Fabrication and Characterization of Photonic Crystal Waveguide Components and Application to Ultra-Fast Optical Signal Processing Devices

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Current status of two-dimensional photonic crystal (2DPC) waveguide technologies and application to a photonic integrated circuit (PIC) has been reviewed. The emphasis is placed on our recent advancement on theoretical design, fabrication and characterization of the 2DPC-based defect-waveguides such as straight, 60°-bend and directional coupler necessary for the PIC application. A scenario and key issues for application to an ultra-fast all-optical switch are also described.

Keywords: photonic crystal, slab waveguide, band structure, transmission spectrum, bend waveguide, directional coupler, nonlinear waveguide, all-optical switch

Introduction

Recently, a two-dimensional (2D) photonic-crystal (PC) slab has attracted much attention as a novel opto-electronic material/structure capable of providing an ultra-small photonic integrated circuit (PIC) with miniaturized light sources, optical switches and waveguide components (1-4). In particular, combination of the 2DPC and an optical nonlinear (ONL) material such as quantum dot (QD) has a potential ability to achieve an ultra-small and ultra-fast all-optical switching device (5). This is because the QD has a large ONL property in itself and the 2DPC waveguide has a large dispersion property including a low group velocity Vg (6). These two features are capable of enlarging the phase shift induced by the ONL refractive-index change, thus reducing the optical switching energy (OSE). So far, our group has developed nano-technologies for achieving such 2DPC- and QD-structures (7-12). This paper reviews fabrication and characterization of 2DPCs for realizing such a PC- and QD-based all-optical switching device.

Concept and Key Issues of PC-SMZ

Proposal of PC-SMZ

In 1993, Tajima has proposed a symmetrical Mach-Zehnder (SMZ)-type all-optical switch with compound semiconductor ONL materials, the speed of which is not restricted to the carrier lifetime of the ONL material (13). Using this device, his group has so far demonstrated sub-ps-level ultra-fast all-optical switching operations and also carried out optical DEMUX experiments. Further developments are going on for reducing an OSE and improving the stable operation. We have recently proposed a 2DPC-based SMZ-type all-optical switch with embedded QDs for the ONL materials (hereafter, referred to simply as a PC-SMZ). This device has a potential ability to further reduce the OSE, thus providing an ultra-small and ultra-fast photonic switch. Figure 1 shows a schematic picture of the PC-SMZ. Owing to the ONL refractive-index-change (Δndot) of the QD, selectively embedded in the two ONL waveguides, the phase shift Δφ is caused by two control pulses whose time slots differ by a delay time generated by the integrated PC-based delay element. At a switch-on time, two ONL waveguides are designed so that Δφ = π between two signal pulses due to the Δndot, quite similarly to the principle of the conventional SMZ switch.
**Key issues of PC-SMZ**

Due to the structural difference between the conventional SMZ and PC-SMZ devices, the PC-SMZ has several technical key issues, as shown in Fig. 2. Here, we take notes of the straight, bend, Y-coupling and ONL defect-waveguides (DWGs). For reduction of the OSE in the PC-SMZ, in particular, usage of the low $V_g$ in the ONL DWG is effective for enhancing the phase shift $\Delta \phi$, as mentioned above. In addition, an optimized design of the ONL DWG for satisfying the low $V_g$ is important. Another important key issue is a design of the output Y-junction DWG. At the junction, an optical beam in one ONL DWG should not propagate into another ONL DWG for preventing unnecessary ring modes. We have proposed the idea of introducing a novel directional coupler for the Y-junction to solve this problem, as shown later. This paper emphasizes the properties of the 2DPC, and fabrication and characterization of the QDs are described elsewhere.

