ELectronics EXpress

LETTER

IEICE Electronics Express, Vol.11, No.15, 1–5

Ultra-compact, self-holding asymmetric Mach-Zehnder interferometer switch using $Ge_2Sb_2Te_5$ phase-change material

Takumi Moriyama[1a)], Daiki Tanaka[1], Paridhi Jain[1], Hitoshi Kawashima[2], Masashi Kuwahara[2], Xiaomin Wang[2], and Hiroyuki Tsuda[1]

[1] *Graduate School of Science and Technology, Keio University, 3–14–1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223–8522, Japan*

[2] *National Institute of Advanced Industrial Science and Technology, 1–1–1 Umezono, Tsukuba, Ibaraki 305–8568, Japan*

a) *moriyama@tsud.elec.keio.ac.jp*

Abstract: An asymmetric Mach-Zehnder interferometer optical switch using phase-change material (PCM) is reported. In this switch, two $Ge_2Sb_2Te_5$ thin films, each 1 µm in diameter, are deposited on a Si waveguide, and are used as phase shifters. The PCM can be reversibly switched between the amorphous and crystalline states. The difference in refractive index between the two states is very large, typically more than 2. Therefore, an optical switch using the PCM can be very small. The switching operation is successfully demonstrated by laser pulse irradiation. The maximum extinction ratio is 26.7 dB, and 2.2-nm peak wavelength shift is verified.

Keywords: optical switch, phase change material, optical waveguide

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

[1] Y. Ikuma, Y. Shoji, M. Kuwahara, X. Wang, K. Kintaka, H. Kawashima, D. Tanaka and H. Tsuda: Electron. Lett. **46** (2010) 368. DOI:10.1049/el.2010.3588

[2] Y. Ikuma, Y. Shoji, M. Kuwahara, X. Wang, K. Kintaka, H. Kawashima, D. Tanaka and H. Tsuda: Electron. Lett. **46** (2010) 1460. DOI:10.1049/el.2010.2538

[3] D. Tanaka, Y. Shoji, M. Kuwahara, X. Wang, K. Kintaka, H. Kawashima, T. Toyosaki, Y. Ikuma and H. Tsuda: Opt. Express **20** (2012) 10283. DOI:10.1364/OE.20.010283

[4] P. Jain, D. Tanaka and H. Tsuda: Photonics in Switching (2012) Th-S4-P09.

[5] T. Moriyama, D. Tanaka, P. Jain and H. Tsuda: Integrated Photonics Research, Silicon and Nano Photonics (2013) IT4A.4.

[6] T. Moriyama, H. Kawashima, M. Kuwahara, X. Wang, H. Asakura and H.

DOI: 10.1587/elex.11.20140538
Received June 5, 2014
Accepted June 23, 2014
Publicized July 11, 2014
Copyedited August 10, 2014

Tsuda: Optical Fiber Communication Conference and Exhibition (2014) Tu3E.4.
[7] V. Weidenhof, I. Friedrich, S. Ziegler and M. Wuttig: J. Appl. Phys. **89** (2001) 3168. DOI:10.1063/1.1351868

1 Introduction

In wavelength division multiplexing (WDM) optical network systems, optical switches can be used to reduce the power consumption and enhance the throughput. In particular, self-holding characteristics are necessary for energy efficient routing nodes. Previously, we proposed optical switches using phase-change material (PCM) [1, 2, 3, 4, 5, 6] that were suitable for such applications. PCM has two stable states at around room temperature, an amorphous state and a crystalline state [7]. The difference in the refractive index between the amorphous and crystalline states is very large, thus making it possible to miniaturize the optical switch. In addition, the switching time is less than 400 ns, which is much shorter than that of thermo-optic switches. With the PCM switch we achieved stable repetitive switching over 2000 times [3]. In this letter, we describe the fabrication of an asymmetric Mach-Zehnder interferometer (MZI) optical switch using $Ge_2Sb_2Te_5$ and report on a demonstration of the switching operation by laser pulse irradiation onto small-area $Ge_2Sb_2Te_5$ films on the Si waveguides.

