Multichannel Tunable Band Pass Filter in 1dpc Composed of Uniaxial Metamaterial at Microwave Frequency

Behnam Kazempour
Department of physics, Ahar Branch, Islamic Azad University, Ahar, Iran
behkazempour@gmail.com

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Abstract

We proposed to design adjustable multichannel optical filter based on the uniaxial indefinite metamaterial/dielectric photonic crystal categories arrangement, which can be used as a valuable variation of peak transmission in the microwave region. Owing to the optical axis and polarization dependent uniaxial metamaterial layer, the position trend in the multichannel optical filter is shown to also rely on the both TE and TM polarizations. The results show that by raising the incidence angle, the width of photonic band gap (PBG) compacts (widens) at TE (TM) polarization and the PBG of the structure shift towards the higher frequency side (blue shift), for both polarizations. In addition, the realizing multichannel optical filter and the shift trend of the PBG are also affected by varying the optical axis of the uniaxial indefinite metamaterial and the results show that without appending defect layer in the proposed structure, the sets of comb-like resonant peaks in transmission modes can be created in the lower (higher) band edge of PBG at TE (TM) polarization.

Keywords: uniaxial indefinite metamaterial; Optical properties; Multilayer design

1- Introduction

During the last two decades, much consideration has been concentrated on the theoretical and experimental investigation of photonic crystals (PCs) or photonic band gap (PBG) materials, due to encouraging demands of PCs in modern photonics devices [1,2]. PCs are regular layered materials and can contains frequency ranges in which the propagation of the electromagnetic waves is prohibited. These regions are labelled photonic band gaps (PBGs) [3, 4]. However, the PBGs depend upon a some factors, such as the optical and physical characterises of the constituents of PCs, filling fraction, kind of arrangements, angle of incidence and state of polarization. Thence, the various compound with different elements to produce a change of specialized functions for designing PCs are presented. Different elements, such as dielectrics, liquid crystals, ferroelectric, metamaterials, and superconductors are applied in the form of photonic devices based on PC structures [5].

It is notable that a filter is extremely desired for multiplicity applications, specifically in photonic crystal circuits. When a defect layer is inserted in to the arranged PCs structure, a localized defect modes are generated, which can be utilized for construction of filters with an exceptionally narrow transmission band. In most study, filters are focused on the PBGs manipulating, i.e., all defect modes are designed to set within PBGs. Newly, a new category of filters based on PCs pass band have also excited researcher's considerable attention [6, 7]. Compared with conventional filters exerting the defect modes, current filters comprising no defect layer, and can be demonstrated as (AB)N. Here, one of the two elements, can be used as a superconductor, plasma, or single negative materials.

In recent years, one –dimensional photonic crystals (1DPCs) containing double- negative (DNG) materials have triggered a flood of researches in the community. DNG materials with contemporaneous negative permittivity (ε) and negative permeability (μ) in a special frequency region, and they have attracted extensive attention for their some abnormal peculiar properties [8]. DNG materials are now categorized as electromagnetic metamaterials and also PCs containing metamaterials are known as metamaterial photonic crystals [9]. Most studies of metamaterials are extensively based on the isotropic ones [10-12], while metamaterials are initially created in experiments are greatly anisotropic. Therefore, the permittivity and permeability should be studied as the tensors [13-15]. Compared with the isotropic PCs, the anisotropic metamaterials PCs represent the exclusive optical properties: the Brewster angle, negative index of refraction, invisibility cloaks, perfect lenses, and hyper lenses that enable subwavelength far-field resolution are some potential applications of metamaterials [16–19]. Among the varieties of metamaterials, recently, indefinite materials are a kind of anisotropic metamaterials in which not all the principal elements of the permittivity and permeability tensors have the similar symptom [20]. In fact, anisotropic left-handed materials are a specific reason of an indefinite medium [21-23]. The optical properties and the Goos– Hänchen (GH) shift of a light wave structure of 1DPCs containing indefinite metamaterials have been examined recently [24–26]. Recently, the metamaterials have been presented into PCs to acquire the filters that, can be tuned by the structure period or the layer thickness [27- 29]. These studies indicate that manipulate of these filtering properties can be controlled by changing the number of period structure or the layer thickness [33-32]. In contrast, only few examine have been reported on the multichannel filters using the anisotropic metamaterials and external parameters. However, the motivation to undertake this research resides in the fact that the authors have found no examines to the effect of the orientation of the optical axis of the indefinite metamaterials and the incidence angle on the multichannel filtering properties without introduce any defect in to the PCs.

