Investigation of a channel-add/drop-filtering device using acceptor-type point defects in a two-dimensional photonic-crystal slab

Takashi Asano,[a)] Bong-Shik Song, Yoshinori Tanaka, and Susumu Noda[b)]
Department of Electronic Science & Engineering, Kyoto University, Core Research for Evolutional Science and Technology (CREST) by Japan Science and Technology Corporation (JST), Kyoto, 606-8501 Japan

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A channel-drop-filtering device using point and line defects in a two-dimensional photonic-crystal slab is investigated. The efficiency to drop light from a line-defect waveguide to the free space via a point-defect cavity is found to be more than 45%, which is very close to the theoretical maximum of the device. The reverse function of the device (channel-add-filtering) is also demonstrated, where photons incident on a point defect from free space are resonantly trapped and transferred to a line-defect waveguide nearby. The spectrum and polarization characteristic of the add-filtering completely agree with those of the drop-filtering. The results indicate that two-dimensional photonic slabs are very promising for realizing ultrasmall optical functional devices. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1592890]

A two-dimensional (2D) photonic-crystal (PC) slab[1–5] has attracted much attention as one of the structures to realize a gap in the photonic mode spectrum with a relatively easy fabrication process. Photons in the structures are controlled in the in-plane direction by the effect of 2D PC and are confined in the vertical direction by the effect of refractive index contrast. It is expected that ultrasmall optical devices, such as lossless waveguides[2–4] or single defect cavity lasers[5] can be developed by using 2D-PC slabs and artificial defects introduced within them.

We previously reported a phenomenon in 2D-PC slabs,[1] where photons propagating in the line defect waveguide are trapped by the point defect, which emit them to free space [Fig. 1(a)]. Based on the phenomenon, we fabricated surface-emitting channel-drop filtering devices operating at optical communication wavelengths,[1] and also showed that the devices have a wide wavelength tunability[6,7] and a certain level of drop efficiency.[7] The polarization properties of the dropped light were also investigated, and the controllability of the polarization was investigated.[8] The possibility of the reverse operation (channel-add filtering), where photons irradiated on the point defect are trapped and transferred to the waveguide [Fig. 1(b)], were also mentioned.[1]

However, there are some important issues which should be investigated before the practical applications. At first, the investigations on the drop efficiency were not quantitative but rather qualitative. Next, the polarization properties were investigated only for elliptically deformed point defects (which contributed to the difficulties in the fabrication process), and those of circular point defects have not been experimentally investigated. Last, the reverse operation have not been actually demonstrated. So far, structural fluctuations of the samples have prevented precise investigation of the devices; however, we have recently succeeded in fabricating samples with very small structural fluctuation. In this letter, we investigate the important device characteristics mentioned earlier by using the new sample.

The sample investigated was an air-bridge-type 0.25-μm-thick Si slab with triangular lattice patterns of air holes. Electron-beam lithography and induction coupling plasma reactive ion etching techniques were utilized for the fabrication. The lattice constant a of the PC and the radii of air holes were designed to be 0.42 μm and $0.29a$, respectively. A line defect waveguide with filled an air-hole row (along Γ–J direction) and an acceptor-type point defect with an enlarged air hole of circular shape (radius $0.53a$) were introduced. The distance between them was set at three air-hole rows, at which distance the theoretical drop efficiency becomes maximum. The fluctuation of the air-hole radius in the fabricated samples was very small as shown in Fig. 1(c).

At first, we quantitatively investigated the drop efficiency. Light was incident to the right waveguide facet, and the intensities of the light emitted from the left facet (transmittance spectrum) and that emitted from the point defect (channel-drop spectrum) were measured and plotted in Figs. 2(a) and 2(b), respectively. The former and the latter show negative and positive peaks at 1550 nm, respectively, which clearly indicates that the light propagating in the waveguide is resonantly dropped via the point-defect mode. The oscillation patterns observed in the spectra are Fabry–Perot inter-

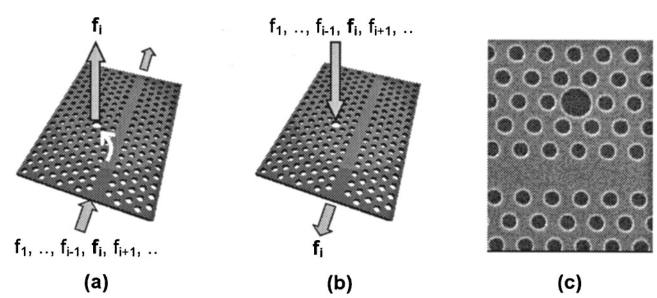

FIG. 1. (a) Schematic of a surface-emitting channel-drop filter based on defects in a 2D-PC slab. (b) Schematic of a surface-inputting channel-add filter based on the same structure. (c) Scanning electron microscope image of the investigated device structure.

