TUNABILITY OF HEXAGONAL AND TRIANGULAR PHOTONIC CRYSTALS

M. Ciobanu[1], L. Preda[2], D. Savastru[1], R. Savastru[1], E.M. Carstea[1], L. Ghervase[1], S. Dontu[1], and A. Marin[2]

[1]*National Institute of R&D for Optoelectronics – INOE2000, Bucharest-Magurele, Romania,*
[2]*"POLITEHNICA" University of Bucharest, Bucharest, Romania*
E-mail: mircea.ciobanu1@yahoo.com

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Abstract

With the aid of numerical simulations, we study the tunability of photonic structures by evidencing the band gaps (BGs) of two interesting particular hexagonal and triangular photonic crystals. Several runs were performed for different values of the dielectric constant ranging from $\varepsilon = 15$ to $\varepsilon = 150$. Results showed that the BGs cover large intervals. The numerical model used for the simulations is presented. We conclude these configurations could be used for a tunable high-reflectivity and high-directionality antenna. The analogy between electronic waves in the crystal and light waves in a three-dimensionally periodic structure and the evidencing of a complete photonic band gap led to further studies, which cover a large range of domains.

1. Introduction

Photonic crystals (PCs) are one of the major recent revolutions in integrated optics. In 1987 E. Yablonovitch [1] and S. John [2] proposed the possibility to build a material able to forbid the propagation of electromagnetic waves in order to control the spontaneous emission and to generate interesting quantum electrodynamics effects. This idea relies on the basic concepts of the solid-state physics and proposes a periodic arrangement of dielectric materials as a means of obtaining the photonic bandgaps. The investigation of other interesting effects derived from this one, such as strong photon localization, is a fascinating phenomenon [3]. Since these pioneering works, novel exciting phenomena related to the richness of the dispersion relation of PCs [4] have been found out. These include the superprism, self-guiding, and negative refraction effects. In 1990, Ho et al. [5], using a plane-wave expansion method, solved the Maxwell's equations for the propagation of electromagnetic waves in a periodic lattice of dielectric spheres in a uniform dielectric background and found that, unlike experiment, a fcc dielectric structure does not have a full photonic band-gap, whereas dielectric spheres arranged in a diamond structure do possess a full photonic band-gap. In 1991, Yablonovitch [6] demonstrated the first three-dimensional photonic band gap in the microwave regime.

Ferroelectrics have many unusual properties; one of them, namely the nonlinear optical response, can be widely exploited for designing tunable photonic crystals [7]. An external quasistationary electric field can cause a substantial nonlinear response especially in the microwave range [8].

As mentioned before, the aim of this paper is to demonstrate, with the aid of numerical simulations, large intervals of BGs in two particular photonic crystals: one with hexagonal symmetry and the other with triangular symmetry. The paper is organized as follows: **Section 2**

describes the numerical model with which the results are obtained together with our methodology, **Section 3** presents the construction of the lattices, **Section 4** contains results and discussion, and **Section 5** contains some conclusions.

2. Numerical model and methodology

The **MIT Photonic-Bands** (**MPB**) package is a free program for computing the band structures (dispersion relations) and electromagnetic modes of periodic dielectric structures using both serial and parallel computers. This program computes definite-frequency eigenstates (harmonic modes) of Maxwell's equations in periodic dielectric structures for arbitrary wavevectors, using fully-vectorial and three-dimensional methods. It is especially designed for the study of photonic crystals (photonic band-gap materials), but is also applicable to many other problems in optics, such as waveguides and resonator systems. (For example, it can be used for the modes of waveguides with arbitrary cross-sections). Some of the main design goals of this package are the followings:

(a) Fully vectorial, three-dimensional calculations for arbitrary Bloch wavevectors (the only approximation is the spatial discretization, or equivalently the planewave cutoff.)

(b) Flexible interface. Readable, extensible, scriptable.

