Angular and Voltage Dependence of Tunable Mode in Ferroelectric Photonic Crystals

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Abstract

The influence of the variation in the incident angle and applied voltage on tunability of defect modes in a one-dimensional photonic crystal made of ferroelectric as a defect layer is theoretically studied for TE and TM polarizations. The amplitude of the TE-polarized defect mode decreases with increasing incident angle, whereas the amplitude of the TM-polarized defect mode increases. In the angle-dependent defect mode, its peak wavelength is shown to be blue-shifted as the angle of incidence increases for both TE and TM waves. In the voltage tuning, for two TE and TM polarized the defect modes are blue-shifted as the positive bias is applied, whereas they are red-shifted when the bias voltage is negative. With change incident angle, a tuning bandwidth up to 56nm is obtained by suitable change of applied voltage from -90to 90V. The analysis of defect mode provides useful information for the design of tunable transmission filter in optoelectronics.

Keywords: Photonic crystal, tunable defect mode, electro-optical effect

1. Introduction

In recent years, Photonic crystals (PCs) are periodic structure that can produce a photonic band gap (PBG) where the propagation of electro-magnetic (EM) waves can be forbidden for a certain range of frequencies [1, 2]. Introducing a defect layer in to the PC destroys the periodic variation of the refractive index and leads to peaks of high transmission within the PBG known as the defect modes [3, 5].

The properties of PCs depend on the configuration of the constituent materials, which cannot be changed after make. On the other hand, photonic band structures are also dependent on the refractive indices of the constituent materials. If the photonic band structures of the PCs can be externally modulated by some other means, the PCs may be applicable as active optical devices [6-8]. The tuned defect mode is clearly illustrated by a transmission peak in the transmission spectrum. This peak is referred to as a channel of the filter [9-12]. Based on the tunable defect mode frequency, it is possible to design and fabricate PCs for various applications in optoelectronic and microwave [13, 14]. Thus, to make a filter tunable, one can choose the tunable element for the defect material. In addition, the location of the defect mode can be further tuned by making use of a defect layer with an externally variable refractive index. To obtain external tunability, we have proposed a ferroelectric material along with the dielectric. Using a variable index defect in a PC, we are thus able to make a tunable filter, which could be of practical use in optical signal processing [15, 16].

Indeed, numerous schemes have been proposed to realize the tunability of PCs by external parameters, such as electric field, magnetic field, temperature, optical kerr effect, and strain have been chiefly used to demonstrate tunable filter in photonic crystals [17-20]. However, these reports on the modulated tunable filters were mainly concentrated on the terahertz, microwave and far-infrared regions [21-27]. Thus, we propose an electric field modulated tunable filter that can be worked in the visible region.

In this paper, we study tunability of a single filter based on a composite ferroelectric-dielectric PCs. An electro-optical material, ferroelectric LiNbO3 (LNO) crystal, is inserted as a defect layer into a periodic PC structure. According to the electro-optic effect, the refractive index of LNO changes under excitation of an applied voltage, which makes the average refractive index of the photonic crystal changes and therefore, the defect mode in the photonic band gap shifts. Thus an electro-optic tunable photonic crystal filter can be realized. Two coupled thin Ag layers with inherently dispersion loss are used as electrical contacts. To produce a single tunable channel, a single-defect PC arrangement with properly choosing the defect layer thickness.

2. Model and Theory

In this work, the defective PCs has a structure of $(AB)^5D(BA)^5$, in which A and B with corresponding thicknesses of d_1 and d_2 are dielectric materials with constant optical parameters and externally tunable defect for designing single tunable optical filter is schematically illustrated in Fig. 1. Two thin Ag layers of width d_3 coupled with an electro-optically tunable LNO layer of thickness d_4, depicted by D is used as the defect. It should be mentioned that for creating a single channel filter, only one defect configuration provided a proper selection of the LNO thickness would be appropriate. The frequency dependent refractive index of Ag is considered by using the Drude model; $n_3=(1-\omega_p^2/(\omega^2+j\Gamma\omega))^{1/2}$, where ω_p and Γ are the plasma and damping frequencies, respectively [28]. All of the layers are placed in the x-y plane and are perpendicular to the z-axes. LNO is a ferroelectric anisotropic crystal that its refractive index depends on applied external electric field [29]. When the external field has been applied parallel to the optical axis of the crystal (along the z-axes in PC structure, as illustrated in Fig. 1), its extra-ordinary refractive index in the direction of the z-axes is given by:

