

# Thermooptically Tuned Photonic Crystal Waveguide Silicon-on-Insulator Mach-Zehnder Interferometers

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**Abstract**—Ultracompact thermooptically tuned photonic crystal waveguide (PCW) silicon-on-insulator Mach-Zehnder interferometers (MZIs) have been proposed and fabricated. A novel thermal design was employed to improve the device switching performance. Both steady-state and transient thermal analyses were performed to evaluate the thermal performance of the thermooptic MZIs. A switching time less than 20  $\mu\text{s}$  has been experimentally achieved, which clearly demonstrated the speed advantage using the new heating approach. The active length of the PCW-based MZIs was 80  $\mu\text{m}$ , nearly one order of magnitude shorter than the conventional silicon waveguide-based MZIs. A maximum modulation depth of 84% for a switching power of 78 mW was obtained at a wavelength of 1548 nm.

**Index Terms**—Mach-Zehnder interferometer (MZI), photonic crystal waveguide (PCW), silicon modulator, thermooptic (TO).

SILICON is the dominant choice of semiconductor for microelectronics. The realization of cost-effective integrated optoelectronic circuits on a silicon platform has been the major motivation for the investigation of silicon photonics. However, despite the steady trend towards scaling down the silicon microelectronic devices, little progress has been made in the miniaturization of silicon optical devices. Most active silicon optical devices have remained in comparatively large sizes, ranging from hundreds of micrometers to a few millimeters [1]–[3], as a result of intrinsically weak interactions between light and other external fields exhibited by silicon material. Recently, a new material system—photonic crystal (PhC)—presents a huge potential for developing ultracompact optical devices [4]–[7] due to its unique properties such as photonic bandgap and slow light group velocity [8], [9]. Size reduction by one order of magnitude has been demonstrated for a silicon thermooptic (TO) Mach-Zehnder interferometer (MZI) based on photonic crystal waveguide (PCW) [10]. The reported PCW-based TO MZI employed a historically traditional thermal design, where a resistive heating element was designed to sit on top of the active region of the MZI. In such a device configuration, a  $\text{SiO}_2$  layer varying from a few hundred nanometers to a few micrometers in thickness has to be inserted between the thin-film metal heater and the silicon waveguide, which provides reliable electrical

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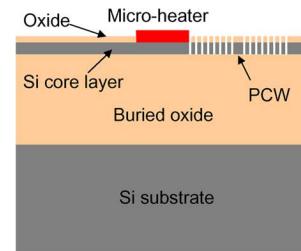


Fig. 1. Cross-sectional schematic diagram of thermooptically tuned PCW SOI MZI.

and optical isolations as well as an adequate mechanical support for the metal heater. However, this  $\text{SiO}_2$  layer is considered an undesirable thermal buffer which hampers the efficiency of the heat exchange between the heater and the silicon waveguide due to the much lower thermal conductivity of  $\text{SiO}_2$  compared with that of silicon. Consequently, it constitutes the true speed-limiting factor for the TO MZIs. On the other hand, to deposit an oxide buffer layer on top of the silicon core layer could be problematic in the fabrication of PCW-based devices. It is because the deposited  $\text{SiO}_2$  could partially block the air holes of the PCWs [5], which may change the designed transmission properties or increase the propagation loss of PhC devices. This letter presents a new thermal design where the resistive metal heater is designed to be in direct contact with the silicon core layer. We deposited the micro-heater at a location closely adjacent to the active PCW region other than on top of the waveguide. A cross-sectional schematic of our device is shown in Fig. 1. Compared with the conventional oxide buffered structure, the direct contact between the micro-heater and the silicon core layer allows a more efficient heat transfer from the heat source to the actively controlled PCW region owing to the high thermal conductivity of silicon which is 100 times larger than that of  $\text{SiO}_2$ . In addition, the buried oxide (BOX) layer of silicon-on-insulator (SOI) wafers functions as a vertical thermal barrier, which further facilitates lateral heat exchange between the heater and the waveguiding region. This novel thermal design is expected to bring various advantages such as high speed, low power consumption, and less complication in device fabrication.

