Efficient propagation of TM polarized light in photonic crystal components exhibiting band gaps for TE polarized light

P. I. Borel, L. H. Frandsen, M. Thorhauge, A. Harpøth, Y. X. Zhuang, M. Kristensen

Research Center COM, Technical University of Denmark Building 345v, DK-2800 Kgs. Lyngby, Denmark
pib@com.dtu.dk, lhf@com.dtu.dk, mk@com.dtu.dk

http://www.com.dtu.dk

H. M. H. Chong

Department of Electronics and Electrical Engineering, Glasgow University, Glasgow G12 8 LT, Scotland, UK

Abstract: We have investigated the properties of TM polarized light in planar photonic crystal waveguide structures, which exhibit photonic band gaps for TE polarized light. Straight and bent photonic crystal waveguides and couplers have been fabricated in silicon-on-insulator material and modelled using a 3D finite-difference-time-domain method. The simulated spectra are in excellent agreement with the experimental results, which show a propagation loss as low as 2.5±4 dB/mm around 1525 nm and bend losses at 2.9±0.2 dB for TM polarized light. We demonstrate a high coupling for TM polarized light in a simple photonic crystal coupler with a size of ~ 20 μm × 20 μm. These promising features may open for the realization of ultra-compact photonic crystal components, which are easily integrated in optical communication networks.

OCIS codes: (130.3120) Integrated optics devices; (130.3130) Integrated optics materials; (220.4610) Optical fabrication; (220.4830) Optical systems design; (230.3990) Microstructure devices; (230.7390) Planar waveguides; (230.5440) Polarization-sensitive devices; (999.9999) Photonic crystals

References and links

1. J. Arentoft, T. Søndergaard, M. Kristensen, A. Boltasseva, M. Thorhauge and L. Frandsen, “Low-loss silicon-on-insulator photonic crystal waveguides,” Electron. Lett. **38**, 274-275 (2002).
2. M. Notomi, A. Shinya, K. Yamada, J. Takahashi, C. Takahashi, and I. Yokohama, ”Singlemode transmission within photonic bandgap of width-varied single-line-defect photonic crystal waveguides on SOI substrates,” Electron. Lett. **37**, 293-295 (2001).
3. T. Søndergaard, J. Arentoft, and M. Kristensen,”Theoretical Analysis of Finite-Height Semiconductor-on-Insulator-Based Planar Photonic Crystal Waveguides,” J. Lightwave Technol. **20**, 1619-1626 (2002).
4. A. J. Ward and J. B. Pendry, “A program for calculating photonic band structures, Green's functions and transmission/reflection coefficients using a non-orthogonal FDTD method,” Comput. Phys. Commun. **128**, 590-621 (2000).
5. A. Lavrinenko *et al*., “Comprehensive FDTD modeling of photonic crystal waveguide components,” in preparation (2003).
6. L. H. Frandsen, P. I. Borel, M. Thorhauge, J. Cheng, M. Kampanis, M. Kristensen, A. Lavrinenko, Y. Zhuang, ”Propagation of TE and TM polarised light through smoothed sixty degree bends in planar photonic crystal waveguides,” (*accepted for publication in Proceedings of CLEO-Europe 2003)*
7. M. Tokushima and H. Yamada, “Photonic crystal line defect directional coupler,” Electron. Lett. **37**, 1454-1455 (2001).

Received June 20, 2003; Revised July 18, 2003

1. Introduction

The recent progress in the design of planar photonic crystal waveguides (PhCWs) has paved the way for exploitation of low-loss propagation in 2D-patterned PhCWs [1,2]. One particularly important goal is to determine the useful bandwidth of the photonic crystal guiding effect by comparing numerical calculations with experimental transmission spectra. Often, the holes in the photonic crystal (PhC) are arranged in a triangular pattern as this arrangement may provide a large photonic band gap (PBG) for TE polarized light [3]. Until now, very little attention has been devoted to investigate the propagation of TM polarized light in such PhCWs, since there is no bandgap for this polarization and, thus, the waveguide should not support leakage-free guidance. In this paper we present extensive experimental and numerical investigations of the propagation of TM polarized light in PhCW structures exhibiting a bandgap for TE polarized light. In contrast with the naive expectation we find low propagation and bend losses for TM polarized light.

