Design of Multi-Band Gap Photonic Crystals by Using Numerical Techniques

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Abstract — The fabrication of photonic crystals (PC) requires extremely high resolution and high expenses. It also requires the accurate modeling and prediction for the characteristics of a novel photonic crystal structure prior to any experimental fabrication. Our research aims to develop a few specific photonic structures which are able to control a multi-frequency band. Numerous proposed photonic structures are numerically simulated in this paper, by using the frequency-domain plane-wave method and scattering matrix method. Results obtained exhibit that few structures are able to achieve our expectation.

Key words — Photonic crystals (PC), Photonic band-gap (PBG), Plane-wave method, Transfer matrix method (T-matrix method)

1. Introduction

Recent years, the explosive growth of the communications and datacom transmission systems has led to unprecedented bandwidth requirements. As a result, there is a need for new advanced technologies that can enable the high-speed processing of such exponentially growing data traffic. Photonic micro-structures on a wavelength scale, as a novel technology, have opened the door to truly high density integrated circuits in photonics [1]. Photonic crystals have shown extensive potential applications from fundamental sciences to practical engineering. The electromagnetic properties of photonic band-gap structures are fundamental to the design of corresponding devices.

The concept of photonic crystal was originally proposed by E. Yablonovitch [2], where photons in periodic structures were described in terms of a band structure as electrons in semiconductors. The periodic photonic crystals can be designed to open up certain frequency bands, within which the propagation of electromagnetic waves is forbidden irrespective of the propagation direction in space [3]. It is expected that various engineering applications can be realized by utilizing the photonic band-gap materials, the introduced defect states and light emitters. To achieve such ultimate controls of light through omni-directional photonic band-gaps, high-quality three-dimensional photonic crystals, whose merits in controls of light in any direction, are necessary to serve as ideal medium for ultra-small optical integrated circuits, but generally very difficult to fabricate. Alternatively, two-dimensional photonic crystals, whose merits in relatively easy controls of light, can provide platforms for realization of some important functional devices.

Since the periodicity of the medium must be of the order of the wavelength of electromagnetic waves, the manufacturing of photonic crystals that operate in the visible region of electromagnetic spectrum requires fabrication techniques with resolutions on an extremely small scale. Due to their high expenses, accurate and efficient models are desirable to allow photonic crystals' optical properties to be computed prior to fabrication. Therefore, novel modelling and optimization techniques for the design of photonic structures are most significant.

Our research aims to develop a few specific photonic structures which are able to control the multi-band propagation. This study is streamlined into two essential phases namely: simulation and optimization design, and experimental fabrication. The simulation and optimization for numerous proposed photonic structures are presented in this paper, by using numerical techniques prior to experimental

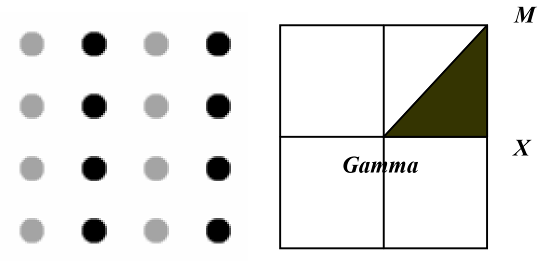
2. Numerical Techniques

A frequency-domain method in a plane-wave basis is employed to analyze and predict the characteristics of electromagnetic propagation as well as band-gap functions for photonic structures. This fully-vectorial three-dimensional algorithm is to expand the fields as definite-frequency states in some truncation of a complete basis and then solve the linear eigen-problem. More details are referred to [5]. To further investigate transmission properties of eletromagnetic waves, the transfer matrix method is also developed and adopted for the analysis of specific photonic structures.

3. Experimental Results

3.1 Periodic Variation of Dielectric Constant in one Dimension

To generate a multi-frequency band, we firstly propose to alternate the dielectric constant ε_r of rods periodically in one dimension shown in Fig. 1a (grey ones for the lower value while black ones for the higher value), where a square-lattice photonic crystal composed of the dielectric rods in air, with the lattice constant, *a* and radius, *r=0.2a*.



