Sensitivity to termination morphology of light coupling in photonic-crystal waveguides

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We use a transfer-matrix method to investigate light coupling problem in single-end photonic-crystal (PC) waveguides. We find that the coupling efficiency is sensitive to the surface termination morphology of the waveguide. A slightly tapering geometry can lead to an order of magnitude difference in the coupling efficiency of an external extended wave into the waveguide. However, this tapering geometry does not necessarily lead to enhanced coupling of a guided wave out of the PC waveguide. We have attributed this strong asymmetric coupling characteristic to the significant difference in the scattering behavior of an extended wave and a localized wave by the complex surface microstructure of a PC waveguide.

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In recent years photonic-crystal (PC) waveguides have attracted extensive interest because they are one of the basic functional elements towards building an ultrasmall all-optical or optic-electronic integrated circuit on the platform of photonic crystals.[1–14] A PC waveguide is a linear defect introduced into an otherwise perfect photonic lattice, and it can support localized defect modes whose frequency is located within the photonic band gap (PBG). Therefore, a PC waveguide can efficiently manipulate propagation of electromagnetic (EM) waves at subwavelength sizes, for instance, through a sharp bend.

Apart from extensive study on EM wave propagation through various functional elements, such as straight waveguides, waveguide bends and branches, and cavities, the problem of connecting a PC waveguide with conventional fiber optics has raised more and more attention in the past several years. Usually a single-mode PC waveguide has a small core size due to its high refractive index contrast between the composite materials. As a comparison, the conventional optical fiber has a far smaller index contrast between the core and cladding materials, and thus a far larger core size. Therefore, significant mismatch between the two waveguides occurs, leading to low coupling efficiency. A usual way to efficiently improve the coupling efficiency is to adopt an appropriate tapering structure at the connection domain, both for the conventional optical fiber and the PC waveguide.[6,10–13] For instance, one can replace the conventional optic fiber by dielectric ridge or wire waveguides with a high index contrast and a small core size, or connect the conventional optic fiber and PC waveguides by an adiabatically tapered ridge or wire waveguide.

Since the coupling process (either into or out of the PC waveguide) is essentially a scattering phenomenon, one might imagine that modification of the termination surface morphology of the waveguide can induce strong change in the coupling behavior, and after careful designs, the coupling efficiency can reach an optimum value as large as possible. In fact, this phenomenon has been observed recently in photonic crystal and photonic-crystal waveguides.[14–16] In this paper we will show that the coupling is highly sensitive to the termination surface morphology of a PC waveguide, and a slightly tapering configuration can lead to an order of magnitude difference in the coupling efficiency of an external extended EM wave into the waveguide.

The system we consider is a two-dimensional (2D) photonic crystal made up of a triangular lattice of dielectric cylinders embedded in an air background. Each cylinder has radius $r=0.18a$ and refractive index $n=3.4$, where a is the lattice constant. This 2D crystal supports a large transverse-magnetic (TM) mode (where the electric field is parallel to the cylinder axis) band gap, which lies between the angular frequencies $\omega=0.296(2\pi c/a)$ and $\omega=0.482(2\pi c/a)$. Here c is the speed of light in vacuum. A linear waveguide can be created by removing one or several rows of cylinders from the crystal. Figure 1 shows the configuration of such a waveguide by removing a single row of cylinders along the ΓJ crystalline direction, which we call $W1$ waveguide. Four different types of surface morphology are considered, representing four relative termination positions within the unit cell of the waveguide. Each unit cell of the waveguide contains two layers of cylinders, and each layer represents a typical surface morphology. In the structure shown in Fig. 1(b) (WG-2), the two cylinders that are in the outermost surface layer and located at the two sides of the waveguide axis have a distance of $\sqrt{3}a$, equal to the apparent core width of the wave-

