Physica B: Condensed Matter 545 (2018) 233–236

Contents lists available at ScienceDirect

Physica B: Condensed Matter

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

Negative Luneburg lens based on the graded annular photonic crystals

Feng Xia[a,b], Shixia Li[a], Kun Zhang[a], Lipeng Jiao[a], Weijin Kong[a,b], Lifeng Dong[c], Maojin Yun[a,b,*]

[a] *College of Physics, Qingdao University, Qingdao, 266071, China*
[b] *Key Laboratory of Photonics Materials and Technology in Universities of Shandong, Qingdao University, Qingdao, 266071, China*
[c] *Department of Physics, Hamline University, Saint Paul, MN 55104, USA*

ARTICLE INFO

Keywords:
Luneburg lens
Graded photonic crystals
Negative refraction

ABSTRACT

Focusing by the designed negative Luneburg lens which is based on graded annular photonic crystals (GAPCs) are studied in this paper. The GAPCs are composed of ring-shaped silicon pillars in a hexagonal lattice. The gradient of refractive index is achieved by modifying the radii of inner holes. The effective negative refractive index is analyzed based on the photonic band structures and verified by the simulation of negative refraction in APCs flat lens. Numerical simulation results show that a 0.6λ focusing spot can be realized by our designed Luneburg lens and it has the potential to be utilized in photonic integrated circuits.

1. Introduction

Integrated optics are the system of light-controlling components combined into a single device in which wires and radio links are replaced by light-guiding optical fibers, and the conventional electrical integrated circuits are replaced by photonic integrated circuits (PICs) [1]. The ultimate goal of integrated optics is to create miniature optical circuits similar to the silicon chips that have revolutionized the electronic industry. However, it is a challenge to fabricate a small enough curved lens to integrate into the integrated optics devices [2]. Luneburg lens is an integrated optics device which can focus the parallel beam from any direction to a point at the opposite side of the lens [3,4]. Recently, the Luneburg lens has been proposed and fabricated for the fiber-to-chip optical links in the future communication networks [5] and the integrated imaging devices in silicon photonics [6]. Zhang et al. demonstrated a plasmonic Luneburg lens that can focus surface plasmon polaritons [7]. B. Arigong et al. showed that Luneburg lens can be used to efficiently couple the normally incident optical signals into the plasmonic slot nano-waveguide [8,9]. Ma and Cui first proposed a three-dimensional Luneburg lens in the microwave frequency [10] and then presented a Luneburg-like cylindrical lens antenna experimentally based on metamaterial [11]. Cui et al. proposed a transformation-optics modified solid immersion lens [12,13] and a semispherical lens for shaping 3D waves [14] which were fabricated by using the full-dielectric metamaterial.

PICs fabricated by photonic crystals(PCs) may be one of the ultimate solution for integrated optics devices because that the introduction of micro/nanometer-sized devices will produce great improvements in performance [1]. Recently, the different Luneburg lens by the different graded PCs have been proposed and studied [15–21]. The Luneburg lens are realized based on the gradient of positive refractive index which can be realized by changing the lattice constant [20]or the radii of rods [21]. Moreover, negative flat lens made by graded PCs' slab was first proposed in 2008 [15], and then aroused great interest and research due to the novel properties [16–19]. Annular photonic crystals (APCs) with negative effective refraction index n_{eff} have attracted many attentions for the more modification parameters, such as filling factor, optical index, and lattice period [22–26]. So, it will be very interesting to design a negative Luneburg lens by the GPCs and study the focusing properties.

In this work, the negative Luneburg lens based on the graded annular photonic crystals (GAPCs) are proposed, the elements of GAPCs are ring-shaped silicon pillars in a hexagonal-lattice. The photonic band properties of the APCs are analyzed and the negative refraction phenomena of APCs flat lens for different inner radii are simulated. The graded negative refractive index is realized by gradual modification of the radii of the inner hole. The focusing properties of the GAPCs Luneburg lens are studied.

2. Negative refraction of the APCs

The graded refractive index of photonic crystals can be realized by modifying the filling factor or the lattice constant [15]. Here, as shown in Fig. 1, we propose a GPCs flat lens based on the annular photonic crystals which are composed of the ring-shaped pillars in a hexagonal lattice.

