The Structural Design of a Complete Band Gap using Non-Uniform Photonic Crystals with Low Index Material

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ABSTRACT:
This study presents a photonic bandgap formation in a non-uniform 2D photonic crystal structure with low index rods relative to the air background. In order to find an absolute photonic band gap formation, photonic lattices of two non-uniform square and triangular configurations with different rod radiuses and ring-shaped rods are studied. Based on PWE simulations, it was possible to achieve PBGs for both TM and TE polarizations by changing parameters such as rod dielectric constants and radius sizes. In the adjusted square lattice, the symmetry reduction opened a 39% PBG width. Both structures' PBGs are strongly influenced by their dielectric constants and geometry parameters.

KEYWORDS: Photonic Crystal, Band Structure, Band Gap, Dispersion.

1. INTRODUCTION

A photonic crystal (PhC) is an optical structure made up of periodic arrangements of dielectric materials [1, 2]. PhCs are widely used in integrated optics. Light cannot propagate in certain frequency regions called PBGs. Researchers are trying to design a PBG with a larger band gap both in terms of TE and TM polarization [3-6]. It is possible for designers to address the issue of polarization in their designs. The spatial distribution of constituents determines the PhC bandgap. The majority of research in this area has been done through trial and error, and PBGs have not been designed systematically. Additionally, it may be difficult to gain larger band gaps between two adjacent energy bands. A complete band gap is not possible in two-dimensional photonic crystals slab with low index contrast. In spite of the fact that several 3D photonic crystals provide a complete bandgap in this range. It is, however, difficult to fabricate 3-D photonic crystals. In this paper, we optimize the PhC structure by varying its topology and calculating its photonic crystal complete bandgap. In this study, we used low index materials that can be applied to a wide range of visible spectrum photonic technologies. Our objective is to find a photonic structure that exhibits large overlapping TE and TM PBGs.

2. THEORY

As a result of obtaining the band structure of the photonic crystal, we can find and analyze the PBG, which is essential for some practical applications. It is usually expressed in dimensionless units as the absolute width of a PBG. The calculation can be done by defining the quantity gap-mid-gap ratio (or normalized gap width) as the frequency width $\Delta\omega$ of the gap divided by the frequency ωg at the middle of the gap: that is, $\Delta\omega/\omega g$ [1]

$$\text{Gap-mid-gap ratio} = \Delta\omega/\omega g \times 100\%$$

Where $\Delta\omega$ is the frequency width and ωg is the frequency at the middle of the gap.

As the structure is scaled up or down, the normalized gap width remains unchanged, but all frequencies scale accordingly. A complete PGB was formed in two dimensions initially for a triangular lattice of air rods in a dielectric material [7] and then for a square lattice of air rods [8]. Since then, a number of relevant studies have been conducted [9, 10]. There are very few 2-D structures that can form a photonic

