Vol 15 No 11, November 2006
1009-1963/2006/15(11)/2471-05

Chinese Physics

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Rapid Communication

Optical properties of the direct-coupled Y-branch filters by using photonic crystal slabs*

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(Received 28 March 2006; revised manuscript received 20 July 2006)

We fabricated a new type of two-dimensional photonic crystal slab filter. The resonant cavities were directly put into the waveguide arms. The optical transmissions of the filters were measured and the results show that the optimized two-channel filters give good intensity distribution at the output ports of the waveguide. A minimum wavelength spacing of 5 nm of the filter outputs is realized by accurately controlling the size of the resonant cavities.

Keywords: photonic crystal filter, micro-cavity, Y-branch splitter waveguide
PACC: 4225B, 4270Q, 4265K

While several initial applications of planar photonic crystals (PCs)[1−3] have been realized as high-Q resonator,[4,5] waveguide,[6,7] channel drop filter[8−10] and Y splitter,[11,12] etc., one of the most attractive devices based on PCs is a wavelength filter, which provides a possibility of dense device integration in optical circuits. Several coupling techniques have been reported for the construction of the PCs optical filters. Shoulder-coupling structure, butt-coupling structure and side-coupling structure were proposed by Kim *et al.*[13] Noda's group has realized in-plane channel drop filters which were composed of two waveguides and an optical resonator.[8] In this paper, we introduce a kind of direct-coupled Y-branch splitter filters, where the microcavities are directly put into the straight waveguides of the Y-branch splitter. In this structure, the coupling distance between the waveguide and the resonator need not be considered. Theoretically, this kind of filter can be realized with the transmission efficiency of 100% without reflection by properly designing the waveguide branches.[14] We optimize the efficiency of the Y-branch splitter by adding small air holes at the centre of the junction and the pass way. Finally, we accurately control the size of the microcavities to realize a filter with two outputs, which have a small wavelength spacing of $\Delta\lambda = 5$ nm.

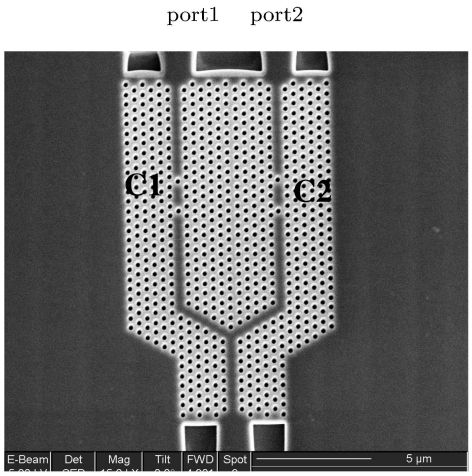
The filters used in this work were fabricated from a silicon-on-insulator (SOI) wafer. The air holes were patterned in the 220 nm thick silicon layer using focused ion beam (FIB) technology.[15,16] An additional silicon dioxide layer with a thickness of 240 nm was deposited on the silicon film by chemical vapour deposition in order to protect the top silicon film from ion beam etching. Finally, the suspended membrane structures was created by removing the 375 nm thick underlying silicon dioxide layer and the coated silicon dioxide layer using a hydrofluoric acid wet etch. The lattice constant of the PC was $a = 430$ nm, and the radius of the air hole was $r = 120$ nm.

The scanning electron micrograph of the filter with two channels is shown in Fig.1(a). This 2D PC slab filter consists of a Y-junction of two branches, which is composed of several segmented waveguides and two resonant cavities (point defects). At the end of the inlet, the waveguide is split into two waveguides, which are linked by a resonant cavity for each. The resonant cavities C1 and C2 are made of two missing air holes, where the cavity edge of C2 is shifted

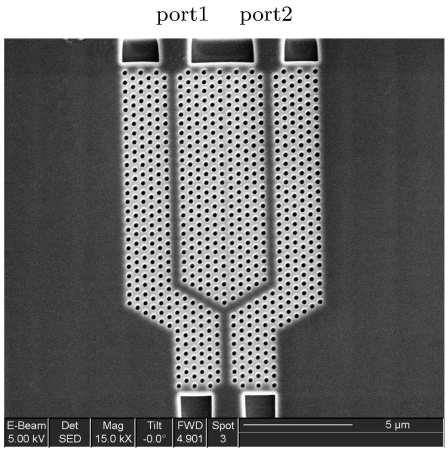
*Project supported by the National Key Basic Research and Development Programme of China (Grant No 2001CB6104), the National Center for Nanoscience and Technology, China (Grant No 2003CB7169) and the National Natural Science Foundation of China (Grant No 10474036).

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outward slightly by $0.05a$ from the regular positions, symmetrically located at each side of the inlet waveguide. It has been found that the different cavity size induces different resonant wavelength. Therefore, at the two outlets of the filter, we can obtain two outputs with different wavelengths.



