Research Article

Numerical method for a one dimensional defective photonic crystal selective filters

Abstract

In this work, we demonstrate via numerical simulation the general design for one dimensional defective photonic crystal (1D- DPC), the defect was fictionalized with two different dielectric layers. In the design procedure, the transfer matrix method is used to determine the transmission coefficient for both TE (Transverse Electric) and TM (Transverse Magnetic) modes. Then, we focused point on a special class of optical elements, namely selective filters. Simulation results obtained showing the number of defect mode within the photonic band gap (PBG) in the asymmetric (1D- DPC) structure, more than in the symmetric (1D- DPC) structure. The dependences of defect modes on the angle of incidence are illustrated.

Keywords: photonic band gap, transfer matrix method, defect mode, transmission, dispersion

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Introduction

The one dimensional photonic crystal (1D-PC) structures have become attractive to optical engineering due to its several beneficial features, such as its ability to control and manipulate the propagation of electromagnetic waves in limited space.[1] These structures have a number of useful properties, which are employed as low-loss optical waveguides, dielectric reflecting mirrors, optical switches, optical limiters, and optical filters etc.[2–4] It has been demonstrated experimentally and theoretically that (1D-PC) structures have complete omnidirectional photonic band gaps (PBGs).[5] Therefore it is possible to create pass bands within the photonic band-gap by introducing of defects layers. When a defect layer is inserted into a one dimensional photonic crystal, localized defect mode will be appeared in the photonic band gaps (PBG), which are much more similar to the defect states generated in the forbidden band in a doped semiconductor. Recently, the defect modes inside the photonic band have been widely studied due to their properties.[6–10] The perfect layer can be realized, by changing physical parameters, such as changing the thickness of one of the layer, adding another medium to the structure, or removing a layer from (1D-PC) structures. The localized defect modes, which are also called resonant transmission peaks, can be generated within the PBG due to the change of the interference behavior of light. The defect models properties can be used to make high quality extremely narrowband frequency selective filters.[7–11] Selective photonic crystal filters have received much research interest in the fields of demultiplexers for WDM systems.[12] Nowadays, the numerical modeling of photonics crystals is based on the calculation of the transmission, and the reflection coefficient properties. These methods including the plane wave expansion (PWE) method, the generalized Rayleigh identity method, the finite-difference time-domain (FDTD) method, and the transfer matrix method (TMM). Each method has its own limitations for finding some important properties of one dimensional defective photonic crystal (1D-DPC). The transfer matrix method is most popular because of its simplicity in algorithm and capability to model complex structures.[13,14] It is recently introduced by Pendry and MacKinnon, to calculate the electromagnetic transmission through the PBG materials.[15] In this paper, the transmission spectrum was obtained by applying the transfer matrix formalism to one dimensional defective photonic crystal (1D-DPC). The effects of the polarization and the angle of incidence on the defect modes in the

transmission spectra are investigated. Several simulation cases by Matlab will be given to show the performance of this approach. The accuracy of the analysis is tested by comparing the computed results with measurements published data.

Theory

Let us consider first the (1D-PC) structure consisting of alternating multilayer of the form $(AB)^N D (AB)^N$ and $(AB)^N D (BA)^N$ shown in Figure 1, there are 2N+1 layer made up of dielectric materials A and B, and dielectric defect layer D. Each layer has to be d_l thicknesses, and refractive index n_l. In order to find the formulation of the structure, we supposed that the incident electromagnetic wave from air to In As and SiO$_2$ medium. Let the layers be in the x-y plane, the z direction being normal to interface of layers.

