Self-holding optical switch using phase-change material for energy efficient photonic network

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Abstract:
We have proposed and fabricated the optical switch using Si waveguides and phase-change material (PCM). The multimode interference (MMI) type optical gate switch using $Ge_2Sb_2Te_5$ is fabricated and it shows wide wavelength range operation of more than 100 nm with an averaged extinction ratio of 12.6 dB. The switching time from the crystalline state to the amorphous state is 130 ns and the switching time from the amorphous state to the crystalline state is 400 ns. We have also designed a 2x2 optical switch based on directional coupling. The size of switch is only 2 μm x 10 μm.

Introduction:
The demand for network capacity grows steadily due to the dramatic increase in communication traffic of the Internet. Figure 1 shows internet traffic in Japan and corresponding energy consumption. They increase at a 30% annual rate. Without any technological development, the energy consumption in the network will be a critical issue.

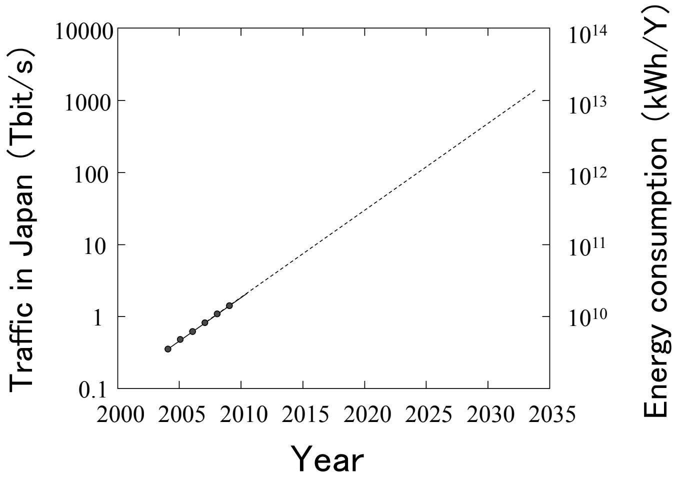

Fig. 1. Increase in internet traffic and corresponding energy consumption in the network in Japan. Circles are cited from MIC white papers.

Photonic switching technology is the key to realize energy efficient, large capacity networks. In particular, high-speed, broadband, large-scale and low-power consumption optical switches are required. Thanks to the large index difference between an amorphous state and a crystalline state, the size of the switch with PCM like $Ge_2Sb_2Te_5$ can be very small compared to the switch using other index control mechanism, as shown in Table 1. Moreover, it has relatively high-speed switching and self-holding characteristics.

Table 1 Comparison of optical switches with various materials.

Material	Switching Mechanism	Index Change	Switching Time	Switch Size	Self-holding Characteristics
Silica	Thermo-optic	0.02%	50 ms	500 × 10000 μm	
Si	Thermo-optic	0.5%	50 μs	100 × 200 μm	
$LiNbO_3$	Electro-optic	0.02%	ps〜ns	50 × 20000 μm	
Ⅲ-V/Si	Plasma Effect	1%	ns	20 × 100 μm	
GeSbTe	Phase Change	> 30%	400 ns	5 × 20 μm	Available

In this paper, we have proposed an MMI type optical gate switch [1-5] and a 2x2 optical switch [6, 7] using PCM and Si waveguides.

MMI-type optical gate switch:

With large change of absorption between amorphous state and crystalline state, very small-sized optical gate switch can be configured. The MMI structure was used to relax tolerance of fabrication because typical Si waveguide width is 450 nm, and it is difficult to deposit a PCM film onto the correct position. Figure 2(a) shows a schematic of an MMI type optical gate switch. The MMI waveguide has one input port and one output port, as shown in Fig. 2(b). The input light excites many propagating modes and they are focused at the center of the MMI waveguide, and again focused at the output waveguide. The PCM film is located on the focusing spot in the MMI waveguide to enhance the interaction of the propagating light and the PCM film.

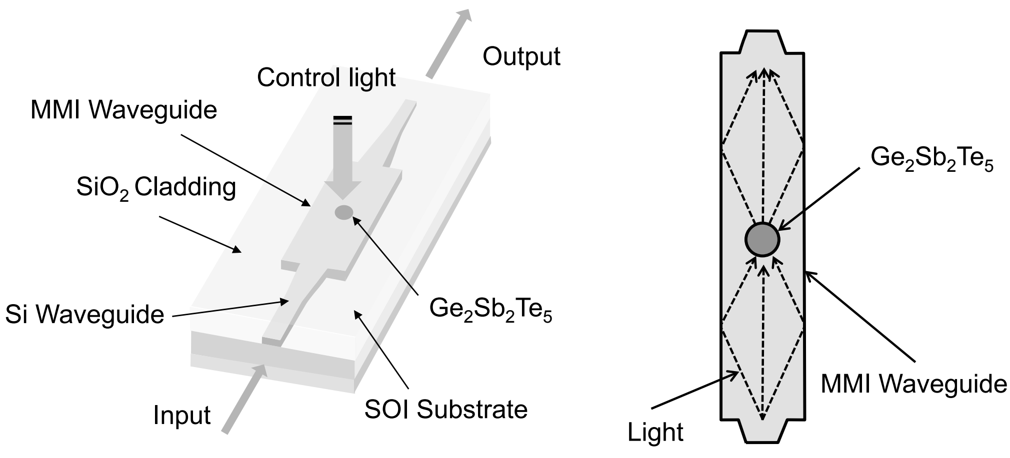

Fig. 2 (a) Schematic of an MMI type optical gate switch. (b) Light propagation in an MMI waveguide.

