European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Ultra-Fast Optical Switching Using Differential Control Method

Kohei Iino and Tomohiro Kita*

Faculty of Science and Technology, Department of Applied Physics, Waseda University,
kohei.bryant24@toki.waseda.jp, *tkita@waseda.jp

Abstract *A differential control method was applied to a thermo-optic MZI optical switch loaded with MMI phase shifters capable of high-speed, low-power-consumption switching operation. The obtained switching time was 28 ns for τ_{rise} and 20 ns for τ_{fall}, extremely fast optical switching operation has been demonstrated.*

Introduction

MZI type optical switches with low loss and wide wavelength band are key devices in short-distance networks and sensing technology such as LiDAR, and are required to have low manufacturing cost, space saving, high speed, and low power consumption. Thermo-optical (TO) SOI optical switches that meet these requirements are the most important components in integrated optical circuits [1-3].

We have previously developed a high speed phase shifter (PS) with directly injecting a current through a silicon optical waveguide using multi-mode interference (MMI), and has achieved high-speed switching operation of several microseconds [4]. The switching time of the TO-MZI optical switch is limited by the thermal time constant of the PS. Although the speed of sub-micro seconds has been increased by reducing the heat capacity of the phase shifter [5], there is a limit to reducing the heat capacity. In this research, further speedup was realized by differentially controlling the voltage applied to the two PSs.

Low loss direct heating phase shifter using multi-mode interference

In the TO-MZI optical switch, since the refractive index of the silicon core is changed by the TO effect, high-speed switching operation is possible by rapidly changing the temperature of the silicon core. When heating a material, the time constant of the temperature change is inversely proportional to the heat capacity of the material, so it is important to reduce the heat capacity of the material to be heated. In the conventional TO-PS, the waveguide core was heated through the thick upper SiO_2 cladding of 1 μm or more, so the heat capacity of the heating region including the upper cladding is large, and the switching speed of several tens of μs is the limit. High-speed switching operation of several μs has been realized by thermo-optic phase shifter that injects current directly into the silicon waveguide However, the scattering of the propagating light due to the electrode structure for injecting a current becomes a serious problem. A low-loss thermo-optical phase shifter using MMI in silicon waveguide with the 10 period electrodes structure was used for current injection [4].

The schematic of a TO-MZI optical switch with MMI-PS is shown in Fig. 1. PS1 and PS2 are loaded on each path of MZI. By heating the PS, the optical switch turns on when the phase difference between PSs is 0, $2\pi\cdots$ and turns off when the phase difference is π or $3\pi\cdots$. In the TO-MZI optical switch, the switching operation is

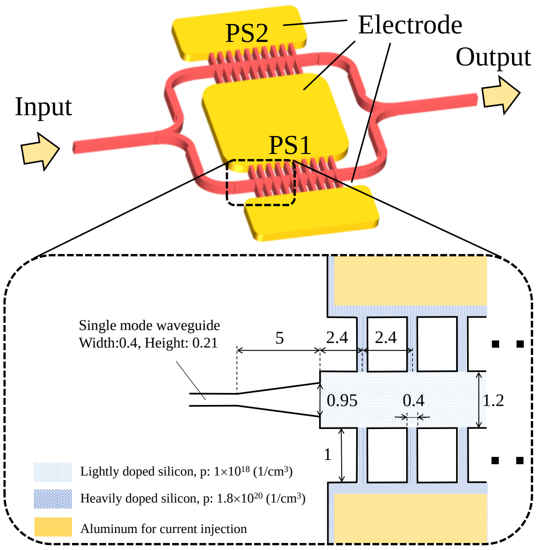

Fig. 1: Schematic of TO-MZI optical switch with MMI PS. The inset shows structural detail of MMI-PS. The unit of dimension in the figure is μm.