The refractive index profile of considered structure can be given as

$$\varepsilon_l(z) = \varepsilon_l(z + d) \qquad (1)$$

And

$$\varepsilon_l(z) = \varepsilon_l(z + d) \qquad (2)$$

Where

L, is number of layer

$$d = d_1 + d_2 , \text{ is period}$$

Based on the Maxwell equations and the boundary conditions, the TMM has been widely used to calculate the amplitude and phase spectra of the light wave propagating in a (1D- PC) structure. We are going to suppose that a space time dependence of all the components of the kin $e^{i(\vec{k}.\vec{r} - \omega t)}$. The transverse components of the E and H fields from Maxwell's equations in the lth layer, for TM polarization, are given by:

$$H_{ly} = A_l e^{i\left(\omega t - k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} + B_l e^{i\left(\omega t + k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} \quad) \ (3)$$

$$E_{lx} = \eta_l \cos\theta_l (A_l e^{i\left(\omega t - k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} - B_l e^{i\left(\omega t + k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)})$$

$$(4)$$

$$E_{lz} = -\eta_l \cos\theta_l \left(A_l e^{i\left(\omega t - k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} + B_l e^{i\left(\omega t + k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} \right) \quad (5)$$
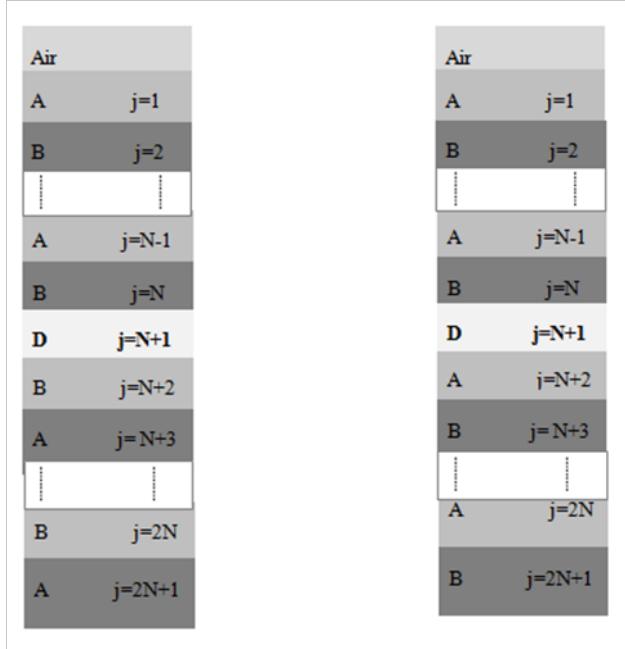

Figure 1 Structure of one-dimensional photonic crystal containing a defect.
Symmetric defective (1D- DPC); Asymmetric defective (1D- DPC)

Where A_l and B_l are the amplitudes of the forward and backward travelling waves in the lth layer.

The transverse components of the E and H fields from Maxwell's equations in the lth layer, for TE polarization, are given by:

$$E_{ly} = A_l e^{i\left(\omega t - k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} + B_l e^{i\left(\omega t + k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} \quad (6)$$

$$H_{lx} = -\frac{\eta_l}{\cos\theta_l}\left(A_l e^{i\left(\omega t - k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} - B_l e^{i\left(\omega t + k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} \right) \quad (7)$$

$$H_{lz} = \frac{\eta_l}{\cos\theta_l}\left(A_l e^{i\left(\omega t - k_l\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} + B_l e^{i\left(\omega t + k_1\left(Z_l.\cos\theta_l + X_l.\sin\theta_l\right)\right)} \right) \quad (8)$$

Where the wave numbers and intrinsic impedances are:

$$k_l = \omega\sqrt{\varepsilon_0\mu\varepsilon_1\mu_1} \quad (9)$$

$$\eta_1 = \frac{k_1}{\omega\varepsilon_1\varepsilon_0} = \sqrt{\frac{\mu_1}{\varepsilon_0\varepsilon_1}} \quad (10)$$

When an electromagnetic wave propagates in (1D- PC) structure, the incident, reflected and transmitted electric fields are connected via the transfer matrix M. By using the boundary conditions and the condition of continuity of E and H fields at the interfaces of $z = 0$ and $z = d_1, d_2, d_3 \dots\dots d_N$, we can find out the relationship between the fields (1D- PC) structure consisting of l layer, this relation is already exposed.[16]

