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Photonic crystal and quantum dot technologies for all-optical switch and logic device

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Abstract. Nano-photonic technologies of GaAs-based two-dimensional photonic crystal (2DPC) slab waveguides (WGs) and InAs-based quantum dots (QDs) are reviewed for a symmetrical Mach–Zehnder (SMZ) type, ultra-small and ultra-fast all-optical switch (PC-SMZ) and logic device. As the first phase, ultra-fast (∼ ps) and ultra-low energy (∼ 100 fJ) switching has been demonstrated using a chip 600 µm x 300 µm in size. The second phase is to create a PC-SMZ-based ultra-fast photonic logic switch with a latch function for a future ultra-fast photonic digital processor. One of the priority subjects is to establish a new design method, i.e., topology optimization (TO) method of 2DPC-WGs with wide/flat bandwidth, high transmittance and low reflectivity. Another one is to develop selective-area-grown, high-density and highly uniform InAs QDs with large optical nonlinearity (ONL) by using a metal-mask (MM) molecular beam epitaxy (MBE) growth method. Recent results regarding these two subjects encourage us to reach the final goal.
1. Introduction

A two-dimensional photonic crystal (2DPC) exhibits unique features such as PC band gap and strong dispersive property. Due to these effects, 2DPC-based novel ultra-small and integrated photonic devices/circuits have been widely studied [1]–[8]. On the other hand, a semiconductor quantum dot (QD) exhibits a high density-of-state. Aiming at this effect, thorough investigation has been made into pursuing an excellent performance of the QD in the linear/nonlinear optical phenomena [9]. By combining these two nano-photonic structures, key photonic-devices can be proposed for future advanced telecommunication systems, as shown in figure 1. In the category of an ultra-fast digital photonic network in future, an ultra-small and ultra-fast symmetrical Mach–Zehnder (SMZ)-type [10] all-optical switch (PC-SMZ) has been developed so far by using GaAs-based 2DPC slab waveguides (WGs) and InAs-based optical nonlinear (ONL) QDs in phase one [11, 12]. In phase two, the PC-SMZ is now evolving into a new functional key device, i.e., an ultra-fast all-optical flip-flop (FF) device essential for the digital photonic network. All through these two phases, design of WGs with wide/flat bands is an important subject for the 2DPC technology, while enhancement of the ONL property in the PC-SMZ is another important subject for the QD technology, as emphasized in figure 1. In figure 1, another category of a future quantum information system is described, where a single photon qubit composed of single QD embedded in a 2DPC-based high-Q cavity is situated as another important product of the 2DPC/QD-combined nano-photonic structure [13, 14].

Figure 2 shows research flows in the development of the all-optical FF device mentioned above. The flows are arising from two major platform technologies; precise 2DPC-WG and large ONL QD technologies. Development of a new design method, i.e., topology optimization (TO) method contributes to achievement of a wide/flat band 2DPC-WG [15], while a metal-mask (MM) method is practically promising for selective-area molecular beam epitaxy (MBE) growth of InAs QDs [16]. To begin with, this paper reviews typical properties of the PC-SMZ developed so far. Then, research results to date on the TO design and MM methods are shown as expected technologies for achieving the all-optical FF device mentioned above.

2. Basic properties of ultra-small all-optical switch: PC-SMZ

2.1. Principle and key issues of the PC-SMZ

Figure 3(a) shows a schematic picture of the PC-SMZ [9]. Optical WGs in the SMZ configuration are composed of 2DPC defect waveguides (DWGs), while ONL-induced phase shift arms are selectively embedded with QDs that exhibit ONL-induced large refractive-index change. The principle of an ultra-fast operation of the PC-SMZ is shown in figure 3(b) [10]. A ‘switch-on’ control pulse (CP) incident in the upper ONL arm causes an ONL-induced refractive-index change $\delta n$, which leads to a phase shift $\phi_1 = 2\pi(\delta n/\lambda) l_{ONL}$ for a series of signal pulses (SPs), where $\lambda$ is a wavelength of the SP and $l_{ONL}$ is an ONL arm length. Similarly, the phase shift $\phi_2$ is generated in the lower ONL arm by the ‘switch-off’ CP. As a result, a phase-shift difference $\Delta \phi = |\phi_1 - \phi_2|$ is generated at the combined Y junction. Only when $\Delta \phi = \pi/2$ or $\pi$ (depending on the junction structure), the SPs are switched spatially. Here, the time response of the $\delta n$ in the semiconductor is in general rapid (sub-ps) in excitation but slow (sub-ns) in relaxation as a carrier lifetime in the semiconductor. However, since the $\delta n$ is excited time-differentially by the ‘switch-on’ and ‘switch-off’ CPs, the $\delta n$ in the tailing slow component are cancelled,
Figure 1. Schematic research scenario of PC/QD combined nano-photonic structures for advanced telecommunication systems.

