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Holographic Fabrication of Three-Dimensional Woodpile-type Photonic Crystal Templates Using Phase Mask Technique

Di Xu¹, Kevin P. Chen¹, Kris Ohlinger² and Yuankun Lin²

¹*University of Pittsburgh,*

²*University of Texas-Pan American
U.S.A.*

1. Introduction

The telecommunication and computing industries are currently facing increasing challenges to transfer data at a faster rate. Researchers believe that it might be possible to engineer a device operate at optical frequencies. Photonic technology using photon instead of electron as a vehicle for information transfer paves the way for a new technological revolution in this field. Photons used for communication has several advantages over electrons which are currently being used in electronic circuits. For example, photonic devices made of a specific material can provide a greater bandwidth than the conventional electronic devices and can also carry large amount of information per second without interference.

Photonic crystals are such kind of material. They are periodic structures that allow us to control the flow of photons. (John, 1987; Yablonovitch, 1987) To some extent it is analogous to the way in which semiconductors control the flow of electrons: Electrons transport in a piece of silicon (periodic arrangement of Si atoms in diamond-lattice), and interact with the nuclei through the Coulomb force. Consequently they see a periodic potential which brings forth allowed and forbidden electronic energy bands. The careful control of this electronic band allowed the realization of the first transistor. Now, we change our perspective from atom scale to wavelength scale and imagine a slab of dielectric material in which periodic arrays of air cylinders are placed. Photons propagating in this material will see a periodic change in the index of refraction. To a photon this looks like a periodic potential analogous to the way it did to an electron. The difference of the refractive index between the cylinders and the background material can be adjusted such that it confines light and therefore, allowed and forbidden regions for photon energies are formed. (Joannopoulos et al., 1995)

Nowadays, extensive theoretical and experimental studies have revealed many unique properties of photonic crystals useful in optical communication. Intrigued by their vast potential in photonics engineering, tremendous efforts have been invested into the fabrication of three dimensional (3D) photonic crystal structures. However, the fabrication of those photonic crystals with a complete photonic bandgap, i.e. can exhibit bandgaps for the incident lights from all directions, still proves to be a challenge. Considerable efforts have been dedicated to develop fabrication techniques to produce large area defect-free 3D

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photonic structures toward device applications. This part of research needs to develop a CMOS-compatible, fast and repeatable technique to produce 3D photonic crystal structures with complete bandgaps around the visible and near infrared telecommunication windows. (Ho et al., 1994; Blanco et al., 2000 ; Campbell et al., 2000 ; Deubel et al., 2004)

The Chapter is organized as follows: Section 2 recalls the definition of photonic crystals, its optical properties and the laser holographic lithography fabrication technique for 3D photonic crystal templates. After that, based on the related fundamentals of optics and the interference principle of light beams, Section 3 introduces the novel phase mask techniques for our laser holographic fabrication. The utilization of the phase masks simplifies the fabrication configuration of photonic crystals and is amendable for massive production and chip-scale integration of 3D photonic structures. In Section 4, we discuss specific cases for 3D photonic crystal template fabrication with phase masks techniques. The templates have woodpile symmetries constructed and synthesized at sub-micron scale by pattern rotation and superposition. Section 5 concludes the chapter.

2. Photonic crystal holographic lithography fabrication

2.1 3D photonic crystals

Photonic crystals are typically classified into three categories: 1D, 2D and 3D crystals according to the dimensionality of the stack. Depending on the refractive index contrast, structure geometry and the periodicity, photonic bandgaps are determined for specific frequency ranges in the electromagnetic (EM) spectra. (Joannopoulos et al., 1995) The band structure of a photonic crystal indicates the response of the crystal to certain wavelengths of the EM spectra for a certain propagation direction. It defines optical properties of the crystal such as transmission, reflection and their dependence on the direction of propagation of light. No EM waves can propagate inside the corresponding bandgap ranges. Using this property allows one to manipulate, guide and confine photons, which in turn makes it possible to produce an all optical integrated circuit.