2 Device structure

The optical switch is based on a 1×1 asymmetric MZI, as shown in Fig. 1. The difference in arm length (ΔL) determines the free spectral range (FSR) of the switch. In our design, ΔL is 150 µm and the calculated FSR is 4.0 nm. A multi-mode interference (MMI) coupler is used as a 3-dB coupler for the switch. Two circular-shaped thin $Ge_2Sb_2Te_5$ films are deposited on one of the arms as phase shifters. $Ge_2Sb_2Te_5$ has complex refractive indices of 4.39–0.16i for the amorphous state and 7.25–1.55i for the crystalline state at a wavelength of 1.55 µm. Although $Ge_2Sb_2Te_5$ was deposited on each arm of the MZI in the optical switch we reported previously [6], $Ge_2Sb_2Te_5$ was deposited on only one of the arms in this design to demonstrate switching by smaller $Ge_2Sb_2Te_5$ features.

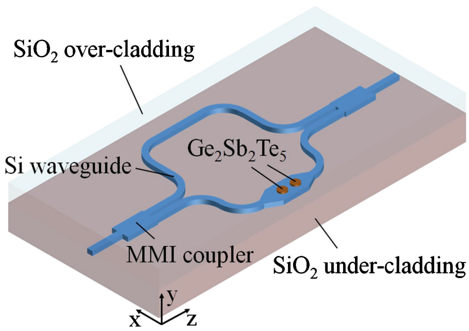

Fig. 1. Structure of asymmetric MZI optical switch using $Ge_2Sb_2Te_5$ and Si waveguides.

© IEICE 2014
DOI: 10.1587/elex.11.20140538
Received June 5, 2014
Accepted June 23, 2014
Publicized July 11, 2014
Copyedited August 10, 2014

The feature sizes of the switch around the $Ge_2Sb_2Te_5$ films are shown in Fig. 2. The diameter and thickness of the thin $Ge_2Sb_2Te_5$ films are 1 µm and 30 nm, respectively. The diameter of the $Ge_2Sb_2Te_5$ films is designed to match the spot size of the laser. To relax the fabrication tolerance, the core width of the Si waveguide on which the $Ge_2Sb_2Te_5$ film is deposited is widened from 0.45 µm to 2 µm using taper waveguides with a length of 100 µm.

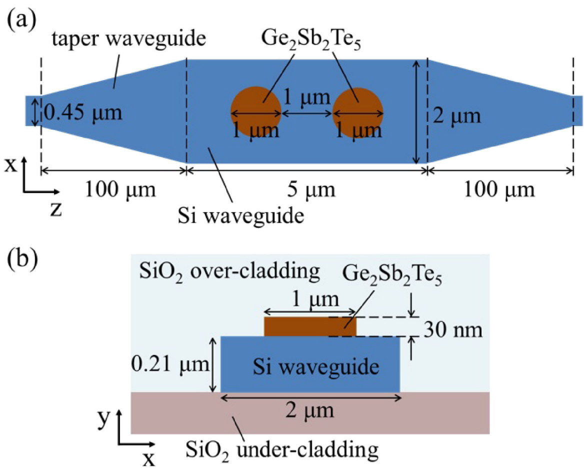

Fig. 2. Feature sizes of the $Ge_2Sb_2Te_5$ films and the Si waveguide. (a) top view. (b) cross-section view.

3 Device fabrication

The optical switch was fabricated using a typical silicon-on-insulator (SOI) wafer, with a 210-nm thick top Si layer. The fabrication process is as follows. The resist on the SOI was patterned using electron beam (EB) lithography, and the Si waveguides were formed by reactive ion etching (RIE). The resist pattern for the thin $Ge_2Sb_2Te_5$ films was formed by another EB lithography process and $Ge_2Sb_2Te_5$ was deposited by sputtering. After that, the thin circular-shaped $Ge_2Sb_2Te_5$ films were formed by a lift-off process. Finally, a 2 µm-thick SiO_2 over-cladding layer was deposited on the whole of the device by plasma-enhanced chemical vapor deposition (PCVD). Microscopic images of the fabricated switch are shown in Fig. 3. In order to optimize the laser pulse conditions for phase change of $Ge_2Sb_2Te_5$, the test pattern of $Ge_2Sb_2Te_5$ was also fabricated near the waveguide. Unremoved resist remains between the $Ge_2Sb_2Te_5$ circles, as shown in Fig. 3(b).

