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ARROW-based photonic crystal waveguides

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Abstract— *A new photonic crystal waveguide based on ARROW structure is proposed to solve the coupling issue with a fiber in the vertical direction. The design and performance of this device are discussed.*

Keywords: *Integrated optics, antiresonant reflecting optical waveguide, photonic crystal waveguide.*

1. Introduction

Photonic crystals are artificial optical materials with periodic changes in dielectric constant, analogous to the crystal structure of semiconductors, and photonic band gaps (PBG) can be created for certain range of photonic energies [1]. The propagation of light for that range is forbidden. By incorporating line defects into PC with PBG, they can work as strongly confined waveguides. In general, the optical confinement in these structures is supported by PBG guiding in a lateral plane and that use index guiding in vertical direction, which are called as PC slab waveguides.

In order to sustain PBG, the core size of traditional PC slab waveguide is less than one micron but optical fibers have sizes on the order of a few micron. Coupling becomes a critical problem between PC waveguides and fibers due to the mismatch of core sizes. The coupling issue also limits the measurements and further applications of PC devices. There are many couplers proposed for efficient coupling, including gratings, mirrors, and tapered structures. However, those can solve the lateral coupling issue only.

ARROW structures utilize the Fabry-Perot cavities as the reflectors instead of the total internal reflection [2]. In comparison with conventional waveguides, ARROW has some great features: relatively large core size suitable for efficient connection to single-mode fibers and flexible structure design roles. It is a new application to design PC waveguides with ARROW structure in the vertical direction for efficiently coupling with general single-mode fibers.

In this presentation, the design of ARROW-based PC waveguides will be discussed. Photonic band structures and transmission efficiencies of ARROW-based PC waveguides calculated by commercial software package R-Soft V.5.1 will be presented.

2. Design of ARROW-based PC waveguides

The design of ARROW-based PC waveguides is divided into two parts, the lateral plane and the vertical direction. In the lateral plane, the periodicity of our device is triangular lattice arranged by air holes, and a 2D PC waveguide is created by removing a row of PC. The TE band map is calculated with the plane wave expansion method (PWE) and supercell approximation [3], and the result is shown in Fig. 1(a). The simulation parameters are: the refractive index n_c of background material is 1.8 ($\mathrm{SiO_xN_y}$); $r_a/a = 0.4$ due to maximum band gap at the ratio, where r_a and a is the radius of air hole and lattice constant, respectively. The complete band gap exists within the normalized frequency from 0.441 to 0.504 (a/λ). In the range of band gap, there are two defect modes induced. The upper is even, and the lower is odd, respectively.

ARROW structures consist of two claddings between core layer and substrate. The first cladding is with a low index and the second is with a high index. To analyze ARROW structures in the vertical direction, the transfer matrix method [4] is used. The refractive index of the core and of the second cladding layer is $n_c = n_l = 1.8$ ($\mathrm{SiO_xN_y}$), and of the first cladding layer is $n_h = 3.5$ (poly-Si), respectively. The free-space operating wavelength λ_0 is 1.55 μm. To attain a low insertion loss for an ARROW-based PC Waveguide, the thickness d_c of core layer is chosen as 7.00 μm. The thicknesses of the first cladding and of the second cladding layers are $d_h = 0.12$ and $d_l = 3.50$ μm, respectively, by satisfying the transverse antiresonance condition [2]

$$d_i = \frac{\lambda_0}{4n_i}\left[1-\left(\frac{n_c}{n_i}\right)^2+\left(\frac{\lambda_0}{2\,n_i d_c}\right)^2\right]^{-1/2}\cdot(2Q+1), \qquad Q=0,1,2,\cdots, \tag{1}$$

where $i = h, l$. Fig. 1(b) illustrates the electric field profiles of $\mathrm{TE_0}$ to $\mathrm{TE_2}$. The profile of quasi-guided mode $\mathrm{TE_0}$ behaves like the fundamental guided mode, because the high reflectivity of Fabry-Perot cavity at the antiresonance condition reduces the loss to the high index substrate ($n_s = 3.5$).

