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Low-loss transmission band in photonic crystal waveguides with sharp cutoff at a frequency below the bandgap

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ABSTRACT

We present TE transmission measurements of photonic crystal waveguides with high hole radius to period ratio r/Λ = 0.388. This geometry introduces a unique low loss transmission band in addition to the traditional PhC guiding band and very sharp transmission edges for devices with a length of 50 μm or longer. Finite difference time domain and plane wave expansion simulations confirm the results and show that the sharpness of the cutoffs can be explained by the spectral shape of the guiding mode in the band diagram.

1. Introduction

Two-dimensional Photonic Crystal (PhC) waveguides have received significant attention during the last decade because they allow ultra-compact realization of integrated optical components [1–4]. Furthermore, PhC waveguides can be realized in SOI wafers and thereby monolithically integrate optical and electronic components to achieve optical and electronic signal transmission and processing in one unit. By defining a triangular array of holes in the silicon epi-layer, a photonic band gap (PBG) in the range 1200–1600 nm can be created for TE-polarized light [5], and by removing a row of holes, a line defect PhC waveguide (PhCW1) with a width of $w=\sqrt{3}\Lambda$ relative to the lattice period Λ [6]. This is highly dispersive for TE-polarized light and group indices of several hundreds are feasible around the mode cut-off at long wavelength within the bandgap [5,7,8]. Transmission loss in PhCW1 waveguides is generally higher than in straight photonic ridge waveguides due to in-coupling loss and scattering [9,10], although it can be reduced by minimizing the field concentration at the hole boundaries [11]. Various waveguide designs have been investigated including high quality membrane PhCW1 structures, also known as air-bridge structures, where it has been shown that loss can be reduced to 2 dB/cm in the low group index region [1,12] when the mode lies below the light line, but the loss near the cutoff is significantly higher [10]. Furthermore, membrane type PhCW1 waveguides are highly fragile and unpractical to implement in commercial devices. Silica imbedded PhCW1 waveguides, although more robust, have a reduced potential for low loss operation compared to air-bridge structures and the top cladding manufacturing procedure adds to the complexity of the fabrication process [13]. Therefore air covered photonic crystal slabs fabricated on a base of silica is still the geometry of choice for CMOS compatible devices. Unfortunately the loss for this geometry is much higher than achieved with the symmetric structures primarily due to the limited region where the band gap mode is below the silica light line. However, we have realized that another transmission band can demonstrate substantially lower losses than the traditional PhCW1 transmission band. In this paper, we report that a low frequency transmission band, previously described as guided by a refractive index mechanism induced by the PhC [5,14], has very low loss and sharp cutoff obtained by increasing the ratio between the hole radius and lattice period (r/Λ) realized in air covered PhCW1 structures with silica lower cladding. To the best of our knowledge, this feature has never been the focus of investigation although it has been observed in simulations [7,15] and there has been indications of it in experiments [6]. Here we present the result of the measured transmission showing the striking sharpness and unexpected low-loss in the transmission band combined with 3D Plane wave expansion (PWE) and finite difference time domain (FDTD) modeling to explain the mechanisms behind this transmission band.

2. Measurement configuration

The PhCW1 waveguides are fabricated in SOI wafers using e-beam lithography (JEOL-JBX9300FS) and inductively-coupled plasma

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etching (ICP), with a final silicon layer thickness of 315 nm. Fig. 1 shows a scanning electron microscope image (SEM) of a fabricated photonic crystal waveguide with a length of 10 μm. The PhCW1 waveguide is defined by removing one row of holes in the Γ-K direction of the triangular crystal lattice. The PhC lattice pitch has been measured from SEM images to be $\Lambda = 367.2 \pm 0.3$ nm, the hole radius is $r = 142.3 \pm 0.4$ nm yielding a r/Λ ratio of 0.388 ± 0.01. The PhC termination is shown in Fig. 1 i.e. $\tau = 0.5$ [16] and all PhCs have 16 rows of holes on either side of the waveguide. Input and output light is guided through ridge waveguides with a width of 455 nm or 620 nm at the PhCW1 interface and then tapered to a width of 4 μm at the chip facets.

Light is generated by a broadband super-continuum source and transmitted through SMF-28 fibers. The polarization-state before and after the device under test (DUT) is aligned with polarization controllers (PC) and polarizers (P), see Fig. 1. The PC's consist of two quarter wave plates and one half wave plate placed between the quarter wave plates in a fiber bench allowing full polarization control and several hundred nanometers bandwidth with at least 20 dB discrimination between polarization states. Fiber input and output coupling to DUT is achieved through tapered lensed fibers with a focus diameter less than 2.5 μm that are aligned with piezo-controlled stages. Finally, light is collected with an Optical Spectrum Analyzer (OSA).

Polarization alignment for the TE-like state is carried out by minimizing the transmission in the region where the PhCW1 waveguide is non-guiding, while maintaining a high transmission in the guiding region. The input polarization is aligned with the output polarizer removed, then the output polarizer is reinserted and the output polarization is aligned. This procedure causes the system to launch and analyze the TE-like state, denoted as TE–TE (input–output) and all transmittance data is obtained using this state.

