

Tunable optical properties of liquid crystals through coupling of magnetic fields with director angles

GIRIJESH NARAYAN PANDEY^{1,*}, NARENDRA KUMAR², PAWAN SINGH³, KHEM B. THAPA³, ANIL KUMAR SHUKLA⁴

¹Department of Applied Physics, Amity Institute of Applied Science, Amity University, Uttar Pradesh, Noida 201303, UP, India

²Department of Physics, SLAS, Mody University of Science and Technology, Lakshmangarh 332311, Sikar, Rajasthan, India

³Department of Physics, School of Physical and Decision Science, Babasaheb Bhimrao Ambedkar University (A Central University), Lucknow 226025, UP, India

⁴Department of E &T, Amity School of Engineering and Technology, Amity University, Uttar Pradesh, Noida 20313, India

In this research article, we show that the coupling of magnetic field with director angle of molecules can tune the optical properties of liquid crystal cell. Depending upon the strength of applied magnetic field, the liquid crystal exhibits phase transition including the twist bending phenomena having rotational order parameter that converts into isotropic phase. The interaction of magnetic field and directional angle is based on the boundary conditions and approximations leading to variation of the strength of coupling. First, while analyzing the optical characteristics, we find that the orientation angle increases with increase in the layer thickness of liquid crystal and decreases after reaching critical thickness of 50 nm, in which the variation is found only when the ratio H/H_F is greater than 1 under increasing field, while in decreasing field similar variation is also found for the H/H_F ratio less than 1. Furthermore, on the basis of the transmission characteristics of asymmetric PC with liquid crystal defect, we note that, it offers the characteristics of multichannel filter in the central region of wavelength 6000 Å, while the transmission is nearly 0.7 to 0.8. Depending on the twist bend phenomena inside liquid crystal cell, it can be employed in bistable and all-optical switching devices, and optical multichannel filters can be designed.

(Received May 19, 2022; accepted December 5, 2022)

Keywords: Liquid crystals (LCs), Magnetic fields, Freedericksz transition field (HF), Order parameter, Phase transitions, Tunable optical properties

1. Introduction

Photonic crystals (PCs) show extraordinary electromagnetic behaviors and also have excellent electromagnetic responses that are not the characteristics of bulk or non-periodic media [1, 2]. A one-dimensional (1D) PC is defined as a nano-layered media, while several 1D PCs have been studied with different dimensions of layers too. Many works have been reported on one-dimensional (1D) PCs using a variety of materials [3-8]. Magnetic materials are now having more attention towards researches on photonics for their considerable applications. Due to the unique optical properties of magnetic materials, they can be introduced in photonic crystals and such PCs are known as magneto photonic crystals (MPCs), i.e., the photonic crystals with at least one magnetic material component. The optical properties MPCs are tuned by the external electric or magnetic field of the magnetic materials [9, 10]. Now it is very interesting to study about effects of electric and magnetic fields on MPCs and nematic liquid crystals (NLCs). The optical properties of liquid crystal depend on the orientation angle of its molecules under the external fields. As the electric or magnetic fields change, the molecule

also changes their positional and rotational order parameters leading to tunable optical properties. The applications of liquid crystal in MPCs are applicable for the tunable optoelectronic devices [11-13]. The binary PC with introduced defects has extensively been studied [14-23]. Recently, Kumar and Saraf [24] investigated the effect of defect layer thickness on the reflectance characteristics of a magnetized cold plasma PC.

In this work, first we have made an analysis for shifting in the orientational angle in a LC layer of thickness 50 nm under changing magnetic field. Further, it is noted that the orientation angle increases with increase in the layer thickness and decreases after reaching critical thickness of the liquid crystal, that is, 50 nm, where the variation is found only when the H/H_F ratio is greater than 1 in increasing field, e.g., not at $H/H_F = 0.7$. In decreasing field similar variation is found even if the ratio H/H_F is less than 1. Further, we consider a binary asymmetric PC with introduced defect of liquid crystal as $(Si/Glass)^3 LC(Si/Glass)^3$ and determine the transmission through the asymmetric defective PC, and discuss its applications. Novelty of the work is to study of a binary PC with introduced defect of liquid crystal. The

characteristics of liquid crystal are first analyzed in which the shifting in the orientational angle is studied under changing magnetic field. Thereafter, transmission features of the defective PC, based on variations parameters of LC, are discussed.

