All-optical Switch and Digital Light Processing Using Photonic Crystals

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Abstract

We have demonstrated all-optical switching operations by coupled resonator-waveguide systems in two-dimensional Si-based photonic crystals. These systems operate at extremely low power and with a very high switching speed compared with conventional devices using the same nonlinear mechanism due to the use of an ultrasmall resonator with a high quality factor. We also describe an all-optical sequential circuit composed of two resonant tunneling filters. Using a two-dimensional FDTD (finite-difference time-domain) calculation, we numerically demonstrate that an optical digital circuit can synchronize input data with its clock.

1. Introduction

Photonic crystal (PhC) is a promising candidate as a platform on which to construct devices with dimensions of a few wavelengths of light for future photonic integrated circuits [1]. It is an artificial periodic structure with dimensions of a few optical wavelengths and an optical band structure similar to the electron band structure widely used in electronics [2]. It has a frequency band called a photonic band gap (PBG) where light cannot exist. This means that a line defect in a PhC acts as a waveguide and a point defect in a PhC acts as a resonator that does not leak light. Although a three-dimensional PhC could theoretically achieve perfect light confinement, it is difficult to fabricate. Therefore, we have been studying two-dimensional (2D) PhC slabs in which the light is confined by the PBG in the in-plane direction and by the refractive index difference in the thickness direction [3]. Such slabs are easily fabricated by LSI processing, and the structure is similar to a conventional planar lightwave circuit. Recently, there have been many studies on suppressing the out-plane radiation loss of 2D-PhC devices and the quality of PhCs has

been rapidly improved [4], [5]. We have reported a PhC-waveguide with a very low loss of less than 2 dB/cm [6] and an ultrasmall resonator with a high quality factor (mode volume V ~ $0.1 \,\mu m^3$, Q-factor ~ 10^5 [6]) in a 2D PhC with a triangular air-hole lattice.

One promising PhC-based device for an all-optical switch is a coupled resonator-waveguide system [7]-[14]. This is a unique system in which single-mode waveguides are effectively coupled to an ultrasmall resonator with a high Q-factor. This system can enhance the interaction between light and the material in the resonator, which leads to large optical non-linearity. Since the switching power is proportional to (V/Q^2) , this system is ideally suited for highly integrated and low-power switching devices. In addition, since this system functions as a digital logic element such as AND and NOT gates and a memory element, the combination of these elements enables us to achieve all-optical digital processing.

2. Two-beam switching operation

First, we describe an active Si-based 2D-PhC device in which light is controlled by light. A scanning electron micrograph of a resonant tunneling filter formed in a 2D-PhC having a triangular air-hole lattice is shown in **Fig. 1(a)**. This device was fabricated on a silicon-on-insulator substrate by a combi-

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Fig. 1. Scanning electron micrograph of resonator-waveguide coupled system and its transmission spectrum.



Fig. 2. Mechanism of switching operation.

nation of electron beam lithography and inductively coupled plasma dry etching. The distance between the centers of the nearest holes (lattice constant) in the PhC is 420 nm. The air-hole diameter is 210 nm and the slab thickness is 200 nm. This filter is composed of a resonator formed by four point defects and two waveguides each formed by a line defect with one missing row. The filter has two resonant modes (modes 1 and 2), as shown in **Fig. 1(b)**. The Q-factors of modes 1 and 2 are 33,400 and 7350, respectively.

Since an intense light resonating in one resonant

mode can change the refractive index of the resonator, it can shift the resonant frequency of the other mode, as shown **Fig. 2**. That is, the control light resonating in mode 1 can modulate the signal light resonating in mode 2. Some examples of switching operations are shown in **Fig. 3**. In Fig. 3(a), the input signal light of wavelength $\lambda 2$ does not resonate with the resonator (OFF state), and the filter does not output any light in the first period. When the $\lambda 1$ control light is input, the resonant frequency shifts to the signal frequency, the signal light resonates with the res-



Fig. 3. Switching and memory operation.

onator (ON state), and the filter outputs the light in the second period. In this case, the filter state switches back to OFF when the control light is off, as shown in the third period. In Fig. 3(b) the filter is bistable. The OFF-to-ON switching mechanism is the same as that in Fig. 3(a). However, the filter maintains the ON state after the control light has been turned off as long as the signal light is input. This means that this filter functions as an optical memory that uses the signal light as an optical bias.

