Compact and broadband waveguide taper based on partial bandgap photonic crystals

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Partial bandgap characteristics of parallelogram lattice photonic crystals are proposed to suppress the radiation modes in a compact dielectric waveguide taper so as to obtain high transmittance in a large wavelength range. Band structure of the photonic crystals shows that there exists a partial bandgap. The photonic crystals with partial bandgap are then used as the cladding of a waveguide taper to reduce the radiation loss efficiently. In comparison with the conventional dielectric taper and the complete bandgap photonic crystal taper, the partial bandgap photonic crystal taper has a high transmittance of above 85% with a wide band of 170 nm.

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For the application of a photonic integrated circuit in a communication network system, the chip sizes of devices are scaled down to the sub-micron-range. This brings many challenges, especially those associated with coupling external light sources efficiently to narrow submicrometer waveguides. Direct butt coupling is not efficient since the mode-mismatching will cause high coupling loss. A taper waveguide is usually used in such a circumstance to couple the light into the micro chips. But in order to get a high transmittance, the conventional dielectric waveguide taper has to be made very long[1]. Photonic crystals (PhCs)[2−5] with complete photonic bandgap (PBG) are then proposed to implement a compact waveguide taper[6,7]. However, the design of PhC with full three-dimensional (3D) PBG and/or two-dimensional (2D) PBG is usually time-consuming and requires high index contrast materials, which limit application areas. Additionally, even the system can supply a complete PBG, the bandwidth of the application still would not be well tuned[6,7].

Fortunately, in many cases[8], PhC with partial PBG can satisfy the application demands and usually the partial PBG has a broader bandwidth than the complete one. This opens new opportunity to solve the above problems. Although a parallelogram lattice PhC[5] waveguide taper based on partial PBG has been efficiently demonstrated previously by our group[8], the characteristic of the partial PBG has not been quantitatively studied clearly. In the previous work, the partial PBG characteristic is only suspected and is not identified in detail. In this letter, to further understand the partial PBG properties, the waveguide taper based on the partial PBG PhC is compared with the conventional dielectric taper and complete PBG PhC taper. The results of the finite-difference time-domain (FDTD) simulations show that the partial PBG PhC has attractive features of broader bandwidth and high efficiency of confining light.

We only consider the 2D PhCs which share many features with the 3D PhC but with a simpler calculation algorithm and a more stable fabrication process. The analysis presented here is also applicable to 3D PhC. The proposed PhCs have a parallelogram lattice of air holes in silicon with a dielectric constant ε=12. The schematic structure of the PhC is shown in the inset of Fig. 1(a). The two basis vectors of the lattice are **a** and **b** (b=2a, where a is the lattice constant of the PhC) respectively, and the angle between them is θ (here, θ=90°. The air-hole radius r is 0.35a with the filling fraction f=0.1924. As a theoretical demonstration, we only consider the TE modes (the magnetic field is parallel to the axis of the air holes) in this case.

The band structure along the high symmetry points calculated by the plane wave expansion (PWE) method is shown in Fig. 1. For the parallelogram lattice PhC, Fig. 1(a) clearly shows that there is not a single complete PBG, and the reciprocal vector Γ-X_2 corresponds to the basis vector **b**. But on the other side, some partial PBGs are formed. The partial

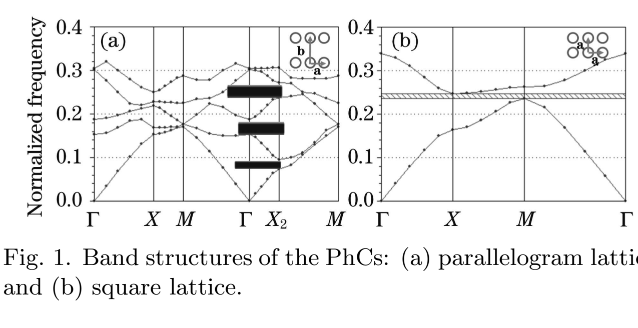

Fig. 1. Band structures of the PhCs: (a) parallelogram lattice and (b) square lattice.

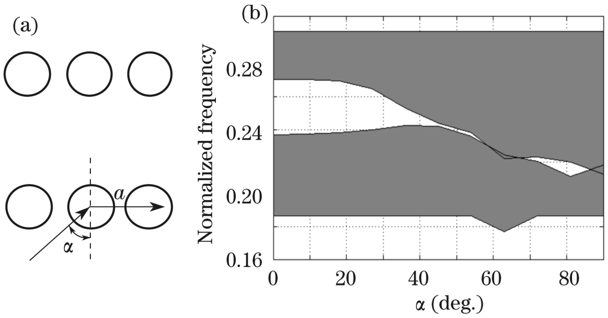

Fig. 2. (a) Definition of the incident angle α and (b) projected band structure of the parallelogram lattice PhC.