$$n(V)=n_e-\frac{1}{2}n_e{}^3\gamma_{33}V/d_4 \tag{1}$$

Where, γ_{33} is the electro-optical coefficient and n_e represents the extra-ordinary refractive index in the absence of the applied voltage. An electromagnetic wave with frequency of ω, the electric field of E and magnetic field of H incidents to the structure at incident angle of θ. To investigate the properties of the defect modes, we shall use the transmission spectrum which can be calculated by the transfer matrix method

(TMM) [28, 29]. The total transfer matrix can be written by

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = (M_A M_B)^5 (M_{Ag} M_{LNO} M_{Ag})(M_B M_A)^5 \quad (2)$$

Where the transfer matrix M_i in individual layer, i (A, B, LNO and Ag layers) is given by:

$$M_i = \begin{bmatrix} \cos(k_i d_i) & j q_i^{-1} \sin(k_i d_i) \\ -j q_i \sin(k_i d_i) & \cos(k_i d_i) \end{bmatrix} \quad (3)$$

Here, k_i and q_i are polarization-dependent given by

$$k_i = \sqrt{\varepsilon_i \mu_i k_0^2 - k_x^2}\ ,\ q_i = {k_i}/{\mu_i k_0} \quad \text{(TE polarization)}$$
$$k_i = \sqrt{\varepsilon_i \mu_i k_0^2 - k_x^2}\ ,\ q_i = {k_i}/{\varepsilon_i k_0} \quad \text{(TM polarization)} \quad (4)$$

Where $k_0 = {2\pi}/{\lambda}$ is the free-space wave number, and $k_x = k_0 \sin\theta_0$ with θ_0 being the angle of incident. Once the Matrix elements in Eq. (8) are known, the transmittance is obtained to be

$$T = |t|^2 = \left| {2P}/{((M_{11} + M_{12}P) + M_{21} + M_{22}P)} \right|^2 \quad (5)$$

Where $P = \sqrt{k_0{}^2 - {k_x{}^2}/{k2_0}} = \cos\theta_0$. All of the materials are assumed nonmagnetic, so in the numerical calculations, the permeability of the layers is set to be unit

Where: $k_j = \frac{\omega}{c}\sqrt{\mu_j \varepsilon_j}\sqrt{1 - \sin^2\theta / \mu_j \varepsilon_j}$, $q_j = \sqrt{\varepsilon_j} / \sqrt{\mu_j}\sqrt{1 - \sin^2\theta / \mu_j \varepsilon_j}$ for TE and $q_j = \sqrt{\mu_j} / \sqrt{\varepsilon_j}\sqrt{1 - \sin^2\theta / \mu_j \varepsilon_j}$ for TM polarization, j represents A, B, LNO and Ag layers [30]. All of the materials are assumed nonmagnetic, so in the numerical calculations, the permeability of the layers is set to be unit.

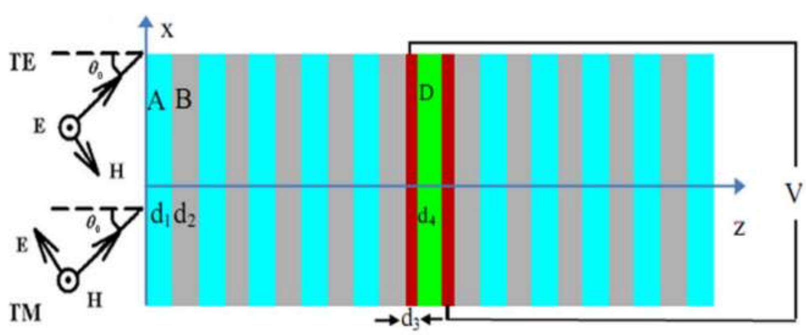

Fig.1. Schematic of proposed 1DDPC structure for single filter designing. Here, A and B are the dielectric materials with corresponding thicknesses of d_1 and d_2, the defects of D is composed of two thin Ag layers and one LNO layer with thicknesses of d_3 and d_4, respectively

