Transmitting light efficiently on photonic crystal surface waveguide bend

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In this letter, the transmission efficiency around waveguide bend on the surface of photonic crystal is investigated. Light is confined to the photonic crystal-air interface by means of surface modes. The transmission efficiency around surface waveguide bend is shown to be very poor. This is due to the phase mismatch of the wave vectors between different sections of the surface waveguide bend. To reduce the phase mismatch between the different waveguide sections, the cell properties at the bend section are modified. As a result, high transmission efficiency of more than 93% around the modified surface waveguide bend structure is achieved. © 2007 American Institute of Physics. [DOI: 10.1063/1.2793175]

Photonic crystal based waveguides (PCWGs) have aroused the interest of many researchers and scientists because of its ability to guide light around bends with length in the order of propagating wavelength. It is believed to have great potential in interconnecting waveguides in dense OIC. In order to be utilized in OIC, it is required to maximize the transmission efficiency of light at PCWG bends.

A recent approach to waveguide design has suggested the possibility of using surface mode on the interface boundary of finite PC and external homogeneous medium (such as air or other slab material) to transmit light. The guiding of electromagnetic lightwaves along the surface boundary of PC is called photonic crystal surface waveguide (PCSWG). The motivation for the study of PCSWG comes from the use of the nonperiodic side, which can be used to open up possibilities for feeding and redistribution of light with the integration of other classes of components, such as mechanical and optical. The microscale photonic devices with dynamic transmission properties could be innovated from the integration of PCSWG with other types of components.

A PC lattice consisting of square array of silicon circular rods with a refractive index of 3.45 is considered. The rods have a radii of 0.2a (where a is the lattice constant) and are surrounded by air. The PBG exists in the normalized frequency of 0.278–0.424 for transverse magnetic (TM) polarization. In order to introduce a defect mode into the PBG, the rod structures at the surface of PCs are perturbed by a few ways. In this letter, the radii of outermost the surface rods of finite PC in both (10) and (01) directions are reduced to 0.1a as shown in Fig. 1(a). For light to be concentrated on the surface, it must have its field components decaying exponentially into the air and PC lattice. Hence, only the part of the defect mode that is below the lightline and in the PBG is labeled the surface mode. The three-dimensional finite-different time-domain (FDTD) method with Bloch boundary conditions is used to calculate the dispersion band diagram, as shown in Fig. 1(b). The height of the rod structures is 2a. For waveguiding along the PC surface, the normalized frequency range of 0.34–0.38 is considered in this letter. This is to ensure that lightwave propagates on the surface with moderate amount of velocity and the surface mode is far enough from the lightline to minimize radiation into air.

A TM polarized light source with frequency of 0.368 is launched from the left side of the surface rods along the (10) direction. The electric field distribution along the surface waveguide bend is shown in Fig. 1(c). It is observed that light is not transmitted to the (01) direction and radiates out into the air. The power collected in the (01) direction is plotted in the transmission spectrum of Fig. 1(d). Very low light power is transmitted to the (01) direction due to poor coupling between different parts of the surface bend.

To analyze the problem, the surface waveguide bend is divided into three separated sections. The waveguide bend is separated into two long waveguide sections in the (10) and (01) directions with a short bend section (the dotted square) in the (11) direction, as illustrated in Fig. 1(a). The dispersion band diagram of the surface mode along the (10) and (01) direction is plotted in Fig. 1(b). Very low light power is transmitted to the (01) direction due to poor coupling between different parts of the surface bend.

FIG. 1. (Color online) (a) Schematic layout of the photonic crystal surface waveguide bend. (b) Dispersion band diagram of the surface mode along the (10) and (01) direction. (c) Electric field (E) distribution waveguide bend showing light leakage to free space. (d) Transmission spectrum of the PC surface bend waveguide.
Dispersion band diagram of the surface waveguide in the (10) and (01) directions has the same wave vector value $k_1(\omega)$ due to identical band diagram. The dispersion band diagram of the waveguide in the (11) direction with a wave vector $k_2$ is shown in Fig. 2(a). It is observed that the band structure in the (11) and (10) [or (01)] directions does not match. The surface mode in the (11) direction occurs at higher frequencies due to lower overall effective index. The transmission coefficient $\vartheta$ between different directions has the relationship given by

$$\vartheta \propto \left\{ 1 + \left[ \frac{(k_1^2 - k_2^2)\sin(k_2L)}{2k_1k_2} \right]^2 \right\}^{-1},$$

where $L$ is the length of the bend section, which corresponds to $0.33a$. Based on Eq. (1), when the phase mismatch is very small, the transmission efficiency around the bending section is very high. On the contrary, the large difference in $k_1(\omega)$ and $k_2(\omega)$, such as those shown in Fig. 2(a), will lead to poor coupling between different sections of the waveguide. To achieve high transmission efficiency, the effective index along the (11) direction needs to be increased so as to shift the surface mode to lower frequencies to match with the wave vectors $k$ in the (10) or (01) direction. In this letter, two approaches are proposed: by increasing either the radius (larger radius method) or the refractive index (higher index method) of the corner unit cell.