[a)]Electronic mail: tasano@kuee.kyoto-u.ac.jp
[b)]Electronic mail: snoda@kuee.kyoto-u.ac.jp

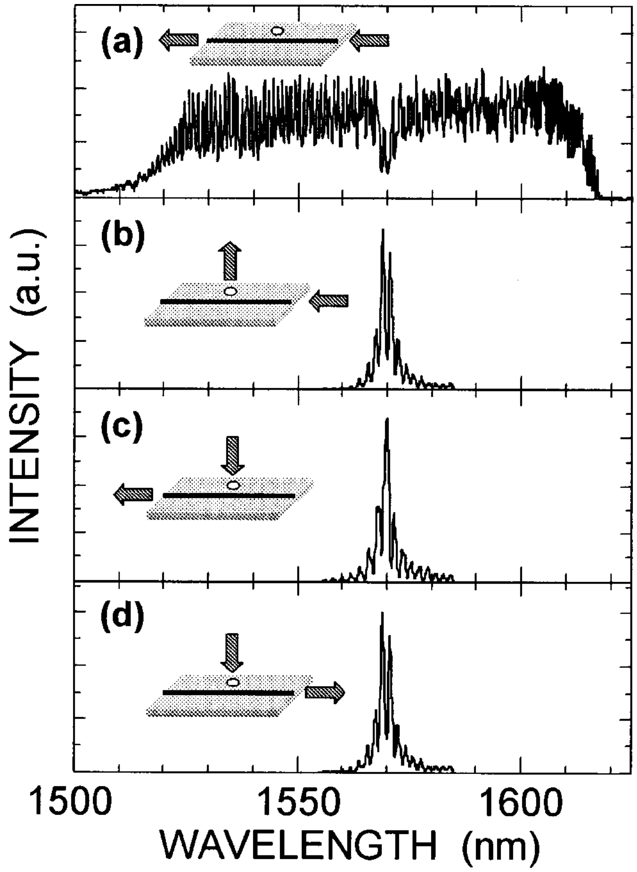

FIG. 2. The measured spectra of transmittance (a), drop-filtering (b), add-filtering (c), and add-filtering (opposite output facet) (d) of the sample. The insets are schematic drawings showing the input and output ports used in the measurements.

ference due to the reflection at the two waveguide facets and also at the point defect itself.

It is difficult to estimate the drop efficiency directly from the dropped light power since the light coupling efficiency at the input waveguide facet is unknown. In contrast, the transmittance at the resonant drop wavelength can be easily evaluated since the transmission at nonresonant wavelengths can be used as a reference. The transmittance is evaluated to be about 20%~30% from Fig. 2(a). We substituted this value to the theoretical relationship between the transmittance and drop, which was reported in the Ref. 6. As a result, we found that the drop efficiency of this sample is at least more than 45%, which is considerably large since the theoretical maximum for the current structure is 50%.[6,7] (The drop efficiency is considered to be improved up to 100% by utilizing cascaded defects.)[9]

Next, we made a reverse experiment to demonstrate the channel-add-filtering function. In this case, light was focused on the point defect directly from free space, and the left waveguide facet was observed [inset of Fig. 2(c)]. Light emission from the waveguide facet was clearly observed when the irradiation position was exactly fitted to the point defect. The facet emission intensity as a function of the irradiated light wavelength was measured and plotted in Fig. 2(c), which exhibits a clear resonant peak at 1550 nm. The agreement between Figs. 2(b) and 2(c) clearly indicates that the light can be dropped from and also added to a line-defect waveguide through the same resonant mode of the point defect. In precise view, the interference pattern overlaps with the envelopes are different between the add and drop spectra. We considered that it is due to the deference in the light path of the two measurements [see insets of Figs. 2(b) and 2(c)]. To confirm this, we measured the add spectrum by measuring the emission from the right facet [Fig. 2(d)]. It is clearly seen that the add spectrum is identical to the drop spectrum, when the exact reverse light path is utilized.

