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LETTER

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Amplitude trimming of Si waveguides using phase change material

Ryutaro Eguchi[1a)], Hideaki Asakura[1], Yasuro Shimazaki[1], Takumi Moriyama[1], Ghanshyam Singh[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] *Malaviya National Institute of Technology Jaipur, J. L. N. Road, Jaipur (Rajasthan) 302017, India*

a) *r.eguchi@tsud.elec.keio.ac.jp*

Abstract: A transmission trimming method for Si waveguides using phase change material (PCM) is proposed. We used a 3D-finite difference time domain (3D-FDTD) method to calculate the phase and the loss of light induced by the trimming structures. With five small square patches of PCM on the waveguide, transmission trimming up to 32 levels can be achieved. It was found that the crosstalk of a MZI type optical switch can be reduced when the splitting ratio of the first coupler is corrected using this method.

Keywords: silicon photonics, after-fabrication trimming, phase change material

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

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1 Introduction

Si photonics [1, 2, 3] has a number of advantages over other communication technologies which can miniaturize optical devices and, moreover, is compatible with complementary metal oxide semiconductor (CMOS) fabrication technology. As such, there has been a great deal of research in this area in recent years. However, Si waveguides, which are important components in Si photonics, are sensitive to the roughness of the sidewall surface. The roughness causes fluctuations in the effective refractive index of the waveguide causing errors in the phase and amplitude of the propagating light. These degrade the performance of optical devices based on light interference such as arrayed waveguide gratings (AWG) and Mach Zehnder interferometers (MZI) [4, 5, 6]. In order to improve the performance of Si optical devices, post-fabrication trimming techniques [7, 8, 9] that suppress amplitude errors are needed.

We have previously reported optical switches using phase change material (PCM) [10, 11, 12, 13], and we have proposed a phase and an amplitude trimming method for Si optical devices utilizing PCM [14]. PCM has two stable states at room temperature, amorphous and crystalline. The refractive indices of PCM in these states are very different; therefore, a small piece of PCM located near to the waveguide is sufficient to adjust the amplitude of the propagating light. The crystalline state changes to the amorphous state by raising the temperature of the PCM above the melting point and rapidly quenching it; and the amorphous state changes to the crystalline state by raising the temperature above the crystallization temperature and gradual cooling it. In this letter, we report on calculations for determining the size and position of the PCM films required to adjust the amplitude of the light for MZI type optical switch.

2 Phase and amplitude trimming structure

The proposed trimming structure for the Si waveguide is shown schematically in Fig. 1(a). Several small-sized thin film PCM layers are deposited on the Si waveguide, and their states are changed to control the phase and amplitude of the

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propagating light. The size of each film is approximately equal to the spot size of the irradiating laser beam.

We used nitrogen-doped GeTe [15], which has a relatively lower refractive index and a lower extinction coefficient than other PCM; hence a scattering loss and an absorption loss can be suppressed compared to other PCMs.

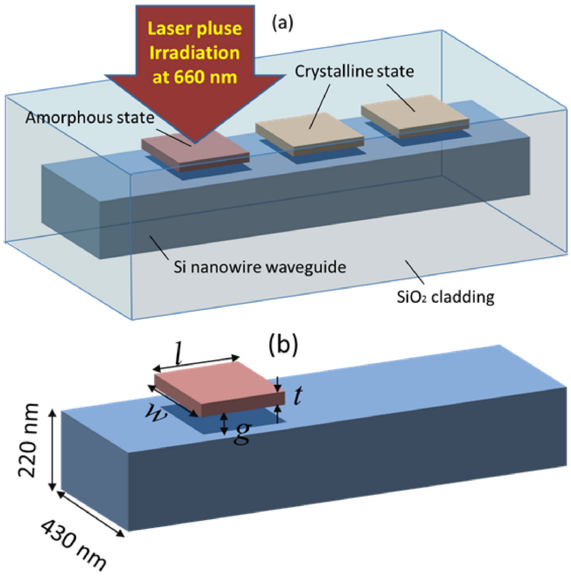

Fig. 1. (a) Trimming structure for a Si waveguide using thin PCM films. (b) Simulation model.