Figure 2. Research flows of ultra-small PC-SMZ all-optical switch and logic device based on the precise 2DPC-WGs and large ONL-QDs.
Figure 3. (a) Schematic diagram of an integrated SMZ-type all-optical switch (PC-SMZ). (b) Principle of the ultra-fast all-optical switch in the SMZ WG configuration.

as shown in figure 3(b). Thus, a rapid time-dependent \( \Delta \phi = \frac{\pi}{2} \) state in the period of several to several tens ps can be achieved. If the structure of the PC-SMZ is realized quite similarly to the conventional SMZ switch, the ultra-fast switching operation mentioned above can be achieved as well.

A conventional SMZ is based on the low refractive-index-contrast WG [10], while the PC-SMZ is composed of an ensemble of the high refractive-index-contrast 2DPC lattices. Due to these structural differences, the PC-SMZ has several technical key issues to be developed. As a first step, we took notes of the 2DPC chip of less than 500 \( \mu \text{m} \times 500 \mu \text{m} \). Demonstration of high transmission and low propagation loss was the first important key issue towards 2DPC integrated circuits. The second important key issue was a design of the output Y junction DWG. At the junction, an optical beam propagating in one ONL-DWG should not enter another ONL-DWG at the junction spot for preventing excitation of unnecessary ring modes in the SMZ ring loop. We proposed the idea of introducing a novel directional coupler (DC) for the Y junction to solve this problem, as shown later [17]. For reduction of the optical switching energy in the PC-SMZ, in particular, usage of a low group velocity \( (V_g) \) in the ONL-DWG was found to be effective for enhancing the phase shift as mentioned above [18]. Therefore, the third key issue was an optimized design of the ONL-DWG for satisfying the low \( V_g \), thus enhancing the ONL phase shift.

Table 1 shows research items and numerical targets for achieving the PC-SMZ device, categorized by the 2DPC, QD and PC-SMZ. The most important item for the switching operation is a realization of more than \( \pi/2 \)-phase shift for the ONL DWG of less than 500 \( \mu \text{m} \) in length. For supporting these target items, a great deal of effort has been made for both precise fabrication of 2DPC-DWGs with high transmissions and low propagation losses, and growth of QDs with high-density and high-uniformity. In the following section, we describe calculated and experimental results concerning these key issues.
Table 1. Research items and numerical targets of PC-SMZ

<table>
<thead>
<tr>
<th>Structure</th>
<th>Item</th>
<th>Numerical target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photonic crystal</td>
<td>Band width</td>
<td>$\geq 40$ nm, single mode</td>
</tr>
<tr>
<td></td>
<td>Propagation loss</td>
<td>$\leq 1$ dB mm$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>SP: 50%, CP: 100%</td>
</tr>
<tr>
<td>Quantum dot</td>
<td>Absorption peak $\lambda$: 1.28 $\mu$m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>$\geq 4 \times 10^{10}$ cm$^{-2}$</td>
</tr>
<tr>
<td></td>
<td>Uniformity</td>
<td>$\leq 30$ meV (PL peak: FWHM)</td>
</tr>
<tr>
<td></td>
<td>NLO phase shift</td>
<td>$\geq \pi/2$ (NLO arm length: $\geq 500$ $\mu$m)</td>
</tr>
<tr>
<td>All-optical switch</td>
<td>CP $\lambda$: 1.28 $\mu$m, energy: $\leq 500$ fJ, pulse width: $\leq 1$ ps</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SP $\lambda$: 1.30 $\mu$m, pulse width: $\leq 10$ ps ($\geq 40$ Gb s$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Switch speed</td>
<td>Rise/fall time: $\leq 1$ ps, window width: $\leq 25$ ps</td>
</tr>
<tr>
<td></td>
<td>Extinction ratio</td>
<td>$\geq 10$ dB</td>
</tr>
<tr>
<td></td>
<td>Chip size</td>
<td>$\leq 0.5$ mm $\times 0.5$ mm</td>
</tr>
<tr>
<td></td>
<td>Insertion loss</td>
<td>$\leq 20$ dB (coupling to optical fibre)</td>
</tr>
</tbody>
</table>

![Fabrication process diagram](image)

**Figure 4.** (a) Schematic diagrams of 2DPC-slab-DWG fabrication processes (upper) and SEM photographs of the cross-sectional views (lower). (b)–(d) SEM photographs showing the whole PC-SMZ WG configuration, cleaved edge of the air-bridge type 2DPC slab WG and cleaved edge of the single-line defect WG.

2.2. Fabrication and transmission properties of GaAs-based air-bridge type 2DPC-WG

A sample was fabricated in an epitaxial hetero-structure grown by MBE. A 250 nm thick GaAs core layer was deposited on top of a 2 $\mu$m thick Al$_{0.6}$Ga$_{0.4}$As cladding/sacrificial layer on the GaAs substrate. An air-bridge WG was fabricated using high-resolution electron beam (EB) lithography, reactive ion beam etching (RIBE), and selective wet-etching techniques [9]. The upper panel of figure 4(a) shows schematic diagrams of such processes. The 2DPC consists of periodic air holes etched into a planar GaAs core slab. A core thickness, lattice constant and...
hole diameter of the 2DPC are 250, 360 and 220 nm, respectively. The lower sacrificial layer was removed by an HF solution via air holes. The DWG consists of a missing row of air holes surrounded by 10-raw air holes on both sides. The lower panel in figure 4(a) shows scanning electron beam microscope (SEM) images of cross-sectional views at each process. Figures 4(b) and (c) are SEM photographs of the whole PC-SMZ patterns and DWG pattern in the vicinity of the cleaved edge, respectively. A black circle in figure 4(d) indicates single-line defect providing a single-mode WG.

