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Experimental Demonstration on Structure-Parameter Dependence of Photonic Crystal Optical Spectrum

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We present fabrication and experimental measurement of a series of photonic crystal waveguides and coupled structure of PC waveguide and PC micro-cavity. The complete devices consist of an injector taper down from 3 μm into a triangular-lattice air-holes single-line-defect waveguide. We fabricated these devices on a silicon-on-insulator substrate and characterized them using tunable laser source. We've obtained high-efficiency light propagation and broad flat spectrum response of photonic-crystal waveguides. A sharp attenuation at photonic crystal waveguide mode edge was observed for most structures. The edge of guided band is shifted about 31 nm with the 10 nm increase of lattice constant. Mode resonance was observed in coupled structure. Our experimental results indicate that the optical spectra of photonic crystal are very sensitive to structure parameters.

Keywords: Transmission Spectra, Photonic Crystal, Silicon-on-Insulator.

1. INTRODUCTION

Two dimension photonic crystal (PC) slabs have ability to form small turning radius waveguide bends[1,2] and wide angle Y branches[3,4] leading to the possibility of dense device integration and is useful for constructing a large-scale passive functional photonic chip. By etching holes into silicon-on-insulator materials, optical confinement is provided via refractive index in the vertical direction and via the photonic band-gap phenomenon in the plane of device.[5–7] Many passive and impassive devices can be constructed by photonic crystals in photonic integrated circuit,[8–10] for example, micro-cavity laser, waveguide, splitter, filter etc. Structure design is flexible and fabrication processes are simple. The guided modes of PC waveguides, the defect modes of PC micro-cavity, polarization states and emitting direction can be changed freely by adjusting the geometry parameters of PCs.

Si-based PC devices applied to near infrared band are in sub-micron scale,[6] so the sample fabrication process should be careful. In this letter, PC waveguides and coupled structures of PC waveguide and PC micro-cavity in different constant lattice a based on PC slabs are fabricated and studied. Transmission spectrum dependence on lattice constant and normalized radius is analyzed.

2. DEVICE STRUCTURE AND FABRICATION

Single-line-defect PC waveguides were fabricated with lattice constant from 410 nm to 470 nm and normalized holes radius 0.3, which are named WG1~WG7 respectively. The overall length of PC waveguides we've chosen is $30a$. Each sample has two 3-μm-wide Si stripe dielectric waveguides for an input port and output port. A nominally identical sample without PC waveguide was also used to calibrate the transmission spectra. In order to improve coupling efficiency between stripe dielectric waveguide and PC waveguide, we've designed a 100-μm-long taper down from 3 μm into PC WGs. The device structure is shown in Figure 1. Coupled structure of PC waveguide and PC micro-cavity concludes of a single-line-defect waveguide and a three-hole-defect micro-cavity with lattice constant from 450 nm to 470 nm and normalized holes radius 0.3. Distance between PC waveguide and PC micro-cavity is $3\sqrt{3}/2*a$. Two air holes are shifted $0.176a$ to improve the Q value[11] of micro-cavity in each side shown in Figure 3.

We prepared a SIMOX type SOI wafer having a thick SiO_2 layer under a 0.23-μm-thick top p-type Si layer. A 200-nm-thick layer of PMMA as electron-beam resist was spun on the SOI wafer. The resist was patterned using Raith150 EBL system. The pattern was then transferred into top Si layer by inductively coupled plasma (ICP) low pressure/high density etching system (Alcatel-601E) with a chemistry based on SF_6-C_4F_8. The complexity of fabrication process is decreased by using PMMA as etching

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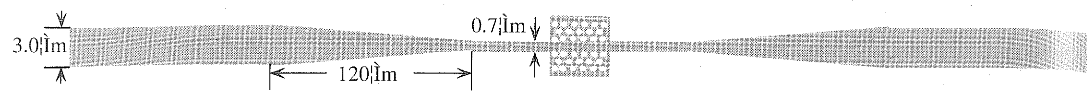

Fig. 1. Complete device consist of an injector taper down from 3 μm into a triangular-lattice air-holes single-line-defect waveguide.

