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Analysis of photonic band gap structure for the design of photonic devices

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Abstract

A detailed analysis, based on Kronig–Penney model and finite-difference time-domain (FDTD) method, is used to explain the air-filling factor effect on the optical properties of defect-free photonic crystals. By the use of the Kronig–Penney model, we calculated the photonic band structure for electromagnetic waves in a structure consisting of a periodic square array of dielectric rods of lattice constant a separated by air holes. Gaps in the resulting band structures are found for waves of both polarisations. We analysed the air-filling factor effect on both polarisations in low and high frequency regions. It is shown that the frequency of the lower TE (transverse-electric) band edge is independent of the air-filling factor in the low frequency region. The opposite behaviour holds for the upper band edge, growing rapidly with the air-filling factor. Using the FDTD we simulated the electric field as the pulse propagates through the structure. The results of both approaches are compared, and the operation characteristics of the measuring air-filling factor device are described. We investigate the optical properties of a single and two defects incorporated in the PC, which can be potentially applied to ultra small surface-emitting-type channel drop filter. It is shown that the frequency and polarisation of the dropped light can be controlled by changing the size and/or shape of the defect. The electric field distribution calculations show that the electric field for a given frequency is located only at the defect, which means that each defect can detect only its corresponding wavelength. ***To cite this article: F. Ouerghi et al., C. R. Physique 5 (2004).***

Résumé

Analyse du gap de photons dans des dispositifs photoniques. En utilisant le modèle de Kronig–Penney et la méthode des différences finies dans le domaine temporel (DFDT), on analyse les propriétés optiques de cristaux photoniques parfaits. Au moyen du modèle de Kronig–Penney, nous calculons la structure de bande photonique dans un réseau carré de tiges diélectriques à distance a séparées par de l'air. Les structures de bande présentent un gap pour les deux polarisations. Nous analysons l'effet du remplissage pour les basses et les hautes fréquences. On montre que dans les basses fréquences, le bas de bande transverse électrique (TE) est indépendant du facteur de remplissage. Par contre, la fréquence du haut de bande augmente rapidement avec le remplissage en air. Par la méthode DFDT, nous simulons le champ électrique lors de la propagation d'une impulsion à travers la structure. Nous calculons les propriétés optiques d'un défaut unique et d'une paire de défauts incorporés dans le cristal photonique. ***Pour citer cet article : F. Ouerghi et al., C. R. Physique 5 (2004).***

Keywords: Photonic band structure; Kronig–Penney model

Mots-clés : Structure de bande photonique ; Modèle de Kronig–Penney

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1. Introduction

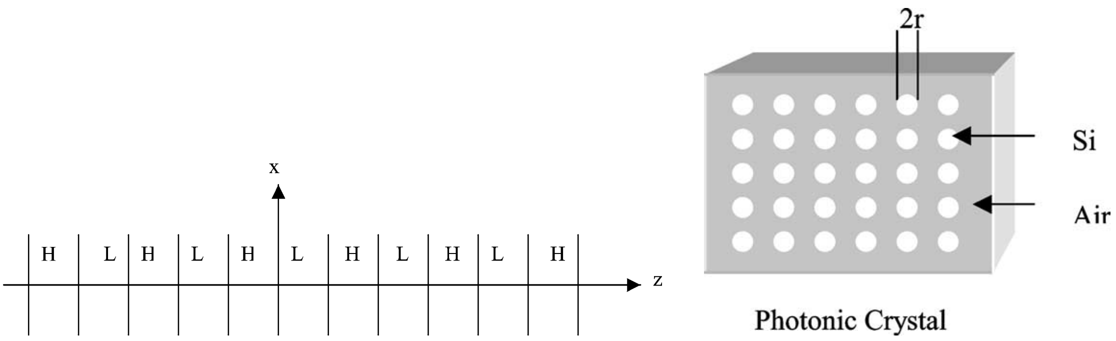
The strong light confinement in high index-contrast structures allows the design of waveguide components that can perform complex waveguide interconnections within a small area. In the photonic crystals, the existence of photonic transmission bands and forbidden bands [1] has opened new avenues to tailor the light-matter interaction, and in particular spontaneous emission, but also to design new photonic systems with superior properties for photon confinement. The case of a periodic waveguide consisting of a similar high index layer supported on a periodic substrate of low index material has also been studied [1], and found to support guided Bloch modes in the high index layer. Photonic states inside a photonic crystal are classified into bands and gaps, frequency ranges over which optical waves are allowed or forbidden to propagate, respectively. The bands and gaps provide a fundamentally new mechanism for steering and localisation light within a semiconductor chip that is different from that based on conventional optics [2,3]. One may think of cavity modes as filters that drop a selected frequency. The gap size is determined by the dielectric contrast of the two materials that constitute the whole structure and by filling fraction of the higher dielectric materials [4]. In this Note, we study the effect of the air filling factor on the dispersion relation. By using two approaches, namely Kronig–Penney model and finite-difference time-domain method, the understanding of the air filling factor effect on the optical properties of the structure is best done. Moreover, the measurement of the air-filling factor is possible by using the TE and TM (transverse-magnetic) polarisations. We report on more detail the optical properties of the dropped light from a single and two defects in the PC. In this approach the structure to be analysed consisting of alternating high- and low-index regions as shown in Fig. 1(a).