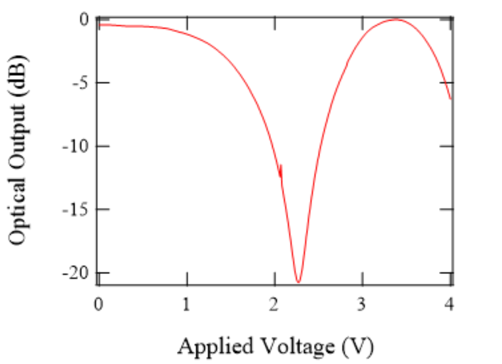

Fig. 2: Optical output applying DC voltage to PS1

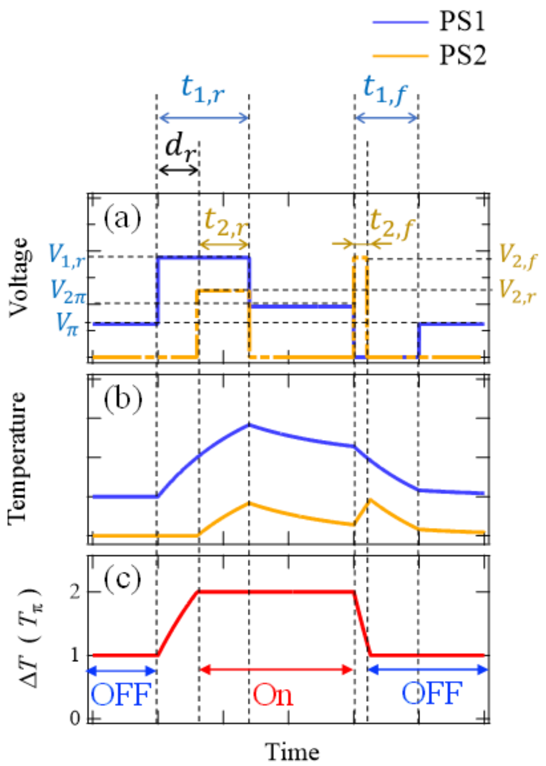

Fig. 3: Scheme of differential control method. (a) Applied voltages to PSs. (b) Temperatures of PSs.

performed by the temperature difference T_π at which the phase difference is π. Figure 2 shows the change in light intensity when a DC voltage is applied to PS1. The power consumption of this optical switch was 20.7 mW, and the switching time when the pulse voltage was applied to PS1 was about 4 μs.

Differential control of MZI optical switch

A scheme of differential control method is shown in Fig.3. Voltage of V_π is applied to PS1 in the initial state, and the optical switch is turned off due to the temperature difference of T_π between the two PSs. Next, when a large pulse voltage $V_{1,r}$ (pulse width: $t_{1,r}$) is applied to PS1, the temperature of PS1 rises sharply. However, the temperature difference ΔT becomes too large due to the too large pulse voltage. By applying a pulse voltage $V_{2,r}$ (pulse width: $t_{2,r}$) to PS2 with delay time d_r, the ΔT is maintained at $2T_\pi$, and the optical switch is turned on. After applying the pulse, apply the voltage of $V_{2\pi}$ to PS1 and maintain the ON state. When switching the light to the OFF state, the voltage of PS1 is set to 0 during $t_{1,f}$ to decrease the temperature of PS1. By applying a pulse voltage to PS2 $V_{2,f}$ (pulse width: $t_{2,f}$) and rapidly raising the temperature of PS2, the temperature difference between PSs rapidly decreases to T_π. Finally, the OFF state is maintained by setting the applied voltage of PS1 to V_π. The differential control method that appropriately controls the applied voltage to the two phase shifters and the method allows us to perform high-speed optical switching that overcomes the limit of the thermal time constant of the PSs.

Time response in overdrive control

In the measurement of the switching time, the signal from a 2-channel function generator (Tektronix AFG3102C) was amplified by a high-speed voltage amplifier (NF corporation HSA4011) and applied to the PSs. TE-polarized light with 1.55 μm wavelength from wavelength tunable laser diode (santec TSL-550) was inputted to TO-MZI, the transmitted light from the optical switch was detected by a photodetector (Terahertz Technology TIA-525), and the rise time τ_{rise} when the light intensity changed from 10% to 90% and the fall time τ_{fall} when the light intensity changed from 90% to 10% were measured by a digital oscilloscope (Tektronix TBS2000B). The rising and falling time constants of the pulse voltage of this measurement system