3. Results and Discussions

Now we consider a multichannel transmission filter that have structure of $(MgF_2/\ TiO_2)^5Ag/LiNbO_3/Ag/(\ TiO_2/MgF_2)^5$, the material parameters Ag layer will be taken on plasma frequency $\omega_p = 2\pi * 2.175 * 10^{15} rad/s$ and damping frequency $\Gamma = 2\pi * 4.35 * 10^{12} rad/s$ in Eq.(2) [28] .the parameters of LNO layer as e defect will be taken $\gamma_{33} = 30.9\ pmV^{-1}$ is the electro optical coefficient and $n_e = 2.20$ extraordinary refractive index in Eq.(3) [29]. The dielectric layer A as MgF_2 with $n_A = 1.45$ and dielectric layer B as $TiO_2$with $n_B = 2.49$, and The thicknesses of the MgF_2 and TiO2 layer are d_1=56nm and d_2=84nm, respectively. The thicknesses of the Ag and LNO layer are taken to be d_3=9nm and d_4=110nm, respectively. With those optical and physical parameters and in the absence of applied external voltage and normally incident waves, the PBG of the proposed PC structure is within the frequency range of 415.7 nm to 620.6nm ,which is visible region, and the defect mode (wavelength peak) is 539.9. We have presented the results for different incident angle with applied voltage zero, as shown in Fig. 2.

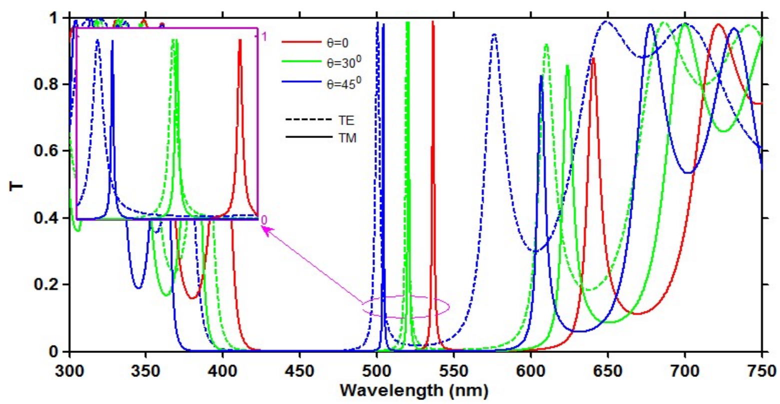

Fig.2. Transmittance spectrum in single biased configuration for d4=110 nm at three different incident angle (0 red, 30 green and 45 V blue).bold lines for TE and dashed lines for TM polarization.

Fig.2 shows the defect modes appeared in PBG for different incident angle, where with increasing angle, defect modes shift to lower wavelengths (blue shift) for TE and TM polarization. It can be seen that the width and amplitude of defect modes for TM increment with increscent incident angle and the width of band gap changes. This shifting property indicates that the structure can be used to design a tunable transmission filter.

