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Temperature Tunability of Dielectric/ Liquid Crystal / Dielectric Photonic Crystal Structures

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Abstract: Recently, photonic crystals doped with liquid crystal (LC) material have gained much research interest. In this article new ternary one-dimensional photonic crystal introduced and studied. The liquid crystal layer of 5CB and 5PCH is sandwiched by two dielectric layers. For the first time, we use four structures SiO_2/UCF35/CaF_2, SiO_2/5CB/CaF_2, NFK51/UCF35/NPSK53 and NFK51/5CB/NPSK53. The effect of temperature on transfer band gap of these photonic crystals is investigated with transferred matrix method. The results show that in all four structures PBG for extraordinary ray (n_e) is very large than ordinary ray (n_o) and with increasing of temperature, PBG shifts to red wavelength. PBG width is very vast and variation of the figure with respect temperature is very sharp for SiO_2/UCF35/CaF_2 structure. Also, the suggested design takes high tunability due to the infiltration of the LC material. One can use the proposed structure as temperature sensing device, narrow band optical filter and in many optical systems.

Keywords: photonic crystal, liquid crystal, temperature sensing device, ternary one-dimensional.

1. INTRODUCTION

Photonic crystals (PhCs) are micro and nano-size structures, where the refractive index or permittivity of different material is periodic. Photonic crystal has photonic band gap (PBG). Therefore, the electromagnetic wave with the frequency in the band gap cannot be transmitted [1- 4]. This is one of the most basic characteristics of the photonic crystal. Photonic nanostructure devices, photonic chips, novel lasers, etc., will presently become available. The worlds of photonic crystals are now expanding to various science and technology areas such as quantum computing, bio-photonics and communications [5-9]. A photonic crystal is described by Bragg reflection and play an important role in

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studies of laser, optical filters [2-3], optical sensors [10] and temperature sensors [5-7]. PhC devices are routinely fabricated and their optical properties may be adjusted by modifying the size or structure design. But, PhC-based structures are often lacking in flexibility and tunability, there are still a few factors that limit the use of PhCs in real devices. Therefore, the research has focused on possibility of increasing the device fine-tune either by correcting or by controlling the optical properties of the PhC to compensate either the temperature sensitivity or the imperfections of the PhC itself. The optical properties of PhCs can be modified by changing the optical length and refractive index of the PhC Structure. The common tuning methods used in optoelectronic devices can be applied to adjust its refractive index by temperature, optical pumping or applying an external magnetic or electric field [7-12].

Among the several techniques that have been proposed, infiltrating some layer of a PhC with an organic material that has a tunable refractive index (e.g. liquid crystals, polymers, liquids, and colloidal quantum dots) has proved to be one of the most hopeful approaches for both trimming and tuning [13-15]. The injection of liquid crystals (LC) in PhCs structure naturally from the following properties of LC:

- They offer a large variety of interesting optical properties both in the visible and in the near-infrared spectral regions that often depend on the molecular organization;

- There exist a wide palette of different molecular organizations depending on the molecule interactions. The complex thermodynamic properties of such molecular mixtures enable one to easily change the molecular order by changing the temperature, applying an electric field and thus, the optical properties of the material itself. In particular, the potential of PhC infiltration with nematic liquid crystals (LCs) has been largely demonstrated for one, two and three-dimensional (1D, 2D and 3D) PhCs. Therefore, besides their classical fields of application, LCs are also having a strong impact in the PhC field [15-18]. In nematic LC, if the electric field of light is perpendicularly or parallel polarized to the axis of the LC molecules, light experiences the ordinary refractive index (n_o) or the extraordinary refractive index (n_e), respectively. The optical response of a PhC infiltrated with nematic LCs can be either trimmed or tuned by applying an external electric field which modifies the orientation of molecules with respect to the polarization direction of a light beam propagating through it. Moreover, when the temperature is increased above the nematic-isotropic (clearing point) phase transition temperature, the molecular order is destroyed and the LC is in its isotropic phase, its optical properties are thus characterized by an isotropic refractive index (n_i) that is independent of the molecule orientation [18-19]. Recently, PhCs doped with liquid crystal (LC) material have gained much

research interest [20-21]. Additional, 1D PhCs with central LC defects have been roughly reported. Ozaki et al. have studied the tunability of the defect modes of 1D PhCs with central nematic LC (NLC) [22] and dye-doped NLC [23] defects. In these investigations, the studied 1D PhC has a bandgap range from the wavelength of 590 nm to 710 nm. Furthermore, the spectral properties of an electrically tuneable 1D PhC infiltrated with twisted-NLC have been reported by Lin et al [24]. Moreover, the electrical and thermal tuning of 1D NLC PhC has been studied experimentally with bandgap range from 11 -18 μm [25].

