Band gap of hexagonal 2D photonic crystals with elliptical holes recorded by interference lithography

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Abstract – Two-dimensional hexagonal photonic crystals can be recorded using the simple superimposition of two interference patterns rotated by 60º. Such process generates high contrast masks, however, it generates elliptical cross section structures instead of cylinders. We study the PBG properties of the experimentally feasible geometries, using this technique and we demonstrate that the effect of this asymmetric shape is a reduction in the PBG map area, for TE polarization, in comparison with cylindrical structures. On the other hand, it appears a PBG for TM polarization.

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References and links

1. M. Notomi, A. Shinya, and E. Kuramochi, “Photonic crystals: Towards ultrasmall lightwave circuits,” NTT Tech. Rev. 2, 36-47 (2004).
2. E. Chow, S. Y. Lin, S. G. Jonhson, P. R. Villeneuve, J. D. Joannopoulos, J. R. Wendt, G. A. Vawter, W. Zubrzycki, H. Hou, and A. Alleman, “Three-dimensional control of light in a two-dimensional photonic crystal slab,” Nature 407, 983-986 (2000).
3. C. J. M. Smith, H. Benisty, D. Labilloy, U. Oesterle, R. Houdré, T. F. Krauss, R. M. De La Rue, and C. Weisbuch, “Near-infrared microcavities confined by two-dimensional photonic bandgap crystals,” Electron. Lett. 35, 228-230 (1999).
4. S. Olivier, H. Benisty, C. J. M. Smith, M. Rattier, C. Weisbuch, and T. F. Krauss, “Transmission properties of two-dimensional photonic crystal channel waveguides,” Opt. Quantum Electron. 34, 171-181 (2002).
5. D. N. sharp, M. Campbell, E. R. Dedman, M. T. Harrison, R. G. Denning, and A. J. Turberfield, “Photonic crystals for the visible spectrum by holographic lithography,” Opt. Quantum Electron. 34, 3-12 (2002).
6. N. Carlsson, N. Ikeda, Y. Sugimoto, K. Asakawa, T. Takemori, Y. Katayama, N. Kawai, and K. Inoue, “Design, nano-fabrication and analysis of near-infrared 2D photonic crystal air-bridge structures,” Opt. Quantum Electron. 34, 123-131 (2002).
7. J. D. Joannopoulos, R. D. Meade and J. N. Winn, Photonic Crystals (Princeton University Press, 1995).
1. Introduction

Two-dimensional photonic crystal slabs are promising candidates for the basic platform of optical integrated circuits. It is possible to design two-dimensional photonic crystals (2D-PC) to implement elements such as ultrasmall photonic-band-gap waveguides, resonators and other functional components [1,2]. The use of semiconductors, such as GaAs, InP, AlGaAs and InGaAsP, in the fabrication of 2D-PC slabs allows the development of processes to produce active components operating in the infrared and near infrared regions [3,4]. The use of optical materials instead of semiconductors allows the production of passive waveguides and PC’s for the visible part of the spectrum [5].

In order to exhibit a photonic band gap for a desired region of the electromagnetic spectrum, the geometry of the two-dimensional structures must be appropriately defined. Dielectric slabs with air holes are more convenient for fabrication of waveguides than dielectric columns because they present higher effective refractive index and they can be self sustained [6]. Besides this fact, structures formed by a hexagonal array of air holes engraved in a dielectric film are more convenient for fabrication of photonic crystal slabs because they exhibit PBG for a large range of geometries [7] and smaller dielectric refractive index [8].

Two-dimensional PC slabs can be fabricated by electron beam lithography [9,10] or holographic lithography [11-13]. The first technique is largely employed because it allows high resolution and flexibility in the fabrication of the structures since arbitrary patterns can be recorded. However, the electron beam lithography requires expensive equipments and the writing time is very slow. In this way, the holographic lithography is an interesting alternative for the generation of high-resolution periodic structures in large areas with low costs.
There are two different ways for generation of 2D or 3D light patterns by holography: using multiple exposures of interference patterns produced by two beams [11] or using a single exposure of an interference pattern generated by multiple beams [5][13].

The superimposition of interference patterns generated by two-beams presents several advantages in relation to a single multiple beams exposures: a) The setup is easier because it employs two co-planar beams instead of aerial multiple beams [11]; b) The interfering beams can be taken with the same polarization (increasing the contrast of the interference pattern) [11]; c) It is possible to lock the interference pattern during the exposure by controlling the phase difference between the two beams [14]. Such advantages result in higher contrast of the intensity light pattern allowing the recording of high aspect ration structures.

The simplest way to obtain two-dimensional structures using holographic lithography is a double-exposure of two-beam interference pattern, with an appropriate rotation of the sample between the exposures. Figure 1 shows the simulated light intensity resulting from the superimposition of two sinusoidal fringe patterns rotated by 90º between them (Fig. 1(a)) and rotated by 60º (Fig. 1(b)).