Optical properties of the GaAs 2DPC-DWG were characterized by observing TE (transverse electric)-polarization transmittance spectra over a broad-wavelength region from 1100 to 1600 nm [8]. Figure 5(a) shows calculated band diagrams for the 2DPC slab structure calculated by using the three-dimensional finite-difference time-domain (3D-FDTD) method. Two dotted-line curves appearing between the upper and lower slab bands show even- and odd-modes specific to the 2DPC-DWG, where a solid straight line shows a light line in the vacuum. So, a single-guided-mode exists on the even mode line in a wavelength range between 1300 and 1400 nm, as indicated by the light blue region. On the other hand, figure 5(b) shows measured transmittance spectra for straight and 60° double bend WGs. From the band diagram, the measured peaks around 1300 nm wavelength were identified as the single-guided-modes below the light line in the band diagram. Their 3 dB band widths were 40–50 nm. It is found that, due to the single mode, a propagation loss for the bend is negligibly small in the vicinity of the peak wavelength.

A propagation loss was experimentally characterized as follows. Figure 6(a) shows transmittance spectra of more than ten samples for different WG lengths, i.e., 1, 4 and 10 mm lengths. Reproducibility in transmission range and spectrum shape is rather good among these samples. The propagation loss was derived from transmittance values at the centre wavelengths by a cut-back method to be 0.76 dB mm⁻¹, as shown in figure 6(b) [19]. This value is record low for the GaAs-based 2DPC slab WGs [20]–[22]. These excellent results suggest that the 2DPC-DWG samples were fabricated with high-precision up to 10 mm in length.

2.3. Characteristics of DC at 2DPC Y junction

As mentioned above, an optical beam propagating in the ONL DWG should not enter another ONL-DWG at the output junction spot for preventing an unnecessary ring mode in the SMZ ring loop, which disturbs a successful SMZ interference. However, as long as the three-fold symmetry Y junction DWG is used, this problem is not avoidable. Alternatively, it was found that usage of a DC is a simple solution for avoiding this problem [17]. In the actual design of the PC-SMZ, however, two different design criteria were needed for two different roles of DCs, i.e., the DC dividing/combining the SPs (DCs) and the DC introducing the CP into the ONL arms (DCC), as shown in figure 7. The DCs should be designed as 50% in coupling strength, while the DCC should exhibit 100% coupling for the CP and 0% (i.e., uncoupled) for the SP. These requirements
could be realized by controlling the DC length according to the relation, DC_C = 4 × DC_S, as indicated schematically at both sides in figure 7 [23, 24].

As a first step for designing the PC-SMZ, a DC with a 50% coupling strength was investigated both experimentally and theoretically as follows. Figures 8(a) and (b) show a plan-view SEM photograph of the sample and near-field pattern spots observed with an infrared vidicon camera at two output ports, respectively. Figure 8(c) shows measured transmission spectra for the TE-like mode. The spectra are normalized by the reference sample. Red and blue lines show spectra for uncoupled intensity DC_{ac} and coupled intensity DC_{ad}, respectively. In the figure, a spectrum for a 60° double-bend WG is also plotted by a black line for comparison. At a wavelength range from 1280 to 1330 nm, high-transmission regions for both DC_{ac} and DC_{ad} were obtained and, in particular, a 50% coupling was achieved at a wavelength of 1320 nm, as indicated by a red arrow. Two identical intensity near field spots in figure 8(b) were measured at this wavelength of 1320 nm. As shown by this experiment, the demonstrated DC shows a 50% coupling at a particular wavelength.

As a second step, a 100% coupling DC performance can be demonstrated by cascading two identical 50% coupling DCs. Figure 8(d) shows transmittance spectra measured at two output ports c and d, as indicated by the inset in the figure. A coupled intensity in the black line (a)–(d)
is more than 10 dB higher in transmittance than an uncoupled intensity in the red line (a)–(c). The result shows that the cascaded 50% coupling DCs exhibit the 100% coupling as expected above. Based on these analyses, two kinds of DC, i.e., DC_C and DC_S were designed and experimentally demonstrated. The results show that the measured spectra are surprisingly in good agreement with the calculated ones although they are not shown here. Some references are available for more details [24].

