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Research Article

Theoretical analysis on one-dimensional metamaterial nanocomposite photonic crystal

J.R. Sofia [a,b,*], K.S. Joseph Wilson [a]

[a] PG & Research Department of Physics, Arul Anandar College, Madurai Kamaraj University, Madurai, 625514, Tamil Nadu, India
[b] Research Centre of Physics, Fatima College, Madurai Kamaraj University, Madurai, 625018, Tamil Nadu, India

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ABSTRACT

Transmission spectra of one-dimensional photonic crystal (1D-PC) comprising metamaterial and silver-dielectric nanocomposite layers are analyzed using the Transfer Matrix Method (TMM). The effective permittivity of the Ag-dielectric nanocomposite is calculated using the Maxwell-Garnett equation, while the permittivity and permeability of the metamaterial are obtained using the Drude model. By varying the photonic crystal parameters, the photonic band gap (PBG) is analyzed. Better results are obtained by optimising the photonic crystal parameters. The transmittance spectra of the 1D-PC are obtained for two different configurations. Of which, one configuration provides propagation mode in the PBG, which can be used in signal processing devices, and the other one has a wider PBG, which can be used as Distributed Bragg Reflectors (DBRs) in solar cells.

1. Introduction

Photonic crystals (PCs) have control over the propagation of electromagnetic waves, and exhibits zero transmittance of band of wavelengths, called as photonic band gap (PBG). The functionality of the PCs with PBG in the visible region, as Distributed Bragg Reflectors (DBRs) in solar cells has been researched widely. Metals are dispersive media, as they show high absorption at frequencies that are lower than the plasmon frequency [1]. The dispersive nature of metals can be utilized by employing metal-dielectric nanocomposites in the photonic crystals, as PBG occur due to damping of electromagnetic waves [2–4]. PCs with metal-dielectric nanocomposites provide the chance of altering the occurrence and width of PBG with the fill fraction of metal in the dielectric host, radius of the metal nanoparticles, and dielectric constant of the dielectric host [5–9]. One-dimensional PCs constructed with silver metal nanocomposites generate wider PBGs, in the visible spectrum as the nanocomposites exhibit resonance peaks of real and imaginary parts of the permittivity that occur in the visible region [10–13].

Materials with simultaneously negative permittivity and permeability termed as Double Negative (DNG) metamaterials, exhibit properties that are strikingly different from the constituent materials [14, 15]. DNG metamaterials have been coupled with dielectrics, metals, semiconductors and superconductors and transmittance spectra have been analyzed. Arafa H Aly et al. [16] studied the transmittance properties of 1D-PC designed with metamaterials and superconductor, and reported that the PBG is determined by the temperature, and hence can be employed in sensors. Sabah et al. [17] designed 1D-PC using DNG metamaterial with dielectric slabs, and observed that transmission modes as well as broad PBG could be achieved. Research carried out extensively with DNG metemerials generated omnidirectional PBGs in the GHz region [18–21].

In the photonic crystal made up of dielectric materials with positive permittivity and permeability, Bragg scattering occurs, and the interference of the scattered waves results in the PBG of the photonic crystal [22]. On the other hand, metamaterial based photonic crystal can give rise to new kinds of photonic band gaps called zero-average index gaps, zero-permittivity gaps, or zero-permeability gaps which are unaffected by the polarization, angle of incidence, periodicity and defects [23,24]. With the advent of novel materials such as negative index metamaterials, absolute manipulation of electromagnetic waves has various applications in self-collimating optical lenses, filters, reflectors, and waveguides [25–32].

Guang Lu et al. [33] analyzed the transmittance spectra of hyperbolic metamaterial based 1D-PC and obtained PBG in the ultraviolet region. They observed that both long wavelength and short wavelength band edges of the PBG red-shifted and blue-shifted with increase in the angle of incidence. Widening of PBG with the angle of incidence makes this 1D-PC superior to conventional all-dielectric PCs. Aliaa. G.Mohamed

* Corresponding author. Research Centre of Physics, Fatima College, Madurai Kamaraj University, Madurai, 625018, Tamil Nadu, India.
E-mail address: jrsofia@aactni.edu.in (J.R. Sofia).