To investigate the electro-optic tunability of the photonic crystal filter, we calculated the transmittance spectrum of the photonic crystal filter as a function of the applied voltage. The effect of applied voltage on the transmittance peaks for TE and TM is shown in Fig.3, 4. It is very clear that the peak wavelength shifts in the direction of longer Wavelength with the increment of applied negative voltage. Whereas, shifts in the direction of lower wavelength with the increment of applied positive voltage. Another feature is of note, that is, the defect modes for different biases voltage with increment incident angle shift to lower wavelength (blue shift). Therefore, for TE polarization (524.4-490.6) 33.8 nm at V=90v and 31.3 at V=-90v wide tunable band width can be obtained. In Fig.4 for TM polarization 34.2nm at V=90v and 38 nm at V=-90v tuning can be obtained and It can be seen that amplitude peak wavelength for TM increment with gain incident angle. The maximum applied voltage is restricted with the material damage voltage threshold. The breakdown voltage of the LNO is about 107 V/cm (1 V/nm) at room temperature [31, 32].

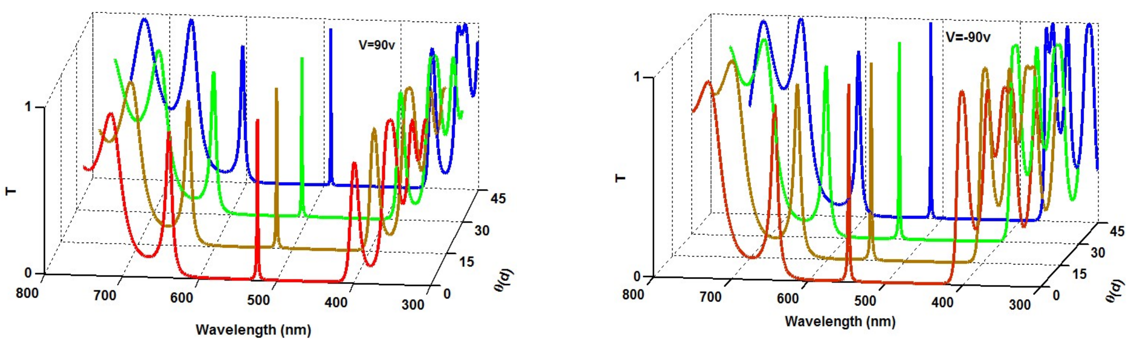

Fig.3. Transmittance spectrum of the photonic crystal filter as a function of incident angle with different bias voltage for TE polarization.

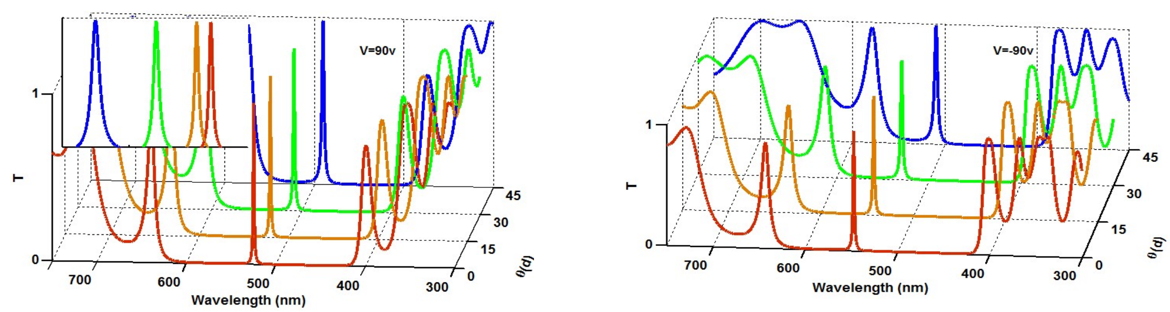

Fig. 4. Transmittance spectrum of the photonic crystal filter as a function of incident angle with different bias voltage for TM polarization, which is enlarged in Fig.4 a.

In order to facilitate comparison of the defect modes wavelength of different incident angles, we investigate the impact of angle wavelength tuning. Fig.5 presents the results of the angle wavelength tuning for TE and TM polarization with different applied voltage. Interestingly, the Tuning range up to34.6nm for TE and TM could still be achieved when the angle of incidence changes from 0^0 to 45^0, and the three-channel filters have no Angular effect when the incidence angle is less than 19^0.