In the present work, we would like to investigate the transmission properties of a

1DPC made of alternate layers of isotropic media and a uniaxial indefinite metamaterial. The computations of the present study were carried out using characteristics matrix method for both TE and TM polarizations. Duo to the anisotropic metamaterial, the effect of the orientation of the optical axis of the anisotropic layers and the incidence angle on the modulation of the PBG and the trend shift frequency position of the multichannel filter are investigated. It will be shown that by increasing of the incidence angle blue-shift was observed in the BPGs, and the frequency positions of the multichannel filter can be tuned by this parameters. Also ,The tunability of the PBGs and the possibility of the designing multichannel filter in the certain frequency is investigated by analyzing the influence of the optical axis of the uniaxial indefinite metamaterial on the transmission properties of the 1DPC.

2- Models and Theory

We consider a 1DPC with the periodic structure $(AB)^N$ embedded in air, as shown in Fig. 1. Here, B represents an isotropic dielectric layer with the permittivity ε_B, permeability μ_B, and thickness d_B, and A is a uniaxial indefinite metamaterial with thickness d_A. N is the period number, and a plane wave is incident at an angle θ upon the 1DPC from air. The interfaces of the layers are parallel to the x-y plane, and the z axis is normal to the structure. We assume that the optical axis of the indefinite medium lies in the x-z plane and makes angle φ with the z axis. In this case, the permittivity and permeability tensors of the indefinite metamaterial medium are given by [24, 33],

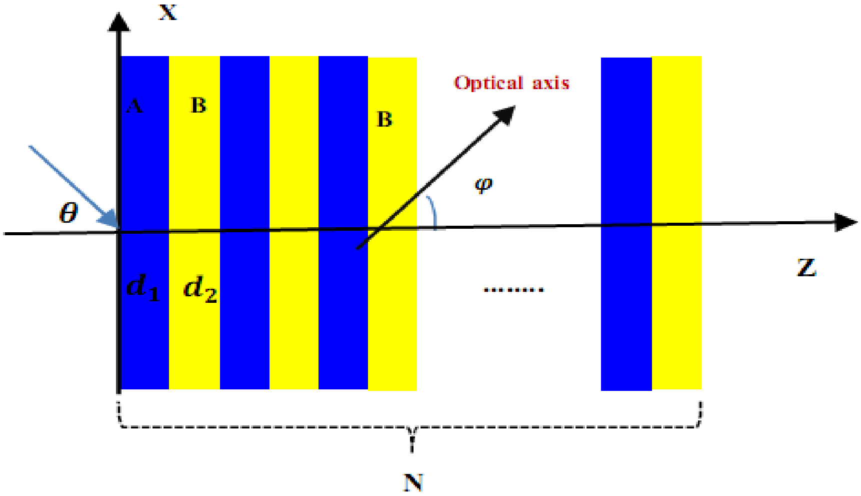

Fig. 1. Schematic of proposed of the 1DPC consisting of alternate layers of isotropic material (B) and uniaxial indefinite metamaterial (A), and N is the number of periods

$$\varepsilon_A = \begin{pmatrix} P & 0 & F \\ 0 & \mu_\perp & 0 \\ F & 0 & W \end{pmatrix},\quad \mu_A = \begin{pmatrix} U & 0 & G \\ 0 & \mu_\perp & 0 \\ G & 0 & V \end{pmatrix}, \tag{1}$$