Finally, generic properties of the DC necessary for applying to the SMZ based optical switch are discussed here. Figures 9(a) and (b) show calculated E-field distributions of optical beams propagating along the DC when two input beams with unit intensities (indicated by 1.0 here) are impinging into two input ports at the phase differences \(\Delta \phi\) of 0° or 180°, and \(\pm 90°\), respectively. In case of \(\Delta \phi = 0°\) or 180°, two output intensities at two different ports exhibit equally 1.0, while they exhibit 2.0 or 0 in case of \(\Delta \phi = -90°\) or +90°. When we operate the PC-SMZ, the \(\Delta \phi\) is induced by the CP-excited \(\delta n\) of the ONL QDs, as discussed in subsection 2.1. In this case, it should be noted that the beam dividing/joining couplers are composed of cascaded identical 50%-coupling DCs, so that two output beam intensities at two output ports in the PC-SMZ exhibit 1.0 and 0, respectively. Taking these into account, if the \(\delta n\)-induced phase shift is \(\pi/2\) in the ONL arms, the resultant output intensity at either output port switches from 1.0 to 0.5 or from 0 to 0.5 (50% switching). Alternatively, if the phase shift is \(\pi\), 100% switching is fulfilled, i.e., switching between 0 and 1.0. This phenomenon is discussed also in subsection 2.5.

2.4. Different wavelength pulse excitation for nonlinear phase shift

As an origin of an ONL phase shift in the PC-SMZ, a relationship between a third order ONL phenomenon of the QD and corresponding refractive index change is discussed in more detail in this section [18, 25, 26]. The ONL phase shift is attributed to the absorption saturation induced by a resonant excitation in a ground-state transition of the QDs. The mechanism of the ONL phase shift is schematically shown in figure 10(a), where the absorption and corresponding refractive index of assembled QD with an inhomogeneous broadening are shown. Solid and dashed line curves

Figure 9. (a) and (b) Calculated E-field distributions of the 50% coupling DCs for 0° or 180°, and ±90° phase-different two incident beams, respectively.

Figure 10. (a) Schematic absorption and refractive index spectra of ONL-QDs. An ONL effect is presented by absorption saturation pumped by a CP and succeeding refractive index change. Solid and broken lines indicate the spectra before and after pumping by the CP, respectively. The refractive index change is an origin of the phase shift in the PC-SMZ. (b) Detuning relationship between the control and SPs in the transmittance spectrum of the 2DPC-QD-DWG. (c) Measured transmittances as a function of pumping pulse energy of the QD. The absorption saturation appears in the transparent range.

indicate the case without and with pumping CPs, respectively. A CP with a wavelength set to the QD absorption peak causes an absorption change $\Delta \alpha$ (spectral hole burning) and a corresponding refractive index change $\delta n$. A SP with some detuning energy receives the changes $\delta n$, resulting in the ONL phase shift $\Delta \phi$. The phase shift depends on the parameters such as CP energy density, detuning energy between the CP and SP and inhomogeneous broadening of the QD absorption peak. The inhomogeneous broadening degrades the phase shift and attenuates the SP power. Figure 10(b) shows a relationship between two wavelengths, one for the CP and another for the SP in the transmission spectrum for the QD-embedded 2DPC-DWG, as indicated by PC + QD. The spectrum shows a sharp dip caused by the QD-absorption peak. The wavelength for the CP is set to the bottom of the dip, while that for the SP is set to the high transmission band outside the dip. Their wavelengths are set to around $1.3 \, \mu m$, while the detuning wavelength is selected to be typically 15–20 nm, given by the QD absorption peak width. Therefore, a band width of the 2DPC-DWG should be more than 20 nm, preferably 40–50 nm.

The value of the $\delta n$ is dominated by the transmittance change $\Delta T$ from a linear to a nonlinear regime when input CP energy increases, as shown in figure 10(c) [27]. In the figure, the TE-mode transmittance curve as a function of input CP energy was derived from the measurement for the sample with ONL InAs-QDs embedded in the GaAs WG. An absorption saturation power $P_s$ of $13 \, fJ/\mu m^2$ suggests that the current PC-SMZ switch has a potential of operating at an optical switching energy as low as 100 fJ or less. A potential ability of the ONL QD in the 2DPC-WG (and not in the non-PC WG) to exhibit a large value of $\Delta T$ can be verified by the following experiment, as shown in figure 11. The measured $\Delta T$ of 16 dB in figure 11(a) is obtained by an air-bridge type 2DPC-WG sample with QDs embedded, as shown at the upper picture in figure 11(b), while a conventional non-PC ridge WG with QDs embedded exhibit the $\Delta T$ of only 3 dB. A large $\Delta T$ is attributed to a strong vertical confinement of the optical beam in the 2DPC-WG as compared to a weak confinement in the non-PC WG.
2.5. Switching operation of PC-SMZ

Many sorts of theoretical and experimental results regarding the PC-SMZ components mentioned above were applied to the grand design and experimental demonstration of the switch operation of the PC-SMZ. For the grand design, assumption of $\delta n \sim -0.001$ for evaluating the ONL DWG in the PC-SMZ resulted in the estimated length as small as $\sim 100 \mu m$ for inducing the $\pi/2$-phase-shift in the PC-SMZ [28]. This small value in length was derived partly by virtue of using the reduced group velocity for a lattice constant of 360 nm and a wavelength of $\sim 1.3 \mu m$. The whole pattern of the PC-SMZ designed in this way is shown schematically in figure 12(a). As a result, the chip size is significantly reduced to $500 \mu m \times 500 \mu m$. Figure 12(b) shows an SEM photograph of the fabricated sample.