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = M_1 M_2 \dots\dots M_N M_d \dots. M_{2N} M_{2N+1} \begin{bmatrix} E_l \\ H_l \end{bmatrix} \quad (11)$$

The matrix M_{l-1} of the lth layer can be written in the form.[17–19]

$$M_{(l-1)} = \begin{bmatrix} \cos\left(\delta_{(l-1)}\right) & i\gamma_{(l-1)}\sin\left(\delta_{(l-1)}\right) \\ i\gamma_{(l-1)}^{-1}\sin\left(\delta_{(l-1)}\right) & \cos\left(\delta_{(l-1)}\right) \end{bmatrix} \quad (12)$$

$\delta_{(l-1)}$ and $\gamma_{(l-1)}$ being the matrix parameters and depending on the incident angle of light, the optical constants and the layer thickness, are expressed as:

$$\delta_{(l-1)} = k_{(l-1)}.d_{(l-1)}.\cos\theta_{(l-1)} \quad (13)$$

$$\gamma_{(l-1)} = \begin{cases} \dfrac{\eta_{(l-1)}}{\cos\theta_{(l-1)}} & TE \quad mode \\ \eta_{(l-1)}\cos\theta_{(l-1)} & TM \quad mode \end{cases} \quad (14)$$

We note that $\theta_{(l-1)}$ is related to the angle of incidence θ_0 by the Snell's Descart's low, that is

$$n_{(l-1)}\sin\theta_{(l-1)} = n_0\sin\theta_0 \quad (15)$$

By considering the transmission matrix of each layer, we are able to obtain the transmission matrix of whole structure. For l number of multilayers; the corresponding transfer matrix can be defined as a product of matrices, is obtained for symmetric PBG structure.[20,21]

$$M = \prod_{k=1}^{(2N+1)} M_k = \left(M_A M_B\right)^N M_D \left(M_A M_B\right)^{(2N+1)} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (16)$$

And for asymmetric PBG structure.

$$M = \prod_{k=1}^{(2N+1)} M_k = \left(M_A M_B\right)^N M_D \left(M_A M_B\right)^{(2N+1)} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (17)$$

Where

M_A is the transfer matrix of the first dielectric layer.

M_B is the transfer matrix of the second dielectric layer.

M_D is the transfer matrix of the dielectric layer defect.

These formulas can be modified by using N number of defect, are obtained for symmetric PC

$$M = \left(M_A M_B\right)^N M_D.M_B.M_D \dots.\left(M_B M_A\right)^{(2N+L)} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (18)$$

Where L is number of dielectrics layers defect and dielectric layer B between the defects. And for asymmetric PC

$$M = \left(M_A M_B\right)^N M_D.M_B.M_D \dots.\left(M_A M_B\right)^{(2N+L)} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (19)$$

Where m_{11}, m_{12}, m_{21} & m_{22} are the complex numbers

The transmittance *t* and reflectance *r* are defined as the ratios of the fluxes of the transmitted and reflected waves, respectively, to the flux of the incident wave. After some derivations, the total transmission and reflection coefficients

are given by

$$r = \frac{\left(m_{11} + p_s^{-1} m_{12} \right) p_0^{-1} - \left(m_{21} + p_s^{-1} m_{22} \right)}{\left(m_{11} + p_s^{-1} m_{12} \right) p_0^{-1} + \left(m_{21} + p_s^{-1} m_{22} \right)} \qquad (20)$$

$$t = \frac{2 . p_0^{-1}}{\left(m_{11} + p_s^{-1} m_{12} \right) p_0^{-1} + \left(m_{21} + p_s^{-1} m_{22} \right)} \qquad (21)$$

Here p_0 and p_s are the first and last medium of the structure which given as

$$p_0^{-1} = \begin{cases} \dfrac{\eta_0 \cos \theta_0}{Z_0} & TE \ mode \\[3mm] \dfrac{\eta_0}{Z_0 \cos \theta_0} & TM \ mode \end{cases} \qquad (22)$$

$$p_0^{-1} = \begin{cases} \dfrac{\eta_0 \cos \theta_0}{Z_0} & TE \ mode \\[3mm] \dfrac{\eta_0}{Z_0 \cos \theta_0} & TM \ mode \end{cases} \qquad (23)$$

