A novel optical beam splitter based on photonic crystal with hybrid lattices*

Zhu Qing-Yi(朱清溢)[a)b)], Fu Yong-Qi(付永启)[a)†],
Hu De-Qing(胡德清)[b)], and Zhang Zhi-Min(章志敏)[a)]

[a)] *School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu* 610054, *China*
[b)] *Department of Electronic Engineering, Sichuan Information Technology College, Guangyuan* 628017, *China*

(Received 2 December 2011; revised manuscript received 8 February 2012)

A novel optical beam splitter constructed on the basis of photonic crystal (PC) with hybrid lattices is proposed in this paper. The band gap of square-lattice PC is so designed that the incident light is divided into several branch beams. Triangular-lattice graded-index PCs are combined for focusing each branch. Computational calculations are carried out on the basis of finite-different time-domain algorithm to prove the feasibility of our design. The waveguide is unnecessary in the design. Thus the device has functions of both splitting and focusing beams. Size of the divided beam at site of full-width at half-maximum is of the order of $\lambda/2$. The designed splitter has the advantages that it has a small volume and can be integrated by conventional semiconductor manufacturing process.

Keywords: optical beam splitter, photonic crystals, hybrid lattices, finite-different time-domain method

PACS: 42.70.Qs, 42.79.Fm, 02.70.Bf **DOI:** 10.1088/1674-1056/21/6/064220

1. Introduction

Bandwidth demanding services such as high-definition TV, video-on-demand, and video conferencing applications are becoming more and more popular, which causes a high requirement for broadband access. To meet this requirement, the access networks are broadly promoting the development of the techniques covering from the traditional digital subscriber line (DSL) and cable techniques to a new generation of fiber-based access. Passive optical network (PON) as a new concept is regarded as the next-generation access network with the existing reliable switching equipment. Optical beam splitter is a basic component of optical access network. Traditionally, the splitter is designed by a fiber coupler or planar optical circuit with branch waveguide structure.[1−5] These approaches mainly make use of waveguides to deliver the light to appropriate locations. Thus they do not have a focusing effect on the light beam. Therefore, it is difficult to compress the beams into a small size. The simple and reliable methods of designing new splitters are still appealing and valuable for communication industries.

On the other hand, photonic crystals (PCs) are widely investigated by many research groups. PCs are materials with periodic dielectric constants in one, two, or three dimensions. They modulate light by modulating periodic structures and consequently photonic band diagrams. Like a semiconductor with a periodic potential, the photonic crystal also exhibits a band gap. PCs-based applications like waveguide bends, channel-drop filters, and the perfect lens have been reported before.[6−10] Meanwhile, by gradually modifying the PC parameters (hole radius or lattice period), graded-index PC can be obtained and used to focus a plane wave.[11−14] In this paper, we design a novel optical beam splitter, in which the characteristics of the band gap of square-lattice PC (SLPC) as well as the focusing property of triangular-lattice graded-index PC (TLGIPC) are adopted. The band gap of SLPC is assumed to split the incident beam into several branches, and TLGIPC is used to focus each branch beam. Finite-different time-domain (FDTD)-based numerical simulation shows that the designed splitter fits well with our purpose. The designed splitter has many advantages in comparison with other beam splitters. It may find future applications in optical networks and corresponding micro-optical systems.

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11079014 and 61077010) and the Fundamental Research Funds for the Central Universities, China (Grant Nos. ZYGX2011YB020 and ZYGX2010J112).

†Corresponding author. E-mail: yqfu@uestc.edu.cn

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2. Splitter structure

Considering future application, we design a 1×2 beam splitter working at 1.55 μm which is the working wavelength of present optical communication networks. As illustrated in Fig. 1, the splitter consists of one SLPC located at the centre and two identical TLGIPCs situated at both sides. The dimensions of the splitter are 4 μm×20 μm×5 μm in x, y, and z directions respectively, the splitter is uniform and extends from 0 to 5 μm in z direction. This PC is two-dimensional (2D) and is constituted by periodic air holes perforated in Si substrate. There are 12 layers and 9 layers of holes in x direction and y direction respectively for the SLPC, the hole radius (r) and lattice period (a) are 0.1 μm and 0.28 μm respectively. The TLGIPC is derived by means of displacing every other column of the air holes of an SLPC with $a = 0.4$ μm by half period. The TLGIPC consists of 9 layers and 19 layers of holes in x direction and y direction respectively, the holes radii are ranging from 0.1 μm to 0.15 μm from its centre to outside along the y direction. To verify our design, computational calculation is carried out on the basis of FDTD algorithm; a commercial professional software (FDTD Solution from Lumerical Inc.[15]) is employed for simulation. In the simulation, the designed splitter is surrounded by air, an x-direction TM-polarized plane wave is incident on the left side of the splitter and the perfectly matched layer (PML) boundary condition is set.