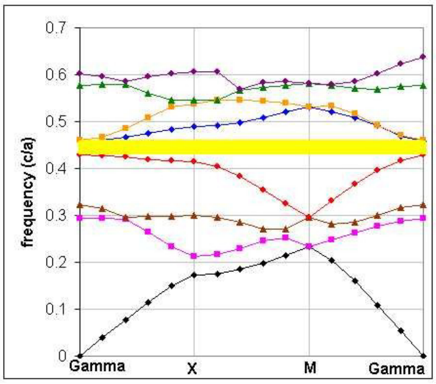
(a) (b)

Fig. 1 A photonic structure with ε_r = 3.8 (odd columns) or 8.9 (even columns) in 1-d

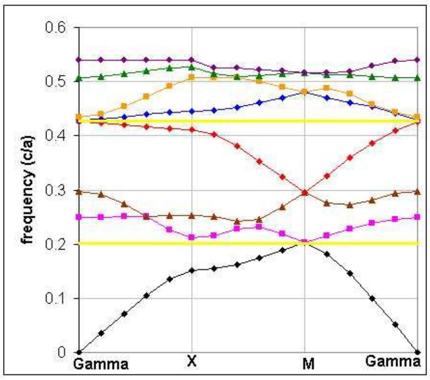
The band-gap functions varying with the dielectric constant for transverse-magnetic (TM) modes, with ε_r = 3.8 (odd columns) or 8.9 (even columns), and ε_r = 3.8 (odd columns) or 13.8 (even columns), are plotted in Fig. 2a and 2b respectively. It is noted that these functions are graphed along the sides of a triangular irreducible Brillouin zone *Γ-X-M-Γ* (shown in Fig. 1b), and the frequencies are measured in the dimensionless

fabrications. The following sections summarize some experimental results.

units *c*/*a*, where *c* is the light velocity and λ is the wavelength in free space.



(a) ε_r = 3.8 (odd columns) or 8.9 (even columns)



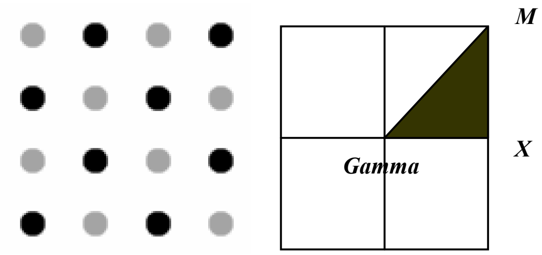
(b) ε_r = 3.8 (odd columns) or 13.8 (even columns)

Fig. 2 Band-gap functions for TM modes based on Fig. 1a

It is observed that a wide band gap is produced with ε_r = 3.8 (odd columns) or 8.9 (even columns) (seen in Fig. 2a), while two narrow band gaps are generated with ε_r increased to 13.8 for even columns (seen in Fig. 2b). These results can give us useful information, and more precise band-gap(s) can be obtained by selecting proper materials. However, detailed optimization is not presented in this paper.

3.2 Periodical Variation of Dielectric Constant in two dimensions

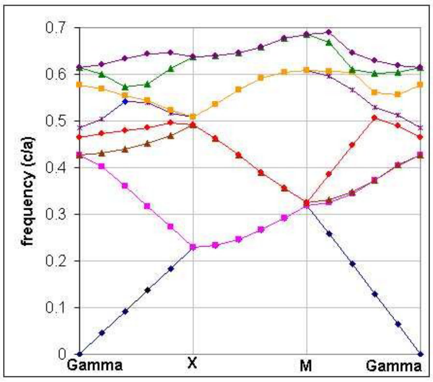
Secondly, another photonic structure, shown in Fig.3a, is to put two types of dielectric rods periodically in two dimensions, where geometrical parameters are used are same as above except the rod dielectric constant ε_r (grey ones for the lower value while black ones for the higher value).