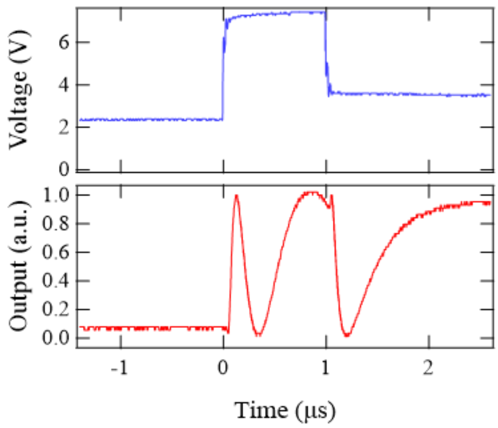

Fig. 4: Time response of optical output by overdrive control when the optical intensity rises.

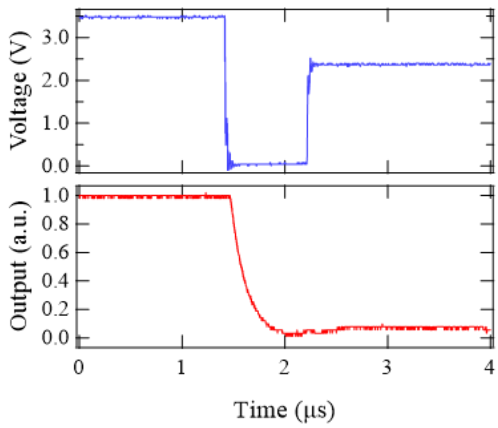

Fig. 5: Time response of optical output by overdrive control when the optical intensity falls.

are 16 ns and 10 ns, respectively.

Before performing the differential control, the time response by the overdrive control in which a voltage larger than V_π was applied to one PS was measured [6]. Figure 4 shows the time dependence of the applied voltage to PS1 and the output light intensity when the optical switch is switched from the OFF state to the On state. Since the pulse voltage to PS2 is not applied, ON state cannot be maintained, but the τ_{rise} of 40 ns was obtained. Similarly, Fig. 5 shows the measurement results of the fall time with overdrive control only for PS1. The τ_{fall} of 330 ns was obtained.

Time response in differential control

The switching speed of the differential control that applies the pulse voltage to both PS1 and PS2 was measured. Figure 6 shows the time response when the optical switch turned on. It can be confirmed that the ON state can be maintained even after the pulse voltage is applied by the differential control. However, the light intensity is slightly decreased after the pulse voltage is applied. This is because, unfortunately, $V_{2\pi}$ has changed slightly from the result of the pre-measurement due to the change of resistance over time. It will be improved by applying appropriate $V_{2\pi}$. The dotted line in the figure is the light intensity of 0.1 and 0.9 normalized by the light intensity when $V_{2\pi}$ is applied. By using differential control method, very fast τ_{rise} of 28 ns was obtained. Figure 7 shows the time response when switching from the ON state to the OFF state. It can be confirmed that the temperature difference between PSs decreases rapidly by applying the pulse voltage to PS2, and the light intensity decreases. The τ_{fall} of the differentially controlled optical switch was 20 ns. The optimized differential control parameters obtained as a result of detailed measurements are shown in Tab. 1. The optical switching time obtained in this study is the world record for a TO-MZI optical switch as far as we know. Moreover, the obtained τ_{rise} and τ_{fall} are comparable to the rising and falling time constants of the applied pulse voltage. Further speedup can be expected by improving the measurement system.

Conclusion

A differential control method was applied to a TO -MZI optical switch loaded with MMI phase shifters capable of high-speed, low-power-consumption switching operation. The obtained switching time was 28 ns for τ_{rise} and 20 ns for τ_{rise}, which was 1/10 or less faster than the previous report. This extremely fast optical switch will be an indispensable key component for short-range communications such as data centers and high-speed real-time sensing such as LiDAR.