PBGs along Γ-X_2 direction are Γ-X_2 would be possible. indicated by the shadow zones in Fig. 1(a). It suggests that a light propagation along Figure 1(b) shows the band structure of the square lattice PhC with the same materials and hole sizes as the parallelogram lattice. We can see that a complete PBG with narrow normalized frequency bandwidth from 0.236 to 0.247 is obtained in this structure.

To get the details of the partial PBG, calculation of the projected band structure is needed. Notice that the partial PBG between band three and band four shown in Fig. 1(a) has a similar normalized frequency with the PBG in square lattice PhC. The projected band structure of the partial PBG between the band three and band four is shown in Fig. 2. The shaded areas are the projections in the direction perpendicular to the guide of Γ-X_2 direction. They are extended modes in the crystal bulk. As shown in Fig. 2(a), the incident angle α is defined as the angle between the incident light and the normal direction of the vector **a.** From Fig. 2(b), in the normalized frequency range of 0.238–0.265 when $\alpha<27°$, there exists a partial PBG. This is in accordance with Fig. 1(a). It also means that if the incident lights is with relatively small incident angles, it will be reflected by this structure. Since small incident angles are normal radiation modes in conventional waveguides, the partial PBG reflection can be tailored to suppress such loss efficiently. And in a taper waveguide, this process will be demonstrated below.

To make clear how efficiently a partial PBG could confine the propagation of light, comparisons are made among the conventional waveguide taper, complete PBG PhC taper, and the partial PBG PhC taper. According to Ref. [6], a taper structure can be expressed as

$$\pm y = w_{\mathrm{i}} + (w_{\mathrm{i}} - w_{\mathrm{o}})[(1 - \frac{x}{l})^{0.5} - 1], \qquad (1)$$

where w_{i} and w_{o} are the input and output widths of the taper, l denotes the total taper length, measured from the input end to the output end, y and x are variables representing the taper width and its corresponding position at the horizontal direction. The power of 0.5 in Eq. (1) indicates that the taper boundary curve has a convex shape. For practical uses, we chose the parameters as follows: w_{i}=6 μm, which is usually the width of a silicon strip waveguide; $w_o = \sqrt{3}a$; l=18 μm, a very compact length. For the partial PBG PhC taper, as shown in Fig. 3(a), a silicon waveguide is sandwiched between two parallelogram lattice PhCs. The air holes are distributed along the convex curves. The vector **b** is always along the vertical direction, while **a** is along the convex boundaries. The horizontal distance between two nearest air holes is a, which equals to 390 nm for a center wavelength of 1550 nm. At the output of the taper, an orthogonal lattice is employed to construct a straight collimating waveguide[8]. Figure 3(b) shows a conventional dielectric waveguide taper. The cladding of the conventional waveguide taper has a refractive index which equals the effective index of the proposed partial PBG PhC. From Ref. [9], the effective index n_{eff} of the PhC can be calculated as 2.9394 and the core is also a silicon waveguide of the same size. In Fig. 3(c), a complete PBG PhC with the lattice shown in Fig. 1(b) is used to form the taper structure. In order to get a fair comparison, we only change the basis vector **b** of the lattice here from b=2a to b=a, and a is slightly changed to 374 nm to obtain an identical central wavelength.

The field distributions shown in Fig. 3 are obtained by exciting a continuous Gaussian beam with λ=1550 nm at the input of the waveguide tapers in FDTD simulations. We notice that there are light radiation losses in both sides along boundaries when the light propagates in all the three kinds of tapers. Near the end of the tapers, the radiation loss intensities get extrema. In Fig. 3(a), the beam is strongly confined in the short partial PBG PhC taper, apart from a small amount of field diffusion at the sharp corner between the taper and the straight collimating waveguide. Contrast to the effective index dielectric taper in Fig. 3(b), the better confinement performance in partial PBG PhC taper is the result of the combination of total internal reflection and the partial PBG reflection. We also notice that there is radiation-loss for the complete PBG PhC taper. This is due to the curve displacement of the PhC boundary which would break the perfect lattice of the complete PBG PhC, thus causing the radiation loss.

