Diseño de láminas de cristales fotónicos bidimensionales basadas en agujeros triangulares: estudio paramétrico

Triangular air-hole based two-dimensional photonic crystal slabs design: a parametrical study

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REFERENCES AND LINKS

RESUMEN:
En este trabajo se investiga la formación de bandas prohibidas para fotones (PBG) en varios diseños de láminas de cristales fotónicos bidimensionales. Los cristales están diseñados desde el enfoque de la reducción de simetría de la red y están basados en la red triangular de agujeros triangulares. El análisis se ha realizado computando los autoestados de las ecuaciones de Maxwell para estructuras dielectricas periódicas con algoritmos de iteración por bloques con condiciones previas y una base de ondas planas. Encontramos un ensanchamiento de las bandas prohibidas para fotones en comparación con la red de agujeros triangulares simples al tiempo que aumenta la separación entre motivos lo que facilita la fabricación con las posibilidades experimentales actuales.

Palabras clave: Nanofotónica, Cristales Fotónicos, Diseño de Nanoestructuras.

ABSTRACT:
We investigate the complete photonic band gap (PBG) formation in several designs of two-dimensional photonic crystal (2D-PC) slabs using the symmetry reduction approach. We have based our designs in the triangular lattice of triangular holes. The analysis has been performed by computing eigenstates of Maxwell’s equations for periodic dielectric structures with preconditioned block-iterative algorithms and a plane-wave basis. We have found an enlargement of the complete PBG with respect to that for plain triangles at the same time that the dielectric walls are enlarged what makes easier the fabrication with the present experimental capabilities.

Keywords: Nanophotonics, Phtonic crystals, Nanostructures design.
1. Introduction

Photonic crystals (PCs) are periodic dielectric structures in one or more spatial directions [1]. Many unusual optical properties of these PC, such as the suppression of spontaneous emission [2] and the possibility of creating localized defect modes [3] lie in the existence of a photonic band gap (PBG), i.e., a frequency range for which light propagation is forbidden inside the structure. For their possibilities in practical applications, three-dimensional PCs exhibiting at least a complete band gap within the range of telecommunications frequencies have been intensely looked for but the fabrication of useful range of telecommunications frequencies have been intensely looked for but the fabrication of useful three-dimensional PCs in the near IR spectra is a difficult task because of technological limitations at the submicronic length scales. An alternative system to achieve a band gap in the photonic spectrum is a two-dimensional photonic crystal (2D-PC) slab, a thin dielectric structure with a 2D-PC pattern that uses index guiding to confine light in the third dimension. In this structure, as in two dimensions, one is able to decompose the guided modes into two non-interacting classes. However, the lack of translational symmetry in the vertical direction means that the states are not purely TM or TE polarized (electric and magnetic fields are normal to the plane of periodicity respectively). Instead, the guided bands can be classified as even (TE-like) or odd (TM-like) with respect to reflections through the plane bisecting the slab. The physical properties of PCs slabs can be significantly different from those of the corresponding 2D systems. For instance, it is well known that the triangular lattice of circular air holes in a purely 2D photonic crystal exhibit a complete band gap at sufficiently large air fractions, nevertheless, the same pattern in a 2D-PC slab does not longer show a complete PBG due to the appearance of degeneracy between the first and second band at highly symmetric J point of the Brillouin zone [5].

Recently it was suggested and experimentally demonstrated by Takayama et al [5] that a 2D-PC slab consisting of a triangular lattice of triangular air holes (TLTH) gives rise to a complete PBG because the reduction of the symmetry of the unit-cell structure solves the degeneracy at the J point. The optimization and improvement of the experimental viability of this structure as well as the design of similar structures is of great technological interest.

Using the symmetry reduction approach [6,7] and basing our designs on the TLTH we have investigated the existence of a complete PBG in 2D-PC slabs with several patterns as well as their experimental feasibility as a function of the pattern parameters from numerical simulations of the photonic bands.