2. Theoretical model and method

Under investigation of optical properties, the constants for liquid crystal to determine the refractive indices are:

$$R=1.7230, \quad S=5.24 \times 10^{-4}, \quad \Delta n=0.3485, \quad \beta=0.2542;$$

and $T_C = 330$ K. The temperature-dependent refractive indices (n_e, n_o) of the liquid crystal (thickness 100 nm) are given as [14, 25]

$$n_e(T) = R - ST + \frac{2\Delta n}{3} \left(1 - \frac{T}{T_C}\right)^\rho; \quad (1a)$$

$$n_o(T) = R - ST - \frac{\Delta n}{3} \left(1 - \frac{T}{T_C}\right)^\rho; \quad (1b)$$

where $R, S, \Delta n$ and ρ are the constants, and T_C be the clearing temperature of the liquid crystal. Here, n_e and n_o are considered at $1.5 \mu\text{m}$ wavelength. The average refractive index of LC is determined as $n_{\text{avg}} = \frac{2n_o + n_e}{3}$.

In order to find the dependence of orientation angle on the externally applied magnetic field in the liquid crystal layer, we solve the differential equation:

$$K_2 \frac{\partial^2 \phi}{\partial Z^2} Z + \Delta \chi^m H^2 \sin \phi \cos \phi = 0, \quad (2)$$

where χ is the magnetic susceptibility, Φ be the orientation field and H is the external magnetic field. H_F is threshold field known as Freedericksz transition field (H_F), where the phase transition happening in LC due to the external magnetic field. If, H is less than H_F , then there will be no phase transition. But, for H greater than H_F then orientation of molecules LC takes place.

Further, we analyze the transmission through a defective asymmetric binary PC in the form of $(\text{Si}/\text{Glass})^3 \text{LC}(\text{Si}/\text{Glass})^3$ with a defect layer D of LC as depicted in Fig. 1.

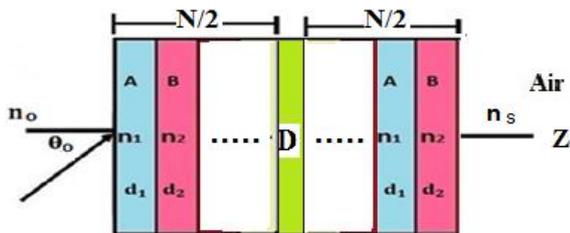


Fig. 1. An asymmetric PC as $(\text{Si}/\text{Glass})^3 \text{LC}(\text{Si}/\text{Glass})^3$ (color online)

Using the transfer matrix method (TMM), the transmittance of the asymmetric PC is obtained with the help of the characteristic matrix as [24, 25]

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

with $k_i = 2\pi \left(\frac{n_i \cos \theta_i}{\lambda} \right)$, $\beta_i = n_i \cos \theta_i$, the refractive index of layer- i is taken as $n_i = \sqrt{\mu_i \epsilon_i}$ with incident angle θ_o . Now, we can write the total characteristics matrix M for the defective asymmetric periodic ternary structure as

$$M = (M_{S_i} M_{\text{glass}})^3 M_{LC} (M_{S_i} M_{\text{glass}})^3 = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}. \quad (4)$$

So the transmission coefficient of the structure can be obtained as [7, 25]

$$t = \frac{2p_0}{(p_0 m_{22} + p_s m_{11}) + (p_0 p_s m_{12} + m_{21})}. \quad (5)$$

Thus, the transmittance of the structure can be obtained as

$$T = \frac{p_s}{p_0} |t|^2, \quad (6)$$

where $p_s = n_0 \cos \theta_0 = p_0$, the refractive index of the incident and substrate layers same, that is, $n_0 = 1.0$ for air.

3. Simulation results and discussion

First, we have analyzed the shifting in the orientational angle in a LC layer of thickness 50 nm under changing magnetic field using equation (2). Fig. 2 shows the plot of variation in orientation angle against H/H_F at LC layer thickness of 50 nm. The orientation angle versus the layer thickness of liquid crystal plots at various ratios of H/H_F , for increasing field are depicted in Fig. 3, and that of the decreasing field are shown in Fig. 4.

