RP Current Trends in Engineering and Technology
Vol. 1, No. 1 (July 2022) pp. 5–8
e-ISSN: 2583-5491

RESEARCH PLATEAU PUBLISHERS

Cite this article: A. Kumar, Numerical analysis of dispersive characteristics of 1D porous silicon photonic crystal, *RP Cur. Tr. Eng. Tech.* **1** (2022) 5–8.

Original Research Article

Numerical analysis of dispersive characteristics of 1D porous silicon photonic crystal

Arun Kumar
Department of Physics, Government College, Bahadurgarh – 124507, Haryana, India
*Corresponding author, E-mail: arun250981@gmail.com

ARTICLE HISTORY
Received: 8 May 2022
Revised: 06 July 2022
Accepted: 07 July 2022
Published online: 08 July 2022

KEYWORDS
Bloch theorem; transfer matrix method; photonic crystals.

ABSTRACT
Today, researchers have deep interest in analyzing the optical properties of photonic crystals (PCs) and the resulting photonic devices because of their numerous potential applications in communications and computing. PCs are the artificial dielectric structures which have periodicity of its dielectric layers in one, two and three dimensions. One-dimensional (1D) PCs consist of alternative dielectric layers of low and high refractive index materials which posses a gap known as photonic band-gap, in which a band of frequencies can be forbidden. A large dielectric contrast is essential for large photonic band gap which ultimately depends on the refractive indices of individual layers. Therefore for the fabrication point of view a sophisticated fabrication technique is required to achieve desired indices of layers. However a wide tunability of refractive index may be obtained with porous silicon based PCs with an ease of fabrication technique. The porous silicon may be regarded as interesting optoelectronic material due to its luminescence and dielectric properties. This article reports on the numerical analysis of dispersive characteristics of 1D porous silicon PC by taking into account the dependence of reflectance/transmittance on incident angle of electromagnetic radiation. For the optimization of optical parameters of 1DPCs, the reflection and transmission coefficients with respect to phase shift have been numerically obtained and analyzed.

1. Introduction

Today, photonic crystals (PCs), a well known class of photonic materials, have received a lot of interest due to their band-gap effects and personification in the well developed modern optoelectronic devices. The concept of PCs was firstly proposed by Yablonovitch [1]. PCs may be regarded as optical materials of micro-meter dimensions where the relative permittivity (dielectric constant) is modulated periodically on the length angle. A PC has unique property that reflects light in one, two and three directions depending upon the periodicity on its dielectric layers. The photonic devices have better advantages over conventional electronic devices, because they offer very high operating speed and greater lifetime.

A one- dimensional photonic crystals has an index of refraction that is periodic in one direction and consists of a repeating stack of dielectric layers, which alternate in the thickness from a to b and in the index of refraction from n_1 to n_2 respectively. The 1D PCs has many applications like dielectric reflectors, optical limiters, threshold less semiconductor lasers [2, 3]. Moreover, the location and dimensions of the reflection band of PCs can be tailored by layers thickness and refractive index of each components material. The PCs with negative refractive index can be used to construct perfect lenses which are used to focus all information about a source object at a point. The various applications of PCs originate from the continuation of PBG in their transmission spectrum. The existence of PBG in the transmission spectrum of PCs is because of the powerful coupling of forward and backwards waves in the well defined energy band. The large value of reflectance existing in the PBG materials is efficacious in operating the well-known photonic component as multi-layer coating, Bragg's reflector, periodic wave-guide and band-gap filter. PCs are composite structures consisting of a periodic collection of media having dissimilar indices of refraction.

For last twenty years, porous silicon is being continuously used to fabricate the 1D and 2D PCs with easy fabrication technique which gives hundred percent reflection of light in one or two directions. The 1D PCs consisting of porous silicon have been demonstrated by various research groups [4, 5]. They present a new type of optical material which has received considerable attention in recent years for fundamental physics studies as well as for potential applications in photonic devices. The experimental as well as theoretical investigations of PCs is now much well-liked due to its important applications in the formation of photonic devices.

