Investigation of high-\(Q\) channel drop filters using donor-type defects in two-dimensional photonic crystal slabs

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This letter describes experimental investigations of surface-emitting channel drop filters using donor-type point defect cavities and line-defect waveguides in two-dimensional photonic crystal slabs. By using donor-type defect cavities with three and four linearly aligned missing air holes, filter quality factors of around 2600 and 6400, respectively, are achieved experimentally, compared to the quality factor of 400 of previous acceptor-type defect cavities. Radiation patterns and polarization properties of light emitted from the defects are also discussed. The results indicate that these donor-type defects are very useful for the development of ultrasmall high-performance channel add/drop filters. © 2003 American Institute of Physics. [DOI: 10.1063/1.1604179]

A two-dimensional (2D) photonic crystal (PC) slab has attracted much attention as a relatively easy material in which to achieve a gap in the photonic mode spectrum. We have previously reported a very interesting phenomenon in which photons propagating along a line defect (waveguide) are trapped and emitted to free space by a single-point defect created in a 2D PC slab when the photon frequency matches the defect frequency [see Fig. 1(a)]. This phenomenon can be applied to ultrasmall surface-emitting channel add/drop filters for wavelength division multiplexed (WDM) optical communication systems.

Up until now, our experiments have mainly focused on devices which utilize acceptor-type defects (enlarged air–hole rods) in 2D PC slabs with a triangular lattice of air holes. Although various device performance properties, such as wide tunability of dropped wavelength and high drop efficiency have been demonstrated, the quality (\(Q\)) factors of these devices, which determine the resolution of filtering operation, are at most 400. For practical applications such as dense WDM (D-WDM) systems, the \(Q\) factors of these devices need be increased much further. In our last work, we theoretically investigated various kinds of donor-type defects apart from acceptor-type defects in an attempt to realize high-\(Q\) cavities, paying close attention to other characteristics required in channel add/drop filters (such as spatial patterns and polarizations of the vertically emitted light, and free spectral range). From these theoretical investigations, a donor-type defect, composed of three linearly aligned missing air holes, was found to be very promising.

In this work, a channel add/drop device is fabricated which utilizes a donor-type defect composed of three linearly aligned missing air holes (defined as L3), and the important properties of this device, such as \(Q\) factors and radiation patterns, are investigated experimentally. A device utilizing a defect composed of four linearly aligned missing air holes (defined as L4) is also investigated, with an expectation of further improvements in \(Q\) factor.

The sample investigated was an air–bridge triangular lattice PC slab fabricated from 0.25-\(\mu\)m-thick Si. The lattice constant (\(a\)) of the PC and radii of the air holes were 0.42 \(\mu\)m and 0.12 \(\mu\)m, respectively. In this structure, the photonic band gap (PBG) is open only for transverse-electric (TE) mode photons in a frequency range of 0.256–0.320 \((c/a)\), where \(c\) is the velocity of light in a vacuum. (Since the PBG is not open for transverse-magnetic mode photons, defect properties were investigated only about TE-like polarization in this work.) A line-defect waveguide and donor-type defect (L3 or L4) were introduced by not making air holes in a row along the same \(\Gamma\)–\(J\) direction. The distance between the line and point defects was chosen so as to maximize drop efficiency. Based on a previous theoretical...
plasma etching technique. The SiO₂ layer under the pat-
then transferred to the Si layer using the inductively coupled
strate by electron-beam lithography. Resist patterns were
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effects devices. The difference between theoretical and experi-
mental values is thought to be due to fluctuations in the
fabricated structures and/or insufficient convergence of the
calculation, 7 a spacing of four air–hole rows was chosen for
L3. In the case of L4, we found that the maximization of the
drop efficiency requires more complex methods, which are
described later.

The devices were fabricated by first drawing design pat-
tterns on the resist mask coating of a silicon-on-insulator sub-
strate by electron-beam lithography. Resist patterns were
then transferred to the Si layer using the inductively coupled
plasma etching technique. The SiO₂ layer under the pat-
terned Si layer was selectively etched off to form the air–
bridge structure. Figures 1(b) to 1(e) show scanning electron
microscope images of the fabricated devices from which
geometrical distortions in the structures can be seen to be
very small. Deviations between the fabricated and designed
structures were of the order of a few nanometers.

First, a channel-drop experiment was carried out on the
L3 defect device in which photons were injected from the
waveguide facet and the radiation emitted vertically from the
point defect was observed. The channel-drop spectrum is
plotted in Fig. 2(b). As can be seen in Fig. 2(b), the full
width at half maximum (FWHM) of the resonant peak is as
narrow as 0.6 nm, corresponding to a Q value of about 2600,
very close to the theoretical prediction (2900) described in a
previous work. 7 For comparison, the channel-drop spectrum
of an acceptor-type defect-based device previously reported 1
is also plotted in Fig. 2(a). In this case, the Q value and
FWHM are around 400 and 4.1 nm, respectively. From Figs.
2(a) and 2(b), it is clear that the Q factor of the L3 defect is
six to seven times greater than that of the acceptor-type de-
fect. These experimental results indicate that drastic im-
provements in the Q factor of the filtering device have been
achieved as theoretically predicted in our last paper. Here,
we should note that the measured Q factor of the device is
not the intrinsic Q factor of the cavity itself. The intrinsic Q
factor is determined by the coupling loss to the free space
mode only. On the other hand, the measured Q factor is also
affected by the coupling loss to the waveguide mode. There-
fore, the intrinsic Q factor should be larger than the mea-
sured Q, which we actually confirmed on an experimental
basis. Further details will be presented in a separate publica-
tion due to limitations in space.

