Optics Communications 382 (2017) 28–35

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Tuning light focusing with liquid crystal infiltrated graded index photonic crystals

B. Rezaei [a,*], I.H. Giden [b], H. Kurt [b]

[a] Research Institute for Applied Physics and Astronomy, University of Tabriz, Tabriz, Iran
[b] Department of Electrical and Electronics Engineering, TOBB University of Economics and Technology, Ankara 06560, Turkey

ARTICLE INFO

Article history:
Received 26 March 2016
Received in revised form
20 July 2016
Accepted 22 July 2016
Available online 29 July 2016

Keywords:
Graded index optics
Liquid crystals
Optical beam focusing
Tuning

ABSTRACT

We perform numerical analyses of tunable graded index photonic crystals based on liquid crystals. Light manipulation with such a photonic medium is explored and a new approach for active tuning of the focal distance is proposed. The graded index photonic crystal is realized using the symmetry reduced unit element in two-dimensional photonic crystals without modifying the dielectric filling fraction or cell size dimensions. By applying an external static electric field to liquid crystals, their refractive indices and thus, the effective refractive index of the whole graded index photonic crystal will be changed. Setting the lattice constant to $a = 400$ nm yields a tuning of 680 nm for focal point position. This property can be used for designing an electro–optic graded index photonic crystal-based flat lens with a tunable focal point. Future optical systems may have benefit from such tunable graded index lenses.

1. Introduction

Photonic crystals (PCs) are scalable periodic dielectric materials designed to affect the propagation of electromagnetic waves in the same way as the periodic potential in semiconductor crystals affects the electrons' motion by defining allowed and forbidden energy bands (i.e., band gaps for photons vs. electrons). Applications of PCs depend on either their photonic band gaps or tunable dispersion within the allowed bands. The first property enables design of many optical devices such as waveguides [1], cavities [2], filters and optical fibers [3], whereas the second property enables self-collimation [4] and negative refraction phenomena [5] to be observed in PCs. Applications of the second approach can be further expanded in PCs by introducing certain types of structural modifications along particular directions forming graded index (GRIN) PCs. GRIN PCs are an important choice for the GRIN media design since the refractive index variation is extended and any type of index distribution can be formed by geometrical manipulations in PC elements [6]. By proper adjustment of index distribution, GRIN PCs can have various potential applications in photonic integrated circuits such as efficient mode coupling [7], mode-order converting [8], wavelength de-multiplexing [9], light super-bending [10], and focusing [11–14].

Possible methods to design GRIN PCs may be gradual change in the filling fraction of the PC unit-cell, the lattice period, and/or the refractive index of composing material. PCs composed of highly symmetric elements such as circular rods or holes are not required if one does not intend to search for photonic band gap features of these structures. Consequently, plenty of new applications of symmetry reduced PCs may emerge by exploring energy diagrams that hold information corresponding to the different orientations of low symmetric elements inside the unit cell. Thus, apart from the above mentioned approaches, we have recently applied a new strategy for designing GRIN PCs with symmetry-reduced PCs made of elliptical dielectric rods in air background [15]. The index distribution was formed by gradual change of elliptical rods' orientations inside the unit cell without altering the filling fractions and unit cell dimensions. The consequence of induced index gradient along the transverse to propagation direction yields oscillatory wave propagation. Appropriate length of the structure starts acting as a focusing optical element with flat front and back surfaces.

In the last decade there has been an increasing emphasis on tuning the optical properties of photonic structures in order to design switchable or dynamical devices. Busch and John in Ref. [16] predicted the tunability of band gap in three dimensional (3D) PCs by utilizing liquid crystals (LCs). Following this publication, some investigations have been done for tuning band gap [17–22], negative refraction [23] and tunable guided-wave photonic devices [24] by infiltrating LC in PCs. In addition to LCs, similar works have been performed using liquids [25,26].

In a recent work, spatial pattern of the transmitted beam was modified via LC infiltrated woodpile PCs [27]. LCs are anisotropic and birefringent, however their birefringence can be controlled by

---

* Corresponding author.
E-mail address: beh_rezaei@hotmail.com (B. Rezaei).

http://dx.doi.org/10.1016/j.optcom.2016.07.062

applying an external electric field. The orientation of LC molecules can be easily changed in response to an applied voltage and consequently a change in the refractive index will be obtained. To the best of our knowledge, the electrical tuning of LC-based GRIN PCs is relatively less studied and reported in the literature [28]. It is studied that, changing the external voltage of each LC cell behind the GRIN PC lens will lead to the steering of the focused beam to the desired direction [28]. We follow different approach in our study, i.e. the background of designed GRIN PC is infiltrated with LC to study the tuning of focal point position. Although the GRIN medium itself achieves light tuning and steering functions by engineering the geometrical parameters, the optical properties of such structures are not tunable once they were fabricated. Thus far, some studies have been made for obtaining active control of GRIN media using dielectric elastomers [29] and plasmonic crystals [30]. Recently, a GRIN lens using LC material has been designed which requires to low-voltage driven input [31]. Because of low driven voltage and low-cost fabrication technology of LCs, these materials seem to be a prominent candidate for tuning the optical properties of GRIN structures. Therefore, in the present study, in addition to designing a GRIN PC by engineering its geometrical parameters, we have used LC material to electrically tuning the focal distance.

In this study, first, the design method of GRIN PC medium using elliptical elements is described. Then, we study the electrically tuning of focal distance (FD) by infiltrating LC into the background of GRIN PC, which can be utilized for designing tunable devices in photonic integrated circuits. Band diagram analysis are performed using plane wave expansion (PWE) method and the two-dimensional (2D) finite-difference time-domain (FDTD) method was performed for monitoring light propagation in the proposed structure [32].

