Self-collimated waveguide bends and partial bandgap reflection of photonic crystals with parallelogram lattice

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The photonic crystal structure with parallelogram lattice, capable of bending a self-collimated wave with free angles and partial bandgap reflection, is presented. The equifrequency contours show that the direction of the collimation wave can be turned by tuning the angle between the two basic vectors of the lattice. Acute, right, and obtuse angles of collimating waveguide bends have been realized by arc lattices of parallelogram photonic crystals. Moreover, partial bandgap reflection of the parallelogram lattice photonic crystals is validated from the equifrequency contours and the projected band structures. A waveguide taper based on this partial bandgap reflection is also designed and proved to have above 85% transmittance over a very wide operating bandwidth of 180 nm. © 2008 Optical Society of America

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1. INTRODUCTION

Photonic crystals (PCs) with photonic bandgaps have been widely studied as the basis of mirrors [1], waveguides [2–4], lasers and cavities [5,6], filters [7,8], and other important components for high-density optical integration. In recent years, the self-collimating phenomenon in PCs has drawn considerable interest due to its great potential in beam collimating [9,10], light splitting [11,12], light routing [13], and configurable waveguides. It has been found that light can be collimated along the diagonal directions of some square lattice PCs. Using the π/2 rotation symmetry of the square lattice, this collimated wave can be bent 90° from one diagonal direction to another by introducing a reflection mirror at the bending corner with lattice truncation or line defect [14–16]. However, due to the intrinsic π/2 rotation symmetry of the square lattice, it is difficult to form other angles of collimating waveguide bends, which limits its applications for ultracompact and configurable optical interconnects. For example, if we want to connect two parallel straight self-collimated waveguides with a small lateral distance or two straight self-collimated waveguides, which have an acute or obtuse angle, the above 90° bending is not effective any more. And for the sake of application efficiency, apart from the self-collimating phenomenon, other properties of collimating PCs still need to be explored to integrate more functions within a uniform PC structure.

In order to solve these problems, we introduce a parallelogram lattice collimating PC with equifrequency contours (EFCs) that are fairly flat in a wide angle range. Moreover, the directions of its EFCs can be easily tuned by changing the angle between the two basic vectors of the lattice. Collimating beam propagation through several angles of waveguide bends are shown by finite-difference time-domain (FDTD) simulation. A unique partial bandgap reflection and its potential for suppressing radiation loss of waveguides are also shown. Finally, a waveguide taper based on this parallelogram lattice PC is designed and predicted to have high transmittance with a large frequency bandwidth.

2. STRUCTURES OF PARALLELOGRAM LATTICE PHOTONIC CRYSTALS AND THEIR EQUIFREQUENCY CONTOURS

The structure of the parallelogram lattice PC is shown in Fig. 1. The dielectric constants of the air holes and the silicon background are 1 and 12, respectively. The two basis vectors of the lattice are \( \mathbf{a} \) and \( \mathbf{b} \) (\( b = 2a \)), and the angle between them is \( \theta \). The air-hole radius \( r \) is 0.35a. When \( \theta = 90° \), the lattice is rectangular in shape. Figure 2(a) shows the Brillouin zone of the rectangular lattice, and Fig. 2(b) shows the band structure along the high symmetry points calculated by the plane-wave expansion (PWE) method.

First, we calculated the EFCs for the fourth band of the lattice by the PWE method, shown in Fig. 3. We will consider only the TE mode case in this paper. Figure 3(a) shows the case when \( \theta = 90° \)—a rectangular lattice. The EFCs also have a rectangular shape. It is known that the...
group velocity direction of light is always normal to the EFC curve. In addition, a flat EFC means that light incident from different angles will be collimated to a uniform group velocity direction. If the flat EFC is long, there will be a wide-angle collimation and vice versa. So this PC lattice should show wide- (narrow-) angle collimation for beams propagating along the direction of \(a\) (\(b\)). The \(a\) direction is suitable to form a collimating waveguide bend because of its great collimating ability at a large angle range. If the vector \(a\) is rotated 30° clockwise so that \(\theta = 120°\), the flat EFCs and their corresponding collimating directions will also be rotated by the same angle, as shown in Fig. 3(b). Even though a small perturbation is introduced to the length of the vector \(a\) or \(b\), the orientation shifts of the flat EFCs remain the same, which is shown in Fig. 3(c). That is, in this distorted lattice, the collimating direction is always along the lattice vector \(a\). This is very convenient for constructing bends of collimated waves. That is, one need not be concerned with the length perturbation of the basis vector when rotating the lattice.

It is further remarkable that the EFCs open to become vertical lines in the normalized frequency range 0.24–0.27 in Fig. 3(a), which means that a partial bandgap reflection may exist at this frequency range when the light is incident to the lattice surface parallel to the direction of \(a\), although there is not a full bandgap from the band structure diagram in Fig. 2(b). But we must keep in mind that here we only guess at its presence from the single frequency contour of the fourth band. In order to make clear whether the partial bandgap really exists, the projected band structures of the third and fourth bands are calculated by the PWE method, as shown in Fig. 4. As shown in Fig. 4(a), incident angle \(\theta\) is defined as the angle between the incident light and the normal direction of the vector \(a\). It is obvious from Fig. 4(b) that there exists a partial bandgap in the normalized frequency range 0.24–0.27 when \(\alpha < 27°\). This proves that the unique reflection is a partial bandgap reflection. This reflection occurs only for light with relatively small incident angles, which are normally radiation modes. So this partial bandgap reflection can be exploited to suppress the radiation loss of a waveguide efficiently, a process that will be discussed in detail below.