Where

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

Hence the reflectance R and transmittance T spectrums of can be obtained by using the expressions:

$$R = |r|^2 \qquad (24)$$

$$R = |r|^2 \qquad (25)$$

Numerical calculation and discussion

In this subsection, the transmission spectra have been calculated using the theory described in previous section. We consider only normal incidence of the electromagnetic wave on the (1D- PC) structure. The structure is restructured as $(A_n B_n)^m$ where n = 1 . . m, m is chosen as 8. We have kept constant the refractive index of the layers, are fixed to be n_{InAs} = 3.3842, and n_{SiO2} = 1.4672 at λ=0.43μm. The layer thicknesses were taken as d_{SiO2} =0.0733μm, and d_{InAs} =0.0318μm. The transmission spectra in Figure 2 is computed and plotted with wavelength centered at 550 nm. According to these results, we are able to see that the structure exhibits various band gaps (or stop band) where the photonic states are forbidden in the structure, can be seen in the transmission spectrum. Furthermore we have observed that the phonic band gap which is limited at 342.7nm to 578.3nm. In order to check the effects of the defect layer, we introduce a defect layer TiO_2 with refractive index n_{TiO2}=2.8717, and thickness d_{TiO2}=0.0187μm, in the (1D-DPC) structures containing InAs and SiO_2. The refractives index of InAs and SiO_2 are n_{InAs}=3.3842, n_{SiO2}=1.4672, and thickness d_{InAs}=0.0318μm, d_{SiO2}=0.0733μm. In Figures 3, we have plotted the wavelength-dependent transmittance spectra for the symmetric and asymmetric (1D- DPC) structures. Because of the existence of

defect layer, it is found that there exists a very narrow pass band or single defect mode within the photonic band gap (PBG) is observed. For the asymmetric (1D-DPC) structure with the configuration (*Air/(AB)⁴D(AB)⁴/ Air*), the bandwidth was calculated as Δ_{Bwp} =(601.504-332.1712) =269.3328nm, and the resonant peak locates at the design wavelength of λ=370.2nm. For the symmetric (1D- DPC) structure with the configuration (*A/(AB)⁴D(BA)⁴/Air*), the bandwidth was calculated as Δ_{Bwp}=(604.294-334.252)=270.042nm, the resonant peak locates at the design wavelength of λ=532.4nm. Additionally, as seen from the figures, in the asymmetric structure the defect modes appear in higher frequencies with a small amplitude compared to the symmetric structure. Accordingly, this reduction in the amplitude of the defect peak becomes more significant for the case of asymmetric structure. These behaviors agree very well with those reported by work.[20–22] The effects of the polarization and the angle of incidence on the defect modes in the transmission spectra for TE or TM modes are illustrated in Figure 4, Figure5 & Table 1. We have clearly observed that the transmittance spectrum of the defect mode is linked to the angle of incidence in TE and TM modes. Also, the position of narrow pass band is changed, and width of the band increases obviously for TE mode, and decrease for TM mode. On the other hand a pick of transmission change in the direction of small values when the angle incidences increase for TM mode. As shown in Figure 4, a pick of transmission occurred at the wavelength 532.4nm when θ=0°, 519.9nm when θ=30°, 492.2nm when θ=60°, and 481.6nm when θ=75° for TE mode. As seen and extracted from the Figure 5, the variation of transmission spectra for TM mode, a pick of transmission with a weak value occurred at the wavelength 504.6 nm when θ=30°, 444.2 nm when θ=60°, and 420.8 nm when θ=75°. Moreover, for both polarizations the frequency of the defect mode is shifted to the higher frequency as the angle increases. In addition, these results reveal that as the angle of incidence increases, the peak height of the defect mode decreases for TM mode and increases for TE mode. A comparative study, between our results and those available in the literature, shows the possibilities of the adjustment of transmission spectra of InAs and SiO_2 mediums in presence of TiO_2.The change in the angle of incidence and the polarization allows us to obtain an adjustable defect mode.[9] In Figure 6, we examine the effects of the two defect layers, by introducing two defect layer TiO_2 having thickness d_{TiO2} = 0.0374μm, in the (1D-DPC) structure symmetric and symmetric. It is found that there exists a two defect mode within the photonic band gap (PBG) in the(1D-DPC) structure symmetric with the configuration ((*Air/(AB)⁴DBD(BA)⁴/Air*)), the bandwidth was calculated as Δ_{Bwp}=(613.312-331.404) =281.908nm, as well as the resonant peak locates at the design wavelength of λ_1=364.9 nm and λ_2=523.6nm. For the (1D- DPC) structure asymmetric with the configuration (*Air/(AB)⁴DBD(AB)⁴/Air*), the bandwidth was calculated as Δ_{Bwp}=(600.4 -335.3)= 265.1nm, and the resonant peak locates at the design wavelength of , λ_1=430.1nm. In Figure 7, *we have examined the effect* the effects of the tree defect layers, by introducing tree defect layer TiO_2 in the (1D- DPC) structures symmetric and asymmetric. It was found that it existed a tree defect mode within the photonic band gap (PBG) in the (1D-DPC) structure symmetric with the configuration (*Air/(AB)⁴DBDBD(BA)⁴/Air*, the bandwidth was calculated as Δ_{Bwp}=(605.107-343.632)=261.475nm, the resonant peak locates at the design wavelength of , λ_1=354.9nm, λ_2=429.9nm and λ_3=545. 3nm. For the (1D- DPC) structure asymmetric with the configuration (*Air/(AB)⁴DBD(AB)⁴/Air*), the bandwidth was calculated as Δ_{Bwp}=(574.54-343.666)=230.874nm, the resonant peak locates at the design wavelength of λ_1=396.8 nm and λ_2=468.9nm. Our results