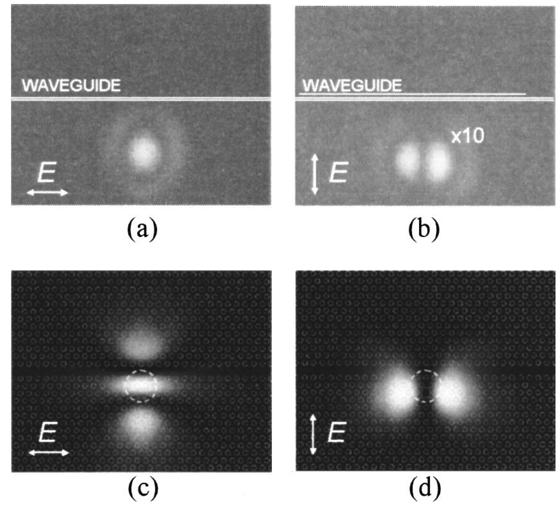

FIG. 3. Observed polarization selected images of the radiation from the point defect for the electric field parallel (a) and vertical (b) to the waveguide. Calculated polarization-selected radiation patterns for the electric field parallel (c) and vertical (d) to the waveguide. Dotted circles in (c) and (d) approximately represent the NA of the objective lens (0.4) used for the measurements.

The add efficiency is investigated by considering the following two factors, (A) internal coupling efficiency between the point defect and waveguide, and (B) external coupling efficiency between the free space and the point defect. The former (A) is the ratio of energy distributed to the waveguide from the point defect, and is estimated to be about 50% (considering the sum of the energies which propagate to both directions). It is because the experimentally obtained drop efficiency of ~50% means that the coupling between the point defect and waveguide is equal to that between the point defect and free space.[6] The latter (B) is determined by the overlap between the electromagnetic field pattern of the incident light beam and that of the light radiated from the point defect because light propagation path is reversible. Since the light beam is incident from only one side of the slab and its solid angle is narrower than the radiation pattern of the defect [see Figs. 3(c) and 3(d)], the external coupling efficiency is estimated to be about ~4%. Therefore, the efficiency of the add operation is considered to be smaller than that of the drop operation at present. The coupling between the point defect and the incident light beam would be improved by employing point defects that can emit light to only one side of the slab[8] with a narrow radiation angle.[10] (This argument can also be applied to the drop operation to improve the collection efficiency of the light dropped from the point defect.)

We also investigated the polarization characteristics of the add and drop operations in the sample. At first, the polarization-selected images of the dropped light were measured for the polarization (electric field) directions parallel

[Fig. 3(a)] and perpendicular [Fig. 3(b)] to the waveguide. A single strong spot and two very weak spots can be seen in Figs. 3(a) and 3(b), respectively, which indicates that the dropped light is almost linearly polarized and that the polarization direction is parallel to the waveguide. We also calculated the radiation pattern from the point defect of the device by using a three-dimensional finite domain time derivative method.[8,10] Figures 3(c) and 3(d) show the polarization-selected radiation patterns at the observation plane, which is distant from the slab surface by $4a$. The experimental and the theoretical results agree well each other when we consider the fact that the observable radiation angle is restricted by the numerical aperture of the lens (N.A.=0.4) utilized in the experiments. It may be strange that linearly polarized light is observed for the circularly symmetric defect, but the reduction of the symmetry due to the existence of the waveguide accounts for the appearance of the linear polarization. It is interesting that a line defect distant from a point defect can have considerable effect on the emitted light. (Polarization control by changing the shape of the defect itself has been already reported by several groups, including us.)[8,10–12] For the add operation, we measured the edge emission intensity by changing the polarization direction of the light irradiated to the point defect. The edge emission became maximum (minimum) when the polarization direction was parallel (perpendicular) to the waveguide. The polarization characteristics of the add operation were shown to be identical to those of the drop experiments.

In summary, the channel-drop device with a circular acceptor-type point defect has been precisely investigated. The light dropping efficiency has been shown to be more than 45% by the quantitative experiment. Also, channel-add-filtering operation of the device has been demonstrated experimentally. Polarizations of the light emission from and injection to the circular point defect have been shown to be linearly polarized, contrary to expectation based on the symmetry of the point defect. Although the acceptor-type defect investigated here has relatively small Q factor of ~ 500, which is insufficient for the actual applications, it is considered that the Q factor can be increased by tailoring the defect geometry.[10,13] We believe that the results are very encouraging for the application of the 2D PCs to very compact components aimed for the optical communication systems.

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