![Fig. 1. Simulated light intensity patterns resulting from the superimposition of two equal fringe patterns with a rotation of 90º (a) and 60º (b) between them. The lines represent the isointensity of the light pattern.](image)

The shape and size of the recorded structures are determined by the iso-intensity surfaces of the interference field, as well as by experimental parameters such as photoresist type, initial photoresist thickness, developer concentration, contrast of the interference pattern, etc [15]. As it can be seen from Fig. 1(a), the rotation of 90º generates a cubic lattice, while the rotation of 60º (Fig. 1(b)) generates a hexagonal lattice. Note that the elements of the lattice are symmetrical (circles or squares) in Fig. 1(a) and present an asymmetric distortion in Fig. 1(b).

Recently it was demonstrated that this asymmetry, in the unit cell structure, might be used to control the polarization mode of the emitted light [16] and that elliptical rods in a hexagonal lattice present negative refraction and superlensing [17].

In this work we study the effect of the asymmetry in the unit cell on the PBG of experimentally feasible hexagonal structures, recorded by double-exposure of two-beam interference patterns.

2. The fabrication process

Figure 2 shows the whole scheme of the fabrication process. We start with the deposition of an a-C:H layer on a glass substrate. The a-C:H was chosen as the dielectric layer to record the photonic crystal because this material present high refractive index, good optical quality of the films and transparency in the near IR [18], and because we have facilities for both deposition and anisotropic etching of such films, using common gases as CH₄ and O₂. The deposition was performed by sputtering, using a pressure of 5mTorr, a power of 150 W, and a mass flow
of CH₄ of 40 sccm and 10 % of Ar. Using these conditions we obtain a-C:H films with refractive index of about 2 and a deposition rate of 1 µm per hour. Thus, by varying the deposition time, a-C:H films with thickness up to 5 µm can be deposited without stress.

The positive photoresist films of AZ 1518 (Hochst) or SC 1827 (Rohm and Haas) are spin coated on the glass substrates, previously coated with a a-C:H, forming a thickness of about 0.6 µm. The photoresist is then exposed twice to an interference pattern, generated by a holographic setup using the line λ = 458 nm of an Ar laser. This setup allows the recording any fringe period from 0.45 µm to 1.8 µm and it is provided with a fringe locker system [14] which warrants the repeatability and the high contrast of the fringes.

By rotating the sample 90° between the two exposures (of 350 mJ/cm² each) and developing the photoresist (AZ 1518) in AZ 351 developer diluted 1:4 in deionized water, for 40 seconds, the resulting structures are isolated photoresist columns forming a cubic lattice as shown in Fig. 3(a). The cross-section of the interference pattern changes from a squared shape to a circle (Fig. 1(a)), resulting in photoresist columns, with a squared base with round corners, a circular top and a height of about 0.6 µm, as shown in Fig. 3(a). Note that as more vertical are the walls of the photoresist structures, less sensitive to the process errors are the geometries. Thus the samples are homogeneous in an area of 2X2 cm and present good repeatability.

For generating a hexagonal lattice the sample is rotated of 60° between the exposures. After the exposures the photoresist (SC 1827) is developed (AZ 351 developer – 1:4). Figure
3(b) shows the resulting hexagonal structures with period of 0.54 µm, recorded in the photoresist, using the fringe period of 0.46µm. The energy of each exposure was 355mJ and the development time was 1 min.

Note the high aspect ratio (~ 3) of the photoresist columns in both lattices (Fig. 3(a), 3(b)), due to the high contrast of the interference pattern [15]. Note also that, as expected by the simulations, for the hexagonal lattice, the cross section of the photoresist columns is elliptical. The maximal ellipticity (E) defined as the ratio between the major axis and the minor axis of the ellipses obtained in our photoresist structures is about 2. If the semi-major axis of the ellipses is called “r”, the ratio between it and the period “a” achieved with better repeatability is about 0.37 (as shown in Fig. 3(b)). Although the interference lithography may generate a large variety of “r/a” ratios, there are preferential geometries that are less sensitive to the process errors [20].

The photoresist columns are then used as a mask in a lift-off process (Fig. 2), using a thermal deposition of an Al film (with 80nm of thickness) as an intermediate mask. Figure 4 shows the resulting elliptical holes recorded after the reactive-ion etching (RIE) of the a-C:H. The RIE conditions were: 100W power, 50 sccm of O₂, and pressure of 100mTorr that results an etching rate of 0.125μm/min. Using these conditions and the etching time until 12 minutes, structures with 1.5µm of depth are obtained, with small variation of the cross section of the holes along the depth, as shown in Fig. 4. Note that the holes recorded in the a-C:H film (Fig. 4) present just the inverse geometry of the photoresist columns (r/a = 0.37 and the ratio between the major axis and the minor axis of the ellipses of 2). For etching times longer than 12 minutes, there is a strong variation of the geometries along the film depth as well as a reduction in the ellipticity E (ratio between the major axis and the minor axis of the ellipses).