Thereafter, we study of transmission characteristics of a binary asymmetric PC with liquid crystal as a defect, that is $(\text{Si}/\text{Glass})^3 \text{LC}(\text{Si}/\text{Glass})^3$, with the following parameters: $n_{LC} = 1.82$, for extraordinary; $n_{LC} = 1.56$, for ordinary; $n_{Si} = 3.4$, and $n_{\text{glass}} = 1.5$. Thicknesses of LC = 100 nm, Glass = 15 nm, and Si = 40 nm. The transmission spectrum of the asymmetric PC is shown in Fig. 5.

In the first case of study, it is noted from Fig. 2 with a constant value of LC layer of 50 nm, that the orientation angle starts increasing from zero when the external magnetic field is equal to the Freedericksz transition field, and further increases with increases in the external field, that is, H/H_F ratio. In the same plot, on decreasing the external field the, orientational angle does not become zero even if both the fields are equal, that is, $H/H_F = 1$ but vanishes for the ratio of H/H_F at 0.7. Fig. 3 shows that, if

we apply external magnetic field and the thickness of LC is increased, the orientational angle increase with thickness under different field ratios H/H_F greater than 1, and then decreases symmetrically after reaching the peak. Fig. 4 illustrates that if we decrease the external magnetic field and the thickness of LC is increased simultaneously, the orientational angle increases with thickness under different field ratios H/H_F even if less than 1 and then decreases symmetrically after reaching the peak.

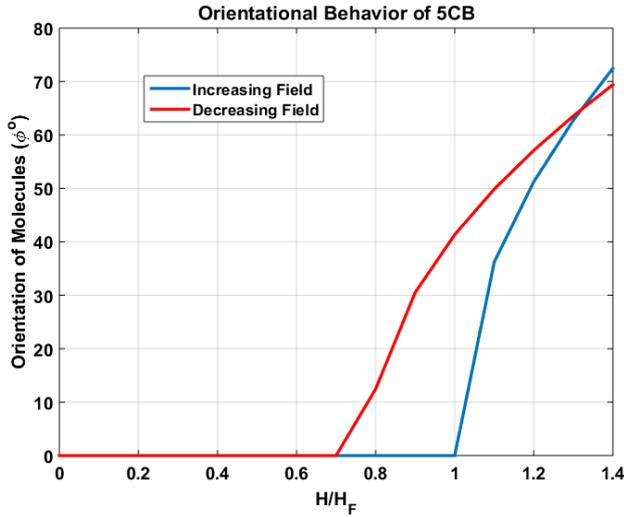


Fig. 2. Plot of variation in orientation angle against H/H_F at LC thickness of 50 nm (color online)

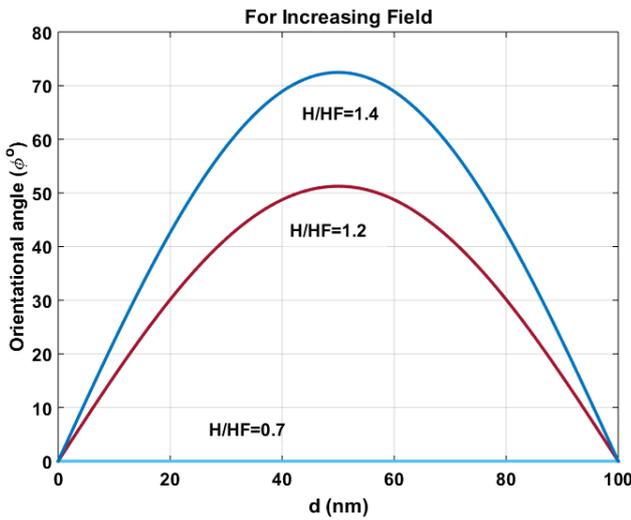


Fig. 3. Plot of variation in orientation angle against the layer thickness of liquid crystal at various ratios of H/H_F for increasing field (color online)

The main difference between increasing and decreasing the external field is that the orientation angle increases with increase in the layer thickness of LC and decreases after reaching critical thickness of the liquid crystal. This variation is found only when the ratio H/H_F is greater than 1 in increasing field, e.g., not at

$H/H_F = 0.7$. However, a similar variation is also found in decreasing field even if the ratio H/H_F is less than 1. Under increasing field, the peak orientation angle is slightly more as compared to decreasing field for same H/H_F ratio. The other finding is that the critical thickness of liquid crystal for which the orientational angle is maximum at critical thickness of LC as 50 nm, where the critical thickness corresponding to the peak remains independent of the increasing and decreasing fields.

