Ultralow-loss 3-dB photonic crystal waveguide splitter

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A photonic crystal waveguide splitter that exhibits ultralow-loss 3-dB splitting for TE-polarized light is fabricated in silicon-on-insulator material by use of deep UV lithography. The high performance is achieved by use of a Y junction, which is designed to ensure single-mode operation, and low-loss 60° bends. Zero-loss 3-dB output is experimentally obtained in the range 1560–1585 nm. Results from three-dimensional finite-difference time-domain modeling with no adjustable parameters are found to be in excellent agreement with the experimental results. © 2004 Optical Society of America

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Optical components based on planar photonic crystal (PhC) structures can substitute for total internal reflection (TIR) components by use of the unique properties of the photonic bandgap (PBG) effect. The PBG effect allows the interaction between light and the PhC structure to take place on a scale of a few wavelengths.[1,2] This can minimize the size of the individual components and thus greatly increase the device-packing density (up to 10^6 times compared with conventional TIR components). The recent progress in deep UV lithography at wavelengths of 248 nm and below[3] has made mass fabrication of ultracompact planar optical devices based on the PBG effect possible by use of existing fabrication technologies widely used in the semiconductor electronics industry.

The PBG effect arises in specially engineered dielectric materials by periodic modulation of the refractive index.[4,5] Planar PhC waveguides (PhCWs) can be formed by the introduction of line defects into an otherwise perfect PhC. Thereby light is confined horizontally by an in-plane PBG and vertically by TIR. Because of the PBG effect in a PhCW, light can be routed around sharp corners with bending radii of the order of the wavelength. However, in single-mode operation small discontinuities in the straight PhCW can introduce large reflections at the interface between different sections of the PhCW. Discontinuities can also excite higher-order modes, which are not necessarily guided in the PhCW. Because the functionality of the PhC component typically arises from discontinuities, care is a necessity when designing PhCW components to avoid losses.

A key optical component is the splitter, which is widely used in interferometers and (de)multiplexers. To date, only few structures with splitters in the PhC platform have been reported.[6–10] We fabricated and modeled PhCW Y splitters for which the discontinuities in the splitter and bend regions were carefully positioned, thereby ensuring ultralow-loss 3-dB splitting for TE-polarized light. Experimental transmission spectra obtained for components fabricated in silicon-on-insulator material were compared with three-dimensional (3D) finite-difference time-domain (FDTD) calculations.[11] The agreement between experimental and theoretical data is found to be excellent.

The planar PhC structures are defined by airholes that penetrate a 220-nm-thick silicon layer placed on top of a 1-μm silica layer. The regular holes are placed in a triangular lattice and have a diameter $d = 0.57\Lambda$, where the lattice constant $\Lambda = 435$ nm. The PhCWs are defined by $W1$ missing hole line defects along the ΓK direction of the triangular lattice. This configuration yields a relatively large PBG below the silica line and allows TE-like single-mode propagation in the PhCWs.[12] Ridge waveguides, gradually tapered from a width of 4 μm at the sample facet to 1 μm near the PhC interface, are used to route the light to and from the PhCWs. The structures are patterned with 248-nm deep UV lithography and transferred onto the top silicon layer by use of a reactive-ion etching process. The fabrication procedure is described in detail in Refs. 3 and 13.

The fabricated components were optically characterized for the transmission of TE-polarized light by use of broadband light-emitting diodes, polarization control equipment, and an optical spectrum analyzer. The setup is described in more detail in Ref. 14. In the FDTD calculations a full 3D scheme was used to include out-of-plane losses by applying new out-of-plane boundary conditions[11] to the Onyx-2 code.[15] The calculations were performed with no adjustable

