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Designing voltage tunable single and multi-channel optical filter with 1DDPC nano-structure

***B. Kazempour*[1,*], *K. Jamshidi-Ghaleh*[2]**

[1] *Department of physics, Ahar Branch, Islamic Azad University, Ahar, Iran*
[2] *Department of Physics, Azarbaijan Shahid Madani University, Tabriz, Iran*

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ABSTRACT: An electro-optic tunable single and multi-channel optical filter based on one-dimensional defective photonic crystal (1DDPC) structure is proposed. A couple of externally tunable defects in arrangement of $(AB)^5D_1(BA)D_2(BA)^5$, where A and B are dielectric materials, D_1 and D_2 are the tunable defects are used. The defects are composed of the ferroelectric $LiNbO_3$ crystals and two pairs of thin Ag layers to make the voltage connections. With this arrangement it is possible to apply different external biases that facilitate the tunability and even more adjustability of the channel frequencies. Depending on the thickness of defect layers, a single or multi resonant peak can be induced inside the photonic band gap which can be employed to filter channels. About 37 nm (46 nm) of blue shift for 300 V and 37 nm (37 nm) of red shift for -300 V biases are observed without (and with) loss incorporation. An important and notable effect that happened was the dispersion loss of the structure due to metal layers is compensated by the negative biases. Our proposed structure can be good candidate to design an externally tunable optical filter and a voltage sensor with potential applications in all-optical signal processing and information communications fields.

Keywords: *Blue-shift; Electro-optical; Defect mode; Photonic crystal; Red shift; Tunable optical filter*

INTRODUCTION

In the recent years, the ability of controlling the optical properties of the material has led to discover new classes of material structures responding to the electromagnetic waves over a desired frequency ranges. Controlling can be exactly characterized by the transmittance or reflectance trough the material. Photonic crystal (PC) structures, introduced by (Yablonovitch, 1987, John, 1987), are artificial structures composed of materials with different dielectric constants, arranged periodically in one, two or three dimension (Joannopoulos, *et al.*, 1995). The most significant features of a PC are the photonic band gaps (PBGs), the regions of the frequencies of electromagnetic waves which cannot propagate from the structure (Wu & Wang, 2010, Gu, *et al.*, 2004, Inouye, *et al.*, 2002). The One-dimensional PC (1DPC) structure is attractive since its production is more feasible at any wavelength scale and its analytical and numerical calculations are comparatively simple. Breaking the periodicity in a PC, such as introducing a layer with different physical or optical properties, usu-

(*) Corresponding Author-e-mail: b-kazempour@iau-ahar.ac.ir

ally, results in a narrow transmission spectral peak in the PBG, which is called a defect mode. This peak can be employed as an optical filter (Chang, 2012, Aly & Elsayed, 2012, Ghosh, *et al.*, 2013, Liu & Wu, 2014). A tunable defect mode peak frequency can be used to design and fabricate the PCs for various applications in optoelectronic and microwave devices such as optical modulators, tunable resonators, switches and sensing devices. Changing, the physical or optical parameters (thickness, permittivity or number of periodicity) of the defect layer would results to shift the peck frequency of the defect mode or PBG. Recently, many studies have been focused on replacing the physical or optical parameters of the PC structure to fabricate the modulating devices (Jamshidi-Ghaleh & Ebrahimpour, 2013, Min, *et al.*, 2004). In our opinion, this procedure cannot be a practical approach to design a controllable device, because, when replacing a material used in the PC structure with another material, new structure will be obtained and should be constructed again for applications. Our approach is to theoretically optimize a device which is made based on PC structure. Fortunately, there are some interesting materials that their optical (even physical) properties can be varied by employing electro, magnetico, thermo, or acousto-optical effects via an external agent (Jamshidi-Galeh & kazempour, 2016, Nemec, *et al.*, 2005). Thanks to this ability, it is possible to manipulate the defect mode and PBG in ranges of frequencies, without reconstructing the PC structure. The external tunability of the defect modes is an interesting possibility in order to enhance the application potential of the PCs. The aim of this paper is to investigate the dynamic tunability of a single and multi-channel filter based on 1DDPC structure. An electro-optical material, ferroelectric $LiNbO_3$ (LNO) crystal, is inserted as a defect layer into a periodic PC structure composed of MgF_2 and TiO_2 layers. Two coupled thin Ag layers with inherently dispersion loss are used as electrical connections. A tunable multi-channel filter can be obtained by two-defect PC arrangement (illustrated in Fig. 1) and proper selection of the defect layers thicknesses. To produce a single or two tunable channels, the single-defect PC arrangement with the defect layer thickness properly selected is appropriate. In this paper, our design is focused on the visible region. The applied electric voltage leads the defect peak to blue shift as the positive biases applied, while red shifts at negative bias voltage.

