

Behrooz Rezaei*, Ibrahim Halil Giden, Mohammad Sadegh Zakerhamidi, Amid Ranjkesh and Tae-Hoon Yoon

Two-Dimensional Hybrid Photonic Crystal With Graded Low-Index Using a Nonuniform Voltage

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Abstract: We proposed a new method for designing graded index lens using liquid crystal infiltration into annular photonic crystals. Applying an external nonuniform voltage in the transverse direction perpendicular to the direction of light propagation yields different orientation of liquid crystal molecules inside the photonic crystal unit cells. As a result, a gradient refractive index was modulated. We numerically investigate focusing properties of the designed graded index structure using plane-wave expansion and finite-difference time-domain methods. The gradient refractive index profile was adjusted by varying the nonuniform voltage excitations, which consequently altered the focal distance of the graded index structure. A wide tuning range of 1856 nm was achieved for focal distance by the proposed graded index structure. This feature can be implemented for planning a flat lens with tunable focal distance based on electro-optic effect. These achievements may have future applications in some optical devices such as near-field imaging and scanning.

Keywords: Focal Distance Tuning; Graded Index Optics; Liquid Crystal; Optical Beam Focusing; Photonic Crystal.

1 Introduction

Photonic crystals (PhCs) have attracted considerable attention because of their unique ability to control the propagation of electromagnetic (EM) waves. Photonic crystals are periodic dielectric structures and contain a region of the forbidden frequency spectrum, termed photonic band gap (PBG) [1]. Based on PBG properties, the challenge for light confinement inside PhCs was solved by designing optical instruments including waveguide [2], cavity [3], and optical fibre [4]. Moreover, the ability of PhCs to control the propagation of EM waves can also be achieved by the gradual variation of filling fraction, lattice periodicity, and/or refractive index along the particular directions. These types of modifications could form a graded index (GI) PhCs. In addition to these methods, recently another approach has been utilised for planning GI PhCs by modifying the orientation of elliptic cylinder within the unit cell [5]. In fact, GI PhCs are a proper alternative for gradient refractive index media because any kind of refractive index gradient can be created by modification of the geometrical and physical parameters of PhC unit cell [6]. Recently, various applications of GI PhCs such as efficient coupler [7], efficient mode converter [8], wavelength-division multiplexing [9], mirage [10], and focusing [11–14] have been reported. Active tuning of optical elements by means of externally applied electric or magnetic fields is paramount importance in optics.

During the last decades, there have been considerable interests on active control of PhCs to design switchable or dynamical devices. In 1999, Busch and John [15] investigated the tunability of PBG in three-dimensional PhCs by utilising liquid crystals (LCs). By inspiring this work, some investigations have been made for tuning PBG [16–19], the negative refraction [20], the modified spectral path of the transmitted beam [21], and guided wave [22] by inserting LCs in PhC media. Moreover, similar investigations were accomplished using liquids [23, 24]. Recently, some works have been performed on tuning the optical properties of GI PhCs using elastomer [25], semiconductor [26], and LC [27, 28]. The LC materials are appropriate for designing tunable GI PhCs due to their low-driving voltage and the low-cost fabrication process [29]. Recently, we infiltrated

*Corresponding author: Behrooz Rezaei, Research Institute for Applied Physics and Astronomy, University of Tabriz, Tabriz, Iran, E-mail: b_rezaei@tabrizu.ac.ir. <https://orcid.org/0000-0002-5965-379X>

Ibrahim Halil Giden: Department of Electrical and Electronics Engineering, TOBB University of Economics and Technology, Ankara 06560, Turkey

Mohammad Sadegh Zakerhamidi: Research Institute for Applied Physics and Astronomy, University of Tabriz, Tabriz, Iran

Amid Ranjkesh and Tae-Hoon Yoon: Department of Electronics Engineering, Pusan National University, Busan, 46241, South Korea. <https://orcid.org/0000-0002-4411-5606> (A. Ranjkesh)

the GI PhCs with LC to tune its focal distance (FD) through applying an external uniform voltage [30, 31].