Where

$$\begin{aligned} P &= \varepsilon_{A\perp}\cos^2\varphi + \varepsilon_{A||}\sin^2\varphi \\ W &= \varepsilon_{A\perp}\sin^2\varphi + \varepsilon_{A||}\cos^2\varphi , \\ F &= -(\varepsilon_{A\perp} - \varepsilon_{A||})\cos\varphi\sin\varphi \\ U &= \mu_{A\perp}\cos^2\varphi + \mu_{A||}\sin^2\varphi \\ V &= \mu_{A\perp}\sin^2\varphi + \mu_{A||}\cos^2\varphi \\ F &= -(\mu_{A\perp} - \mu_{A||})\cos\varphi\sin\varphi \end{aligned} \tag{2}$$

Here, $\varepsilon_{A\perp}$, $\varepsilon_{A||}$, $\mu_{A||}$ and $\mu_{A\perp}$ are the principle elements of the permittivity and permeability tensors of the layer A along the optical axis and perpendicular to the optical axis, respectively, and φ is the angle between the optical axis and the z-axis. The permittivity and permeability of layer A are complex given by [34].

$$\varepsilon_{A\perp} = 1 - \frac{100}{\omega^2}, \mu_{A\perp} = 1 - \frac{200}{\omega^2} \tag{3}$$

Where ω is the angular frequency of the incident wave, and is measured in units of ($10^9\ rad/s$).Consider an electromagnetic wave with frequency of ω, electric and magnetic fields of E and H, respectively, incident to the structure with angle θ with respect to the z-axis. The fundamental equations for an electromagnetic wave are given by the following Maxwell equations:

$$\begin{aligned} \vec{\nabla}\times\vec{E}(\vec{r},t) &= i\,\omega\,\mu_0\,\vec{\mu}\,\vec{H}(\vec{r},t) \\ \vec{\nabla}\times\vec{H}(\vec{r},t) &= -i\,\omega\,\varepsilon_0\,\vec{\varepsilon}\,\vec{E}(\vec{r},t) \end{aligned} \tag{4}$$

where ε and μ is the relative permittivity and permeability tensors, which, for anisotropic metamaterial with arbitrary optical axis is described Eq. (1). At first, we focus only on the TE waves. According to the Maxwell equations, the electric field $E = E_y(z)e^{i(k_x x-\omega t)}\hat{y}$ inside the indefinite layer satisfies the wave equation:

$$\frac{d^2E_y}{dz^2} + 2i\frac{G}{V}k_x\frac{dE_y}{dz} + \left(\frac{\omega^2}{c^2}\frac{\varepsilon_{A\perp}\mu_{A\perp}\mu_{A|\ |}}{V} - \frac{U}{V}k_x^2\right)E_y = 0, \tag{5}$$

where $k_x = \frac{\omega}{c}\sin\theta$ is the vacuum wave vector. By imposing the continuity condition on E_y and H_x at the interfaces and introducing a wave function as,

$$\psi(z) = \begin{pmatrix} E_y \\ -\omega\mu_0 H_x \end{pmatrix} \tag{6}$$

The following relation is derived between the electric and magnetic fields at any two positions z and $z+\Delta z$ of the same medium:

$$\psi(z) = M(\Delta z + \omega)\psi(z + \Delta z) \tag{7}$$

here, M_A is the transfer matrix of the indefinite medium,

$$M_A(\Delta z + \omega) = e^{i\alpha_1 z}\begin{pmatrix} cos(\alpha_2\Delta z) & \frac{-i}{q_A}sin(\alpha_2 \\ -iq_A sin(\alpha_2\Delta z) & cos(\alpha_2\Delta \end{pmatrix} \tag{8}$$

where $\alpha_1 = \frac{G}{V}k_x$,

$\alpha_2 = \left(\frac{\omega}{c}\right)(\sqrt{\mu_{A\perp}\mu_{A||}(V\varepsilon_{A\perp} - \sin^2\theta/V^2)})$ and

