# Analysis of Photonic Crystal Tuned by Nematic Liquid Crystals

F. Karaomerlioglu

*Abstract*—**Modelling of left-handed metamaterial-based photonic nanostructures in functional optoelectronic devices have been studied in present paper. Two dimensional photonic crystal array on a narrow-band semiconductor base filled with a liquid crystal was analyzed. Photonic band structure and isofrequency contours of the nanostructures containing both inorganic and organic components were calculated for both TE and TM modes by using the plane wave expansion method. Silver telluride was used as a narrow-band semiconductor and E7 type as a liquid crystal. The photonic crystal structure that is designed as hexagonal rods shape in an air background is planned for the square lattice.**

*Index Terms*—**Metamaterial, Organic Compound, Photonic Crystal, Semiconductor.**

## I. Introduction

Optics of nanotechnology and 3D artificial structures have actuated the research in the properties of photonic crystals (PCs) and have concluded the increase of applications of photonic band (PB) gap materials [1, 2]. The PCs essential characteristic is the light presence of allowed and forbidden frequency bands. It is feasible manipulating the light by PCs. Thanks to this property, it is designed new optical devices with PCs. In order to design devices, research on tuning the optical properties of PB gap has been an increase. Some research on one dimension (1D), two dimensions (2D), and three dimensions (3D) PCs has been studied [3-7].

It has been researched negative refraction recently. In opposition to left-handed materials (double-negative metamaterials), single-negative materials and indefinite materials, PCs can display negative refraction behaviors that are only detected by the properties of their PB structures and isofrequency contours [8-14].

In recent years, novel investigations have reached a viewpoint of LCs owing to the tunable light. Refractive indices of LCs can be changed by rotating LCs' directors [15-17].

**F. KARAOMERLIOGLU**, is with Department of Electrical Engineering University of Mersin University, Mersin, Turkey, (e-mail: filizkrm@mersin.edu.tr).

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It is familiar that the concept of topological order provides a new perspective. It has generated intense recent interest in searching for nontrivial topological materials, topological insulators (TIs) [18]. The differential feature of a TI is existence of robust conducting edge or surface states on the boundary of insulators. These typical boundary states have a topological origin, and so have potential for applications in spintronics and quantum computation devices [19]. Until now, TIs have been theoretically and experimentally affirmed [19, 20].

In this paper, it is proved and enhanced the optical properties in the 2D PC structure in TI rods based on the left-handed metamaterial tuned by LCs in theory. The investigation was achieved by controlling the intensity of the optical properties that had different materials added to a certain structure.

## II. Methodology

The plane wave expansion (PWE) methods' principles are depended on a direct numerical solution of the Maxwell's equations. Bloch's theorem [21] is used to expand the $H(\vec{r})$ field in terms of plane waves because the light waves are transmitted in periodic structures, as

$$H(\vec{r}) = \sum_{\vec{G}} h(\vec{G}) \hat{e}_{\vec{G}} e^{i(\vec{k}+\vec{G})\cdot\vec{r}} \tag{1}$$

where $\vec{k}$ is a wave vector in the Brillouin zone of the lattice and $\hat{e}_{\vec{G}}$ is the direction that is perpendicular to the wave vector $(\vec{k}+\vec{G})$ because of the transverse character of the magnetic field $H(\vec{r})$, $\nabla \cdot H(\vec{r}) = 0$.

## III. Results and Discussion

Using the PWE methods, the PC structure, composed of a PC in TI rods based on the left-handed metamaterial infiltrated with LCs, is designed for the square lattice. PCs structures that are designed as hexagonal rods shape are computed. Silver telluride ($Ag_2Te$) was used as TI material and E7 type as nematic LCs. $Ag_2Te$ is a narrow-gap semiconductor and has been predicted to be new families of TIs with a highly anisotropic.

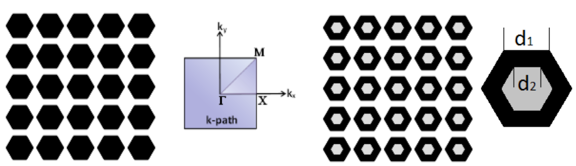
This paper is intended for characterising and comparing 2D PC structures which differ by the characteristics of their PB gap and isofrequency dependences.