4 Experimental setup

Fig. 4 shows the experimental setup for device characterization. The transmission characteristics of the switch were measured with continuous wave (CW) light emitted from a tunable laser source (TLS). The wavelength range was set to 1540 nm–1560 nm and the input power was 0 dBm. The polarization of the light was fixed to be in the transverse electric (TE) mode, and light was coupled to the Si waveguide with a lens fiber. Each input and output waveguide at the edge of the chip had a spot size converter to reduce coupling loss. The output light was also collected by a lens fiber and detected by a

DOI: 10.1587/elex.11.20140538
Received June 5, 2014
Accepted June 23, 2014
Publicized July 11, 2014
Copyedited August 10, 2014

ELectronics EXpress

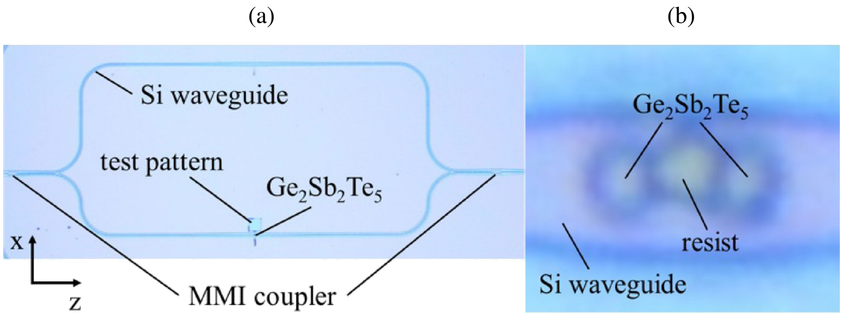

Fig. 3. Microscopic images of the fabricated switch. (a) Top view of the switch. (b) Enlarged view around the $Ge_2Sb_2Te_5$.

photo diode (PD). A laser diode (LD) with a lasing wavelength of 660 nm was used to change the phase of the $Ge_2Sb_2Te_5$. This was biased at the threshold and directly modulated by a pulse generator (PG). The laser pulses were guided by a single mode fiber (SMF) and focused onto the $Ge_2Sb_2Te_5$ film with a spot-size of about 1 µm using a lens with a numerical aperture (NA) of 0.8. A broad, weak pulse for crystallization and a relatively short, intense pulse for amorphization are used in general. We optimized the pulse conditions, and decided to use a pulse with a width of 400 ns and a peak power of 70 mW for crystallization, and a pulse with a width of 70 ns and a peak power of 160 mW for amorphization. The two $Ge_2Sb_2Te_5$ films were both irradiated.

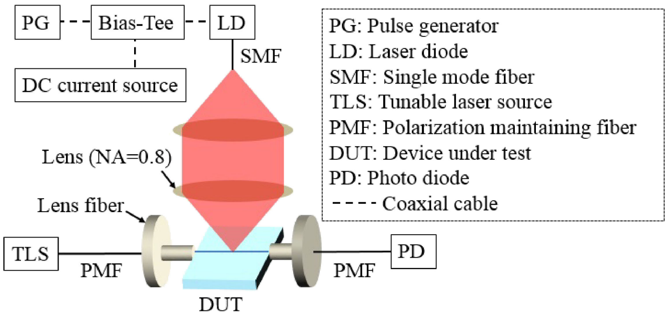

Fig. 4. Experimental setup for device characterization.