2. Experimental procedure

2.1 Fabrication

The PhC structures were created in a $SiO_2/Si/SiO_2$ trilayer film by arranging holes with diameter $D_{glass}=0.76\Lambda$ in a triangular array with lattice constant $\Lambda=428$ nm. This configuration is known to give the largest bandgap below the silica-line for TE polarized light [3]. The PhCWs were defined by removing single rows of holes in the otherwise perfect photonic crystal. Ridge waveguides, gradually tapered from a width of 4 µm at the sample facet to 1 µm at the PhC interface, are used to route the light to and from the PhCWs. The silicon-on-insulator (SOI) wafer had a 340 nm layer of silicon (Si) on top of a 1 µm layer of silica (SiO_2). The hole patterns were defined using e-beam lithography. The pattern was transferred to the Si layer by reactive ion etching (RIE) utilizing the e-beam resist as a mask. The Si layer acted as a mask when RIE afterwards was employed to transfer the pattern to the SiO_2 layer. Finally, the sample was thermally oxidized in order to grow a thin SiO_2 layer on top of the Si layer and on the inner walls of the air holes. The silica top cladding increases the vertical symmetry of the structure and smoothens out surface roughnesses of the structure. Figure 1 shows examples of fabricated straight and bent PhCWs.

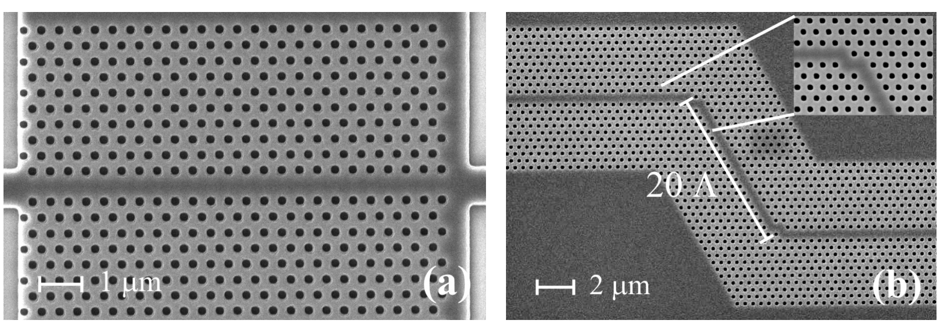

Fig. 1. Scanning electron micrographs of (a) a 10 µm long straight PhCW and (b) a 150 µm long PhCW containing two modified 60° bends, which are separated by a 20Λ long straight PhCW. The black spots are the air holes.

2.2 Characterization

The fabricated components were characterized using the setup sketched in Fig. 2. Tapered lensed fibers were used to couple light in and out of the ridge waveguides connected to the PhCWs. The light sources were broadband light emitting diodes (LEDs) centered at 1322 nm and 1544 nm (ANDO AQ-4222), respectively. Two polarization controllers and a polarizer with an extinction ratio better than 35 dB were used to control the polarization of the light sent into the device under test (DUT). The optical spectra for the transmitted light are recorded with a spectral resolution of 10 nm using an optical spectrum analyzer (ANDO AQ6315E).

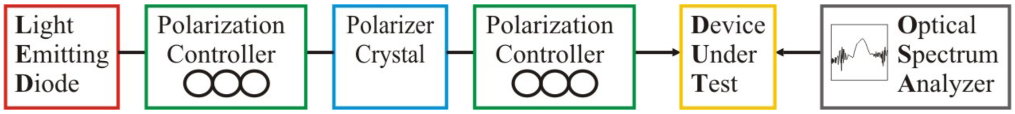

Fig. 2. Experimental setup used to characterize the waveguide samples.

3. 3D FDTD calculations

The employed 3D finite-difference-time-domain (FDTD) calculations of transmission spectra for TM polarized light were performed using an improved version of the basic ONYX-2 FDTD code presented in Ref. [4]. A full 3D scheme was utilized in order to include out-of-plane losses by employing perfectly matched layers as boundary conditions to the original ONYX-2 code [5]. As in the experimental case the modelled PhC structures were designed as planar triangular patterns of holes made in a SOI material. The holes of the PhC structures had a normalized radius of 0.375Λ. In order to mimic the fabricated structures, in which the holes have a layer of silica on the inner side, an averaged dielectric constant ε_{avg} = 1.4111 was applied to the holes in the 3D FDTD calculations. The vertical layer structure used in the 3D calculations consisted of a 1Λ silica base cladding, a 0.625Λ silicon core, a 0.25Λ silica top cladding, and a 0.75Λ air layer, respectively. The output light intensity of the PhCW was normalized to the entrance light intensity.