$q_A = V\alpha_2 / (\mu_{A\perp}\mu_{A||}\,\omega/c)$ .Similar results can be obtained for the isotropic layer B :

$$M_B(\Delta z+\omega)=\begin{pmatrix}\cos(k_z^B\Delta z) & \frac{-i}{q_B}\sin(k_z^B\Delta z)\\ -iq_B\sin(k_z^B\Delta z) & \cos(k_z^B\Delta z)\end{pmatrix} \quad (9)$$

where $k_z^B=(\omega/c)(\sqrt{(\varepsilon_B\mu_B-\sin^2\theta)})$ is the z component of the wave vector in the medium B , and c is the light speed in vacuum, and $q_B=(\frac{1}{\varepsilon_B})\sqrt{\varepsilon_B-\sin^2\theta}$ .For the TM waves, the wave equation in the metamaterial layer A can be obtained similarly as

$$\frac{d^2H_y}{dz^2}+2i\frac{F}{W}k_x\frac{dH_y}{dz}+(\frac{\omega^2}{c^2}\frac{\varepsilon_{A\perp}\mu_{A\perp}\mu_{A||}}{W}-\frac{P}{V}k_x^2)H_y=0, \quad (10)$$

here, M_A is the transfer matrix of the indefinite medium for TM polarization:

$$M_A(\Delta z+\omega)=e^{i\alpha_1 z}\begin{pmatrix}\cos(\alpha_2\Delta z) & \frac{-i}{q_A}\sin(\alpha_2\Delta z)\\ -iq_A\sin(\alpha_2\Delta z) & \cos(\alpha_2\Delta z)\end{pmatrix} \quad (11)$$

where $\alpha_1=\frac{F}{W}k_x$,

$\alpha_2=\left(\frac{\omega}{c}\right)(\sqrt{\varepsilon_{A\perp}\varepsilon_{A||}(W\mu_{A\perp}-\sin^2\theta/W^2)})$ and

$q_A=W\alpha_2/(\varepsilon_{A\perp}\varepsilon_{A||}\omega/c)$. By means of the transfer matrix method [29], we obtain the transmission of the structure as,

$$T(\omega)=|t|^2=\left|\frac{2p}{(M_{11}+M_{12}p)p+(M_{21}+M_{22}p)}\right|^2 \quad (12)$$

where, (ω) (i, j=1, 2) ij.M $p=\sqrt{k_0^2-k_x^2}/k_0$ are the elements of the total matrix $M_N(\omega)=[M_A(d_A)M_B(d_B)]^N$

3- Numerical Resultsand Discussions

The material parameters to be used in the following calculations are: $\varepsilon_B=3$, $\mu_B=3$, $d_B=10mm$, $d_A=5mm$, $\varepsilon_{A||}=1$, $\mu_{A||}=1$ and N=60 [33]. It is important to know the behaviour of the elements of the permittivity and permeability tensor of the indefinite metamaterial as a function of frequency (ω) and optical axis (φ). It is clear that in the range of 0–10GHz, the $\varepsilon_{A\perp}$ and $\mu_{A\perp}$ has a negative value and the medium.

Now, we present the transmittance spectra for the considered structure 1DPC. First, we investigate the effect of the incidence angle on the transmission spectra. In Fig. 2, we plot the transmittance spectra under the TE polarization at different values of $\theta=0^\circ,30^\circ,60^\circ$ and 85°. Here, we have taken the optical axis of indefinite metamaterial at $\varphi=0^\circ$. It is seen that, at $\theta=0^\circ$, there exists a PBG whose band edges are at $\omega_L=4.98GHz$ and $\omega_H=7.18GHz$, respectively. It is noted that the width of the BPG is decreased (compressed) compared to that of $\theta=0^\circ$ with the increase in the incidence angle from $\theta=30^\circ$ to $\theta=60^\circ$. Also, it is seen that, as the incident angle increases, the lower edge band gap shift towards the high frequency side (blue shift), whereas the higher edges band gap remains almost constant as the incident angle increases. Moreover, it is clear from this figure that, by increasing the incidence angle, the sets of comb-like filter channels appearing in the higher edge band gap.