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et al. [34,35] analyzed the transmittance spectra of 1D-PC with alternate layers of metamaterial and nanocomposite layers. The metamaterial possessing negative permittivity and permeability ensured PBG occurrence in the GHz region. When metal fill fraction is increased, the PBG gets blue-shifted. Therefore, a DNG metamaterial, possessing simultaneous negative permittivity and permeability in the visible region would ensure zero-index band gaps in the visible region. Adding to that, blue-shifting of PBG with the fill fraction (f) of the nanocomposite would localize the high energy photons with the solar cell, and hence improves the efficacy of the DBRs.

On this outlook, one-dimensional photonic crystal comprising DNG metamaterial, as layer A and Ag–MgF_2 nanocomposite as layer B is designed. The transmission spectra of the photonic crystal are analyzed by Transfer Matrix Method (TMM) for various number of periods (N), angle of incidence (θ_0) & Ag-fill fraction (f) of the nanocomposite.

2. Theory and calculation

The proposed one-dimensional photonic crystal (1D-PC) as depicted in Fig. 1 comprises a DNG metamaterial as layer A and metal-dielectric nanocomposite made of silver (Ag) nanoparticles dispersed in the dielectric (MgF_2) matrix as layer B. The layers A and B have refractive indices n_1 and n_2 and their thicknesses are d_1 and d_2 respectively.

The effective permittivity and permeability of the DNG metamaterial (layer A) are given according to the Drude model [36,37] as

$$\varepsilon_1 = \varepsilon - \frac{\omega_p^2}{\omega^2 + j\omega\gamma} \tag{1}$$

$$\mu_1 = \mu - \frac{\omega_p^2}{\omega^2 + j\omega\gamma} \tag{2}$$

where ω_p is the plasma frequency of the metamaterial, ω is the frequency of the incident electromagnetic wave and γ is the damping factor that contributes to absorption and loss.

The effective permittivity of Ag-NPs doped nanocomposite is given by the Maxwell-Garnett equation as [10].

$$\varepsilon_{eff}(\omega) = \frac{2\varepsilon_b f(\varepsilon_m(\omega) - \varepsilon_b) + \varepsilon_b(\varepsilon_m(\omega) + 2\varepsilon_b)}{2\varepsilon_b + \varepsilon_m(\omega) + f(\varepsilon_b - \varepsilon_m(\omega))} \tag{3}$$

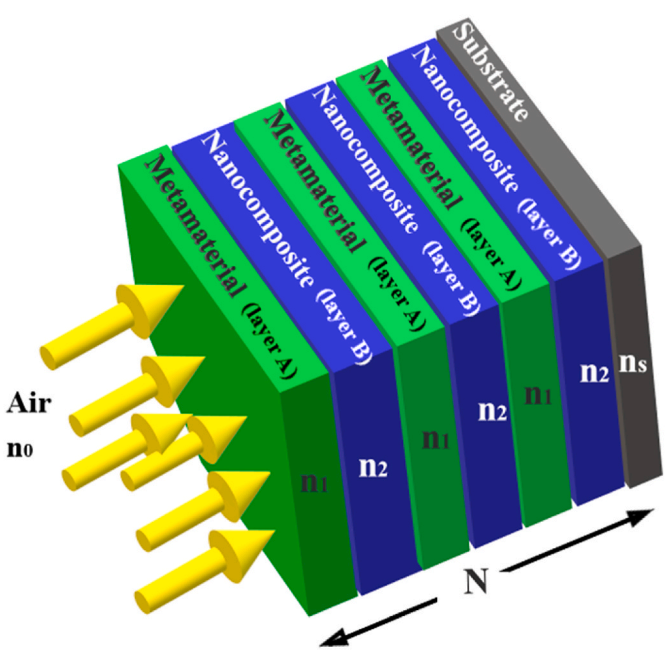

Fig. 1. Schematic Diagram of proposed one-dimensional photonic crystal.

where, f is the fill fraction of Ag-NPs, ε_m and ε_b are the permittivity of Ag-NPs and dielectric host material (MgF_2) respectively.

