Photonic crystal-based optical beam splitter in silicon

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An optical power splitter with one input and three output ports is proposed and demonstrated for near infrared applications in the wavelength range from 2.3 to 2.5 μm. The device operates on the principle of directional coupling by introducing photonic crystal line-defect waveguides. Its functionality and performance have been numerically investigated and simulated by finite-difference time-domain method. Required optical power from each of the output waveguide can be easily controlled by adjusting the coupling length of interaction for photonic crystal line-defect waveguides. The total length of the 1×3 power splitter is 30 μm, which is significantly less than conventional non-photonic crystal power splitter. This is a promising device for future ultracompact and large-scale nanophotonic integrated circuits.

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Photonic crystals have many fascinating characteristics while two-dimensional (2D) waveguides made up from such crystals have many advantages such as relatively easy fabrication and convenience to integrate into photonic integrated circuits. Therefore, in recent years, much interest has been developed in 2D photonic crystal waveguide-based passive devices[1]. Among them, optical power splitter is a key passive component and plays important multi functional role in photonic integrated circuits. Optical power splitters built from conventional non-photonic crystal waveguides have been widely used in near infrared fiber-optic communications and networks. Recently, photonic crystal waveguides and devices are rapidly being proposed, designed, and simulated due to their ultrasmall device size[2−5]. Koshiba *et al.* have already proposed and constructed photonic crystal power splitters in a big T-shaped branch[5], which are difficult to scale them to 1×N ports due their shapes. Park *et al.* theoretically investigated a 1×2 Y-shaped photonic crystal power splitter based on a directional coupling principle[6]. In this work, we propose an extension of the 1×2 photonic crystal power splitters to 1×3 application so that it can be easily incorporated in DWDM-based photonic integrated circuits. The proposed design has been theoretically investigated based on the directional coupling principle. Device functionalities and properties have been numerically simulated by using finite-difference time-domain method.

The power splitter we proposed and simulated are based on a 2D photonic crystal consisting of an array of dielectric rods with a triangular lattice structure as depicted in inset of Fig. 1. Dielectric rods with a radius of $r = 0.18a$ are formed in silicon ($n = 3.4$ for near infrared wavelengths of 2.0–3.0 μm), where a and n are lattice constant of the photonic crystals and the refractive index of the dielectric rods, respectively. For this photonic crystal lattice, a band gap exists in a frequency range of $\omega a/2\pi c = a/\lambda = 0.3$ to 0.46 for transverse electric (TE) modes as shown in Fig. 1, where ω is the angular frequency, c the light velocity, and λ the wavelength in free space.

In the 2D photonic crystal shown in the inset of Fig. 1, line-defect waveguides are formed by removing one or more column of rods. Figure 2 shows a schematic diagram of the proposed 1×3 symmetric photonic crystal power splitter by introducing line-defects to form waveguide couplings. In Fig. 2, the coupling length of the photonic crystal waveguides is L, and the bending angle of the waveguides is 60°. The coupling coefficient of the device strongly depends on the number of dielectric rods in the interaction region of length L. If the rows of the dielectric rods between the two parallel line-defect waveguides are reduced and the two line-defect waveguides are close enough, the coupling coefficient becomes larger and causing more power coupling from one waveguide to the other. As a result, L can be shortened and the device size reduced dramatically.

In this design, one row of dielectric rods in the interaction region of length L of the 1×3 power splitter is as shown in Fig. 2. For this structure, when an input light beam enters to the interaction region, optical power will be coupled to three output waveguide channels and be outputted from ports 1, 2, and 3. By adjusting L, this

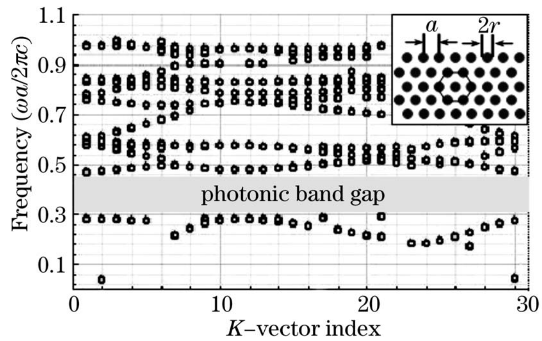

Fig. 1. Photonic band gap of constructed 2D photonic crystal.

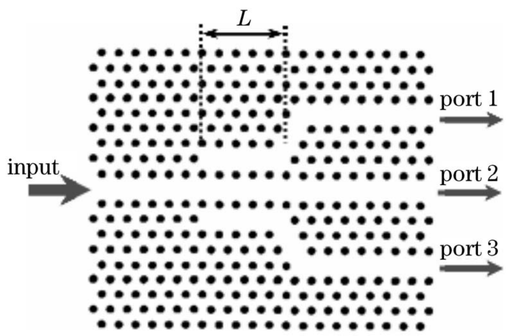

Fig. 2. Schematic diagram of the proposed 1×3 photonic crystal power splitter.