3 Simulation of the trimming conditions

The transmission loss, loss change, and phase shift induced by the phase change for the transverse electric (TE) mode at a wavelength of 1.55 µm were calculated using a 3D-finite difference time domain (3D-FDTD) method. The complex index of nitrogen-doped GeTe changes depending on the amount of doping. In our research, we assumed the complex indices of nitrogen-doped GeTe in the crystalline and amorphous states to be 3.89 − 0.018 and 3.31 − 0.000i, respectively. The phase shift $\varDelta\varPhi$ and loss change $\varDelta L$ are defined by the following equations;

$$\varDelta\varPhi = |\varPhi_{cry} - \varPhi_{amo}| \tag{1}$$

$$\varDelta L = |L_{cry} - L_{amo}| \tag{2}$$

where $\varPhi_{amo}$, $\varPhi_{cry}$ are the phases of the output light when the PCM film is in the crystalline and amorphous states, respectively. L_{amo}, L_{cry} are the losses for the crystalline and amorphous states, respectively. We studied the dependence of $\varDelta\varPhi$, L, and $\varDelta L$ on the PCM thickness, t, and the gap between the Si waveguide and the PCM film, g, as shown in Fig. 1(b). The refractive index and extinction coefficient of the crystalline state are higher than those of the amorphous state for nitrogen-doped GeTe. Therefore, the phase of the light in the crystalline state is delayed compared to that in the amorphous state, and the transmission loss in the crystalline state is higher than that in the amorphous state. That is, $\varPhi_{cry} > \varPhi_{amo}$, $L_{cry} > L_{amo}$.

The range of t used in the calculations was from 20 to 50 nm because the state of the PCM film can be changed by a single laser pulse when t is less than about 50 nm. Fig. 2 shows the simulation results when the length, l, and width, w, of the

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PCM were fixed at $l = 1000$ nm and $w = 350$ nm. As t increases in thickness or g decreases, L and ΔL become larger as seen in Fig. 2(a) and 2(c).

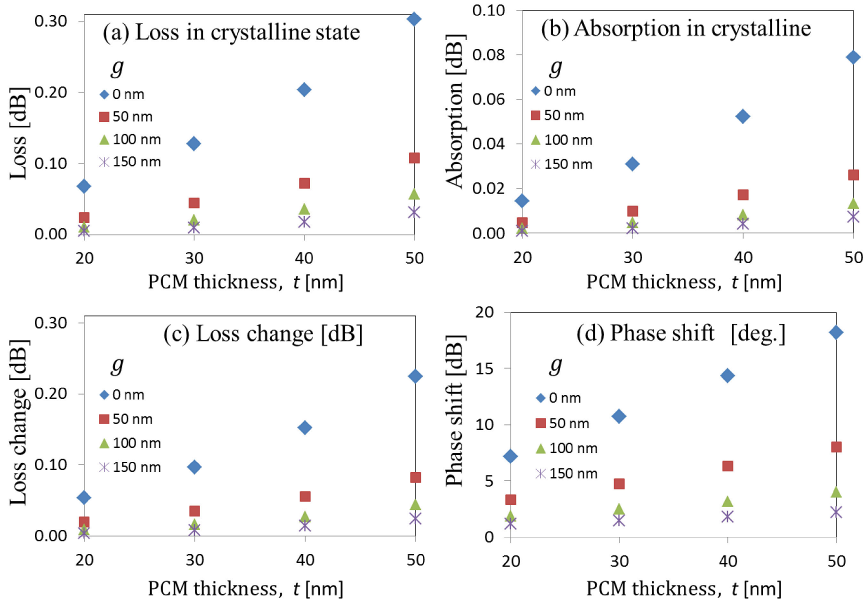

Fig. 2. Calculated (a) L_{cry}, (b) absorption in the crystalline state, (c) ΔL and (d) $\Delta\Phi$ by 3D-FDTD.

Since the phase shift $\Delta\Phi$ is relatively small compared to the L and ΔL, the unallowable large loss and loss change will be caused when phase trimming will be performed. Therefore, to perform phase trimming with PCM is difficult unless the loss and loss change is reduced. Transmission trimming is shown in the following.

We can perform 2^n level transmission trimming with n PCM patches. If there are five PCM patchs on the trimming structure with $\Delta L = x$, $2x$, $4x$, $8x$, and $16x$ [dB], respectively, 32-level transmission compensation can be performed. Using this 32 level transmission trimming as shown in Table I, a deviation of up to 5.6% in the splitting ratio of the first coupler can be balanced. The maximum loss change is about 0.768 dB with a phase shift of 18.56 degree if all size of PCM patches are used.

Table I. Parameters of the PCM patches in the trimming structure. g = 50 nm, t = 50 nm for all PCM films.

ΔL [dB]	w [nm]	l [nm]	$\Delta\Phi$ [deg.]	Excess loss (in amorphous state)
0.023	300	200	0.74	0.07
0.048	300	400	1.89	0.09
0.098	400	400	2.91	0.11
0.200	600	400	4.35	0.16
0.399	700	600	8.67	0.21

4 Amplitude trimming for MZI type optical switch

The performance of a MZI, such as the crosstalk, can deteriorate if there is an imbalance between the splitting ratios of the couplers. For the MZI type optical

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switch, the imbalance of the first coupler can be compensated using our trimming method.

