Sub-μs Switching Time in Silicon-on-Insulator Mach–Zehnder Thermooptic Switch

Mikko Harjanne, Markku Kapulainen, Timo Aalto, and Päivi Heimala

***Abstract*—We have demonstrated both rise and fall times below 1 μs with 10%–90% modulation in a silicon-on-insulator thermooptical Mach–Zehnder switch. The switch is based on 9-μm-thick and 10-μm-wide single-mode rib waveguides. Very fast switching was achieved by using a differential control method. The switch was driven with a digital signal processor accompanied by simple electronic circuitry.**

***Index Terms*—Integrated optics, optical switches, optical waveguides, silicon-on-insulator (SOI) technology, thermooptic (TO) effects.**

I. INTRODUCTION

SILICON-ON-INSULATOR (SOI) waveguides are very promising for realizing dense photonic integrated circuits [1]. The transparency of silicon in the infrared spectral region is very high. A typical SOI waveguide has a silicon core (refractive index $n = 3.5$) surrounded by a cladding oxide, with n less than two. Therefore, the silicon core has a very high index difference with respect to the cladding, which strongly confines the electric field into the silicon layer. This means that cladding oxide layers can be made relatively thin (<1 μm) when compared, e.g., with silica-on-silicon waveguides where the required cladding oxide thickness is typically over 10 μm. SOI waveguide technology is compatible with electrical integrated circuit technology and micromechanics.

Despite the large refractive index difference, the silicon waveguide can be made single-moded even with large waveguide dimensions using a rib structure [2]. This makes SOI waveguide technology compatible with fiber-based telecommunication and interconnection devices. Large SOI waveguides have been used to demonstrate, e.g., optical couplers [3], wavelength multiplexers [4], and waveguide gratings [5], [6].

Fast modulators based on free-carrier dispersion and absorption effects have been demonstrated in silicon. Modulation frequencies as high as 1 GHz have recently been demonstrated [7]. Drawbacks of free-carrier effects are higher manufacturing costs and losses in optical switching. An alternative, particularly for low-loss, low-cost, and low-frequency applications, is to use the thermooptic (TO) effect for optical switching or modulation. SOI technology offers a relatively inexpensive method to fabricate TO switches. The high thermooptical constant ($1.86 \cdot 10^{-4}\mathrm{K}^{-1}$) and good thermal conductivity of silicon can make SOI switches faster than most other TO switches.

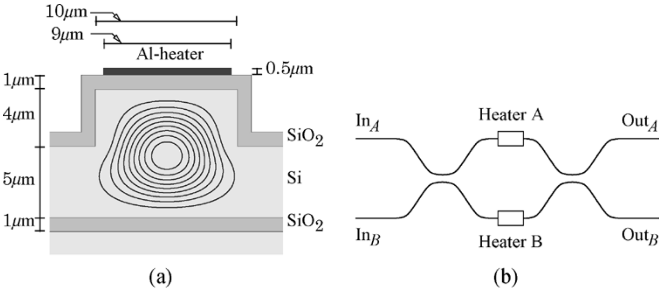

Fig. 1. (a) Cross section of the processed rib waveguide with structure dimensions. Field intensity contours are equispaced and run from 10% to 90%. (b) Schematic structure of the MZI used for measurements.

In this work, a TO switch has been realized based on SOI rib waveguides. Switching time below 1 μs was achieved by using a differential modulation technique [8].

II. SWITCH

The fast switching scheme was demonstrated with an existing 2 × 2 TO Mach–Zehnder interferometer (MZI) switch. Detailed information of the design and fabrication process of the switch is published in [8]. The switch is constructed of 9-μm-thick SOI rib waveguides with rib width of 10 μm and etch depth of 4 μm, as illustrated in Fig. 1(a). The buried oxide layer and the thermal oxide (TOX) cladding layer were both 1 μm thick. These waveguides have good coupling to standard single-mode fibers, and are also single-moded according to theory [2], computer simulations [9], and measurements.

The MZI switch structure is presented in Fig. 1(b). A TO-MZI consists of two identical 3-dB couplers and a heating resistor in one or both optical branches. The heaters are used to change the index of refraction, and hence, cause a phase difference $\Delta\varphi$ between the two optical branches. When branches have equal optical lengths, that is $\Delta\varphi = 0$, the switch is in a cross state. In this case, signal at input A comes out from output B and vice versa.