In this work, first, we present a new method to construct a GI medium by applying nonuniform voltage to LC-incorporated two-dimensional (2D) PhC. The PhC is composed of LC-infiltrated annular cylinders in a square lattice arrangement. By assuming that the applied nonuniform voltage is in the transverse direction (perpendicular to the direction of light propagation), the orientation of LC molecules inside the PhC unit cells will be different along that direction. As a result, the refractive index gradient will be obtained. We indicate that the designed GI PhC effectively focuses the incident beam within a wide frequency range. Then, we modify the gradient refractive index profile by varying the nonuniform voltage excitations, which consequently alters corresponding FD of the GI PhC. This feature can be further utilised for planning a flat lens with tunable FD based on electro-optic effect. This work is arranged as follows: In Section 2, the designing procedure of GI PhC is explained by applying an external nonuniform voltage excitation to LC-infiltrated annular PhCs. In Section 3, we investigate the tunability of the FD for planned GI PhC via changing the nonuniform voltage excitations. Finally, In Section 4, we summarise our study.

2 Model Description

In this study, we have considered a 2D PhC with square lattice composed of indium tin-oxide (ITO) rings with refractive index $n_1 = 1.738$ [32] in air background with $n_b = 1$. The inner and outer radii of ITO rings are $r_{in} = 0.30a$ (a is the lattice constant) and $r_{out} = 0.40a$, respectively, as shown in Figure 1a. This material is mostly transparent in the visible part of the spectrum and has nearly zero absorption coefficient in this wavelength range. The ITO rings are infiltrated with LCs. Commonly, LCs have

two refractive indices, called ordinary (n_o) and extraordinary (n_e) refractive indices. It is worth mentioning that we choose high birefringence LC materials in PhC devices to achieve large tuning of their optical properties. The studied LC material is phenylacetylene type [33] and has $n_o = 1.590$ and $n_e = 2.223$. The anisotropy of LCs can be modified conveniently by altering the orientation of LC molecules as a result of the applied bias voltage. Figure 1b shows the director $\vec{n}$ of an LC molecule with rotation angle θ relative to the x axis. The external electric field is applied from the top and bottom electrodes of the LC-infiltrated ITO rings. In the absence of applied voltage, the LC molecules are in the perpendicular direction to the z axis, because as it is explained in the last paragraph of the article, the polyimide polymer layer can be coated on electrodes for homogeneous alignment of LC molecules. When the applied voltage reaches an appropriate value, the LC directors tend to vary its direction towards the z axis. Therefore, an optical wave, which is propagating in the x direction and polarised in the z direction, experiences the effective refractive index (ERI) of n_{LC} as [34]:

$$n_{LC}^2 = \frac{n_e^2 n_o^2}{n_e^2 \cos^2(\theta) + n_o^2 \sin^2(\theta)} \quad (1)$$

where the orientation angle θ of LC directors can be tuned through the bias voltage. Therefore, according to (1), the ERI of the LC varies from $n_{LC} = n_o$ at $\theta = 0^\circ$ to $n_{LC} = n_e$, when $\theta = 90^\circ$. The TM-polarised wave (electric field parallel to z axis) will experience n_o in the absence of applied voltage ($\theta = 0^\circ$) and n_e when the LC directors are aligned along the z axis ($\theta = 90^\circ$).

To design GI medium using the LC-infiltrated PhC, it is essential to achieve required knowledge on how their photonic band structures modified by altering the direction of LC molecules. The plane wave expansion (PWE) method is employed to calculate the dispersion characteristic of PhCs [35] using the MIT Photonic Band package [36]. The first TM photonic band diagram is calculated along the Γ -X direction at two values of $\theta = 0^\circ$ and $\theta = 90^\circ$, as is shown in Figure 2a. It is obvious that the band structure remarkably depends on the orientation angle. Figure 2b shows the corresponding group indices ($n_g = c(\partial\omega/\partial k)^{-1}$), termed ERI of PhC unit cell. From Figure 2a, it is clear that, in the long wavelength range, photonic band diagrams for different rotation angles of LC directors are fairly flat; i.e. their slopes stay almost constant. Therefore, as it can be seen from Figure 2b, the ERI of PhC unit cell for different rotation angles is nearly constant for normalised frequencies below $a/\lambda = 0.20$. The numerical results show that the ERI can be altered by changing the LC directors by applying an external electric field. Therefore, with the purpose of

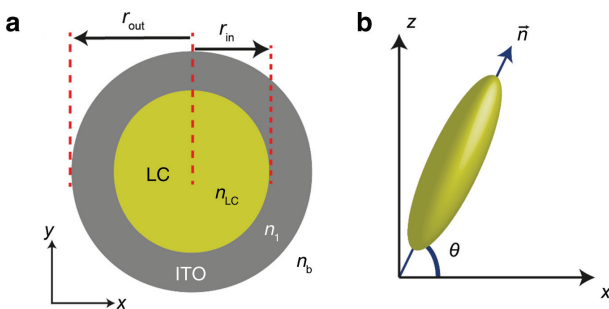


Figure 1: (a) Schematic diagram for ITO ring unit cell infilled with LC and (b) orientation of LC molecule along x - z plane.