2. Results and discussion

An optical guided wave traveling in a planar dielectric waveguide is our basic problem, as shown in Fig. 1(b). The photonic crystals (PCs) that act on such a beam are arrays of dielectric rods normal to the guide plane separated by an air gap. The structure has the following parameters: radius of the rod, $r = 0.5$ μm, and the refractive indices $n = 3.4$ (Si) and $n = 1$ (air), the air gap width, W, is varied in order to understand its effect on the optical properties of the proposed structure and to control the air filling factor. The TE modes have the electric field polarised in the plane of the waveguide, and TM modes have the magnetic field polarised in the plane of the wave guide. One initial reason to study such crystal was that they may display a photonic band gap in both polarizations TE and TM for a triangular lattice and a sufficiently large air-filling factor. However, it became obvious a few years ago that large air holes could be very detrimental to wave guiding and lead to losses out of the guide [5,6].

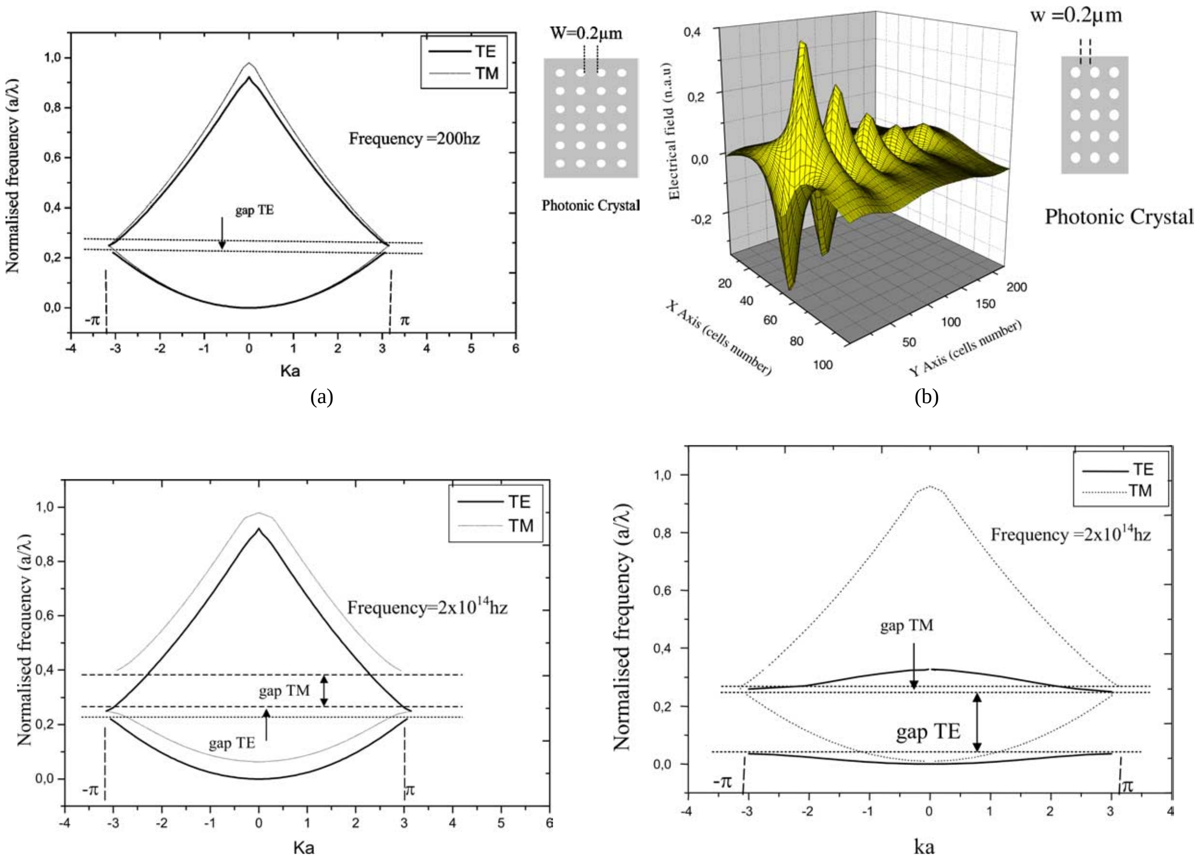
Since the air filling factor may vary owing to the fabrication process, the air gap width is a good piece of information. The resonant modes of a patterned dielectric slab surrounded by air, however, are not purely TE or TM but rather what we designate TE-like and TM-like.