In this paper, a theoretical modeling followed by the numerical analysis of dispersive characteristics of 1D porous silicon PC is undertaken by taking into account the dependence of the transmittance/ reflectance on the angle of incidence of the electromagnetic wave. For the optimization of optical parameters of 1D PCs, the transmittance (transmission coefficient) and / or reflectance (reflection coefficient) and electric field components with respect to phase shift have been numerically obtained and analyzed.

2. Mathematical approach

For the analysis of electric field distribution, initially, we consider a three layer structure with refractive indices n_1, n_2 and n_3 for corresponding layers. We assume, here $n_1 = n_3 = 1$ and $n_2 = n$. Since in the case of normal incidence, the transverse magnetic (TM) and the transverse electric (TE) polarizations do not differ. So the Fresnel formula may be expressed as [6]:

$$r_{12} = r_{23} = \frac{n-1}{n+1} = -r_{12} = -r_{32} \equiv \rho$$

$$t_{12} = t_{32} = \frac{2}{n+1}$$

$$t_{21} = t_{23} = \frac{2n}{n+1} \qquad (1)$$

By using Airy's formula, the expression for reflection and transmission coefficients may be expressed as [7]

$$r = \frac{r_{12} + r_{23}e^{-2i\phi}}{1 + r_{12}r_{23}e^{-2i\phi}} \qquad (2)$$

$$t = \frac{t_{12}t_{23}e^{-i\phi}}{1 + r_{12}r_{23}e^{-2i\phi}}\,. \qquad (3)$$

Using equations (1), (2) and (3), we obtain

$$r = \frac{\rho(e^{-2i\phi} - 1)}{1 - \rho^2 e^{-2i\phi}} \qquad (4)$$

and

$$t = \frac{(1-\rho^2)e^{-i\phi}}{1 - \rho^2 e^{-2i\phi}}\,, \qquad (5)$$

where ρ is the reflection coefficient r_{21} or r_{23}.

The electric field in the region $x = 0$ and $x = d$ is given by

$$E = Ce^{-ik_2 x} + De^{ik_2 x}\,, \qquad (6)$$

where C and D are the field amplitudes.

By taking the expressions of field amplitudes and equation (1), the electric field may be expressed as

$$E = \frac{(1-\rho)A}{1 - \rho^2 e^{-2i\phi}}[1 + \rho e^{2i(k_2 x - \phi)}]e^{-k_2 x}\,. \qquad (7)$$

Here $\phi = k_2 d$ is the phase angle and A is the amplitude of the incident wave and the electric field varies with respect to phase angle. If

$$t = |t|e^{-i\psi}\,, \qquad (8)$$

where ψ is the phase shift which varies with respect to ϕ and it may be obtained as [8]

$$\psi = \phi + \tan^{-1}\left(\frac{\rho^2 \sin 2\phi}{1 - \rho^2 \cos 2\phi}\right). \qquad (9)$$

Further, for the solution of 1D photonic band-gap transfer matrix method has been used that co-relates the backward and forward travelling electromagnetic wave electric field amplitudes exactly at the boundary of two consecutive layers of PCs.

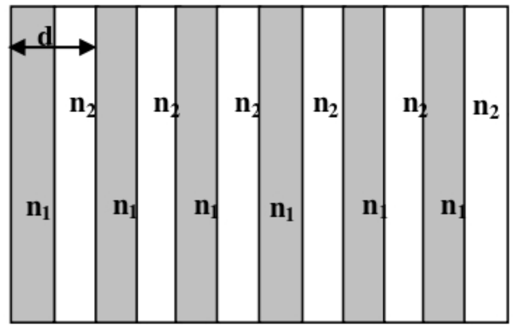

Figure 1. 1D PC consisting of alternative layers of index of refraction n_1 and n_2, respectively.