structure can perform 1×3 and 1×2 power splitting functions for different wavelengths. Figures 3(a) and (b) show the normalized output optical power versus wavelength for the proposed 1×3 symmetric photonic crystal power splitter at $L = 7a$ and $L = 8a$, respectively. In Fig. 3, the transmission spectrum curves in ports 1 and 3 are superposed to be due to ports 1 and 3 formed a symmetric structure. From Fig. 3(a) we can see that, for the coupling length of $L = 7a$, there are four positions which can be used for high performance 1×3 power splitters to split input optical power into three output ports equally. The four positions are labeled as (1), (2), (3), and (4) in Fig. 3(a) and located in the vicinity of wavelengths of 2.32, 2.35, 2.38, and 2.45 μm, respectively. Normalized output powers for the four positions (1), (2), (3), and (4) are 31.2%, 33.2%, 26.7%, and 29.1%, respectively. As an example, the simulated 1×3 optical field for $L = 7a$ at position (3) with $\lambda = 2.38$ μm is shown in Fig. 4(a). The 1×3 structure can also perform 1×2 power splitting function by simply adjusting L. For example, when $L= 8a$, the transmission spectra are shown in Fig. 3(b). It illustrates that 1×3 splitter can be used to perform good 1×2 power splitting function for the wavelength of 2.38 μm. The simulated optical fields are shown in Fig. 4(b). Moreover, insertion losses for the devices can be calculated based on the definition of $-10\log_{10}(P_{\mathrm{out}} \ / \ P_{\mathrm{in}})$, where P_{out} is total output optical power and P_{in} is total input optical power. For the 1×3 power splitting function, calculated insertion losses in the positions (1), (2), (3), and (4) showed in Fig. 3(a) are 0.287, 0.017, 0.963, and 0.59 dB, respectively, and for the 1×2 power splitting function in the position (3) showed in Fig. 3(b) is 0.97 dB. Further more, as shown in Fig. 3(b), the 1×3 power splitter is also a good optical filter for the wavelengths in the vicinity of 2.38 and 2.48 μm at the calculated positions (3) and (5). For example, when the 2.38 and 2.48-μm wavelengths signals are coupled into the input port of the 1×3 power splitter simultaneously, the 2.38-μm signal will be outputted at the ports 1 and 3 while the 2.48-μm signal is outputted at the port 2. It demonstrates the capability of the device to work as a wavelength division demultiplexer or an optical filter.

In conclusion, a 1×3 power splitter in silicon-based 2D photonic crystals was proposed and simulated for near infrared applications in the wavelength range from 2.3 μm to 2.5 μm. Device properties were theoretically investigated using finite-difference time-domain method and the results show that the device performances are good for photonic integration circuits. For the 1×3 structure, it can serve as 1×3 and 1×2 power splitters and filters for different wavelengths. The total size of the 1×3 power splitter is 10 μm wide and 30 μm long, which is significantly less than the conventional non-photonic crystal-based power splitter. By cascading N-stage 1×3 power splitters, a 1×3^N power splitter can be achieved. This is a promising passive device for future ultracompact and large scale nanophotonic integrations and has potential applications in next generation all optical networks.

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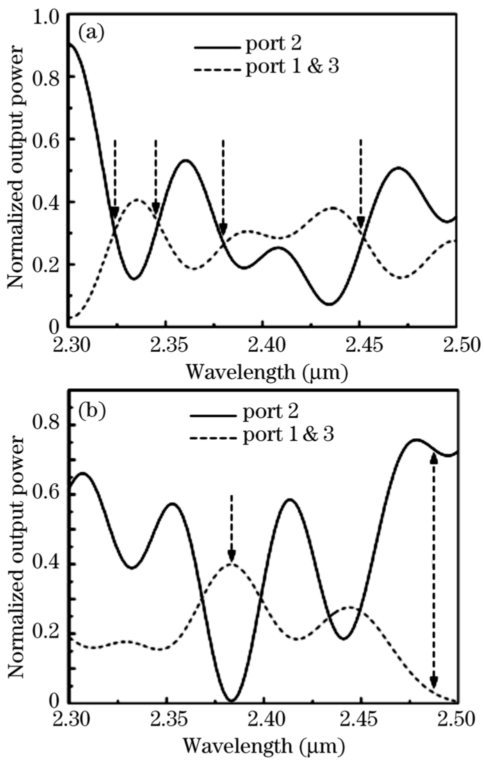

Fig. 3. Normalized output optical power versus wavelength for the constructed 1×3 symmetric photonic crystal power splitter at $L = 7a$ (a) and $L = 8a$ (b).

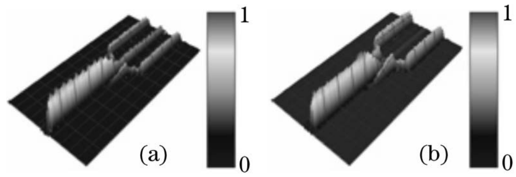

Fig. 4. Examples of the simulated optical fields at position (3) with $\lambda = 2.38$ μm for $L = 7a$ for 1×3 power splitter (a) and $L = 8a$ for 1×2 power splitter (b).

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