In Fig. 2(a), we plot the band structure of a 2D photonic crystal made of dielectric rods when the air gap width is $W = 0.2$ μm at low frequency $f = 200$ Hz. It shows that the TE polarisation presents a photonic band gap of width 0.04 normalised arbitrary unit (n.a.u.). This can be explained by the fact that the guide mode bands are folded back into the first Brillouin zone, and Bragg reflections can open up band gaps at the zone edges. However, the TM polarisation allows the wave propagation in the structure. An initial TE-polarised electric field is used to excite the TE-like modes of the structure, then the initial field is evolved in time with the FDTD method. The FDTD method predicts a smooth variation of the band gap width of the PC for both polarisations the evolution of the electric field calculated by the FDTD is shown as an inset in Fig. 2(b). As we increase the frequency to 2×10^{14} Hz it is clearly noted that the TM polarised waves are confined in the dielectric rods and do not propagate down the



(a) (b)

Fig. 1. (a) The medium consisting of alternating layers of high and low index; (b) the 2D photonic crystal to be analysed.



(a)

(b)

(c)

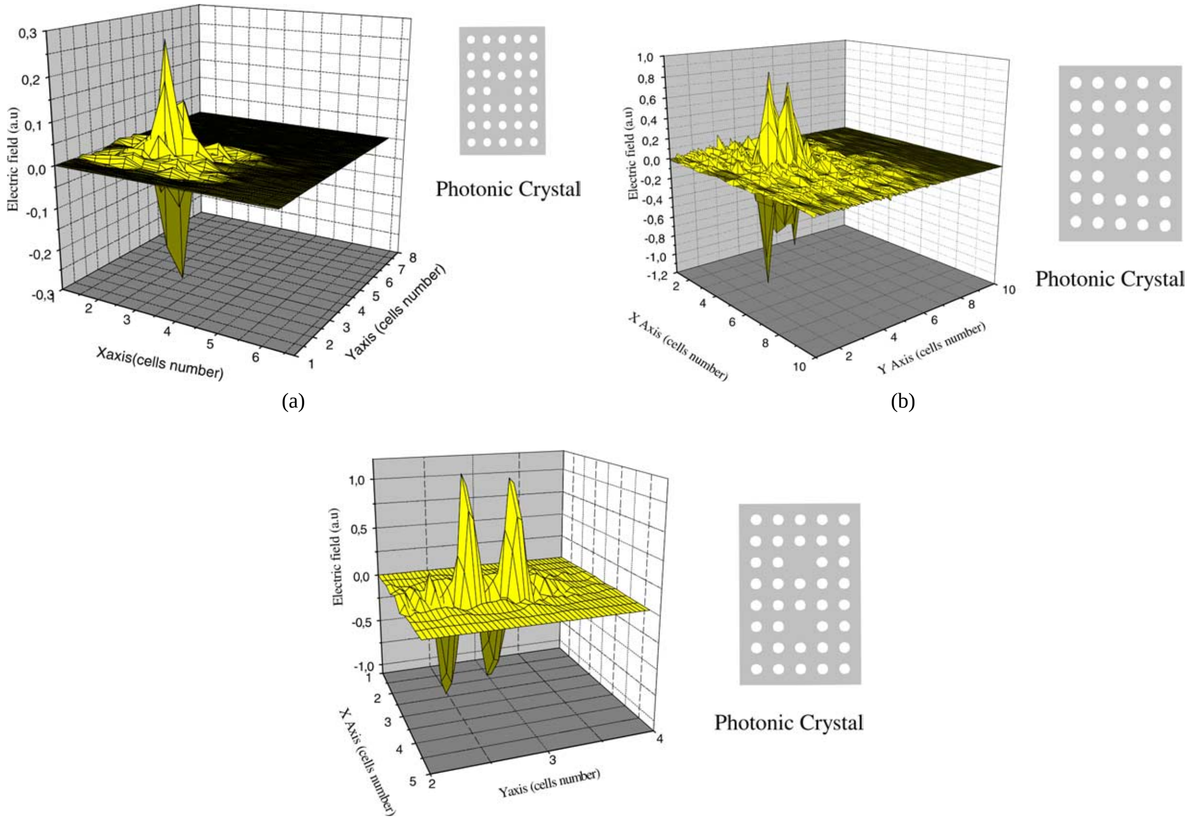
(d)

Fig. 2. (a) The band structure of the photonic crystal at low frequency when $W = 0.2$ μm for both polarisations; (b) the evolution of the electric field calculated by FDTD in the photonic crystal when $W = 0.2$ μm. The band structure of the photonic crystal at high frequency for both polarisations when (c) $W = 0.2$ μm; (d) $W = 0.1$ μm.

structure, the band gap width is the consequence of the constrictive interfering waves, however, TE waves propagate further in the structure through the air gap as it is shown in Fig. 2(c). It can be seen that the TE polarised waves are not affected by increasing the frequency. We keep the frequency equal to 2×10^{14} Hz and we reduce W to 0.1 μm, it clearly noted from Fig. 2(d) that the TE polarised waves present a photonic band gap of a width 0.2 n.a.u., much larger than that of the TM, which is about 0.025 n.a.u.