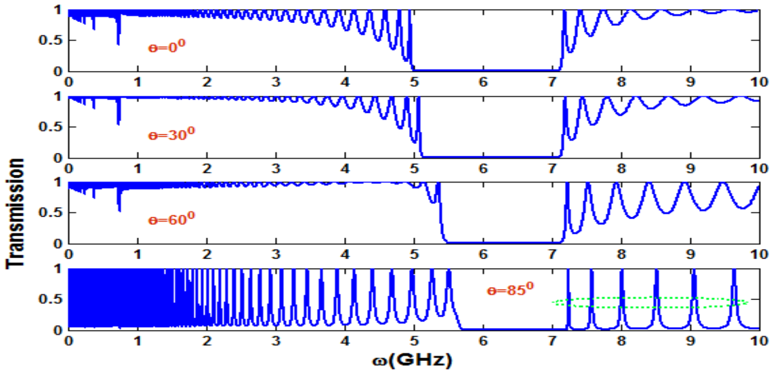

Fig.2. Transmission spectrum of the 1DPC as a function of the angular frequency at four different incident angles when optical axis $\varphi = 0^{\circ}$, under TE polarization

Next, we would like to investigate how the tuning of the frequency position of the multichannel filters and tuning the PBG is affected by adjusting the incidence angle under the TM polarization. In Figure 3, we plot the transmission spectra in the four different values of the incident angles $\theta = 0^{\circ}, 30^{\circ}, 60^{\circ}$ and 85°, by keeping the optical axis at $\varphi = 0^{\circ}$. The other parameters are same as those in Fig. 2. In this case, by increasing the incidence angle, the PBG are shifted towards the higher frequency (blue shift), which is similar to the TE polarization, while the lower edge band gap has no sensible change, whereas the width of the PBG increases. Also, it is illustrated that, in the case of $\theta = 85^{\circ}$, the sets of comb-like filter channels appearing in the lower edge band gap. Therefore, the proposed structure can be used as an optical multichannel filter in this frequency range, which is enlarged in Fig.3 in the frequency range ($1.45 \langle \omega \langle 5.18 GHz$). Another feature is of note that, in the case of TM polarization, the widths of the transmission modes become narrow as the incidence angle increases, which indicate that the quality factor of the filter increases. This property will be useful for us to design the response frequencies of the multichannel filter.

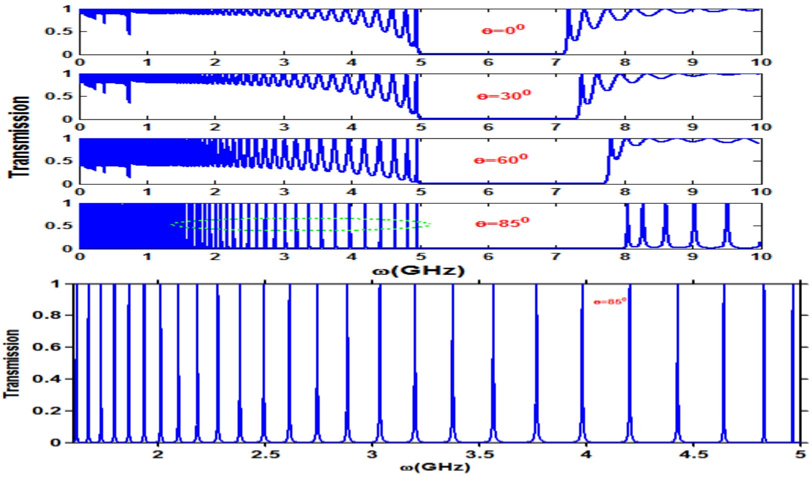

Fig.3. Transmission spectrum of the 1DPC as a function of the angular frequency at four different incident angles when optical axis $\varphi = 0^{\circ}$, under TM polarization.