imply that the number of defect mode can be increased by adding the layer TiO$_2$ in structure.[8]
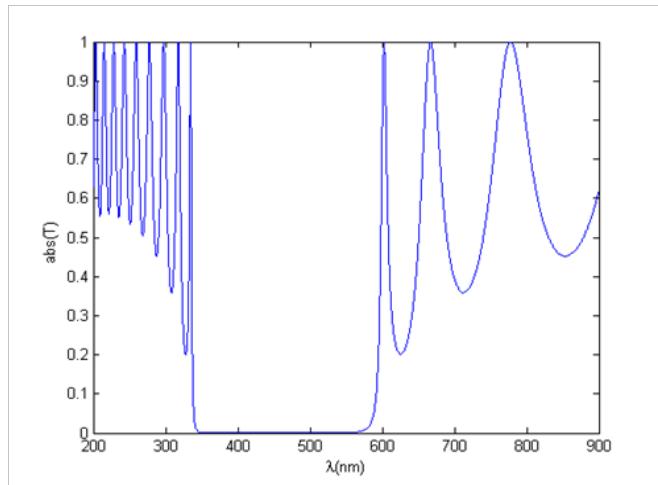
**Figure 2** Transmission spectra of (1D- PC) structure, n$_{InAs}$=3.3842, n$_{SiO2}$=1.4672, d$_{InAs}$=0.0318μm, d$_{SiO2}$=0.0733μm.
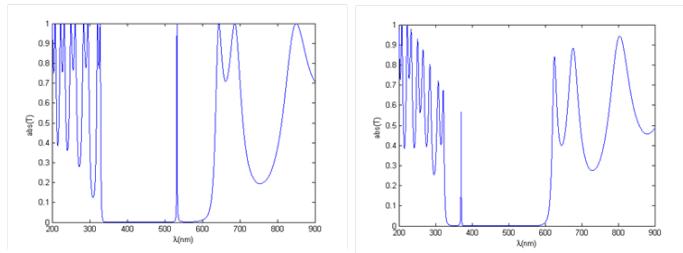

Figure 3 Transmission spectra of symmetric and asymmetric (1D-DPC) structure.