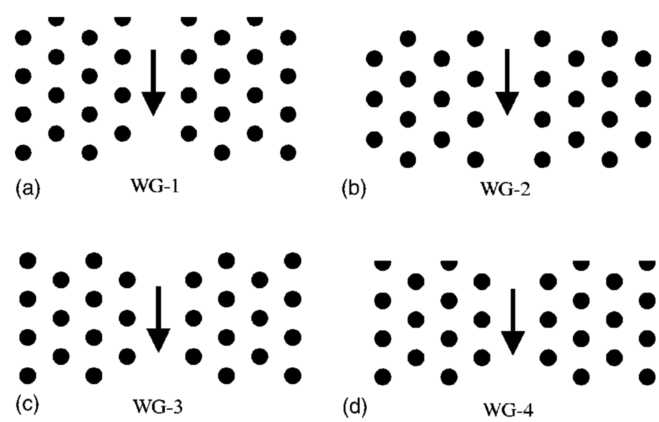

FIG. 1. Schematic geometric configuration of four single-end $W1$ PC waveguides with different surface termination morphologies. The waveguides are created in a 2D triangular lattice of dielectric cylinders in air by removing a single row of cylinders.

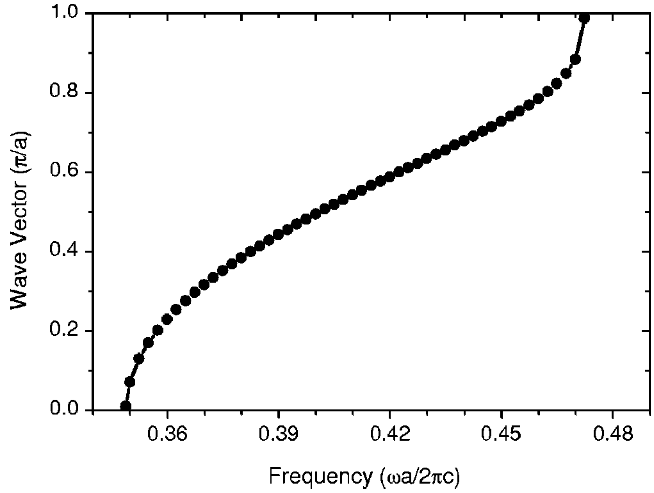

FIG. 2. Calculated dispersion of the TM guided mode in the $W1$ PC waveguide shown in Fig. 1.

guide. In the structure shown in Fig. 1(c) (WG-3), the distance between the two adjacent cylinders in the outermost layer is $2\sqrt{3}a$. This structure can be deduced from the former one by removing the outermost layer of cylinders there. The structures in Figs. 1(a) (WG-1) and 1(d) (WG-4) can form by cutting one half of the cylinders in the outermost layer of WG-2 and WG-3, respectively.

The most significant difference between the two waveguide structures (WG-1 and WG-2) and the other two waveguide structures (WG-3 and WG-4) is the presence of a slightly tapering geometric configuration in the latter group, where the opening size of the waveguide in the outermost layer is twice that in the second outermost layer. Either from physical intuition or from previous experiences, one might imagine that the tapering structure can help to couple an external signal into the PC waveguide, and also help to couple a guided wave out of the waveguide. To see whether it is really the situation, we investigate quantitatively the coupling efficiency of EM waves into and out of these PC waveguides. As a first step, we should have a clear knowledge of the guided mode dispersion. Figure 2 shows the calculation result for the $W1$ waveguide by means of a plane-wave-based transfer-matrix method (TMM).[17–20] In the calculation, a supercell with a sufficient size (and sufficiently thick waveguide walls) has been adopted. The waveguide supports a single band of guided modes, which spans from $\omega=0.349(2\pi c/a)$ at the wave vector $k=0$ to $\omega=0.473(2\pi c/a)$ at $k=\pi/a$. The lower band edge is in quite a distance away from the lower PBG edge of the background photonic crystal, while the upper band edge is close to the upper PBG edge. The waveguide cutoff phenomenon takes place at both the lower and upper band edges.

