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Original Research Article

Numerical analysis of reflection and transmission in 1D porous silicon crystal

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ABSTRACT
In photonic bandgap structures there exists an interesting phenomenon for the propagation of electromagnetic waves. These photonic band structures are made up of artificial dielectric materials. Depending on the structural details, photonic crystals (PCs) posses a photonic bandgap where the electro-magnetic wave propagation is forbidden. Among various types of photonic bandgap structures, the simplest types are one-dimensional periodic or quasi-periodic multilayer stacks. An efficient mathematical treatment is needed for the analysis of optical characteristics of one dimensional PCs. Out of many mathematical techniques for the designing of 1D PC, the transfer matrix method offers an excellent approach. In this wok, the transfer matrix method has been adopted for the numerical calculations. It is found that the photonic bandgap (for TE polarization) is a function of dielectric contrast of two corresponding layers and becomes wider as it is increased and it is also dependent on lattice constant and angle of incidence. The reflection and transmission of single quarter wave layer (porous silicon layer) as function of operating frequency has been analyzed.

1. Introduction

The subject area of experimental and theoretical investigations of photonic crystals (PCs) is the subject of deep interest of researchers due to its attracting applications in the fabrication of photonic devices. First of all, Yablonovitch [1] and John [2] developed the PCs. PCs are periodically dielectric materials which exhibit the frequency bands which are absolutely independent of electro-magnetic states. Depending on the periodicity the PCs may be categorized as: one dimensional (1D) PCs, two dimensional (2D) PCs, and three dimensional (3D) PCs [3, 4]. These possess a bandgap in which photon propagation is strictly prohibited. Such unique properties of PCs have focused the development of a new class of active and passive components for advanced photonics. For today's VLSI/ULSI and communication technology PCs provides high speed performance as it uses photons hence speed is greater than electro-optical devices [5]. Hence optical integrated circuits can be developed and fabricated using PCs such as lasers, filters, channel drop filters, multiplexer/ demultiplexer, lasers, waveguides [6] etc.

PCs has the dimensions of nano-sizes hence very compact size devices are possible. Therefore it has all three basic features (speed, information carrying capacity & size) that are needed for advanced semiconductor and optoelectronics technology. 1D PCs may be regarded as the multi-layered structure of alternate layers with high and low index of refraction. Among the various PCs, including elemental and compound semiconductors, silicon is preferred in the electronics and photonics industry due to its various advantages such as availability, low cost of fabrication, integration with electronic components, and on-chip fabrication technology. Photonic devices based on silicon have attracted considerable attention because of established technology compatible with CMOS processing.

The most attractive aspects of fabricating conventional as well as nano-photonic devices on silicon are the availability of well established microelectronic tools and processes in general and starting materials technology, nano lithography and dry etching processes etc. Porous silicon is a nano-structured material that introduces nano-pores in its micro-structure and it can retain growing challenge in the fabrication and development of photonic devices [5]. In the history of semiconductor technology, the porous silicon was first synthesized by Uhlir in 1956 during the electro-polishing of silicon. Because of its room temperature luminescence, it provides the possibility tofabricate light emitting diodes.

For last twenty years, porous silicon has been utilized to fabricate the 1D and 2D PCs with easy fabrication technique which gives hundred percent reflection of light in one or two directions. The development of theoretical model to study the propagation of electromagnetic waves, including the transmission and reflection, through 1D porous silicon PCs leads to the designing and the fabrication of photonic devices such as filters, channel drop filters, antireflection coating etc. In this paper, by adopting the transfer-matrix-method, a theoretical model describing the reflection and transmission in 1D porous silicon crystals has been done for TE polarization case. For validation, the developed theoretical model is followed by the numerical analysis.

2. Mathematical approach

The transfer matrix method (TMM) is very useful for the calculation of reflection and transmission of multilayer structure. It is applicable for both periodic and non-periodic multilayered structure with complex refractive index. This method involved the intensity of reflected and incident light. By using TMM method, the dispersion relation can be obtained by Bloch wave number which gives the photonic bandgap. For the analysis of 1D PCs, we have considered an infinite periodic stack of alternate layers of small and large indices of refraction n_1 and n_2 with widths d_1 and d_2, respectively

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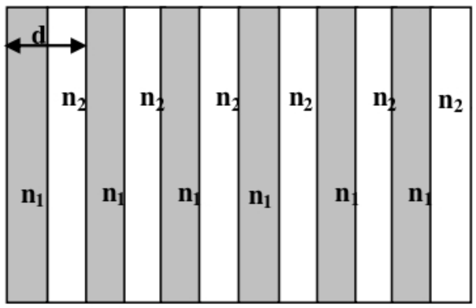

Figure 1. Structure of 1D PC consisting of alternating layers of small and large indices of refraction n_1 and n_2, respectively.

