase delay by changing $\Delta\delta_{5i}$ from 0 to π. Figure 3 shows simulated iso-intensity surfaces of the five-beam interference patterns related to the phase change $\Delta\delta_{5i}$ varying from 0 to π with 0.2π increment. If the phase shift is zero, the low-intensity iso-intensity surface of the five-beam interference looks like spheroid-type simple FCC or FCT structure as shown in Fig. 3 [12,13]. With a phase shift of 0.2 π, spheroids start to touch each other in one direction. With increasing phase shifts, the spheroids start to interconnect in two directions and form rods among spheroids. When the phase delay reaching the optimal value $\Delta\delta_{5i} = \pi$, a diamond-like photonic structure can be formed [8,9].

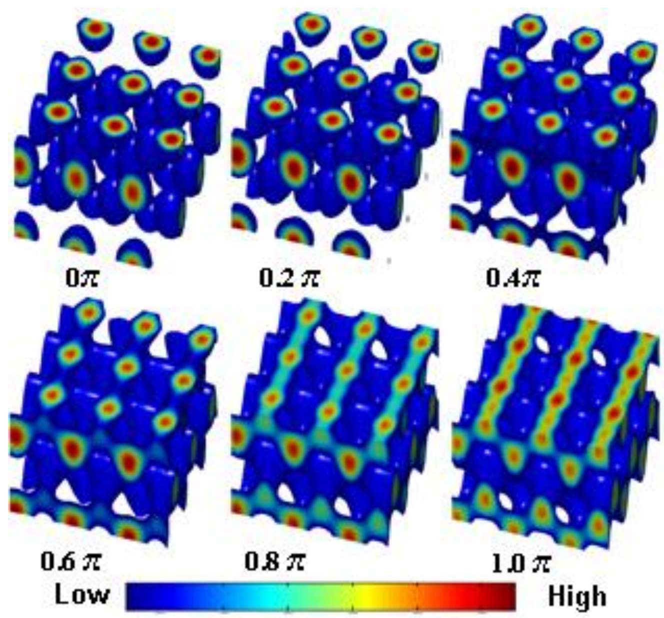

Fig. 3. Iso-intensity surface of the five-beam interference pattern related to the phase change $\Delta\delta_{5i}$ varying from 0 to π.

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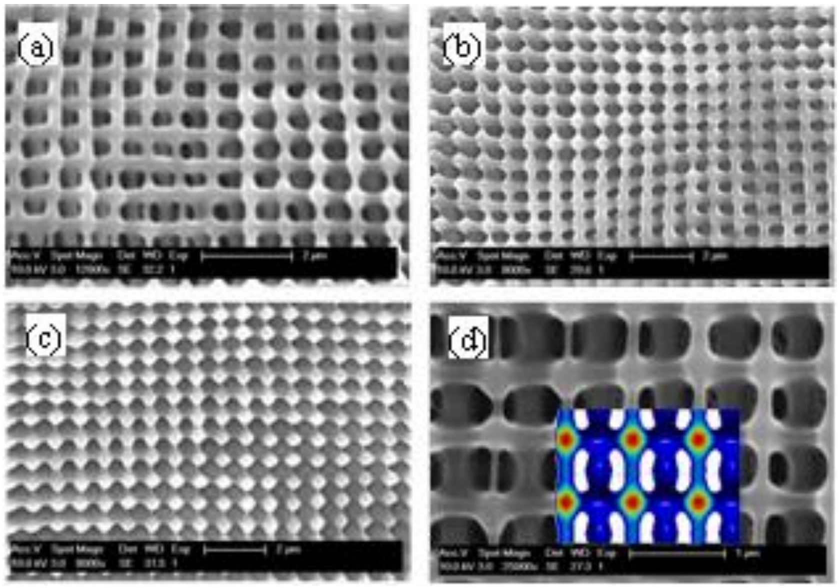

Fig. 4. SEM of recorded five beam interference pattern in photoresist polymer. (a-c) The photonic structure fabricated with the glass slide rotation angle of 2, 4, and 6 degrees, respectively. (d) Enlarged view of the SEM (a) and the inserted simulation of structure with a phase delay of π.

The same photoresist mixture as the one used for the grating is used to record the 3D interference pattern. The photoresist mixture is spun onto the glass substrate at 2000 rpm for 2 minutes. A laser power of 750 mW is used. After going through the diffraction grating, the first-order diffraction beam has power between 4 and 5 mW. The central non-diffracted beam has a power of 17 mW. The photoresist is exposed to the interference pattern for 10 seconds. After exposure, the photoresist mixture is developed in PGMEA for 5 minutes, rinsed by in isopropanol for 1 minute and left to dry in air. After development, a colorful sample with a size of around 4 mm is obtained.

