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A photonic crystal waveguide with silicon on insulator in the near-infrared band*

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A two-dimensional (2D) photonic crystal waveguide in the Γ–K direction with triangular lattice on a silicon-on-insulator (SOI) substrate in the near-infrared band is fabricated by the combination of electron beam lithography and inductively coupled plasma etching. Its transmission characteristics are analysed from the stimulated band diagram by the effective index and the 2D plane wave expansion (PWE) methods. In the experiment, the transmission band edge in a longer wavelength of the photonic crystal waveguide is about 1590 nm, which is in good qualitative agreement with the simulated value. However, there is a disagreement between the experimental and the simulated results when the wavelength ranges from 1607 to 1630 nm, which can be considered as due to the unpolarized source used in the transmission measurement.

Keywords: photonic bandgap, photonic crystal waveguide, SOI
PACC: 4270Q, 4280L, 4225B

1. Introduction

Photonic crystals are periodic dielectric structures that exhibit a photonic bandgap (PBG), the light with a frequency in the PBG is strictly forbidden to propagate in the photonic crystal.[1] Using this property, many applications of photonic crystals are expected to develop.[2–5] Theoretically, a three-dimensional photonic crystal can achieve an omnidirectional PBG. However, it is very difficult to fabricate this kind of photonic crystal by the state-of-art semiconductor technology. Thus, its two-dimensional (2D) counterparts, i.e. photonic crystal slabs (PCSs), have attracted much attention.[6] In such a structure, the light can be confined in the horizontal plane by PBG and in the vertical direction by total internal reflection. If a line defect is introduced into a perfect photonic crystal slab, the light with the frequency in the PBG can propagate along the defect. Therefore, the line defect forms a guided-light channel, namely a photonic crystal waveguide (PCW), in which the light is guided by the guide-wave effect of defect states and the good lateral confinement of the photonic bandgap.[7] The light-controlling ability of such a waveguide is stronger than that of a traditional waveguide by total internal reflection. Therefore, a PCW may be bent randomly with leakage-free guidance of the light,[8] which makes it possible to reduce the volume of integrated optical devices greatly and to realize the on-chip optical circuits.

As an initial material for the PCW, a silicon on insulator (SOI) slab is an attractive choice because it is robust and easily fabricated and compatible with conventional complementary metal–oxide–semiconductor (CMOS) technology, and also provides a feasible platform for the realization of all-silicon optoelectronic integrated circuits.

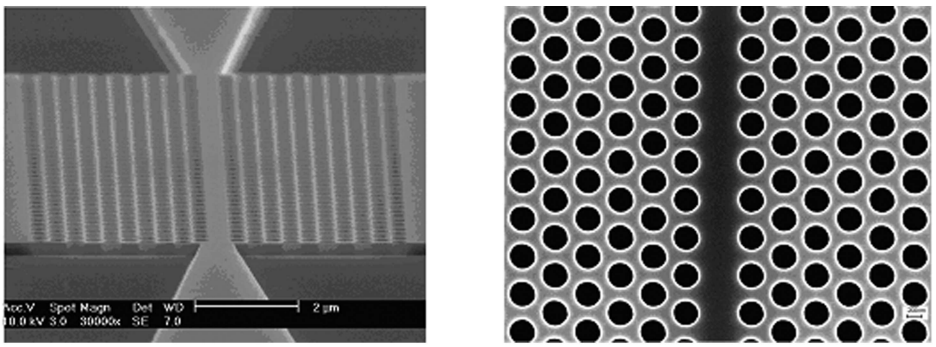
In this paper, a two-dimensional PCW based on SOI in the near-infrared band is fabricated by the combination of electron beam lithography (EBL) and inductively coupled plasma (ICP) etching. Its transmission characteristics are measured and analysed from the stimulated band diagram by the effective index and the two-dimensional plane wave expansion (2D PWE) methods.

2. Fabrication

A SOI wafer with the top silicon waveguide layer of 240 nm and a lower cladding silica layer of 1 μm is

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used to fabricate the PCW. This thick silica cladding layer can provide good optical isolation between the top silicon layer and the substrate. A single-line defect PCW consisting of triangular-type air-hole lattice is fabricated by the combination of EBL and ICP etching through the top silicon. The lattice constant of photonic crystal (i.e. the period of air holes), a, and the radius of air holes, r, are 410 and 127.1 nm, respectively. The waveguide is in the Γ–K direction. Because the waveguide width, defined as the distance between the centres of the two air holes to be adjacent to the PCW, is very narrow, only about 710 nm, the two tapered ridge waveguides are used to connect the PCW for the measurement of transmission characteristics in order to reduce the coupling loss of the input light. They are 9 μm wide at the cleaved edge of the sample and 700 nm wide near the PCW, respectively. Figures 1(a) and 1(b) give the scanning electron microscope (SEM) micrograph of such a fabricated sample used in transmission measurement and the detailed view of the PCW area, respectively. The length of the PCW is 55a.