In this case, medium is periodic in one direction, therefore, the refractive index profile may be expressed as [3]

$$n(z) = \begin{cases} n_1, & 0 < z < d_1 \\ n_2, & d_1 < z < \Lambda \end{cases} \tag{1}$$

In equation (1), $n(z) = n(z+\Lambda)$ in z-direction, where $\Lambda = d_1 + d_2$ is the lattice constant. According to Bloch theorem, for such a periodic medium, one may express [3]

$$E(r) = E(z)e^{i(-k_y y + \varpi t)}, \tag{2}$$

where k_y is the Bloch wave number. Using transfer matrix method, the dispersion relation may be obtained as [9]

$$K\Lambda = \cos^{-1}\left[\frac{1}{2}(A+D)\right]. \tag{3}$$

The important information regarding the eigen-modes of PC, which describes the property of Bloch waves is contained in Equation (3). In equation (3), A and D are the coefficients and these may be expressed as [3]

$$A = e^{ik_1 d_1}\left[\cos(k_2 d_2) + \frac{1}{2} i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2}\right)\sin(k_2 d_2)\right] \tag{4}$$

and

$$D = e^{-ik_1 d_1}\left[\cos(k_2 d_2) - \frac{1}{2} i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2}\right)\sin(k_2 d_2)\right]. \tag{5}$$

Owing to linear geometry of the considered structure, the propagation of electromagnetic field through PC may be bi-fracted into two (polarizing state) components, viz. the transverse magnetic (TM) polarization state, and the transverse electric (TE) polarization state. In the TM polarization state, the magnetic field vector is parallel to the layers interface, while in the TE polarization state, the electric field vector is parallel to the layer interface. Hence, one may consider the two independent states of the electromagnetic field, corresponding to the TM and TE polarization states. However, in present work we have considered TE polarization.

For reflection/transmission analysis we have considered single layer of porous silicon layer with quarter wavelength thickness. The expression of reflection response is given as [3]

$$|R|^2 = \frac{2\rho_1^2[1+\cos(2k_1 l_1)]}{1+2\rho_1^2\cos(2k_1 l_1)+\rho_1^4}. \tag{6}$$

Equation (6) may be expressed in terms of operating frequency as [3]

$$|R|^2 = \frac{2\rho_1^2[1+\cos(\varpi T)]}{1+2\rho_1^2\cos(\varpi T)+\rho_1^4}. \tag{7}$$

Equation (6) may be used to study the reflection and transmission in porous silicon PCs.

3. Results and discussions

The reflection and transmission responses as function of operating frequency of single porous silicon layer with quarter wavelength thickness are shown in Figure 2(a) and 2(b).

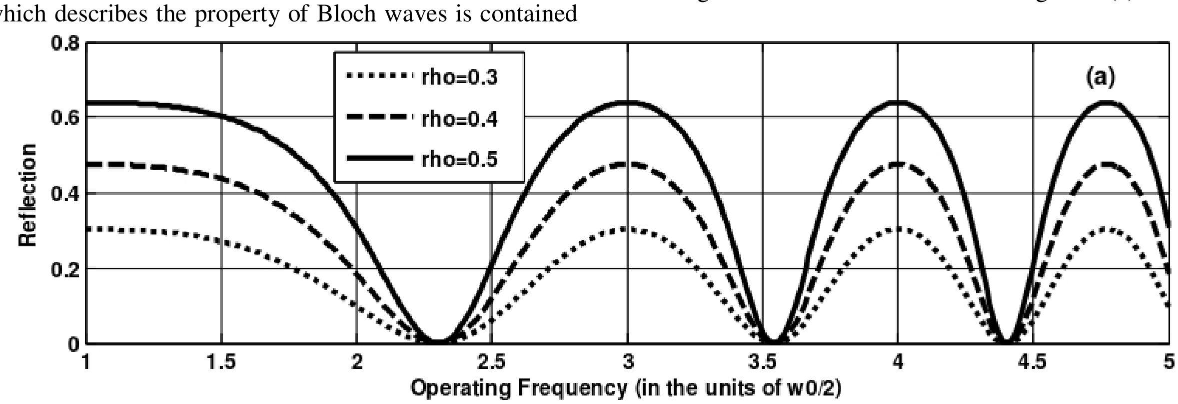

Figure 2. (a) Reflection response of single porous silicon layer versus operating frequency for three different values of reflection coefficients.