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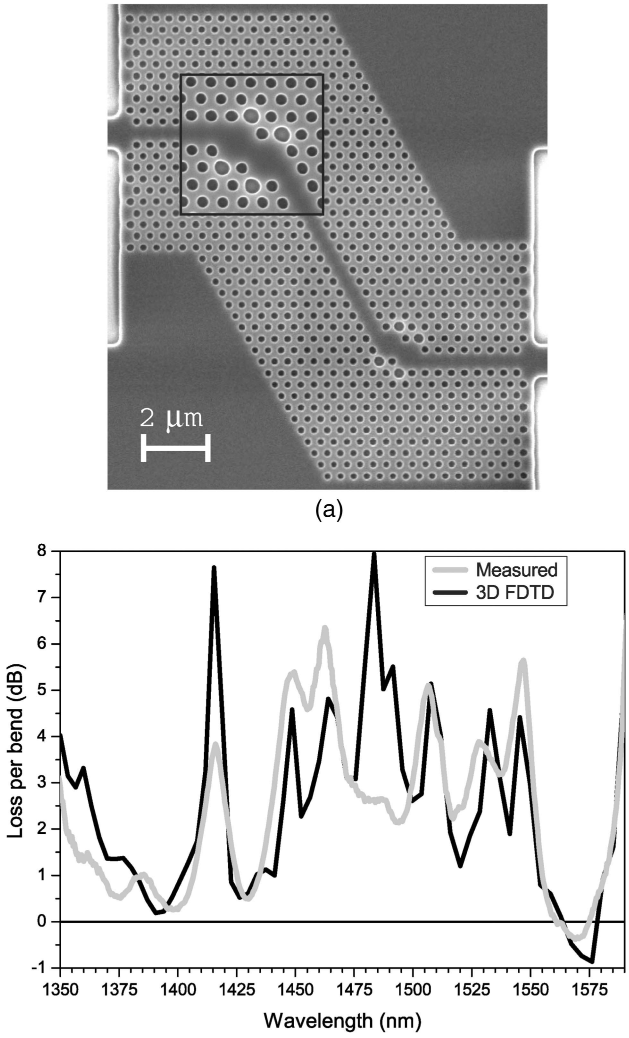


(a)

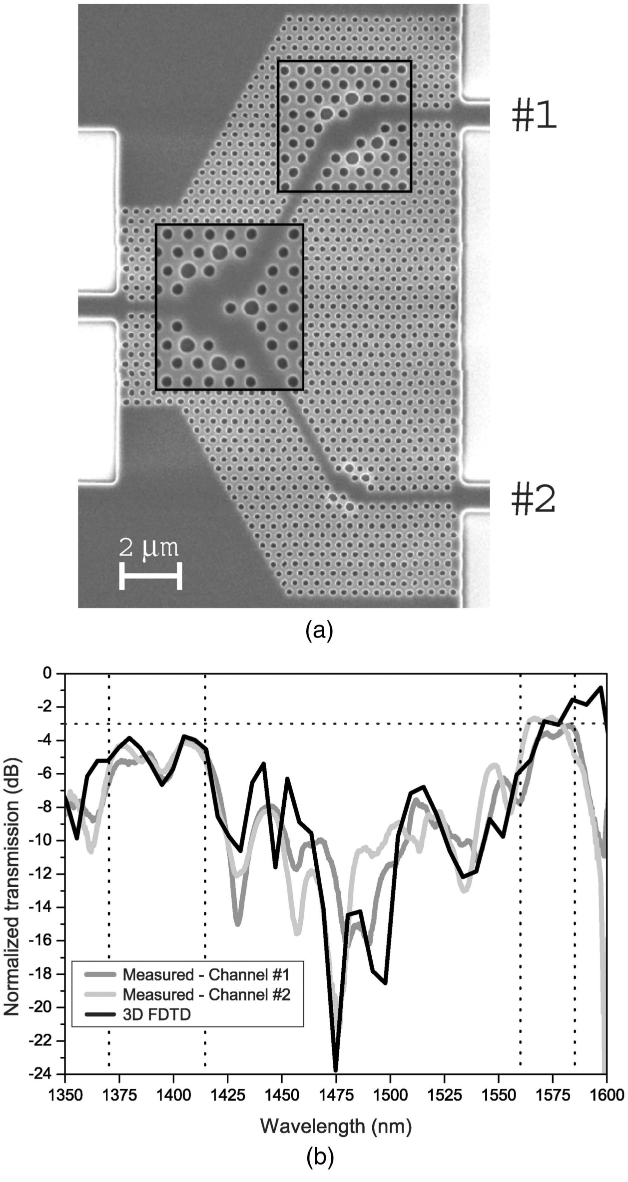
(b)

Fig. 1. (a) Scanning electron micrograph of the fabricated structure containing the novel 60° bends. Also shown is an enlargement of one of the bends. The diameter of the large holes is $D = 0.77\Lambda$. (b) Measured (gray curves) and calculated (black curves) loss per bend for the fabricated structure.

parameters on components identical to the fabricated ones. All the measured and calculated transmission spectra were normalized to spectra for straight PhCWs of equivalent propagation length.