(c) Parallel (can run on a single-processor machine, but is also supports parallel machines with MPI.)

(d) "Targeted" eigensolver: find modes nearest to a specified frequency, not just the lowest-frequency bands (for defect calculations.)

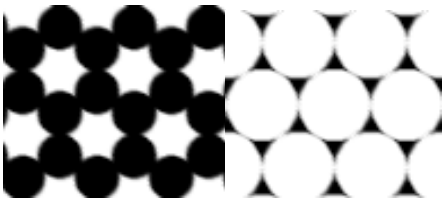
(e) Modularity. The eigensolver, Maxwell's equations, user interface, and so on, should be oblivious to each other as much as possible. This way, they can be debugged separately, combined in various ways, replaced, and used in other programs (all the usual benefits of modular design).

(f) Take advantage of inversion symmetry in the dielectric function, but don't require it (this means that we have to handle both real and complex fields.)

Calculation of the dispersion relation and the associated band gaps in an ideal photonic material is well understood. The periodicity of the medium allows using the Bloch's theorem leading to an eigenvalue problem. For the numerical solutions of the eigenvalue problem, we used the free available MPB package developed by Joannopoulos and associates. Their description of this package reads "Fully vectorial eigenmodes of Maxwell's equations with periodic boundary conditions were computed by preconditioned conjugate – gradient minimization of the block Rayleigh quotient in a plane wave basis using a freely available software package" [9]. The source of the electromagnetic field has the form: $E(x,t) = A(x)B\exp(i\omega t)$, with $A(x) = 1$ and $\omega = 2\pi c/\lambda$. As it is well known, the numerical code of Joannopoulos et al. works with adimensional units.

3. Lattices

The elementary cell of the hexagonal symmetric structure (Fig. 1a) consists of six rods of radius 0.2*a*, where *a* is the lattice constant. For the other photonic crystal (Fig. 1b), a 2D triangular lattice consisting of holes of ferroelectric was envisaged. The elementary cell consists of three holes of radius 0.5*a*, where *a* is the lattice constant, *a* = 5 cm.



a b

Fig. 1. Photonic crystals structures (top view): (a) hexagonal symmetry and (b) triangular symmetry.

4. Results and Discussion

4a. Hexagonal photonic crystal

Several runs were performed, for the dielectric constant taking different values (only three of them shown in this study). In the following, we present the BGs structures for ε=25 (Fig. 2), ε=50 (Fig. 3), and ε=100 (Fig. 4).

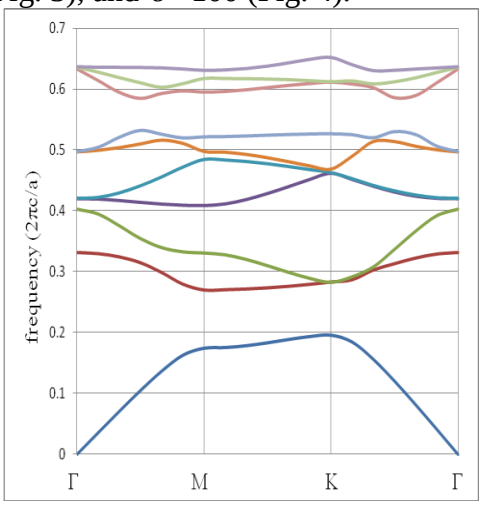


Fig. 2. BGs ($(2\pi c/a)units$) for ε = 25.

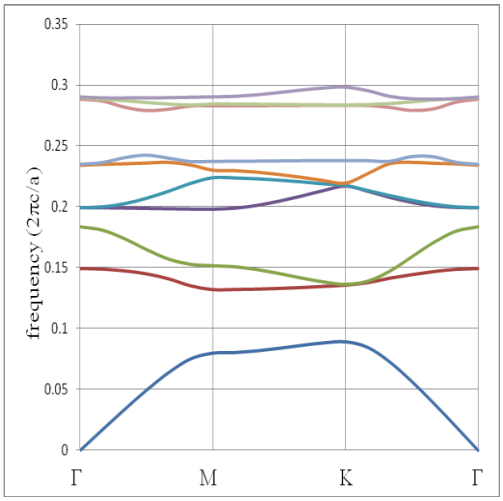


Fig. 3. BGs($(2\pi c/a)units$) for ε = 50.