When the radius of the corner cell is increased to the radius of 1.5$a$, the effective index along the (11) direction is increased and the surface mode is shifted down to match with the (10) and (01) directions. Although the effective index is increased, a higher order multipole field pattern exists. The propagating electromagnetic waves travel at a slower group velocity and this longer time interaction between waveguide sections improves the transmission efficiency. In order to enhance the transmission efficiency, the effective length of the waveguide bend is increased. The larger radius corner cell is shifted inward along the (11) direction with a distance of $\Delta d$. When $\Delta d$ is set to 0.31$a$, phase matching occurs at frequency of 0.368 ($a/\lambda$) between the different sections of the waveguide. This is illustrated in the dispersion band diagram between the different waveguide sections in Fig. 2(b). The electric field distribution is shown in Fig. 3(a). It shows the presence of dipole field pattern assists in coupling light from (10) to (11) then to (01). In three-dimensional geometry structures, power may leak out from the large dipole rod due to the coupling between surface modes and radiation modes above the lightline. Higher power leakage occurs when surface and radiation modes are close at the operating frequency.

Similarly, the refractive index of the corner cell is increased by $\Delta n$=0.68 and the position of the corner cell is shifted inward diagonally with $\Delta d'=0.403a$. The dispersion band diagram for these values of $\Delta n$ and $\Delta d'$ is plotted, as shown in Fig. 2(c). As the higher index method does not introduce dipole field emission pattern to the bend section, the group velocity reduced slightly and has phase matching over a broader range of frequency. The propagating electric field distribution of the higher index bend section is shown in Fig. 3(b). The transmission spectra for larger radius and higher index methods are approximately 94% and 90.8%, respectively, as shown in Fig. 3(c). Both methods give different transmission bandwidths due to different ranges of frequencies covered. The higher index method is useful for transmitting a decent range of frequencies while the larger radius method can be used for filtering purposes due to its narrow bandwidth. The higher index method has slightly lower transmission efficiency because of shorter interaction time. Hence, the coupling efficiency is slightly inferior and some light will leak out to the surrounding at the corner cell.
The additional slabs at the top and right side are set to different due to different lattice arrangements. Hence, to guide is created by having an addition nonperiodic slab section consists of a triangular array of air holes extending through the top and left boundaries, as shown in Fig. 4. The perpendicular distance from the cut angled surface to the center of the holes along the direction is 1.26a. The modified structure of the bend is shown as the dash line in Fig. 4(a). The method serves two purposes: first is to eliminate the possibility of cavity resonance forming at the waveguide bend and second is to increase the effective length of the waveguide bend for optimum transmission efficiency. Figure 4(d) demonstrates the magnetic field travels around the surface waveguide bend without being. The transmission spectrum of this PC slab surface waveguide is shown in Fig. 4(e) with a transmission efficiency of 93%.

In summary, this letter studies the transmission characteristic of PCSWG. High transmission efficiency of lightwaves is demonstrated for two-dimensional surface waveguide bend based on rods. By increasing the effective index along the diagonal direction and the effective length, the transmission efficiency is enhanced. The letter also investigates the transmission characteristic for PC slab based surface bend waveguiding. In order to obtain a transmission efficiency of more than 93%, a method is proposed to eliminate light trapped at the sharp slab bend and to increase the effective length at the bend. It is believed that the PC based surface waveguide can be expanded to a vast range of applications.

The authors wish to express their sincerest gratitude to Prof. Steven G. Johnson of MIT for his useful discussion and also appreciate Dr. Zhang Xuming for his friendly help.

In this letter, waveguiding around the surface bend of photonic crystal slab is also discussed in this letter. The PC slab structure consists of a triangular array of air holes extending through a silicon slab. The holes have radii of 0.3a with a slab thickness of 0.75a. The PC slab surface waveguide is created by having an addition nonperiodic slab section of width d between the center of the outermost holes and the top and left boundaries, as shown in Fig. 4(a). The dispersion band diagram along the (10) and (01) directions are different due to different lattice arrangements. Hence, to match the wave vectors in these two directions, the widths of the additional slabs at the top and right side are set to \( d_1 = 1.138a \) and \( d_2 = 1.26a \). Using the three-dimensional FDTD method, the dispersion band diagram for the TE (transverse electric) polarization is shown in Fig. 4(b).

When an input light with a normalized frequency of 0.25 is launched into the slab, the magnetic field distributions for the PC slab surface bend waveguide is shown in Fig. 4(c). It is observed that light is trapped in the corner of the slab and cannot be transmitted to the (01) direction due to Fabry-Pérot resonance, where the phase condition at the corner given by \( 2\pi L_1 \) is a multiple of \( 2\pi L_0 \) is the length of the cavity formed at the corner and k is the wave vector in unit of \( 2\pi/a \) along the bend corner. In order to solve this problem, a method is proposed to improve transmission efficiency of light around the slab surface waveguide bend.

In stage one, a single hole cell is removed from the top-right corner. In the second stage, the sharp right angle slab bend is truncated at an angle of 30° with respect to the vertical plane so that the resultant surface is parallel to the hole array axis along the (11) direction (using hexagonal crystal system). The perpendicular distance from the cut angled surface to the center of the holes along the direction is 1.26a. The modified structure of the bend is shown as the dash line in Fig. 4(a). The method serves two purposes: first is to eliminate the possibility of cavity resonance forming at the waveguide bend and second is to increase the effective length of the waveguide bend for optimum transmission efficiency. Figure 4(d) demonstrates the magnetic field travels around the surface waveguide bend without being. The transmission spectrum of this PC slab surface waveguide is shown in Fig. 4(e) with a transmission efficiency of 93%.

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