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A ministop band in a single-defect photonic crystal waveguide based on silicon on insulator*

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This paper reports that a two-dimensional single-defect photonic crystal waveguide in the Γ-K direction with triangular lattice on a silicon-on-insulator substrate is fabricated by the combination of electron beam lithography and inductively coupled plasma etching. A ministop band (MSB) is observed by the measurement of transmission characteristics. It results from the coupling between the two modes with the same symmetry, which is analysed from the stimulated band diagram by the effective index and the two-dimensional plane wave expansion methods. The parameter working on the MSB is the ratio of the radius of air holes to the lattice constant, r/a. It is obtained that the critical r/a value determining the occurrence or disappearance of MSB is 0.36. When r/a is larger than or equal to 0.36, the MSB occurs. However, when r/a is smaller than 0.36, the MSB disappears.

Keywords: photonic bandgap, photonic crystal waveguide, silicon-on-insulator, ministop band
PACC: 4270Q, 4280L, 4225B

1. Introduction

Photonic crystals are artificial materials with periodic dielectric structures, they have photonic bandgap (PBG) similar to electric gap of semiconductors, the light with the frequency in the PBG is strictly forbidden to propagate in the photonic crystal.[1−4] If a line defect is introduced into a perfect photonic crystal, which forms a guided-light channel, the light with the frequency in the PBG can propagate along the defect. Therefore, it is called the 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 PBG. The light-controlling ability of such a waveguide is superior to that of a traditional waveguide by total internal reflection. The light can be guided without losses in a PCW, even through sharp corners, which makes it possible to reduce the volume of integrated optical devices greatly and to realize the on-chip optical circuits. In the past years, various PCWs have been investigated and fabricated.[5−8] Ministop bands (MSBs) existing for the guided modes of PCWs in a high dielectric background and in air have been revealed in theory, and have also been experimentally demonstrated for PCWs in GaAs-based heterostructures.[9−11]

In this paper, a two-dimensional single-defect PCW based on silicon-on-insulator (SOI) is fabricated by the combination of electron beam lithography (EBL) and inductively coupled plasma (ICP) etching. And a MSB is observed by measuring its transmission characteristics. Its origin is 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 240nm and a lower cladding silica layer of 1μm is 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 600nm and 240nm, respectively. The waveguide is in the Γ-K direction.

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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 1μm, 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 9μm wide at the cleaved edge of the sample and 1μm wide near the PCW, respectively. Figure 1 gives the scanning electronic microscope (SEM) micrograph of such a fabricated sample used in the transmission measurement. The length of the PCW is chosen to be 55a.

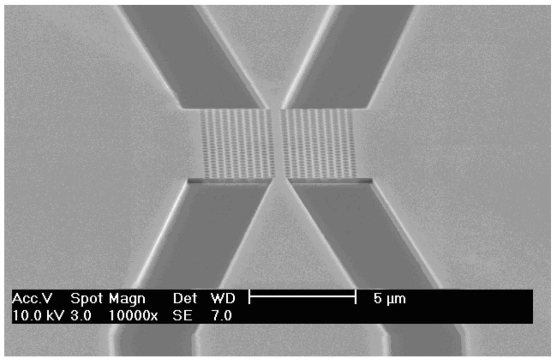


Fig.1. SEM micrograph of the fabricated sample used in the transmission measurement.

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 1510nm to 1630nm. The light from the tunable laser is coupled into the input tapered ridge waveguide via a tapered fibre, transmitted through the 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 transmissivity automatically. The measured transmission spectrum is shown in Fig.2.

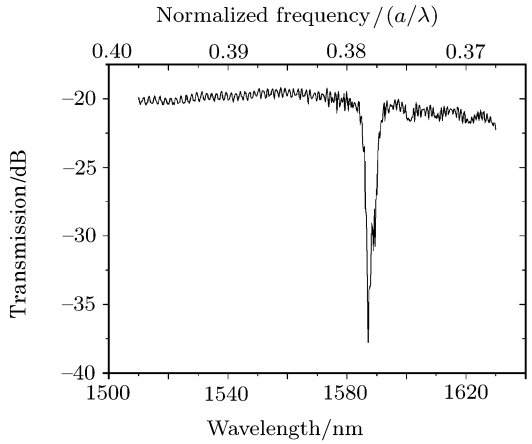


Fig.2. Measured transmission characteristics of the fabricated PCW in the Γ-K direction.

In Fig.2, there is a transmission dip in the wavelength range from 1583nm to 1593nm, corresponding to the normalized frequency range from 0.377 to 0.379, where the transmissivity is minimum, only –37.5dB, and outside the range, the transmissivity approaches maximum, about –20dB. Notice that the transmissivity in the longitudinal coordinate is denoted by dB. It can be seen that the transmissivity is very low even in the pass band, which is attributed to the additional loss in our measurement. It includes not only the transmission loss in the PCW, but also the coupling loss between the input fibres and the input waveguides, the coupling loss between the output fibres and the output waveguides, the transmission loss in the input and output waveguides, the scattering loss due to the rough sidewalls of the input and output waveguides and the etched air holes, and so on.

In order to analyse the origin of the transmission dip, the band diagram of the PCW is calculated by the combination of the effective index and the 2D PWE methods. 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 to calculate the band diagram of the PCW by the 2D PWE method. The band diagram of the single-defect PCW is calculated out as shown in Fig.3.