The permittivity of Ag-NPs is given by Drude model as

$$\varepsilon_m = \varepsilon_0 - \frac{(\omega_p')^2}{\omega^2 + i\omega\delta'(r)} \tag{4}$$

ω_p' is the plasma frequency, ε_0 is the high-frequency dielectric constant and δ'(r) is the damping frequency.

The damping frequency is a function of the electron velocity at Fermi energy (v_f) for Ag-NPs and radius (r) of the Ag-NPs, and is given by

$$\delta'(r) = \delta_0' + \frac{v_f}{r} \tag{5}$$

The refractive indices of layer A (metamaterial) and layer B (nanocomposite) is defined by $n_1 = \sqrt{\varepsilon_1 \cdot \mu_1}$ & $n_2 = \sqrt{\varepsilon_{eff}}$.

According to the Transfer Matrix Method (TMM), the characteristic matrix which defines the interaction of the incident electromagnetic radiation with the photonic crystal is given by [29].

$$M_i = \prod_{i=1}^{k} \begin{bmatrix} \cos\delta_i & \frac{j}{p_i}\sin\delta_i \\ jp_i\sin\delta_i & \cos\delta_i \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{6}$$

where the phase difference is given by

$$\delta_i = \left(\frac{2\pi}{\lambda}\right) n_i d_i \cos\theta_i \tag{7}$$

in which n_i, d_i and θ_i are the refractive index, thickness of ith layer in the system and angle of incidence at the interface.

The angle of incidence is given by

$$\cos\theta_i = \sqrt{1 - \frac{n_0^2 \sin\theta_0}{n_i^2}} \tag{8}$$

$$\text{For TE mode, } p_i = \sqrt{\frac{\epsilon_i}{\mu_i}}\cos\theta_i \tag{9a}$$

$$\text{For TM mode, } p_i = \sqrt{\frac{\mu_i}{\epsilon_i}}\cos\theta_i \tag{9b}$$

Using the total matrix, the Reflectance (R) and Transmittance (T) of the system can be estimated by

$$R = |r|^2, r = \frac{n_1 m_{11} + n_1 n_s m_{12} - m_{21} - n_s m_{22}}{n_1 m_{11} + n_1 n_s m_{12} + m_{21} - n_s m_{22}} \tag{10}$$

$$T = \mathrm{Re}\left(\frac{n_s}{n_1}\right)|t|^2, t = \frac{2n_1}{n_1 m_{11} + n_1 n_s m_{12} + m_{21} - n_s m_{22}} \tag{11}$$

where n_1 and n_s are the refractive indices of first and last layers of the system.

3. Results and discussion

The proposed one-dimensional photonic crystal consists of alternating layers of DNG metamaterial (layer A) and Ag–MgF_2 nanocomposite (layer B), with the thicknesses of $d_1 = 350$ nm and $d_2 = 500$ nm. In order to calculate the permittivity (ε_1) and permeability (μ_1) of the metamaterial, equations (1) and (2) are used with the parameters $\varepsilon = 1.21$, $\mu = 1$, $\omega_p = 2\pi \times 3.53 \times 10^{15}$ Hz and $\gamma = 10^{-4}\,\omega_p$ [36,37]. The region in which the permittivity (ε_1) and permeability (μ_1) of the metamaterial attain negative values as well as the zero index region is depicted in Fig. 2.