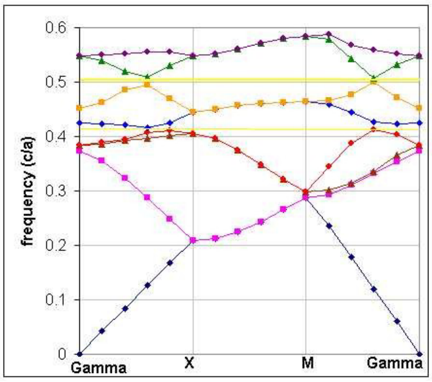
(a) (b)

Fig. 3 A photonic structure with ε_r = 3.8 (odd columns) or 8.9 (even columns) in 2-d

The band-gap functions varying with the dielectric constant for transverse-magnetic (TM) modes, with ε_r = 3.8 (odd columns) or 8.9 (even columns), and ε_r = 3.8 (odd columns) or 13.8 (even columns), are plotted in Fig. 4a and 4b respectively. It is noted that these functions are graphed along the sides of a triangular irreducible Brillouin zone *Γ-X-M-Γ* (shown in Fig. 3b), and the frequencies are measured in the dimensionless units *c*/*a*, where *c* is the light velocity and *λ* is the wavelength in free space.



(a) ε_r = 3.8 (odd columns) or 8.9 (even columns)



(b) ε_r = 3.8 (odd columns) or 13.8 (even columns)

Fig. 4 Band-gap functions for TE modes based on Fig. 3a

It is observed that no band gap is produced with ε_r = 3.8 or 8.9 being alternately varied (seen in Fig. 4a), while two narrow band gap are generated with replacing ε_r = 3.8 or 13.8 (seen in Fig. 4b). However, there is no much change in terms of band gaps for TM modes, being compared to TE modes in Table 1. It is noted that these functions are graphed along the sides of a triangular irreducible Brillouin zone *Γ-X-M-Γ* (shown in Fig. 3b), and the frequencies are measured in the dimensionless units *c*/*a*, where *c* is the light velocity and *λ* is the wavelength in free space.

ε_r of odd/even rods			3.8/8.9	3.8/13.8
TE Modes	Band 1	From	No gap	0.48341
		To		0.48570
	Band 2	From	No gap	0.54808
		To		0.55810
TM Modes	Band 1	From	0.27649	0.23491
		To	0.29529	0.29233
	Band 2	From	0.38236	0.37867
		To	0.46006	0.43475

Table 1 Band-gap information vs. dielectric constant of odd/even columns

3.3 Periodic Variation of Sizes in two dimensions

The third photonic structure is shown in Fig. 5. This simulation is to show the effect of the various sizes of rods on band-gap functions, considering the ratio of the larger radius r_l to the smaller one r_s, r_l/r_s = 1.2 and 1.5 respectively.

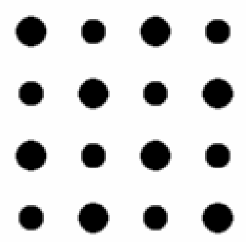


Fig. 5 A photonic structure with different sizes of rods in 2-d

The band-gap information is listed in Table 2. It is worthy to state that the ratio of the larger radius to the small one has effect on band-gap functions for both TE and TM modes, and a stop band can be transferred to a pass band. This simulation will provide reference for the design of specific frequency bands and multi-band optimization.

Ratio of larger radius to smaller one			1.2	1.5
TE Modes	Band 1	From	No gap	0.41267
		To		0.41654
	Band 2	From	No gap	0.50026
		To		0.50727
TM Modes	Band 1	From	0.30972	0.22189
		To	0.41604	0.22707
	Band 2	From	No gap	0.29911
		To		0.36791

Table 2 Band-gap information vs. sizes of odd/even rods

3.4 Double-Rod Periodic Structure

In this section, the propagation properties of a finite-size PBG structure in terms of transmission characteristics will be studied applying the T-matrix method. A finite-size PBG material with a double-rod periodic structure is shown in Fig. 6, that is, it is periodically arranged by every two rods instead of conventional single one, where the radius of rods $r = 0.15a$, the distance between two double rods $d = 0.3a$ and $0.5a$ respectively ($a = dx$).