Figure 4 shows SEM images of fabricated 3D photonic structures in polymer using the single diffraction element. Figures 4(a-c) are the structures fabricated with the inserted glass slide rotated by 2, 4 and 6 degrees, respectively. A woodpile-like (or diamond-like) structure is clearly seen in Fig. 4(a), indicating a phase delay $\Delta\delta_{5i}$ close to π [8,9]. From Fig. 4(c), we can see that the spheroid is sitting in the lattice of FCT structure, similar to the simulated structures in Fig. 3 with a small phase shift. Figure 4(b) has a structure with a phase delay between above two phase delays. From these figures, it is clear that the optical setup using the phase tunable single diffraction optical element can be used to fabricate 3D structures with well-controlled features. From the calculations $\Delta\delta_{5i}$(4 degrees)- $\Delta\delta_{5i}$(2 degrees) = 0.32π, $\Delta\delta_{5i}$(6 degrees)- $\Delta\delta_{5i}$(2 degrees) = 0.85π and by comparing the Fig. 4 with Fig. 3, Figs. 4 (a-c) can be corresponded with simulated structures with a phase delay of π, 0.68π, and 0.15π, respectively. Figure 4(d) shows the enlarged view of the structure in Fig. 4(a) and the inserted simulation with a phase shift of π. The agreement between the SEM and the simulated structure is very good. The period of diamond-like structure in Fig. 4(a, d) is measured to be 0.78 μm in agreement with the period of grating shown in Fig. 1.

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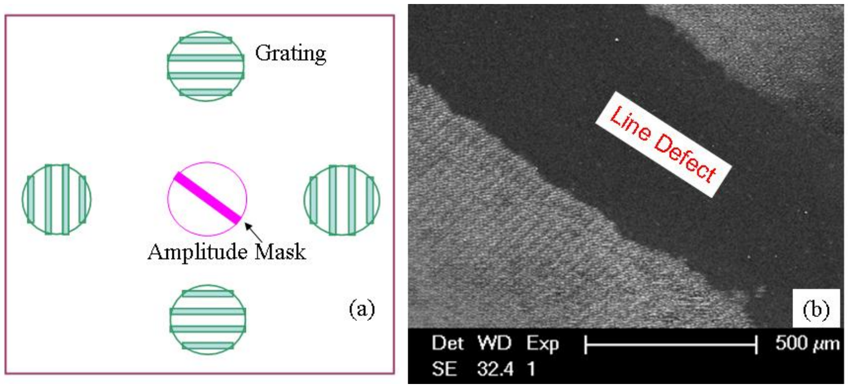

Fig. 5. (a) Scheme of single diffractive optical element setup consisting of four gratings and an amplitude mask. (b) SEM of fabricated 3D PhC structures with a line defect, introduced by the amplitude mask.

4. Simultaneous fabrication of line defects and 3D photonic crystal templates by combining amplitude mask with the diffractive optical element

In addition to the phase tunability in the demonstrated method, the single diffractive optical approach can be further extended to produce 3D photonic crystals with functional defects. This demonstration is shown in Fig. 5(a). In order to insert a line defect in photonic crystal structures, an amplitude mask is placed in the central region of the optical element. The amplitude mask casts a shadow of the central beam on the photoresist. In the shadow region, four side-beams overlap and forms interference patterns. However the power of the side beam is more than 3 times smaller than that of the central beam. The intensity of the four-beam interference in the shadow region is less than the threshold needed for photopolymerization in the photoresist. After exposure, the shadow region will be washed away. As a proof-of-concept, we put a bar in the central opening as an amplitude mask to fabricate a line defect in 3D photonic crystal template. Using the same experimental conditions as these in section 3, we fabricate a line defect with a width of approximate 500 μm as shown in Fig. 5(b). Further studies are needed on the diffraction effect of the amplitude mask if small feature sizes of defect shapes are employed in the amplitude mask. Nevertheless this is the first demonstration, to author's best knowledge, of simultaneous fabrication of line defects and 3D photonic crystal template using the one-step holographic lithography.

5. Summary

In summary, this letter demonstrates a phase tunable five-beam holographic fabrication of 3D photonic crystal templates using a single diffractive optical element. The phase mask is fabricated with four diffraction gratings surrounding the opening center. The fabricated 3D photonic crystal templates show a clear transition of structures from FCT to diamond-like lattice through the phase tuning. A simultaneous fabrication of the line defect and 3D photonic crystal templates is also demonstrated by combining the amplitude mask with the phase mask, using the one-step holographic lithography. The demonstrated mask method is compatible with traditional photolithography processes used for optoelectronic chip fabrication.

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