A Si waveguide had a width of 450 nm and a height of 210 nm and it was formed on SiO_2 under cladding. The length of multi-mode section is 15.3 μm and the width was 2.25 μm. The circular $Ge_2Sb_2Te_5$ film with a diameter of 1 μm was deposited on the center of MMI and covered with ZnS-SiO_2 layer. The thicknesses were 35 nm and 37 nm, respectively. Waveguides were varied with upper cladding of SiO_2.

Control optical pulses with a wavelength of 660 nm were generated by directly modulating a laser diode. They were focused onto the $Ge_2Sb_2Te_5$ film and the spot size was about 1 μm. A laser pulse with a width of 40 ns and a peak power of 160 mW was used for amorphization, and a laser pulse with a width of 400 ns and a peak power of 50 mW was used for crystallization. The probe light with a wavelength of about 1550 nm was input by focusing lens and was coupled to TE mode in the Si waveguide. The output light was guided to the photo diode connected to the oscilloscope. Figure 3(a) and 3(b) show switching responses of amorphization and crystallization, respectively. The rise time of the MMI type gate switch was 130 ns, and the fall time was 400 ns. It showed wide wavelength range operation of more than 100 nm with an averaged extinction ratio of 12.6 dB. In addition, we observed thousand repetitions of switching cycles with an extinction ratio of 9.2 dB.

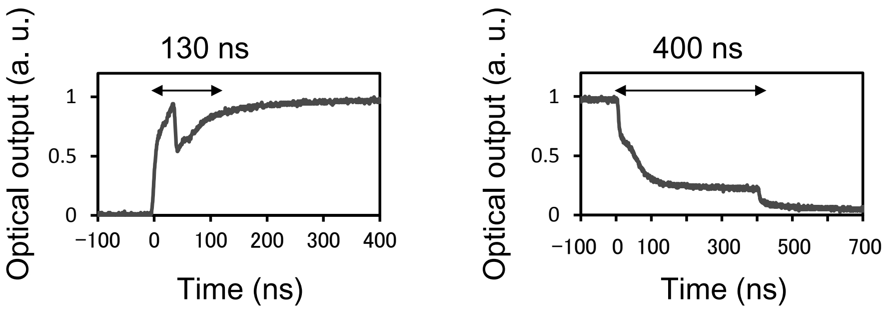

Fig. 3(a) Switching from crystalline state to amorphous state. (b) Switching from amorphous state to crystalline state.

2x2 directional coupling optical switch:

A structure of proposed 2×2 optical switch is shown in Fig. 4(a). This switch is based on directional coupling and has a triple Si waveguide in a switching region. A $Ge_2Sb_2Te_5$ thin film is placed on the center waveguide.

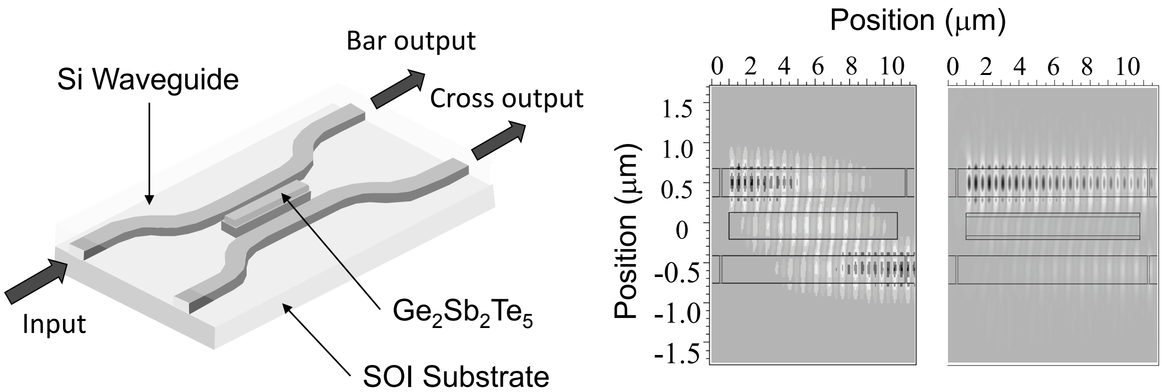

Fig. 4(a) Schematic structure of 2x2 directional coupling optical switch. (b) FDTD calculation results; cross (amorphous) state (left), and bar (crystalline) state (right).

Three optical supermodes are existed in a triple waveguide for TE polarization. An input light excites these modes and they are interfered with each other and change power distribution in the waveguides. When $Ge_2Sb_2Te_5$ is in amorphous state, light is output from a cross port; and when $Ge_2Sb_2Te_5$ is in crystalline state, light is output from a bar port. The switch structure was optimized using FDTD (finite-difference time-domain) simulation method. The examples of light propagation in the switch are shown in Fig. 4(b). This switch had only 2×10 μm^2 dimensions. Switching operation was successfully demonstrated by FDTD method. The loss of 0.5 dB and the crosstalk of -20.5 dB were achieved for the cross-state with an optimized structure. The loss of 3.0 dB and the crosstalk of -7.8 dB were achieved for the bar-state.

Conclusion:

We proposed optical switches using phase change material. The MMI type optical gate switch was fabricated and fast switching, wide operating wavelength range, and more than two thousand switching cycles were confirmed. A 2x2 directional coupling optical switch was designed and the characteristics were simulated with FDTD method.

Acknowledgements:

Authors are very grateful to Dr. Yuya Shoji of Tokyo Institute of Technology for fabrication of devices. This work is partially supported by research and development program for innovative energy efficiency technology program (the New Energy and Industrial Technology Development Organization).

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