Currently, the fabrication of photonic crystals is quite a hot topic; many groups with many different techniques have shown the formation of photonic crystals with different dimensionalities. Among them, 3D photonic crystals have attracted enormous interest in the last decade in both science and technology communities. Its unique capability to trap photons offers an interesting scientific perspective and can be useful for optical communication and sensing. It is now possible to produce 1D or 2D photonic crystal, at high volume and low cost, through use of deep ultraviolet photolithography, which is the standard tool of the electronics industry. But efficient micro-fabrication of 3D photonic bandgap microstructures, especially at a large-scale has been a scientific challenge over the past decade. So far, a number of fabrication techniques have been employed to produce sub-micron 3D photonic crystals or templates. They include: conventional multilayer stacking of woodpile structures by using semiconductor fabrication processes, (Ho et al., 1994) colloidal self-assembly, (Hynninen et al., 2007) and multi-photon direct laser writing, (Deubel et al., 2004). Each method possesses some extent of success. However, we still need to find an economic and rapid way to produce defect-free nano/micro-scale structure over uniform and large area. This mission has been accomplished by the application of the holographic lithography method. (Berger et al. 1997)

2.2 Holographic lithography method

Holographic lithography has recently been employed to fabricate 3D photonic crystals by exposing a photoresist or polymerizable resin to interference patterns of laser beams. (Campbell et al., 2000) This interference technique requires that multiple coherent beams converge on the same spatial region, which is also called multi-beam interference lithography. It is promising because it creates periodic microstructures in polymers without extensive lithography and etching steps. The monochromaticity and spatial volume of laser light has produced nearly defect-free structures, at submicron scale and over large substrate areas. Photonic structures are defined in photoresist by iso-intensity surfaces of interference patterns. In the case of negative photoresist, the underexposed material is then dissolved away in the post-exposure processing. The overexposed region forms a periodic network motif and acts as a 3D photonic crystal template. In the post processing step, the template can be infiltrated at room temperature with SiO₂ and burned away, leaving behind a daughter inverse template. Then, the daughter SiO₂ template is inverted by infiltration with silicon and selective etching of SiO₂. (Tétreault et al., 2006) The final structure has relative higher index contrast ratio (Si/Air holes) in 3D form, corresponding to relative larger photonic bandgap.

Holographic lithography allows complete control of the translational symmetry of the photonic crystal and provides considerable freedom for design of the unit cell. The electrical field of a laser beam can be described by

$$\vec{E}_i(\vec{r}, t) = E_i \cos(\vec{k}_i \cdot \vec{r} - \omega t + \delta_i) \quad (1)$$

where $\vec{k}$ and ω are the wave vector and angular frequency, respectively, E is the electric field strength, and δ is the phase. When two or more coherent laser beams are presented simultaneously in the same region, the waves interfere with each other and generate a periodic spatial modulation of light. The intensity distribution of the interference field I for N laser beams can be described by a Fourier superposition,

$$I = \left\langle \sum_{i=1}^N E_i^2(\vec{r}, t) \right\rangle + \sum_{i < j}^N \vec{E}_i \cdot \vec{E}_j \cos[(\vec{k}_i - \vec{k}_j) \cdot \vec{r} + (\delta_i - \delta_j)] \quad (2)$$

The structure of the interference pattern can be designed by controlling beam properties such as electric field strength, polarization, wave vector, and phase. The photonic structure formed through holographic lithography has the translational periodicity determined by the difference between the wave vectors $\vec{k}_i - \vec{k}_j$ of the interfering beams. Therefore, lattice constants of the photonic structure are proportional to the wavelength of the interfering laser beam. The polarization, represented by the electric field vector, determines the motif placed within the unit cell of the photonic lattice. The initial phase difference shifts the interference pattern and changes the motif within the unit cell. The laser intensity, exposure time, photoresist preparation, and post-exposure development condition will also contribute to the motif of the interference pattern. The photonic structure formed through holographic lithography should have good connectivity in both the dielectric and the air component so that the structure is self-supporting and the unwanted photoresist can be dissolved away.

The N coherent laser beams produce an intensity pattern with maximal $(N-1)$ dimensional periodicity if the difference between the wave vectors is non-coplanar. For example, two interfering beams form a 1D fringe pattern and three crossed beams form a 2D hexagonal

log-pile pattern. By using a 4-beam interference setup, a pattern with 3D symmetry can be designed. (Shoji et al., 2003; Lai et al., 2005) Hence, by selecting different beam combinations, and even performing some pattern translations, patterns with different lattice symmetries are possible to make.

To have successful interference lithography, coherence requirements must be met. It is preferred to use a monochromatic and coherent light source. This is readily achieved with a laser or filtered broadband sources. The monochromatic requirement can be reached if a diffraction element is used as a beam splitter, since different wavelengths would diffract into different angles but eventually recombine anyway. In this case, spatial coherence and normal incidence would still be necessary. The coherent length for our laser system requires that the path difference not exceed 10 cm.