3. Performance of ARROW-based PC waveguides

A 3D waveguide with a 2D PC waveguide structure in the lateral plane and ARROW structure in the vertical direction is shown in Fig. 2(a). The light could be confined laterally by the 2D PC based on PBG, and vertically in the core layer by satisfying antiresonance condition in the cladding layers. Fig. 2(b) depicts the simulation results calculated by 3D FDTD method, and shows that the transmission reaches to the maximum as the air holes are etched to 7.00 μm deep. Because the field of the fundamental TE mode for an ARROW structure is mainly confined in the core layer vertically.

Fig. 3(a) shows the performance of ARROW-based PC waveguides by the 3D FDTD method and the effective index method, in which the refractive indices of dielectric materials in the vertical direction are replaced by the effective index of fundamental TE mode in an unperturbed 3D heterostructure. This converts the 3D problem to 2D problem. For our case, $n_a/n_c/n_h/n_l/n_s = 1.0/1.8/3.5/1.8/3.5$ are replaced by $n_{eff} = 1.79 - j9.86 \times 10^{-8}$, the effective index of the fundamental TE mode in our designed ARROW structure. There is about 10% difference in the transmission spectra within the frequency from 0.44 to 0.50 (a/λ). Thus, the effective index method gives good observations for our designed waveguides.

The transmission gradually decays as the frequency decreases, because the odd defect mode spans out of the band gap and couples with the dielectric band below the band gap. It is shown that high transmission is within the frequency from 0.47 to 0.50 (a/λ) and the central frequency of this range is 0.485 (a/λ). Fig. 3(b) shows the field pattern of propagation at the central frequency of this range in our device. For the operating wavelength $\lambda_0 = 1.55$ μm, the lattice constant $a = 0.75$ μm and the radius of air hole $r_a = 0.30$ μm. The transmission efficiency of waveguide is 86.8% (0.61-dB loss).

4. Summary

ARROW-based PC waveguides are designed. The optical confinement of this structures are supported by PBG in the lateral plane and by antiresonance reflection in the vertical direction. In comparison with traditional PC slab waveguide, this structure has a large core size to improve coupling efficiency with single-mode fibers. The structure supports single mode propagation with high transmission efficiency of 86.8% (0.61-dB loss). The ARROW-based PC waveguide provides a new platform for PC waveguides. It is expected that the transmission efficiency can be further enhanced and optimization is under development.

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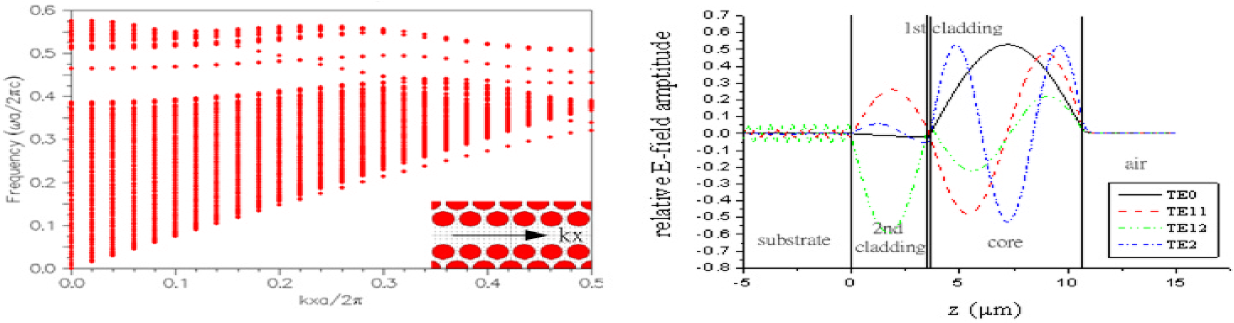
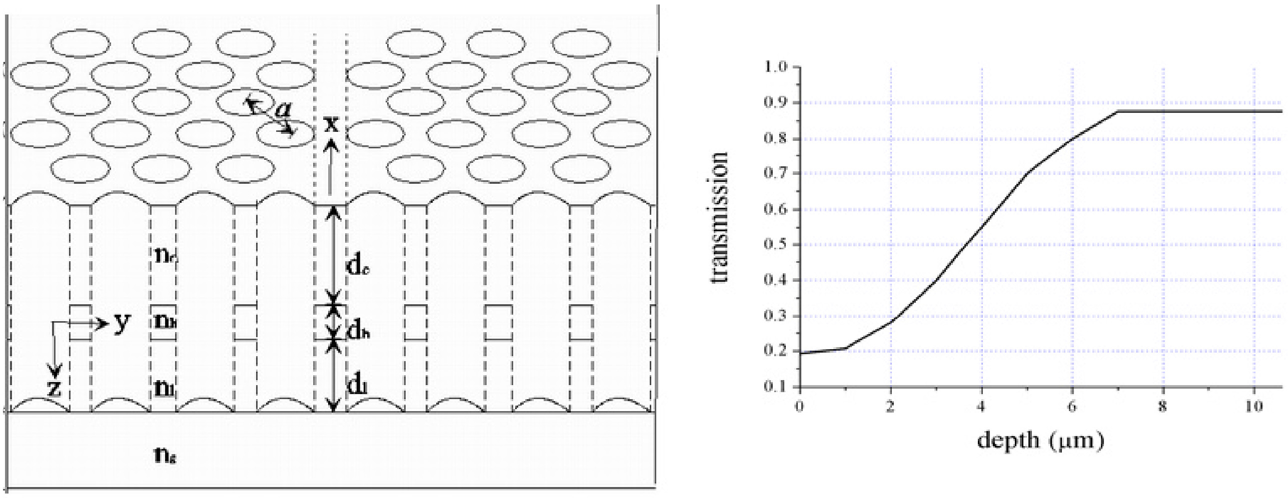