In the present article, we consider a liquid crystal material as one of the layers of a ternary one-dimensional photonic crystal. The dielectric property of liquid crystals depends not only on temperature but also on wavelength. The suggested design has also high tunability due to infiltration of the LC material. Further, the effects of the polarization angle of light incident and temperature on the transmission characteristics of the suggested design are investigated.

2. BASIC EQUATION

One-dimensional ternary dielectric/ liquid crystal / dielectric Photonic crystal (LDPCs) structure is shown in Fig. (1). In this structure liquid crystal layer sandwich with two dielectric layers.

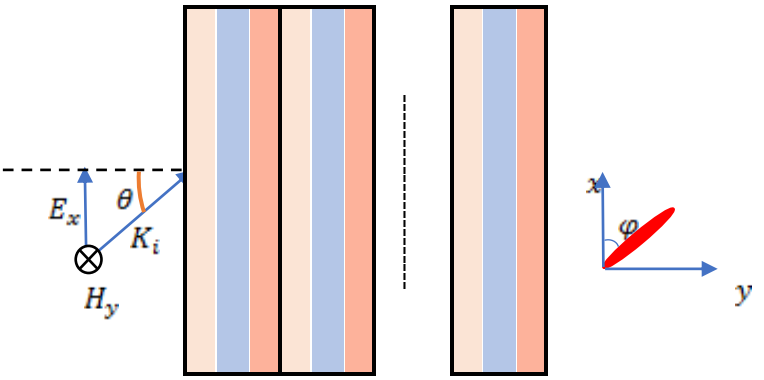

Fig 1. Structure of the one-dimensional photonic crystal with LC (blue) layers. Here, φ denotes the angle between the optical axis of the anisotropic LC layer and the x-axis [33].

We assume that the dielectric layers are in the x–y plane and the z-direction is normal to the interface of each layer. where φ is the angle between the optical axis of the liquid crystal layer and the x-axis. We know thickness and refractive index of the medium are changed with temperatures variation. Modification of

thickness and refractive index for dielectrics layers are [26]:

$$\Delta d = \alpha d(\Delta T) \tag{1}$$

$$\Delta n = \gamma n(\Delta T) \tag{2}$$

where α, γ and ΔT represent thermal expansion, thermo-optic coefficient for dielectrics and temperature variation of LC respectively. From the Vuks semi-empirical equation relating the refractive indices with the molecular polarizabilities for anisotropic materials [27]:

$$\frac{n_{eo}^2 - 1}{\langle n^2 \rangle + 2} = \frac{4\pi}{3} N \alpha_{eo} \tag{3}$$

In Eq. (3), n_o and n_e are refractive indices for the ordinary and extraordinary ray, respectively, N is the number of molecules per unit volume, α_{eo} is the molecular polarizability, and $\langle n^2 \rangle$ is defined as:

$$\langle n^2 \rangle = \frac{n_e^2 + 2n_o^2}{3} \tag{4}$$

In Eq. (4), n_e and n_o are coupled together. To disclose this relating, we should decouple n_e from n_o by solving Eq. (3). Replacing Eq. (4) to Eq. (3) and separating n_e and n_o, we derive:

$$n_e(T) \approx \frac{3\sqrt{2}}{4} + \frac{\sqrt{2}\pi N \langle \alpha \rangle}{1 - \frac{4}{3}\pi N \langle \alpha \rangle} + \frac{\frac{2\sqrt{2}}{3}\pi NS \langle \gamma_e - \gamma_o \rangle}{1 - \frac{4}{3}\pi N \langle \alpha \rangle} \tag{5}$$

$$n_o(T) \approx \frac{3\sqrt{2}}{4} + \frac{\sqrt{2}\pi N \langle \alpha \rangle}{1 - \frac{4}{3}\pi N \langle \alpha \rangle} - \frac{\frac{\sqrt{2}}{3}\pi NS \langle \gamma_e - \gamma_o \rangle}{1 - \frac{4}{3}\pi N \langle \alpha \rangle} \tag{6}$$