(A) Symmetric (1D-DPC) structure; (B) Asymmetric (1D-DPC) structure (*Air/ (AB)⁴ D (BA)⁴/ Air) (Air/ (AB⁴D (AB)⁴/ Air*)
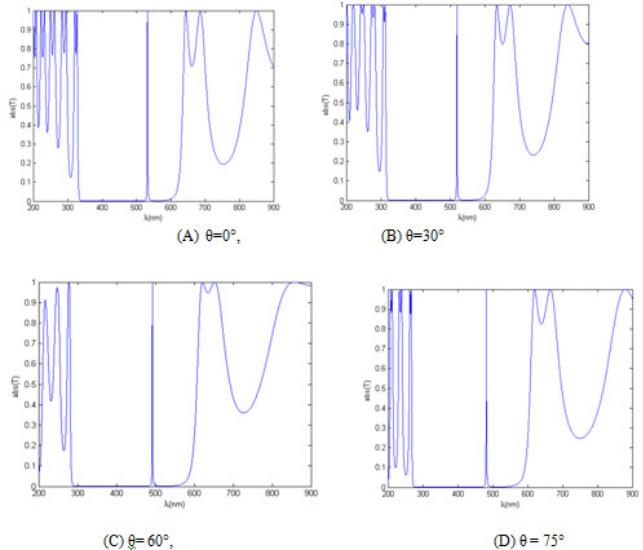
Figure 4 Transmission spectra of (1D-DPC) structure symmetric (*Air/ (AB)⁴D(BA)⁴/Air*), TE mode (n$_{InAs}$=3.3842, n$_{SiO2}$=1.4672, d$_{InAs}$=0.0318μm, d$_{SiO2}$=0.0733μm, n$_{TiO2}$=2.8717, d$_{TiO2}$=0.0187μm).

(A) θ =0°   (B) θ= 30°

(C) θ= 60°   (D) θ = 75°
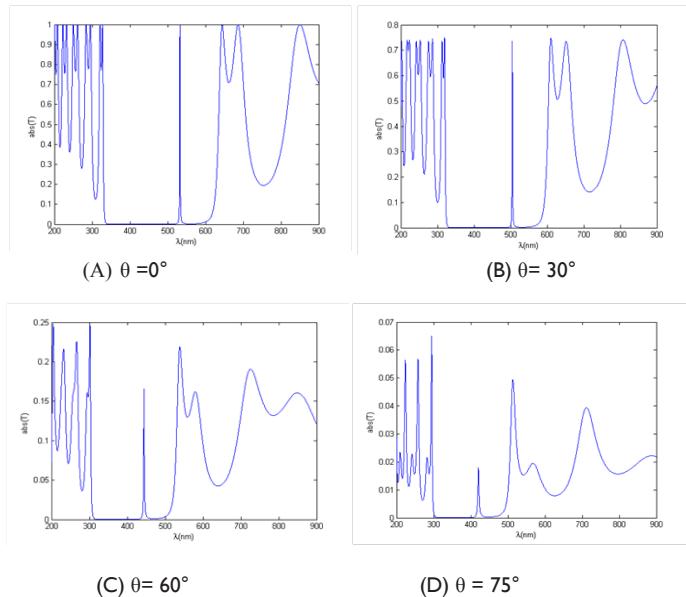
Figure 5 Transmission spectra of (1D- DPC) structure symmetric (*Air/ (AB)⁴D(BA)⁴/Air,* TM mode