The considered structure of 1D PC is depicted in Figure 1. It consists of alternative layers of porous silicon with index of refraction n_1 and n_2. In the present numerical analysis, the author choose $n_1 = 1.4$ and $n_2 = 2.4$. The thickness of corresponding layers are a and b and $d = a + b$ is the lattice constant. The author also assumed that the alternative layers of chosen 1D PC are isotropic as well as homogeneous such that the whole structure may be represented as [9]:

$$n(x) = \begin{cases} n_1 & 0 < x < a \\ n_2 & a < x < d \end{cases}. \qquad (10)$$

By considering the Bloch wave theorem and applying boundary conditions, the dispersion relation for the case of normal incidence may be expressed as [10]

$$k(\omega) = \frac{1}{d}\cos^{-1}\left[\cos\left(\frac{\omega n_1 a}{c}\right)\cos\left(\frac{\omega n_2 b}{c}\right) - \frac{1}{2}\left(\frac{n_2}{n_1} + \frac{n_1}{n_2}\right)\sin\left(\frac{\omega n_1 a}{c}\right)\sin\left(\frac{\omega n_2 b}{c}\right)\right]. \qquad (11)$$

In equation (11), a, b, and ω are the thickness of first and second layer and angular frequency, respectively. Equation (11) is obtained by making the use of transfer matrix method [11].

3. Results and discussions

The distribution of electric field as a function of phase angle ($\phi = k_2 d = (2\pi/\lambda)n_2 \cos\theta$) is shown in Figure 2. Since the electric field is continuous function of phase angle (ϕ) then for the case of interface $x = 0$, the electric field is minimum at

$\phi = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \ldots$ and it is maximum at $\phi = 0, \pi, 2\pi, \ldots$

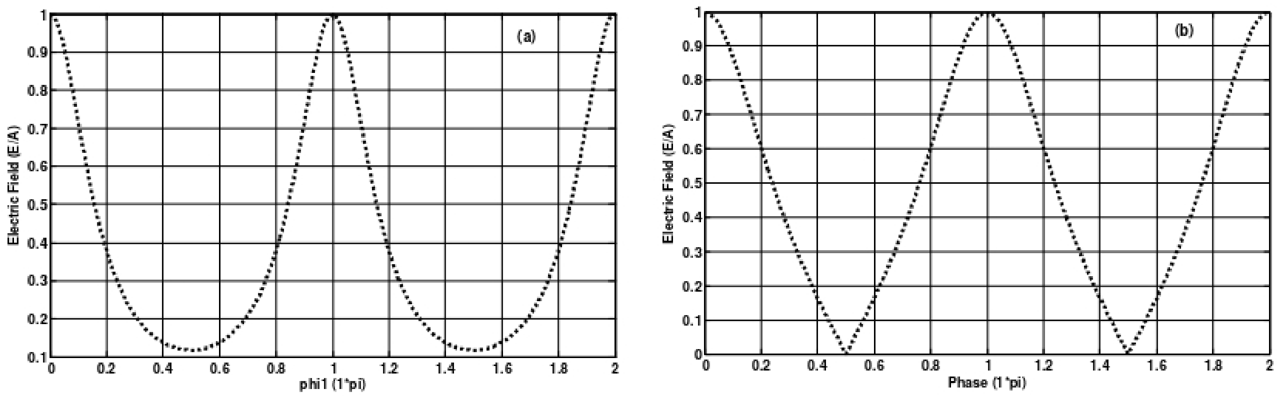

Figure 2. Electric field as a function of phase angle at:
(a) interface $x = 0$, and (b) $x = d$.