Where $N\alpha$ is small, Birefringence of an LC material is defined as (Δn). Subtracting Eq. (6) from Eq. (5), we find:

$$\Delta n\ (T) \approx \frac{\sqrt{2}\pi NS \langle \gamma_e - \gamma_o \rangle}{1 - \frac{4}{3}\pi N \langle \alpha \rangle} \tag{7}$$

The refractive indices equation has the following simple terms:

$$n_e = \langle n \rangle + \frac{2}{3}\Delta n \tag{8}$$

$$n_o = \langle n \rangle - \frac{1}{3}\Delta n \tag{9}$$

In theory, both n_e and n_o are functions of wavelength and temperature. The wavelength effect has been talked widely [19,28]. Here, we focused on the temperature effects. According to our treatments and fitting results, the average refractive index <n> decreases linearly as the temperature increases:

$$\langle n(T) \rangle = A - BT \tag{10}$$

Equation (10) has a negative gradient. The value of B is around 10^{-4} K^{-1}. In contrast, birefringence is dependent on the order parameter S. Based on Haller's approximation, the order parameter can be approximated as $S = \left(1 - T/T_c\right)^{\beta}$ thus, the temperature-dependent birefringence has the following form:

$$\Delta n = (\Delta n)_0 \left(1 - \frac{T}{T_c}\right)^{\beta} \tag{11}$$

In Eq. (11), $(\Delta n)_0$ is the LC birefringence in the crystalline phase (or $T = 0^O K$), the exponent β is a material constant, and T_c is the clearing temperature of the LC materials under investigation. Substituting Eqs. (10) and (11) back to Eqs. (8) and (9), one can derive the four-parameter model for describing the temperature effect on the LC refractive indices [19,27]:

$$n_e(T) \approx A - BT + \frac{2(\Delta n)_0}{3}\left(1 - \frac{T}{T_c}\right)^{\beta} \tag{12}$$

$$n_o(T) \approx A - BT - \frac{(\Delta n)_0}{3}\left(1 - \frac{T}{T_c}\right)^{\beta} \tag{13}$$

By taking temperature derivatives of Eqs. (12) and (13), the temperature gradient for n_e and n_o can be derived:

$$\frac{dn_e}{dt} = -B - \frac{2\beta(\Delta n)_0}{3T_c}\left(1 - \frac{T}{T_c}\right)^{\beta-1} \tag{14}$$

$$\frac{dn_o}{dt} = -B + \frac{\beta(\Delta n)_0}{3T_c}\left(1 - \frac{T}{T_c}\right)^{\beta-1} \tag{15}$$

In this work, we use two different liquid crystals: 5CB and UCF35. At room temperature, the Physical properties, clearing temperatures and birefringence, of the compounds are shown in the table (1).

Table 1. Physical properties of 5CB and UCF35 compounds at 589 nm [29].

LC	*A*	$B(K^{-1})$	$(\Delta n)_0$	β	$T_C(^0k)$
5*CB*	1.7674	5.79×10^{-4}	0.3505	0.1889	306.6
$UCF-35$	1.8187	5.32×10^{-4}	0.5727	0.2719	368.3

The Physical properties of dielectrics (optical glass), are shown in table (2).

Table 2. Physical properties of dielectrics [26].