DNG metamaterials, with both permittivity (ε) and permeability (μ) having negative values show unique properties of negative refraction, i.e. the energy flow is in the direction opposite to that of the wave vector.

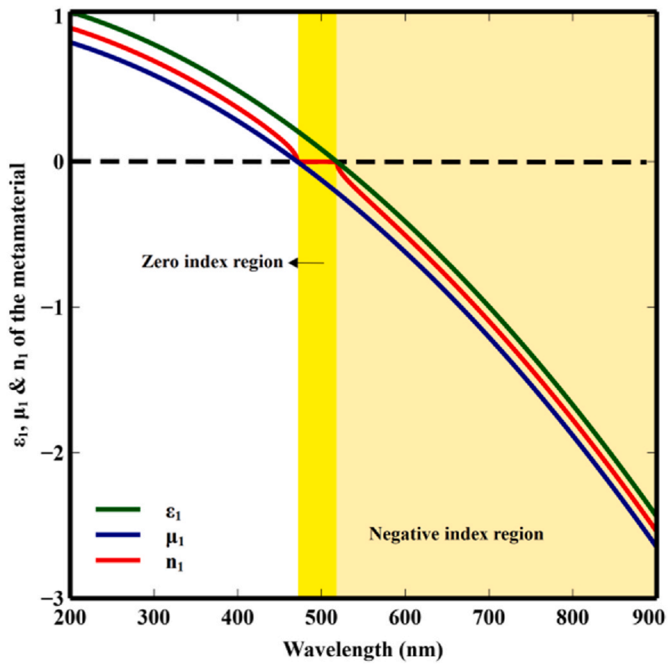

Fig. 2. Permittivity (ε_1), Permeability (μ_1) & Refractive index (n_1) of the Metamaterial as function of wavelength.

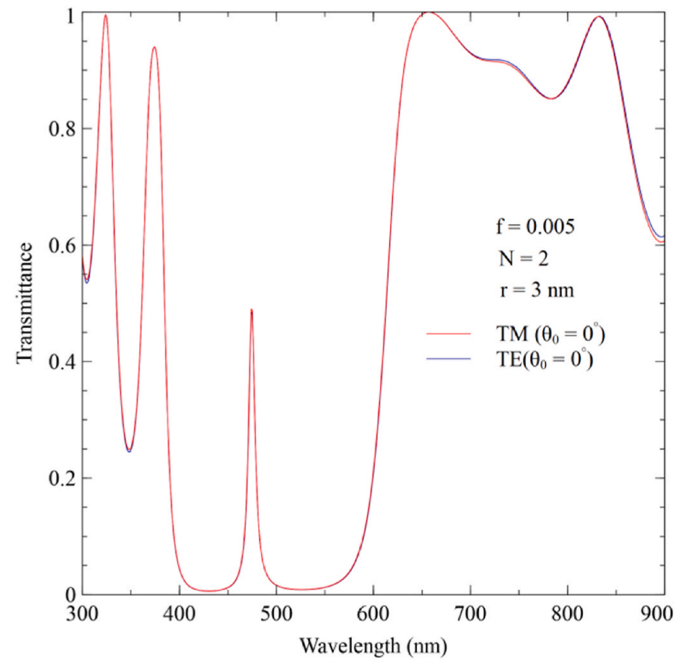

Fig. 3(a). Transmittance spectra of the 1D-PC for TE and TM mode with f = 0.005 for configuration I at normal incidence.