(a)



(b)

Fig.1. SEM images: (a) Top view of the sample with different defect cavities C1 and C2, (b) A straightforward Y-splitter.

The resonant wavelengths of the cavities calculated by 2D finite difference time domain (FDTD) method are shown in Fig.2, where the dashed and dotted lines denote the transmission spectra of port1 and port2, respectively. The quality factors of C1 and C2 are 692 and 877, respectively. We also calculated the transmission spectra of the straightforward Y-splitter for the port1 and port2. They are coincident and are shown by the transmission spectrum drawn in solid line in Fig.2. It is found that at the wavelengths of the resonant modes the transmittance can be as high as that of corresponding straightforward Y-branch waveguide.

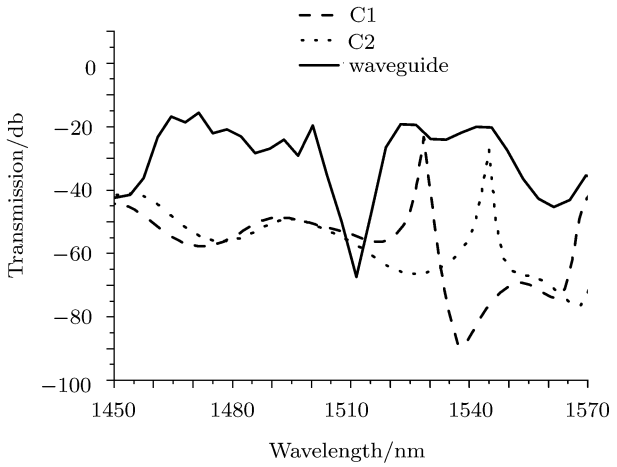


Fig.2. Simulated transmission spectra at the outlets of the filter for waveguide with defect cavities and straightforward Y-splitter waveguide.

We used a fibre-to-fibre system to couple the light going into and out of the PC filters and measure the optical characteristics of the device in the near-infrared region. The light propagated along the waveguide and was observed at the end of the output waveguide. An infrared camera was used to monitor the pass way of the guided light. The optical properties of the filters were detected using an infrared camera. A monochromatic light beam enters the device from the port3 and the outputs from the port1 and port2, which are monitored through the camera (see Fig.3). Figure 3(a) and 3(b) show the near-field images of the output light at port1 and port2 in the case that the input light is in resonance with the C1 and C2, respectively. When the wavelength is set at 1523 nm, the resonant light spot can only be observed at port1 (Fig.3(a)). When the wavelength is set at 1543 nm, the resonant light spot can only be observed at port2 (Fig.3(b)).

The resonant lights output from port1 and port2 were measured by changing the wavelength of laser source. Figure 4(a) shows the measured transmission spectra, where the circle- and triangle-symbolled lines are obtained from port1 and port2, respectively. It is clearly seen that there is a single sharp resonant peak at port1 or port2, corresponding to the resonant wavelength of 1523 nm or 1543 nm, respectively, which indicates that the two-channel filters based on direct coupling have been successfully achieved. The full widths at half maximum of the peaks are 3 nm and 4 nm, which correspond to the Q factor of 583 and 385, respectively.