### 3. FREE-ANGLE SELF-COLLIMATED WAVEGUIDE BANDS IN PARALLELOGRAM LATTICE PHOTONIC CRYSTALS

In the following, two examples will be given to validate the above two properties of the parallelogram lattice PCs and to show their great application potentials.

As mentioned in Section 2, light propagation direction in the distorted parallelogram lattice is always along the local lattice vector \(a\). If the local vector \(a\) changes its direction gradually, the light path will be bent accordingly and self-collimated waveguide bends can be easily realized. In order to avoid unacceptably large radiation losses due to the abrupt lattice interface at the bend, a sector of circular arc lattice is proposed to change the lattice orientation gradually. The radius of the waveguide bend is set to be 30\(a\). The air holes are placed on the straight and arc
lines, and the curvature distance of adjacent holes is set to be \( a \). The bend angle \( \varphi \) is defined as the angle between the right horizontal direction and the output straight waveguide. The field distributions in different angles of bends were simulated by the FDTD method, shown in Figs. 5(a)–5(d). For example, for optical-telecom applications, the wavelength in this paper is chosen to be 1550 nm and \( a \) is 391 nm. Plane-wave excitation at 1550 nm and width 3\( b \) are incident from the left sides of these waveguides. The field distributions reveal that the light can be bent smoothly across the arc lattice and remain well confined in the subsequent straight lattice. Bending angles can be tuned freely by changing the radius of the transition arc lattice.

In order to examine the transmission spectra of the proposed self-collimated waveguide bends, pulsed sources with vertical width of 3\( b \) are excited at the inputs. Field probes with width of 3\( b \) are placed at the cross sections of the input and output waveguides to measure power fluxes. The bend efficiency, defined as the ratio of optical power flux after the bend to optical power flux before the bend, was also calculated by FDTD, as shown in Fig. 6. When the bend angle is 30°, the bend efficiency exceeds 90% across a wide wavelength range from 1470 to 1630 nm. After the bend angle is increased further to 60°, 90°, and 120°, the bending efficiency falls slightly, which may be due to the backreflection and lateral radiation at large bending angles. However, the bending efficiency is still above 80% in the range of 1510 to 1580 nm even for the case of a 120° bend. This bandwidth is still adequate for most optical-communications applications. It should also be noted that the spectra exhibit interference resonances when the bend angle is greater than 30°. This may due to a light-
When the light-path difference $\Delta s$ between arcs with different radii is an integer multiple of light wavelength $\lambda$ in vacuum, the bend efficiency exhibits a local maximum corresponding to constructive interference.

4. LOW-LOSS AND WIDE-BAND WAVEGUIDE TAPER BASED ON PARTIAL BANDGAP REFLECTION

The other example is a waveguide taper based on the partial bandgap reflection of the parallelogram lattice PC. In the traditional waveguide taper based on index contrast confining, there will be a large radiation loss if the taper length is short. According to ray theory, this radiation loss is due to the coupling of guided modes to radiation modes when the incident angle at the taper boundary becomes less than the critical angle of total inner reflection. As mentioned above, the lattice surface parallel to the direction of $\mathbf{a}$ can reflect light efficiently when the incident angle $\alpha<27^\circ$. This lattice surface can thus be used to reduce the radiation loss of index confining waveguides.

Here we present a waveguide taper based on the parallelogram lattice PC. The structure and field distribution are shown in Fig. 7(a). A silicon waveguide is sandwiched between two parallelogram lattices PCs, and the boundaries of the waveguide are symmetric convex in shape. The air holes are distributed along the convex curves. The vector $\mathbf{b}$ is always along the vertical direction, but $\mathbf{a}$ is along the convex boundaries, and $b=2a$. The horizontal distance between nearest air holes is $a$. The input and output widths of the converter are 6 and $0.8\,\mu m$, respectively, and the length between them is $18\,\mu m$. At the output of the converter, an orthogonal lattice is employed to construct a straight collimating waveguide.

A Gaussian beam with $\lambda=1550$ nm is input to the converter in a continuous-wave FDTD simulation. It can be seen from Fig. 7(a) that the beam is well confined in the short converter, apart from a small amount of field diffusion at the sharp corner between the converter and the straight waveguide. This good confinement is the composite result of total inner reflection and partial bandgap reflection. Figure 7(b) shows the transmittance of the converter. The transmittance is above 85% from 1470 to 1650 nm, which covers the $S$, $C$, and $L$ optical-communication bands. Thus, the proposed field-size converter provides an excellent example of a broadband operating device based on a collimating PC.
5. CONCLUSIONS
A parallelogram lattice PC has been presented. EFC calculations show that a large-angle collimation is always along the short lattice vector and that the collimating direction can be tuned easily by changing the angle between the two basic vectors of the lattice. Several angles of waveguide bends have been studied based on the proposed PC. FDTD simulations demonstrate that the bend efficiency exceeds 80% with a bandwidth of 70 nm even when the bending angle is as large as 120°. Moreover, the EFC and projected band structure calculations reveal that there exists a partial bandgap reflection at the lattice surface along the short basic vector \(a\). A field-size converter based on the partial bandgap reflection is also presented and is shown to have a very wide operating bandwidth of nearly 180 nm. Although the results are based on 2D simulations, they are sufficient to show the conceptual framework of the proposed parallelogram lattice PCs and its great potential application in nano-optical integration as well as for interconnects between nano-optical and more conventional optical devices.

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