To show the influence of φ on the transmission properties of the structure is plotted for different optical axis $\varphi = 0^{\circ}, 30^{\circ}, 60^{\circ}$ and 85°, for TE polarizations in Fig. 4, for the normal incidence of the waves. We know that the orientation of the optical axis for $\varphi \neq 0$ (Eq. 3) is resulted in non-zero off-diagonal elements of the dielectric permittivity and permeability tensor. The results show that by increasing the angle φ, a new gap as the angular gap band is observed in the lower frequency side, and the PBGs appearing within the considered frequency region are blue-shifted. Also, it is evident from the figure that the position of the angular gap remains invariant as optical axis larger than $\varphi = 30^{\circ}$. Another feature is of note, that is, at the $\varphi = 30^{\circ}$, the one very narrow PBG known as Bragg gap is observed and the sets of comb-like filter channels appearing in this frequency range. The inset of Fig. 4 show the enlarged transmission spectra around in the frequency range ($4.85 \langle \omega \langle 5.28 GHz$).

Under the same conditions, we would like to investigate how the PBGs can be influenced by the optical axis under the TM polarized wave, we have fixed the incidence angle at $\theta = 0^{\circ}$. The transmission spectrum for $\varphi = 0^{\circ}, 30^{\circ}, 60^{\circ}$ and 85° are depicted in Fig. 5. It is observed this figure that the PBG appearing within the considered frequency region is blue-shifted as the optical axis increases. In addition to such shifting behavior of PBGs, it is noteworthy to consider the change in the bandwidth of PBGs. The bandwidth of PBGs decreases as the optical axis increases appreciably from $\varphi = 0^{\circ}$ to 60°, and then nearly unchanged. For optical axis larger than $\varphi = 60^{\circ}$, the PBG disappeared and in the lower frequency side, the angular gap band is seen. Therefore, it is evident from the figure that the transmission spectrum of the structure strongly depends on the value of φ. Specially in the higher values of φ, the transmission of the 1DPC significantly reduces and finally the pass-bands in the lower given frequency side (0 to 7 GHz) are washed out.

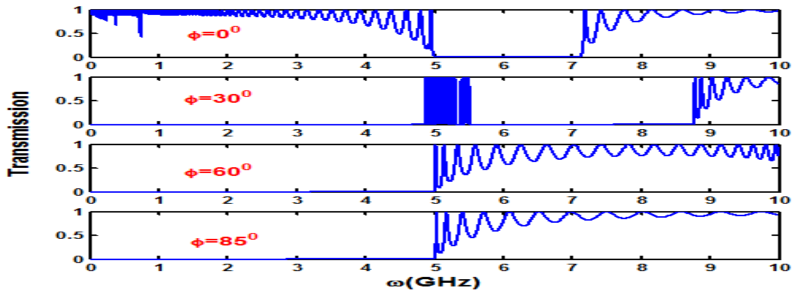

Fig. 4. Transmission spectrum of the 1DPC as a function of the angular frequency at four different optical axis $\varphi = 0^{\circ}, 30^{\circ}, 60^{\circ}$ and 85°, for the normal incidence of the waves, under TE polarization.

To optimize the proposed PC structure, we can change the optical axis along with the certain incidence angle are used in PC structure. Figure 6 shows the effect of the optical axis in four different values ($\varphi = 0^{\circ}, 30^{\circ}, 60^{\circ}$ and 85°) on transmission spectra behavior, at the oblique incidence of light for $\theta = 85^\circ$, under the TE wave polarization. The other parameters are the same as in Fig. 2. It can be seen in the figure that the transmission peaks are blue shifted as φ increases, which means that such a filter possesses tunable working frequency. Meanwhile, the proposed structure at $\varphi = 30^\circ$ can be designed for realizing multichannel filter in the higher frequency sides, which is enlarged and attached in Fig.6. Also, we see that the position of the angular gap band is shifted toward the higher frequency from 0° to 30° and then nearly unchanged as angles larger than 60°. In addition, it can be seen from Fig. 6 that as φ increases in the higher frequency side, the number of the transmission peaks increases and the width of the transmission modes become narrow, which illustrate that the quality factor of the filter raises.