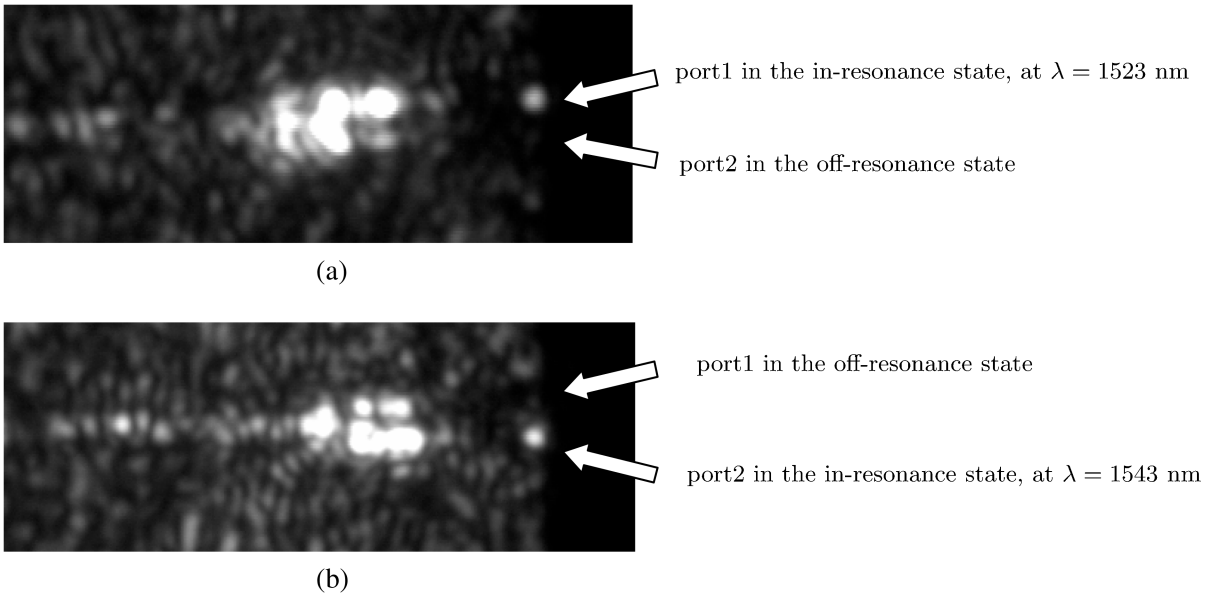


Fig.3. Near-field images when the input light was tuned at wavelengths of 1524 nm (a) and 1543 nm (b), respectively.

As a comparison, the pass-band spectra of the Y-branch waveguide were measured, as shown in Fig.4(b). The circle- and triangle-symbolled lines are from outlet1 and outlet2, respectively. The intensity variation between outlet1 and outlet2 is about 11.7%, which may result from the uncertainty of hole diameter and the lattice constant during the fabrication. The estimated transmittance of C1 and C2 are 52.6% and 30%, respectively.

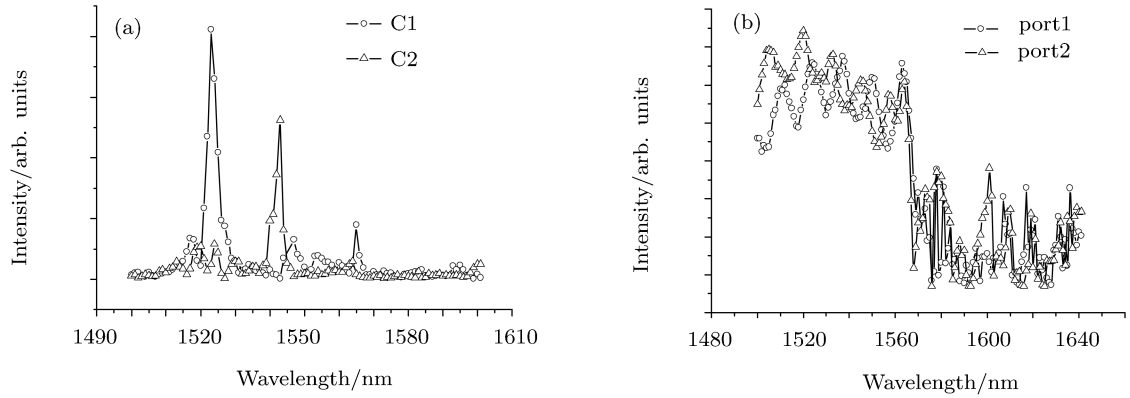


Fig.4. The measured transmission spectra at the outlet from (a) the resonant filter and (b) the straightforward splitter, circles and triangles denote the spectra from port1 and port2, respectively.

The most straightforward Y-splitter design consists of three single-line defect waveguides joined together at 120°. Both the Y junction and the 60° bend represent severe discontinuities in the PC waveguides, which lead to strong reflection and narrow-bandwidth. The first part we considered is the Y-junction, as shown in Fig.5(a), a small hole is placed at the centre of the junction so as to perturb the incoming mode as gently as possible based on the concept by Boscolo *et al.*[17] The second part we considered is the 60° bend waveguide. The bend geometry has been modified by displacing one hole. One important difference between the straightforward Y-splitter and the optimized Y-splitter can be clearly seen that there is a high transmission region 1510–1570 nm of the optimized structure when comparing their transmission spectra

in Fig.4(b) and Fig.6(a). When viewed with the infrared camera, the optimized structure output modes are clearer than that of the straight Y splitter. The optimized Y-splitter filter structure is shown in Fig.5(b). The resonant cavities are symmetrically arrayed at the central line of the inlet waveguide, where the cavities are marked by C3 and C4, respectively. The two air holes at the cavity edges are shifted outward slightly, namely ls3= $0.12a$ and ls4= $0.1a$, from the regular positions, respectively. The transmission spectra at the two outlets are measured and shown in Fig.6(b). For each channel, there is only one wavelength output and the output densities are almost equal. The quality factors of C3 and C4 are about 783 and 850, respectively. Obviously, there is a small difference between the resonant wavelengths of the outputs of the two outlets and the wavelength spacing is $\Delta\lambda = 5$ nm. The cavity size variation of $0.02a$ is the reason of the resonant wavelength shifts.

