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Wavelength tuning of photonic crystal waveguides fabricated using 248-nm deep UV lithography

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Abstract: Wavelength tuning of characteristic features of straight photonic crystal waveguides has been obtained by varying the exposure dose in deep UV lithography. The experimental results agree very well with numerical simulations.

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1. Introduction

The recent progress in the design of planar photonic crystal waveguides (PCWs) has paved the way for exploitation of low-loss propagation in 2D-patterned PCWs [1,2]. Often, the holes in the photonic crystal (PC) are arranged in a triangular pattern as this arrangement may provide a large photonic band gap (PBG) for TE polarized light [3]. It is very important to determine the useful bandwidth and the transmission features of the photonic crystal guiding effect by comparing numerical calculations with experimental transmission spectra. In our previous work [4], we have observed a sharp cut-off for TE polarized light at longer wavelength in straight PCWs. This property may have potential applications in optical filters. In order to investigate the impact of fabrication tolerances on the PCW features, straight PCWs with various hole diameters and lengths have been fabricated using 248 nm deep UV (DUV) lithography. Experimental transmission spectra are compared to spectra obtained from three dimensional finite-difference-time-domain (3D FDTD) calculations.

2. Experimental procedure

2.1 Fabrication of PCWs

Straight PCWs with various lengths have been fabricated in a Silicon-On-Insulator (SOI) material by arranging air holes in triangular arrays with lattice constants around $\Lambda = 410$ nm. Since e-beam lithography is not suitable for mass production of PCWs, we have utilised DUV lithography in the fabrication process. In this work, the PC structures have been printed using 248 nm DUV lithography with various exposure doses of 32 mJ, 34.5 mJ, and 37.5 mJ, and developed using a 2-stage reactive ion etching-based etch process. The fabrication procedure is described in detail in Ref. [5]. The PCWs were defined by removing single rows of holes in the photonic crystal as shown in Fig. 1. Due to the various DUV exposure doses used in the fabrication, the hole diameters are different for each PCW.

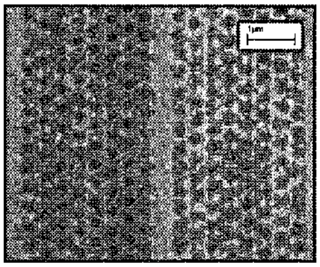

Fig. 1 Scanning electron micrograph of a straight PCW fabricated by deep UV lithography.

For each hole diameter PCWs with lengths 21-51Λ have been fabricated. Ridge waveguides, gradually tapered from a width of 4 μm at the sample facet to 1 μm at the photonic crystal interface, are used to route the light to and from the photonic crystal waveguides. Straight tapered ridge waveguides were also fabricated and used to normalize the PCW transmission spectra. The SOI wafer has a 220 nm layer of silicon (Si) on top of 1 μm layer of silica (SiO_2).

Since the feature size of the photonic crystals is close to the illumination wavelength proximity effects are introduced by the lithography. This causes non-uniform hole sizes in the PC structures, especially at the boundaries of the lattice and near defects. Although an optical proximity correction is utilized during deep UV lithography, the hole sizes are still not uniform across the PC structures as shown in Fig. 1. It is seen that the border holes near the PCW are larger than the bulk holes, and that the second row of holes (counted from the core defect) are smaller than the bulk holes.

2.2 Characterization of PCWs

The fabricated PCWs have been characterized using the setup sketched in Fig. 2. Tapered lensed fibers are used to couple light in and out of the ridge waveguides connected to the PCWs. Two polarization controllers and a polarizer with an extinction ration better than 35 dB are 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. A more detailed discussion about the characterization method can be found in Ref. [6].

Fig. 2 Experimental setup used to characterize the photonic crystal waveguides.

3. Three dimensional finite difference time domain calculations

The employed 3D FDTD calculations of transmission spectra for TE polarized light for all the PCWs with lengths 21-51Λ are performed by applying perfectly matched layers as boundary conditions [6]. The actual calculations are performed using a commercial software package [7]. Both the vertical layer structure as well as the hole diameters have been selected to match the fabricated structures as closely as possible. In the calculations, the optical proximity effects have been taken into account, and different hole diameters are used for border holes, the second row of holes and the bulk holes, respectively. The calculated output intensity of the PCW is normalized to the entrance light intensity.

