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Polarization-independent and tunable flat lenses based on graded index two-dimensional photonic crystals

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ABSTRACT

In this paper, we perform numerical analyses on polarization-independent and tunable graded index lenses based on two-dimensional graded photonic crystals and utilizing liquid crystals. A simple triangular lattice is used for the graded lens, in which the refractive index profile in the transverse direction varies in such a way that the modulus of the refractive index is biggest at the centre and decreases towards the edges. Three variation functions of linear, parabolic and hyperbolic are implemented for creating graded structures and investigating focusing characteristics of the designed lenses, using plane wave expansion and finite-difference time-domain methods. Finally, we study the variation of the lenses properties by changing the optical axis orientation of liquid crystals. Our numerical results show that, through an appropriate set of design geometrical parameters, polarization-independent and tunable lenses can be achieved.

1. Introduction

The great interest to the periodic arrangements of materials with different refractive index, called photonic crystals (PCs), has begun with the pioneer works of Yablonovitch and John [1,2] as one can efficiently control and manipulate the propagation of the electromagnetic waves in a similar way as semiconductors modify the properties of electrons in solid-state physics. This refractive index distribution gives rise to a periodic dielectric function that, as for the periodic potential generated by regular arrays of atoms and molecules, produces an energy band structure in which band gaps may occur [3,4]. The presence of photonic band gaps (PBGs) forbids the propagation for specific frequencies and in certain directions. This feature makes the PCs an excellent framework to engineer the materials for the optical control and manipulation. By introducing point defect or line defect into PCs a variety of passive and active optical devices can be constructed, based on PBG properties. Nowadays, the researchers propose some new applications for PCs, such as light bending [5] focusing [6] self-collimation [7] super prism effect [8] negative refraction [9] beam shifter and electromagnetic cloaks [10]. Some of these applications can be achieved by gradual modifications of PCs parameters such as: refractive index, filling factor or lattice constant. This modified type of PCs is called graded index PCs [11].

In a general classification, there are three basic gradient index types. The first is an axial gradient where the refractive index varies in a continuous way along the optical axis of the medium. The second is a radial gradient where index profile varies continuously from the optical axis to the periphery along the transverse direction in such a way that iso-indicial surfaces are concentric cylinders about the optical axis. The last type is the spherical gradient where index changes symmetrically around a point so that iso-indicial surfaces are concentric spheres [12]. During recent years, all these types are implemented perfectly in PCs structures for many applications such as optical lenses.

To briefly exemplify some pioneering graded index based PC lenses investigations, in 2008 H. Kurt et al. showed that by changing the lattice space along the transverse direction to propagation in two-dimensional PCs, strong focusing behaviour is observed [13]. Later in 2011, P. Shi et al. proposed and studied a PC flat lens with a graded index in a honeycomb two-dimensional lattice [14]. In 2012 F. Gaufillet et al. designed a flat graded lens made of metallic materials in a two-dimensional structure [15] and P. N. Dyachenko et al. introduced graded photonic quasicrystals and studied properties of such structure on the example of Luneburg lens [16]. In 2014, another type of graded photonic quasicrystals such as sunflower type Luneburg lens have been introduced and investigated [17]. In 2015 M. Turduev et al. proposed and studied inhomogeneous graded index medium as a flat lens [18]. In 2016, L. Wei et al. have developed graded PC lenses based on Luneburg structure [19]. It is well known that in two-dimensional PCs the

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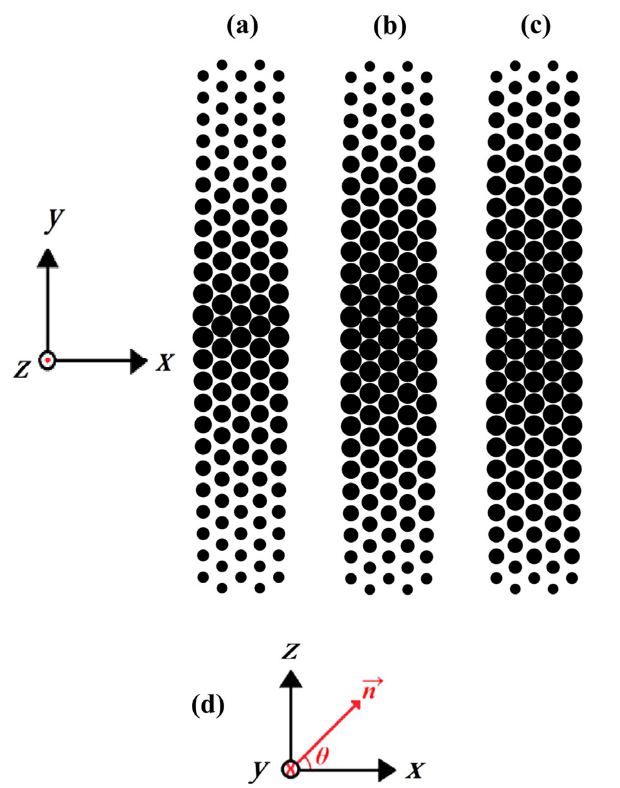

Fig. 1. The schematic of graded index flat lens with (a) linear, (b) parabolic and (c) hyperbolic variation functions and (d) rotation angle of liquid crystal molecules with respect to x-axis.

electromagnetic waves can be decomposed into the E-polarization (TM-mode) and H-polarization (TE-mode) modes and almost all mentioned works only operate for one type of the polarizations or in other words they are monomode or polarization-dependent systems.