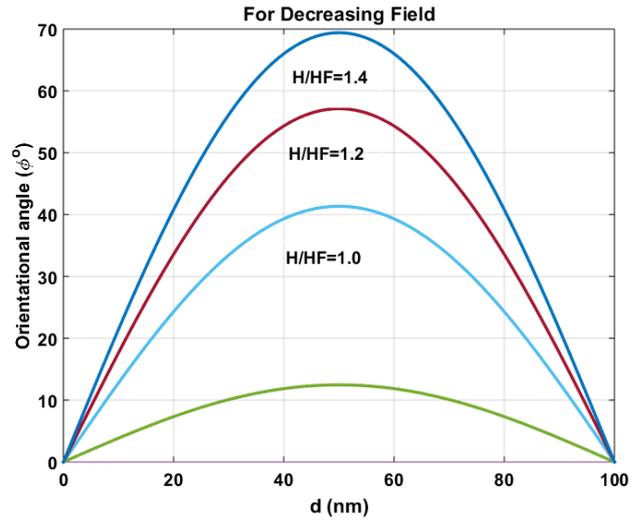


Fig. 4. Plot of variation in orientation angle against the layer thickness of liquid crystal at various ratios of H/H_F , for decreasing field (color online)

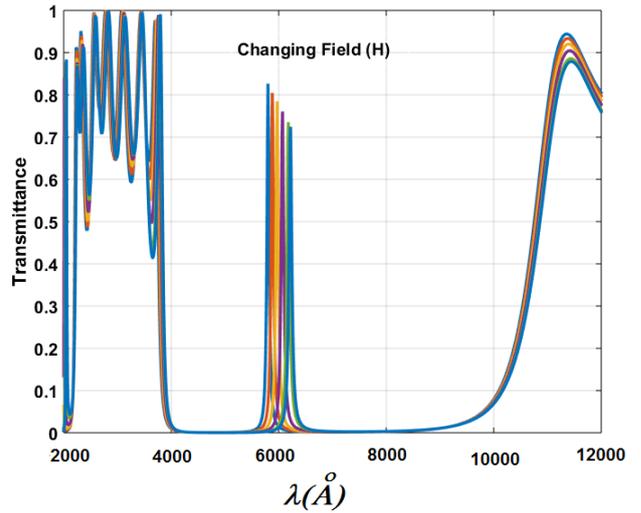


Fig. 5. Plot of transmission spectra of an asymmetric photonic crystal $(Si/Glass)^3 LC(Si/Glass)^3$ with liquid crystal as the defect at various H/H_F ratios (color online)

In the second case of study with the chosen parameters, if we consider an asymmetric PC with liquid crystal defect as $(Si/Glass)^3 LC(Si/Glass)^3$, whose transmission spectra shown in Fig. 5. Such PC is found to

be offering the characteristics of multichannel filter in the central region of wavelength 6000 Å, while the transmission is nearly 0.7 to 0.8. This multichannel filtering behavior is tunable with externally applied field.

Therefore, twist bend phenomena inside liquid crystal cell makes it eligible candidate for applications in bistable device, optical multichannel filters, and all-optical switching devices. In recent works, Zhang et al. [26] reported that, electrically switchable PCs based on TiO₂ inverse opals infiltrated with LCs can be employed to design active photonic devices. The submicrosecond switching of chiral LCs with 1D photonic microstructures promises for potential applications in soft photonic devices with the adjustable refractive indices [27]. Such applications may also be realized with the insights provided in the manuscript for the proposed model.