Dielectric	*n*	$\gamma(\frac{1}{k^0})$	$\alpha(\frac{1}{c^0})$
SiO_2	1.444	0.55×10^{-6}	11.9×10^{-6}
CaF_2	1.4226	19×10^{-6}	-11.7×10^{-6}
*NFK*51	1.486	-5.7×10^{-6}	13×10^{-6}
*NPSK*53	1.620	-2.3×10^{-6}	9.4×10^{-6}

The transmission properties of one-dimensional PC consisting of LC are distributed in a transparent matrix. Let us consider a one-dimensional ternary PC, with N elementary cells with lattice constant SiO_2. Each cell consists of one dielectric layer of width d_1 with refractive index n_1 and one layer of LC of width d_2 with refractive index equal to n_e or n_o (uniaxial crystals) and one dielectric n_3 with width d_3 and refractive index n_3. The lattice constant is $a = d_1 + d_2 + d_3$. To compute the PBG in the transmission spectra due to the temperature and light incident angle dependence with respect to wavelength, we use the transfer matrix method (TMM) [30-31]. The relative permittivity of the layers *A* and *B* are denoted by ε_A and ε_B respectively. The dielectric tensor of the anisotropic liquid crystal layer in the coordinate system shown in Figure (1) is [32]:

$$\varepsilon_D = \begin{pmatrix} n_o^2 Sin^2\varphi + n_e^2 Cos^2\varphi & \frac{1}{2}(n_e^2 - n_o^2)Sin2\varphi & 0 \\ \frac{1}{2}(n_e^2 - n_o^2)Sin2\varphi & n_o^2 Cos^2\varphi + n_e^2 Sin^2\varphi & 0 \\ 0 & 0 & n_o^2 \end{pmatrix}$$

The transmission properties of the structure are studied using the well-known 4 $\times$ 4 transfer matrix formulation [32-33] which is a very useful method in the presence anisotropic materials. In such cases, it is assumed that the electromagnetic wave consists of four partial waves and mode coupling (between TE and TM modes) takes place at the interfaces of the anisotropic material. however, for the cases of $\varphi = 0$ and $\varphi = 90^{\circ}$, the dielectric tensor of the LC defect layer will be diagonal and a simpler 2×2 transfer matrix method can be used to investigate the optical properties of the structure [33]. Each layer of PC has its own transfer matrix, and the complete transfer matrix of the system is the product of the individual transfer matrices. For TE wave, each single cell has a transfer matrix according to TMM and is given by:

$$M(d) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \prod_{l=1}^{3} \begin{bmatrix} \cos\delta_l & -\frac{i\sin\delta_l}{n_l} \\ -in_l \sin x_l & \cos\delta_l \end{bmatrix} \tag{16}$$

Where l represents either dielectric or liquid crystal layer. The phase δ_l is expressed as $\delta_l = k_l d_l = \frac{2\pi d_l}{\lambda} n_l$ for the entire structure of dielectric/LC /dielectric, after temperature effects the δ_l given by:

$$\delta_l = \frac{2\pi(n_l + \Delta n_l)(d_l + \Delta d_l)\cos\theta_l}{\lambda_0} \tag{17}$$

Where d_l, n_l, Δn_l and λ_0 represents the dielectric and liquid crystal layer thicknesses, refractive index, refractive index variation and the free space wavelength respectively. For the entire structure of $(D/LC/D)^N$, the total transfer matrix is given by:

$$T = (M_D M_{LC} M_D)^N \tag{18}$$

Where N is the number of cells, and the matrix elements can be obtained in terms of the elements of the single-period matrix. The transmission coefficient for tunneling through such a structure is given by:

$$t = \frac{4}{(T_{11}+T_{22})^2+(T_{12}+T_{21})^2} \tag{19}$$

where T_{ij} are the elements of the matrix T .

3. RESULTS AND DISCUSSION

In this one-dimensional ternary D/LC/D photonic crystal, we use four structures $SiO_2/UCF35/CaF_2$, $SiO_2/5CB/CaF_2$, $NFK51/UCF35/NPSK53$ and $NFK51/5CB/NPSK53$. The temperature dependence of PBG for normal incidence of TE light on one-dimensional binary structures with $N=20$ period at liquid crystalline phase temperatures without any alignment is shown in Figs. (2) – (8).