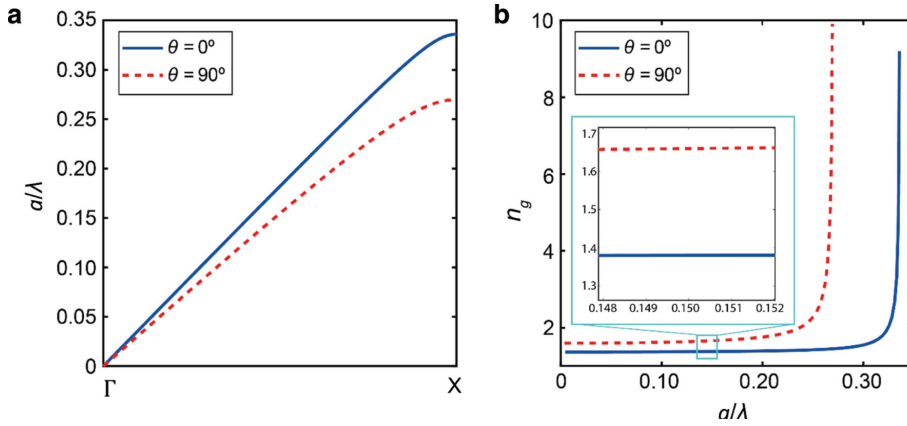


Figure 2: (a) The first TM-polarised photonic band structure along the Γ -X direction for $\theta = \{0^\circ, 90^\circ\}$ and (b) their group indices.

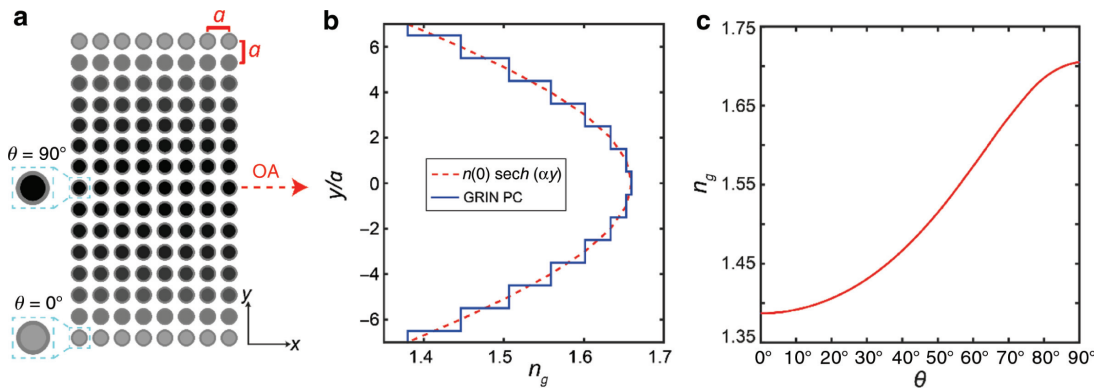


Figure 3: (a) The geometric scheme of designed GI PhC as obtained by applying an external nonuniform voltage to LC-infiltrated ITO rings along the transverse direction. OA and a represent optical axis and lattice constant. The orientation angle of LC molecules are $\theta = \{0^\circ, 38^\circ, 52^\circ, 62^\circ, 70^\circ, 76^\circ, 85^\circ, 90^\circ\}$ at positions $y/a = \{\pm 7, \pm 6, \pm 5, \pm 4, \pm 2, \pm 1.0\}$, respectively. (b) Stairstep ERI profile along with continuous curve HS function. (c) Group index variations depending on the LC orientations θ at fixed frequency $a/\lambda = 0.15$.