MODEL AND THEORY

The 1DDPC structure with two externally tunable defects for designing single and multi-channel tunable optical filter is schematically illustrated in Fig. 1. Layers A and B with corresponding thicknesses of d_1 and d_2 are dielectric materials with constant optical parameters. Two thin Ag layers of width d_3 coupled with an electro-optically tunable LNO layer of thickness d_4, depicted by D_1 and D_2, are used as the defects. It should be mentioned that for creating a single or even double channel filter only one defect configuration provided a proper selection of the LNO thickness (it should be thicker for creating two defects) would be appropriate. The frequency-dependent refractive indexes of Ag are considered by using the Drude model: $n_3 = \sqrt{1-\omega_p^2/(\omega^2+j\gamma\omega)}$, where ω_p and γ are the plasma and damping frequencies, respectively (Markos & Soukoulis, 2008). 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 (Yariv & Yeh, 1983). 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:

$$n_e(V) = n_{eo} - \frac{1}{2} n_{eo}^{\;3} r_{33} \frac{V}{d_4} \tag{1}$$

where, r_{33} is the electro-optical coefficient and n_{eo} represents the extra-ordinary refractive index in the absence of the applied voltage.

An electromagnetic wave with frequency of ω, the electric field E and magnetic field H, is impending to the structure at incident angle of θ. The well-known transfer matrix method is employed to perform numerical calculations (Markos & Soukoulis, 2008, Yariv & Yeh, 1983). According to this convention, the tangential components of the electric and the magnetic fields across the j th layer of thickness d_j, refractive index n_j, electric susceptibility ε_j and magnetic permeability μ_j are related by the following matrix:

$$M_j = \begin{bmatrix} \cos(k_j d_j) & q_j^{-1}\sin(k_j d_j) \\ -q_j \sin(k_j d_j) & \cos(k_j d_j) \end{bmatrix} \qquad (2)$$

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 (Born & Wolf, 1980). All of the materials are assumed nonmagnetic, so in the numerical calculations, the permeability of the layers is set to be unit. The transfer matrix of the proposed structure, embedded in air, can be obtained by multiplying all the transfer matrices of the subsequent layers with each other as follows:

$$(M_A M_B)^5 M_{D1} M_A M_B M_{D2} (M_B M_A)^5 = \begin{pmatrix} M_1 & M_{\mathbf{2}} \\ M_{\mathbf{2}} & M_2 \end{pmatrix} \qquad (3)$$

where, $M_{D1} = M_{D2} = M_{\mathbf{g}}\ M_{LNO} M_{\mathbf{g}}$. We have used different D_1 and D_2 notations because they can be biased with different voltages. Once the matrix elements of the structure are determined, the transmittance T is given by:

$$T(\omega) = \frac{4\cos^2\theta}{\left|(M_1 + M_2)\cos\theta - i(M_{\mathbf{2}}\cos^2\theta - M_{\mathbf{2}})\right|^2} \qquad (4)$$

RESULTS AND DISCUSSION

For the numerical calculations, titanium oxide (MgF_2) with refractive indexes of 1.38 and d_1=56 nm and magnesium fluoride (TiO_2) with refractive indexes of 2.49 and d_2=84 nm are used for layers A and B, respectively. Ag layers with 9 nm thickness, plasma and damping frequencies of $\omega_p = 2\pi\times2.175\times10^{15}$ rad/s and $\gamma = 2\pi\times4.35\times10^{12}$ rad/s are employed for voltage connection (Markos & Soukoulis, 2008). The electro optical coefficient and the constant extra-ordinary refractive index of the LNO layer are set to r_{33}=30.9 pmV^{-1} and n_{eo} = 2.20, respectively (Yariv & Yeh, 1983). With those optical and physical parameters and in the absence of applied external voltage, the PBG of the proposed PC structure is within the frequency range of 450 nm to750 nm. To consider the effect of the defect (LNO) layer thickness, we have presented the results for two different thicknesses of d_4 =110 and 300 nm, respectively. In this work, the transmittance spectrum properties of normally incident waves are investigated inside the PBG.