In recent years, there has been an increasing attempt an emphasis on tuning the optical properties of PC based system in order to design dynamical or switchable devices. In 1999, Bush and John proposed that by infiltrating three-dimensional PCs with liquid crystal (LC), an applied electric field would tune the PBG [20]. Following this paper, some studies have been done for tuning band gap [21–23], tuning temporal shape of ultra short pulses [24] and tunable guided-wave photonic devices [25] by utilizing LCs in PCs.

In this study, we propose a planar graded index lens with two-dimensional PCs by varying the PCs parameters so that its effective refractive index changes along the transverse direction of the lens. The PC is composed of circular and narrow LC infiltrated glasses column embedded in an air background with triangular structure. In these structure different variation functions of LC infiltrated glasses along transverse direction of optical axis have been considered. Then, we discuss the focusing properties of the designed lenses by changing the director of LC for both TM and TE polarizations.

2. Structures and computational methods

In the present study, we have considered a two-dimensional triangular PC made of LC infiltrated cylindrical glasses. We assume that the graded index lens is obtained by decreasing the size of glasses from the centre towards the edges along transverse direction. The optical axis is along the $\Gamma - M$ direction of the lattice while the transverse direction of the lens is along $\Gamma - K$ direction. We studied three type of graded structure with linear, parabolic and hyperbolic variations while the distance between nearest neighbour glasses, a, is maintained

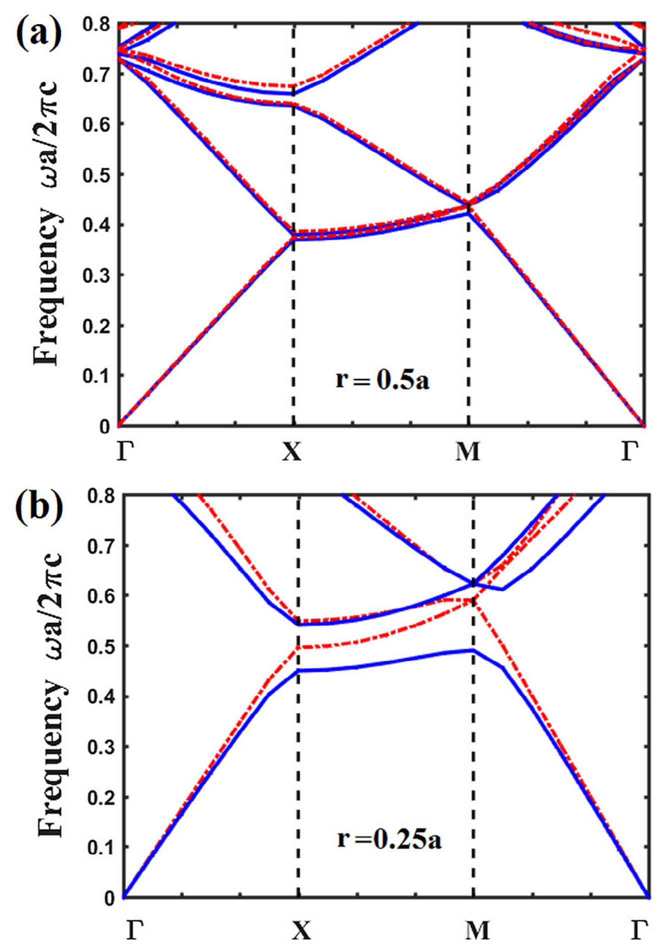

Fig. 2. Dispersion relation of E-polarization (solid blue line) and H-polarization (dashed red line) for triangular lattice of LC infiltrated circular glasses for $\theta = 0°$ in air with (a) $r = 0.50a$ and (b) $r = 0.25a$.

constant throughout the structures. The schematic configurations of the structures under consideration are shown in Fig. 1(a–c). Generally, LCs behave as an anisotropic material with ordinary and extraordinary refractive indices, n_o and n_e, respectively. For the phenylacetylene-type nematic LCs, $n_o = 1.59$ and $n_e = 2.223$ [24]. The alignment of LCs can be tuned and controlled by an applied external static electric field, the conditions for which are schematically shown in Fig. 1. The figure indicates the director $\vec{n}$ of a LC molecule and the rotation angle θ of the director with respect to z-axis. Without any applied voltage, LCs directors are aligned parallel to the x-axis, but by applying appropriate voltage, it starts to change its direction towards z-axis. The effective index of LC can be expressed as [24]:

$$n^2_{eff,LC} = \frac{n_e^2 n_o^2}{n_e^2 \cos^2(\theta) + n_o^2 \sin^2(\theta)} \tag{1}$$

The tilt angle, θ has a relationship with the applied voltage, V:

$$\theta = \begin{cases} 0, & V \le V_C \\ \frac{\pi}{2} - 2\tan^{-1}(\exp(-\frac{V - V_C}{V_0})), & V > V_C \end{cases} \tag{2}$$

V_C is the critical voltage at which the tilting process begins, and V_0 is a constant. The critical voltage at which the molecules tilting process begins is typically a few volts. When the applied electric field is sufficiently large, most of the molecules tilt, except those adjacent to the glass surfaces. Due to Eq. (2), the tilt angle θ for most molecules is an increasing function of voltage. It should be note that in this study,