Both steady-state and transient thermal analyses have been performed to assess the thermal performance of our TO SOI MZIs. ANSYS, a commercial finite-element engineering software, was used to model the temperature distribution across the device active region and evaluate the rise/fall time of the TO devices. The layout of the thermal simulation followed the same dimensions of the TO MZIs we fabricated. The simulated structure is illustrated in Fig. 1. The device was designed on an SOI wafer consisting of a 0.26- $\mu\text{m}$ -thick silicon top layer, a 2- $\mu\text{m}$ -thick BOX layer, and a silicon substrate. A

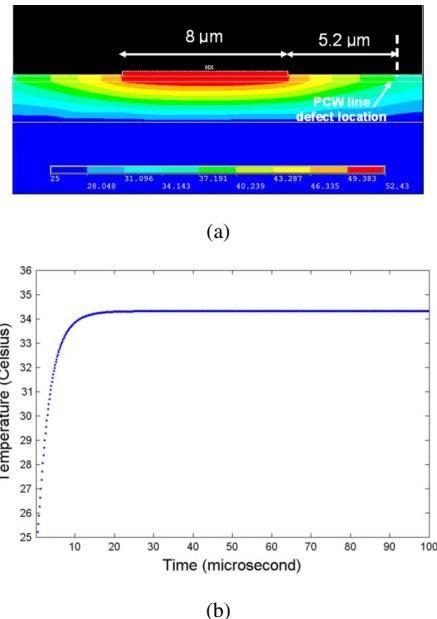


Fig. 2. ANSYS steady-state and transient thermal analyses: (a) temperature distribution across the device under a heating power of 70 mW; (b) temperature rise versus time at the center of the active region.

60-nm-thick oxide layer was thermally grown on top of the silicon core layer, which served as the etching mask for silicon in reactive ion etching. A  $160\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$  cross-sectional area of silicon substrate was chosen in the simulations to ensure a room-temperature boundary condition valid at the bottom and the left/right side of the device. The third dimension of the device was assumed to be infinite in a two-dimensional thermal analysis. Each layer of the device structure was meshed independently. The maximum meshing size was restricted to be smaller than  $0.02\text{ }\mu\text{m}$  to ensure the accuracy of the simulation results. An  $8\text{-}\mu\text{m-wide by }250\text{-nm-thick}$  aluminum micro-heater was placed on top of silicon core layer. The micro-heater was separated from the center of the active PCW by  $5.2\text{ }\mu\text{m}$ . A  $5\text{-}\mu\text{m-wide}$  air trench that provided thermal isolation between the active arm and passive arm was added on the silicon core layer, measuring  $40\text{ }\mu\text{m}$  away from the resistive heater. Given the fact that the resistively generated heat was mainly transported away from the micro-heater through the underneath silicon core layer rather than dissipating in the ambient air because of the extremely large thermal conductivity of silicon versus air [11], we ignored the small portion of heat transferred away by the air above the device and assumed the insulated boundary condition at the top surface of the device. The temperature profile across the device under a heating power of 70 mW is shown in Fig. 2(a). A temperature rise of  $9\text{ }^{\circ}\text{C}$  at the center of the PCW active region was observed. We can do a simple calculation for the required device length to achieve  $\pi$  phase shift in an MZI using a formula  $\Delta\phi = (2\pi/\lambda)(dn_{\text{eff}}/dT)\Delta TL$ , where  $\Delta\phi$  is the phase shift of guided-wave,  $n_{\text{eff}}$  is the effective refractive index of the waveguide,  $\lambda$  is the wavelength of the light signal,  $\Delta T$  is the temperature variation, and  $L$  is the length of the active arm of the MZI. For a  $9\text{ }^{\circ}\text{C}$  rise in temperature, the required length of the active arm in a conventional silicon waveguide-based MZI was  $460\text{ }\mu\text{m}$  as  $(dn_{\text{eff}}/dT)$  of the conventional waveguide