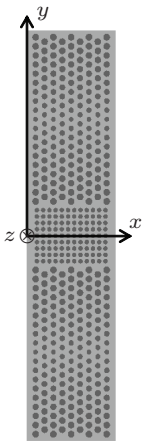


Fig. 1. Structure of the 1×2 splitter. The dimensions of the splitter are 4 μm×20 μm×5 μm in the x, y, and z directions respectively, the splitter is uniform and extends from 0 to 5 μm in the z direction.

3. Results and discussion

First, the transmissions of the SLPC (without other structures) are calculated. The wavelength (λ) of the incident plane wave varies from 1 μm to 2 μm, transmission is recorded at the right side of the PC. As shown in Fig. 2, a total band gap appears for $\lambda = 1.5$ μm–1.7 μm. It means that there is no transmission in the SLPC for the working wavelength of 1.55 μm.

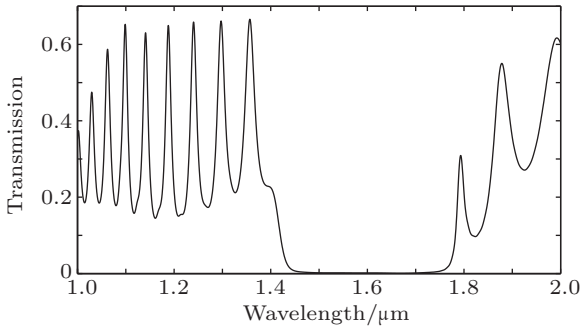


Fig. 2. Transmission spectrum of the SLPC with $r = 0.1$ μm and $a = 0.28$ μm.

Next, we simulate the focusing property of the above-mentioned TLGIPC (single PC without other structures). Function $r = 0.1 + c \times j^n$ is used to represent the radius of each hole, where r is the hole radius in units of μm, c is the constant for each set value of n, and j is an integer ranging from 0 to 9 which refers to the hole number from centre to outside. According to Ref. [11], the PC with large air hole has a high wave vector magnitude, and thus a large effective refractive index as well. Thus by increasing the holes radii from centre to outside, the modulus of the effective index is smallest at the centre and increases towards the outside. Focusing properties (such as the focal length and spot size) of the PC can be determined by the Eikonal equation, and the optical path can be obtained by multiplying the effective index with the thickness of the PC. Therefore, within the paraxial approximation, the designed TLGIPC with a certain index profile can produce a diffraction-limited focal point. The focal length and spot size are determined by index gradient. Different index profiles can be obtained by changing the n value and the corresponding constant c. We simulate the focusing property of four TLGIPCs with $n = 0.5$, 1, 1.5, and 2. We find out that the focusing property of the TLGIPC with $n = 0.5$ is superior to the others. As illustrated in Fig. 3, the maximal intensity appears at $x = 6.95$ μm behind the PC. The calculated full-width at half-maximum (FWHM) of the focal spot is 0.91 μm, which is on the order of $\lambda/2$ (0.75 μm). So the TLGIPC with $n = 0.5$ is used in the beam splitter.

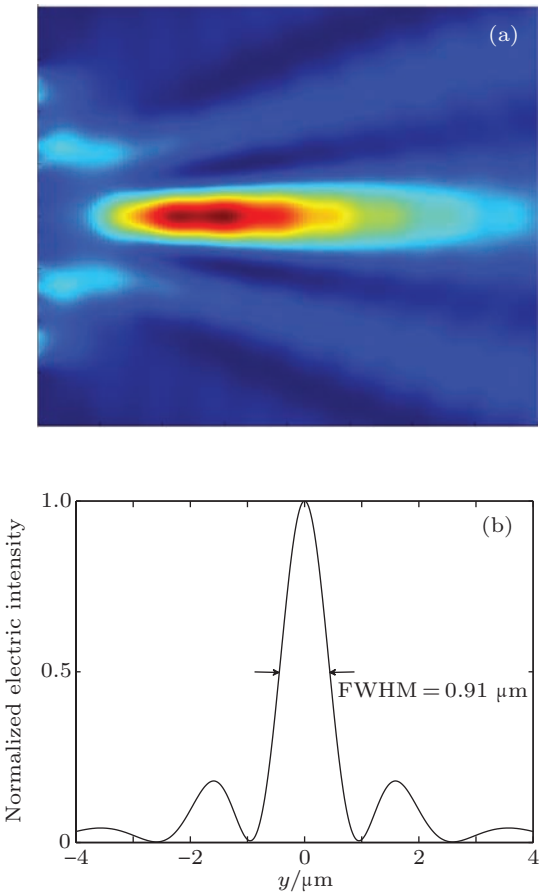


Fig. 3. (colour online) (a) Focusing effect of the $n = 0.5$ TLGIPC, (b) the intensity profile at the focal point along the y direction at site of $x = 6.95$ μm.