(n$_{InAs}$=3.3842, n$_{SiO2}$=1.4672, d$_{InAs}$=0.0318μm, d$_{SiO2}$=0.0733μm, n$_{TiO2}$=2.8717, d$_{TiO2}$=0.0187μm).
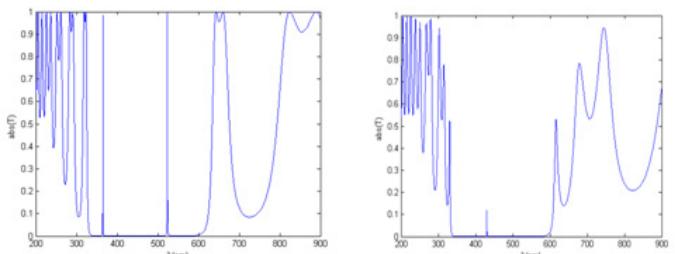
(A) Symmetric (*Air/(AB)⁴DAD(BA)⁴/Air*); (B) Asymmetric (*Air/(AB)⁴DBD(AB)⁴/Air*)

Figure 6 Transmission spectra of (1D- DPC) structure (n$_{InAs}$=3.3842, n$_{SiO2}$=1.4672, d$_{InAs}$=0.0318μm, d$_{SiO2}$=0.0733μm, n$_{TiO2}$=2.8717, d$_{TiO2}$=0.0374μm, θ=0°).
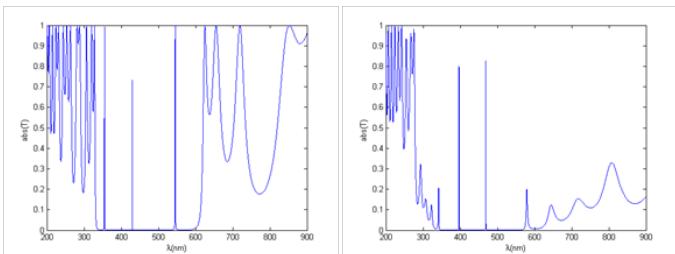
(A) Symmetric (*Air/(AB)⁴DADAD(BA)⁴/Air);*   (B)Asymmetric (*Air/ (AB)⁴DBDBD(AB)⁴/Air*)

Figure 7 Transmission spectra of (1D- DPC) structure (n$_{InAs}$=3.3842, n$_{SiO2}$=1.4672, d$_{InAs}$=0.0318μm, d$_{SiO2}$=0.0733μm, n$_{TiO2}$ =2.8717, d$_{TiO2}$ =0.0748μm, θ=0°).

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Table 1 Bandwidth and wavelength with different the angle of incidence and polarization of Transmission spectra of (1D- DPC) structure symmetric (*Air/(AB)⁴D(BA)⁴/Air*), (n_{InAs}=3.3842, n_{SiO2}=1.4672, d_{InAs}=0.0318μm, d_{SiO2}=0.0733μm, n_{TiO2}=2.8717, d_{TiO2} = 0.0187μm)

θ	TE mode		TM mode	
	ΔBwp(nm)	λ(nm)	ΔBwp(nm)	λ(nm)
0°	(604.294-334.252)= 270.042	532.4	(604.294-334.252)=270.042	532.4
30°	(597.66-318.9)=278.76	519.9	(579.1-325.4)=253.7	504.6
60°	(576.5-285.9)=290.6	492.2	(518.1-306.3)=211.8	444.2
75°	(574.4 -271.6)=302.8	481.6	(504.9-296.6)=208.3	420.8

Conclusion

In summary, we have used the transfer matrix method to study one-dimensional photonic crystal defectives. We have discussed the properties of the defect modes for the asymmetric and symmetric structures for both TE and TM modes at different incidence angles. The results have shown the calculated the transmission with defects separated by different layers. When the order of the defect layer increased such as m=1, 2, 3 etc, additional modes occurs in photonic band gap. We can conclude that when the existence of defect layer, there is a very narrow pass band whose pick of transmission is observed. The maximum of transmission was obviously observed at these wavelengths for TE mode. Besides the dependence on angle of incidence of the defect mode, it has been noticed that selection of wave mode has significant effect on the peak position and amplitude of the defect mode. In other words, defect modes peak is related to the angle of incidence. For TM mode, the magnitude of transmission of the pass bands decrease for higher angle incidence. However, in TM waves, the frequency increases as the angle of incidence increases.

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Conflict of interests

Authors have declared no conflict of interests.

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