3. Experimental results

Optical transmission spectra of the TE–TE polarization state shows that the PhCW1 transmission cutoff (cutoff 1) of the traditional PhCW1 transmission band is located at $\Lambda/\lambda \approx 0.267$ (1370 nm) and has a discrimination of more than 20 dB (see Fig. 2). The spectra have been normalized to the transmission through a ridge waveguide with the same dimensions of the PhCW1 but without the PhC. Cutoff 1 is well defined in wavelength for PhCW1 structures of 10 μm or longer although there is always at least one ripple in the transmission close to the cutoff (see Fig. 4). The short 5 μm PhCW1 structures in contrast, possess several strong ripples around cutoff 1. These ripples may be explained by transient coupling across the PhC, etalon effects and by surface roughness in the PhC structure introduced by the e-beam lithography process. The transient coupling mostly affects the short PhCW1 structures and may be the cause of the increased ripple formation in the spectra of these waveguides. In the region below the cutoff: $\Lambda/\lambda > 0.267$ ($\lambda < 1370$ nm), we see a flat transmission profile indicating single-mode guidance down to $\Lambda/\lambda \approx 0.289$ (1270 nm) which coincides with the optical fiber cutoff [17]. This is in agreement with previous mappings of this structure and indicates the increase in relative hole size has not compromised the quality of the PBG.

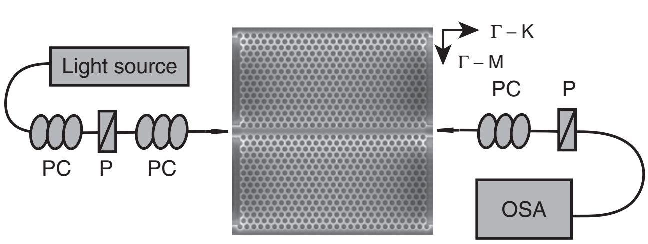

Fig. 1. Characterization setup, with light source, polarization controllers (PC), polarizers (P) and optical spectrum analyzer (OSA) connected by SMF-28 fiber. The central SEM image shows the device under test (DUT), here a 10 μm long PhCW1. Light from a super-continuum source is introduced to the DUT through the lensed fibers.

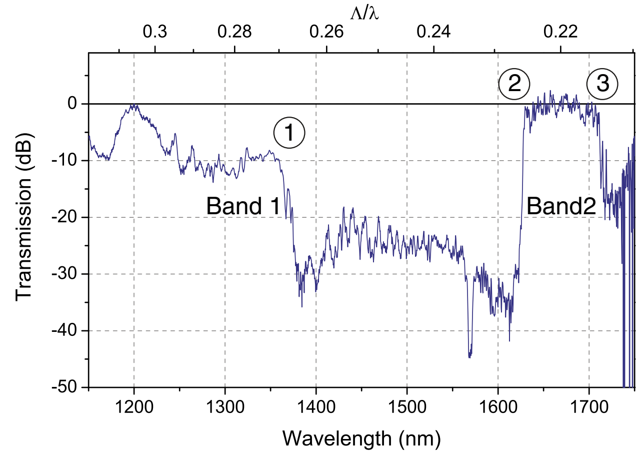

Fig. 2. Transmission spectrum of a 50 μm PhC waveguide aligned for TE–TE transmission at 0.227 and 0.264 for input and output polarizers, respectively. The in-coupling waveguide width is 455 nm. The different cutoffs are designated by circled numbers.

The behavior at low frequency ($\Lambda/\lambda < 0.225$) is more striking. Here an unusually strong transmission band with unexpectedly low loss, very sharp edges and a width of $\Delta\Lambda/\lambda \approx 0.011$ ($\Delta\lambda \approx 85 nm$) is observed below the low-f (low frequency) cutoff of the fundamental PBG defect mode. This corresponds to 4.8% of the normalized frequency. To the authors' best knowledge the spectral features have never been observed before with such striking appearance, even though they have been observed in theoretical studies [7,15] and other broadband experiments have seen indications of it [6]. Furthermore, the low-f transmission band shows a very sharp cutoff (cutoff 2) at $\Lambda/\lambda \approx 0.225$ (1632 nm) with a discrimination of more than 30 dB for the 50 μm long PhC. The cutoff on the low-f side of the band (cutoff 3) at $\Lambda/\lambda = 0.214$ (1717 nm) is also sharp with a discrimination of 15 dB. The input polarization is aligned to maximize the discrimination at cutoff 2 and due to the wavelength dependence of the polarization state the discrimination at cutoff 3 is not completely realized in Fig. 2. In fact, optimization carried out at cutoff 3 showed a discrimination of 25 dB is possible (data not shown). The TE-like state is preserved even though the polarization alignment was performed for the input state at $\Lambda/\lambda \approx 0.227$as evident by the ~20 dB intensity discrimination at the conventional transmission band.

In the region between band 1 and band 2 there are only two significant spectral features: two transmission dips centered at $\Lambda/\lambda \approx 0.234$ and 0.230 (1569 and 1595 nm). These dips are most prominent in TM–TM spectra with depths of up to 19 and 4 dB respectively. However, both features are also observable in TE–TE spectra, especially the deep one, suggesting that they are related to TE–TM interactions. In addition, the features are also close to the TM stopgap observed by Canning et al. [17].

4. Modeling of waveguide properties

The transmission properties of the PhCW1 were investigated using 3D finite difference time domain (FDTD) simulations using the commercial program Crystal Wave [18] with a grid spacing of $\Lambda/24$ in combination with 3D plane wave expansion (PWE) simulations using the open source program MIT-PB with the grid spacing of $\Lambda/16$ [19] to establish the dispersion relation for the supported modes. The simulation results are presented in Fig. 3 with the dispersion relations from the PWE simulations to the left and transmission curve from the FDTD simulation to the right. In comparison to other PhCW1 simulations the most significant difference is the hole radius relative to lattice pitch ratio is increased to $r/\Lambda = 0.388$ from the values around 0.34 that are commonly used since they provide a good discrimination