2.1 Thermo-optic switching operation

We can use the thermo-optic (TO) effect caused by two-photon absorption (TPA) in Si [15] to control the cavity resonance [8], [9]. This effect induces a change in the resonator's refractive index through the heat generated by optically produced carriers and shifts the cavity resonance to a longer wavelength (red shift). The input-power-dependent transmission spectra [8] of mode 1 are shown in **Fig. 4**. Since the input light is scanned from a short wavelength to a long one, the measured spectra are deformed towards the longer wavelength side. Bistability appears when the operating wavelength is set close to the wavelength at which the transmittance attenuates rapidly. Bistable transmission spectra for several detuning operations (δ = the resonant wavelength minus the signal wavelength) are shown in **Fig. 5**. The minimum limits of δ and the bias power for bistable operation are 100 pm and 40 μ W [8], [9], respectively. The maximum ON-



Fig. 4. Input-power-dependent transmission spectra in an all-optical switch using the TO effect.



Fig. 5. Bistable transmission spectra for several detuning values in an all-optical switch using the TO effect.

OFF contrast is 18 dB.

Next, let us consider what happens when we modulate the signal light resonating in mode 2 by a control light resonating in mode 1. Here, we focus on the output signal, which has the same wavelength as the signal light. When $\delta \leq 0$, the control light changes the switching state of the output signal from ON to OFF. If the signal light is a continuous wave, the system outputs the "NOT" signal of the control light (NOT operation). When $\delta > 0$, the control light changes the switching state of the output signal from OFF to ON. In this case, the system outputs the "AND" signal of the two input lights (AND operation). Some experimental results for "NOT" and "AND" operations are shown in Fig. 6. They demonstrate that our two-port system can act as a nonlinear switch with a very low switching power of -15 dBm (approx. $32 \mu W$) [9].

2.2 Carrier-plasma effect operation

We can also utilize the carrier-plasma effect, which improves the switching speed of Si-PhC-based devices [9]. Optically produced carriers in the resonator augment the background electron-hole density. If the generation of an excess amount of plasma exceeds the rate of loss by recombination or diffusion on the time scale of interest, then the plasma will modify the optical properties of the material [16]. In accordance with the Drude model, the refractive index decreases as the carrier density increases. As a result, this effect induces a cavity resonance shift to a short wavelength (blue shift).

Here, we used another resonant tunneling filter with Q-factors of 23,000 (mode 1) and 11,500 (mode



Some experimental results related to the memory operation are shown in **Fig. 8**. The dotted line represents the light input into the PhC resonator. We set the step input DC power slightly below the bistable threshold power of 0.4 mW with $\delta = -0.15$ nm [10]. The solid lines represent three outputs. We then applied an additional set pulse (< 74 fJ) to switch the state to ON. This system stayed in the ON state until the DC input was turned off. The measured switching time was ~100 ps, which is much shorter than that of conventional carrier-plasma-effect devices. This extremely low switching energy and high operating speed are comparable to the characteristics of existing electronic transistor gates (sub-fJ switching energy and GHz operation) used in Si integrated circuits.



Fig. 6. Some all-optical logic operations using the TO effect.



Fig. 7. All-optical switching resulting from TPA-carrierplasma effect.



Fig. 8. Bistable memory operation resulting from TPAcarrier-plasma effect. (1) When no set pulse was applied and no reset was performed, (2) When a set pulse was applied at *t* = 400 ps, (3) When a set pulse was applied and reset was performed.

3. Optical sequential circuit

The combination of basic logic gates and memories can achieve a simple digital optical processing. For example, counters and registers in the electric circuits are composed of flip-flop (FF) circuits that combine AND and NOT gates. Here, an FF circuit is a memory element that keeps the input information over a period of time and is a kind of sequential circuit which temporarily stores the past input/output information and process it with present input signals to determine the present output condition. This feature is different from that of the combination of logic circuits such as AND and NOT gates that process only present input signals. Although all-optical sequential circuits with above functions are indispensable for achieving reamplification, retiming, and reshaping for the future photonic network, electric circuits are usually used because their architecture is very complicated for on-chip photonic circuit. To solve this problem, we devised a new sequential circuit with a very simple architecture [11].

The structure of our sequential circuit based on 2D-PhC is shown in **Fig. 9**. In this report, we describe how we simulated the system using the 2D-FDTD (finite-difference time-domain) method. We chose a Kerr coefficient of $n_2 = 1.5 \times 10^{-17}$ m²/W for nonlinear operation, which is a value that can be achieved with many nearly instantaneous nonlinear materials. The lattice constant *a* is 400 nm, the air-hole diameter is 0.55*a*, and the effective refractive index of the slab is 2.78. This circuit contains two different res-



Fig. 9. Structure of all-optical sequential circuit.

onators (C1 and C2) and two kinds of waveguide (P1 = P2 and P3 = P4). The two resonators have one identical resonant frequency (wavelength $\lambda 1$ =1548.48 nm) and two different resonant frequencies (wavelength $\lambda 2$ = 1493.73 nm for C1 and wavelength $\lambda 3$ = 1463.36 nm for C2). Their quality factors for $\lambda 1$, $\lambda 2$, and $\lambda 3$ are Q1 = 4496, Q2 = 6076.34, and Q3 = 4143, respectively. The widths of P1 and P3 are $W_0 = a\sqrt{3}$ and 0.8W₀, respectively. The widths are tuned so that the $\lambda 2$ and $\lambda 3$ lights can propagate in all the waveguides and the $\lambda 1$ light can propagate only in P1 and P2.

