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Design, Fabrication, and Measurement of Two-Dimensional Photonic Crystal Slab Waveguides *

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Two-dimensional photonic crystal slab waveguides on SOI wafer are designed and fabricated. Photonic band gap, band gap guided mode, and index guided mode are observed by measuring the transmission spectra. The experimental results are in good agreement with the theoretical ones.

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The photonic crystal (PC)[1] is a promising technology for providing a novel way to guide, control and manipulate the photons. The two-dimensional slab PC is one of the best potential structures because of its compatible fabrication method with the traditional semiconductor wafer process. Many novel devices based on it have been reported.[2−7] A PC waveguide (PC-WG),[8] formed by introducing a line-defect in the slab PC, is the fundamental part of most PC-based devices. In this study, we design and fabricate several different PC-WGs with traditional stripe waveguide for joint.[9] By measuring the transmission spectra, photonic band gap, band gap guided mode, and index guided mode are observed to be in good agreement with the theoretical results.

Figure 1 shows the PC-WG structure. SOI wafer was used and a symmetry SiO_2 clad structure was selected to reduce the radiation loss in the vertical direction. The period and the radius of the PC are a and r, respectively.

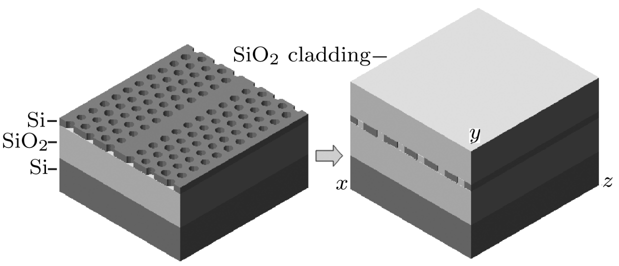

Fig. 1. SOI based photonic crystal slab waveguide with SiO_2 cladding.

We calculate the dispersion curve of TE mode in a triangle lattice PC-WG with a single line of missing holes in the $\Gamma - K$ direction (W1 PC-WG) by two-dimensional effect reflection index-plane wave expansion method, and show the results in Fig. 2. We can see that there are two guided modes in the band gap. One is even mode, its majority electrical field component E_x is even symmetry to the $y-z$ plane, and the other is odd mode with odd symmetry. Since the odd mode cannot be excited easily, we can only consider a single even mode in the band gap here. This even mode extends off the band gap into the upper shadow region, where it becomes radioactive to the PC holes so can only supply a short propagation distance. Although the propagation band width of the band gap guided mode is restricted by the light line, for a short propagation distance, e.g. tens of micrometres, the loss can be ignored even above the light line. Outside the band gap, there are two index guided modes. Both are even fundamental mode. Because of the periodical structure in the propagation direction, these two index guided modes couple and form a small transmission gap, just like a Bragg grating.[4]

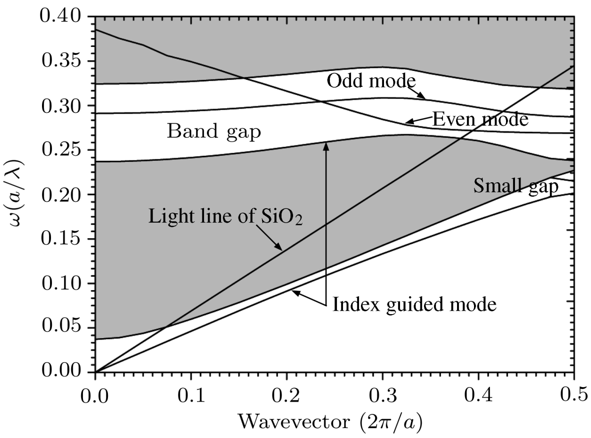

Fig. 2. Typical dispersion curve of W1 PC-WG calculated by 2D plane wave expansion method, where $n_{\rm eff} = 2.78$, $n_{\rm hole} = 1.45$, and $r/a = 0.357$.

We design slab PC without line defect (Fig. 3(a))

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and a line defect PC-WG along $\Gamma - K$ direction (Fig. 3(b)) with proper structure parameters to ensure the band gap guided mode around the wavelength of $1.5\,\mu$m. In order to compare, we also design some stripe waveguides without any PC structures. All the designs are based on three-dimensional plane wave expansion method and FDTD simulation. Size enlargement is considered because hole size is enlarged during fabrication.