2. Structures description and simulations

The patterns of 2D lattices under consideration are depicted in Fig. 1. The basic structure from which we have designed the rest of the patterns of the 2D-PC slabs is the TLTH (Fig.1a). The modified structures are the triangular lattice of triangular air holes with interstitial circular holes (TLTH-CH), the triangular lattice of triangular air holes with interstitial triangular holes (TLTH-TH) and the triangular lattice of rounded triangular holes (TLRTH) (Fig. 1b, 1c and 1d respectively). In Fig. 1a, 1b and 1c the parameter L denotes the length of the side of the triangular holes. The parameters r and l denote the radius of the included circular holes and the length of the side of the included triangular holes in Fig. 1b and 1c respectively. In the case of Fig. 1d the parameter r denotes the radius of the circles that conform the rounded triangles while l denotes the distance between the centres of such circles. The angle of rotation θ of the motifs is defined as the angle between the bottom side of the triangle and the lattice vector a. Fig.1e represents the first Brillouin zone and the path Γ-X-J-Γ along the calculations were performed.
In order to obtain the dispersion relations we have used a plane-wave expansion method consisting of the fully vectorial solution of Maxwell’s equations with preconditioned conjugate-gradient minimization of the Rayleigh quotient [8,9]. Moreover, to take into account the finite thickness of the slab we have used the effective refractive index [10], i.e., the mode refractive index of the guided waves without PC in the slab. To compare our results with that on Ref. [5] we have calculated the effective index assuming a slab of Si of 320 nm thick suspended in air obtaining a values neven=2.92 for the TE-like mode and nodd=2.51 for the TM-like mode.

3. Photonic band gaps

In this section we will present the results of the simulations we have performed on the structures described above. We have limited our study to the first and second band for the even and odd modes in order to ensure that the PBG frequency lies well below the light cone so the PBG occurs between guided modes in the slab. To analyze the formation of the PBG we have calculated the gap-maps of the 2D-PC slabs as a function of the size of the motifs and in some cases as a function of the angle of rotation of them.

3.a. Triangular lattice of triangular air holes (TLTH)

We begin our discussion with the basic TLTH (Fig. 1a). Contrary to the triangular lattice of circular holes, that have a C₃ᵥ symmetry, the utilization of triangular-shaped holes (C₃ᵥ symmetry) solves the degeneracy at the J point of the Brillouin zone for the odd modes. This leads to a maximum normalized width of the complete PGB of about Δω/ωg=6.56% centred at ωg=0.294a/λ for L=0.92a and θ=0º. Here, the parameters Δω and ωg denote the frequency width of the gap and the frequency at the middle of the gap respectively. This values, for a gap centred at wavelength of 1550 nm, correspond to an experimental lattice parameter of a=456 nm and a critical distance, i.e., the minimum distance between adjacent holes, of Δ=36 nm.

In Fig. 2a are drawn the frequencies of gap boundaries between first and second bands as a function of the size of the triangles for an angle of rotation θ=0º until adjacent triangles begin to overlap (L/a=1). The gap map shows that the maximum complete PBG appears at L/a=0.92 that corresponds to the size of the triangle when the even mode PBG and the odd mode PBG begin to non completely overlap.
The study of the evolution of the PBG with the angle of rotation indicates that the maximum absolute gap occurs for $\theta=0^\circ$, or the analogous situation $\theta=60^\circ$, and disappears completely for $\theta=30^\circ$, as shown in Fig. 2b for triangular holes of side $L/a=0.92$. This behaviour reveals the fact that to solve the degeneracy at the J point of the Brillouin zone for the odd modes the vertices of the triangular-shaped holes must point in the real space at the J points of the Wiegner-Seitz cell while pointing at the X points ($\theta=30^\circ$) the degeneracy is recovered. Moreover the band gaps exhibit a symmetry with respect to a rotation angle $\theta=30^\circ$ due to the inverse symmetry of the structure. We would also like to remark the opposite behaviour of the even mode PBG and the odd mode PBG, that is, when the even mode gap increases the odd mode gap decreases and vice versa, but since the even mode PBG is considerably greater than that for the odd mode is the latter who limits the complete PBG.

3.b. Triangular lattices of triangular air holes with interstitial figures (TLTH-CH and TLTH-TH)

The next structures we have investigated are the basic TLTH with the inclusion of holes with different shapes in the interstitial positions in order to increase the air filling fraction (FF) as a way to increase the gap size. The first structure that we consider is the TLTH-CH (Fig. 1b). For this structure, instead of the expected behaviour, the gap for the even mode decreases as the radius of the interstitial circle is increased while the gap for the odd mode decreases for small radii, closes completely (the degeneracy is recovered) and reopens for large radii (the degeneracy is again solved) reaching a width three times larger than that for plain triangles but now both gaps don’t overlap (Fig. 3). Although for the odd modes the gap is considerably increased for large radii, the even mode PBG rapidly decreases and the first and interstitial circle is increased, as is shown in Fig. 4. For this reasons this structure doesn’t improve the results obtained with plain triangles only.