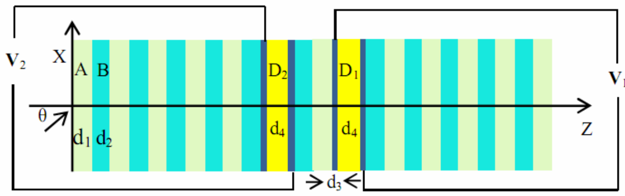

Fig. 1. Schematic of proposed 1DDPC structure for single and multi-channel filter designing. Here, A and B are the dielectric materials with corresponding thicknesses of d_1 and d_2, the defects of D_1 and D_2 are composed of two thin Ag layers and one LNO layer with thicknesses of d_3 and d_4, respectively

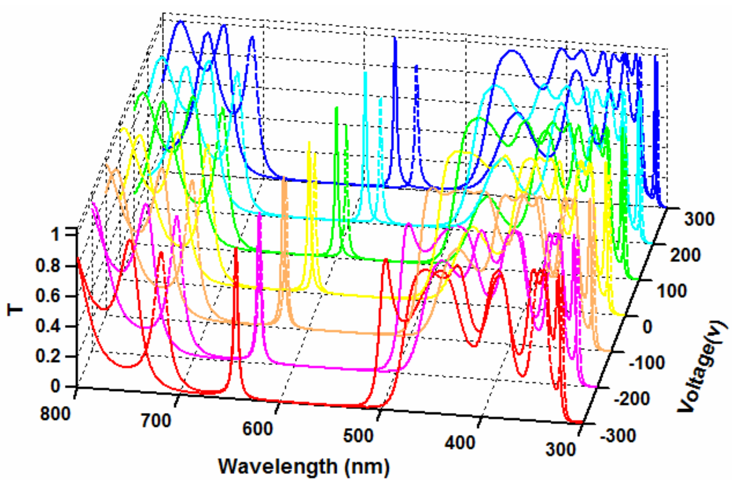

Fig. 2. Transmittance spectrum in single biased configuration for d4=110 nm at different applied voltages without (bold lines) and with (dashed lines) including the dispersion loss in Ag layers. For both cases blue shift for positive biases and red shift for negative biases are seen. Also, red-shifting and transmittance reduction compensations are clear for negative biases

In Fig. 2, we have plotted the transmittance spectrum for single biased configuration with d_4= 110 nm at different applied voltages (positive and negative biases) with (dashed lines) and without (bold lines) considering the dispersion loss in Ag layers. Only one defect mode is appeared inside the PBG region (centered at 612.8 nm in zero bias and without dispersion loss) that can be tuned with voltage. The blue shift (shift to higher wavelengths) for positive biases and the red shift (shift to lower wavelengths) for negative biases are clearly seen. As it was expectable, including the dispersion loss in Ag layers, caused to reduce the transmittance and a little bit blue shifting of the defect mode at all biases. But, a very important effect that should be noted is that the negative bias has compensated for the reduction of transmittance and blue shifting due to loss. As it is clearly seen in (Figs. 2 & 3), at applied voltage of -300 V, the shift and reduction of transmittance are completely compensated and both curves (with and without loss) are completely overlapped. This can be very important in designing the metal/dielectric or metal-contented (such as metamaterials or metal nano-composite) PC structures that are restricted due to metals intrinsic dispersive losses.