Prior to switch operation of the PC-SMZ, a 500 $\mu m$ long straight DWG with a PC/QD structure was prepared for characterizing an enhancement effect of the ONL phase shift in the PC-WG with QDs. Figure 13(a) shows an ONL-induced phase shift as a function of a peak wavelength of the SP [12]. Here, solid line curves show group indices for the PC and slab WGs, respectively, as shown in the inset, both defined by the reciprocal of the group velocity. As estimated from the band calculation, the group index rapidly increases due to a large dispersion near 1325 nm wavelength at the band edge of the single-missing-line defect. The similar dependence was reported in Fabry–Perot interference measurement. A large phase shift results from the following two enhancement effects: one is due to a high-index-contrast-induced
strong optical-beam confinement in the vertical direction in the air-bridge structure for both SP and CP. Another is due to a long light–matter interaction due to the low group velocity mainly for the SP. Thus, the enhanced electric field of the pulse increases the interaction with the electronic state in the QD. Figure 13(b) shows the CP energy dependence of the ONL-induced phase shift for the SP at 1325 nm in wavelength. The lower circles show a similar dependence for a 1 mm long non-PC ridge-WG with a similar QD. The CP energy necessary for the $\pi/2$ phase shift in the PC WG is more than three orders of magnitude lower than that in the non-PC ridge WG. The
Figure 14. (a) Measured switching characteristics of the SP transmittance in the PC-SMZ for exciting by ON CP only (blue line) and simultaneous exciting both by ON and OFF CPs (red line). (b) Measured switching characteristics at two output ports, i.e., bar (red line) and cross (blue line) ports, as indicated in figure 14(a). An extinction ratio was 50% due to the ONL-induced phase shift being $\pi/2$, as schematically indicated in the upper inset.

A large enhancement effect in this figure is attributed to the similar effect appearing in the previous figure. It should be noted that the $\pi/2$ phase shift in the PC-WG was obtained at the CP energy of less than 100 fJ. The result means that the QD combined with the PC-WG is promising for ONL device applications.

Optical switching responses in the PC-SMZ are shown here [12]. Figure 14(a) shows a decay characteristic of the output SP energy. Measurement was carried out by changing the time delay between the SP and CP. The peak wavelengths of the CP and SP were 1285 and 1305 nm, respectively. The ON-CP and OFF-CP energies coupled into the WG were estimated as $\sim 100$ fJ. In the case of ON-CP excitation only, the SP power slowly decays due to the slow carrier relaxation. It should be noted that, after the OFF-CP is introduced in the CP-off port 27 ps after the ON-CP, the slow decay component is successfully cancelled based on an SMZ switch principle, as indicated by the ‘ON/OFF’. This is the first observation of a switching-window demonstrated by using the PC-based SMZ all-optical switch. Since the switching-window works...
as a filter in time domain, the SP intensity can be modulated depending on the switching-window shape, resulting in a demultiplexing. Here, the measured rise and fall times were \( \sim 2 \) ps, which were limited by a timing jitter between the electrically synchronized SP and CP. Figure 14(b) shows the switching-window measured at the bar- and cross-ports indicated in figure 12(a). From this result, the current PC-SMZ sample exhibited 50% switching instead of 100%. Taking into account the calculation in figure 9, the obtained phase shift \( \Delta \phi \) is likely to be \( \pi/2 \) and not \( \pi \), as indicated schematically in the upper inset in figure 14(b). Under the current experimental conditions, we could not reach the \( \pi \) phase shift necessary for 100% switching because of the deficiency of the optical power in the PC-WG. That is, the coupling efficiency between the input optical fibre and the PC-WG was rather low (less than \( -10 \) dB), and furthermore a large amount of the CP energy was absorbed by the QD before reaching the ONL-WG. If we can increase the power of the CP by a factor of two, by improving the fibre/PC-WG coupling and also by using the sample with the QDs formed selectively in the ONL-WG region only, the 100% switching will be realized, as indicated by the calculation in figure 9. On the other hand, achievement of the abrupt rise/fall time (\( \sim 2 \) ps) suggests that all the PC-based functional elements including the wavelength-selective DC were successfully operated due to the fine-pattern fabrication techniques.

Here, we refer to the maximum switching frequency predicted by the current switching experiment. The exponential time constant of the decay characteristics in the PC-SMZ was 60 ps, equivalent to the switching frequency of \( \sim 17 \) Gb s\(^{-1}\), as shown in figure 2 in [12]. A similar decay characteristic is seen also in figure 14(a). Furthermore, the current 60 ps decay provides a possibility of higher switching frequency than \( 17 \) Gb s\(^{-1}\), say, by a factor of more than 2, due to the possible effect that un-relaxed carriers are relaxed to some extent by the time of the next excitation. In addition, if we take into account other possibilities for the fast carrier relaxation mechanism such as non-radiative recombination at the QD/matrix boundary and an effect of the carrier confinement via a strong optical confinement in the PC-WG, we can say that there will be a possibility of achieving more than 40 Gb s\(^{-1}\) switching frequency.