(a) (b)

Fig.1. (a) SEM micrograph of the fabricated sample used in transmission measurement. (b) Detailed view of the PCW area.

3. Experimental results and discussion

The transmission characteristics of the fabricated sample are measured by an automatic align and coupling system (Newport PM-500) and an Agilent DWDM measurement system. The scanning wavelength range of the tunable laser is from 1510 to 1630 nm. The light from the tunable laser is coupled into the input tapered ridge waveguide via a tapered fibre, transmitted through the single-line defect waveguide, and then coupled into the output tapered ridge waveguide. The output light signal from the output waveguide is collected by another identical fibre and introduced back to the Agilent system to record. The Agilent system records the power of output light and converts it into the transmission loss automatically. The measured transmission spectrum is shown in Fig.2.

From Fig.2, it can be seen that the transmission loss is only 17 dB when the wavelength ranges from 1510 to 1590 nm. As the wavelength becomes longer than 1590 nm, the transmission loss increases abruptly. When the wavelength is 1607 nm, the transmission loss approaches maximum, about 30 dB.

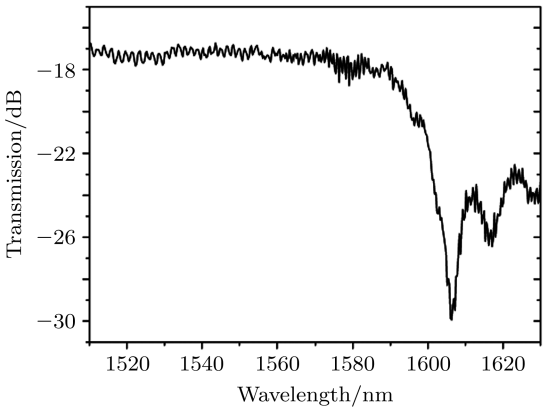


Fig.2. Measured transmission characteristics of the fabricated PCW in the Γ–K direction.

Therefore, it is deduced that the transmission range is from 1510 to 1590 nm within the tunable range of laser and the wavelength 1590 nm should be the transmission band edge in a longer wavelength of the PCW. In order to analyse the experimental result well, the band diagram of the PCW is calculated by the combination of the effective index and the 2D PWE meth-

ods. The effective index of the fundamental mode in the SOI slab without the PCW is calculated to be 2.92 by the effective index method, which is taken as the index of the SOI slab for calculating the band diagram of the PCW by the 2D PWE method. The band diagram of the perfect photonic crystal calculated is shown in Fig.3, where the parameter values used for the calculation are exactly those measured on the fabricated sample by SEM, namely, a and r are 410 nm and 131 nm, respectively.

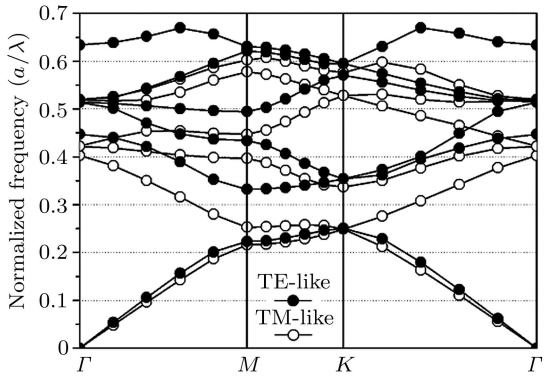


Fig.3. Calculated band diagram of the perfect 2D photonic crystal.

It can be seen that there is a PBG for the TE-like modes, but not for the TM-like modes. Therefore, in the PCW formed by removing a row of air holes in the perfect photonic crystal, the TM-like modes can propagate only by total internal reflection effect, while the TE-like modes can be allowed to propagate by PBG effect. So the design of PBG devices can only be for TE-like modes. Here only the TE-like modes are considered. The calculated band diagram for the TE-like guided modes of such a photonic crystal single-line defect waveguide in the Γ–K direction is shown in Fig.4.

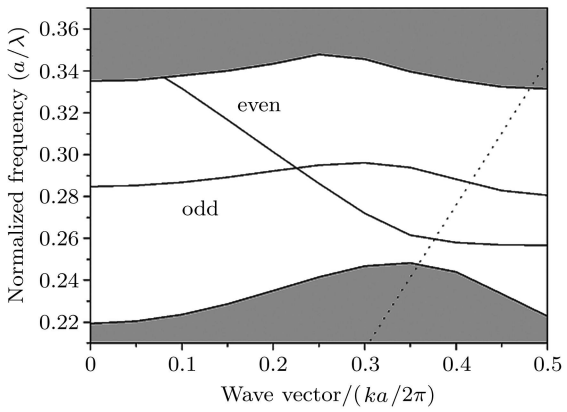


Fig.4. Calculated band diagram of the fabricated 2D photonic crystal single-line defect waveguide.