Fig. 3 shows the behavior of the defect mode with applied external voltage inside the PBG with (γ=0) and without (γ=0) considering dispersion loss in Ag layers. It is seen that for biases from 300 V to -300 V the defect mode peak wavelength displaces from 568.3nm to 643.8 nm (75.5 nm) for γ=0 and from

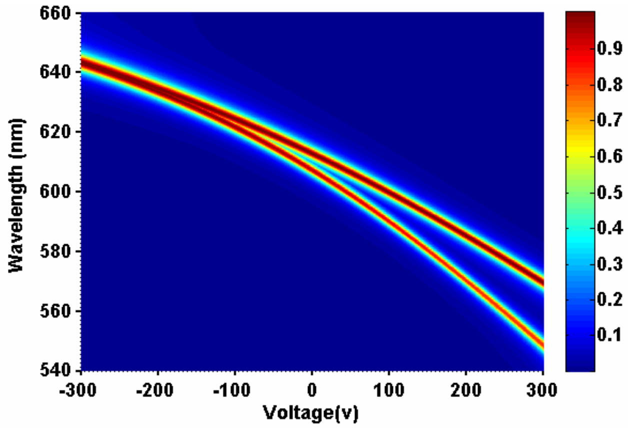

Fig. 3. Transmittance spectrum versus the applied voltage from 300 V to -300 V, with ($\gamma \neq 0$) and without (γ=0) considering dispersion loss in Ag layers when d4=110 nm. Overlapping modes is clearly seen at -300 V

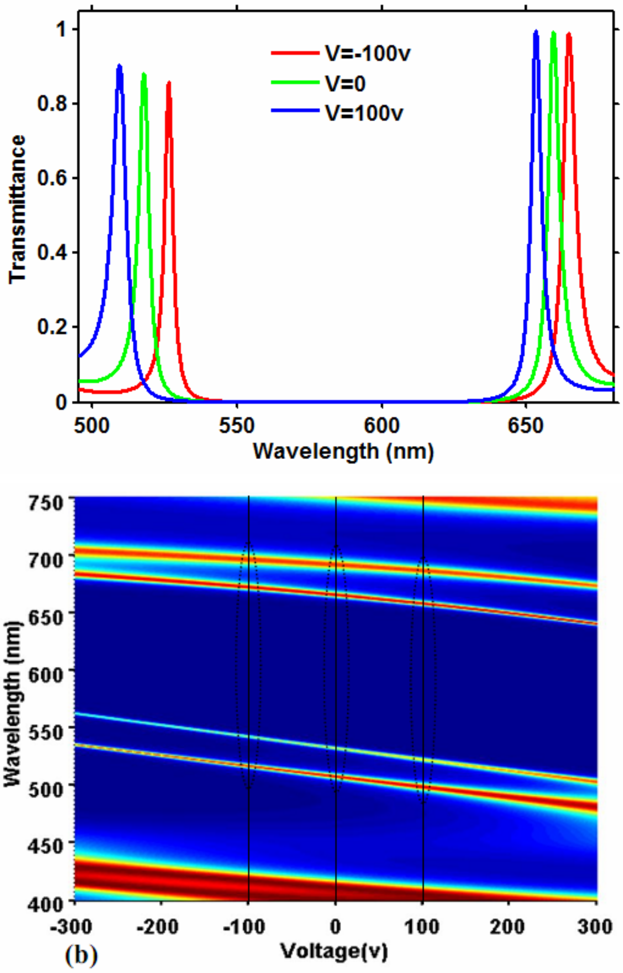

Fig. 4. Spectrum of single biased 1DDPC structure with LNO layer thickness of 300 nm. Two defects, placed at 517.7 nm and 659.2 nm at zero-bias. Compressing for negative biases and brodeding for posetive biases seen in lower-wavelength mode

550nm to 643.8nm (93.8 nm) for γ=0. This indicates continuous tunability of the defect mode (75 nm and 93.8 nm in these cases) by applied external voltage. It is evident that for higher applied voltage ranges, more displacements are possible. The maximum applied voltage would be restricted with the material damage threshold. The compensation of the mode shifting and the transmittance reduction due to the Ag layers dispersion loss is clearly seen for negative biases.