3. Phase mask techniques

Fabrication strategies that rely on interference of multiple independent beams can introduce alignment complexity and inaccuracies due to differences in the optical path length and angles among the interfering beams as well as vibration instabilities in the optical setup. In order to improve the optical setup, diffractive optical elements or phase masks have been introduced to create the interference pattern for the holographic fabrication of photonic crystals. (Diviliansky et al., 2003; Lu et al., 2005; Lin et al., 2005) Other than the traditional bulk optical reflective/refractive elements such as mirrors, beam splitters and top-cut prisms (Campbell et al., 2000; Yang et al., 2002), a diffractive optical element is a promising alternative CMOS-compatible choice for 3D holographic lithography. It can be incorporated into phase/amplitude masks used in optoelectronic circuit fabrications to enable a full integration of 3D photonic structures on-chip. A phase mask, typically a phase grating with periodically index variation in height direction, can create multiple laser beams in various diffraction orders that are inherently phase-locked and stable for reproducible creation of 3D interference patterns from a single laser beam. Fig. 1 shows a schematic of the propagation of a laser beam through a 1D phase mask as a diffractive optical element. The phase mask will create three major stable co-plane output beams. These coherent beams then generate a pattern inside the overlap region below the phase mask, in the shape of 2D log-pile. The pattern is recorded in a photoresist to form a periodic template.

Fig. 1. (left) phase mask based interference. A phase mask can replace a complex optical setup for a generation of interference pattern; (middle) a simulated woodpile-type photonic structure formed in the doubly-exposed photoresist; (right) a schematic illustration of woodpile-type photonic structure with orthorhombic or tetragonal symmetry and its lattice constants.

Theoretically, when a single beam goes through a one-dimensional phase grating, the beam will be diffracted into three as shown in Fig. 1 (left). Beams 1 and 2 are from first order diffraction and beam 3 is from zero order diffraction. Beam 1 and 2 has a diffraction angle θ relative to beam 3. Mathematically these three beams are described by:

$$\vec{E}_1(\vec{r}, t) = E_1 \cos[(k \cos \theta)z - (k \sin \theta)x - \omega t + \delta_1] \quad (3)$$

$$\vec{E}_2(\vec{r}, t) = E_2 \cos[(k \cos \theta)z + (k \sin \theta)x - \omega t + \delta_2] \quad (4)$$

$$\vec{E}_3(\vec{r}, t) = E_3 \cos(kz - \omega t + \delta_3) \quad (5)$$

These three beams will generate a two-dimensional interference pattern. The interference pattern is determined by the laser intensity distribution I in 3D space:

$$\begin{aligned} I = & \frac{1}{2}E_1^2 + \frac{1}{2}E_2^2 + \frac{1}{2}E_3^2 + (E_1E_2)\cos[(2k \sin \theta)x + (\delta_2 - \delta_1)] \\ & + (E_1E_3)\cos[(2k \sin^2(\frac{\theta}{2}))z + (k \sin \theta)x + (\delta_3 - \delta_1)] \\ & + (E_2E_3)\cos[(2k \sin^2(\frac{\theta}{2}))z - (k \sin \theta)x + (\delta_3 - \delta_2)] \end{aligned} \quad (6)$$

Fig. 1 (left) shows the interference pattern generated behind the phase mask, assuming the incident laser beam has polarization in y direction. The interference pattern is periodic in the z-direction as well as in x-direction. The periodicity of the interference pattern along x direction is $\lambda/(\sin\theta)$ (where λ is the wavelength of laser beam generating the interference pattern). The periodicity c of the interference pattern along z direction is $\lambda/(2\sin^2(\theta/2))$. (Lin et al., 2006a) After the photoresist is exposed to such interference pattern, the sample is rotated by an angle of α along the propagation axis of the incident beam and its position is displaced along the laser propagation direction by $1/4$ times $\lambda/(2\sin^2(\theta/2))$. Then the photoresist receives second exposure. The doubly-exposed photoresist is then developed to form a 3D woodpile-type photonic crystal template. Fig. 1 (middle) shows a simulated photonic structure formed with the rotation angle $\alpha=90^\circ$ if a negative photoresist is used. After the photoresist development, the under-exposed area is dissolved away while the area exposed with above-threshold laser dosage is networked to form periodic structures. We illustrate in Fig. 1 (right) how we construct crystal lattices. We set a fundamental length scale $L=\lambda/(\sin\theta)$ for such structure because the three beam interference pattern is determined by the laser wavelength and the interference angle θ . L is actually equal to the grating period of the phase mask. The lattice constants in xy plane depend on the angle. They are related by $a=L/(\cos(\alpha/2))$ and $b=L/(\sin(\alpha/2))$, respectively. The photonic crystal template has a lattice constant $c=\lambda/(2\sin^2(\theta/2))=L(\cot(\theta/2))$ along the z direction. If the sample rotation angle is 90° , we have $a=b$. Thus the 3D structure has a face-centered-tetragonal or face-centered-cubic symmetry. (Lin, 2006a) If the angle α is less than 90° , a face-centered-orthorhombic ($a \neq b \neq c$) or face-centered-tetragonal ($a \neq b = c$) structure is formed in the photoresist.