The two grey areas represent the photonic crystal slab modes areas. The dotted line represents the light line of the oxide cladding, whose slope c/n is determined by the refractive index of the oxide cladding. The region above the light line consists of radiation modes that extend out the slab infinitely. The white area gives the range of the PBG of the perfect photonic crystal, where only the modes that fall below the light line and the slab bands are truly guided in the line defect, decaying exponentially away from the waveguide. It can be observed that there are two defect modes in the PBG, which are labelled the even mode and the odd mode. The former is symmetric in regard to the plane perpendicular to the slab and containing the central line of the waveguide, while the latter is antisymmetric.[9] Because the taper ridge waveguide in the fabricated sample is single-mode, the even mode of the PCW will be preferentially excited. It can be observed that the normalized frequency ranges from 0.2567 to 0.3316 for the even mode, corresponding to the wavelength range from 1236 to 1597 nm. Thus, the wavelength 1597 nm is the longer cut-off wavelength of the even mode, which is in good agreement with the measured value (1590 nm). Notice that the normalized frequency range from 0.2596 to 0.3316 is above the light line, in which the modes should suffer from the radiation loss by coupling with the radiative modes of the cladding. And the normalized frequency range from 0.2567 to 0.2596 is below the light line, in which the modes should have no loss. Therefore, theoretically, the light with the wavelength range from 1236 to 1579 nm should suffer more transmission loss than that from 1579 to 1597 nm. However, it can be seen from the measured result that the global transmission loss above and below the light line are comparable, which suggests that there is a bad coupling from the guided modes below the light line to the radiation modes above the light line. In addition, according to the simulated result as shown in Fig.2, there is a minigap existing between the lower slab modes area and the even mode in the normalized frequency range from 0.2487 to 0.2567, corresponding to the wavelength range from 1597 to 1648 nm, which is due to an anticrossing at the first Brillouin zone boundary between two counterpropagating waves.[10] Hence the transmission loss should slightly fluctuate near that at the wavelength 1597 nm. However, in Fig.2, when the wavelength is longer than 1590 nm, the transmission loss begins to reduce and there are two peaks in the wavelength range from 1607 to 1630 nm. The dis-

agreement between the measured and the simulated results may be due to the unpolarized source used in the transmission measurement. The modes in the tunable laser include the TE-like modes and the TM-like modes. Though no TE-like modes exist in the PCW in the wavelength range from 1607 to 1630 nm in theory, the TM-like modes can transmit through the PCW. Hence the two peaks at the wavelength longer than 1607 nm in the transmission spectrum may originate from the TM-like modes.

4. Conclusions

In summary, we have fabricated a 2D photonic crystal waveguide in the near-infrared band based on an SOI by the combination of EBL and ICP etching. Its transmission characteristics have been measured. The result is analysed from the stimulated band diagram by the effective index and the 2D plane wave expansion methods. In the experiment, the transmission band edge in a longer wavelength of the PCW is about 1590 nm, which is in good agreement with the simulated value. However, there are a disagreement between the experimental and the simulated results when the wavelength range is from 1607 to 1630 nm, which can be attributed to the unpolarized source used in the transmission measurement.

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References

[1] Zhou M, Chen X S, Xu J, Zeng Y, Wu Y R, Lu W, Wang L W and Chen Y 2005 *Acta Phys. Sin.* **54** 411(in Chinese)

[2] Li M Y and Gu P F 2005 *Acta Phys. Sin.* **54** 2358 (in Chinese)

[3] Gu P F, Huang B Q and Zheng Z R 2005 *Acta Phys. Sin.* **54** 3707 (in Chinese)

[4] Zhou M, Chen X S, Wang S W, Zhang J B and Lu W 2006 *Acta Phys. Sin.* **55** 3725 (in Chinese)

[5] Yin J L, Huang X G, Liu S H and Hu S J 2006 *Acta Phys. Sin.* **55** 5268 (in Chinese)

[6] Tian J, Ren C, Feng S, Liu Y Z, Tao H H, Li Z Y, Cheng B Y, Zhang D Z and Jin A Z 2006 *Chin. Phys.* **15** 2471

[7] Han S Z, Tian J, Feng S, Ren C, Li Z Y, Cheng B Y and Zhang D Z 2005 *Acta Phys. Sin.* **54** 5659 (in Chinese)

[8] Mekis A, Chen C J, Kurland I, Fan S H, Villeneuve P R and Joannopoulos J D 1996 *Phys. Rev. Lett.* **77** 3787

[9] Zelsmann M, Picard E, Charvolin T, Hadji E, Heitzmann M, Dal'zotto B, Nier M E, Seassal C, Rojo-Romeo P and Letartre X 2004 *J. Appl. Phys.* **95** 1606

[10] Olivier S, Rattier M, Benisty H, Weisbuch C, Smith C J M, De La Rue R M, Krauss T F, Oesterle U and Houdré R 2001 *Phys. Rev.* B **63** 113311