designing a GI PhC, instead of uniformly applied electric field, an external nonuniform voltage can be applied in the transverse direction to propagation direction of light. Therefore, the different orientation of LC molecules at different PhC unit cells along the transverse direction can be accomplished by obtaining the gradient refractive index. Zooming the Figure 2b in the region of design frequency, $a/\lambda = 0.15$, reveals that the ERI of PhC unit cell varies from $n_g = 1.3799$ at $\theta = 0^\circ$ to $n_g = 1.6595$ at $\theta = 90^\circ$, and hence, a large change of the ERI of $\Delta n_g = 0.2796$ is obtained. The schematic GI PhC is shown in Figure 3a. The distance between neighbouring rods along the x and y axes is fixed at $1.0a$. The optic axis of the GI PhC is indicated by OA in Figure 3. The ERI distribution can fit to any known mathematical function. Here, the Hyperbolic–Secant (HS) function, $n(y) = n(0)\text{sech}(\alpha y)$, is adopted, where parameter α is the gradient factor and $n(0)$ is maximum value of the ERI at $y = 0$. Setting vertical dimension of the proposed GI PhC to $d_y = 15a$ yields $\alpha = 0.08947a^{-1}$ with the index gradient of $\Delta n_g = 0.2796$, which corresponds to an

effective index distributions varying from $n(0) = 1.6595$ to $n(y = \pm 7a) = 1.3799$. Therefore, the orientation angle of LC directors at different transverse positions of $y/a = \{\pm 7, \pm 6, \pm 5, \pm 4, \pm 2, \pm 1.0\}$ will be $\theta = \{0^\circ, 38^\circ, 52^\circ, 62^\circ, 70^\circ, 76^\circ, 85^\circ, 90^\circ\}$, respectively. Figure 3b shows that the index profile of the designed GI PhC is stairstep, and its average value fits to HS function. Figure 3c implies a gradient index effectively produced by different orientation of LC directors inside the unit cells in the transverse direction.

3 FDTD Results and Discussion

The time-domain analysis of the designed HS GI PhC structure is carried out using the 2D finite difference time domain (FDTD) method [37]. The computational area is surrounded by perfectly matched layers [38] to get rid of unwanted back reflections. Also, the mesh size of the simulation domain is set to $\Delta x = \Delta y = a/30$. Here we only consider the TM polarisation. The time-domain analysis

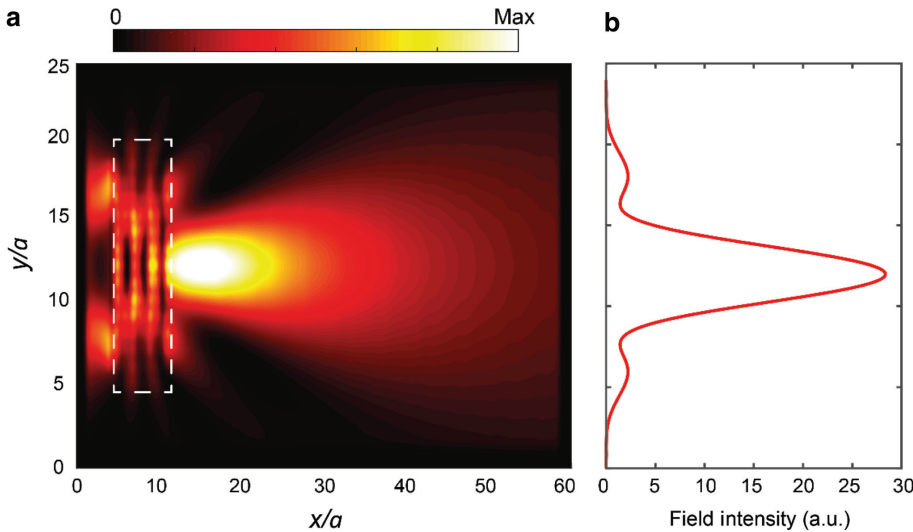


Figure 4: (a) The steady-state electric field intensity distribution of thin GI PhCs at operating frequency of $a/\lambda = 0.15$ with an FD of $5.24a$ (b) The transversal cross-section of focused beam's electric field intensity at the focal plane with $\text{FWHM} = 0.585\lambda$.