### *A. Photonic band structure of 2D PC with hexagonal rods*

It is considered the results obtained from the computing of PB structure of the spectrum for the 2D PC of the TI rods type. This type composes of the elements in the form of dielectric hexagonal shaping a square lattice filled with and without LC. $Ag_2Te$ is a highly anisotropic TI. $Ag_2Te$ has two different basis refractive indices as the ordinary-refractive index $n_0 = 3.7977$ and the extraordinary refractive index $n_e = 4.6960$ at $\lambda > 1\ \mu m$. The calculations are performed for TI PCs with the permittivity of the hexagonal rods 14.423 and the period of the structure $a = 1\ \mu m$. LCs have commonly two kinds of dielectric constants; $\varepsilon_o$ and $\varepsilon_e$., ordinary and extraordinary dielectric constants. According to the electric fields perpendicular and parallel light waves, the director of the LC have ordinary and extraordinary refractive indices, respectively. The ordinary-refractive index of E7 type LCs is $n_0 = 1.51$ and the extraordinary refractive index, $n_e = 1.69$ at $\lambda = 1.55\ \mu m$ [22].

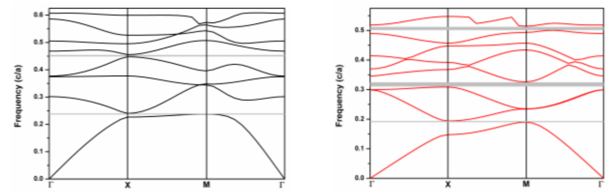
Schematic views of the proposed 2D PC of TI hexagonal rods without and with LC-infilled in an air background $(\varepsilon_a = 1)$ in a square lattice are shown in Fig.1. PB structure for TE and TM mode is calculated along direction that includes the high symmetry points Γ, X and M for the Brillouin zone in a square lattice. It is assumed that $d_1 = 0.45a$ and $d_2 = 0.2a$ denote the outer and inner edge of TI hexagonal rods.




(a) (b)

Fig.1. 2D PC structure of TI hexagonal rods for square lattice (a) without (b) with LC-infilled.

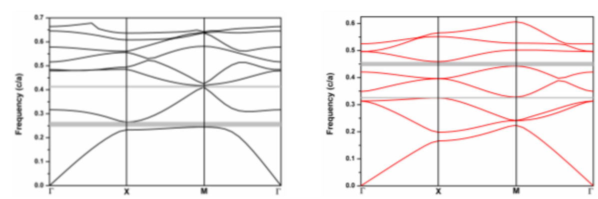
Fig.2 shows the seed PB structure of the PC (inset, from Fig.1 (a)) with the permittivity of the dielectric hexagonal and the permittivity of free space 1. For the ordinary refractive index, this PC has two PB gap of TE mode and three PB gap of TM mode. In TE mode the PC band gap along the direction between high symmetry points $\Gamma - X$ direction of the Brillouin zone lies in the frequency range from $0.237(2\pi c/a)$ to $0.240(2\pi c/a)$ and from $0.448(2\pi c/a)$ to $0.456(2\pi c/a)$. For TI hexagonal rods without LC-infilled, relative widths are 1.24% from band 1 to band 2 and 1.70% from band 4 to band 5 of TE mode, respectively (Fig.2 (a)). For TM mode, the frequency ranges have from $0.190(2\pi c/a)$ to $0.194(2\pi c/a)$, from $0.309(2\pi c/a)$ to $0.326(2\pi c/a)$, and from $0.501(2\pi c/a)$ to $0.515(2\pi c/a)$. Similarly, relative widths are 1.86% from band 1 to band 2, 5.39% from band 3 to band 4, and 2.76% from band 7 to band 8 of TM mode in Fig. 2 (b).



(a) (b)

Fig.2. PB structure of (a) TE (b) TM mode for TI hexagonal rods without LC-infilled.

In order to determine the optical properties of PC, structure and material are very important. For that reason, it is changed the PC structure that TI hexagonal rods are infiltrated with LC obtaining optimum results. Dispersion of PC in combination with the LC causes the appearance of different PB gaps in the continuous spectrum of PC, imperceptible on the scale of Fig.2. These effects are illustrated in Fig.3. It can be seen from Fig.3 (a) that the presented fragment of the PB structure of the spectrum exhibits different band gap situated in the frequency range between $0.245(2\pi c/a)$ and $0.265(2\pi c/a)$ and between $0.411(2\pi c/a)$ and $0.418(2\pi c/a)$ of TE modes. Relative widths are 8.07% from band 1 to band 2 and 1.61% from band 2 to band 3. When TI hexagonal rods are infiltrated with LC of the extraordinary refractive index, two band gaps in TM mode is shown in Fig.3 (b). PB gap has relative widths of 1.19% from band 3 to band 4 and 3.65% from band 5 to band 6, and the frequency range between $0.325(2\pi c/a)$ and $0.329(2\pi c/a)$ and between $0.443(2\pi c/a)$ and $0.459(2\pi c/a)$ of TM modes.