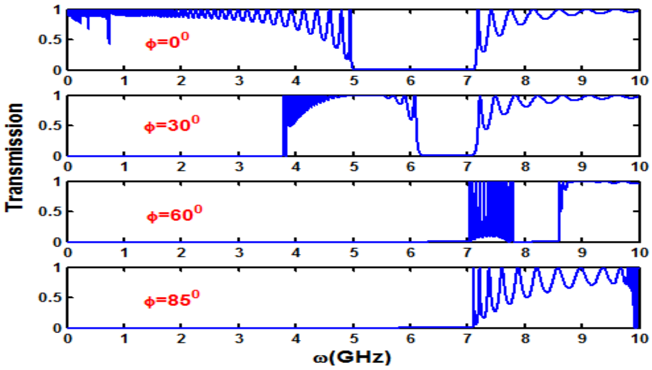

Fig. 5. Transmission spectrum of the 1DPC as a function of the angular frequency at four different optical axis $\varphi = 0^\circ, 30^\circ, 60^\circ$ and 85° for the normal incidence of the waves, under TM polarization

Finally, to show the effect of the optical axis (φ) on the tunability of the filtering properties such as the number, the widths and the positions of the transmission modes, under the TM polarization wave, is plotted in Fig.7, for different optical axis $\varphi = 0^\circ, 30^\circ, 60^\circ$ and 85°. It is illustrated hat, by increasing the optical axis, the PBGs appearing within the considered frequency side are blue-shifted. Also, it is found that as φ increases, the frequencies of the transmission peaks increase. Therefore, the proposed structure at $\varphi = 0^\circ$ and $\varphi = 30^\circ$ can serve as a tunable multichannel filter in the lower frequency sides (in lower edge band gap), which are enlarged and attached in Fig.7. Also, it can be seen from Fig.7 that at $\varphi = 0^\circ$ and $\varphi = 30^\circ$ in the lower frequency side, the number of the transmission peaks increases as well as the width of the transmission modes becoming narrow and the separation of the filter decreases, which indicate that the quality factor of the filter increases. The amount of increasing quality factor for TM polarization is greater than for TE polarization, and the transmission peaks compresses in the TM polarization. In addition, we see that the position of the angular gap band is shifted toward the higher frequency (blue shift) and the bandwidth of the angular gap increases as the optical axis (φ) increases. This transmission property indicates that the structure can be utilized for realizing multichannel filter in different frequency ranges.

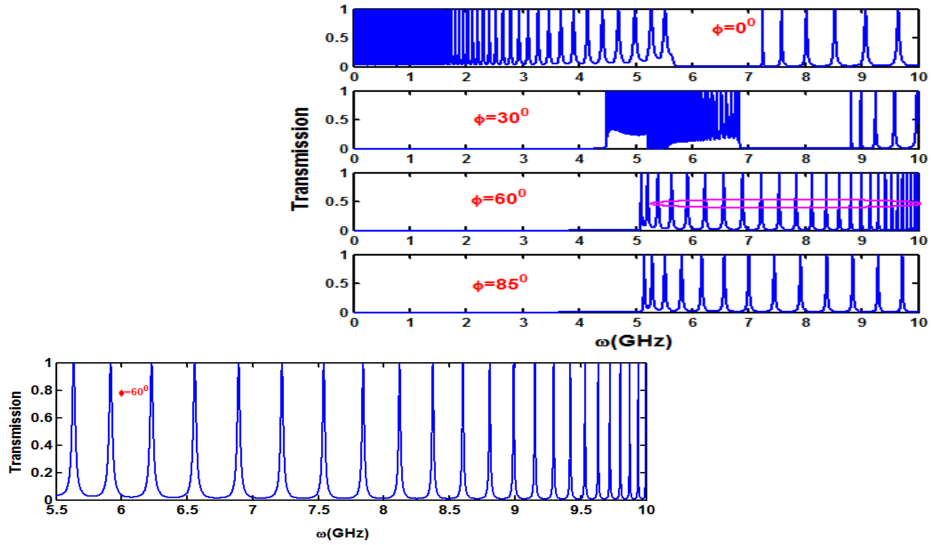

Fig. 6. Transmission spectrum of the 1DPC as a function of the angular frequency at four different
optical axis $\varphi = 0^\circ, 30^\circ, 60^\circ$ and 85° at $\theta = 85^\circ$ under TE polarization.