Both the background and the holes are set to be air, while the material of ring-shaped pillar is chosen as silicon with the ε of 12.96. The

---

[*] Corresponding author. College of Physics, Qingdao University, Qingdao, 266071, China.
E-mail address: mjyun@qdu.edu.cn (M. Yun).

https://doi.org/10.1016/j.physb.2018.06.023
Received 7 April 2018; Received in revised form 22 May 2018; Accepted 20 June 2018

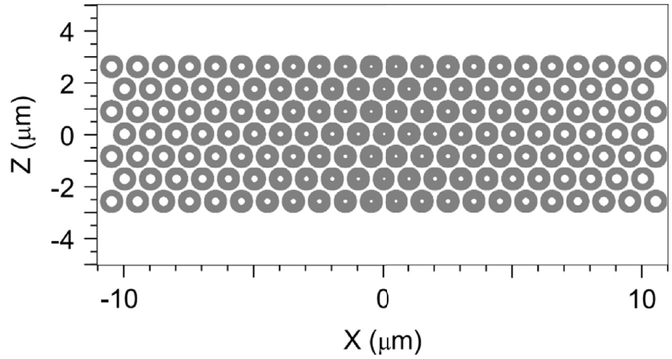

Fig. 1. The GAPCs flat lens with the ring-shaped silicon pillars, the inner radii increase from center of 0.1 μm to edge of 0.25 μm along X-direction linearly.

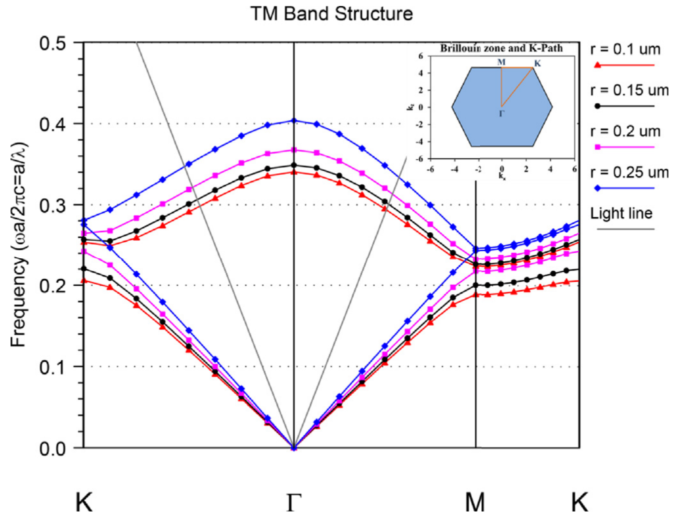

Fig. 2. Second photonic band structures of APCs with inner radii of 0.1 μm, 0.15 μm, 0.2 μm and 0.25 μm for TM polarization. The bands trends indicate that these APCs are effective negative refractive index materials. The inset shows the Brillouin zone and the K-path.

