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J. Cai
S. Kim

See next page for additional authors

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High Efficiency 90° Silica Waveguide Bend Using an Air Hole Photonic Crystal Region

Seunghyun Kim, Student Member, IEEE, Gregory P. Nordin, Member, IEEE, Jianhua Jiang, and Jingbo Cai, Student Member, IEEE

Abstract—We propose the hybrid integration of an air hole photonic crystal (PhC) structure with a high $\Delta$ (0.75%) single-mode silica waveguide to achieve an ultracompact high efficiency 90° bend for transverse-magnetic polarized light. Diffraction from the periodic boundary between the PhC and silica waveguide regions is shown to seriously degrade the optical efficiency of the bend. A microgenetic algorithm ($\mu$GA) combined with a two-dimensional finite-difference time-domain method is used to modify the PhC and its boundary layer to suppress this diffraction which in turn maximizes bend efficiency. The final optimized structure has a 99.4% bend efficiency at a wavelength of 1.55 $\mu$m and occupies an area of only $27 \times 27 \mu$m.

Index Terms—Integrated optics, optical losses, optical waveguides, photonic crystals (PhCs), waveguide bends.

I. INTRODUCTION

Silica waveguides are an attractive technology platform for planar lightwave circuits (PLCs) because of their low propagation loss, low coupling loss to optical fiber, and mature microfabrication processes [11]–[7]. However, a key drawback is the relatively large radius of curvature (on the order of multiple millimeters to centimeters [4]) required to achieve high efficiency waveguide bends, which limits the compactness of PLC components.

Alternatively, two-dimensional (2-D) photonic crystal (PhC) slab structures have recently been the focus of intense research because of their potential to achieve ultracompact PLCs [8]. Despite high propagation losses [9], most research has focused on material systems that have a large refractive index contrast ($\Delta n \geq 1.5$) in the PhC to maximize the photonic bandgap. Liguda et al. recently reported fabrication of a relatively low refractive index contrast ($\Delta n = 0.5$) PhC composed of a 2-D array of air holes in a polymer slab waveguide. Both numerical and experimental results verify the presence of a directional bandgap (photonic bandgap only for specific lattice direction) [10].

In this letter, we propose the use of an air hole PhC region in a high $\Delta$ (0.75%), $\Delta = (n_{\text{core}} - n_{\text{clad}})/n_{\text{core}}$ single-mode silica waveguide to achieve an ultracompact high efficiency 90° bend. As we have recently reported [11]–[13], hybrid PhC and conventional waveguide (CWG) structures take advantage of the PhC to manipulate light propagation within a very small area while CWGs guide light with low loss. By use of hybrid PhC and CWG structures, we reported designs and 2-D numerical analyses for bends [11], splitters [11], and a polarizing beam splitter [12] that use high index (Si posts) PhC regions. We also performed a three-dimensional analysis [14] of our hybrid 90° bend structure [11] and found that loss in the third dimension for 2-D designed structures is insignificant as long as the PhC posts are deep enough to fully intersect the waveguide mode [14]. This result implies that 2-D numerical analysis can be used to accurately design hybrid PhC and CWG structures. In this letter, we apply 2-D numerical analysis to optimize a periodic air hole array in a silica waveguide to suppress diffraction from the periodic PhC boundary to achieve a high efficiency 90° bend for transverse-magnetic (TM) polarized light (electric field out of the 2-D plane).

II. DESIGNS AND NUMERICAL SIMULATION RESULTS

We initially consider the hybrid structure shown in Fig. 1(a). The silica waveguide core has a 6-μm square cross section. The core and cladding refractive indexes are 1.456 and 1.445, respectively. For our 2-D calculations, we used the 2-D effective index of the core region, which is 1.453. As shown in Fig. 1(a), the PhC is composed of a square air hole array (which has a wider directional bandgap for TM polarization than a triangular array) that is designed based on the dispersion relation shown in Fig. 1(b). Although a full photonic bandgap is not found, there is a directional bandgap shown as the shaded region in the normalized frequency range from 0.375 ($\alpha/\lambda_0$) to 0.429 ($\alpha/\lambda_0$) along the $\Gamma-X$ lattice direction (which has the widest directional bandgap). To obtain an initial structure for the PhC region, we select a normalized frequency of 0.402 ($\alpha/\lambda_0$) which is in the middle of the directional bandgap. Then we match this normalized frequency to the desired operational wavelength, which is 1.55 μm. The period of the air hole array for the PhC is calculated to be 0.623 μm and the air hole radius is 0.25 μm ($r/a = 0.4$). This PhC structure is placed at the silica waveguide 90° bend. The boundary surface between the PhC region and silica waveguide region is along the $\Gamma-M$ lattice direction of the PhC and this surface is oriented at 45° with respect to the input waveguide. The hybrid structure is rigorously simulated by a 2-D finite-difference time-domain (FDTD) method [15] with Berenger perfectly matched layer boundary conditions [16].