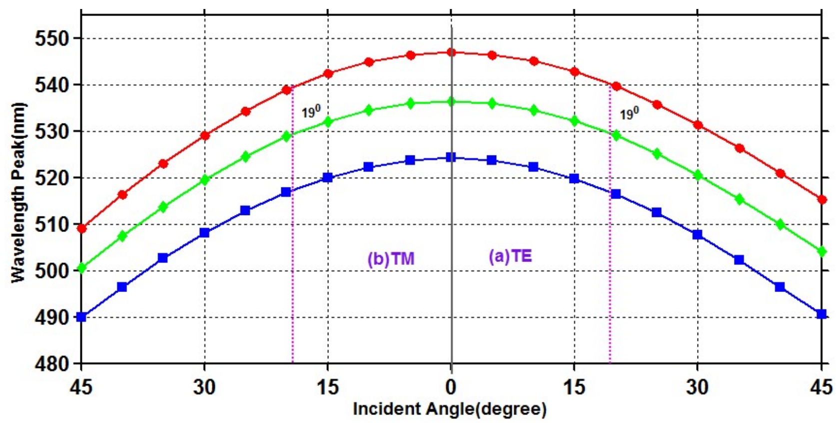

Fig. 5. Dependence of wavelength peaks on the angle of incidence for TE and TM polarization.

An external voltage is applied to the structure in Fig.1. Accordingly, electro -optic effect the effective refractive index of defect layer (LNO) increases with the increment of the applied negative voltage, whereas decreases with the increment of the applied positive voltage. As a result, the photonic band gap and the defect modes shift in the long or short wavelength direction, respectively. The optical properties of the filters are relevant to the incidence angle and polarization of incident light; the projected gap maps of the above optimized hetero structure at various applied voltage between-90v and 90v for TE and TM modes are shown in Fig. 5. Therefore, for TE polarization (514.8-490.3)24.5nm and for TM polarization (509.3-488.9) 20.4nm at incident angle 45^0 wide tunable band width can be obtained. With the applied voltage changed from -90v to 90v, the peaks transmittance has an obvious blue shift. Generally speaking, when the incidence angle and applied voltage change from negative bias to positive bias, defect modes are shifted from red to blue for TE and TM mode, respectively.

The results in Fig.5 are for the case of incidence angle with variation applied voltage shows that position of wavelength peaks. As can be seen in this figure, while wavelength peaks changed with incident angle and applied voltage variation. We can by alteration applied voltage and incident angle fixate position of the defect modes in a specific wavelength, for TE mode in the angle of the 14.6^0, 30.6^0 and 41.1^0 the wavelength peaks located in 520nm and for TM mode in the angle of the $28.4, 38.05^0$and 44.4^0 the wavelength peaks located in 510nm. The intensity of defect modes in wavelength in results are plotted in Fig.7.