![Fig. 4. Two-dimensional structures with hexagonal lattice recorded in a-C:H film. The size of the scale bar is 1μm.](image)

3. The PBG Map

To calculate the band diagrams of two-dimensional photonic crystals we developed a software based on 2D Finite Element Method [21]. In the calculus we considered an infinite array of air columns engraved in a dielectric material with refractive index n = 2. The air columns form a lattice with hexagonal symmetry. Figures 5 and 6 shown, respectively, the hexagonal unitary cells and their corresponding Brillouin zones for the two cases of air columns: circular and ellipses. The asymmetric structures were considered as ellipses with length of semimajor axis equal to twice the semiminor axis because it is the preferential ratio obtained in our fabrication process.

Due to the breakdown of symmetry, the 3 k-lines Γ-M-K of 1/12 of the irreducible Brillouin zone, correspondent to the circular case, are not enough to calculate the photonic band diagrams for the elliptical holes. Thus, it is necessary to add new directions to represent now ¼ of the Brillouin zone [12].
The band diagrams, for the directions of light propagation (shown in Fig. 5(b) and in Fig. 6(b), were calculated for the two orthogonal directions of light polarization, TE and TM. TE being the direction in which the electrical light field is parallel to the x-y plane (Fig. 5(a) and 6(a)) while for the TM polarization the direction of electric field is in the z axis (parallel to the column axis). Figure 7 shows an example of the band diagram, for the TE polarization, for the directions \( \Gamma, K, M, K', M' \) corresponding to the elliptical unitary cell shown in Figure 6, for the \( \frac{r}{a} \) parameter = 0.37. In the case elliptical structures \( \frac{r}{a} \) is defined as the ratio between the major semi-axis \( r \) and the period \( a \) of the structure.

From the calculated band diagrams for different \( r/a \) parameters we obtain the gap maps for the hexagonal lattices of circular (E=1) and elliptical air holes (E=2) in a dielectric material with refractive index \( n = 2 \). These maps are shown in Fig. 8. Note that, \( r/a = 0.5 \) is the limit for the circular air holes when the circles start touching each other. For the case of the ellipses this limit is equal to \( r/a = 0.65 \) (because of the inclination of the ellipses). Values above those ones represent the inverse structures: columns of dielectric material instead of holes.

By comparing both diagrams we can observe that, for TE polarization, there is a strong reduction in the PBG area for the elliptical holes (E=2). On the other hand, it appears a PBG for TM polarization, which does not occur for the circular holes. Diagrams corresponding to intermediate ellipticities (1<E<2) present a PBG area in-between those shown in Fig. 8(a) and (b), as expected. By varying the refractive index of the dielectric material from 1.6 to 3, keeping the same ellipticity E=2, the calculated map diagrams present the same behavior: a reduction in the PBG area for TE polarization and existence of gap for TM polarization for smaller values of the refractive index. In spite of this reduction of the PBG gap area, for TE polarization, the PBG area is large enough to allow the design of photonic crystals feasible using this simple technique of superimposition of two interference patterns. In particular the
experimental geometries obtained preferentially in our samples (r/a = 0.37) are inside the PBG area (dotted line in Fig. 8(b)).

![Fig. 7. Band Diagram for the elliptical holes with r/a = 0.37 in a dielectric material with n = 2.](image)

**Fig. 7.** Band Diagram for the elliptical holes with r/a = 0.37 in a dielectric material with n = 2.

![Fig. 8. Gap map for a hexagonal lattices of: (a) circular holes and (b) elliptical holes (E=2), in a dielectric material with refractive index n = 2.](image)

**Fig. 8.** Gap map for a hexagonal lattices of: (a) circular holes and (b) elliptical holes (E=2), in a dielectric material with refractive index n = 2.

### 4. Conclusion

The superimposition of interference fringe patterns, generated by two beams, allows the recording of high contrast masks for fabrication of 2D photonic crystals. The superimposition of two fringe patterns, rotated by 60º, allows the recording of hexagonal lattices of photoresist structures with high aspect ratio structures (~ 3), but with elliptical cross section.

The calculated band diagrams for the inverse elliptical structures, for TE polarization, exhibits smaller PBG areas in comparison with those for circular holes and it appears a PBG for TM polarization, for smaller refractive indexes. In despite of the reduction, the PBG area is large enough to allow the design and fabrication of hexagonal photonic crystals using the simple double-exposure of two-beam interference technique. Besides this fact, another interesting point is that the process errors tend to reduce the ellipticity of the structures, thus they increase the PBG area.

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