By stimulating a pulse beam and using the time-domain Fourier transform, we investigate the spectral transmittance of the patterns. The transmittance is defined as the ratio of the output to input intensity. We set three monitors: two at the position near the source to test the input and reflection intensity, the third one at the taper output. Figure 4 shows the transmittance

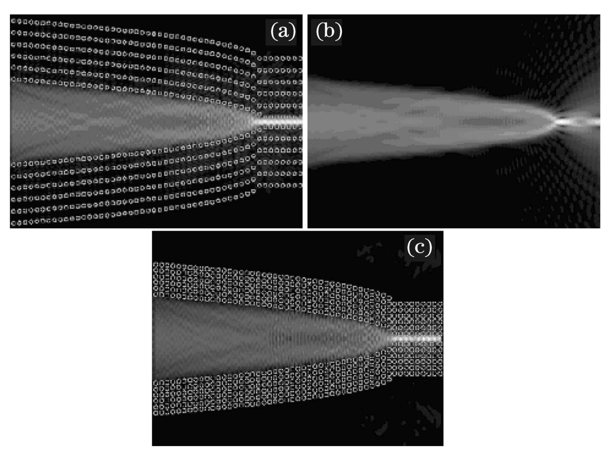

Fig. 3. Field distributions of the simulation layout. (a) Partial PBG PhC taper, (b) conventional waveguide taper, and (c) complete PBG PhC taper.

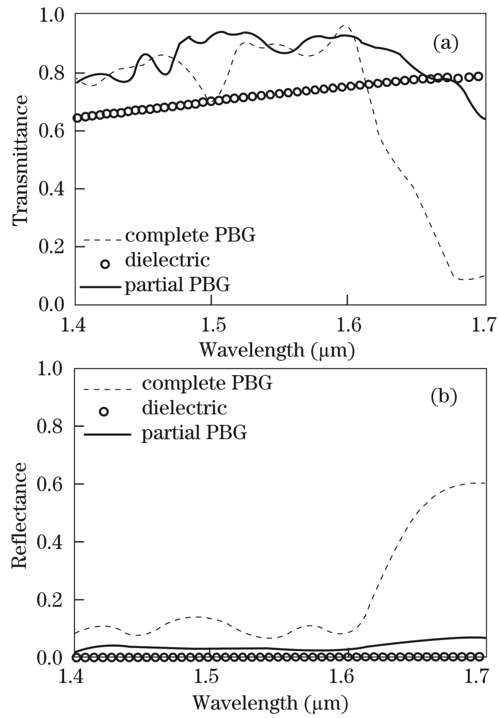

Fig. 4. (a) Transmission and (b) reflectance spectra of the waveguide tapers.

and reflectance spectra of the partial PBG PhC taper, the effective index dielectric waveguide taper, and the complete PBG PhC taper. The transmittance of the partial PBG PhC taper is 85%−93.9% for the wavelength range from 1470 to 1640 nm, corresponding to the normalized frequency band from 0.2378 to 0.2653. This meets very well with previous results obtained by projected band. While at the same bandwidth, for the effective index dielectric taper, the transmittance is only 69.0%−76.7%, which agrees very well with our previous prediction. For the complete PBG PhC taper, only a narrower bandwidth between 1516−1609 nm (0.2324−0.2467) can be achieved with the transmittance above 85%. Note that at the short wavelength edge, the value meets the PWE result, but at the long wavelength edge, the value is larger than the PWE result. This is due to the partial PBG effect in this complete PBG PhC, and the partial PBG of PhC is usually broader than the complete PBG of PhC. Figure 4(b) shows that the complete PBG PhC taper has the largest reflection among all the tapers in a very broad frequency band, which is the reason that partial PBG PhC taper has a better transmittance than the complete PBG PhC one. A complete PBG PhC taper with high transmittance of 97% was demonstrated in 2005[6], but vacuum was used as the taper core in the configuration, which will cause difficulty to confine light in vertical direction for a practical application of 2D PhC slab. As a more practical consideration, dielectric taper core like that used in this letter should be applied to limit the light leaky to air background. From Fig. 4, the partial PBG taper is demonstrated with a slightly better transmittance and a much broader bandwidth than the complete PBG PhC taper. The most attractive merit of the partial PBG PhC taper is that it can strongly confine the light as the complete PBG PhC taper with a much broader bandwidth.

In conclusion, partial PBG properties of the parallelogram lattice PhC are investigated in detail. Compared with the conventional waveguide taper and the complete PBG PhC taper, the partial PBG PhC one exhibits a broader frequency bandwidth from 1470 to 1640 nm with a high transmittance of above 85% in a very compact length of 18 μm. The successfully demonstrated device exhibits that the partial PBG PhC taper has unique merits of broad bandwidth, low requirements for materials, and efficient light control capability. The aspect of partial PBG PhC emphasized here is especially useful and important for low index contrast dielectric material systems. For example, PhC of silica-air system, which usually has narrow complete PBG or even does not have a complete PBG, would support a broad partial PBG. In these cases, the existence of partial PBG would offer new opportunities for applications. It is also valuable in high index contrast dielectric material systems for which broader bands are demanded.

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