**Two-Dimensional Photonic-Crystal Waveguide Technologies**

**Slab waveguide structure**

In general, an application of the 2DPC to the miniaturized low-loss PIC requires a slab structure with core/clad refractive-index contrast for strong optical beam confinement in the vertical direction. One candidate is an air-bridge (AB)-type structure and another is an oxide-cladding (OC)-type one. Figures 3 (a) and (b) show schematic cross-sectional views of the AB- and OC-types, respectively, where SEM photographs of the fabricated structures are also shown. The AB-type structure was fabricated by using electron-beam (EB) lithography, dry etching (chlorine-based reactive ion beam etching) and selective wet etching, while the OC-type structure was fabricated by thermally oxidizing the lower sacrificing clad layer instead of the wet-etching method. The sample wafer was a 250-nm-thick Al$_{0.1}$Ga$_{0.9}$As core layer grown by MBE on top of a 2-µm-thick Al$_x$Ga$_{1-x}$As lower sacrificing clad layer ($x=0.7$-$0.9$) on a GaAs substrate. As shown later, simulated and measured transmission spectra were obtained mainly for the AB type, while the OC-type is currently under development for the future practical application.
Fig. 3 Two types of 2DPC slab waveguide; (a) AB-type. (b) OC-type. Left: schematic cross-sectional views. Right: SEM photographs of the experimented structures.

Fig. 4 Triangular-lattice DWG pattern with single missing line.

Figure 4 shows a schematic plan-view diagram of the triangular-lattice straight DWG pattern on the 2DPC slab with a missing single-line air-hole array. For designing a single mode at a wavelength of ~1.3 μm, a lattice constant (a) of 360~420 nm, air-hole diameter of ~200 nm and slab thickness of 200~250 nm are needed.

Air-Bridge (Al_{x}Ga_{1-x}As)

- a = 350 nm
- d = 200 nm

Minimum Uniform Nano-Hole:

- \( d_{\text{small}} = 120 \text{nm} \approx 0.34a \)

Fig. 5 Demonstrated nano-fabrication of ultra-small air-holes resulted from the precise EB dose adjustment.

Fabrication of triangular-lattice defect waveguide

A key technology for precise fabrication of the 2DPC array is an establishment of high-precision EB lithography. One of the main reasons for the site/size fluctuation in the EB
patterning is a proximity effect specific to the EB irradiation on the substrate. This effect is prominent if patterns with different sizes coexist in the same area. In many cases for 2DPC patterning, introduction of the DWG in the homogeneous 2DPC array leads to coexistence of air holes with different diameters. In such a case, precise EB dose adjustment is inevitable for complete suppression of the proximity effect mentioned above. For this reason, EB doses were carefully adjusted depending on the 2DPC patterns. Typical uniform nano-holes in the bend DWG in the AB-type 2DPC are shown in Fig. 5. It should be noted that the minimum diameter of the air-hole array is 120nm.

Characteristics of 2DPC Defect Waveguides

Band structure of the straight defect waveguide

A photonic band diagram is calculated by using a three-dimensional finite-difference time-domain (3D FDTD) method. Figure 6 shows the resultant band diagram of the DWG, as shown in Fig. 4, for the TE-like guided modes. There are two bands between the lower and upper slab bands, that is, the even and odd guided modes in the photonic bandgap (PBG). However, since the odd mode is not easily excited in the practical experiment, later calculations are performed only for the even mode. This even mode is single and non-leaky in the normalized frequency range $0.258 \leq a/\lambda \leq 0.276$, where $c$ is a velocity of the light in the vacuum.

![Fig.6 Band structure of the GaAs-based straight defect-waveguide with a triangular-lattice air-holes.](image)

Straight and 60°-bend defect waveguide

Transmittance spectra of these DWGs were theoretically calculated by using the 3D FDTD method. They were also measured by using a wide wavelength-range optical transmission measurement system developed recently\(^{(17)}\). Figures 7 and 8 show measured and calculated transmittance spectra for the GaAs-base straight and 60°-bend DWGs in the 2DPC slabs, respectively\(^{(17)}\). It should be emphasized that they are in good agreement between the measured and calculated spectra both for the straight and bend DWGs. This suggests that the air-hole array used in the experiment has been fabricated with excellent accuracy.
Fig. 7 Measured and calculated transmission spectra of the GaAs-based straight DWG with a triangular-lattice air-hole array. The hatched frequency area gives the single mode.

Fig. 8 Measured and calculated transmittance spectra of the GaAs-based 60°-bend DWG with a triangular-lattice air-hole array.