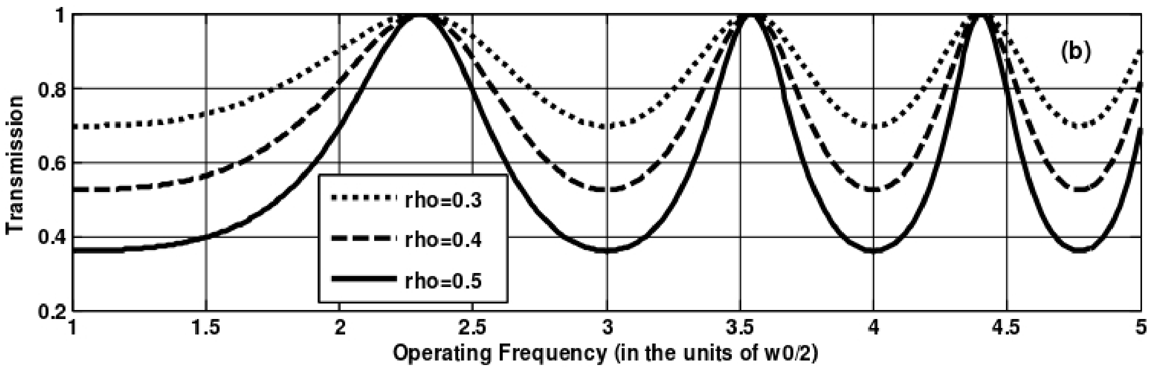

Figure 2. (b) Transmission response of single porous silicon layer versus operating frequency for three different values of reflection coefficients.

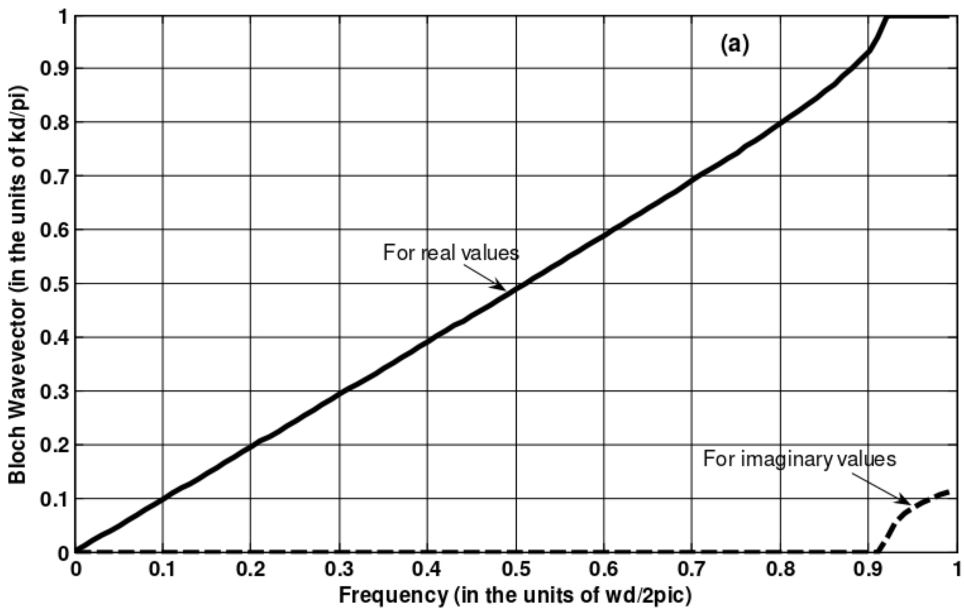

Figure 3: (a) One dimensional photonic bandgap versus normalized frequency for imaginary and real values of Bloch wave vector with alternate layers of n_1 = 1.6 and n_2 = 2.4, respectively.