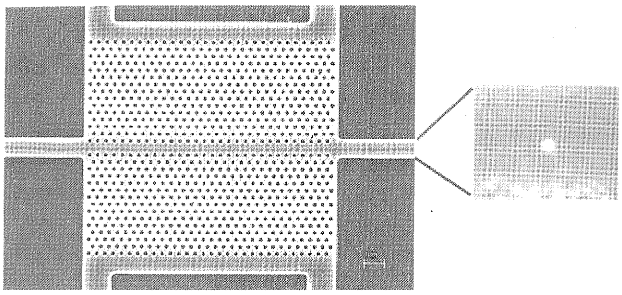

Fig. 2. SEM micrograph of single-line-defect PC waveguide with lattice constant 430 nm and normalized radius $r/a = 0.3$.

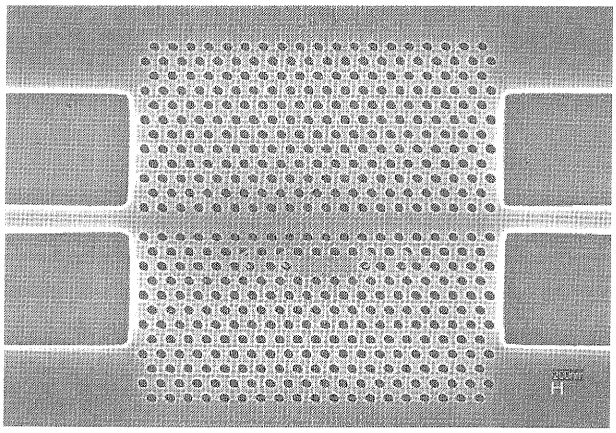

Fig. 3. SEM micrograph of coupled structure of photonic crystal waveguide and photonic crystal micro-cavity with lattice constant 470 nm and normalized holes radius $r/a = 0.3$.

masks directly. We made a considerable effort to improve the fabrication accuracy. With our fabrication procedure, the accuracy was better than 1% for the period and better than 5% for the air-hole diameter. As shown in Figures 2 and 3 scanning electron microscopy (SEM) micrograph, the edge of holes is very smooth and the shape nearly identical. The experiment results of Ref. [12] indicate that it's a convenient way.

3. RESULTS AND DISCUSSION

To characterize PC waveguides and coupled structure of PC waveguide and PC micro-cavity, Agilent 8164A/B lightwave measurement system was used, which includes compact tunable laser modules with tuning wavelength range from 1510 nm to 1640 nm. Scan step is 0.01 nm. Lensed fiber was used to couple light into the strip dielectric waveguides connected to PC waveguide. The output from PC waveguide was recorded by power meter. Accordingly, the output power of stripe dielectric waveguide was used as a reference for the characterization of PC waveguides in order to separate transmission loss. For all measurement, we had the same launched power, propagation length, as well as identical in-coupling and out-coupling mechanisms. The output spot is observed by infrared CCD clearly shown in Figure 2, though coupling loss is large when input lensed fiber and PC waveguide was aligned. Total size of our sample under test is 1∗1 mm^2 shown in Figure 4.

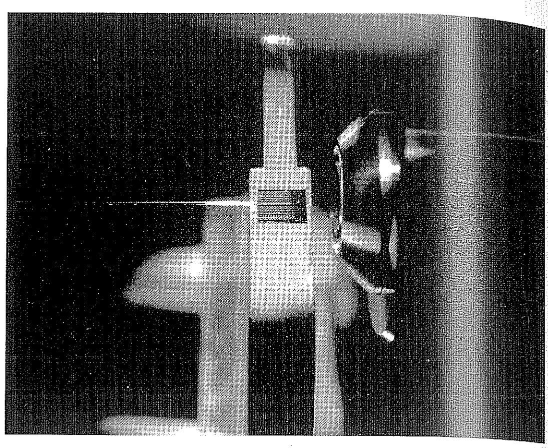

Fig. 4. Input lensed fiber and PC waveguide were aligned. Total size of the sample under test is about 1∗1 mm^2.