Then, the propagation behaviour of the 1×2 beam splitter as shown in Fig. 1 is simulated. The band gap of the SLPC is so designed that the incident plane wave is separated into two branches, and then each branch will be focused by the corresponding TLGIPC. Hence two beam spots will appear behind the splitter. The simulation results prove our assumption: light intensity behind the band gap region is much smaller than that of the other regions; and the incident plane wave is divided and focused properly, two separate focal spots appear behind the splitter as imagined before (see Fig. 4).

As can be seen in Fig. 4(c), these two focal spots have equal intensity and FWHM. The y-direction distance of two focal spots is determined mainly by the size of the SLPC and can be easily adjusted in specific applications in future. Corresponding maximal electric intensity appears at $x = 6.38$ μm behind the PC with FWHM=0.81 μm ($\sim \lambda/2$), i.e., the focusing resolution approaches the diffraction limit. The small FWHM compared with Fig. 3(b) may attribute to the interference of two fields respectively modulated by two TLGIPCs. To our knowledge, no beam splitter can possess such a small spot at present. On the other hand, unlike other splitters, the designed splitter divides the incoming light into two branches, and then each branch travels in free space. No waveguide is necessary accordingly. Meanwhile, the designed splitter has the advantage that it has a small volume and can be integrated by conventional semiconductor manufacturing process.

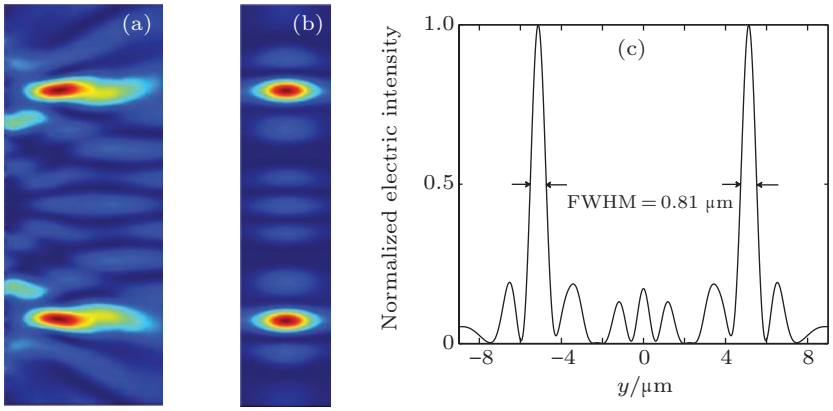


Fig. 4. (colour online) (a) Electric intensity distribution in x–y plane behind the 1×2 splitter with $z = 2.5$ μm; (b) electric intensity distribution in the focal plane (x–y plane); (c) intensity profile along the y direction in the focal plane of the 1×2 splitter.

Furthermore, similar to the 1×2 beam splitter, a $1 \times N$ splitter (N is an arbitrary number) can be constructed with N TLGIPCs alternatively separated by $N - 1$ SLPCs. Following this rule, we design a 1×3 splitter and simulate its interesting propagation behaviour. As shown in Fig. 5, the incident light is divided and focused into three focal spots (see Fig. 5(a)). The intensity of the central focal spot is slightly larger

than those of the other two spots (see Fig. 5(b)). As shown in the figure, the central focal spot has a smaller FWHM (0.75 μm), while the FWHMs of the other two spots are both 0.83 μm. The larger intensity and the smaller FWHM of the central spot is caused by the interference of three fields modulated respectively by three TLGIPCs. These effects can be reduced by increasing the y-direction size of the SLPC.

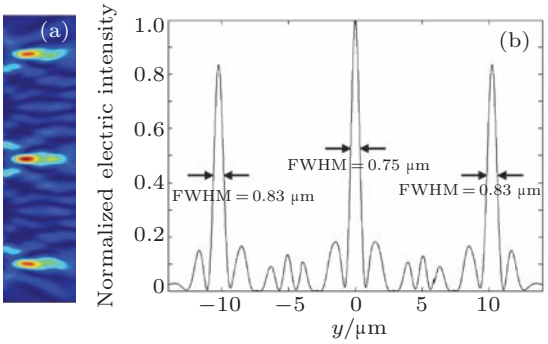


Fig. 5. (colour online) (a) Electric intensity distribution in the x–y plane behind the 1×3 splitter with $z = 2.5$ μm, and (b) intensity profile along the y direction in the focal plane of the 1×3 splitter.

4. Conclusion

A novel optical beam splitter design is proposed, in which the band gap of SLPCs and focusing property of TLGIPC are utilized. Computational numerical simulation is carried out by means of FDTD algorithm for proving the feasibility of our design. Near diffraction-limited resolution is achieved and no waveguide is necessary in the design. $1 \times N$ splitters can be constructed with the same approach. The designed splitter has the advantages that it has a small volume and can be integrated by conventional semiconductor manufacturing process. With the significant advantages of splitting and focusing beams in small volume, the designed splitter may find extensive applications in optical networks and corresponding micro-optical systems.

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