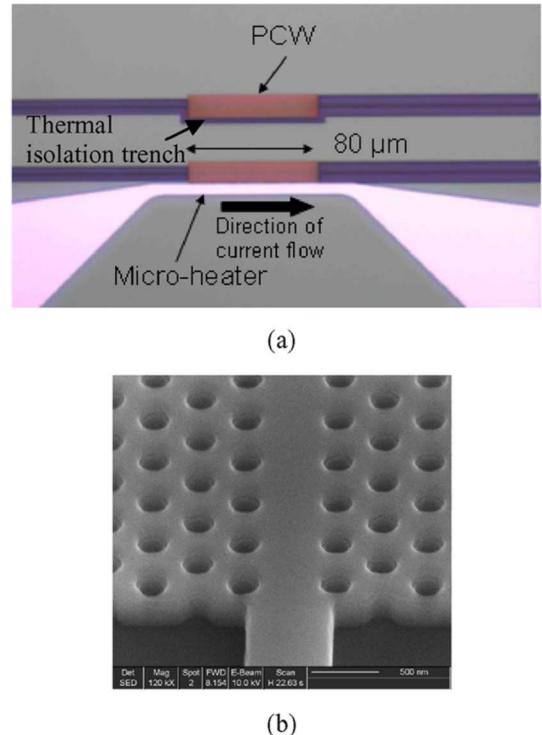


Fig. 3. (a) Microscope picture of the fabricated TO MZI; (b) SEM image at a  $45^{\circ}$ -viewing angle of the input end of a PCW.

is almost equal to the material TO coefficient, which is of a typical value of  $1.86 \times 10^{-4}\text{ K}^{-1}$  in silicon. However, later in this letter one will see that a significant size reduction of the device has been experimentally realized by incorporating highly dispersive PCWs into MZI structures. Transient thermal analysis was also performed with a calculation time increment of  $0.1\text{ }\mu\text{s}$ . The temperature rise sampled at the center of the active PCW versus time was plotted in Fig. 2(b). Our simulation showed the temperature rise time of the designed structure was less than  $20\text{ }\mu\text{s}$ . This simulation indicated that our device should be faster than the previously reported PCW-based SOI TO MZI, where a conventional thermal design was employed and a typical switching time over  $100\text{ }\mu\text{s}$  was characterized [10].

A real PCW-based TO MZI employed aforementioned device structure was fabricated and characterized. A microscopic image of the main section of the PCW-based TO MZI is shown in Fig. 3(a). Two  $80\text{-}\mu\text{m-long}$  PCWs were obtained by removing central rows of air holes in a hexagonal lattice of silicon PhCs for both active and passive arms. The input and output waveguides of the MZIs were gradually widened to  $2\text{ }\mu\text{m}$  at the edge of device chips to facilitate the light coupling. The lattice constant and the air hole diameter were designed to be 400 and 212 nm, respectively. An air trench was added between two PCWs to achieve a good thermal isolation between the active arm and passive arm of the MZI. The device structure was defined by electron-beam lithography and reactive ion etching. The scanning electron microscope image at a  $45^{\circ}$ -viewing angle of the PCW input end is shown in Fig. 3(b). A window for metal deposition was opened through the top oxide layer by photolithography. A  $250\text{-nm-thick}$ ,  $8\text{-}\mu\text{m-wide}$ , and  $120\text{-}\mu\text{m-long}$  aluminum heater was formed by electron beam evaporation and a standard lift-off

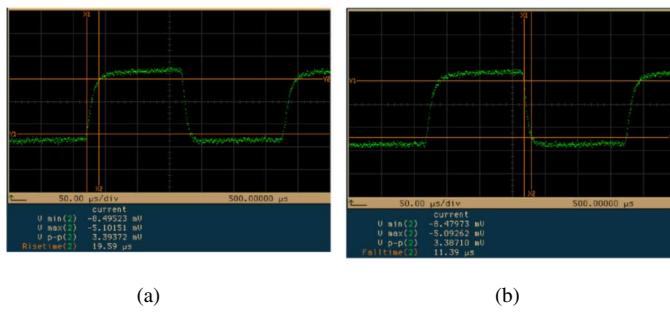


Fig. 4. Switching characteristics of PCW-based SOI TO MZI at 3 kHz: (a) rise time of  $19.6\ \mu s$ ; (b) fall time of  $11.4\ \mu s$ .

process on top of the silicon core layer. It was placed closely adjacent to the active arm of the MZI. The measured resistance of the micro-heater was about  $20\ \Omega$ .

