Transmission of Slow Light through Photonic Crystal Waveguide Bends

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The spectral dependence of a bending loss of cascaded 60-degree bends in photonic crystal (PhC) waveguides is explored in a slab-type silicon-on-insulator system. Ultra-low bending loss of $(0.05 \pm 0.03)$dB/bend is measured at wavelengths corresponding to the nearly dispersionless transmission regime. In contrast, the PhC bend is found to become completely opaque for wavelengths range corresponding to the slow light regime. A general strategy is presented and experimentally verified to optimize the bend design for improved slow light transmission.

Planar two-dimensional photonic crystal (PhC) waveguides have a strong potential to realize ultra-dense photonic integrated-circuits. An important component of a compact photonic circuit is a small-radius low-loss waveguide bend that efficiently maneuvers light around sharp corners. Many papers have investigated PhC bends focusing mainly on the optimization of the amplitude transmission. Largely ignored, however, is the spectral dependence of the bend loss. It is known that PhC waveguides are characterized by very large group velocity dispersion especially at wavelengths close to the onset of the waveguiding mode. The strong distributed feedback at these wavelengths results in significantly reduced group velocity. The possibility to slow down the propagation of light is envisioned to have a broad range of applications from all-optical data storage to quantum computing. Therefore transmission in this "slow light" regime needs to be carefully studied for various optical components, if the "slow light"-based circuits are to be built. This paper focuses on the spectral dependence of losses of PhC bends with a special emphasis on the "slow light" regime.

The PhC waveguides were fabricated on 200nm silicon-on-insulator (SOI) wafers with 2µm thick buried oxide (BOX) and 220nm thick silicon layer. The periodic array of holes with a triangular lattice (lattice constant $a=437$nm) was first written in the resist layer with electron beam lithography. The PhC waveguides were formed by removing a row of holes in the Γ-K direction of the lattice. The pattern was then transferred to an oxide hard mask using $C_{4}F_{6}/C_{2}H_{2}F_{5}/Ar$ chemistry and the Si layer was etched next with an HBr-based chemistry. The underlying BOX was wet etched in the PhC section to create a suspended Si membrane. An additional lithography step defined the polymer cladding of the inverted taper spot-size converter for efficient fiber coupling.

In order to improve the experimental accuracy of loss measurements, devices with a number of bends cascaded in series were fabricated as shown in Fig.1a. The bends were separated from each other by straight waveguide sections 20 lattice constants long. To optically characterize the devices, light from a broadband LED source (1200 to 1700nm) is coupled to the PM fiber, transferred through the polarization controller and finally launched into the device with a microlensed PM fiber tip. Transmission spectra were measured for the TE polarization (E-field parallel to the slab plane) with a resolution of 5nm. The measured transmission spectra through straight and bent PhC waveguides were normalized on transmission through a reference straight strip waveguide following the method of Ref. The design of the PhC bend similar to the one shown in Fig.1b was characterized first. This simple bend is formed by connecting two W1 waveguides rotated by 60 degrees with respect to each other. Figure 2 represents...
Attaining low bending loss in the region I is crucial for constructing optical circuits utilizing slow group velocity. Surprisingly, comparison of transmission spectra (Fig.2a) of a straight PhC waveguide and PhC bends reveals that bends are completely opaque in this region. The long-wavelength cutoff of the bend around 1655nm appears to be blue shifted by 30nm (blue arrow) with respect to the 1687nm cutoff characteristic of the straight PhC waveguide. This blueshift is too large to be explained by small variation of the lattice parameters between reference PhC straight waveguide and the bend structure. Moreover, detailed inspection of a number of SEM images as in Fig.1 reveals that the hole radii and the lattice constant in both structures are identical within 1nm.

This spectral blueshift can be explained by making analogy to conventional strip and rib waveguide bends. It is known that the mode in curved waveguides is pulled analog to conventional strip and rib waveguide bends.
Figure 3: Transmission spectra for PhC structures with a hole radius of 144nm (0.33a). A) Spectrum (black curve) of a straight PhC waveguide with a length of 181um and spectra of structures with 10 (blue curve) and 20 (red curve) cascaded simple bends. B) Spectra of structures with 10 (blue curve) and 20 (red curve) cascaded modified bends. Arrows indicate a blueshift of the cutoff.

To experimentally verify this strategy, an additional device set consisting of cascaded simple bends analogous to that studied earlier (see Fig.1b), and the cascaded modified bends (Fig.1c) designed for better transmission in the slow light regime.

Figure 3a shows transmission spectra of a straight PhC waveguide and a simple cascaded PhC bends. The low-loss transmission window for a straight PhC waveguide is defined by a long-wavelength cutoff at 1493nm and a light-line at 1466nm. Band structure calculations similar to Fig.2b showed that the "slow light" regime in this case corresponds to wavelengths range of 1478nm-1493nm. Similar to the results obtained in Fig.2a, the spectrum of the simple bend is characterized by a relatively low-loss transmission band extending over the "linear" regime and interrupted by sharp dips. The long-wavelength cutoff of a bend spectrum at 1478nm is blue shifted by almost 15nm with respect to the cutoff position in a straight PhC waveguide. Thus, the simple bend in this structure appears to be completely opaque in the "slow light" regime as previously observed in the results of Fig.2.

Figure 3b represents spectra of 10 and 20 cascaded bends, which are modified by reducing the radius of four holes adjacent to the bend section to 105nm (0.24a) as shown in Fig.1c. Transmission spectra of 10 and 20 cascaded modified bends have similar spectral features as seen in the spectrum of a simple bend. The "linear" regime of a modified bend is characterized by a relatively low loss 0.1dB/bend comparable to the results of Fig.2a. As expected, the long-wavelength cutoff of the modified bend occurs at wavelengths longer than for a simple bend. Hence, by increasing the average refractive index at the bend the initial 15nm blueshift of the cutoff is significantly reduced to only 6nm rendering a large portion of the "slow light" regime transparent.

The modified bends with 4 small holes clearly do not fully compensate the initial blueshift. The experiments described above can be viewed as a proof-of-principle demonstration of a general strategy, rather than a final solution. Following the analogy with the bends in conventional waveguides, the transmission in the "slow light" regime might be improved not only by the increase of the refractive index at the bend as shown here, but also by creating an offset of the bend section with respect to the straight PhC waveguide.

In conclusion, ultra-low bending loss of only (0.05±0.03)dB/turn is measured in a simple 60-degree PhC bend. It is found that simple PhC bends are completely opaque for the wavelength region corresponding to small group velocity regime of a straight PhC waveguide. Increasing the average refractive index at the bend by decreasing the radius of 4 holes adjacent to the bend section allows to almost compensate the blueshift of the transmission cutoff and to restore transparency for slow light.

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