4. Results

4.1 Straight photonic crystal waveguides

We first investigate the transmission of TM polarized light through the 10 μm long (23Λ) straight PhCW shown in Fig. 1(a). The measured and calculated transmission spectra are shown in Fig. 3.

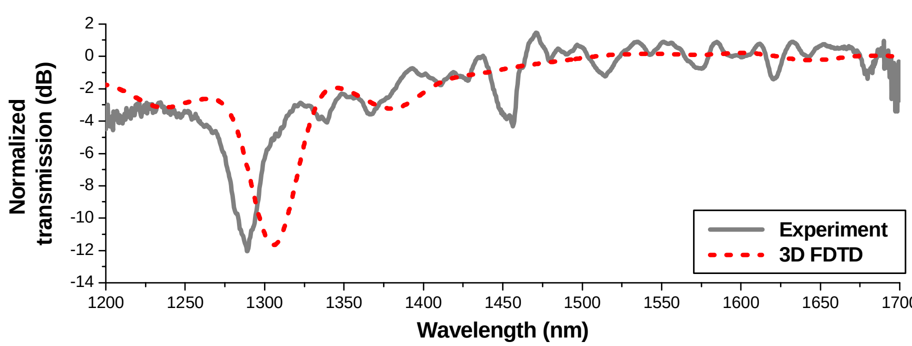

Fig. 3. The measured (gray) and calculated (dashed red) transmission spectra for TM polarized light through a straight 10 μm (23Λ) long PhCW.

The experimental spectrum is normalized to the transmission spectrum for a ridge waveguide located on the same sample. The figure shows that the 3D FDTD calculation successfully explains the actual transmission level and essential features of the experimental spectrum such as the pronounced dip around 1300 nm. The small frequency shift (approximately 1-2%) between the measured and calculated spectra may be due to uncertainties in the experimental parameters and a limited Λ/16 grid resolution of the 3D FDTD calculations. Both the experiment and the simulation show a broad transmission window for longer wavelengths.

Figure 4(a) displays representative raw transmission spectra recorded for TM polarized light through PhCWs of various lengths (10-150 μm). For comparison, the measured transmission spectrum for a ridge waveguide is also shown (black). For wavelengths longer than ~1500 nm very low propagation and coupling losses (between the ridge waveguide and the PhCW) are observed for TM polarized light as all spectra blend together. Figure 4(b) shows calculated transmission spectra for TM polarized light for PhCWs of various lengths (23-60Λ). The 3D FDTD calculations predict a broad low-loss transmission window in the range 1500-2000 nm. This is in excellent agreement with the experimental spectra in Fig. 4(a).

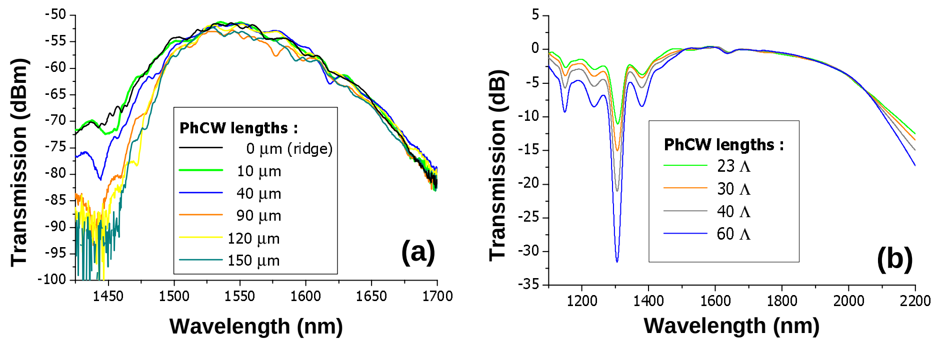

Fig. 4. (a) The un-normalized experimental spectra recorded using the LED centered at 1544 nm for a ridge waveguide and straight PhCWs of various lengths. (b) 3D FDTD calculations of the transmission through PhCWs of various lengths.

A direct comparison between the experimental and calculated propagation losses for TM polarized light in the PhCWs is shown in Fig. 5. For a given wavelength the propagation loss is extracted by finding the slope of the best linear fit, when plotting the measured transmission as a function of the PhCW length.