In the end, the ONL-induced phase shift is achieved at sufficiently low optical-energy (e.g. \( \pi/2 \) phase shift at \( \sim 100 \) fJ CP energy) due to the small saturation energy of the QD enhanced in the 500 \( \mu \)m-long PC-WG. A narrow switching window (\( \sim 15 \) ps) with abrupt rise/fall times of \( \sim 2 \) ps was also confirmed in the 600 \( \mu \)m long PC-SMZ chip integrated with the wavelength-selective PC-DC and other PC-WGs. Taking into account the fine fabrication technology which has already achieved the low propagation loss (\( \sim 0.76 \) dB mm\(^{-1}\)) and the successful integration of several PC elements, above results imply that the PC- and QD-based monolithically integrated photonic circuits are highly feasible for applications to the multi-channel demultiplexer in future telecom systems.

### 3. Advanced design of TO for PC-SMZ logic device

#### 3.1. Principle of optical FF operation using PC-SMZ

As shown in figures 15(a) and (b), the PC-SMZ exhibits ultra-fast optical switching excited by two CPs, i.e., set and reset pulses. This fact can be paraphrased in the term that the PC-SMZ exhibits pseudo FF operation. In order to change the pseudo FF into the normal FF operation, an ‘on-state’ in figure 15(a) should not be restricted by the carrier relaxation time in the semiconductor ONL.
Figure 15. (a) Principle of ultra-fast switching operation of the conventional SMZ all-optical switch. (b) Time chart showing an optical pseudo FF operation of such an SMZ all-optical switch controlled by set/reset pulses. (c) Proposed block diagram of an optical FF operation based on the PC-SMZ. Introduction of the clock pulse and insertion of the feedback loop of the output SP are main features of this structure. (d) Time chart of the PC-SMZ-based optical FF operation featured by introduction of the clock pulse as a refresh pulse for an on-state extension and insertion of the feedback loop for control of the clock pulse by set/reset pulses.

Material (this decay time is $\sim 100$ ps in the experiments mentioned above). Figure 15(c) shows a unique 2DPC-WG configuration which enables the normal FF operation using the PC-SMZ. An output signal of the PC-SMZ impinges into the optical ‘AND’ element via a feedback loop, where another input pulse, i.e., a clock pulse impinges. An output of the ‘AND’ element is combined to the set pulse, as shown in the block diagram [29]. Figure 15(d) shows a time chart showing the principle of the FF operation by using the idea, as shown in figure 15(c). The clock pulse serves as a refresh pulse to expand the ‘on-state’ period against the relaxation of the carrier, while the feedback signal restricts the clock pulse to be controlled by the set and reset pulses.

The feasibility of this idea has already been verified by computer simulation, as shown in figures 16(a)–(d). The optical ‘AND’ element can be assigned to the PC-SMZ, as shown in figure 16(a). The resultant output signal shows a bi-stable FF operation, as indicated by figure 16(c). In the calculation, period and width of set-reset pulses were 200 and 1 ps, respectively, while a repetition rate of the clock pulse, delay time for the feedback loop and carrier relaxation time
were 25, 10 and 250 ps, respectively. Current simulated results are available for the FF operation at the speed of \( \sim 10 \text{ Gb s}^{-1} \). A design of the FF device at more than 40 Gb s\(^{-1}\) processing speed is likely to be available by optimizing the simulation parameters.

In order to achieve this optical FF device, new technologies for improvement of the following problems should be developed, as follows:

1. Achievement of 2DPC-WGs with wide/flat bands capable of flexible designs for ultra-small photonic integrated circuits.
2. Physical size reduction of the PC-SMZ to meet the rapid feedback operation with a negligible delay time. A target of the chip size adaptive to the optical FF operation at over 160 Gb s\(^{-1}\) processing speed is \( \leq 100 \mu\text{m} \) in length.
3. Enhancement of the ONL effect of the QDs to meet the second condition.

Regarding the 1st condition, the transmission spectra of the PC-SMZ obtained so far are shown in figure 17, being compared with those of straight and bend WGs. In fact, the band widths of the straight and bend WGs are as wide as 50 nm in wavelength, while that of the PC-SMZ is degraded to \( \sim 20 \) nm. The PC-SMZ is composed of cascaded three sets of DC having eight bend structures between input and output ports. Since the band width of the bend WG is sensitive to deviation of air hole structure parameters (filling factor and so on), the band-narrowing of the PC-SMZ is attributed to the mode conversion–divergence at the bend. In the next section, a new design method, i.e., TO method is discussed for achieving wide/flat band 2DPC-WGs.

For improvement of the 2nd and 3rd conditions, on the other hand, closely packed growth of uniform QDs in the desired ONL area and increase of light–matter interaction by using low group velocity are being studied. Recent results on these techniques are shown in the later sections.