Our fabricated MZI devices were tested on a fully automated Newport Photonics Alignment/Packaging Station. A tunable external-cavity laser source was pigtailed to a single-mode lensed fiber and butt coupled into the MZI device. The output signal was collected by a multimode lensed fiber. The input and output lensed fibers can be accurately aligned with silicon waveguides by two five axis high-precision stages under a computerized control. The input laser was polarized to transverse electric wave for optical measurements. The switching properties were obtained by applying a square wave heating current to the micro-heater. The optical performance of our MZI was characterized at a wavelength of  $1548\ nm$ , which is near the edge of the defect mode transmission spectrum. The switching curves under the modulated signal at  $3\ kHz$  were demonstrated on a digital communication analyzer. The switching rise time (from 10% to 90% transmission) and fall time (from 90% to 10% transmission), shown in Fig. 4(a) and (b), were measured to be  $19.6$  and  $11.4\ \mu s$ , respectively. The measured rise time agrees well with the simulation result from the ANSYS transient thermal analysis. Switching time around  $100\ \mu s$  of a PCW-based SOI TO MZI with a micro-heater sitting on the top of a PCW was previously reported. Our experimental results clearly demonstrated a speed improvement using a novel thermal strategy where the heater was placed on the side of the active arm instead and was in direct contact with the silicon core layer. The output optical intensity against the applied heating power at  $\lambda = 1548\ nm$  was plotted in Fig. 5. A maximum modulation depth of 84% has been obtained for a switching power of  $78\ mW$ . A completely symmetric structure, which has micro-heaters on both the reference and signal arms of the MZI, may help increase the modulation depth through equalizing the optical intensity of two interfering beams. It was previously shown by our ANSYS steady-state thermal analysis, a small temperature variation of  $9\ ^\circ C$  was obtained in the active PCW region under a supplied heating power of  $70\ mW$ . As we have already calculated, it would require an active region at least  $460\ \mu m$  to achieve a  $\pi$  phase shift in a conventional rib or strip waveguide-based silicon TO MZI. Our device has shown almost a one-order of magnitude reduction in the length of the device active region by incorporating PCWs into MZIs. Such a significant size reduction benefited from the slow group-velocity of the PCW [4].

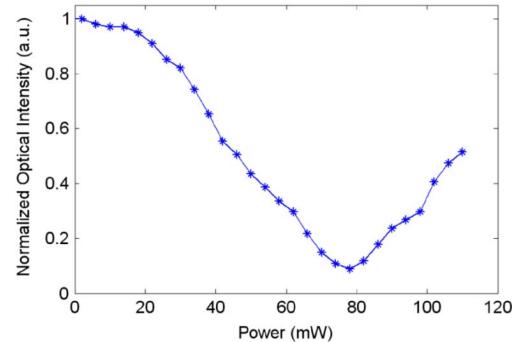


Fig. 5. Output optical intensity against the applied heating power.

In summary, a novel thermal design was proposed for thermo-optically tuned SOI PCW MZIs. Steady-state and transient thermal analyses were performed to assess the thermal performance of the TO MZI. Carefully designed devices were fabricated and characterized. The switching rise time and fall time were measured to be  $19.6$  and  $11.4\ \mu s$ , respectively, which were substantially lower than those of the reported TO PCW-based MZI. Experimental results were in a good agreement with theoretical predictions. A maximum modulation depth of 84% has been obtained for a switching power of  $78\ mW$  within an interaction length of  $80\ \mu m$ . Reduction by one order of magnitude in the length of the device active region compared with the conventional silicon rib or strip waveguide-based MZIs has been experimentally demonstrated.

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