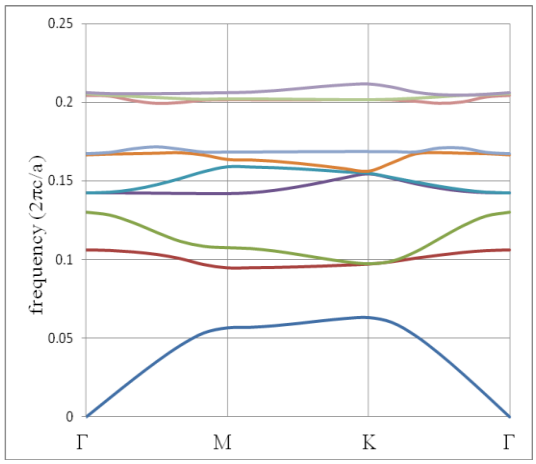
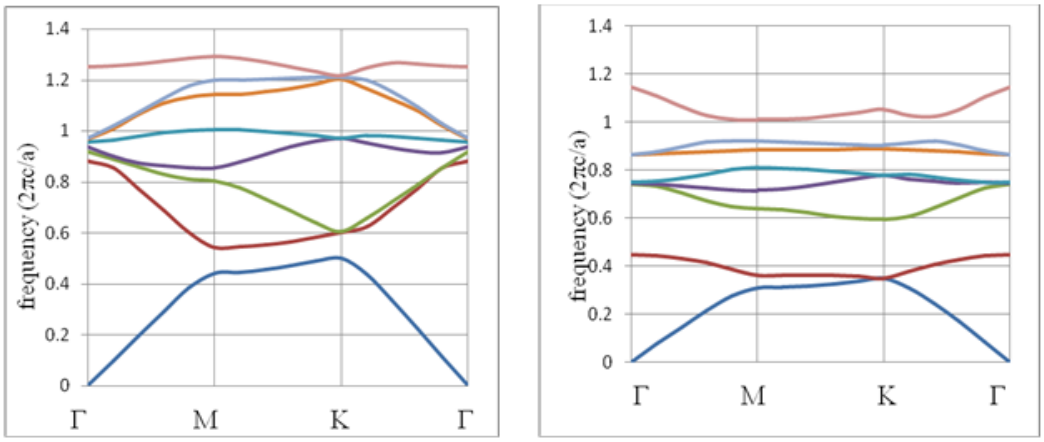


Fig. 4. BGs ($(2\pi c/a)units$) for ε = 100.

In this scope, we could fabricate a photonic crystal on ferroelectric materials and then apply an electric field. It is clear that the voltage applied to the structure must be appropriatelly triggered by an antenna in order to obtain the corresponding band gap, which can be quite simply implemented in actual practise, because a field of a few hundreds of V/cm must be applied depending on the ferroelectric structure.