Figure 16. (a) Simulation model of the PC-SMZ-based optical FF operation by using an identical PC-SMZ as an optical AND element. (b)–(d) Pulse shapes at a set/reset input, FF output and feedback, respectively.
3.2. TO of the 2DPC-WG

The TO method, originated from the design of vehicles and other mechanical structures, has been developed for the design of PC structures very recently [15], [30]–[33]. Figures 18(a) and (b) show schematic as well as simulated Z-shaped WGs with TO-designed unique patterns. The optimized pattern is composed of deformed islands. Figure 18(c) shows a calculated transmittance spectrum for the TO method as compared with that for the conventional method. Drastic broadening and flattening effects are easily found.

As another case study, a 2DPC-WG intersection was adopted for application of the TO method to the design of the element for integrating dense and compact PC-SMZ chips, as shown in figure 19(a), where 2DPC-WGs with broad bandwidths and low cross-talk for a SP ($\lambda_1$) and CP ($\lambda_2$) are design targets [34, 35]. We consider a 2DPC with a hexagonal lattice (lattice constant $a$) of air holes in a dielectric substrate. An intersection is formed by a line DWGs composed of one missing row of air holes, as shown in figures 19(b) and (c). A TO procedure is executed to maximize transmittance in a straight forward line (a)–(d) by continuously changing a refractive index distribution around the intersection. To avoid a leaky-mode and hence low-transmittance range, target frequencies are restricted to the frequency range for a non-leaky guided mode which is limited by a light line in the band diagram for an air-bridge type 2DPC slab structure. Figures 19(d) and (e) show respective transmission spectra for the standard and TO designs as shown in figure 19(b) and (c). For the TO design, high transmittance and low cross-talk ($-20$–$-30$ dB) are obtained in a wide frequency range. We can also suppress the cross-talk sufficiently for two different wavelengths ($\lambda_1, \lambda_2$) by restricting the frequency range. Therefore, we can say that the effectiveness of the TO method for the PC intersection design has been shown clearly.

The sample was fabricated in an epitaxial hetero-structure grown by MBE. A 250 nm thick GaAs core layer was deposited on top of a 2 um thick Al$_{0.6}$Ga$_{0.4}$As cladding/sacrificial layer on...
Figure 18. (a) and (b) Schematic diagram and actual 2DPC pattern of a Z-shaped WG designed by using a TO method, respectively. (c) Comparison of calculated transmittance spectra for the Z-shaped WGs designed by using the TO method and standard FDTD method.

the GaAs substrate. The air-bridge WG was fabricated using high-resolution EB lithography, dry etching, and selective wet-etching techniques [4]. The core thickness, lattice constant and hole diameter are typically 250, 360, 210 nm, respectively. Figures 19(f) and (g) show measured transmission spectra for the standard and TO-design samples, respectively. Plan-view SEM photographs of the used samples are inserted in both figures. In the lower photograph, uniquely shaped air-hole patterns near the crossing spot are the actually fabricated patterns corresponding to the calculated TO-design ones, as shown in figure 19(e). For the standard sample, transmission in the straight forward beam spectrum a–d is degraded seriously due to large cross-talk a–c, while more than 15 dB higher transmission is obtained at the port d than at the port c for the TO-design sample. Here, a 3 dB bandwidth is largely narrowed from the calculated 70 nm to about 20 nm, as shown in figure 19(g). This is thought to be badly influenced by the band-narrowing of the fabricated double bends as well as imperfection of the intersection structure, as described in figure 17. When the TO method is applied to the bend WG, wide/flat band 2DPC-WGs can be designed, as shown in figures 20(b) and (c), where the bend pattern designed with the conventional FDTD method is shown in figure 20(a). It is noted that the TO method gives us a
4. Selective area growth of nonlinear QD for PC-SMZ logic device

Recent development of self-assembled InAs QDs has attracted a great deal of attention because of its potential for use in telecommunication systems. As indicated in figure 3(a), the PC-SMZ we
Figure 20. (a) and (b) Bend WG patterns designed by using the standard and TO methods, respectively. (c) Comparison of calculated transmittance spectra for the bend WGs designed by using the standard (black line curve) and TO (red and blue line curve) methods.

have proposed and experimentally demonstrated so far requires InAs QDs partially embedded in the GaAs 2DPC-WG. For this purpose, two kinds of selective area growth of QDs have been developed, i.e., the MM method [16] and the nano-jet probe (NJP) method [36]. The MM method enables us to grow the QD ensemble selectively in an area of several tens to several hundred µm in size, while the NJP method has an ultimate ability of site-controlled InAs QDs with nm-scale spatial accuracy. In this section, recent results of these technologies are reviewed.