4. Results and discussion

Fig. 3a shows the measured transmission spectra of TE polarized light through 21Λ long PCWs for three different deep UV exposure doses. The experimental spectra are normalized to the transmission spectra of a tapered ridge waveguide located on the same sample. The sharp cut-off for TE polarized light at longer wavelength is clearly observed for all three PCWs. The high transmission at shorter wavelength is due to guided TE PBG modes. Beyond the cut-off wavelength light is not guided by the PBG effect and the transmission level drops dramatically for longer wavelengths. This feature may be exploited to employ filter functionalities to PC structures. The sharp cut-off moves to shorter wavelengths with increasing exposure dose as the enhanced exposure dose increases the hole diameter. It demonstrates that the transmission features of straight PCWs can be tuned by changing the exposure parameters. The cut-off wavelength is located approximately at 1532 nm, 1492 nm, and 1449 nm for an exposure dose of 32 mJ, 34.5 mJ, and 37.5 mJ, respectively. Fig. 3b gives the normalized transmission spectra of straight PCWs with varius lengths ranging from 21Λ to 51Λ but all written with an exposure dose of 34.5 mJ. It is clear that the sharp cut-off is located nearly at the same wavelength in all cases, indicating that the fabrication procedure is reproducible and that the cut-off wavelength is independent on the lengths of the PCWs.

Fig. 4 shows a comparison between the measured and calculated spectra for the 21Λ long PCW written with the 34.5 mJ exposure dose. An excellent agreement is found between the experimental and theoretical data both regarding the position of the cut-off and the actual transmission level. The small shift in the position of the cut-off is due to uncertainties in the experimental hole diameters as well as the limited grid resolution in the calculations.

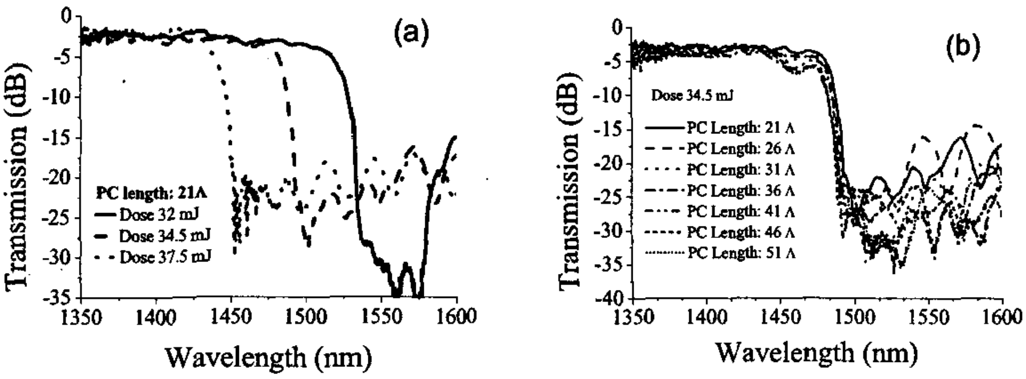

Fig. 3 Normalized transmission spectra for various (a) hole sizes and (b) PCW lengths.

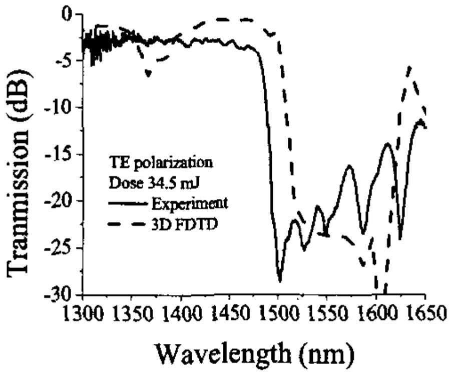

Fig. 4 3D FDTD calculated transmission spectra of the straight PCWs with length 21Λ.

5. Summary

Straight PCWs with various hole diameters and PCW lengths have been fabricated using 248 nm DUV lithography. The experimental transmission properties have been investigated and compared to 3D FDTD calculations. A sharp transmission cut-off for TE polarized light has been observed for straight PCWs. We have found that the cut-off wavelength can be changed by varying the hole diameters in the PCWs and that it is possible to fabricate PCWs with very reproducible features when the same exposure dose is utilized. The experimental results agree very well with numerical simulations. This cut-off feature may be exploited to design optical filters based on PCW structures.

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