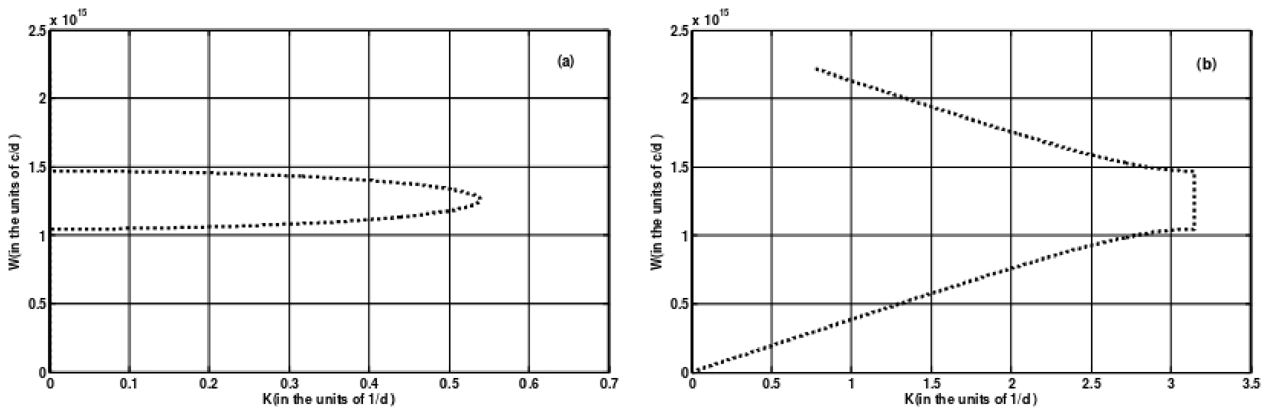

Figure 3. Dispersive relation of 1D PC for:
(a) imaginary values, and (b) real values of Bloch wave vector.

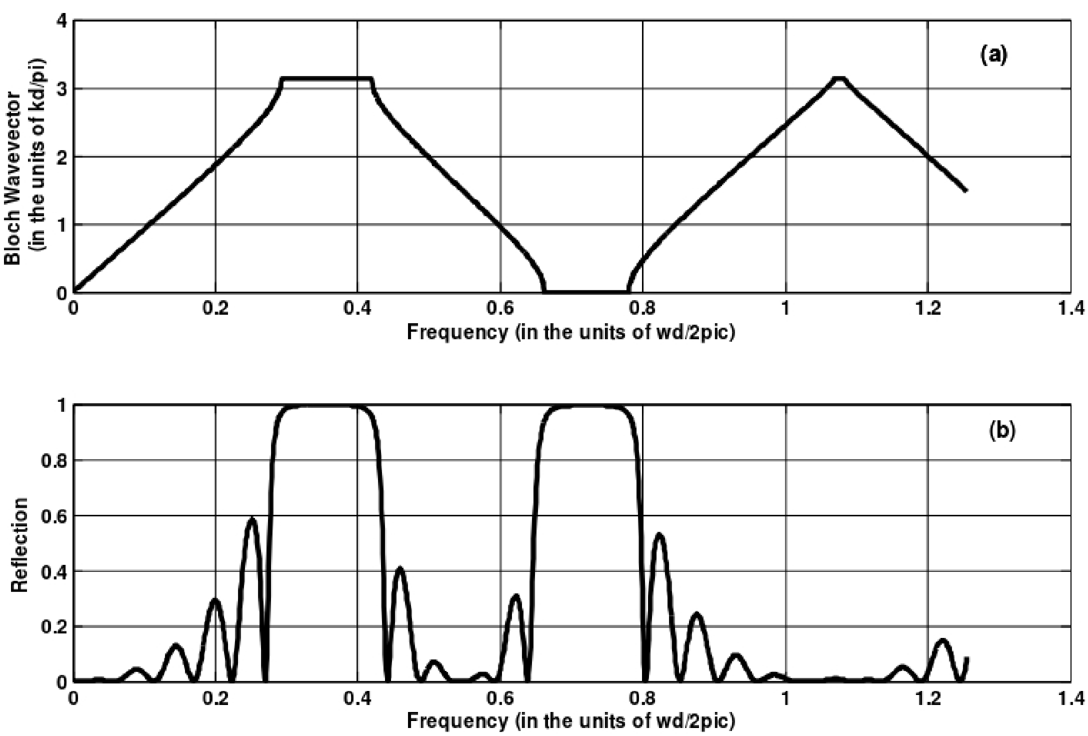

Figure 4. (a) Variation of 1D photonic band-gap versus normalized frequency
(b) Variation of reflection versus normalized frequency.

When electric field is maximum in a certain region, it means that the transmission of light is maximum or reflection is zero through the layer. However, the electric field is maximum in case of interface $x = d$ which is shown in Figure 2(b), i.e. variation of electric field with respect to phase angle.