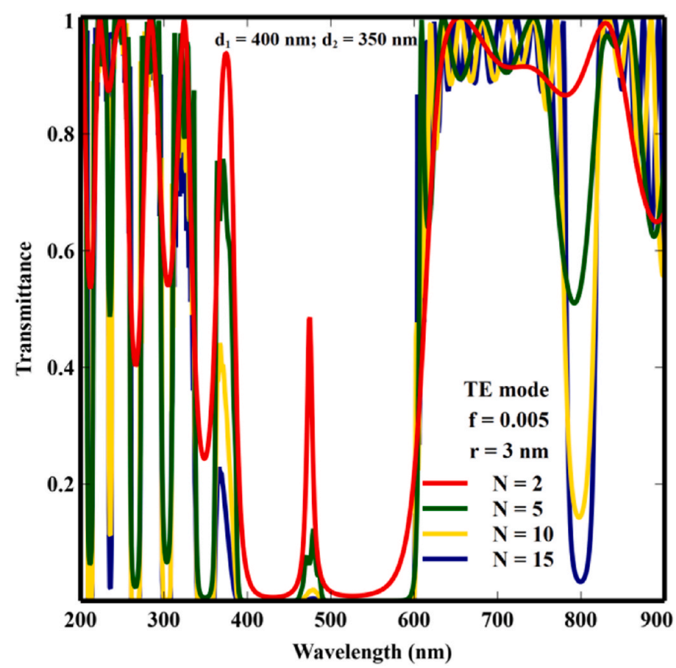

Fig. 3(b). Transmittance spectra of the 1D-PC for TE mode with various number of periods (N) for configuration I.

Also, unusual photonic band gaps, such as zero index gaps occur with photonic crystals containing metamaterial & conventional material. PBG that occur due to Bragg scattering gets affected by the unit cell, angle of incidence and minor disorders in the periodicity of layers. The peculiarity of the zero index band gap exhibited by metamaterial is that it remains unaltered by the above said factors [25].

The permittivity of Ag is calculated using Drude model as defined by equation (4) [34,35]. The high-frequency dielectric constant of Ag-NPs is $\varepsilon_0 = 5$, the Plasmon frequency (ω_p') and the decay constant (δ_0) of Ag–NPs are $2\pi \times 2.17 \times 10^{15}$ Hz and $2\pi \times 4.8 \times 10^{12}$ Hz, respectively. The damping frequency (δ'(r)) is calculated by equation (5) with the values of spherical radius (r) of the Ag–NPs as 20 nm and the electron velocity at Fermi energy (v_f) as 1.39×10^6 m/s. The permittivity of Ag–MgF_2 nanocomposite is calculated with Maxwell-Garnett equation as given by equation (3) [10]. The transmittance spectra of the photonic crystal are analyzed using the Transfer Matrix Method (TMM).

3.1. *Transmittance spectra of the 1D-PC with various number of periods (N)*

The investigation of this behavior involves the study of two distinct configurations, labeled as I and II. In configuration I, the photonic crystal is characterized by the thicknesses of layers A (metamaterial) and B (nanocomposite), with $d_1 = 400$ nm and $d_2 = 350$ nm, respectively. In configuration II, the photonic crystal is designed with different layer thicknesses, specifically, $d_1 = 200$ nm for layer A (metamaterial) and $d_2 = 300$ nm for layer B (nanocomposite).

For configuration I, the transmittance spectra of the 1D-PC for TE and TM modes do not show distinct variation at normal incidence as shown in Fig. 3(a). And so the transmittance spectra of the 1D-PC are analyzed for the TE mode. The transmittance spectra of the proposed photonic crystal for TE mode, vary with the number of periods (N) and are analyzed for these two different configurations, I and II, as depicted in Figs. 3(b) and 3(c).

In configuration I, the transmission peak is observed at 475 nm with a periodicity of N = 2, as depicted in Fig. 3(a). However, these transmission peaks gradually disappear as the number of periods (N) increases. When N is set to 15 in configuration I, we observe a PBG with a width of 200 nm, spanning from 400 nm to 600 nm.

Wider PBGs in the visible spectrum are observed for the configuration II. A complete PBG occurs at N = 15, and is found to be from 244 nm to 600 nm, covering almost the entire visible spectrum as shown in Fig. 3 (b). With the control on the number of periods (N) of the photonic crystal, the proposed structure can serve in both the applications of signal processing in the field of communication as well as DBRs in solar cells.