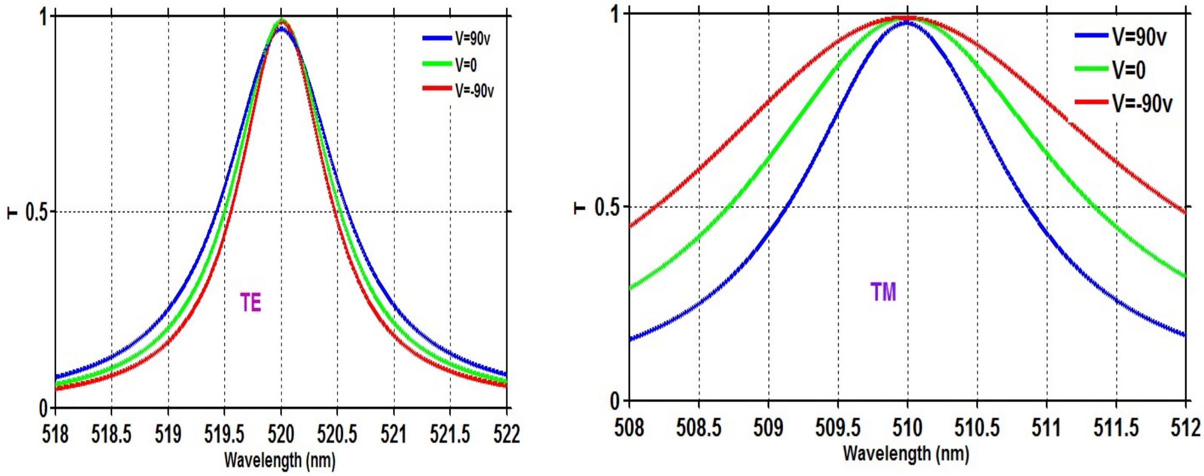

Fig.7. Calculated peaks wavelength as a function of the wavelength with different applied voltage for Both **TE** and *TM* waves.

4. Conclusions

We have investigated the filtering properties for defective PCs $(AB)^5D(BA)^5$ with a defect of D being a ferroelectric crystal, $LiNbO_3$. It is found that there is a transmission peak which is the so-called defect state. In the angular dependence, the defect mode is blue-shifted as a function of the angle of incidence for both TE and TM waves and amplitude of the defect mode for TE-polarized decreases with increasing incident angle, whereas the amplitude of the defect mode for TM-polarized increases. In the dependence of applied voltage on defect layers, for two TE and TM polarized the defect modes are blue-shifted as the positive bias is applied, whereas they are red-shifted when the bias voltage is negative. However ,with changing in incident angle a tunable bandwidth Up to 56nm is obtained by 180Vvariation of applied voltage alteration. It can be concluded that our proposed PCs defect mode is achievable for the design of a tunable filter which could be of practical use in optoelectronic applications.

References

[1] E .Yablonovitch, Inhibited spontaneous emission of photons in solid-state physics and electronics, Phys. Rev. Lett. 58 (1987) 2059-2061.

[2] S. John, Strong localization of photons in certain disordered dielectric super lattices, Phys. Rev. Lett. 58 (1987) 2486-2489.

[3] H. Jiang, H. Chen, H. Li, Y. Zhang and S. Zhu, Omnidirectional gap and defect mode of one-dimensional photonic crystals containing negative-index materials, Appl. Phys. Lett. 83 (2003) 5386-5391.

[4] S. Massaoudi, A. de Lustrac and I. Huynen, Properties of Metallic Photonic Band Gap Material with Defect at Microwave Frequencies: Calculation and Experimental Verification, J. Electtromagn. Waves and Appl. 20 (2006) 1967-1980.

[5] X. Gu, X.F. Chen, Y.P. Chen, X.L. Zheng, Y.X. Xia and Y.L. Chen, Narrow band multiple wavelengths filter in a Periodic optical super lattice, Opt. Commun. 237 (2004) 53–58.

[6] Q.-R. Zheng, B.-Q. Lin, Y.-Q. Fu and N.-C. Yuan , Characteristics and Applications of a Novel Compact Spiral Electromagnetic Band-Gap (EBG)

Structure, J. Electtromagn. Waves and Appl. 21 (2007) 199-213.

[7] Y.H. Chang, Y.Y. Jhu and C.J. Wu, Temperature dependence of defect mode in a defective photonic crystal, Opt. Commun. 285 (2012)1501–1504.

[8] A.H. Aly and H.A. Elsayed, Defect mode properties in a one-dimensional photonic crystal, Physica B 407 (2012) 122-125.

[9] R. Ghosh, K. and R. Chakraborty , Narrow band filter using 1D periodic structure with defects for DWDW systems, Opt. Commun. 289 (2013) 75-80.

[10] T.C. King, D.X. Chen, W.C. Lin, and C.-J. Wu, Photonic band gap structure for a ferroelectric photonic crystal at microwave frequencies, Appl. opt. 54 (2015) 8738-8741.

[11] K. Jamshidi-Ghaleh and Z. Ebrahimpour, One-way absorption behavior in defective 1D dielectric-metal photonic crystal, Eur. Phys. J. D. 67 (2013) 27.