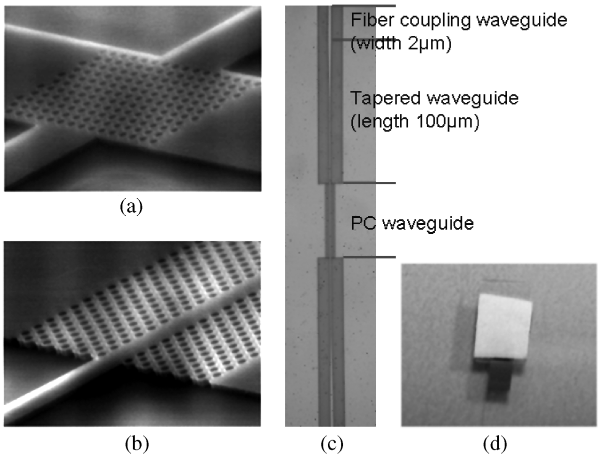

Fig. 3. (a) SEM image of the 2D slab PC. (b) SEM images of the PC-WG. (c) Optical microscope picture of the PC-WG with tapered joint waveguide. (d) Cleaved sample for measurement.

In our previous experiment works, we measured the coupling loss between tapered fibre and stripe waveguide. For a tapered fibre with $1.7\,\mu$m focus diameter, we found that a 2-μm-wide waveguide has the lowest coupling loss of -7 dB per facet, which is enough for measurement. In this study, for slab PC, we use a 2-μm-wide waveguide to couple the light in and out, while for W1 PC-WG, we add a 100-μm-long tapered waveguide to couple light to the narrow line defect (Fig. 3(c)).

The SOI wafer has a 200-nm-thick Si on top and a 3000-nm-thick buried SiO_2. Using ZEP-520A as a resist mask, PC pattern was generated perfectly by EB lithography. Then ICP dry etching was employed to transfer the pattern to the silicon film. After removing the resist mask, a 600-nm-thick SiO_2 cladding layer was deposited on the surface. Finally, we ground the wafer to the thickness about $100\,\mu$m, and cleaved them into about 1-mm-long samples for measurement (Fig. 3(d)). We removed some of the sample's upper SiO_2 cladding layer by HF etching to verify the hole size by a scanning electron microscope (SEM) then recalculated the dispersion curve.

The transmission spectra of these samples were measured. The measurement system was consisted of a tunable laser with tuning range from 1350 nm to 1630 nm, a fibre polarization controller, a precise fibre alignment system with computer control, and an optical power meter. The polarization state was determined by using a long range surface plasma waveguide, which can only guide TM mode.[10] The total inserting loss included the coupling loss of both facets and the propagation loss along the slab PC or W1 PC-WG.

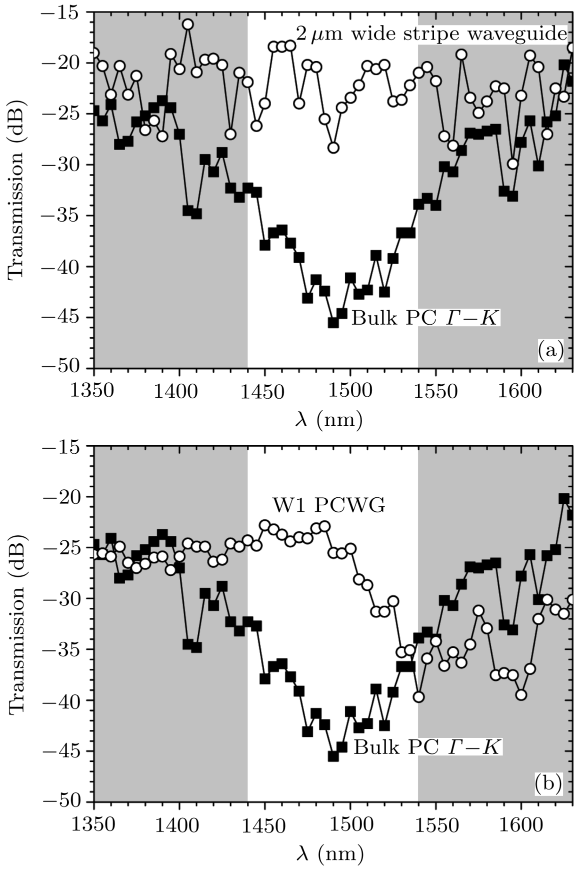

Fig. 4. (a) Transmission spectra through the slab PC compared with the measured one through a stripe waveguide without PC structure. (b) Transmission spectra of W1 PC-WG with length of 60 periods compared with that of the slab PC, where $a = 380$ nm, $r = 90$ nm (the grey areas are the band gap regions).