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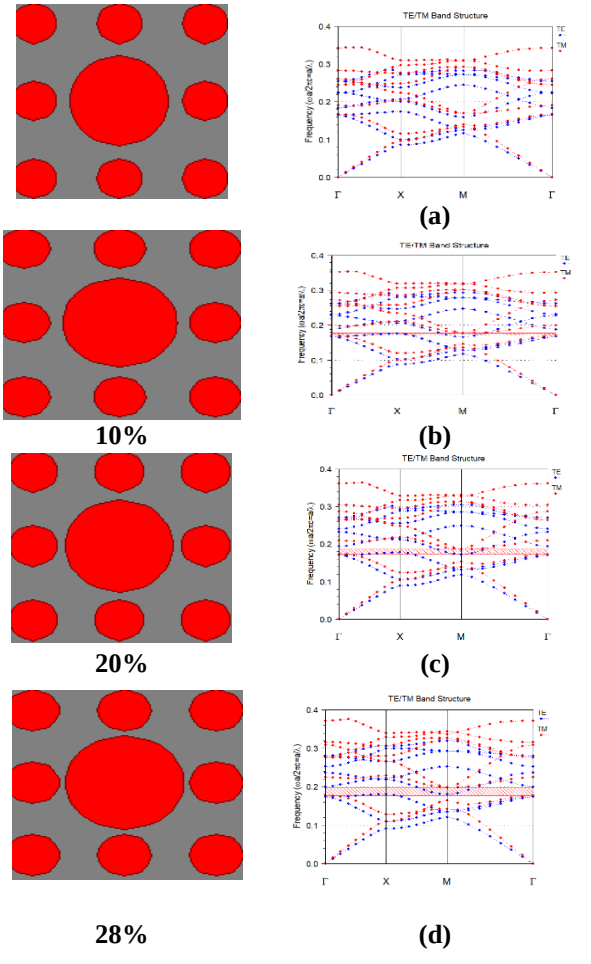
energy gap with a gap-mid-gap ratio of greater than 20%. As an example, the square lattice has the following excess relative energy gap: A square lattice with circular columns (4.3%) and square columns (8/13%), as well as a square-circular scatterer lattice with circular columns (4.3%) a circular rod (10%). The gap in the square-square structure with a square rod can reach 2.15%. It is our objective to determine whether there is a photonic structure that exhibits wide overlaps between TE and TM photonic bandgaps. In the simulations, the focus is on 3D PCSs and 2D PhCs. A PhC structure can be divided into two main types: A structure with high dielectric index pillars in air that tends to open TM PBGs, and a second type of structure with air holes in a high dielectric background tends to open TE PBGs. The general properties of these two kinds of PhC structures are used. As a result, we propose a new kind of PhC structure with alternate arrays of holes and rods (AARH). It exhibits large overlapping PBGs with suitable material and structural parameters. In the proposed 2D photonic crystals, we will discuss the structure, design, and characteristics of the photonic bandgap formation.

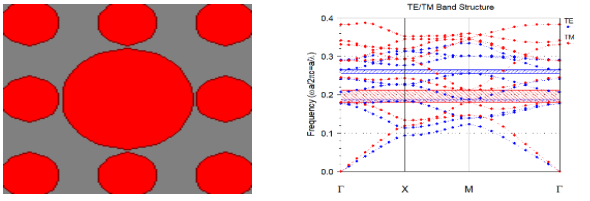
Since their discovery, photonic crystals have become an indispensable technology across the entire field of optical physics due to their ability to confine and control light of an arbitrary wavelength [11–14]. This critical feature is achieved by designing the crystal lattice to possess a complete photonic bandgap, a range of frequencies for which no light can propagate regardless of its momentum or polarization. Unlike their electronic counterparts in conventional crystals, whose band structure is limited to the crystal lattices available in atomic and molecular structures, the dielectric structure comprising a photonic crystal can be specified with nearly complete arbitrariness, yielding a vast design space for optimizing photonic crystals for specific applications that is limited only by the index of refraction of available materials at the operational wavelength. For example, photonic crystals have been developed to promote absorption in monolayer materials [15,16]

3. STRUCTURE DESIGN AND BANDGAP ANALYSIS

A supercell with a non-uniform photonic crystal structure is shown in Fig. 1-(a). According to the band structure, there is no band gap between TM and TE modes. In this study, many attempts were made to reform the band structure. A part of the attempts focused on the geometric structure of the lattice. Having a suitable bandgap is essential in one polarization; this is because, if a bandgap is large in one polarization mode, it increases the likelihood of creating a full bandgap in another polarization mode. There is a strong correlation between symmetry and the opening of absolute PBGs [17]. PBG formation is limited by the degeneracies of photonic bands in the Brillouin zone due to high symmetry points. When symmetry is broken, these degeneracy effects are removed and a complete PBG can be formed [18]. In TE mode, the bandgap formed between Bands 3 and 4 overlapped with the bandgap in TM mode, resulting in a complete bandgap. As compared to isolated dielectric elements, structures with large TM bandgaps do not have TE bandgaps. A lattice structure typically has a large bandgap and no TM bandgap, in contrast.

Schematics of 2D dimensional photonic crystals consisting of rods with refractive index n = 1.53 in an air background are shown in Figs. 1 (a-e). No PBG is present in any polarization mode, as shown in Fig 1(a). The PBG is opened in TM mode by changing the radius rod of the structure as shown in Fig.1 (b), (c) and (d) for the rod radius r=0.23a, r=0.25a, r=0.27a, r=0.30a, and r=0.32a, respectively, with gap-mid-gap ratios of 10%, 20.6%, 28.8%, and 39.8%. Fig. 1 (e) shows the opened absolute PBG.