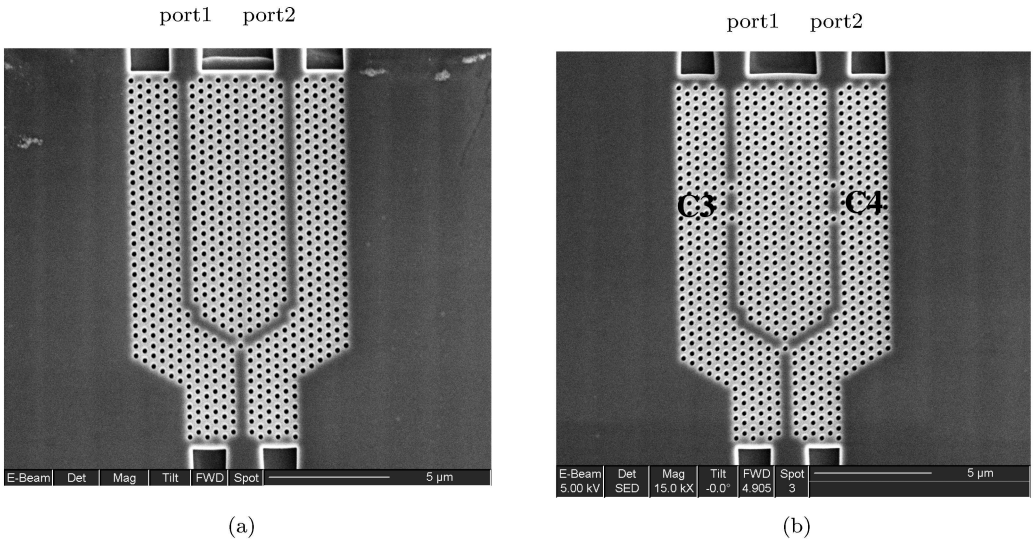


Fig.5. SEM images: (a) Top view of an optimized straightforward Y-splitter, (b) an optimized structure with different defect cavities C3 and C4.

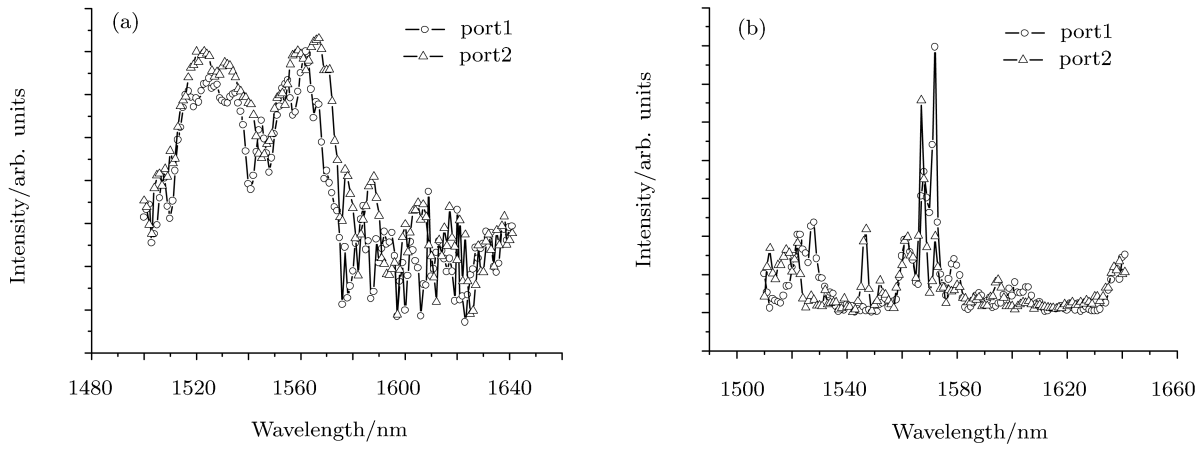


Fig.6. The measured transmission spectra (a) at the outlet from the optimized straightforward splitter, circles and triangles denote the spectra from port1 and port2, (b) at the outlet from the optimized resonant filter, circles and triangles denote the spectra from port1 and port2, the average wavelength spacing between neighbouring output wavelengths is $\Delta\lambda = 5$ nm.

In summary, we have investigated experimentally and theoretically the two-channel filters that were realized by putting resonant cavities directly into the waveguide arms in the 2D PC slab. Different cavity sizes with shifted air holes had been adopted to achieve different wavelength selections. We also fabricated a filter with ultra-short wavelength spacing of 5 nm from two channels. The resonant operation in the near-infrared region demonstrated it can be used in the optical communication systems. It is valuable for introducing the PC filters to the all-optical integrated circuits.

Acknowledgment

The authors gratefully acknowledge the support from Supercomputer Center (CNIC, CNS).

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