5 Experimental results

Fig. 5 shows the transmittance of the asymmetric MZI switch as a function of wavelength. This result includes a coupling loss between the lens fiber and the Si waveguide. The initial state of the $Ge_2Sb_2Te_5$ is crystalline. We performed amorphization and crystallization of $Ge_2Sb_2Te_5$ alternately and verified the switching operation. In the wavelength range of 1540 nm–1560 nm, the average FSR is 3.8 nm, and the average peak wavelength shift of the 1st switching (crystalline to amorphous), 2nd switching (amorphous to crystalline) and 3rd switching (crystalline to amorphous) events are 2.3 nm, 2.4 nm and 2.3 nm, respectively. The maximum extinction ratio, achieved at a wavelength of 1554.1 nm for the 1st switching event, is 26.7 dB, with a peak wavelength shift of 2.2 nm, as shown in Fig. 5(b). This result means that greater than π-phase shift of the light is obtained by the phase change in the $Ge_2Sb_2Te_5$. During each state, transmission spectra were maintained without any input light.

DOI: 10.1587/elex.11.20140538
Received June 5, 2014
Accepted June 23, 2014
Publicized July 11, 2014
Copyedited August 10, 2014

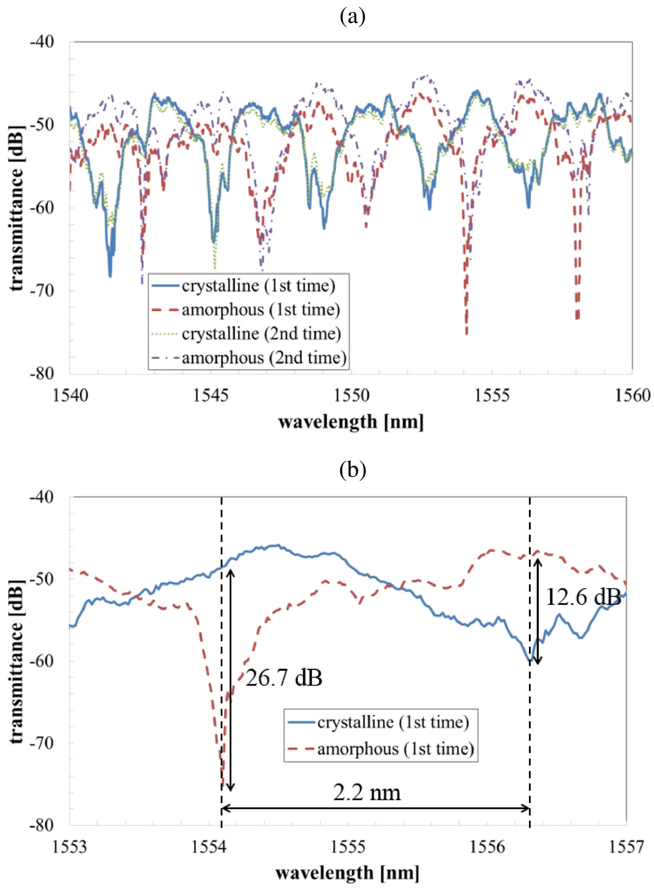

Fig. 5. Wavelength dependence of the asymmetric MZI switch. (a) Wavelength range of 1540 nm–1560 nm. (b) Wavelength range of 1553 nm–1557 nm (1st switching).

Thus, self-holding characteristics of this device were confirmed. However, the insertion loss is very large because of the large absorption coefficient of $Ge_2Sb_2Te_5$ (The insertion loss of Si waveguide is about 25 dB and that of $Ge_2Sb_2Te_5$ (crystalline)/Si waveguide is about 40 dB). This issue will be solved by using a PCM that has a lower absorption coefficient than $Ge_2Sb_2Te_5$. In addition, one of the reasons of the large loss may be due to the imperfect fabrication and the remaining resist flake near the PCM film.

6 Conclusion

A small-sized phase-change optical switch was designed and fabricated. In three times of switching operations, the maximum extinction ratio and peak wavelength shift were 26.7 dB and 2.2 nm, respectively. The total length of the phase shifter on the Si waveguide was only 3 µm. Switching operation was demonstrated by laser irradiation of the thin $Ge_2Sb_2Te_5$ film. Moreover, self-holding characteristics were confirmed, enabling us to operate with low power.

Acknowledgments

This research was partially supported by the Ministry of Education, Culture, Sports, Science and Technology.

DOI: 10.1587/elex.11.20140538
Received June 5, 2014
Accepted June 23, 2014
Publicized July 11, 2014
Copyedited August 10, 2014