(a) (b)

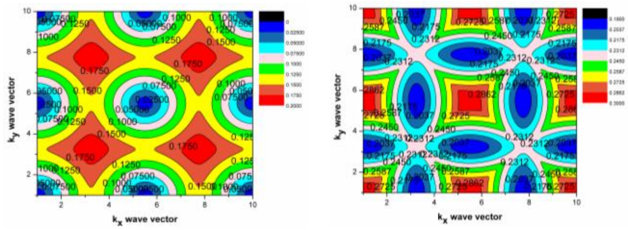
Fig.3. PB structure of (a) TE mode (b) TM mode for TI hexagonal rods with LC-infilled.

A comparison of Fig.2 and Fig.3 shows that the spectra of both types PC have different PB gaps between different bands.

### *B. Isofrequency surface of 2D PC with hexagonal rods*

Dependency of the isofrequency has a simple physical meaning to analyze 2D geometries. Because this dependence describes all of the possible waves with the given frequency and various wave vectors, the directions of the reflected and the refracted rays can be determined by elementarily finding the points in isofrequency dependences of media at a known orientation of the boundary and a given angle of incidence of the wave [23].

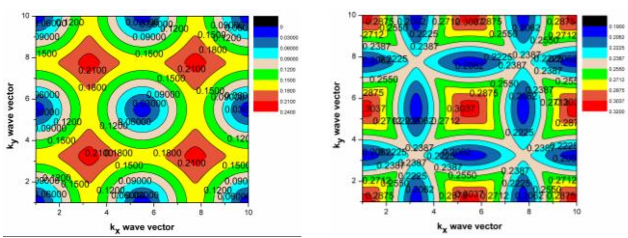
It is made use of symmetry calculating the isofrequency surfaces over the irreducible zone of the entire Brillouin zone. First, it is considered the isofrequency surface of TI hexagonal rods without LC-infilled for the first two TM bands of a square lattice. In Fig.4, it is reproduced PC with TI hexagonal rods with the same parameters. For the first band, the map was discretized using five field points per edge of the unit cell in Fig.4 (a). The map was discretized using four field points per edge of the unit cell for the second band in Fig.4 (b).



(a) (b)

Fig.4. The isofrequency contours of PC with TI hexagonal rods without LC-infilled for the square lattice (a) first band (b) second band.

In Fig.5, it is derived for PC with TI hexagonal rods of LC-infill for the first two TM bands. For the first band, the map was discretized using five field points per edge of the unit cell in Fig.5 (a). The map was discretized using four field points per edge of the unit cell for the second band in Fig.5 (b).



(a) (b)

Fig.5. The isofrequency contours of PC with TI hexagonal rods with LC-infilled for the square lattice (a) first band (b) second band.

The conventional PB structure plot only shows modes along the Γ–X–M–Γ line. The isofrequency contour allows to see all of the possible wave vectors uniformly sampled in a space. In fact, the PB structure shows all frequencies correspond to each given wave vector, while the isofrequency contour shows all wave vectors correspond to each given frequency. The information of PB structure and the isofrequency contour are correlated and complement each other.

Although the arms have different lengths, the figure uses a fixed number of sample points along each arm of the Γ–X–M–Γ contour. In order to estimate the shape of the contour from PB structure plot this is an important detail. It is easy to see the shape of the contour when it is calculated the isofrequency contour. (Figures 4 and 5). The circular region means isotropic propagation for the first band, while other shapes indicate anisotropic behaviors for the second band.

It can be found that PB structures deduced from the observed isofrequency contours are in overall agreement with that of the simulation results. The observability of the isofrequency contour due to any distortion in structures is important and could be used to research the dispersion of periodic structures and understand light propagation properties in the periodic photonic structures.

## IV. Conclusions

It was analyzed the optical properties in a 2D PC structure of TI hexagonal rods filled without and with LCs in a square lattice. For TE and TM mode, the PB structure is calculated along with the high symmetry point for the Brillouin zone.

These results have been shown that the dispersion of 2D photonic structure in combination with the nematic LC leads to qualitative changes in PB structure of the electromagnetic spectrum.

In practical usage, kind of LC infilled PCs based on a left-handed metamaterial are promising materials in order to use in the design of solar cell, super-lens applications, and a novel optoelectronic devices.

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## BIOGRAPHIES

**FİLİZ KARAOMERLIOGLU** received B.S. degree in Hacettepe University, Department of Physics Engineering, Ankara, Turkey in 1997. She received M.Sc. degree in Electrical-Electronics Engineering and Ph.D. degree in Physics from Cukurova University, Adana. She was a Research Assistant with Electrical-Electronics Engineering. From 2013 to 2014 she was a Visiting Researcher with Nanotechnology Research Center (NANOTAM), Bilkent University, Ankara. She joined Mersin University (Mersin, Turkey) in 2009, where she is currently an Assistant Professor in Electrical-Electronics Engineering Department. Her research interests include optics, optical devices, optical materials, optics and photonics, photonic crystals, nanophotonics and metamaterials.