Fig. 3 shows schematic of MZI type optical switch with the trimming structure. The output electric fields, E_{bar} and E_{cross}, which are the bar port output and cross port output, respectively, are represented by:

$$E_{bar} = \sqrt{m_2}E_1{}' - \sqrt{(1-m_2)}E_2' \tag{3}$$

$$E_{cross} = \{\sqrt{(1-m_2)}E_1' + \sqrt{m_2}E_2')\}\exp\left(-\frac{i\pi}{2}\right) \tag{4}$$

where $E_1{}'$ and $E_2{}'$ are electric fields in arm1 and arm2 after passing through trimming part of PCM, respectively and the splitting ratios of the first and second couplers are $m_1{:}1 - m_1$ and $m_2{:}1 - m_2$, respectively. $E_1{}'$ and $E_2{}'$ are represented below:

$$E_1' = \sqrt{m_1 10^{\frac{-L_1}{10}}}E_1\exp(-i\phi_1) \tag{5}$$

$$E_2' = \sqrt{m_2 10^{\frac{-L_2}{10}}}E_2\exp\{-i(\phi_L + \phi_2)\} \tag{6}$$

where L_1 [dB] and L_2 [dB] are losses generated by all PCM patches on arm1 and arm2, respectively. ϕ_1 and ϕ_2 are phase shifts generated by all PCM patches on arm1 and arm 2, respectively, and ϕ_L is phase difference. Therefore, a substantive splitting ratio of the first coupler, $m_1{}'$ is:

$$m_1' = \frac{|E_1'|^2}{|E_1'|^2 + |E_2'|^2} \tag{7}$$

State of each PCM patch are arranged and L_1 and L_2 are changed so that the value of $m_1{}'$ closes to 0.5. As a result, worse crosstalks which can be calculated using equations (3) and (4) are improved. On the otherhand, the imbalance between optical lengthes of both arms that arises with amplitude trimming can be corrected by the bias conditions of the optical switch.

The crosstalk in the bar state and the cross state of a MZI type optical switch was successfully supressed both for $m_1 > m_2$, $m_1 < m_2$ and $m_1 = m_2$, as shown in Table II.

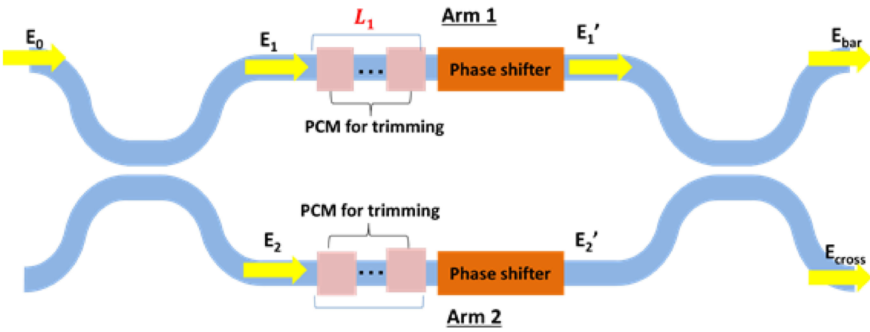

Fig. 3. MZI-type optical switch with the trimming structure.

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Table II. Crosstalk before and after compensation. CT (bar) is the crosstalk of output 1 in the bar state. CT (cross) is the crosstalk of output 2 in the cross state.

Before compensation			After compensation		
m_1	m_2	Worst CT [dB]	CT (bar) [dB]	CT (cross) [dB]	Excess loss [dB]
0.47	0.47	−24.42	−30.48	−30.42	−1.18
0.48	0.48	−27.95	−34.01	−33.94	−1.02
0.49	0.49	−33.98	−40.25	−39.76	−0.88
0.51	0.51	−33.98	−40.25	−39.76	−0.88
0.52	0.52	−27.95	−34.01	−33.94	−1.02
0.53	0.53	−24.42	−30.48	−30.42	−1.18
0.47	0.5	−30.45	<−60	<−60	−1.18
0.48	0.5	−33.98	<−60	<−60	−1.02
0.49	0.5	−40.00	<−60	<−60	−0.88
0.47	0.52	−26.01	−33.93	−34.02	−1.18
0.48	0.52	−27.95	−33.94	−34.01	−1.02
0.49	0.52	−30.45	−33.85	−34.10	−0.88

5 Conclusions

A transmission trimming method for Si waveguides that utilizes PCM in order to compensate for the deterioration in performance is proposed. The phase and the loss of light propagating through the structure with the PCM patches were calculated using a 3D-FDTD method. The phase shift and loss change resulting from the change in phase of the PCM were calculated. 2^n level transmission trimming can be performed with n PCM patches and this can be used to balance the splitting ratios between the MZI couplers. We calculated the crosstalk of a MZI type optical switch with couplers of variable splitting ratios before and after transmission trimming. The trimming method was found to be effective for reducing the crosstalk in the MZI.

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