Figure 4(a) shows the transmission spectra of the slab PC (Fig. 3(a)) with $2\,\mu$m wide joint stripe waveguide (square marks) to let the light input along the $\Gamma - K$ direction, compared with that measured from the same joint waveguide without the slab PC structure (circles). Here, the holes period of the slab PC is 380 nm and the radii is 90 nm. It can be seen that even though there are only 10 periods of holes in the light propagation direction, a deep transmission dip still formed due to the strong index comparison between Si and SiO_2. The blank region between the shadow areas is the photonic band gap calculated using the practical structure parameters measured by SEM. The measured transmission dip is in good agreement with the calculated band gap.

We used the same PC structure ($a = 380\,\mathrm{nm}$, $r = 90\,\mathrm{nm}$) to form a W1 PC-WG, with the length of 60 periods. Its transmission spectra are shown in Fig. 4(b) by circle marks. We can see that compared with the transmission spectra of the slab PC (squares), light can propagate in the band gap region. This corresponds to the line defect mode, namely band gap guided mode. From the dispersion curve shown in Fig. 2, we know that the defect mode is above the light line in most of the wavelength region. However, because of the short distance, the propagation loss is not too large. We compared transmission spectra of W1 PC-WG with different lengths, and found that a 120 periods long PC-WG suffers more loss above the light line than 60 period ones. It can be seen from Fig. 2 that this defect mode extends into the upper guided region. This was confirmed from the experimental results in Fig. 4 (b), where power of the defect mode did not reduce obviously at the short wavelength edge.

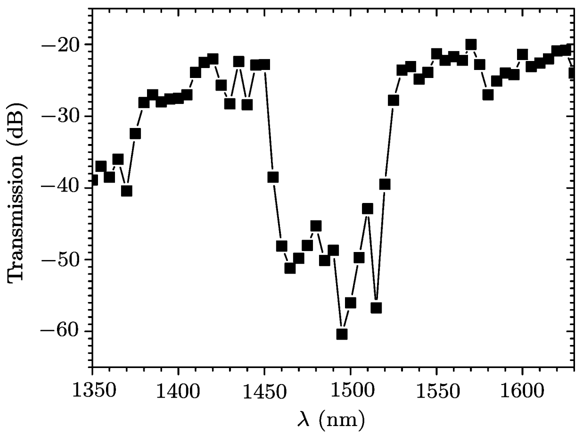

Fig. 5. Measurement result for small gap formed by coupling of the index guided mode, where $a = 320\,\mathrm{nm}$ and $r = 120\,\mathrm{nm}$.

We also studied the index guided mode, for which it was predicted in the dispersion curve (Fig. 2) that a small gap appears in the guided band of the slab PC due to the coupling of the index guided modes. We fabricated the slab PC with different structure parameters of $a = 320\,\mathrm{nm}$ and $r = 90\,\mathrm{nm}$ to let this small gap appear around wavelength of $1.5\,\mu\mathrm{m}$. The measured transmission spectra are shown in Fig. 5. We can find an obvious dip in the transmission spectra, around the predicted wavelength.

There are some ripples in our measured transmission spectra. This phenomenon was also reported in the literature.[8] It can be considered as the F-P oscillation caused by reflection of the sample facet or the interface between the PC-WG and stripe waveguides. Imperfection of the EB lithography, which induces some microcavity- like effects, and instability of the measurement system, can also cause such ripples.

In conclusion, we have designed and fabricated a 2D slab PC and a line defect PC-WG based SOI structure. The transmission spectra were measured and analysed. Photonic band gap around the wavelength of $1.5\,\mu\mathrm{m}$ was obtained from the 2D slab PC. For the line defect PC-WG, the defect mode was observed within the band gap. We also confirmed the existence of the index guided mode and their coupled small gap. All of these experimental results are in good agreement with the theoretical results. Successful fabrication on 2D PC and PC-WG makes it possible to develop new functional and compact devices based PC structure.

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