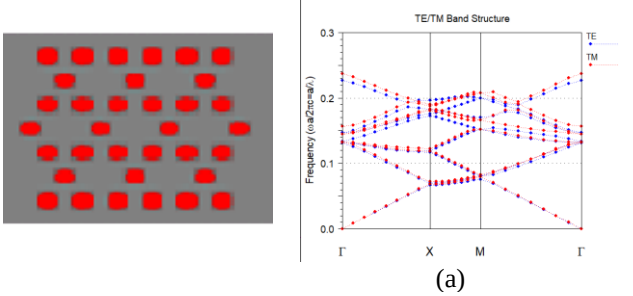


39% **(e)**

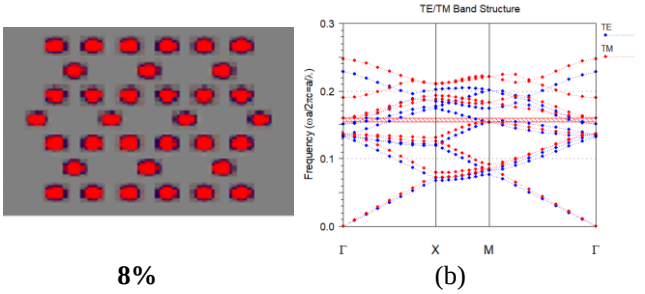
Fig. 1. The structure and corresponding photonic bands for the structure of rods with an index of 1.53 in air background for the rod radius r=0.23a, r=0.25a, r=0.27a, r=0.30a and, r=0.32a as shown in Figs (a), (b), (c), (d) and (e), respectively. The absolute PBG is indicated by the shaded area.

The second structure is a triangular photonic crystal structure consisting of rods with an index of 1.78 in the air (Fig. 2). In Fig. 2.a, the photonic band structure is shown for rod radius r=0.3a. Neither TM nor TE modes have PBGs. We now consider Fig 2(b-e), which shows ring-shaped rods with a red and blue layer. The blue and red indexes were assumed to be 1.78 and 1.65, respectively. The dispersion curves of structure are shown in Fig. 2 (b-e). By varying the radius of the photonic crystal structure shown in this figure, we were able to modify the Photonic Band Structure (PBG). In the case of TM, the absolute PBG reaches its maximum normalized width of $\Delta\omega/\omega g$=17.5%. As a result of the overlap between TE1-2 (the gap between the first and second photonic bands) and TM2-3 polarization gaps, the absolute PBG is formed.

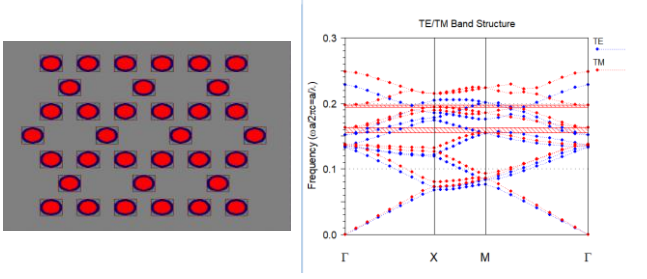
In addition, we modified the photonic band structure (PBG) by changing the radius cross-section of the photonic crystal structure shown in Figs. 1&2.



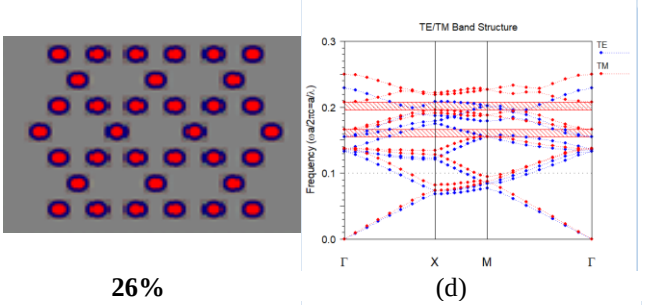
(a)