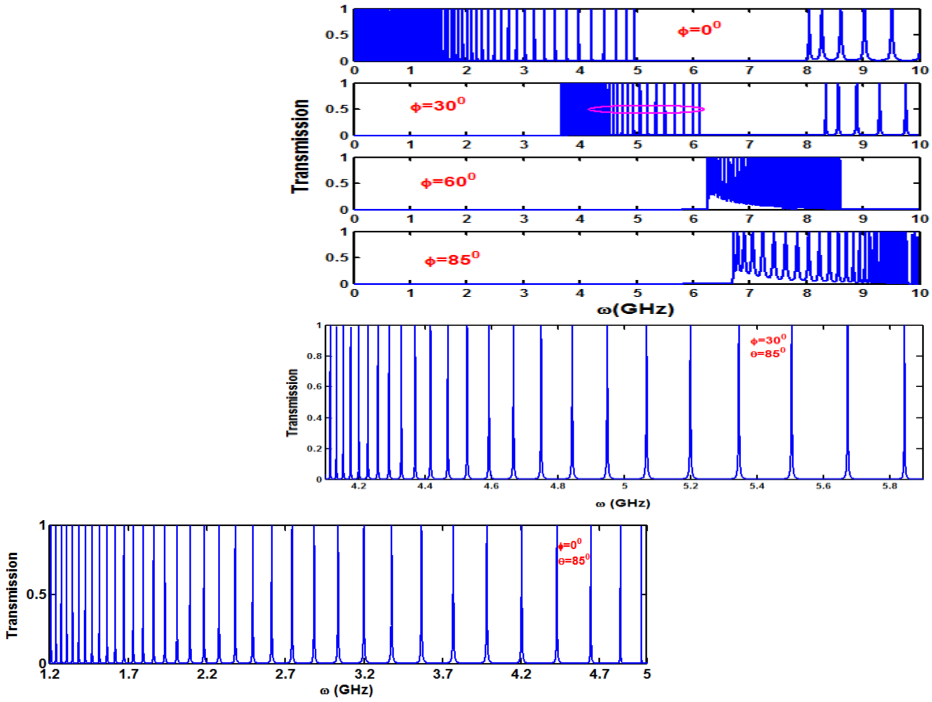

Fig. 7. Transmission spectrum of the 1DPC as a function of the angular frequency at four different
optical axis $\varphi = 0^\circ, 30^\circ, 60^\circ$ and 85° at $\theta = 85^\circ$ under TM polarization.

Conclusions

In summary, theoretical investigation of the multichannel optical filter based on the uniaxial indefinite metamaterial/dielectric photonic crystal categories arrangement has been designed and discussed. Unlike the usual filters, the results reveal that a multichannel filter can be achieved by using such a periodic structure without appending any defect layer. From the analysis of the transmission spectra ,it is found that the orientation of the optical axis of the anisotropic medium and the incidence angle have a noticeable response only on the width, shift trend of the PBGs and filtering properties in a multichannel filter. For oblique incidence, when the φ=0, it is found that the position of the PBG is blue-shifted, as the incidence angle raises for both TE and TM polarization. In addition to this, the bandwidth of the BPG can be narrowed for TE polarization while the width of the PBG broadened for TM polarization, by increasing the incidence angle. Moreover,, by tuning the optical axis and to optimizing the incidence angle for TE polarization, the sets of comb-like filter channels appearing in the higher edge band gap, whilst, for TM polarization, the sets of comb-like filter channels appearing in the lower edge band gap, thus, the proposed structure can be used to design the multichannel filter by the proper choice of the parameters in a desired frequency range.

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