Contrary to an intensity (amplitude) mask, the laser beam travels through a phase mask and accumulates an additional phase relative to light that travels through the air gap. However, a phase mask has much larger diffractive efficiency than an amplitude mask. This property enables those periodic structures have enough contrast ratio to the background in the photoresist polymerization.

The fabrication technique of 1D phase masks has been demonstrated by H. Jiang etc in 1999, (Jiang etc., 1999). E-beam lithography has been used to pattern fine gratings in Si substrate. Then an inversed elastomer mask is obtained by casting a layer of silicon-based organic Polydimethylsiloxane on the substrate. After curing and removal of the master mold, the elastomer mold is used as a mask again in the photolithography process to reproduce a photoresist phase grating on glass substrate. The phase grating fabricated has high quality surface and profile but the required processes are costly, laborious and time-consuming.

Here we demonstrate our holographic approach for phase mask fabrication. (Xu et al., 2008) The experimental setup is based on the principle of a Mach-Zehnder interferometer. As shown in Fig. 2, two coherent beams were cleaned, collimated, separated and focused back into the same photoresist region to produce interference patterns directly. The pattern recorded is a series of parallel fringes with sinusoidal profile. Thus we obtain the phase grating made of photoresist. This phase grating has refractive index difference between photoresist ($n=1.67$) and air gap, which can produce three coherent beams when it is used as a mask. This approach simplified the previous process and can be applied to more complicated fabrication. If we do multiple exposures and rotate the receiving photoresist between each exposure, we can get a phase mask with higher dimension. In the next section we will describe some concrete experimental steps to fabricate holographic phase masks and use them for the interference lithography fabrication of complex photonic crystal templates.

Fig. 2. Experimental setup for holographic fabrication of phase masks.

Overall, the optical diffractive elements are designed to avoid the alignment complexity and inaccuracies due to differences in the optical path length and angles among the interfering beams as well as vibration instabilities in the optical setup. They provide improved convenience in holographic lithography. It is useful to note that the current optical elements, such as beam splitter, mirrors, prisms and phase masks, can be used to generate pattern with all fourteen Bravais lattices in the space group. (Berger et al., 1997; Sharp et al., 2003) All that remains is a need to establish a better understanding of the relationship between the resulting symmetries and the beam parameters.

4. 3D woodpile photonic crystal fabrication by using 1D phase mask

It is well known that a 1D phase mask can generate three beam interference patterns, which has a 2D log-pile structure. The structure is polarization dependent of the incident EM wave thus lacks completeness of bandgap required for photonic communication. Previous researchers have proposed a method of building a 3D structure using two orthogonal 1D phase masks. (Chan, et al., 2006; Chanda et al., 2006) The beams that propagate through two phase masks will have two log-pile patterns recorded inside the photoresist. If well controlled, a 3D woodpile structure may be piled up by the log-pile structure. However, additional diffractions occur. The distance between two phase masks can also bring unwanted phase delay, which is difficult to adjust in practice. Our solution consists of multiple exposures through one 1D phase mask, which is spatially shifted between exposures, demonstrating an new approach for controllable 3D woodpile structure fabrication.

4.1 Pattern transformation

Here we demonstrate the fabrication process of 3D woodpile photonic crystals template, which can have orthorhombic or tetragonal structure depending on the rotational angle. (Lin et al., 2006a; Poole et al., 2007) Furthermore, the elongation in the z-direction can be compensated by rotating phase mask by an appropriate angle, which increases the lattice constant in the other direction. Theory predicts that the optimized rotation angle of a phase mask can achieve up to a 50% increase in photonic bandgap compared with those formed by two orthogonally oriented phase masks.