In order to make the numerical calculation of dispersion relation of 1D PC, the author choose the two alternative layers of porous silicon with index of refraction $n_1 = 1.4$ and $n_2 = 2.4$ at wavelength $\lambda = 1.5$ micron. For the case of normal incidence the dispersion relation, Bloch wave vector has been calculated which gives complex values where imaginary and real values are correspond to forbidden and pass bands, as shown in Figure 3(a) and 3(b) versus the frequency of electromagnetic wave. The range of photonic band-gap region is $\omega = 1.1 - 1.45 \times 10^{15}$ (in the units of c/d). Figure (4) shows the variation of photonic band-gap and reflection versus normalized frequency for the case of TE polarization. In this figure it is observed that within the photonic band-gap the reflection is maximum for certain number of porous silicon layers. We have also observed that as the angle of incidence change the range of band-gap varies which ultimately shifts the position of reflection curve.

4. Conclusions

For the study of dispersive properties of 1D porous silicon PCs the electric field, reflection/ transmission and dispersion relation for both normal incidence and TE polarization have been numerically analyzed. The electric field component at the interface $x = 0$ and $x = d$ for single dielectric layer has been numerically analyzed. It is observed that at particular phase angle, the electric field is maximum or minimum. The maximum or minimum electric field means that at particular angle, the reflection of light is low or high and accordingly the phase will change and it shifts between π and $-\pi$. For the estimation of photonic band-gap two layers of porous silicon with index of refraction $n_1 = 1.4$ and $n_2 = 2.4$ have been assumed. The dispersion relation for the case of normal incidence and TE polarization ($\theta = 45^o$) has obtained which gives complex values i.e. imaginary values corresponding to the forbidden bands and real for pass bands. Within photonic band-gap regions, it is found that reflection response is maximum through the structure. However, with change of angle of incidence it is observed that there is shifting of the position of reflection curve.

Acknowledgements

The authors would like to thank Dr. Manjeet Singh, Assistant Professor, Department of Physics, Govt. College, Matanhail, Jhajjar – 124106 (Haryana) India for careful reading of this manuscript during second stage of the revision.

References

[1] E. Yablonovitch, Inhibited spontaneous emission in solid state physics and electronics, *Phys. Rev. Lett.* **58** (1987) 2059-2062.

[2] J.D. Joannopoulos, R.D. Meade, J.N. Winn, Photonic Crystals: Molding the Flow of Light, Princeton University Press, Princeton, N.J. (1995).

[3] K. Sakoda, Optical Properties of Photonic Crystals, Springer Series in Optical Sciences, Springer, Berlin (2001).

[4] C. Mazzoleni, L. Pavesi, Application of optical components of dielectric porous silicon layers, *Appl. Phys. Lett*. **67** (1995) 2983-2985.

[5] M.D. Tocci, M. Scalora, M.J. Bloemer, J.P. Dowling, C.M. Bowden, *Phys. Review A* **53** (1996) 2799-2803.

[6] R.S. Dubey, D.K. Gautam, Photonic band-gap analysis in 1D porous silicon photonic crystals using transfer matrix method, *Optoelectron. Adv. Mater*. **1** (2007) 436-441.

[7] M. Beresna, R. Tomaoifl, J. Volk, G. Kadar, Modeling of reflectivity in 1D porous silicon photonic crystal, *Lithuanian J. Phys*. **47** (2007) 415-419.

[8] A.M. Ahmed, A. Mehaney, Ultra-high sensitive 1D porous silicon photonic crystal sensor based on the coupling of Tamm/Fano resistances in the mid-infrared region, *Sci. Rep*. **9** (2019) 6973.

[9] O. Soltani, S. Francoeur, M. Kanzari, Superconductor-based quaternary photonic crystals for high sensitivity temperature sensing, *Chin. J. Phys*. **77** (2022) 176-188.

[10] V.B. Novikov, S.E. Svyakhovskiy, A.I. Maydykovskiy, T.V. Murzina, B.I. Mantsyzov, Optical pendulum effect in one-dimensional diffraction-thick porous silicon based photonic crystals, *J. Appl. Phys*. **118** (2015) 193101.

[11] M.B. de la Mora, J.A. del Rio, R. Nava, J. Taguena-Martinez, J.A. Reyes-Esqueda, A. Kavokin, J. Faubert, J.E. Lugo, Anomalous patterned scattering spectra of one-dimensional porous silicon photonic crystals, *Opt. Exp*. **18** (2010) 22808-22816.