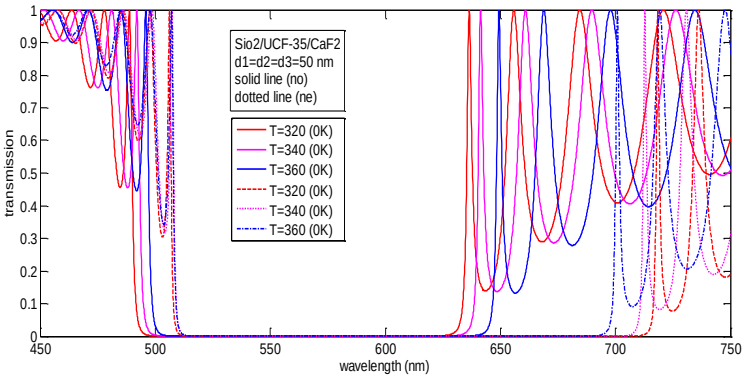

Fig. 2. Transmission PBG for $SiO_2/UCF35/CaF_2$ structure with N=20 and $\theta = 0^o$

Fig. (2) shows that the increase in temperature, PBG increase and shifts to red wavelength. The PBG for extraordinary ray (n_e) is very large than ordinary ray (n_o). Temperature dependence of transition light for $SiO_2/5CB/CaF_2$ structure is plotted in Fig. (3). The results represent for n_e situation PBG width is very vast and variations of figure with respect temperature in the right side of gap is very sharp.

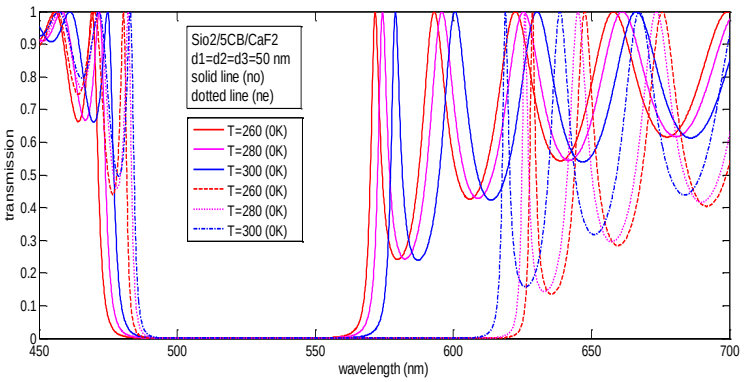

Fig. 3. Transmission PBG for $SiO_2/5CB/CaF_2$ structure with N=20 and $\theta = 0^o$

Figure (3) shows that with increase of temperature, PBG increase and shifts to red wavelength. The PBG variations of structure with based UCF-35 liquid crystal for long wavelength is noticeable, but for 5CB liquid crystal this result is obvious for short wavelengths.

Table 3. PBG with temperature and refractive index (n_e or n_o) for $SiO_2/UCF35/CaF_2$ and $SiO_2/5CB/CaF_2$

Structure	PBG (nm)	PBG Width	$T(^O K)$	PBG (nm)	PBG Width
	n_o			n_e	
$SiO_2/UCF35/CaF_2$	488.7-636.4	147.7	320	506.2-718.4	212.2
	492.0-641.4	149.4	340	507.4-712.8	205.4
	495.9-649.4	153.5	360	507.1-700.8	193.7
$SiO_2/5CB/CaF_2$	469.2-571.7	102.5	260	480.5-628.6	148.1
	471.8-574.4	102.6	280	482.2-625.9	143.7
	474.8-579	104.2	300	483.0-618.9	135.9

Table (3) shows that PBG width of n_e rays is broader than n_o rays, also with temperature rise, in both structure, PBG increase and decreases for n_o and n_e respectively.

Figure (4) and (5) show the temperature effects on $NFK51/5CB/NPSK53$ and $NFK51/UCF35/NPSK53$ structures respectively. In figure (4) we see that PBG of $NFK51/5CB/NPSK53$ construction with increasing of temperature increase (decrease) for n_o (n_e) state. One can see from figure (4), temperature rise shifts band gaps to long and short wavelength for n_o and n_e rays respectively, also for the right side of PBG these shifts are clear obviously.