Replacing the LNO layer of the 110 nm thickness with another one of 300 nm thickness, two modes (localized at 517.7 nm and 659.2 nm at zero bias) appeared inside the PBG region (see Fig. (4a) and (4b)). One of the modes which is localized near the higher band-edge (around of 660 nm),completely transmit-

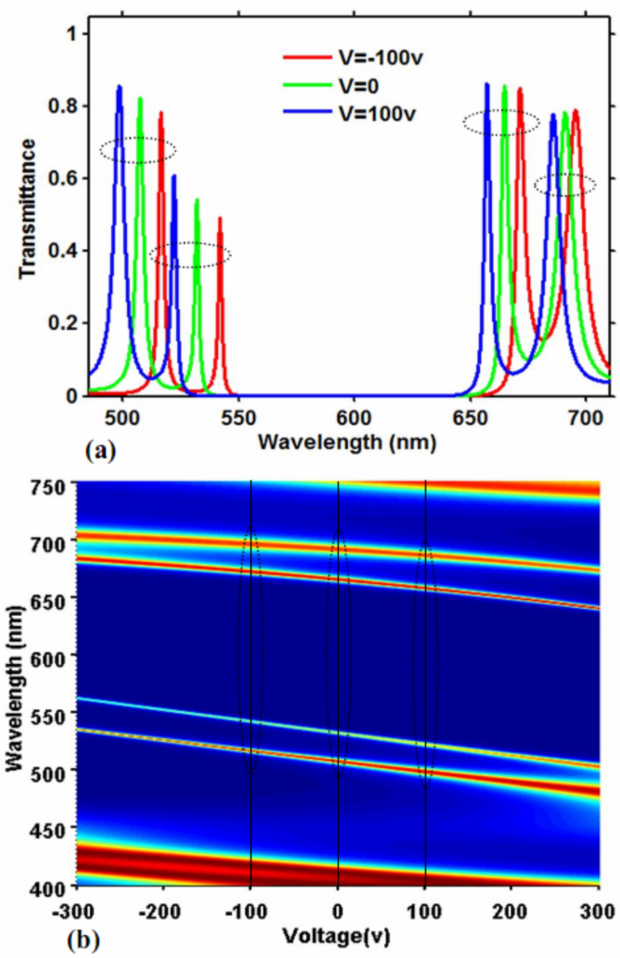

Fig. 5. Spectrum of duble-biased 1DDPC structure with LNO layer thickness of 300 nm. Four defects are localized at 507.2 nm, 531.6nm, 664.6 nm and 690.7 nm in zero bias. Each of the modes, have different trendes with external biases

tance all applied volages. Its peak frequency displaces very slowly and without brodening by increasing the voltage. Another mode, placed on 520 nm is compressed and reduced intransmittance at positive biases and is brodened and increased intransmittance at negative biases (see Fig. 4b).

Now we apply two external biases to the PC structure as depicted in Fig. 1. The transmittance spectrume around the defect modes inside the PBG is plotted for d_4= 300 nm at different applied voltages. Four peaks, localized at 507.2 nm, 531.6 nm, 664.6 nm and 690.7 nm in zero bias, with different transmittances and widths are seen in Fig. (5a). Each of the modes display different behaviours at external biases that can be deduced from Fig. (5b). These kinde of behaviours increase our ability to design tunable optical filters with different actions that can have potential applications in future nano-photonic devices.

CONCLUSIONS

An electrically tunable single and multi-channel optical filter was proposed based on 1DDPC structure with arrangement of (AB)5D1(BA)D2(BA)5. Two thin Ag layers for applying the external voltage, coupled with an LNO layer were used as the defects (D1 and D2) in the arrangement. Single and two defect configuration with two different LNO thicknesses (110 nm and 300 nm) applied in numerical calculations. With this arrangement, it is possible to apply different external biases that facilitate the tunability and even more adjustability of the channel frequencies. The blue shift (shifts to lower wavelengths) for positive biases and the red shift (shifts to higher wavelengths) for negative biases are clearly observed. Taking the inherently dispersion loss of Ag layers into account, causes to reduce the transmittance and a little bit blue shift of the defect modes in positive biases. But, a very interesting and important effect that occurred is that, the negative biases compensate for shifting and reduction of the transmittance compared to the zero voltage bias. For example, at -300 V bias, the loss effect was completely compensated. Applying two voltages to the 300 nm thick defect layers in this arrangement, results in four localized modes with different trends depending on the applied voltage.

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AUTHOR (S) BIOSKETCHES

Behnam Kazempour, Assistant Professor, Department of physics, Ahar Branch, Islamic Azad University, Ahar, Iran, *Email: b-kazempour@iau-ahar.ac.ir*

Kazem Jamshidi-Ghaleh, Professor, Department of Physics, Azarbaijan Shahid Madani University, Tabriz, Iran