With a certain temperature difference, $\Delta\varphi = \pi$ between the branches, and the switch is in a bar state, so that signal at input A is seen at output A. The amount of heat required for this depends on several factors such as heater and waveguide dimensions, as well as thermal conductivities of materials.

In our implementation, both optical branches are equipped with 1-mm-long heating resistors having electrical resistance of approximately 9 Ω. The two 3-dB couplers were found to have nonideal coupling lengths, which led to a maximum of 15-dB power extinction ratio (ER). The fact that the maximum ER was obtained when heating was OFF suggests that the couplers are

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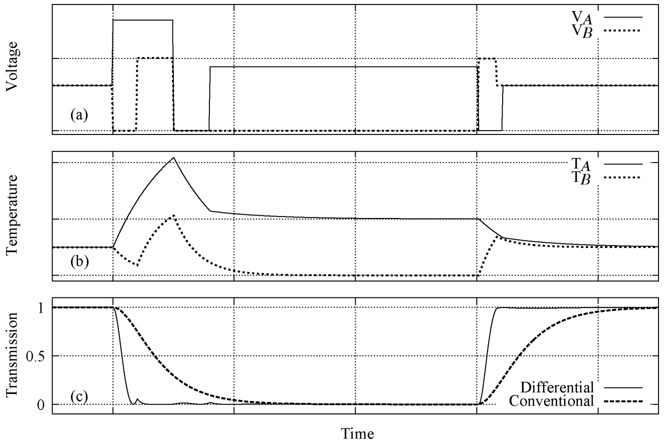

Fig. 2. Differential control method. (a) Control voltages for the two heaters A and B. (b) The resulting waveguide temperatures. (c) Optical power transmission to cross port with the differential (solid) and conventional control (dashed).

identical, and the optical power measured from the cross port is related to $\Delta\varphi$ as

$$P_X \sim \frac{1}{2}\left(1 + cos(\Delta\varphi)\right). \tag{1}$$

The switch is somewhat polarization-dependent due to the stress induced by the TOX cladding. This polarization dependency can be lowered by using a tetraethylorthosilicate layer instead of TOX [9].

III. CONTROL METHOD

In a TO MZI switch, the phase difference required for operating the switch is induced by heating the waveguide with a thin-film heater. The conventional way is not to apply any heating when the switch is in the cross state, and to use a constant heating voltage when switch is changed to the bar state. This leads to an exponential temperature stabilization during both state changes, which limits the achievable switching time.

When using an MZI-structure having heaters at both branches, such as in Fig. 1(b), switching times can be significantly reduced by driving both heaters simultaneously with different signals [8]. Fig. 2 shows the basic principle of this switching method.

A bias heating, equal in both branches, can optionally be used during the cross state to reduce the cooling time when switching from bar to cross state. The biasing adds the power consumption of the device, but this drawback is usually compensated by the shortened switching time.

To have a fast temperature change, a high voltage pulse is applied to heater A, and heater B voltage is dropped to zero. If there would be no further action, $\Delta\varphi$ would go over π, but by applying a smaller corrective pulse to heater B at exactly the same time as $\Delta\varphi = \pi$, the overshoot can be compensated. This leads to a stepwise optical response and leaves both waveguides above their target temperatures. However, the heaters cool down together along exponential curves, keeping $\Delta\varphi$ essentially the same. If the two waveguide branches cool down at different rates, some fine-tuning can be added to the heater voltages in order to keep $\Delta\varphi$ at π during the cooling period.

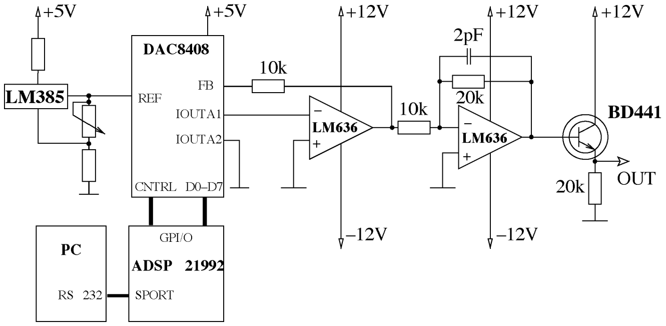

Fig. 3. Schematic representation of the control circuit.