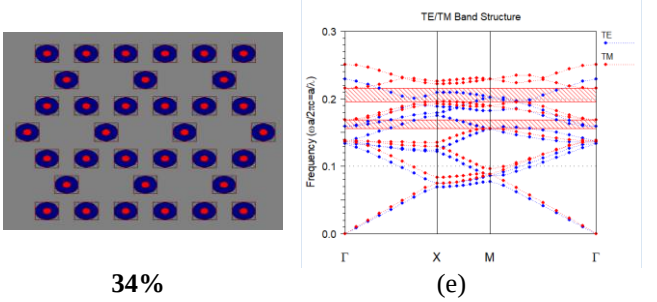
8% (b)



21% (c)



26% (d)



34% (e)

Fig. 2. The structure and corresponding photonic bands for the structure of rods with an index of 1.53 in air background for the rod radius r=0.3a, r=0.25a, r=0.23a, r=0.18a and, r=0.1a as shown in (a), (b), (c), (d) and (e), respectively. The absolute PBG is indicated by the shaded area.

4. CONCLUSION

The supercell method has been used in this study to determine the photonic band structure of a 2D non-uniform photonic crystal. We tested how symmetry reduction, achieved by changing the radius of square unit cells, affects absolute PBG properties. As we showed, the symmetry reduction for a modified square lattice opens up an absolute PBG width of 39% when the lattice is modified. We discuss a second structure consisting of rods with low index material in an air background, which is a triangular photonic crystal. When ring-shaped rods are arranged in a triangular lattice, the absolute PBG is obtained. In both structures, PBGs are strongly affected by dielectric constants and geometry parameters. As a result of the dielectric constant, the gap size is determined.

REFERENCES

[1] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, "**Photonic crystals: molding the flow of**

light", *Princeton University Press*, 2008.

[2] S. Fan, J. N. Winn, A. Devenyi, J. C. Chen, R. D. Meade, and J. D. Joannopoulos, "**Guided and defect modes in periodic dielectric waveguides.**" *JOSA* B, pp. 1267–1272, 1995.

[3] R. L. Chern, et al. "**Large full band gaps for photonic crystals in two dimensions computed by an inverse method with multigrid acceleration**." *Physical Review E 68.2 026704*, 2003.

[4] Wang, X. H., Gu, B. Y., Li, Z. Y., & Yang, G. Z. "**Large absolute photonic band gaps created by rotating noncircular rods in two-dimensional lattices**". *Physical Review B*, 60(16), 11417, 1999.

[5] N. Susa. "**Large absolute and polarization-independent photonic band gaps for various lattice structures and rod shapes.**" *Journal of Applied Physics* 91.6 3501-3510, 2002.

[6] Fu, H. K., Chen, Y. F., Chern, R. L., & Chang, C. C. "**Connected hexagonal photonic crystals with largest full band gap.**" *Optics Express*, Vol. 13(20), pp. 7854-7860, 2005.

[7] M. Plihal and A. A. Maradudin, "**Photonic band structure of two-dimensional systems: the triangular lattice**", *Phys. Rev. B 44*, 8565, 1991.

[8] P. R. Villeneuve and M. Piche, "**Photonic band gaps in two-dimensional square lattices: Square and circular rods**", *Phys. Rev. B 46*, 4973, 1992.

[9] M. Agio and L. C. Andreani, "**Complete photonic band gap in a two-dimensional chessboard lattice**", *Phys. Rev. B 61*, 15519, 2000.

[10] M. Qiu and S. He, "**Large complete band gap in two-dimensional photonic crystals with elliptic air holes**", *Phys. Rev. B 60*, 10610, 1999.

[11] E. Yablonovitch, Phys. Rev. Lett. 58, 2059, 1987.

[12] S. John, Phys. Rev. Lett. 58, 2486, 1987.

[13] J. D. Joannopoulos, P. R. Villeneuve, and S. Fan, Nature 386, 143 (1997)

[14] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, Photonic Crystals: Molding the Flow of Light (Second Edition) (Princeton University Press, 2011.

[15] J. R. Piper and S. Fan, ACS Photonics 1, 347, 2014.

[16] J. R. Piper, V. Liu, and S. Fan, Appl. Phys. Lett. 104, 251110, 2014.

[17] T. Trifonov, et al. "**Effects of symmetry reduction in two-dimensional square and triangular lattices**." *Physical Review B 69*.23 235112, 2004.

A. Cerjan and S Fan. "**Complete photonic band gaps in supercell photonic crystals.**" *Physical Review A 96.5* 051802, 2017.