2. Designing grin PC

In the present study, we have considered a 2D square lattice PCs made of elliptical rods in air background. The rods are composed of Si with dielectric permittivity of $\varepsilon_s=(3.45)^2$, and the background is air, $\varepsilon_b=1.0$. To determine the photonic band structure of PCs, we study the propagation of electromagnetic waves from Maxwell's equations. In inhomogeneous and source-free dielectric materials, Maxwell's equation can be written as the following formula for the magnetic field which is called master equation [33]:

$$\nabla \times \left[\frac{1}{\varepsilon(\vec{r})} \nabla \times H(\vec{r}) \right] = \frac{\omega^2}{c^2} H(\vec{r}) \tag{1}$$

where c is the light velocity in vacuum, ω is the radial frequency of light and $\varepsilon(\vec{r}) = \varepsilon(\vec{r} + \vec{R})$ is position-dependent dielectric function which is periodic with respect to the real space lattice vector $\vec{R}$. The photonic band structure is calculated by solving Eq. (1) by means of the plane wave expansion method [34].

The MIT Photonic Band (MPB) [35] software is used to calculate the band structure and group indices. The major and minor radii of elliptical rods are assumed to be $(a_e, b_e)=(0.40a, 0.20a)$, where a is the lattice constant. So that the corresponding eccentricity is $e=b/a=0.5$. It is known that reducing the symmetry of PC unit-cell influences the dispersion properties of the PC modes especially at high symmetry points [36]. One approach to reduce the symmetry of PC structures is to rotate the noncircular scatterers of PC unit-cell. The rotation angle of elliptical rods (ϕ) is defined as the angle between its major radius and the lattice axis (x-axis), as shown in Fig. 1(a).

The orientation of elliptical rods inside the PCs can be adjusted in accordance with proper applications in mind, such as photonic band gap enhancement [37], collimation [38], and focusing [39] effect. The calculated transverse magnetic (TM) photonic band diagram of elliptical PC with two rotation angles $\phi=0°$ and $90°$ is shown in Fig. 1(b) for the Γ–X direction. The non-zero magnetic and electric field components of the TM polarization are H_x, H_y and E_z, respectively. To better understand the angle dependency of the band structure, group indices ($n_g=c(\partial\omega/\partial k)^{-1}$) at the first TM bands of elliptical PC are calculated for the rotation angles of $\phi=0°$ and $90°$, c is being the light velocity in vacuum. The results are presented in Fig. 1(c). Zooming the graph around the designed frequency of $a/\lambda=0.15$, shows that the effective index ranges from $n_{eff}=2.42$ at $\phi=90°$ to $n_{eff}=2.26$ when the rotation angle equals $\phi=0°$ and hence, an effective index change of $\Delta n=0.16$ appears. That corresponds to relatively small index variation with respect to elliptical rod orientation (angle sensitivity): $\Delta n/\Delta\phi=0.0018\ \mathrm{deg}^{-1}$ in spite of the fact that there is only orientation change of PC unit-cell element and filling factor is kept the same. It is important to note that the dispersion diagram ($\omega - k$) gives the group indices and group velocities of each band. In the long wavelength region, the photonic bands for different rotated ellipses are fairly flat, i.e., their slopes stay almost constant. Essentially, the group indices refer to effective index values. Dispersion analysis gives the effect of orientation of elements. On the other hand, the effective medium theory will give the same refractive index value for different orientations. Therefore, our

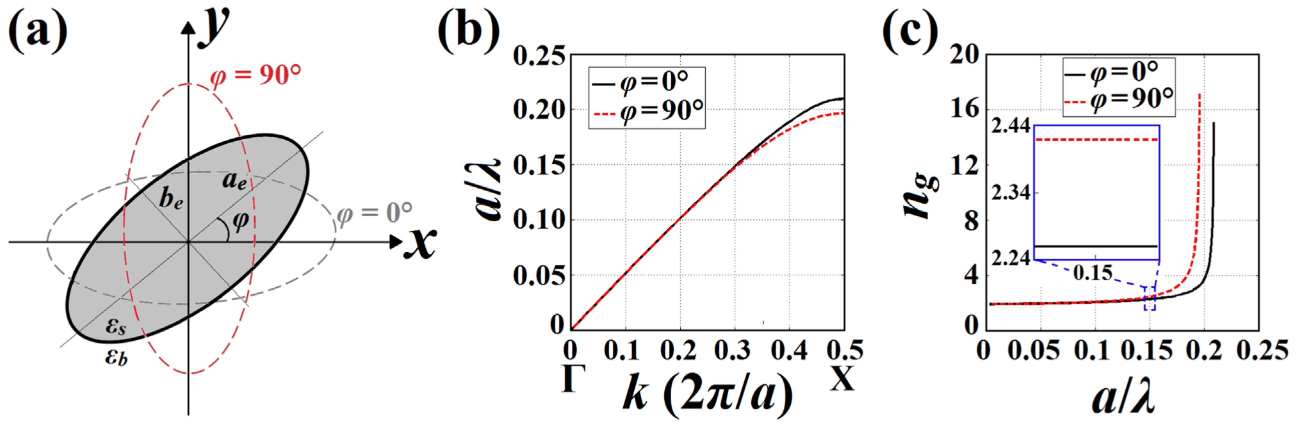

Fig. 1. (a) Geometrical scheme for elliptic unit cell of 2D square lattice PC. (b) The first TM band structure in Γ–X direction for rotation angles of $\phi=\{0°, 90°\}$ and (c) The corresponding group indices.