The change from bar to cross state is handled similarly; a high-voltage pulse is applied to heater B and at the same time voltage at heater A is set to zero. When the branch temperatures coincide, both heaters are set to their cross state bias voltages. Again, some fine-tuning of voltages may be needed to compensate different cooling rates.

The temperature curves in Fig. 2(b) were calculated from the heater voltages in Fig. 2(a) by difference equation

$$T_n = T_{n-1} - \frac{(T_{n-1} - V_n K)}{\tau \Delta t} \tag{2}$$

where V_n is heater voltage during the nth time step, K is the experimentally determined relation between voltage and temperature, Δt is the time-step length, and τ is the temperature time constant which can be different for cooling and heating, as well as for the two branches. As the phase is linearly dependent on temperature, the cross port transmissions, shown in Fig. 2(c), could be calculated from the temperatures by using (1).

IV. MEASUREMENT SETUP

To demonstrate the feasibility of the differential control method, a controller shown in Fig. 3 was constructed. The heating patterns were designed on a personal computer, and these were then sent to the memory of a digital signal processor (ADSP-21 992) via serial cable. The processor was programmed to send the data as fast as possible to an 8-bit digital-to-analog (D/A) converter (DAC 8408). The low-level output of the converter was amplified with operational amplifiers to a range of 0–6.5 V, and then buffered by high-power transistors. This setup could generate 330-ns voltage pulses with a slew rate of 16 V/μs.

The processor in the setup is capable of receiving new patterns from the computer at the same time as it repeatedly sends the previous pattern to the D/A converter. This allowed for a near real-time observations of switch operation when changes were made to the heating pattern.

All measurements were made at 1550-nm wavelength with transverse-electric-polarized light. The laser light was butt-coupled to the waveguide with a polarization maintaining fiber. Power at the output was gathered from the cross-state port with a multimode fiber, and measured with a fast 15-MHz detector.

Optical power extrema were measured by letting $\Delta\varphi$ go below zero and over π at some point during one state change. The measured power was then normalized to this range, so that the nonideal switch structure would not affect the measurement of the switch state.

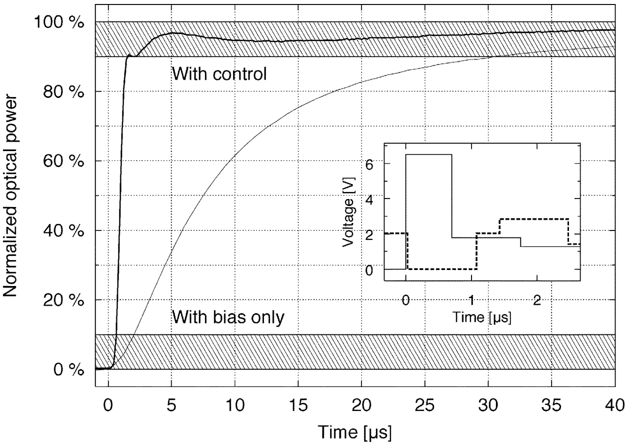

Fig. 4. Cross port signal rise times (change from bar to cross), both with differential heating and when using only bias. Rise times (10%–90%) are 725 ns and 29.2 μs, respectively. The heating patterns are shown in inset.

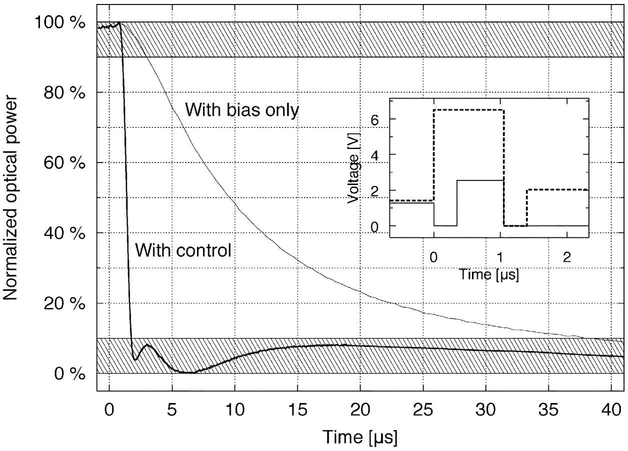

Fig. 5. Cross port signal fall times (change from cross to bar), both with differential heating and when using only bias. Fall times (90%–10%) are for differential control 700 ns and for biased control 35.0 μs.