4.1. Selective area growth of InAs QD using MM method

Figures 21(a) and (b) show an MM configuration in the growth chamber and a relationship between an open window in the MM and a required ONL area in the PC-SMZ chip. The MM has a large open window for real-time observation of reflection-high-energy-electron-diffraction (RHEED) patterns to obtain high-quality InAs QDs as well as open windows for selective area growth of QDs. Figures 22(a)–(c) show a photograph of the MM and its holder, a schematic of open window structures in the MM and a configuration of an open window against the PC-SMZ chip, respectively [37]. An incident EB for RHEED observation goes into tunnels formed on a frame of the MM holder and is diffracted at the centre region of the substrate where molecular beams are irradiated through the large open window during MBE growth. InAs QDs were characterized with photoluminescence (PL) spectra. Figure 22(d) shows PL spectra obtained from the unmasked and masked regions of the GaAs substrate. A PL peak, as shown in the solid line, corresponds to the QD in the unmasked region and has a peak at around 0.97 eV (1280 nm). The FWHM of the peak was approximately 38 meV, which is almost equal to that of a peak from InAs QDs grown without the MM. On the other hand, no peak was found in a PL spectrum from the masked region. These results indicate that the MM method is useful for the selective area growth of high quality QDs.

4.2. Site-controlled InAs QD using NJP method

To date, we have developed a scanning tunnelling microscope (STM) probe-assisted site-control technique for InAs/GaAs QDs and demonstrated two-dimensionally arrayed QDs with varying as well as constant (50–100 nm) pitches [36]. However, it becomes clear that the capability of the current selective QD formation with the STM probe is not sufficient for practical nanofabrication, since the throughput of the technique is 0.5–1 s dot\(^{-1}\). Instead, we have developed a
NJP method using a specially designed atomic force microscope (AFM) cantilever nano-probe capable of the available throughput of 1–10 ms dot^{-1}, as shown in figure 23(a). Using this probe, we have reproducibly fabricated uniform indium (In) nano-dots at the selected point. Since the AFM chamber is connected to a MBE chamber via an ultra-high-vacuum (UHV) tunnel, the In nano-dots can be directly converted to InAs QDs by subsequent irradiation of arsenic flux in the MBE chamber using a droplet epitaxy technique [38]. Figures 23(b)–(e) show a series of ‘in-vacuum’ formation of site-controlled InAs QD.

In figure 23(a), the nano-dot formation was realized using a UHV-AFM probe with a specially designed cantilever, having a hollow pyramidal tip with a sub-micron size aperture on the apex and an In-reservoir tank within the stylus. This cantilever is a piezoelectric type with a hollow pyramidal tip, and is used for nano-dot fabrication as well as for sensing the atomic force in AFM observations. By applying a voltage pulse between the pyramidal tip and the sample, In clusters were extracted from the reservoir tank within the stylus through the aperture, resulting in the In nano-dot formation. These In nano-dots were directly converted to InAs QDs by subsequent irradiation of arsenic flux in the MBE chamber, which is connected to the AFM chamber via the UHV tunnel in our system (figure 23(c)). Then, a necessary number of QDs in the desired region with high uniformity and high density can be formed by a conventional stacking technique, as shown in figures 23(d) and (e).

Figures 24(a) and (b) are AFM images of the site-controlled In nano-dots before the conversion process and InAs-QDs after the conversion process via irradiation of As in the MBE.
growth chamber, respectively. Before the conversion process, the In nano-dots exhibit a cone shape, while they are changed to an anisotropic shape elongated in the [110] direction, exhibiting formation of InAs-QDs.

This technology has a perfect selectivity for the QD formation area, since no QDs will be formed in the area where the In nano-dots are not deposited. This characteristic is very important when considering application to the PC-SMZ.

5. Conclusion

Two kinds of nano-photonic technologies, i.e., GaAs-based 2DPC slab WG and InAs-based QDs were reviewed for discussing a future possibility of PC/QD-based ultra-fast all-optical switch and logic device. As the 1st phase, ultra-fast (∼ps) and ultra-low energy (∼100 fJ) switching was demonstrated using a chip 600 μm × 300 μm in size. Aiming at the 2nd phase to create a PC-SMZ-based ultra-fast photonic logic switch with a latch function, two important techniques developed recently were shown. One was a new simulation method, i.e., the TO method of 2DPC-WGs with wide/flat bandwidth, high transmittance and low reflectivity. This technique is powerful for the establishment of an optical integrated circuit which requires flexible design of a variety of 2DPC-WGs. Another was a new selective-area-growth method, i.e., MM method of InAs QDs. This technique will contribute to the achievement of high-density and highly uniform InAs QDs in a desired area such as an ONL-induced phase shift arm in the PC-SMZ. When these new technologies will be combined, further advancement in performance of the conventional PC-SMZ can be expected, i.e., achievement of QDs with largely enhanced ONL effects in more reduced area and flexible design of unique 2DPC-WGs such intersection and feedback loop. The results will pave the way for the evolved fashion of the PC-SMZ, i.e., PC-SMZ-based optical FF device needed for a future ultra-fast optical digital processing system.

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References


[36] Ohkouchi S, Nakamura Y, Nakamura H and Asakawa K 2004 Site-control technology for InAs quantum dot formation by direct deposition of indium nano-dots with a nano-jet probe *Proc. MRS 2003 Fall Meeting Boston, November*

[37] Takata Y, Ozaki N, Ohkouch S, Sugimoto Y, Nakamura Y, Ikeda N and Asakawa K 2006 Selective area growth of InAs quantum dots with a metal mask towards optical integrated circuit devices *Proc. MBE XVII, Tokyo, August*