A TM waveguide mode source is launched in the 2-D FDTD computational space and a line detector is used to calculate the...
bend efficiency at the output waveguide illustrated in Fig. 1(a). The waveguide mode source and line detectors are 16 μm long. The bend efficiency of the hybrid structure is calculated with the mode overlap integral (MOI) [17] and is defined as the ratio of the power in the guided mode at the output detector to the incident guided mode power.

In Fig. 2(a), the magnitude squared time averaged electric field calculated by 2-D FDTD is shown superimposed on the hybrid structure geometry. Since the incident light propagation direction (Γ-X lattice direction of the PhC) corresponds to the directional bandgap for TM polarized light at λ = 1.55 μm, we can see that no light is coupled into the PhC region. However, the bend efficiency is only 8.3%. Most of the incident light is diffracted backward nearly toward the source.

We can understand the origin of this diffraction using the wave vector diagram in Fig. 2(b). The orientation of the wave vector diagram corresponds to the geometry shown in Fig. 2(a). The 45° tilted gray line corresponds to the Γ-M direction of the PhC (i.e., the boundary between the PhC and CWG regions). The solid semi-circle indicates allowed wave vectors in the silica waveguide region (which is assumed to be quasi-homogeneous with a refractive index of 1.451). The dotted curves represent allowed propagation modes in the PhC region. The solid arrow corresponds to light from the waveguide incident at a 45° angle to the Γ-M boundary surface. The dashed dark gray arrow along the Γ-M boundary denotes the grating vector associated with the periodicity of the PhC boundary. The wave vector diagram clearly shows that no light can be coupled to allowed modes in the PhC region. Therefore, light can only be reflected or diffracted into the CWG region. These allowed states are denoted as dotted arrows in Fig. 2(b), and are precisely what we observe in Fig. 2(a), with most of the optical power carried in the diffraction order caused by the periodic PhC boundary.

Clearly, the diffracted light needs to be suppressed to obtain high bend efficiency. To this end, a microgenetic algorithm (μGA) combined with 2-D FDTD [18], [19] is used to modify the boundary layer of the PhC [13]. The variables to be optimized are the air hole radii of both the PhC and the boundary layer, the period of boundary layer, and the X and Y position of the boundary layer. After μGA optimization, the bend efficiency is improved to 97.7% from 8.3% at λ = 1.55 μm.
GA optimization is based on 2-D FDTD results, m for the boundary layer.


Since μGA optimization is based on 2-D FDTD results, we calculated with a relatively small number of time steps (8000) and low resolution (31-nm Yee cell size) in order to minimize computation time, a more detailed manual search is then performed. After all optimization processes, we obtained a bend efficiency of 99.4% at λ = 1.55 μm. The ratio of the power calculated at the detector to the input source power as a function of wavelength for the final optimized structure is shown in Fig. 3(a) along with the power ratio before the optimization process. Using an MOI calculation, over 99.0% bend efficiencies are obtained for wavelengths between 1.54 and 1.56 μm.

The final optimized structure has an air hole radius in the PhC region of 0.26 μm while in the boundary layer radius is increased to 0.275 μm and the period is unchanged. The position of the boundary layer is shifted 0.2 μm in the X direction and 0.82 μm in the negative Y direction. The magnitude squared time averaged electric field plot with its optimized geometry is shown in Fig. 3(b). There is no evidence of the diffraction order that spoiled the bend efficiency of the original structure. For the optimized structure, destructive interference from light diffracted by the bulk PhC region and the shifted first

hole layer effectively suppress the unwanted diffraction order to achieve a bend efficiency of 99.4% at λ = 1.55 μm. A fabrication tolerance analysis shows that the bend efficiency is greater than 96.0% over the 1.54–1.56-μm wavelength range for an air hole radius between 0.24–0.27 μm for the PhC region and 0.255–0.295 μm for the boundary layer.

III. CONCLUSION

We have proposed a high efficiency (99.4%) silica waveguide 90° PhC/CWG bend structure for TM polarized light that occupies an area of 27 × 27 μm. Diffraction associated with the periodic boundary of the PhC region can be effectively suppressed by use of a μGA optimization procedure.

REFERENCES