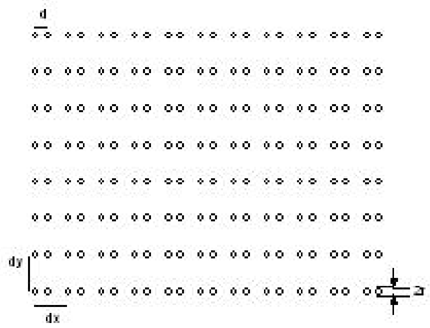


Fig. 6 A finite-size photonic structure with a double-rod periodic structure

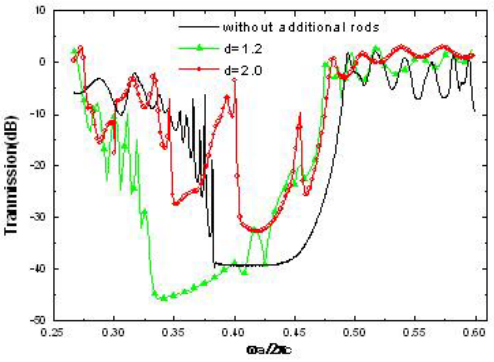
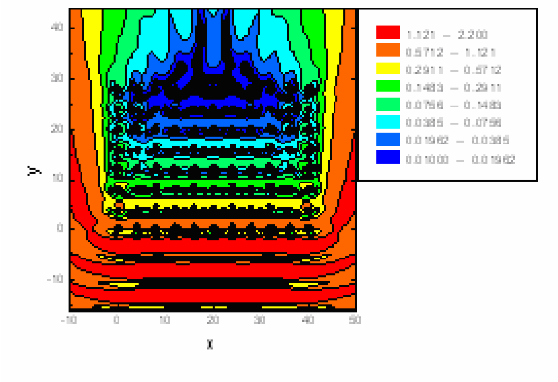
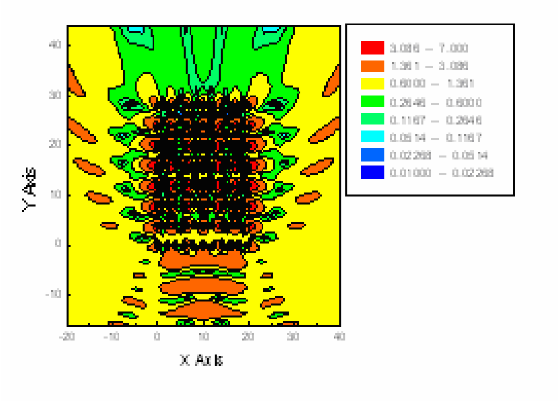


Fig. 7 Transmission coefficients based on Fig. 6

The transmission coefficients with $d = 0$ (single rod), 1,2 and 2.0 are plotted in Fig. 7, respectively, where we can obviously see that this structure can covert a stop band into a pass band and produce multi-band gaps as d increases. The field distributions with single and double rods at $\omega a/2\pi c = 0.401$ are plotted in Fig. 8a and 8b.



(a) For the single-rod structure



(b) For the double-rod structure

Fig. 8 Field distributions at $\omega a/2\pi c = 0.401$

4. Conclusions

Photonic band-gap functions periodically varying with properties of the dielectric rods in one and two dimensions are simulated by using a frequency-domain method in a plane-wave basis. The results demonstrate that specific multi-band gaps can be generated if the material properties of the dielectric rods are properly selected. In addition, this study shows that the sizes of the dielectric rods can affect the propagation properties of electromagnetic waves in photonic structures, which is able to shift a stop band to a pass band or generate a new stop band. In conclusion, a good guideline to design novel multi-band photonic devices by varying dielectric parameters is proposed in this paper. Further research on numerical simulations and experimental fabrications will be carried out.

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