We input the $\lambda 1$ and $\lambda 2$ lights from P1 and the $\lambda 3$ light from P3 so that this circuit can be regarded as a structure composed of three kinds of filters (F1, F2, and F3), as shown in Fig. 10. We can tune these filters so that their resonators can be in the ON state when two or more signals are input. Here, ON (OFF) indicates a state where the light is resonant (non-resonant) with the resonator. For example, the combination of the $\lambda 1$ and $\lambda 2$ lights can turn on F2 because both lights can enter C1. In this case, F1 can also be ON because the resonant frequencies of C1 and C2 in F1 have the same value of the $\lambda 1$. The combination of the $\lambda 2$ and $\lambda 3$ lights cannot turn on F2 or F3 because they do not have a common resonator. Moreover, the combination of the $\lambda 1$ and $\lambda 3$ lights cannot turn on F1 or F3 because the $\lambda 1$ light cannot enter C2 before the C1 state is ON and the $\lambda 3$ is forbidden from entering C1.

The above combinations enable us to achieve a complex function as follows. Consider the input light



Fig. 10. Equivalent filters for several operating wavelengths.



Fig. 11. Mechanism of all-optical sequential circuit.

sequence shown in **Fig. 11**. Here, the $\lambda 1$ light is input continuously. First, the $\lambda 3$ light is also input. Since F1 and F3 are OFF, no lights are output. Second, the $\lambda 3$ light is cut and the $\lambda 2$ light is input. Since F1 turns ON, the $\lambda 1$ light is in C2. Third, the $\lambda 2$ light is cut and the $\lambda 3$ light is input. If F1 is bistable, F3 turns ON because the $\lambda 1$ light is in C2. This is the mechanism of our sequential circuit.

Next, let us consider the clock operation of our circuit. The clock pulse (CLOCK) of the λ 3 light is input from P3. And the data signal (DATA) of the λ 1 light with a non-return-to-zero (NRZ) format in which the signal level is low for '0' and high for '1', but does not return to zero between successive bits, and the inverse CLOCK (CLOCK) of the λ 2 light are input from P1. We set their powers to 61 mW and

tune the δ values of DATA, CLOCK, and CLOCK to +0.59, +0.43, and +0.92 nm, respectively, so that the initial states of C1 and C2 are "OFF", and the state of C1 becomes "ON" when both DATA and CLOCK are input, and the state of C2 becomes "ON" when CLOCK is input while the state of C1 is "ON". As a result, this circuit can function as a sequential circuit that outputs the λ 3 light when the λ 1 DATA is input before the λ 3 CLOCK is input before the λ 1 DATA.

The time chart of our system for a clock pulse width of 40 ps is shown in Fig. 12. The input NRZ-format DATA deviates slightly from an ideal signal synchronized with the clock (dotted line). This figure shows that the system response time is about 10 ps, which corresponds to its Q-factor. Moreover, it shows that our system outputs the AND signal between the ideal DATA and the CLOCK. That is, this system can regenerate the ideal DATA with a return-to-zero (RZ) format in which the signal returns to the rest state during a portion of the bit period. Basically, one AND gate can achieve such a function for the first three output signals. But a complicated circuit that can distinguish the third-to-last from the second-to-last CLOCK signals should be used to suppress the output of the AND signal between the DATA and the third-to-last CLOCK and to output the AND signal

between the DATA and the second-to-last CLOCK signal. Since our system is a sequential circuit, as described above, it can automatically achieve such sophisticated functions. This makes it advantageous for digital systems operating with their own clocks.

4. Conclusion

We described active 2D-PhC-based devices in which light is controlled by light. These devices are based on a resonant tunneling filter in which singlemode waveguides are effectively connected to an ultrasmall resonator with a high Q-factor and can operate at extremely low power with a very high switching speed. First, we demonstrated that a resonant tunneling filter can act as an AND gate or a NOT gate with an operating power of $32 \,\mu W$ and as an optical memory with bias power of 40 μ W by using the thermo-optic effect. We also described a fast switching operation of about 100 ps with a very low energy of a few tens of femtojoules, and memory operation with bias power of 0.4 mW based on the carrier-plasma effect. Next, we described an all-optical sequential circuit that combines two resonant tunneling filters and demonstrated numerically that this circuit can synchronize input NRZ optical data with its clock and regenerate input data with RZ format. These



Fig. 12. Time chart of all-optical sequential circuit calculated by 2D-FDTD.

functions are indispensable in digital systems. These ultrasmall nonlinear devices have the potential to provide various signal processing functions in photoniccrystal-based optical circuits.

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