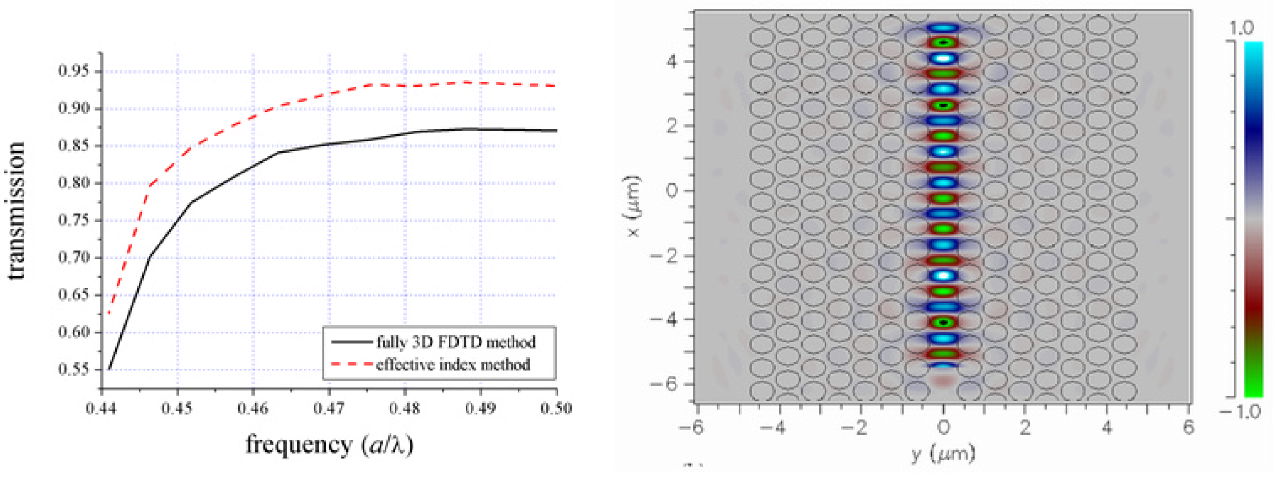
(a) (b)

Figure 1: (a) Defect modes of PC waveguide in the lateral direction. (b) Relative E-field amptitude of an ARROW structure in the vertical direction.



(a) (b)

Figure 2: (a) The ARROW-based PC waveguide. (b) The relation between the transmission and the depth of etched air holes.



(a) (b)

Figure 3: (a) The transmission spectra with the 3D FDTD method and effective index method. (b) The field pattern of propagation.