We have used the same TMM technique to calculate the normalized transmission coefficient of an external collimated plane wave (a good representation of an extended wave) incident on the waveguide (Fig. 3). This coefficient is defined as the ratio of the total-energy flux coupled into the waveguide and the total incident energy flux within a line whose size is equal to the apparent width of the waveguide ($\sqrt{3}a$ here). Obviously the group of waveguides (WG-3 and WG-4) with a slightly tapering morphology exhibits a much better coupling efficiency than the group of waveguides without any tapering termination (WG-1 and WG-2). In some frequency domains, the difference can be one order of magnitude high. The coupling behavior for WG-3 and WG-4 is quite similar to each other. In contrast, WG-1 and WG-2 exhibit very different coupling characteristics. The coupling efficiency for WG-1 first quickly rises to a maximum value, then decreases to almost zero at $\omega\approx0.42(2\pi c/a)$, and then rises again, until it finally drops to zero at the cutoff frequency. The coupling efficiency in WG-2 first monotonously rises to a peak value at $\omega\approx0.44(2\pi c/a)$, then descends to zero at the waveguide cutoff. Besides difference in the qualitative behavior, the two waveguides also show significant quantitative difference in the coupling efficiency, where WG-1 can have a maximum coupling efficiency two to three times that of WG-2.

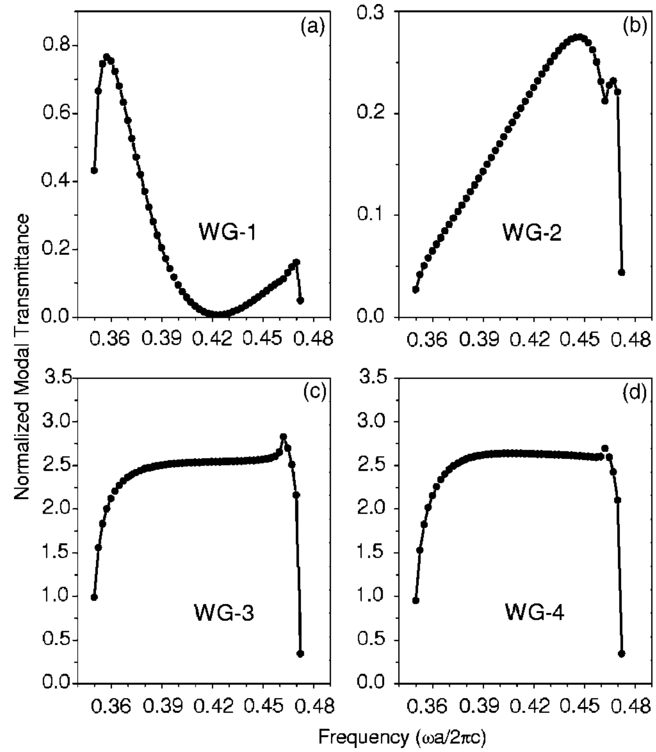

FIG. 3. Calculated normalized transmission coefficients of a plane wave incident onto the four single-end $W1$ PC waveguides shown in Fig. 1.

We also examine multimode PC waveguides ($W3$ waveguides), which are created by removing three rows of cylinders from the crystal along the ΓJ direction. Still, we consider four types of surface morphology, as shown in Figs. 4(a)–4(d), which exactly correspond to those shown in Figs. 1(a)–1(d). We have employed the TMM to calculate the dispersion of the guided modes and the coupling efficiency of an external plane wave into these waveguides. The results are displayed in Figs. 5 and 6, respectively. The waveguides support three guided modes, with two modes ($E1$ and $E3$ modes) having an even mirror-reflection symmetry with respect to the waveguide axis, and one mode ($O2$ mode) hav-

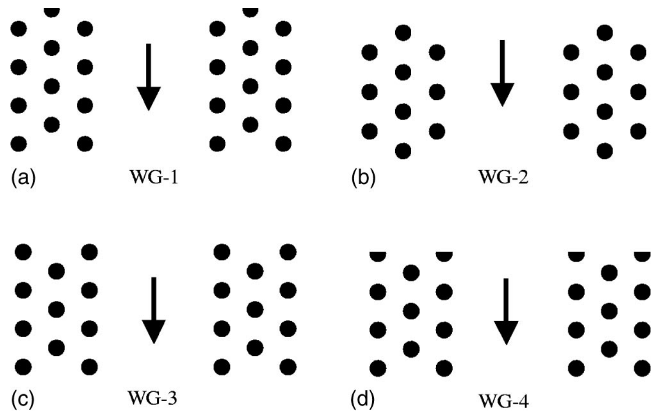

FIG. 4. Schematic geometric configuration of four single-end $W3$ PC waveguides with different surface termination morphologies.