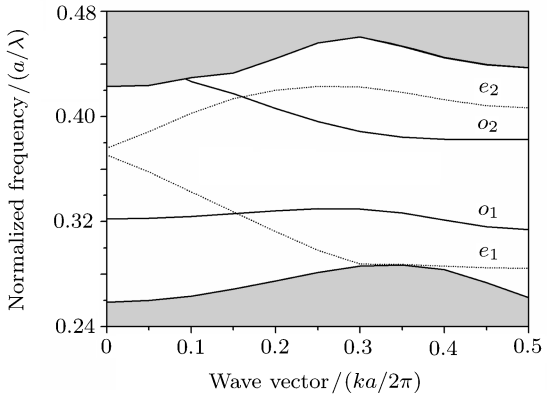


Fig.3. Calculated band diagram of the fabricated single-defect photonic crystal waveguide.

In Fig.3, the grey areas represent the PC slab mode areas, and the white area gives the range of the PBG, the states in which are guide modes confined in the waveguide. It can be observed that there are four guide modes in the PBG, which are labelled the even(dotted lines, e_1 and e_2) modes and the odd modes(solid lines, o_1 and o_2) according to their symmetry with respect to the plane perpendicular to the slab and containing the central line of the waveguide. The former are symmetric in regard to the above-mentioned plane, while the latter are antisymmetric.[12] There is a coupling between e_1 and e_2 modes due to their same symmetry, which results in an anticrossing at the first Brillouin zone boundary in the band diagram. Thus a MSB occurs, its normalized frequency range from 0.372 to 0.376. In the same way, o_1 and o_2 modes also have the same symmetry, their coupling will open a MSB in the normalized frequency range from 0.329 to 0.387. However, the even modes(e_1 and e_2) and the odd modes (o_1 and o_2) cannot couple due to their different symmetry. Therefore, their crossings have no effect on their dispersion curves(for instance, e_1 and o_1 at $a/\lambda = 0.326$, e_2 and o_2 at a/λ=0.415).[13] By comparing the experimental and the simulated results, the dip in the transmission spectrum can be considered to be the MSB between e_1 and e_2 modes at the Γ point， related to the periodical corrugation of the waveguide.[14]

However, in another PCW with the lattice constant, a, 410nm and the radius of air holes, r, 131nm, the MSB can not be observed.[15] By analysis, it is deduced that the structure parameter working on the MSB is the ratio of the radius of air holes to the lattice constant, r/a, and when r/a is very small, the MSB does not exist, but when r/a is very large, the MSB occurs. That is to say, there should be a critical r/a value determining the occurrence or disappearance of MSB, which is calculated to be 0.36. When r/a is smaller than 0.36, for example, r/a is equal to 0.35, the band diagram of the PCW is calculated out as shown in Fig.4(a). It can be seen that only e_1 mode exists and e_2 mode does not exist， and the MSB does not occur. However, when r/a is larger than or equal to 0.36, for example, r/a is equal to 0.36, the band diagram of the PCW is calculated out as shown in Fig.4(b). It can be seen that the modes in the top photonic crystal slab mode areas begin to be pulled down to the PBG and become e_2 mode, the MSB occurs due to the coupling between e_1 mode and e_2 mode. According to this critical condition, the structure parameters of PCW can be designed to utilize or eliminate the MSB.

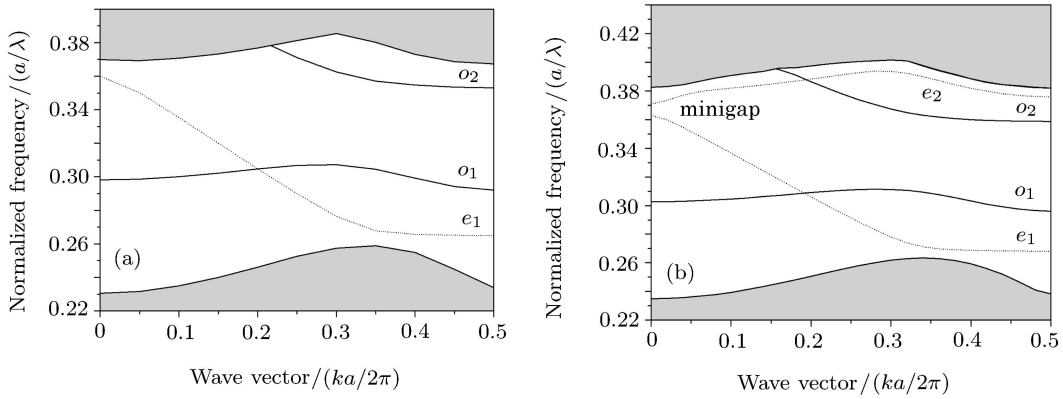


Fig.4. Calculated band diagram of the single-defect photonic crystal waveguide (a) r/a=0.35, (b) r/a=0.36.

In conclusion, we have fabricated a 2D PCW based on a SOI by the combination of EBL and ICP etching. Its transmission characteristics have been measured and a MSB has been observed. Its origin is analysed from the stimulated band diagram by the effective index and the two-dimensional plane wave expansion (2D PWE) methods. It is obtained that the MSB results from the coupling between two modes with the same symmetry. And the parameter working on the MSB is the ratio of the radius of air holes to the lattice constant, r/a. There is a critical r/a value determining the occurrence or disappearance of MSB, which is calculated to be 0.36. According to this critical condition, the structure parameters of PCW can be designed to utilize or eliminate the MSB.

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