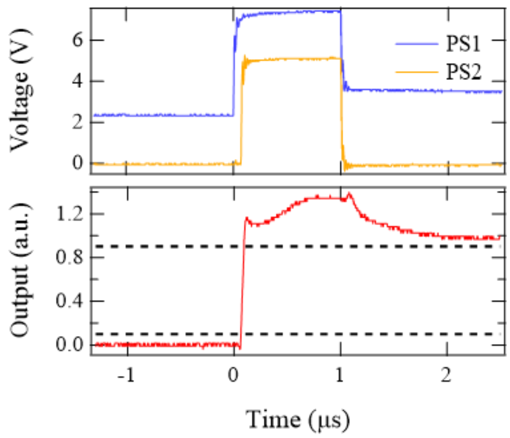

Fig. 6: Time response of optical output by differential control when the optical intensity rises.

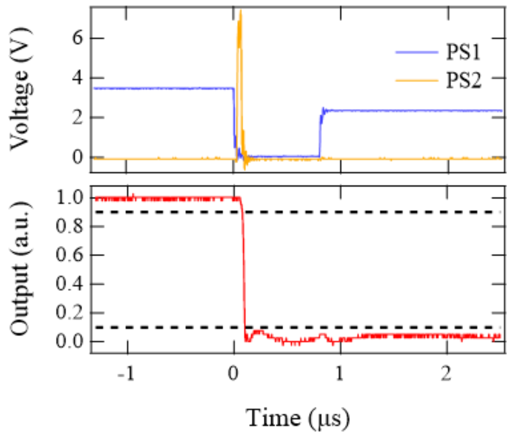

Fig. 7: Time response of optical output by differential control when the optical intensity falls.

Tab. 1: Optimized parameter in differential control method.

$V_{1,r}$ (V)	7.4	$V_{2,r}$ (V)	5.3
$t_{1,r}$ (μs)	1	$t_{2,r}$ (μs)	0.92
$t_{1,f}$ (μs)	0.8	$V_{2,f}$ (V)	7.4
V_π (V)	2.32	$t_{2,f}$ (μs)	0.04
$V_{2\pi}$ (V)	3.52	d_r (μs)	0.08

Acknowledgement

This study was supported in part by the Commissioned Research of the National Institute of Information and Communications Technology (NICT), Japan, and JSPS KAKENHI Grant Number JP 19H02634.

References

[1] Qixiang Cheng, Sebastien Rumley, Meisam Bahadori, and Keren Bergman, "Photonic switching in high performance datacenters," Optical Express, Vol 26, No. 12, pp. 16022-16043, 2018.

DOI: 10.1364/OE.26.016022

[2] Noel H. Wan, Tsung-Ju Lu, Kevin C. Chen, Michael P. Walsh, Matthew E. Trusheim, Lorenzo De Santis, Eric A. Bersin, Isaac B. Harris, Sara L. Mouradian, Ian R. Christen, Edward S. Bielejec, and Dirk Englund, "Large-scale integration of artificial atoms in hybrid photonic circuits," Nature, Vol. 583, pp. 226-231, 2020.

DOI: 10.1038/s41586-020-2441-3

[3] Christopher Rogers, Alexander Y. Piggott, David J. Thomson, Robert F. Wiser, Ion E. Opris, Steven A. Fortune, Andrew J. Compston, Alexander Gondarenko, Fanfan Meng, Xia Chen, Graham T. Reed, and Remus Nicolaescu, "A universal 3D imaging sensor on a silicon photonics platform", Nature, Vol.590, pp. 256-261, 11 Feb. 2021.

DOI: 10.1038/s41586-021-03259-y

[4] Manuel Mendez-Astudillo, Masaki Okamoto, Yoshiaki Ito, and Tomohiro Kita, "Compact thermo-optic MZI switch in silicon-on-insulator using direct carrier injection" Optics Express, Vol. 27, No. 2, pp. 899-960, Jan. 2019.

DOI: 10.1364/OE.27.000899

[5] Tomohiro Kita and Manuel Mendez-Astudillo, "Ultrafast silicon MZI optical switch with periodic electrodes and integrated heat sink", Journal of Lightwave Technology, Vol. 39, pp. 5054-5060, 2021.

DOI: 10.1109/JLT.2021.3082634

[6] Masaki Okamoto, Manuel Mendez-Astudillo, and Tomohiro Kita, "Thermo-optic phase shifter with sub-microsecond switching time and low power consumption", Japanese Journal Applied Physics, 59, SOOA03, pp.1-5, Jun. 2020.

DOI: 10.35848/1347-4065/ab9c42