The PhCW splitter is designed as a Y junction formed by the intersection of three PhCWs at 120°. To have the output channels of the Y splitter be parallel to the input channel, the two output channels have a 60° bend spaced 15Λ from the Y junction. Both the Y junction and the 60° bend represent severe discontinuities in the PhCWs and are potentially regions in which the single-mode operation might suffer from large transmission losses. Therefore the discontinuities in these regions were carefully designed. The 60° bends were modified by displacing one hole and removing two holes in the bend. Moreover, four border holes were replaced with larger holes with diameter $D = 0.77\Lambda$ [see the enlargement in Fig. 1(a)]. The Y junction is altered in a similar way by removing three holes on both sides of the junction and replacing five border holes with larger holes. However, this could transform the Y junction into a multimode optical cavity, which could decrease the performance of the splitter because the cavity modes might not be supported by the PhCWs.[7] Therefore an additional hole is added in the splitting region, whereby the size of the junction cavity is reduced. The design of the Y junction is shown in the enlargement in Fig. 2(a).

To investigate the performance of the modified 60° bend, a PhCW containing two consecutive bends



(a)

(b)

Fig. 2. (a) Scanning electron micrograph of the fabricated PhCW splitter. Insets, enlargements of the Y junction and the 60° bend. The diameters of the airholes are $d = 0.57\Lambda$ nm and $D = 0.77\Lambda$ for the normal and large holes, respectively, with a lattice constant of $\Lambda = 435$ nm. (b) Measured spectra for TE-polarized light output (light and dark gray curves) of the fabricated PhC Y splitter. Three-dimensional FDTD spectrum (black curve) calculated with no adjustable parameters.

spaced by 15Λ was fabricated [see Fig. 1(a)]. The measured (gray curve) and calculated (black curve) losses per bend for the structure are shown in Fig. 1(b). A noteworthy feature is the remarkable similarity between the measured and the calculated spectra. This clearly demonstrates our ability to fabricate devices behaving in accordance with design guidelines. The small deviations between the experimental and the simulated spectra may stem from the uncertainties of the hole diameter and the thickness of the silicon layer. Two bandwidth ranges distinguish themselves: In the range 1555–1585 nm the bend loss is experimentally found to be 0.25 ± 0.58 dB. Resonance effects are believed to cause the below-zero loss achieved in this region. Hence the bends can transmit light better than an equivalent length of straight PhCW. In the wavelength range 1370–1410 nm the loss is found to be 0.70 ± 0.35 dB per bend. Thus our 60° bend shows very low bend losses in the two 30-nm windows.

The fabricated PhCW Y splitter is shown in Fig. 2(a). The total size of the splitter is only 15 μm × 20 μm. The experimental and numerical transmission spectra for the Y splitter are shown in Fig. 2(b). Again, the calculated spectrum (black curve) correctly replicates all major features, and the transmission level of the measured spectra (light and dark gray curves). Moreover, the measured spectra for the two output channels are practically identical in perfect accordance with the symmetry of the structure. The low-loss bandwidths of the Y splitter overlap with those of the 60° bend. In the range 1560–1585 nm, zero-loss 3-dB output is obtained from each channel of the Y splitter. In the wavelength range 1370–1410 nm the excess loss is found to be in the range 1–2 dB. Here the bend loss accounts for approximately half of the observed loss, and hence optimizing the bends might improve the performance of the splitter in this region.

In conclusion, we have demonstrated that our Y splitter displays zero-loss 3-dB output when compared with a straight PhCW in a 25-nm bandwidth from 1560 to 1585 nm. The low-loss bandwidth can be further extended by careful optimization of the Y junction and the bends of the splitter. The splitter has been designed with sufficient tolerances for fabrication with standard deep UV lithography. Hence it can be readily utilized in future PhC components.

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