V. MEASUREMENT RESULTS

The proposed method was used to optimize single rise and fall times for the switch. Transition times between 10% and 90% of the achievable power extremes were used as the only optimization criteria, i.e., the power consumption and the power variations below 10% and above 90% were not considered. The optimal heating patterns are shown in Figs. 4 for rise time and 5 for fall time, together with the normalized optical signals obtained with the differential control method. For comparison, normalized optical signals obtained by driving the switch with conventional step-wise control signal also implementing bias are shown in the Figs. 4 and 5.

As seen from Figs. 4 and 5, the differential control method enabled the rise and fall times to be suppressed from 29.2 and 35.0 μs to 725 and 700 ns, i.e., by a factor of over 40 in both cases. The power variations above 90% and below 10% after the rise and fall times are due to the different temperature settling times and the minimum time step of 330 ns allowed by the control electronics, which prohibits the precise timing of the compensation pulse. When compared to the step-wise biased control, the differential control adds the energy consumption by 4.8 and 5.8 μJ for rise and fall times, respectively. For continuous 1- and 10-kHz switching speed, this corresponds to a change in power consumption from 250 mW of the conventional switching to 260 and 360 mW, respectively.

The characteristic behavior of the measurement results with and without the differential control method is in good agreement with that depicted in Section III.

VI. CONCLUSION

We have achieved rise and fall times of 725 and 700 ns, respectively, with 10%–90% modulation, in an MZI TO-switch with 9-μm-thick rib waveguides by applying a differential temperature control. Switching times were reduced by a factor of over 40 when compared to conventional switching.

With the differential control, the switching speed increase can be freely selected by using appropriately high heating voltages. The switching speed is limited by the heater breakdown point, the speed of controller circuit, and the possible channel temperature heat build-up.

The switch controller used in the demonstration is more complex than is needed in an actual component. With SOI waveguides, the required electronics could well be monolithically integrated with the optical switch, so that the differential control would be totally transparent to the end user.

The proposed method can be used to speed up also other interferometry-based components, providing that both interferometer branches are controllable, and that the switching speed is mainly limited by the speed of the optical effect used.

REFERENCES

[1] B. Jalali, "Silicon-on-insulator photonic integrated circuit (SOI-PIC) technology," *Proc. SPIE*, vol. 2997, pp. 60–71, 1997.

[2] R. A. Soref, J. Schmidtchen, and K. Petermann, "Large single-mode rib waveguides in GeSi-Si and Si-on-SiO$_2$," *J. Quantum Electron.*, vol. 27, no. 8, pp. 1971–1974, 1991.

[3] T. Zinke, U. Fischer, B. Schüppert, and K. Peterman, "Theoretical and experimental investigation of optical couplers in SOI," *Proc. SPIE*, vol. 3007, pp. 30–39, 1997.

[4] P. D. Trinh, S. Yegnanarayanan, F. Coppinger, and B. Jalali, "Silicon-on-insulator (SOI) phased-array wavelength multi/demultipelexer with extremely low-polarization sensitivity," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 940–942, July 1997.

[5] T. Aalto, S. Yliniemi, P. Heimala, P. Pekko, J. Simonen, and M. Kuittinen, "Integrated Bragg gratings in silicon-on-insulator waveguides," *Proc. SPIE*, vol. 4640, pp. 117–124, 2002.

[6] A. Cutolo, M. Iodice, A. Irace, P. Spirito, and L. Zeni, "An electrically controlled Bragg reflector integrated in a rib silicon on insulator waveguide," *Appl. Phys. Lett.*, vol. 71, pp. 199–201, 1997.

[7] A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, "A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor," *Nature*, vol. 427, pp. 615–618, 2004.

[8] T. Aalto, M. Kapulainen, S. Yliniemi, P. Heimala, and M. Leppihalme, "Fast thermo-optical switch based on SOI waveguides," *Proc. SPIE*, vol. 4987, pp. 149–159, 2003.

[9] T. Aalto, M. Harjanne, M. Kapulainen, P. Heimala, and M. Leppihalme, "Development of silicon-on-insulator waveguide technology," *Proc. SPIE*, vol. 5355, pp. 81–95, 2004.