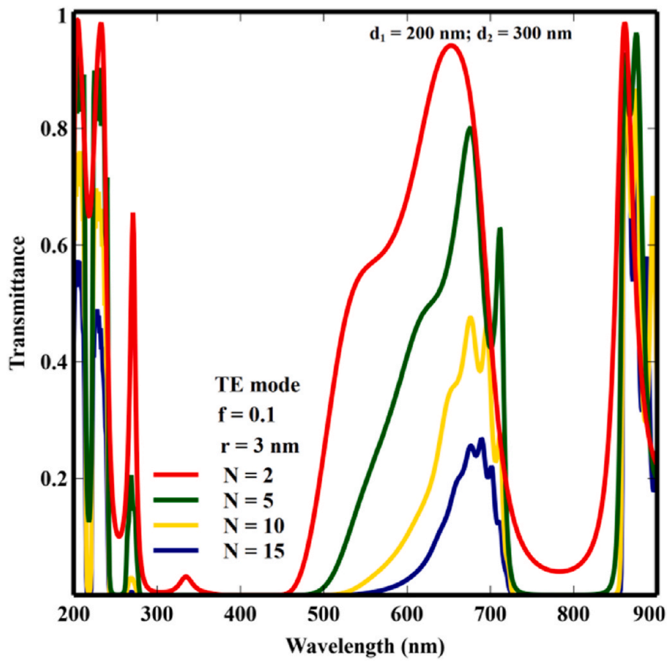

Fig. 3(c). Transmittance spectra of the 1D-PC for TE mode with various number of periods (N) for configuration II.

3.2. Analysis of occurrence of transmission peak in the PBG with the angle of incidence (θ_0)

With N = 2 and fill fraction f = 0.005, for configuration I, the transmittance of the photonic crystal for TE mode is plotted as a function of wavelength for various angles of incidence (θ_0) as shown in Figs. 4(a) & 4(b). It is revealed that the occurring transmission peak is unaffected with the angle of incidence.

On the other hand, for f = 0.05 & f = 0.1, the transmission peak vanished and omni-directional photonic band gap (OPBG), which is unaffected by the varying angle of incidence is observed, as shown in Figs. 4(c) and 4(d). The OPBG exists from 376 nm to 532 nm (156 nm) for f = 0.05, and the OPBG occurs from 364 nm to 570 nm (206 nm) for f = 0.1.

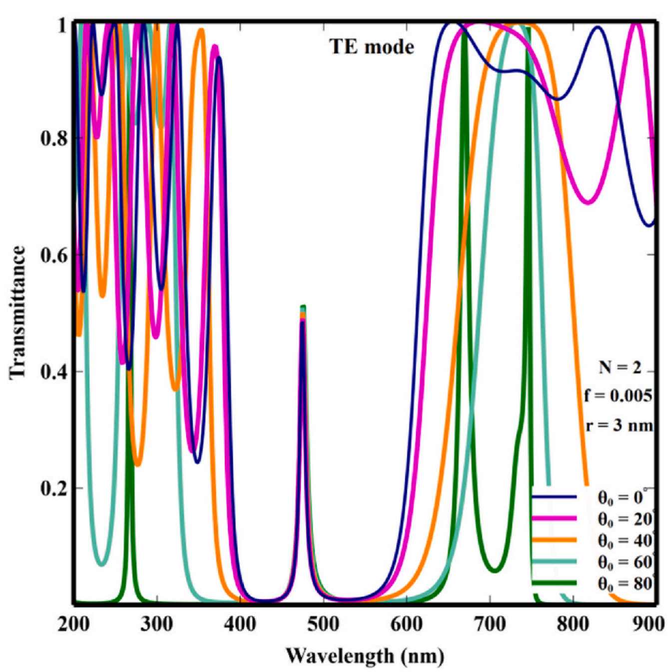

Fig. 4(a). Transmittance spectra for various angles of incidence (θ_0) for f = 0.005 for TE mode with configuration I.