References

- [1] E. Yablonovitch, *Phys. Rev. Lett.* **58**, 2059 (1987).
- [2] S. John, *Phys. Rev. Lett.* **58**, 2486 (1987).
- [3] Pawan Singh, Khem B. Thapa, Girijesh N. Pandey, *Optoelectron. Adv. Mat.* **13**(7-8), 401 (2019).
- [4] Girijesh Narayan Pandey, Bhuvneshwer Suthar, *Journal of Macromolecular Symposia* **397**, 2000340 (2021).
- [5] Girijesh Narayan Pandey, Bhuvneshwer Suthar, Narendra Kumar, Khem Bahadur Thapa, *Journal of Superconductivity and Novel Magnetism* **34**, 2031 (2021).
- [6] Alok Kumar Pandey, Girijesh Narayan Pandey, Narendra Kumar, Khem Bahadur Thapa, J. P. Pandey, *Optoelectron. Adv. Mat.* **16**(1-2), 26 (2022).
- [7] Girijesh Narayan Pandey, Bhuvneshwer Suthar, *Materials Today Proceedings* **49**, 3214 (2022).
- [8] N. Kumar, Mahima Singh, G. N. Pandey, B. Suthar, *Springer Proceedings in Energy IWRESD 2021*, 81 (2022).
- [9] M. Inoue, R. Fujikawa, A. Baryshev, A. Khanikaev, P. B. Lim, H. Uchida, O. Aktsipetrov, A. Fedyanin, T. Murzina, A. Granovsky, *Magnetophotonic Crystals*, *J. Phys. D: Appl. Phys.* **39**, R151 (2006).
- [10] Mitsuteru Inoue, Alexander V. Baryshev, Alexander B. Khanikaev Maxim E. Dokukin Kwanghyun Chung, Jinheo Hiroyuki Takagi, Hironaga Uchida, Pang Boey Lim, Jooyoung Kim, *IEICE Trans. Electron.* **91**, 1630 (2008).
- [11] E. Graugnard, J. S. King, S. Jain, C. J. Summers, Y. Zhang-Williams, I. C. Khoo, *Phys. Rev. B* **72**, 233105 (2005).
- [12] Hai-Xia Da, Z.Y. Li, "Manipulating Nematic Liquid Crystals-based Magnetophotonic Crystals" *New Developments in Liquid Crystals*, Book edited by: Georgiy V. Tkachenko, I-Tech, Vienna, Austria, pp. 49-70 (2009).
- [13] P. V. Shibaev, V. I. Kopp, A. Z. Genack, *J. Phys. Chem.* **B107**, 6961 (2003).
- [14] E. P. Kosmidou, E. E. Kriezis, T. D. Tsiboukis, *IEEE Journal of Quantum Electronics* **41**, 657 (2005).
- [15] T. C. King, C. J. Wu, *Physica E: Low-dimensional Systems and Nanostructures* **69**, 39 (2015).
- [16] O. A. Abd El-Aziz, H. A. Elsayed, M. I. Sayed, *Applied Optics* **58**, 8309 (2019).
- [17] Si-Jia Guo, Zhi-Jian Li, Fen-Ying Li, Yi Xu, Hai-Feng Zhang, *Journal of Applied Physics* **129**, 093104 (2021).
- [18] S. Srivastava, A. Aghajamali, *Optica Applicata* **49**, 37 (2019).
- [19] J. Liua, P. Hanb, G Qiao, J. Yang, *Journal of Intense Pulsed Lasers and Applications in Advanced Physics* **1**, 69 (2011).
- [20] Arafa H. Sly, D. Mohamed, *J. Supercond. Nov. Magn.* **28**, 1699 (2015).
- [21] N. R. Ramanujam, Hala J. El-Khozondar, Vigneswaran Dhasarathan, Sofyan A. Taya, Arafa H Aly, *Physica B: Physics of Condensed Matter* **42**, 551 (2019).
- [22] Igor Lyubchanskii, Yuliya Dadoenkova, Nataliya Dadoenkova, Andrei Zabolotin, Maciej Krawczyk, *Transparent Optical Networks (ICTON)*, 18th International Conference **16263771**, 2161 (2016).
- [23] N. N. Dadoenkova, I. L. Lyubchanskii, Y. P. Lee, Th. Rasing, *8th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics - Metamaterials* **6948643**, 193 (2014).
- [24] Narendra Kumar, Jyoti Saraf, *Optik* **252**, 168 (2022).
- [25] N. Kumar, B. Suthar (eds.), "Advances in photonic crystals and devices," CRC Press, Taylor & Francis, Boca Raton, USA, 2019.
- [26] Ying Zhang, Ke Li, Fengyu Su, Zhongyu Cai, Jianxun Liu, Xiaowen Wu, Huilin He, Zhen Yin, Lihong Wang, Bing Wang, Yanqing Tian, Dan Luo, Xiao Wei Sun, and Yan Jun Liu, *Optics Express* **27**, **15391** (2019).
- [27] Lingling Ma, Chaoyi Li, Luyao Sun, Zhenpeng Song, Yanqing Lu, Bingxiang Li, *Photonics Research* **10**, 786, (2022).

*Corresponding author: gnpandey@amity.edu