4b. Triangular Photonic Crystal

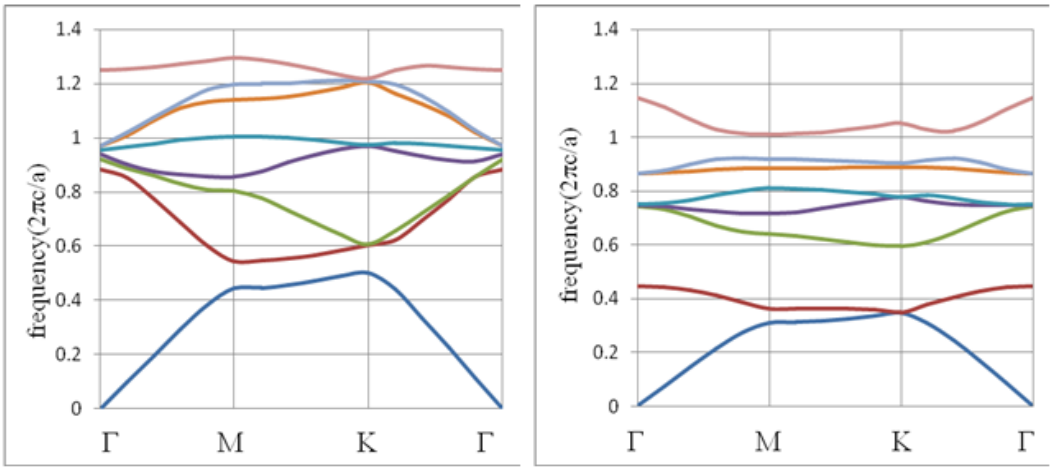
In this case, ten runs were performed for the dielectric constant taking different values (only three of them shown in this study). Only the results of three runs are presented in Figs. 5a,b – 7a,b below, namely the band structures for both TE and TM modes, for dielectric constant values of ε = 15, 25, and 75.



a b

Fig. 5. (a) TE mode for ε =15 and (b) TM mode for ε = 15.

From the above figures, we observe the band gaps for TE mode between ~ 0.45 to 0.55 (in 2πc/a units), and for the TM mode between ~ 0.4 and 0.6 (in the same units).

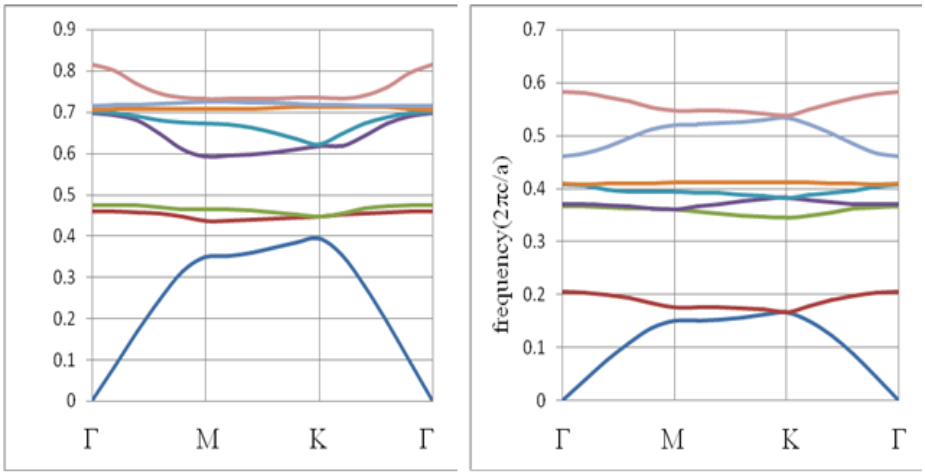


a b

Fig. 6. (a) TE mode for ε =25 and (b) TM mode for ε = 25.

Figures 7a and 7b show band gaps for TE mode between ~ 0.5 and 0.55, and for the TM

mode between ~ 0.4 and 0.6 (in the same units).



a b

Fig. 7. (a) TE mode for ε =75 and (b) TM mode for ε = 75.

The band gap for TE mode between ~ 0.4 and 0.45, and for TM mode between ~ 0.2 and 0.35 (in the same units as above).

5. Conclusions

We studied the possibility of tuning the band gap of a photonic crystal in radar range by numerical simulations. In this scope, a hexagonal lattice of rods and a 2D triangular lattice consisting in holes of ferroelectric were envisaged. The dielectric constant can be varied in practice by an external electrical field. For dielectric constant between 15 and 200, the entire range of ~ 10–60 GHz is covered with band gaps. So, the first application comes from manufacturing tunable antennas.

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