Fig. 3. Experimental setup for 3D photonic crystal template fabrication. Zoom in view is the schematic sketch of the double exposures procedure.

The interference pattern for a single exposure through a phase mask is in 2D log-pile structure, which is periodic in the z direction as well as in the x (or y) direction, as shown in Fig. 3. If we do a second exposure to record another log-pile structure on the same region, with appropriate relative rotation and shifting, we can have a 3D woodpile structure, which has periodic structure in all x , y and z directions, as shown in Fig. 4. It demonstrates a simulated structure from the dual-exposure procedure. Similar to how the photoresist reacts to illumination, the structure represents the receiving laser intensity distribution, i.e. the interference region, in the negative photoresist. The boundary of the 3D pattern is defined by setting a threshold value. The regions with intensity lower than the threshold value are removed and the regions with intensity equal and greater than the threshold value are sustained. Thus the photoresist records the interference pattern and can be visualized after development.

Fig. 4. Simulated 3D woodpile structure generated by double exposures. The rotational angle of phase mask is 60° . The scale bar shows the accumulated laser energy density upon two exposures.

Theoretically, the rotation of the interference pattern can be regarded as replacing the wave vector $\mathbf{k}$ of the diffractive beams, by a coordinate transform with rotation angle α ;

$$\bar{k}_1 = (k \cos \theta)z - [(k \sin \theta) \cos \alpha]x - [(k \sin \theta) \sin \alpha]y \quad (7)$$

$$\bar{k}_2 = (k \cos \theta)z - [(k \sin \theta) \cos \alpha]x + [(k \sin \theta) \sin \alpha]y \quad (8)$$

$$\bar{k}_3 = (k \cos \theta)z \quad (9)$$

while the spatial movement of the pattern can be induced through the phase shift of interfering beams. When a phase difference $(\rho_i - \rho_j)$ is introduced between interference beams, the interfering term I_{int} in Eq.(2) becomes

$$I_{\text{int}} = \sum_{i < j}^3 \vec{E}_i \cdot \vec{E}_j \cos[(\vec{k}_i - \vec{k}_j) \cdot \vec{r} + (\rho_i - \rho_j) + (\delta_i - \delta_j)] \quad (10)$$

Such a phase difference between laser beams will translate the interference pattern by r_s as described by (Lin et al., 2006b)

$$I_{\text{int}} = \sum_{i < j}^3 \vec{E}_i \cdot \vec{E}_j \cos[(\vec{k}_i - \vec{k}_j) \cdot (\vec{r} + \vec{r}_s) + (\delta_i - \delta_j)] \quad (11)$$

where the translation r_s is determined by $(k_i - k_j) \cdot r_s = (\rho_i - \rho_j)$. In general, the initial phase difference $\delta_i - \delta_j$ is a constant if the laser beams are mutually coherent. It will shift the interference pattern relative to the one generated with $(\delta_i - \delta_j) = 0$. But the initial phase difference will be the same for two exposures. The interference pattern generated by the second exposure needs to be shifted relative to the first one to fabricate the woodpile photonic crystal. The shifting is produced through the extra phase shift of $(\rho_i - \rho_j)$. Specifically, the initial phase difference is zero if all diffracted beams are generated through a single diffractive optical element. Then the final 3D structure can be expressed by adding up the interfering terms I_{int} for two exposures, normalizing and setting proper threshold isosurface values.