The TE gap width is a good measure of the air filling factor. Dispersion diagrams showing normalized frequency versus in-plane wave vector for TE and TM modes of the structure. We are focusing on active region with predominantly TE gain. The propagation of electromagnetic waves is prohibited for all wave vectors in PBG, and various important scientific interests and engineering applications such as ultra-small optical integrated circuits are expected with the PBG and the artificially introduced defect states and/or light-emitters.

Recently, Imada et al. [7] proposed and demonstrated very unique phenomenon of trapping and emission of photon by a single defect created in the 2D photonic crystal slab, which can be potentially applied to a surface-emitting-type channel drop filters for WDM application [8,9]. Only the TE slab modes will couple to such defects (cavity, quantum wells, ...) placed at the center of wave guide, coupling will be limited to TE-like modes. For this reason we focus on designing defect cavities that support TE-like localised modes. When a single defect is introduced into the photonic lattice a strong emission may occur, the total detected power will be enhanced. It can be seen that the field is well located at the defect as it is shown in Fig. 3(a). We design two defects in the PC and we vary the optical coupling length between them. In Fig. 3(b) we plot the fields profile in the structure; it is clearly observed that the field is located at each defect, we keep varying the optical coupling length a shift of the maximum field amplitude along with the position peak is expected. In Fig. 3(c) we plot the optical field, it is clearly noted that the field is mostly confined in each defect, and the amplitude is equally distributed in the two defects. Also, in Fig. 3(c) we report the results of a photonic band gap with two weakly coupled defects, each field is selectively enhanced in a single defect.



(a)

(b)

(c)

Fig. 3. The FDTD calculation of the electric field in the structure with: (a) a single defect; (b) two defects. (c) The evolution of the electric field calculated using the FDTD method in the photonic crystal with two defects.

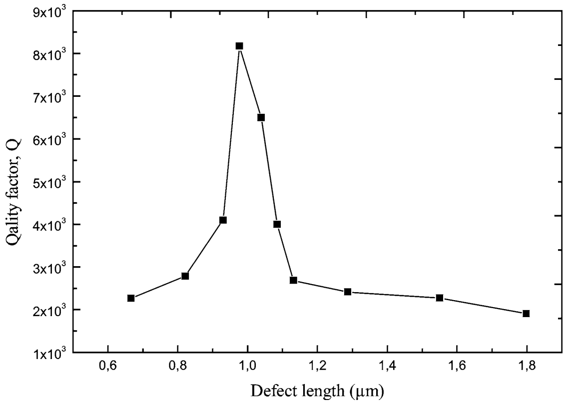


Fig. 4. The variation of the quality factor as a function of the defect width.

Such structures offer simultaneous detection of WDM signals. We change the width of the incorporated defect and we calculate the quality factor Q, in Fig. 4, we plot the quality factor variation with the defect width. It is clearly shown that Q presents a maximum value at 1 µm which is 8×10^3, such structure exhibits a good confinement of photons.

3. Conclusion

Two approaches have been used to understand and analyse the effect of the air filling factor on the band structure at low and high frequencies. The band gap structure for both polarisations TE and TM is performed. It is reported that the air filling factor affects strongly the optical properties of the PC. Also, the TE gap width depends on the air gap size and the frequency as well. By increasing the air gap width the TM gap width increases. It is shown that the FDTD method agrees reasonably with the Kronig–Penney model. It is demonstrated that the TE gap width is a good measure of the air filling factor. These models allow control and study of new interesting phenomena, including flat branches of dispersion curves that can be used for spontaneous emission enhancement, gaps in the long wave regions. We have investigated the optical properties of a single and two defects. It has been shown that the resonant wavelength of the dropped light can be tuned by changing the defect size. It is reported that by changing the optical coupling length between two defects, the maximum field amplitude might be shifted from one defect to the other one, such device may offer simultaneous detection of WDM signals. Also, we have analysed the defect modes of the structure of high index material. The quality factor of the cavity modes are calculated for various membrane thickness. A maximum Q is calculated to be as great as 8×10^3 for a slab thickness of 0.4 µm.

Editor's note

PBG: Photonic Band Gap
WDM: Wavelength Division Multiplexing

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