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Light coupling for single-mode photonic crystal waveguides

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Abstract

We use a transfer-matrix method (TMM) to investigate light coupling into and out of single-end single-mode photonic crystal waveguides. Without multi-reflection complexity, we give clearly the unambiguous quantitative determination of the coupling efficiency of external light into guided mode and the transition among guided modes. It is shown that the waveguide with a line defect along ΓJ direction exhibits a much better coupling efficiency than that with a line-defect orientation along ΓM direction.

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Starting from the pioneering works of Yablonovich [1] and John [2] in 1987, the past decades have witnessed an extended development in photonic crystals (PCs), also known as photonic band gap (PBG) materials. The dielectric constituents of these materials are periodically arranged in space, either in one, two, or three dimensions, with important applications in the optical, microwave and infrared fields [3]. One of their important properties is to mold and control the flow and distribution of the light at the microscopic level. In the PCs, the synergetic interplay between the microcavity resonance within each constituent and the Bragg scattering resonance among constituents leads to the formation of the PBG, within which no propagating electromagnetic (EM) modes are allowed. The photonic density of states in PCs is suppressed in the PBG [4]. This feature opens the possibility for many technical applications including lossless PC waveguides, low-threshold PC lasers, and high-Q PC nanocavities [3].

By introducing a properly designed line defect in a PC structure, propagating modes confined within the defect can be created. Depending on the nature of the guided defect mode, waveguiding with low losses even around sharp bends can be achieved, as well as connecting PC optical devices of the size of λ/n and forming highly integrated optical circuits [5–8]. Due to the fact that their waveguiding mechanism is fundamentally different from that of conventional dielectric waveguide, such as optical fibers, which are dependent on total internal reflection, a large variety of different techniques have been proposed and evaluated by means of the experiments and numerical simulations [7–9].

One important subject about a PC waveguide is that the efficient coupling of light into and out of the waveguide for practical applications. As a consequence of the small core size, insufficient light is coupled into PC devices, and this serious problem will hinder their functionality and reliability. For this reason, much progress from both the theoretical and experimental sides has been made towards the goal of deeply and fully understanding the coupling behavior of EM waves into and out of a PC waveguide [10–18]. A usual way to efficiently improve the coupling efficiency is to excite surface waves in PC waveguides [10,14]. By means of adopting an appropriate tapering structure of the waveguide, surface modes will exist in PC structures and the transmission will be enhanced [10,19]. The main function of the tapered waveguide is to provide low-loss connections between waveguides with different

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cross-sectional areas. It has been shown that due to similarity between the mode patterns of a PC waveguide and a slab (or ridge) waveguide with similar slab thickness, the two waveguides can be efficiently coupled over a large bandwidth [11]. The coupling process (into or out PC waveguide) is essentially a scattering phenomenon. Therefore, by changing the termination surface morphology of the waveguide, the coupling efficiency can be modified. After careful designs, the coupling efficiency can reach an optimum value as large as possible. For instance, Lin and Li have found that the coupling efficiency is sensitive to the surface termination morphology of the waveguide [14]. However, the coupling efficiency for a line defect along different directions and the coupling characteristic as a function of the surface termination morphology are still not explored completely up to now. In this paper, to obtain an optimum value for the coupling efficiency, we theoretically investigate light coupling into and out of single-mode PC waveguides [20]. In order to completely remove the multiple-reflection contamination to the useful information induced by the second exit in a finite-length waveguide, it is of great benefit both physically and numerically to adopt a single-end PC waveguide, in a similar consideration as discussed by Li and Ho [20].

There have been some theoretical approaches to solve wave propagation in a single-mode PC waveguide [20,21]. Li and Ho have given a highly efficient plane-wave-based transfer-matrix method (TMM) [20,22–24], which can successfully deal with light propagation in semi-infinite PCs and related waveguide structures. The physical background of this method is: (1) divide the whole PC structure into thin slices along the z-axis direction, within each slice ε is approximated as z-independent (however xy-dependent). It is known that a partitioned lamellar slice in a general three-dimensional PC can be approximated as a 2D grating. We denote the primitive lattice of the grating by two unit vectors $\mathbf{a}_1$ and $\mathbf{a}_2$, the corresponding reciprocal lattice by $\mathbf{b}_1$ and $\mathbf{b}_1$. We let an incident plane wave propagate along the z-axis with a wave vector $\mathbf{k}_0 = (k_{0x}, k_{0y}, k_{0z})$. The EM field at an arbitrary point $\mathbf{r}$ can be expressed as a superposition of Bragg waves:

$$\mathbf{E}(\mathbf{r}) = \sum_{ij} \mathbf{E}_{ij}(z) \mathrm{e}^{\mathrm{i}(k_{ij,x}x + k_{ij,y}y)}, \tag{1}$$

$$\mathbf{H}(\mathbf{r}) = \sum_{ij} \mathbf{H}_{ij}(z) \mathrm{e}^{\mathrm{i}(k_{ij,x}x + k_{ij,y}y)}, \tag{2}$$

where the Bragg wave vector $\mathbf{k}_{ij} = (k_{ij,x}, k_{ij,y}) = (k_{0x}, k_{0y}) + i\mathbf{b}_1 + j\mathbf{b}_2$, $\mathbf{E}_{ij}(z)$ and $\mathbf{H}_{ij}(z)$ are expansion coefficients of the EM field to be determined. (2) It is assumed that each slice is surrounded by two thin air films with zero thickness; (3) express the EM field in the air films by Floquet harmonics; (4) express the EM field in each slice by the eigenmodes in the slice; (5) use of the boundary conditions between EM fields in the slice and two neighboring air films to obtain the transfer matrix or the scattering matrix [22].

To deal with our problem, one first can solve the eigenstate of the PC waveguide and obtain an eigenstate space, among which there is one propagating guided mode, while others are evanescent modes; then project external incident waves onto the eigenstate space through matching of boundary conditions for the fields and, finally pick up the projection amplitude of the guided mode, from which the coupling efficiency can be readily calculated because only the guided modes can exist in the regions well away from the waveguide exit. The inverse problem of coupling a guided wave out of the waveguide can be done in the same framework [15].

Further, by using the TMM method, Lin and Li have investigated light coupling problem in single-end two-dimensional (2D) PC waveguides along a certain crystalline direction [14]. It has been found that the coupling efficiency is highly sensitive to the surface termination morphology of the waveguide, and a slight surface geometry can lead to an order of magnitude difference in the coupling efficiency of an external wave into the waveguide. Here, we consider a linear waveguide in a triangular lattice by removing a single row of cylinders along several directions [25]. Apart from the ΓJ crystalline direction studied, which we call W1 waveguide, a waveguide with a line-defect orientation along ΓM crystalline direction can also be created, which we call W2 waveguide. The structures for both the waveguides are shown in Fig. 1. To obtain an optimum information about the dependence of the coupling efficiency on the surface termination morphology, it is not enough to just consider four different termination geometries as done by Lin and Li. Hence, we consider 20 different geometries here. It is worth noting that each unit of the PC waveguide contains two layers of dielectric cylinders. We divide equally each dielectric layer into 10 sub-layers, and each sub-layer represents a typical surface morphology. In order to study the properties of the coupling efficiencies for two directions as a function of the surface morphology, we use a parameter τ, as shown in Fig. 2. Finally, it is indicated why the coupling-in efficiency is sensitive to the surface termination morphology.

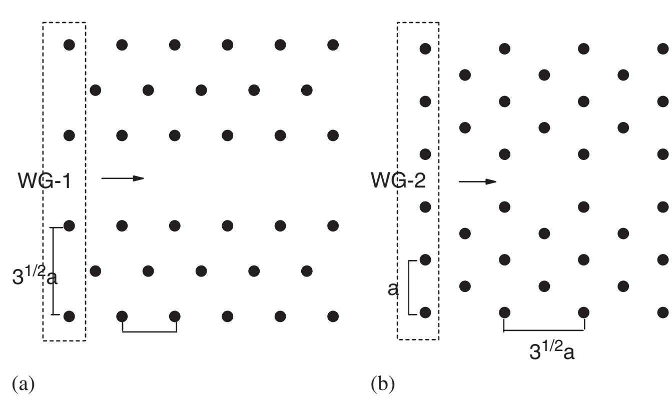

Fig. 1. Schematic geometric configuration of two photonic crystal waveguides with different line-defect orientations. The waveguides are created in a two-dimensional triangular lattice of dielectric cylinders in air by removing a single row of cylinders.