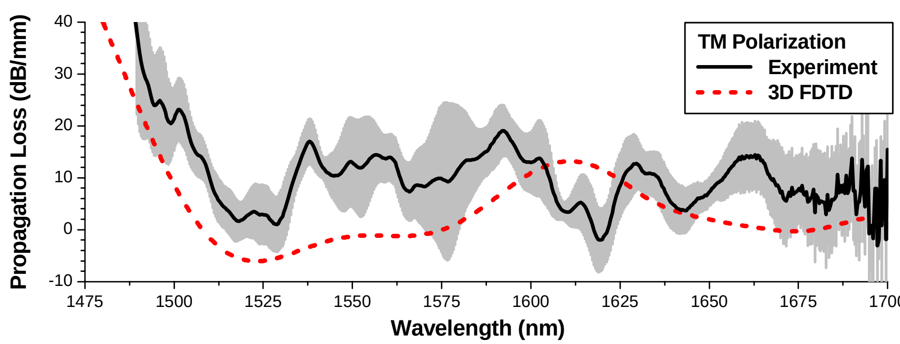

Fig. 5. The measured (black) with the uncertainty (gray) and calculated (dashed red) propagation loss for TM polarized light in straight PhCWs.

Figure 5 shows an experimental propagation loss as low as 2.5±4 dB/mm in the wavelength region around 1525 nm for TM polarized light. Again, good agreement is found between experiment and simulation. The negative propagation losses are due to numerical artifacts when calculating near zero losses and the fact that scattered light may be recollected in longer waveguides. In the transmission window between 1500-1700 nm the average coupling loss

#2619 - $15.00 US
Received June 20, 2003; Revised July 18, 2003

between the PhCW and the connecting ridge waveguide is found to be 0.07±0.39 dB for the experimental data and 0.06±0.27 dB for the 3D FDTD calculation. Band calculations show that the low propagation losses for TM polarized light take place in a region, which resembles an index-guided mode in a traditional ridge waveguide. However, unlike a true index-guided mode there is a cut-off at the edge of the Brillouin zone. Thus, the guided TM mode can be characterized as an index-*like* mode. An interesting point is that the wavelength range of the low-loss TM mode propagation overlaps one of the TE photonic bandgap modes. This feature of the PhCW may be exploited to fabricate integrated polarization controllers or polarization independent components.

4.2 Bent photonic crystal waveguides

In order to investigate the propagation of TM polarized light through PhCW bends we have fabricated and modelled PhCWs containing two consecutive 60º bends as illustrated in Fig. 1(b). The two fabricated 60º bends are separated by a straight 20Λ long PhCW. As shown in the figure the bend geometry has been modified by displacing one hole. Figure 6 shows the measured transmission spectrum for TM polarized light through a 150 μm long PhCW, which contains such two consecutive 60º bends. The transmission spectrum is shown both normalized to a ridge waveguide and to a straight PhCW of length 150 μm. In the latter case, the normalized transmission expresses the total bend loss for the two 60º bends in the PhCW. The measured average loss per bend in the range 1540-1670 nm is found to 2.9±0.2 dB. This is a significant improvement of the bend loss compared to the bend loss of 7.2±0.5 dB per bend that we found from additional measurements performed on PhCWs, which contained unmodified bends. A lower limit of the bend loss for TE polarized light is found to be 2 dB for an identical bend [6]. Hence, the modified bend works equally well for the TE and TM polarization, though the PhC only exhibit a bandgap for TE polarized light. Thus, modifying the bend geometry significantly reduces the bend loss for the TM mode, which cannot be assumed to be stripped off in bends. Figure 6 also displays 3D FDTD calculations of the transmission through a PhCW containing two modified 60º bends. The calculated spectrum predicts a theoretical average loss 2.5±0.1 dB per bend in the range 1540-1670 nm. Thus, it is seen that the 3D FDTD calculations successfully explain the observed bend losses for TM polarized light.

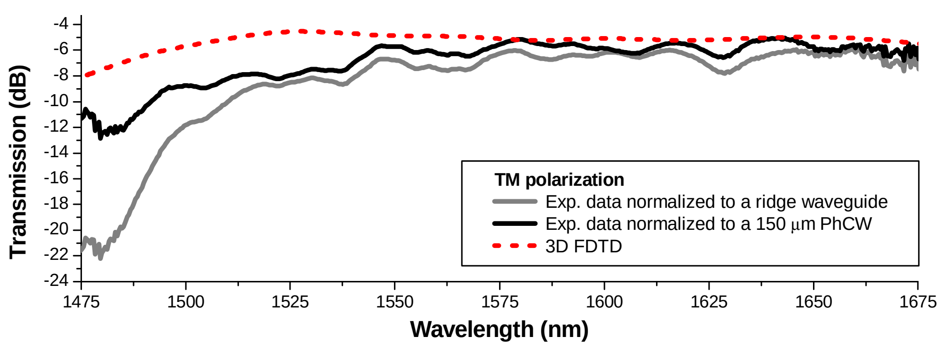

Fig. 6. The measured (black and gray) and calculated (dashed red) transmission for TM polarized light through a PhCW containing two consecutive 60° bends each having one hole displaced as shown in Fig. 1(b).