Experimentally, the basic approach utilized to fabricate an interconnected periodic polymeric structure is the double-exposure of photosensitive material to three interfering laser beams generated by a 1D phase mask as shown in Fig. 3. A linearly polarized beam from an argon ion laser at 514.5nm is expanded, collimated, and passed through a phase mask to produce two 1st order and one 0th order diffracted beams (intensity ratio 1:5). A layer of photoresist on a silicon wafer is first exposed to the interference of the three laser beams. Thus, a spatially modulated chemical change in the photoresist is produced. A second rotated and translated phase mask is then used to induce a second set of spatially modulated chemical changes in the photoresist. The orientation of the second interference pattern is controlled by the orientation angle α of the second phase mask with respect to the first one. To form an interconnected 3D woodpile structure, the phase mask was shifted along the z direction (c-axis) by a distance $r_s = (0, 0, \Delta z)$ for the second exposure. This shift has a significant impact on the size of overlap between the two interference patterns and consequently on the size of the bandgap formed in the final structure. A translation of $\Delta z = 0.25c$ of the second interference pattern along the c-axis yields an optimized fully-interconnected woodpile structure as shown in Fig. 4. High-precision motion stages were used to control the movements of the phase masks with $\pm 100\text{nm}$ accuracy. By controlling the rotational angle and the relative shift of the phase mask along the optic axis, both orthorhombic and tetragonal photonic crystal structures were formed. Fig. 4 shows a simulated face-centered orthorhombic photonic crystal structure formed by rotating the phase mask by $\alpha = 60^\circ$ between two exposures. The lattice constants (a, b, c) labelled in Fig. 4 are determined by the angle of diffraction θ of the 1st order beams in the photoresist and by

the angular rotation of the phase mask α as $(L/(\cos(\alpha/2)), L/(\sin(\alpha/2)), \text{ and } L(\cot(\theta/2))$, (Lin et al., 2006a) respectively. Where L is the grating period given by $L = \lambda/\sin\theta$, and λ is the laser wavelength in the photoresist material.

4.2 Band diagram of woodpile photonic crystal

The woodpile-type photonic crystal template will be converted into high refractive index materials using the approach of CVD infiltration (Miguez et al., 2002; Ttreault et al., 2005) in order to achieve a full bandgap photonic crystal. (Maldovan & Thomas, 2004) We calculated the photonic bandgap for converted silicon structures where ‘logs’ are in air while the background is in silicon. The calculation has been performed for photonic structures formed with various interference angles θ and rotation angles α . Fig. 5 (left) shows the first Brillouin surface of the face-centered-orthorhombic lattice. Coordinates of high symmetric points on the Brillouin surface varies with different structures. MIT Photonic-Bands Package (Johnson & Joannopoulos, 2005) was used to calculate the photonic bandgap of the converted silicon structure. Fig. 5 (right) shows the photonic band structure for the converted silicon woodpile-type structure with $c/L=2.4$ and $\alpha=51^\circ$ (the dielectric constant of 11.9 was used for silicon in the calculation). (Toader et al., 2004) We would like to clarify that the λ_{photon} in the y-axis label of the Fig. 5 (right) is the wavelength of photons in the photonic band, not the wavelength of the exposure laser. The band structure shows that a photonic full bandgap exists between the 2nd and 3rd bands with a bandgap size of 8.7 % of the gap central frequency.

Fig. 5. (left) First Brillouin surface of face-centered-orthorhombic lattice; (right) photonic band structure for an orthorhombic photonic crystal. λ_{photon} is the wavelength of photons in the photonic band.

4.3 Bandgap size vs shifting Δz and rotation α

The significance of the overlap between the two alternating high-intensity stacks controlled by the translation Δz of the second phase mask along the optical axis is depicted in Fig. 6. The relative bandgap size is measured from the bandgap diagram as shown in Fig. 5 (right) and defined by the ratio of central frequency and the frequency range of the bandgap. From

Fig. 6 we can see that a global bandgap of 4% exists in structures with $\alpha=60^\circ$ and $\Delta z=0.03c$. The maximum photonic bandgap appears at $\Delta z=0.25c$, where the 2nd log-pile pattern moves to a location closest to the 1st log-pile pattern, symmetrising the whole 3D woodpile structure. In structures where $\Delta z \leq 0.03c$, the width of the bandgap reduces rapidly and eventually vanishes. A maximum bandgap of 17% was achieved at a shift $\Delta z=0.25c$.

Fig. 6. Photonic bandgap as function of the phase mask displacement Δz between two exposures. The phase mask rotational angle α is 60° . Insets are the first Brillouin surface and photonic band diagram for the face-centered-orthorhombic structure.