\[ \text{Fig. 2. Photonic gap-maps between first and second bands of the triangular lattice of triangular air holes as a function of a) the side of the triangle for a fixed angle of 0º and as b) the angle of rotation for a fixed side of the triangle of } L/a=0.92. \]

\[ \text{Fig. 3. Photonic gap-map between first and second band for the triangular lattice of triangular air holes with interstitial a) circles as a function of the circle radius and b) triangles as a function of the size of the included triangles for a fixed size of the main triangles of } L/a=0.92. \text{ Both gap-maps are calculated until adjacent figures begin to overlap.} \]
Another way to increase the air FF trying to avoid the tendency of the even modes to appear degenerate at the J point is to introduce triangles as interstitial figures (Fig. 1c). Even though it is true that the tendency of the even modes to degenerate is reduced with respect to the previous situation this design doesn’t lead to an enlargement of the complete PBG. Contrary to that, the behaviour of the gaps for both modes is the same as in the case of interstitial circles, the PBG for the odd modes decreases as the included triangle increases for small sizes closing completely to reopens at larger lengths of the side of the interstitial triangle without overlapping the gap for the even modes (Fig. 3b). It is also remarkable that the included triangles don’t lead to an enlargement of the odd mode PBG as strong as the included circles. This is probably due to the fact that the air-FF is considerably greater when the circle is about to overlap the adjacent triangles than when the included triangle is near the close-packed condition.

So, even though the utilization of large air-FF is in general an effective method to increase the gap size, in this case the inclusion of interstitial figures doesn’t improve the results obtained with plain triangles. This is mainly because of the tendency of the even mode to degenerate at the J point as the size of the included figure increases and because of the lack of overlap between the gaps for both modes at large air-FF.

Fig. 4 Dispersion relations of the triangular lattice of triangles with interstitial circular holes for a fixed side of the triangle L/a=0.92 and a radius a) r/a=0.10, b) r/a=0.15, c) r/a=0.20 and d) with r/a=0.25. The black line is the light cone.

3.c. Triangular lattice of rounded triangular air holes (TLRTR)

For the TLRTH we define a parameter $\beta=l/r$ with the intention to investigate if there’s an optimal relation between the radii of the circles that conform the rounded triangles and the distance between its centres finding that this relation is not general (Fig. 5a). For a particular radius there’s an optimal distance $l$ leading to an optimal $\beta$ value different than that for other radii, but at the optimal $\beta$ value for each radius the width of the complete PBG doesn’t differ a lot. It varies from a minimum value $\Delta\omega/\omega_g=9.17\%$ for $r=0.350a$ and $l=0.225a$ ($\beta=0.643$) centred at $\omega_g=0.377a/\lambda$ and a maximum value $\Delta\omega/\omega_g=11.47\%$ for $r=0.250a$ and $l=0.400a$ ($\beta=1.600$) centred at $\omega_g=0.347a/\lambda$. The best result enlarges the complete PBG for plain triangles by a factor 1.75. The values of the parameters that lead to the maximum PBG correspond, for a gap centred at wavelength of 1550 nm, to an experimental lattice parameter $a=537$ nm and a critical distance $\Delta=54\text{nm}$.
so not only the width of the PBG is improved but also the dielectric walls are increased by a factor 1.5. The fact that with rounded vertices we’re able to increase the air FF, increasing the critical distance at the same time, gives a clue of the improvement of the width of the gap. The inspection of the air FF at the optimous parameteres for plain triangles (FF=42.3%) and for rounded triangles (FF=65.3%) highlights this fact.

To study the experimental feasibility of this structure we represent the normalized width of the complete gap as a function of the critical distance for a wavelength of 1550 nm for different radii (Fig. 5b). It seems that, albeit there’s not a general relation between the radii of the circles and the distance between its centres, there’s an optimal value of the critical distance at about 60 nm and there’s also gaps with similar widths as in the case of the plain triangles with a critical distance at about 100 nm. This means that this structure is easier to fabricate not only because its rounded vertices but also because the dielectric walls are bigger for the same width of the gap.

Finally, in Fig. 6 we have represented the gap-map of this structure for \( \beta=1 \) as a function of the radii of the circles (and as a function of 1 since for the case \( \beta=1 \) the distance between the centres of the circles is equal to the radius) and as a function of the angle of rotation for a rounded triangle with \( l=r=0.300a \) in order to compare this structure with the TLTH. The main difference between the two structures is that making round the vertices of the triangles rises slightly the photonic bands and enlarge both the even mode and the odd mode gaps. The behaviour of the gaps with respect to the angle of rotation of the rounded triangles is, as expected, the same as for plain triangles, i.e., the gap is maximum for \( \theta=0^\circ \) and closes at \( \theta=30^\circ \).

4. Summary
We have investigated the photonic band gaps of 2D-PC slabs with several patterns basing our designs on the basic triangular lattice of triangular air holes finding that making round the vertices of the triangles produces an enlargement of the complete PBG by a factor 1.75 and increases the dielectric walls by a factor 1.5 what makes this structure easier to fabricate. The fact that with rounded vertices we’re able to increase the air FF, increasing the critical distance at the same time, gives a clue of the improvement of the width of the gap.

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