In the expectation of further improvements in Q factor,
devices containing L4 defects were first theoretically inves-
tigated using a three-dimensional finite-difference time-
domain method. 10,11 The Q factor of the L4 defect was found
to increase by a factor of 3 over the L3 defect, with a slightly
lower fundamental mode resonant frequency. At this lower
frequency, the group velocity in the line-defect waveguide (a
filled row of air holes) is too low to be applied to practical
devices. The width of the waveguide was therefore increased
a little (0.11 a) to adjust the high group velocity region 12 to
match the fundamental mode of the L4 defect. In addition,
the distance between the point and line defects (d) was re-
adjusted, since the coupling between the defects depends on
changes in the lateral mode distribution of the line-defect
waveguide. Drop efficiency was found to become maximal
(48%) for a separation d of three rows, where the total Q
factor was calculated to be around 10 000. Based on this
theoretical analysis, the device was fabricated and dropping
spectrum measured, as shown in Fig. 2(c). As can be seen,
the Q factor of the dropping peak is around 6400. This total
Q factor is approximately 16 times greater than acceptor-
type defect devices, and about 2.5 times higher than L3 de-
fect devices. The difference between theoretical and experi-
mental values is thought to be due to fluctuations in the
fabricated structures and/or insufficient convergence of the
calculation.

In addition to the high-Q factor, the fact that the cavity
has a single-resonant mode in the spectral range of concern is
important for the application to the channel add/drop filters.
From both calculation 7 and experiment, both L3 and L4 de-
fects are found to have only one resonant mode in a wide
spectral range of more than 60 nm, as shown in Figs. 2(b)
and 2(c). These single-mode ranges are wide enough for the
usual WDM applications.

Radiation patterns of the devices were also measured.
Near-field images of the light emitted from the L3 and L4
defect devices are shown in Figs. 3(a) and 3(b), respectively.
As can be seen in Figs. 3(a) and 3(b), each defect exhibits a
different radiation pattern, with the L3 defect exhibiting a
single spot while L4 exhibits two spots separated along the
axis of the defect. For coupling to external optics, the effi-
ciency of L4 is much lower than that of L3 due to the split-
ing of the radiation pattern. To verify the experimental re-
sults, radiation patterns of the defects were calculated using a
previously reported method. 7 Theoretical radiation patterns
for the L3 and L4 defects are shown in Figs. 3(c) and 3(d),
respectively, with white circles indicating the numerical ap-
erature (NA) of the objective lens used in the measurements
(NA = 0.40). Experimental and theoretical results are in
good agreement when the effects of the limited NA is con-

FIG. 2. Channel drop spectra of samples composed of a waveguide and (a) acceptor-type, (b) L3 donor-type, and (c) L4 donor-type point defects. The distances between the point defect and waveguide in (a), (b), and (c) are four, four, and three rows of air holes, respectively. Q factors of the L3 and L4 donor-type defects are much higher than those of the acceptor-type defects.

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be calculated from a simple spatial integration of the electric field. Since $E_x (E_y)$ of the L4 defect mode are odd about the $x$ ($y$) axis as shown in Fig. 4(a) [Fig. 4(b)], the spatial integration of $E_x (E_y)$ inevitably becomes zero. Therefore, radiation perpendicular to the slab plane is prohibited for both polarizations, and the radiation pattern splits into two spots. On the other hand, $E_z$ of the L3 defect mode is even about both $y$ and $x$ axes as shown in Fig. 4(c), which typically yields a non-zero integration. Spatial integration of $E_z$ of the L3 defect mode yields zero since it is odd about both $y$ and $x$ axes. Therefore, only the light with $E_z$ polarization can be emitted vertically from the L3 defect. This leads to the general rule that the number of air holes filled should be odd to produce vertical radiation from the fundamental modes of line-shaped donor-type defects.

Finally, a brief description of the reasons for the $Q$ factor of the L4 defect being higher than that of the L3 defect is given. One reason is the difference in cavity sizes. Another reason is the deference in the symmetry of the in-plane mode fields, with vertical emissions cancelled out in the case of the L4 defect. More importantly, a sharp decay in the defect mode field at the boundary between the defect and surrounding crystal was found to have a very large effect on $Q$ factors. Further details are to be presented in a separate publication due to limitations in space.

In summary, we have experimentally demonstrated that donor-type point defects are very useful for improving the filtering resolution of channel add/drop devices. The devices, which consist of line-shaped defects of three or four missing air holes, were shown to have very high filtering resolutions with $Q$ factors as high as 2600 and 6400, respectively. Light emitted from both of these defects is linearly polarized with the electric field perpendicular to the axes of the defects. The radiation pattern of the L3 defect is a single spot while that of the L4 defect is divided into two spots. Although simultaneous improvement of $Q$ factor and radiation patterns is a future task, these results are encouraging for the application of 2D PC slab devices to D-WDM communication systems.

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