To study the dependence of the size of the bandgap on α , photonic bandgap calculations were performed with various c/L ratios as shown in Fig. 7. Since all the laser beams come from the same half-space, the interference pattern generated will be elongated along the c -axis due to relatively small interference angles. This elongation, along with a rotational angle of 90° , causes the lattice constant c to be larger than a and b , yielding a face-centered tetragonal structure. When the rotation angle of phase mask decreases from 90° , the lattice constant b increases, while a decreases; in effect reducing the photonic crystal structure to a lattice with orthorhombic symmetry. A small phase mask rotational angle α can transfer the lattice back into tetragonal again when the lattice constant b is equal to c . When the value of b approaches that of c , the structure becomes more symmetric and the bandgap increases. From simulation, we found that the maximum bandgap occurs when the structure has the highest possible symmetry. For relatively small c/L ratios, where c approaches a and b , and

$\alpha=90^\circ$, the widest bandgap is produced. For larger c/L ratios, the maximum bandgap occurs at a rotational angle $\alpha \neq 90^\circ$. Fig. 7 also illustrates the rotation angles α that maximize the bandgap for structures with a large c/L values. When c is larger than $1.9L$, a small rotational angle of the phase mask is required to maximize the bandgap. For $c/L=2.0$, a 60° rotational angle maximizes the photonic bandgap. Maximizing the bandgap for structures with c/L ratios larger than 2 requires less than 60° angular displacements. For this c/L ratio, varying the rotation angle from 90° initially results in a drop in the width of the gap followed by an increase. This is consistent with the symmetry transformation of the photonic structure, changing from tetragonal symmetry to orthorhombic symmetry then back to tetragonal symmetry.

Fig. 7. Photonic bandgap as a function of the phase mask rotational angle α .

4.4 Bandgap size vs c/L ratio

Fig. 8 shows the optimum bandgap size in face-centered-tetragonal photonic structures which is formed with the rotation angle $\alpha=90^\circ$ and in face-centered-orthorhombic structure where $\alpha \neq 90^\circ$, under different beam interference geometries. When c/L is small (beams have a larger interference angle), a rotation angle of 90° is preferred in order to have a larger bandgap. However if c/L is larger than 2.0, then the face-centered-orthorhombic structure is preferred for a larger bandgap. At $c/L=2.3$, the optimum bandgap size is 11.7% of the gap central frequency for a face-centered-orthorhombic structure formed with a rotation angle near 55° . While the face-centered-tetragonal structure formed with $\alpha=90^\circ$ has a gap size of 6.7%.

To demonstrate the feasibility of the proposed fabrication technique, both orthorhombic and tetragonal structures were recorded into a modified SU-8 photoresist. Utilizing the phase mask method a number of photonic structures can be generated; however there are some practical issues in realizing a photonic structure with a full photonic bandgap. Fig. 8 shows that a photonic bandgap exists in structures with smaller c/L values. Because $c/L = \cot(\theta/2)$, a bigger interference angle is required in order to generate an interference pattern for a structure with a full bandgap. When the photoresist is exposed into an interference pattern, the interference pattern recorded inside the photoresist will be different from that in air. In the case of $c/L=2.5$, an interference angle $\theta=43.6^\circ$ is required, which is greater than the critical angle of most of photoresist.

Fig. 8. Photonic bandgap size in face-centered-tetragonal structures ($= 90^\circ$) and in face-centered-orthorhombic structures ($< 90^\circ$) for various structures with a different c/L value.

4.5 Experimental results

In order to expose the photoresist to an interference pattern formed under a bigger interference angle, a special setup is arranged for the phase mask and the photoresist as shown in Fig. 9 (left). The photoresist is placed on the backside of the phase mask with the contact surface wetted with an index-match mineral oil. The design of the phase mask is modified correspondently. As a proof-of-principle, we show in Fig. 9 (right) scanning electron microscopy (SEM) of woodpile-type structures in SU-8 photoresist formed through

the phase mask based holographic lithography. An Ar ion laser was used for the exposure of 10 μm thick SU-8 photoresist spin-coated on the glass slide substrate. The photoresist and phase mask were both mounted on high-precision Newport stages. Both the phase mask and photoresist were kept perpendicular to the propagation axis of the incident Ar laser beam.

Fig. 9. (left) an arrangement of the phase mask and the photoresist. The interface between the backside of the phase mask and the photoresist is wetted with an index-match fluid; (right) SEM top-view of an orthogonal woodpile-type structure in SU-8 photoresist formed through the phase mask based holographic lithography.