ing an odd symmetry. As the incident plane wave is evenly symmetric, only $E1$ and $E3$ modes can be excited. The coupling-in efficiency overall exhibits a complicated spectrum for all waveguides from WG-1 to WG-4. But two significant common features can be found. One is that $E1$ mode has a much larger coupling-in efficiency than $E3$ mode, the other is that WG-1 and WG-2 have a better coupling-in efficiency than WG-3 and WG-4. The first feature can be well understood from the fact that $E1$ mode is the lowest guided mode, so its field pattern is much flatter and is much better in match with the field profile of the incident plane wave than the higher $O2$ and $E3$ modes. The second feature can be explained by noting that now WG-1 and WG-2 have a slightly tapering geometry, while WG-3 and WG-4 do not have. This direct connection between the superior coupling-in efficiency and the presence of a tapering morphology once again demonstrates the importance of a tapering termination geometry in a PC waveguide.

One might image that similar phenomena on the difference of the coupling efficiency due to the presence or absence of a tapering geometry in the termination morphology should also be found in the opposite propagation process,

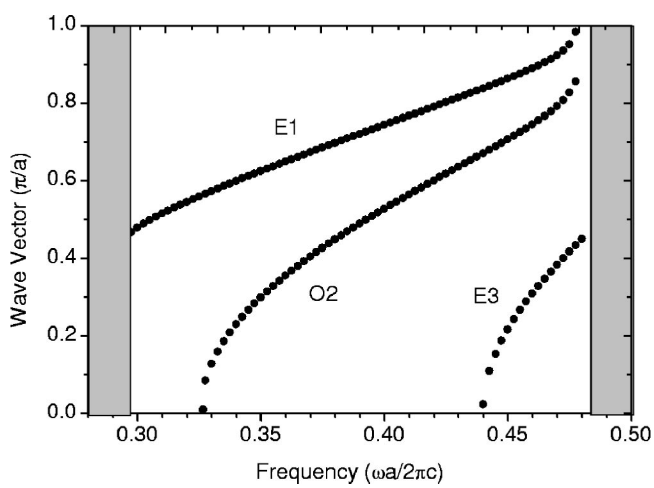

FIG. 5. Calculated dispersion of the TM guided modes in the $W3$ PC waveguide shown in Fig. 4.

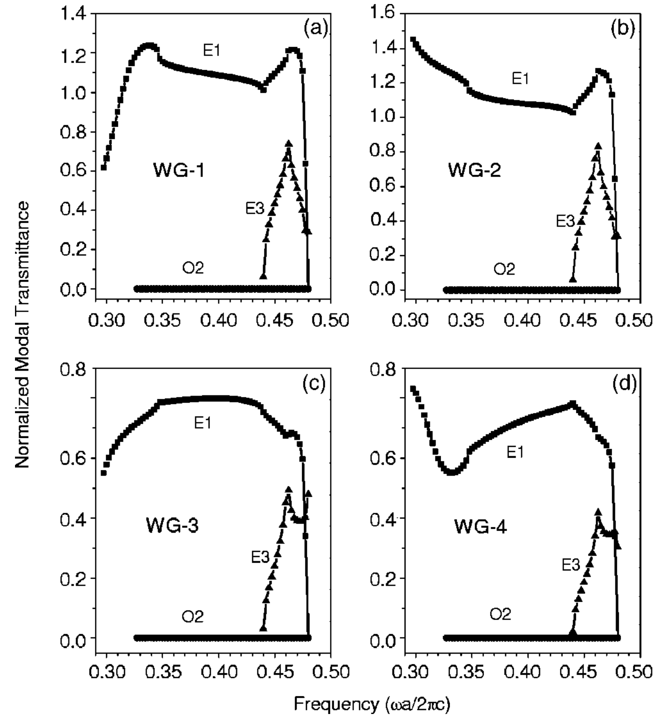

FIG. 6. Calculated normalized modal transmission coefficients of a plane wave incident onto the four single-end $W3$ PC waveguides shown in Fig. 4.