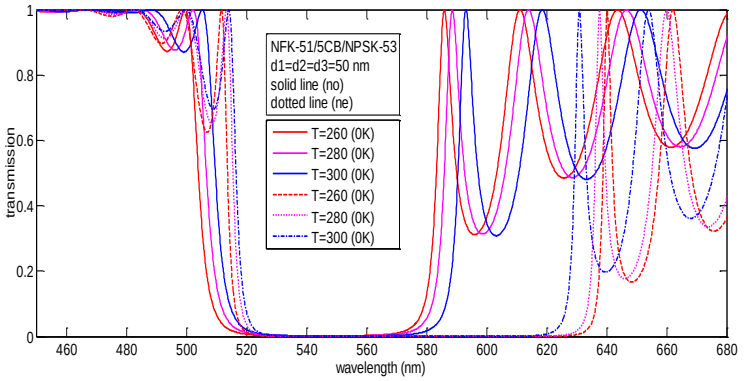

Fig. 4. Transmission PBG for $NFK51/5CB/NPSK53$ structure with N=20 and $\theta = 0^o$

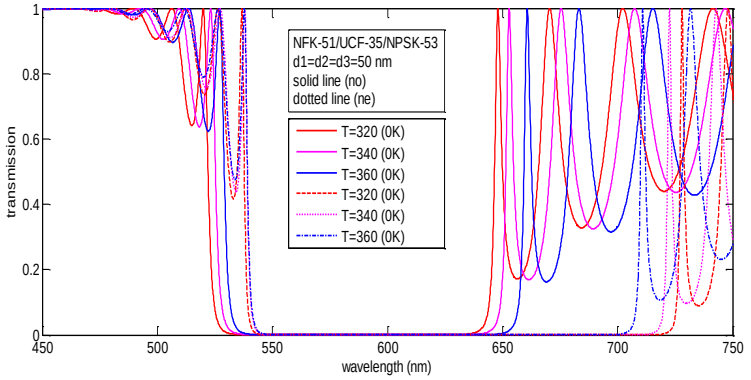

Fig. 5. Transmission PBG for $NFK51/UCF35/NPSK53$ structure with N=10 and $\theta = 0^o$

Figure (5) shows that PBG of $NFK51/UCF35/NPSK53$ configuration with increasing of temperature increase (decrease) for n_o (n_e) state. we can see from

figure (5), temperature increase moves band gaps to long and short wavelength for n_o and n_e rays respectively, but for the right side of PBG these shifts are obvious.

Table 4. PBG with temperature and refractive index (n_e or n_o) for $NFK51/5CB/NPSK53$ and $NFK51/UCF35/NPSK53$

Structure	PBG(nm)	PBG Width	$T(^{O}K)$	PBG(nm)	PBG Width
	n_o			n_e	
	499.6-585.9	86.3	260	511.7-640.2	128.5
NFK51/5CB/NPS53	502.2-588.6	86.4	280	513.4-637.6	124.2
	505.3-593.1	87.8	300	514.1-630.9	116.8
	519.9-648	128.1	320	536.7-728	191.3
NFK51/UCF35/NPS53	523.2-652.9	129.7	340	538-722.5	184.5
	527-660.7	133.7	360	537.8-710.9	173.1

Table (4) displays that PBG width of n_e rays is broader than n_o rays, also with temperature rise in both structures, PBG increase for n_o and decreases for n_e.

4. CONCLUSION

In this paper, we use one-dimensional ternary D/LC/D photonic crystal for structures $SiO_2/UCF35/CaF_2$, $SiO_2/5CB/CaF_2$, $NFK51/5CB/NPSK53$ and $NFK51/UCF35/NPSK53$. The results show that in all four structures an increase of temperature, PBG shifts to red wavelength, but an increase of temperature PBG increase for n_o and decrease for n_e. It is clear from figures and tables the PBG for extraordinary ray (n_e) is very large than ordinary ray (n_o), also the results represent for UCF-35 liquid crystal PBG width is very vast and variations of figure with respect temperature are very sharp. These variations for $SiO_2/UCF35/CaF_2$ structure is more than other. PBG for SiO_2 and CaF2 dielectric structure great than NFK51 and NPSK35. We can use the proposed structure as

temperature sensing device, narrow band optical filter and in many optical systems [15,20,22].

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