[12] K. Min, J.E. Kim, and H.Y. Park, Channel drop filters using resonant tunneling processes in two-dimensional triangular lattice photonic crystal slabs, Opt. Commun. 237 (2004) 59-63.

[13] N.C. Panoiu, Bahl M and Osgood R M, All-optical tunability of a nonlinear photonic crystal channel drop filter, Opt. Express. 12 (2004) 1605- 1619.

[14] J.W. Liu, T.W. Chang and C.J. Wu, Filtering Properties of Photonic Crystal Dual-Channel Tunable Filter containing superconducting Defects J. Super. Conduct Nov. Mag. 27 (2013) 67-72.

[15] D. Park, S. Kim, I. Park and H. Lim, Higher order optical resonant filters based on coupled defect resonators in photonic crystals IEEE. J. Light wave Tech. 23 (2005) 1923-1928.

[16] Y.-K. Ha,Y.-C. Yang, J.-E. Kim ,and H.Y. Park, Tunable omnidirectional reflection bands and defect modes of a one- dimensional photonic band gap structure with liquid crystals, Appl. Phys. Lett , 79 (2001) 15-19.

[17] Q. Zhu and Y. Zhang, Defect modes and wavelength tuning of one-dimensional photonic crystal with lithium niobate , Optik, 120 (2009) 195–198.

[18] H. Chung, W.L. Jia, J.W. Chien , Effects of superconducting film on the defect mode in dielectric photonic crystal heterostructure, Solid State Comm. 157 (2013) 54–57.

[19] L. Chunxia, D. Suihu and H. Peide, Properties of the defect mode in one-dimensional ferroelectric Si/C60 photonic crystals, Optik, 124 (2014) 4712–4715.

[20] X. Hu, Q. Gong, S. Feng, B. Cheng and D. Zhang, Tunable multichannel filter in nonlinear ferroelectric Photonic crystal, Opt. Commun. 253 (2005) 138-144.

[21] H. Tian and J. Zi, One-dimensional tunable photonic crystals by Means of external magnetic fields , Opt. Commun 252 (2005) 321-328.

[22] M. Baum, I. Alexeev, M. Latzel, S. H. Christiansen, and M. Schmidt, Determination of the effective refractive index of an particulate ITO layers, Opt. Exp. 21 (2013) 22754-22759.

[23] D. Villar, C. R. Zamarreño, M. Hernaez, F. J .Arregui, andI. R. Matias, Generation of Lossy Mode Resonances with Absorbing Thin-FilmsJ. Ligh. Tech. 28 (2010) 3351 -3357.

[24] A.P. Vasudev, J.H. Kang, J. Park, X.L. and M. L. Brongersma, Electro-optical modulation of a silicon waveguide with an epsilon-near-zero material, Opt. Exp. 21 (2013) 26387-26398.

[25] Yariv and P. Yeh, Optical Waves in crystals propagation and control of laser radiation, Wiley and Sons, New York, 1983, ch.7, pp.220-247.

[26] H. Guana , P. Hana, Y. Lia , X. Zhang , W. Zhang, Analysis and optimization of a new photonic crystal filters in near ultraviolet band, Optik 123 (2012) 1874–1878.

[27] M.Born and E.Wolf ,Foundations of geometrical optics, in Principles of Optics, 7thed.Oxford, U. K.:Pergamon,1980.

[28] M. Molotskii, A. Agronin, P. Urenski, M. Shvebelman and Y. Rosenwaks, Ferroelectric Domain Breakdown Phys, Rew. Lett. 90 (2003)107601-4.

[29] G. Rosenman, P. Urenski, A. Agronin and Y. Rosenwaks, Submicron ferroelectric domain structures tailored by high-voltagescanning probe microscopy, Appl. Phys. Lett.82 (2003) 103-107.

[30] M. Luennemann, U. Hartwig, G. Panotoulos and K. Buse, Electrooptic properties of lithium niobate crystals for extremely high external electric fields, Appl. Phys. B 76 (2003) 403-408.