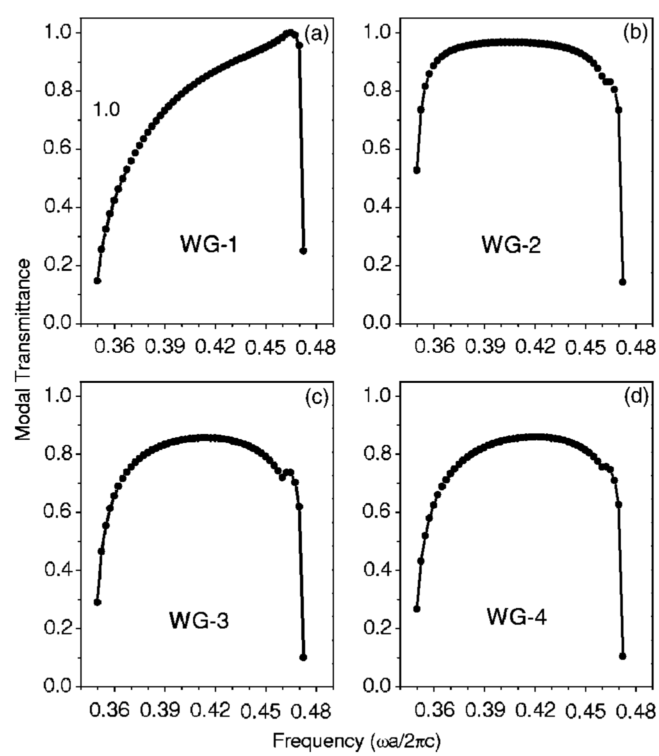

FIG. 7. Calculated transmission coefficients of a guided wave coupled out of the four single-end $W1$ PC waveguides shown in Fig. 1.

where a guided wave is coupled out of the waveguide into free space. To see this, we also employ the TMM to solve this problem, and the calculated modal transmission spectrum is shown in Fig. 7 for the four $W1$ waveguides (WG-1 to WG-4) as displayed in Fig. 2. Since the incident wave is space limited, it is possible to define a true transmission coefficient as the ratio of the total-energy flux dispersed into air to the total-energy flux of the incident guided wave. The calculation result is quite surprising and beyond our expectation. The coupling-out efficiency in WG-3 and WG-4 is even smaller than that in WG-1 and WG-2 within a wide range of frequency, not to mention one order of magnitude enhancement as is expected from Fig. 3. This is especially the case for WG-2, where the coupling-out efficiency is above 90% from $\omega = 0.36(2\pi c/a)$ to $\omega = 0.45(2\pi c/a)$, 10% larger than the coupling-out efficiency of WG-3 and WG-4 at the same frequency. Comparison between the coupling-in and coupling-out spectra clearly indicates an asymmetric characteristic in these two inverse physical processes. Whereas a tapering surface morphology can significantly enhance coupling of an external extended wave into the PC waveguide, it does not necessarily help to couple a localized guided wave out of the waveguide. This asymmetry might source from the different scattering behaviors of an extended wave and a localized wave by the same surface termination geometry. This feature can offer some hints for designing high performance PC waveguide connectors.

In summary, we have employed a plane-wave-based TMM to investigate coupling of EM waves into and out of a PC waveguide, and found that a slightly tapering geometry can result in one order of magnitude enhancement of the coupling efficiency of an external extended wave into the waveguide, but it does not necessarily help to couple a guided wave out of the PC waveguide. This feature can help to design appropriate termination geometry of a PC waveguide to achieve optimal input and output functionality.

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