We've measured the transmission spectra of WG3, WG5, WG6 and WG7 at TE polarization state simultaneously using Mueller Stokes method.[12] Figure 5 provides us with an indication of high-efficiency light propagation and of flat spectra response among all these PC WGs in the frequency range of guided modes. The edge of these

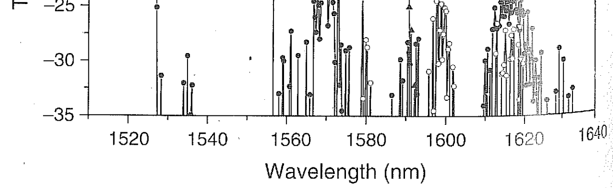

Fig. 5. Transmission spectra measured for WG3, WG4, WG5, WG6 and WG7 with lattice constant 430 nm, 440 nm, 450 nm, 460 nm and 470 nm denoted by different line style. The edge of PC WG modes is shifted about 31 nm with 10 nm increase in lattice constant.

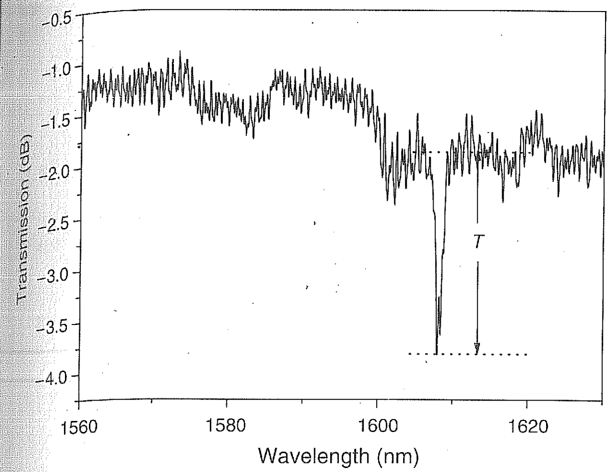

Fig. 6. Transmission spectra measured for coupled structure of photonic crystal waveguide and photonic crystal micro-cavity with lattice constant 470 nm. At wavelength 1608 nm, guided modes of PC waveguide and defect modes of micro-cavity are resonated.

guided bands is shifted about 31 nm with the 10 nm increase of the lattice constant, which is followed the scaling law of photonic bands:[13] two photonic crystals which are similar to each other essentially have the same photonic band structure, that is, the difference between the two band structures is simply the scales of frequency and the wave vector. The uniformity of the wavelength intervals between these guided mode edge indicates that our fabrication accuracy is enough. Comparing with WG3 and WG4, it's seen that WG5, WG6 and WG7 have suffered more loss. This is caused mainly by the roughness of output edge of stripe waveguide. On the contrary, for WG1 and WG2, we didn't observe output spot from the cleaved facet of PC WGs obviously in the wavelength range we measured.

Transmission spectra from PC waveguide in coupled structure of PC waveguide and micro-cavity with lattice constant 470 nm have been obtained in TE polarization state. At wavelength 1608 nm, guided modes of PC waveguide and defect modes of micro-cavity are resonated. Based on coupled mode theory, the relationship between transmission coefficient and Q value in this coupled structure is as follow:[11]

$$T = \left(\frac{Q}{Q_v}\right)^2 \tag{1}$$

$$\frac{1}{Q} = \frac{1}{Q_{\text{plane}}} + \frac{1}{Q_{\text{vertical}}} \tag{2}$$

Combining the data we measured in Figure 6 and Eq. (1), the coupling coefficient between PC waveguide and micro-cavity can be estimated as 64% and Q value of micro-cavity as 1531. Transmission spectra from PC waveguide in coupled structure of PC waveguide and micro-cavity with lattice constant 450 nm, 460 nm indicate that no resonator phenomena exist, so we can conclude that the conditions of resonator are sensitive to the structure parameters.

4. CONCLUSION

We've fabricated a series of air-hole PC WGs and coupled structure of PC waveguide and PC micro-cavity based on silicon-on-insulator photonic crystal slabs structure. By employing Mueller Stokes method, transmission spectra were obtained at TE polarization. We've obtained high-efficiency light propagation and broad flat spectra response of PC waveguides in the frequency range of guided modes and observed a sharp attenuation at the mode edge for most structures. With the increase of lattice constant, the edge of guided modes shifts to long wavelength, which is followed the scaling law of photonic bands. In coupled structure of PC waveguide and micro-cavity, modes resonator are observed in transmission spectra. From experiment results, we can conclude that photonic crystal optical spectra are very sensitive to structure parameters. Design and fabrication of complex photonic crystal devices need paying more attention.

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