for the incident frequency of $a/\lambda = 0.15$ shows that the half pitch of the propagated field has nearly a value of $P/2 = 38a$ for vertical dimension of $d_y = 15a$, where the relation $\alpha P = 2\pi$ is satisfied by the values of P and α [39]. Regarding the pitch value of the propagating beam and considering the appropriate value for the length of the GI PhC, d_x , we can obtain different effects such as focusing, collimation, and diverging. By setting $d_x < 0.25P$, the incident beam focuses outside the structure [39, 40]. The dimensions of the designed GI PhC is considered as $(d_x, d_y) = (7a, 15a)$ to investigate its focusing effect. We select a thin GI PhC to easily trace the motion of focal point. The focusing capability of the GI PhC is analysed for incident plane waves in the first TM band around the design frequency, where a linear relationship exists between ω and k . The numerical results demonstrate the ability of the GI PhC in moderate focusing of the incident beam over the frequency range of $a/\lambda = 0.10$ to 0.20 . This feature makes it appropriate for designing flat lens and coupler. The FD is defined as the relative distance from the end face of the GRIN lens to the focal point. The designed GRIN structure is excited by an incident plane wave with frequency of $a/\lambda = 0.15$. The corresponding electric field intensity distribution is shown in Figure 4a. Moreover, to demonstrate more details of the focusing ability of the structure, the electric field intensity profile at the focal plane is depicted in Figure 4b. As shown in this figure, the proposed GI PhC represents an obvious focusing of the incident frequency of $a/\lambda = 0.15$. Focal distance in our proposed structure is $5.24a$, and the focused power is mostly concentrated at the main lobe with negligible side lobes. The full width at half maximum (FWHM) at the focal point is calculated to be $3.9a$, which corresponds to a subwavelength focusing of

0.585λ . The index profile of the proposed GI PhC can be modified by changing the external nonuniform voltage, which provides the flexibility to manipulate the propagation of the incident wave.

Now, we analyse the tuning characteristics of the FD for the designed GI PhC lens at the normalised operating frequency of $a/\lambda = 0.15$. Figure 5 shows the ERI profile of GI PhC lens for different values of gradient factors. The orientation angle of LC directors inside the different PhC unit cells along the transverse direction is obtained from Figure 3c for a given value of α . Here, the gradient factor can be tuned by changing the external nonuniform voltage. Thus, it is used as an adjustable parameter for tuning the FD of the GI medium, and its effect is discussed on the focusing properties

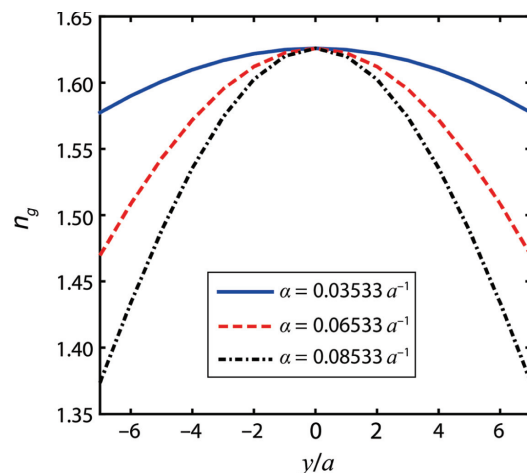


Figure 5: The effective index profile of designed GI PhC for various gradient factors at the normalised operating frequency of $a/\lambda = 0.11$.

of the system. Figure 6 shows the steady-state electric field intensity distributions at two values of gradient factors $\alpha = 0.08533a^{-1}$ and $\alpha = 0.03533a^{-1}$. These gradient factors correspond to ERI of $n(0) = 1.6259$ at $\theta = 90^\circ$ and $n(y = \pm 7a) = 1.3735$ at $\theta = 0^\circ$ with $\Delta n_g = 0.2524$ and $n(0) = 1.6259$ at $\theta = 90^\circ$ and $n(y = \pm 7a) = 1.5774$ at $\theta = 70^\circ$ with $\Delta n_g = 0.0485$, respectively. The calculated field intensities in Figure 6 show an increase of the emerging FD by enhancing the gradient factor. The reason can be explained by increasing the gradient factor; the refractive index gradient is decreased. The calculated FD values vary from $2.17a$ to $6.81a$ with a tuning of $4.64a$, when α changes from $\alpha = 0.08533a^{-1}$ to $\alpha = 0.03533a^{-1}$. Therefore, large tuning range of the focal point up to 1856 nm can be achieved by considering $a = 400$ nm for $a/\lambda = 0.11$. In other words, the FD varies from 868 to 2742 nm as α changes from $\alpha = 0.08533a^{-1}$ to $\alpha = 0.03533a^{-1}$. The simulated results show that the square lattice annular PhC composed of LC-infiltrated ITO rings can be used for designing GI medium by applying external nonuniform voltage. Moreover, the FD of the designed GI lens can be controlled by modifying the external nonuniform voltage. Finally, a practical approach for designing the proposed GI PhC is explained.