Characteristics of Y-Coupling Waveguide

As mentioned above, an optical beam propagating through one ONL DWG and impinging into the Y-junction in the PC-SMZ, as shown in Fig. 9 (a), should not propagate into another ONL DWG for preventing an unnecessary ring mode which disturbs a successful SMZ interference. However, as long as the three-fold symmetry Y-junction DWG is used, the incident beam splits into both the ONL DWG and the output port. Usage of a directional coupler (DC) instead of the three-fold symmetry Y-junction DWG is a simple solution for this problem. Figure 9 (b) shows the DC based on the 2DPC slab with a parallel-coupled single-
defect waveguide (PSW) separated by a triple-line air-hole array. Some missing air holes named the coupling-strength-control defect (CCD) are inserted in the middle of the separation. Hereafter, the DC with the CCD is referred to as the coupling-strength-controlled DC (CC-DC) \(^{(18)}\). The CCD length is defined in the figure. The DC is connected with 60°-bend waveguides. In the figure, calculated beam intensities at each port for the design of the 3-dB beam splitter are also shown. Calculation was carried out by using a 2D FDTD method with an effective refractive-index of 2.81, other parameters being the same as those used for the band and transmittance calculation in Fig. 6 to Fig. 8. It is noted that, since the output at the port b is zero, this structure is available for the output Y-coupling region in the PC-SMZ, as mentioned above. Another note is that the CCD length of only 7.2\( \mu \)m for a wavelength of \(~1.3\mu\)m is short enough for realizing a very compact PC-SMZ.

![Fig.9](image)

**Fig.9** (a) Schematic picture of the DWG configuration in the PC-SMZ, showing the beam-propagation direction for the three-fold symmetry Y-junction DWG. (b) Schematic picture of the CC-DC and the CCD length. Beam intensities at each port for the design of the 3-dB beam splitter are also shown.

**Characteristics of Nonlinear Waveguide**

As mentioned in the introductory section, prediction of the refractive-index-change (\(\Delta n\))-induced phase shift \(\Delta \phi\) in an AB-type AlGaAs 2DPC slab DWG is important for designing the ONL DWG in the PC-SMZ. First of all, if the ONL-induced \(\Delta n\) will change the propagation band so seriously that the transmittance will be changed significantly, the principle of the SMZ does not operate well. For checking this point, we calculated the \(\Delta n\) effect on the transmission spectrum by using the 3D-FDTD method. We sent an input pulse into the input waveguide and measured the flux in the output waveguide, as shown in Fig. 10 (a) \(^{(19)}\). Calculated transmission spectra, as shown in Fig. 10 (b), resulted in the shift to higher frequency with \(\Delta n\) changing from 0 to -0.01 and -0.1. Since the predicted \(\Delta n\) for the present ONL material, that is, the QD is \(~-0.001\), the QD-induced transmittance change is negligibly small in this case. Next, we calculated the \(\Delta n\)-induced phase shift by using the 3D-FDTD method. At the input In-1 and In-2 in Fig. 10 (a), the structure was excited by using dipole sources of the fixed frequency \(f = 0.270\ c/a\). Figure 10 (c) shows two output waveforms of the optical beams detected at Out-1 (\(\Delta n =0\)) and Out-2 (\(\Delta n =0.07\)) and their composite waveform. The resultant extinction ratio between amplitudes of the input and composite waveforms is -20dB, an enough value for an optical switch.
Fig. 10 (a) Waveguide structure for calculating the phase shift in the ONL DWG. (b) Calculated transmission spectra as a function of the $\Delta n$ (0, -0.01 and -0.1). (c) Calculated waveforms for $\Delta n =0$ and -0.07, and composite waveform subject to the extinction ratio of -20dB.

Grand Design of the PC-SMZ

Taking into account $\Delta n$ of ~ -0.001 for a predicted actual material for evaluating the ONL DWG in the PC-SMZ, a waveguide length necessary for the $\pi$-phase-shift in the PC-SMZ was found to be ~100$\mu$m owing to the reduced group velocity for a lattice constant of 0.36$\mu$m and a wavelength of ~1.3$\mu$m. The resultant grand design for the PC-SMZ is shown by the schematic picture in Fig. 11. The result suggests the possibility of achieving a 500$\mu$m x 500$\mu$m compact ultra-fast all-optical switch.
Conclusion

Simulation, fabrication and characterization of several 2DPC DWGs suggested that the PC-SMZ is promising for integrated ultra-small and ultra-fast all-optical switches with a low optical switching energy.

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