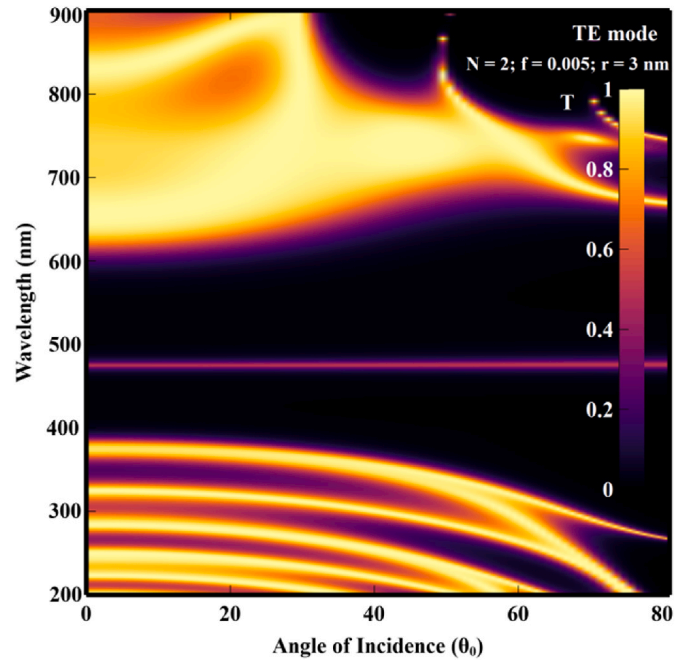

Fig. 4(b). Transmittance of photonic crystal as function of wavelength and angle of incidence (θ_0) for f = 0.005 for TE mode with configuration I.

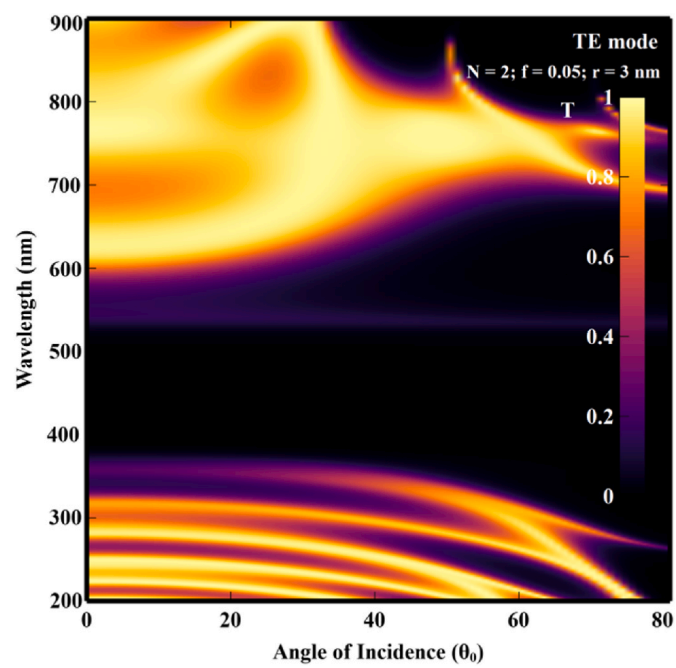

Fig. 4(c). Transmittance of photonic crystal as function of wavelength and angle of incidence (θ_0) for f = 0.05 for TE mode with configuration I.

Figs. 5(a) and 5(b) show the transmittance spectra of the 1D-PC for TM mode for configuration I, with N = 2 and f = 0.005. It is observed that the transmittance peak remains un-shifted up to $\theta_0 = 40^\circ$. For angle of incidence greater than 40°, the transmittance peak spreads and vanishes.

As depicted in Figs. 5(c) & 5(d), transmittance spectra do not exhibit transmission peaks, and OPBGs unaffected with the angle of incidence