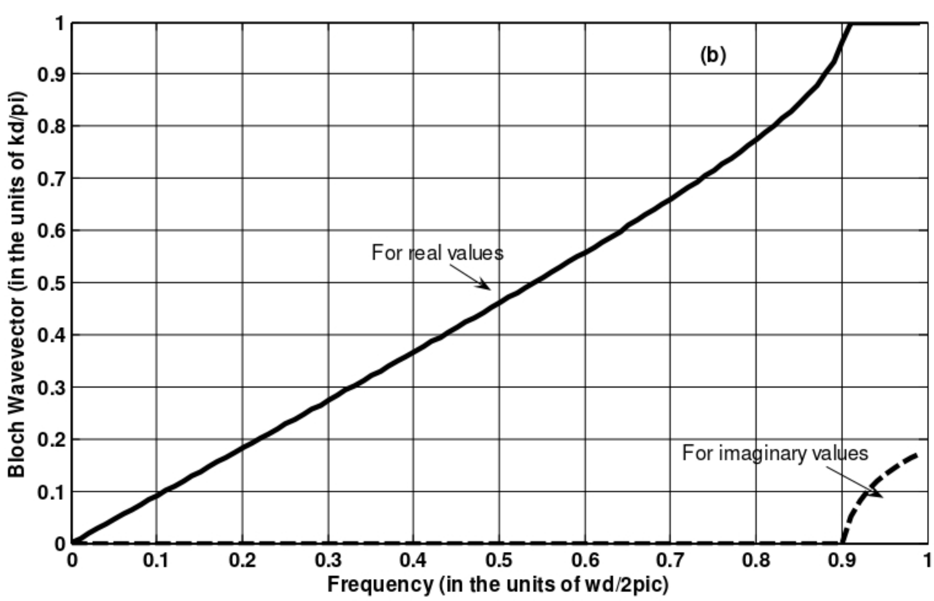

Figure 3. (b) One dimensional photonic bandgap versus normalized frequency for imaginary and real values of Bloch wave vector with alternate layers of n_1 = 1 and n_2 = 2.5, respectively.

Each curves in Figure 2 are for different values of reflection coefficients (*rho* = 0.3, 0.4 and 0.5). From these graph, it is observed that at higher value of reflection, coefficient the reflection (transmission) response is maximum (minimum) as shown in Figure 2(a) and 2(b) as solid lines whereas the reflection (transmission) response is decreased (increased) for lower values of reflection coefficients as shown in Figure 2(a) and 2(b) as dashed and dotted lines, respectively. It is also observed that with increasing the values of reflection coefficients, the width of reflection (transmission) response becomes wider. Figure 2(b) shows the transmission response with respect to frequency at different values of reflection coefficients.

The dispersion relation of 1D porous silicon PCs versus normalized frequency are depicted in Figure 3(a) and (b) for imaginary and real values of Bloch wave vector**.** Figure 3(a) depicts the opening of photonic band gap for n_1 = 1.6 and n_2 = 2.4 at frequency 0.92 (in the units $\omega d/2pic$).

Similarly, Figure 3(b) is for n_1 = 1 and n_2 = 2.5 in which the forbidden band opened at frequency 0.9 (in the units $\omega d/2pic$). When the solution of Bloch wave vector equation ($K\Lambda$) is complex then photonic bandgap is obtained. The real and imaginary values of Bloch wave vector are stands for pass band and forbidden band. By comparing Figures 3(a) and 3(b), it is observed that as the index of refraction contrast increases/ decreases accordingly, the range of photonic bandgap will be increased/decreased. Therefore, the bandgap can be adjusted by refractive index contrast and lattice constant. The plotted dispersion relation graphs are for TE polarization in which the photonic bandgap is a function of angle of incidence.

4. Conclusions

For the analysis of 1D PCs, the transfer matrix method has been used. It is found that the photonic bandgap (for TE polarization) is a function of refractive index contrast of two corresponding layers and becomes wider as it is increased. It is also dependent on lattice constant and angle of incidence. The reflection and transmission response of single quarter wave layer (porous silicon layer) has been analyzed. It is observed that at higher values of reflection coefficient, the reflection (transmission) response is maximum (minimum) whereas the reflection (transmission) response is decreased (increased) for lower values of reflection coefficients. However, with increasing the values of reflection coefficients the width of reflection (transmission) response becomes wider.

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