4.3 PhCW directional couplers

A key optical component is the wavelength selective directional coupler [7], which is widely used in interferometers, filters, and (de-) multiplexers. The PhCW coupler shows novel features not realizable in traditional ridge waveguide couplers. Its superior properties stem from the strong confinement of the light and from the possibility for the PhCW coupler to interact with the light on a scale of the order of a wavelength. Furthermore, the PhCW coupler may easily be designed to exhibit coupling for specific wavelengths or a specific polarization. We have fabricated and modelled PhCW couplers based on PhCs, which hold PBGs for TE polarized light, and investigated the coupling spectra for TM polarized light. Figure 7(a) shows a scanning electron micrograph of a fabricated coupler.

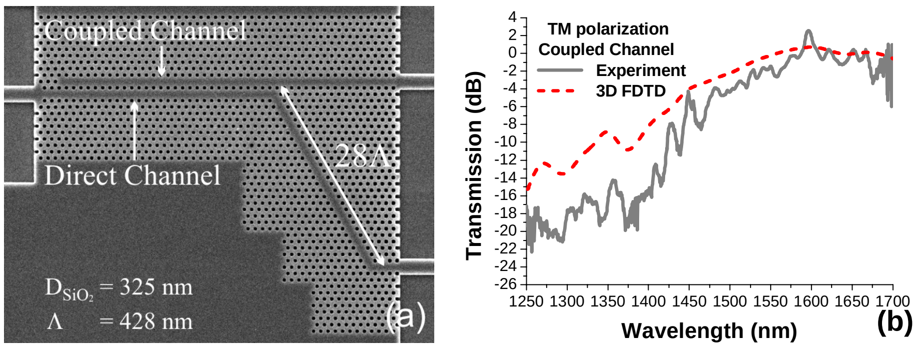

Fig. 7. The directional coupler based on photonic crystals. (a) Scanning electron micrograph of the fabricated coupler. The fabricated coupler has a larger separation between the two output channels compared to the modelled coupler. (b) The measured (gray) and simulated (dashed red) transmission spectra for TM polarized light in the coupled channel.

The coupler has a coupling region with two PhCWs placed next to each other separated by a single row of holes. The length of the region is 27Λ. Coupling of light is expected to take place from the direct channel to the coupled channel (see Fig. 7(a)). The simulated coupler is identical to the fabricated; except that the length of the intermediate PhCW connecting the two bends is 5Λ and 28Λ in the simulations and experiments, respectively. The longer intermediate PhCW in the fabricated coupler is needed in order to avoid coupling between the two output ridge waveguides used in the experiment to route light from the PhCW coupler. Figure 7(b) displays the experimental and simulated spectra for the coupled channel. The experimental spectrum has been normalized to a spectrum for a ridge waveguide. Especially noteworthy is the transmission level for TM polarized light in the coupled channel, experimentally found to be –1.3±1.5 dB in the wavelength range 1500-1700 nm. In this wavelength region, the transmission level in the direct channel has a large dip centered around 1600 nm and all TM polarized light is essentially routed to the coupled channel. Again, the 3D FDTD calculations successfully predict the behavior of the fabricated PhC component.

5. Conclusion

We have investigated TM mode propagation in planar PhCWs. We find a propagation loss as low as 2.5±4 dB/mm around 1525 nm in straight photonic crystal waveguides. We have shown that TM polarized light can be effectively guided through 60° bends in photonic crystal waveguides. The experimental bend loss is 2.9±0.1 dB in the range 1540-1670 nm. Finally, we demonstrated an effective coupler, which experimentally has a spectrally flat coupling at 1.3±1.5 dB for TM polarized light. These properties for TM polarized light were obtained despite the fact that the photonic crystals only exhibit photonic bandgaps for TE polarized light. The fabricated structures have successfully been modelled using a 3D finite-difference-time-domain code. Based on the results, we believe that it is possible to fabricate ultra-compact planar photonic crystal components, which work for both TE *and* TM polarized light.

Parts of this research were carried out in the context of the European IST-PICCO project.