The photoresist solution was prepared by mixing 40 gram SU-8 with 0.5 wt % (relative to SU-8) of 5,7-diiodo-3-butoxy-6-fluorone (H-Nu470), 2.5 wt% of iodonium salt co-initiator (OPPI) and 10 ml Propylene Carbonate to assist the dissolution. Due to the large background energy presented in the generated interference pattern (53% of 0th order), the photoresist solution was further modified by the addition of 20 mol percent Triethylamine. Subsequent exposure to light generates Lewis acids that are vital in the crosslinking process during post exposure bake. The addition of Triethylamine, acting as an acid scavenger, allowed the formation of an energy gap which prevented the polymerization process in locations exposed below the energy threshold. The substrates utilized for crystal fabrication were polished glass slides cleaned with Piranha solution and dehumidified by baking on a hot plate at 200 °C for 20 min. Each substrate was pre-coated with 1 μm layer of Omnicoat to enhance adhesion. The SU-8 mixture was spin-coated onto the pre-treated substrate at speeds between 700 and 1500 rpm; resulting in a range of thicknesses from 25 to 5 μm . Pre-bake of SU-8 films was preformed at a temperature of 65 °C for about 30 min. The prepared samples were first exposed under 500mw illumination for 0.9 s using the first phase mask. A second phase mask, which was rotated by α about the optic axis and translated by Δz with respect to the first, was then used for an additional 0.9 s exposure. The samples were post-baked at 65 °C for 10 min and 95 °C for 5 min and immersed in SU-8-developer for 5 min.

Fig. 10(a) shows an SEM top view picture of a woodpile orthorhombic structure recorded in SU-8 with an α of 60°. The inset of the same figure details the predicted structure from simulation. The 3D span of the structure visible in Fig. 10(b) was also imaged by SEM. The layer-by-layer, woodpile nature of the structure is clearly demonstrated. The overlapping and cross-connection of neighbouring layers ensures a stable formation of 3D structures for

further processing. From figure 10 (a) and (b), we measured in the SEM the lattice constants to be $b=1.3\text{ }\mu\text{m}$ and $c=3.4\text{ }\mu\text{m}$. The elongation in the z-direction was thus compensated by the 60° rotation, compared with $b=1.06\text{ }\mu\text{m}$ and $c=6.13\text{ }\mu\text{m}$ in the structure generated by two orthogonally-oriented phase masks with similar period used in this work.

Fig. 10. (a) A SEM top view picture; and (b) a SEM side view picture of a woodpile orthorhombic structure recorded in SU-8 with $\alpha=60^\circ$. Simulated structures are inserted in Fig.s.

5. Conclusion

In summary, we demonstrate the fabrication of 3D photonic crystal templates in SU-8 using phase mask based holographic lithography technique. Both face-centered-orthorhombic and

face-centered-tetragonal woodpile-type photonic crystals have been fabricated. The usage of phase mask dramatically simplified the optical setup and improved the sample quality. The structure and symmetry of the photonic crystals have been demonstrated by controlling the rotational angle of a phase mask to compensate the structural elongation in z-direction in order to enlarge the photonic bandgap. Photonic bandgap computations have been performed optimally on those woodpile structures with α between 50° to 70° as well as traditional 90° rotation. Our simulation predicts that a full bandgap exists in both orthorhombic and tetragonal structures. The study not only leads to a possible fabrication of photonic crystals through holographic lithography for structures beyond intensively-studied cubic symmetry but also provides a blueprint defining the lattice parameter for an optimum bandgap in these orthorhombic or tetragonal structures.

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Recent Optical and Photonic Technologies

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Research and development in modern optical and photonic technologies have witnessed quite fast growing advancements in various fundamental and application areas due to availability of novel fabrication and measurement techniques, advanced numerical simulation tools and methods, as well as due to the increasing practical demands. The recent advancements have also been accompanied by the appearance of various interdisciplinary topics. The book attempts to put together state-of-the-art research and development in optical and photonic technologies. It consists of 21 chapters that focus on interesting four topics of photonic crystals (first 5 chapters), THz techniques and applications (next 7 chapters), nanoscale optical techniques and applications (next 5 chapters), and optical trapping and manipulation (last 4 chapters), in which a fundamental theory, numerical simulation techniques, measurement techniques and methods, and various application examples are considered. This book deals with recent and advanced research results and comprehensive reviews on optical and photonic technologies covering the aforementioned topics. I believe that the advanced techniques and research described here may also be applicable to other contemporary research areas in optical and photonic technologies. Thus, I hope the readers will be inspired to start or to improve further their own research and technologies and to expand potential applications. I would like to express my sincere gratitude to all the authors for their outstanding contributions to this book.

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University Campus STeP Ri
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51000 Rijeka, Croatia
Phone: +385 (51) 770 447

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Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
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