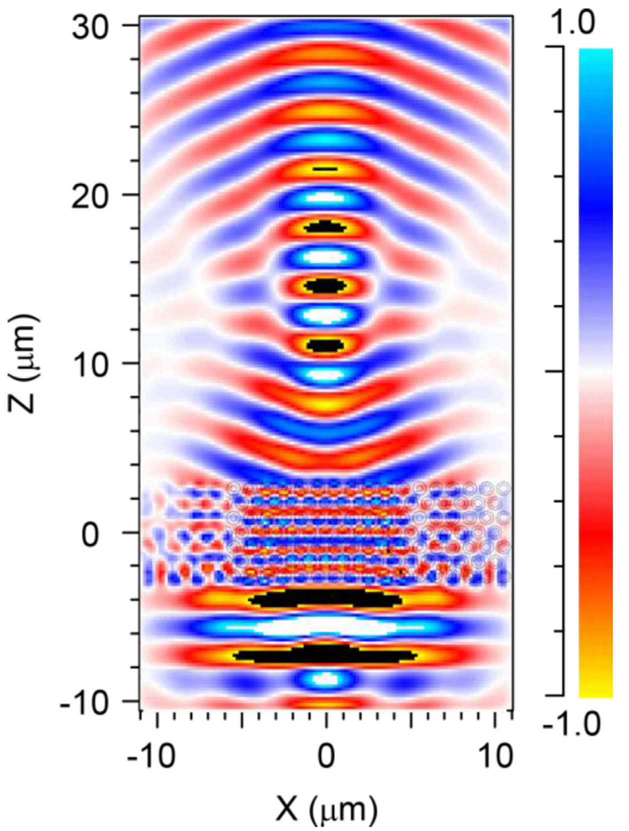

Fig. 4. FDTD simulation results of the focusing phenomenon by GAPCs flat lens at the normalized frequency of 0.30(a/λ).

lattice constant *a* is 1 μm and the outer ring radius *R* is 0.4 μm. The inner radii increase from the center 0.1 μm to the edge 0.25 μm along the X-direction linearly. Fig. 2 shows the second photonic band structures of APCs with the inner radii of 0.1 μm, 0.15 μm, 0.2 μm and 0.25 μm for TM polarization which are calculated by using the plane wave expansion(PWE) method. It can be found that the 4 s photonic bands decrease along the Γ-M direction and the Γ-K direction. For the

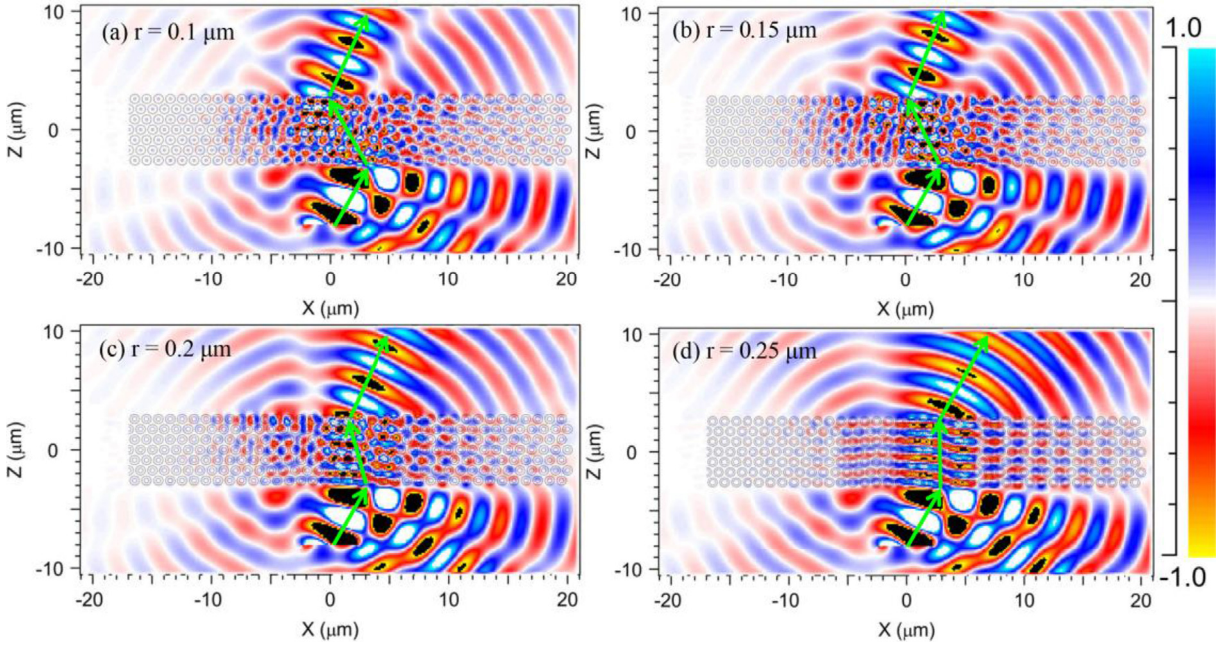

Fig. 3. The refraction phenomena for the inner radii of 0.1 μm, 0.15 μm, 0.2 μm and 0.25 μm at the normalized frequency of 0.30(a/λ).