First, it must be noted that in order to apply a nonuniform voltage in electro-optical systems the well-known thin-film transistor (TFT) technology could be utilised [41, 42]. The TFT cells are created on silicon plate using very common and widely used deposition techniques. A layer of ITO can be deposited on TFT cells as ITO electrode, shown in Figure 7a. Then, the ITO electrodes are coated with polymer such as polyimide. It is worth mentioning that the alignment of LC molecules is paramount importance in manufacturing the LC-based systems. Therefore, for homogeneous arrangement of LC materials on the surface of ITO electrodes (pixel electrode), the polyimide layer can be rubbed. This gives the homogeneous alignment of LC

molecules [43]. For the practical fabrication of the proposed PhC on the surface of polyimide layer, the ITO rings can be fabricated by using photolithography [44] or electrodeposition [45] methods, where the ITO rings are isolated from ITO electrodes by polyimide. Finally, the LC can be infiltrated into the ITO rings by using a micropipette [21] or capillary action in an evacuated flask [46]. We proposed to use the lecithin (as depicted in green colour) to obtain homeotropic alignment inside the ITO rings. Furthermore, the surface anchoring energy can be decreased by increasing the concentration of lecithin or surfactant [47]. Therefore, the anchoring energy at the inner surface of the ITO rings will be lower than that of the polyimide one at the surface of the ITO electrodes. As a result, the alignment of the LC directors at the inner of the ITO rings will follow the homogeneous alignment of the polyimide layer, and the overall LC orientation will be roughly homogeneous. At the next step, the SiO_2 plate, which is coated with ITO and the ITO plate, is coated with polyimide, placed on top of the system or ITO rings. Figure 7a and b show the schematic of the proposed GI PhC with a side view for practical implementation in two cases: without and with applied nonuniform voltage, respectively. This is the most common technique in practical fabrication of LC-based devices using the TFT technique. Figure 8 shows the schematic representation of the upper and bottom electrodes, where the controlled electric field is applied only through the ITO electrodes from the bottom and upper silicon plate. The TFT system plays an important role in controlling the applied voltage for each pixel electrode, as performed in many LC panel devices. Therefore, a voltage can be easily applied across only one pixel without interfering from the other pixels. The upper ITO electrodes in the columns or rows are connected to TFT systems for each pixel. In fact, each pixel acts as a small capacitor with a layer of insulated LC placed between transparent conductive ITO electrodes. Now, to achieve

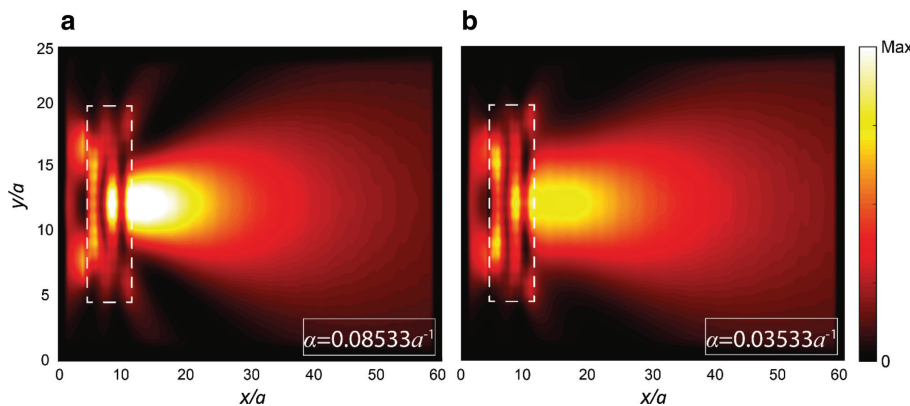


Figure 6: The steady-state electric field intensity distribution at gradient factors (a) $\alpha = 0.08533a^{-1}$ (b) $\alpha = 0.03533a^{-1}$ for operating frequency of $a/\lambda = 0.11$.

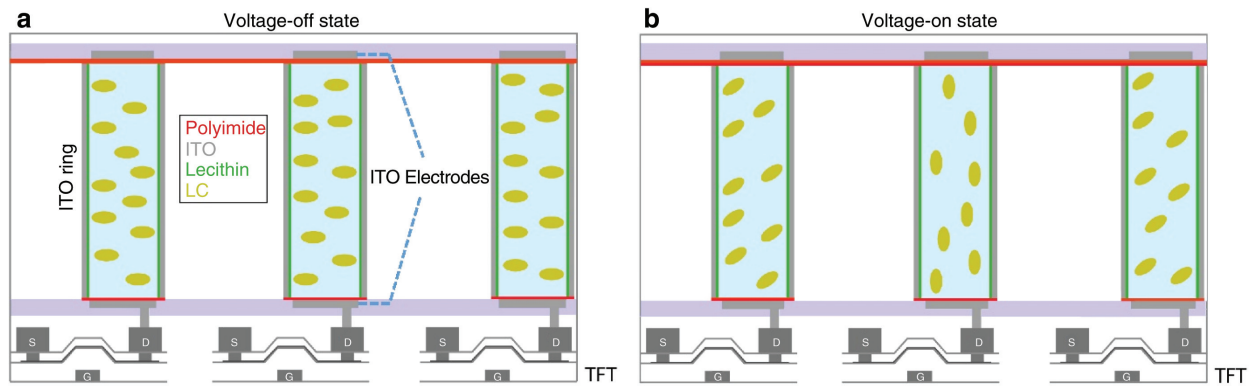


Figure 7: The side-view schematic representation for practical application of the designed GI PhC in cases (a) without and (b) with applied nonuniform voltage.

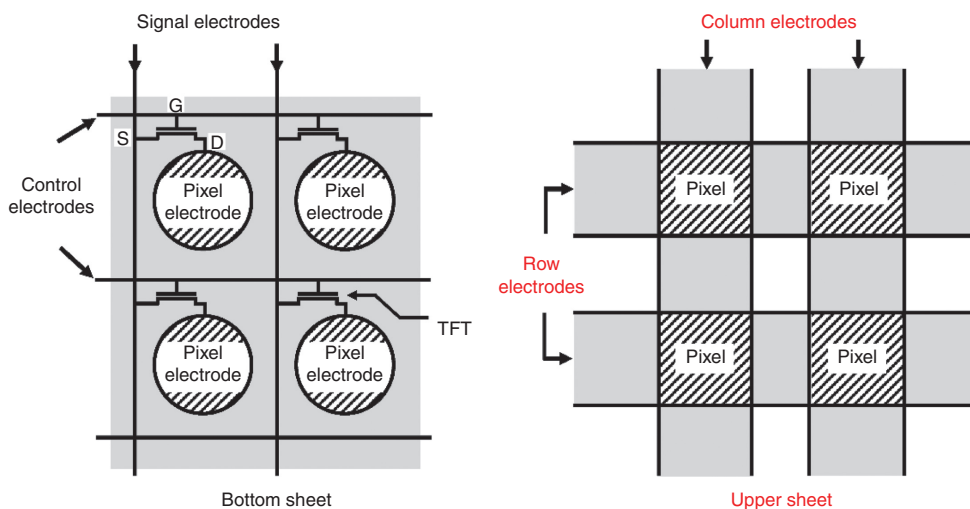


Figure 8: Schematic representation of the upper and bottom electrodes of the designed GI PhC shown in Figure 7.

different orientation of LC molecules inside different ITO rings along the transverse direction, the different voltages were applied through TFT segments. The existence of TFT systems makes a significant contribution in controlling the applied voltage in each ITO ring, and the different ERI could be obtained in different unit cells. Therefore, by applying the preferred voltage to different ITO unit cells in the transverse direction, the GI PhC can be designed. By controlling the applied voltage to LC-infiltrated annular rings using the TFT segments, the wave propagation can be controlled actively. The LC-based GI PhCs could be considered as a tunable electro-optic lens.

4 Conclusion

By performing numerical analysis using the PWE and FDTD methods, we presented a GI square lattice PhC made of LC-infiltrated ITO rings in the air background. It was

demonstrated that by applying an external nonuniform voltage along the transverse direction, the different orientation of LC directors was achieved inside the different PhC unit cells. Therefore, the refractive index gradient was obtained along the transverse direction. The gradient refractive index profile of the system was adjusted by varying the external nonuniform voltage. Based on this property, we designed a GI PhC lens having a tunable FD with a large tuning range of 1856 nm. We believe that our findings include potential electro-optic applications in photonic devices such as near-field imaging and scanning.

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