Sub-Microsecond Thermal Reconfiguration of Silicon Photonic Devices

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Abstract: Using the experimental data we show the possibility of sub-microsecond reconfiguration of silicon photonics microresonators through pulse shaping of micro-heater excitation. Also, a novel heater structure based on small microdisk resonators with sub-hundred-nanosecond reconfiguration speed is proposed and investigated theoretically.
OCIS codes: (130.3130) Integrated optics materials; (160.6840) Thermo-optical materials (230.5750) Resonators.

Large-scale photonics integration motivated by the cheap and mature silicon fabrication is being extensively approached for the realization of different interconnect, communications and signal processing applications. The notion of low-power reconfiguration of silicon photonics devices promises an unprecedented level of optical signal processing applications. Strong thermo-optic effect in silicon, which is intrinsically loss-less, is a low-power and low-loss reconfiguration method for large-scale photonics applications [1-4]. However, the reconfiguration speed of thermo-optic devices is low and is in the range of a few micro-seconds. Structural and material optimizations have been shown to marginally improve the tuning speed [4]. In this work, sub-microsecond reconfiguration speed of microring resonators is shown to be possible by applying a high-energy pulse at the beginning of the heater excitation signal. Also, we propose a new architecture for reconfigurable silicon photonics based on small microdisk resonators [5], with the possibility of sub-hundred-nanosecond reconfiguration using the aforementioned pulsed-signaling technique.

In the conventional architecture for thermal tuning of photonic devices, a metallic micro-heater is placed over a separation layer (usually PECVD SiO_2) right on top of the optical device. Figure 1(a) shows the distribution of temperature at the cross-section of such device. Here, an SOI ridge waveguide is covered with SiO_2 cladding material and a 1μm wide thin-film micro-heater is placed on top of the waveguide. Previous structural optimization for improving the speed of these architectures has lead to 4μsec reconfiguration time [4]. This reconfiguration speed is limited by the intrinsic thermal conductivity and heat capacity of the buried oxide (BOX) and cladding material. In this work we increase the speed of reconfiguration of this device through applying a high-energy pulse at the beginning of the excitation signal. This pulse which has a much shorter width compared to the rise-time of the device, forces a large slope in the temperature rise which consequently increases the reconfiguration speed.

This idea is experimentally tested by integrating a micro-heater over a microring resonator and observing the thermal response of the device. Figure 1(b) shows the optical micrograph image of the 20μm diameter microring resonator fabricated on SOI wafer with Si slab thickness of 220nm, and a buried oxide layer of 1μm. The widths of the bus waveguide and micro-ring are 480nm.

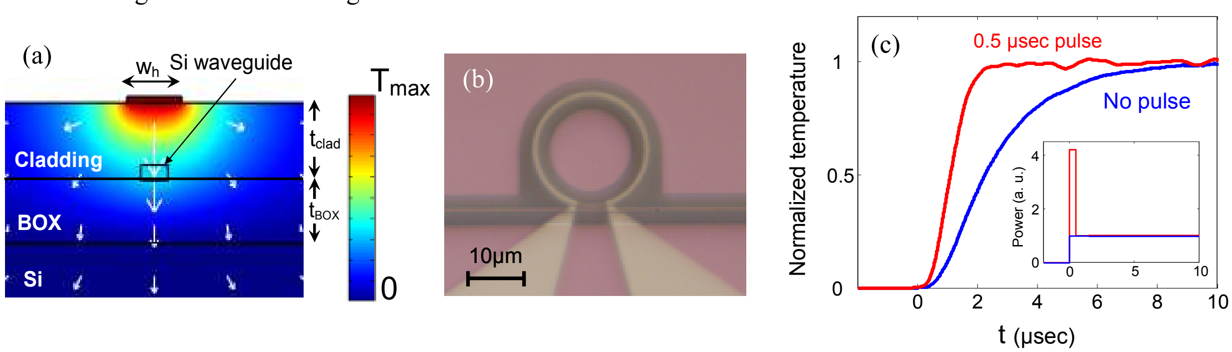

Fig. 1. (a) Distribution of temperature at the cross-section of a SOI waveguide as heat is generated in the metallic micro-heater. (b) Optical micrograph of a 20μm diameter micro-ring with 1μm wide micro-heater on top. (c) Response of the device to a step signal with and without an overdriving short pulse.

Using electron-beam lithography, the pattern is written on ZEP electron-beam resist and etched in Si by inductive-coupled-plasma using a combination of Cl_2 and HBr gases. Then, 1µm SiO_2 is deposited using PECVD and micro-heater patterns are defined by a lift-off process. Micro-heaters are composed of 75 nm thick Ni and contact pads are composed of 150 nm Au for better electrical contact. The step response of the heater is measured by fixing the laser wavelength at the linear region of the resonance line-shape and by applying a small voltage step to the heater using a function generator and monitoring the optical output of the system on an oscilloscope. Blue curve in figure 1(c) shows the step response of the device. The rise-time of this device that is defined as the time that takes the signal to grow from 10% to 90% of its steady-state is 4.5 µsec. Taking the step response of the system, we are able to simulate the device response to an excitation with a short high-energy pulse at the beginning. Red curve in figure 1(c) shows the simulation of the response to a pulse with a width of 0.5 µsec and a power of 4.2 times that of the steady-state value. The inset in figure 3(c) shows the applied step and also the pulsed step signal. It is observed that the rise time of the system is improved to 1.1 µsec. By applying a 100 nsec pulse with a power of 23 times that of the steady-state, 0.94 µsec rise-time can be achieved. Using an appropriately shaped short pulse, the reconfiguration time can be improved at most down up to approximately 0.5 µsec.

The saturation in the improvement of the tuning speed observed above, results from the low thermal conductivity of SiO_2 material separating heater from the optical device. In order to lift this limitation, we propose a new architecture based on small microdisk resonators [5], where the heater is directly placed on the Si slab towards the center of the disk and far enough from the resonator optical mode. Figure 2(a) depicts the distribution of heat at the cross-section of a 5 µm diameter microdisk with a 0.5 µm heater with a radius of 0.75 µm. Because of the high thermal conductivity of Si slab, generated heat immediately reaches the end of the disk. As a result, the rise time of the device can be reduced even beyond 50 nsec by an appropriate high-energy pulse at the beginning of the reconfiguration signal. Figure 2(b) shows the rise time of this device versus the width of the initial pulse. We should note that the amplitude of the pulse is appropriately set so that the response does not exhibit an overshoot. Figure 2(c) shows the step response for three cases of no initial pulse, 1 µsec and 0.5 µsec initial pulse in blue, red and black curves, respectively. The steady-state dissipated power is 1mW over the whole microdisk; and the power of the initial pulses with 1 µsec and 0.5 µsec widths are 1.8 mW and 2.8 mW, respectively. It is observed that as the initial pulse is narrowed the rise-time can be improved considerable.

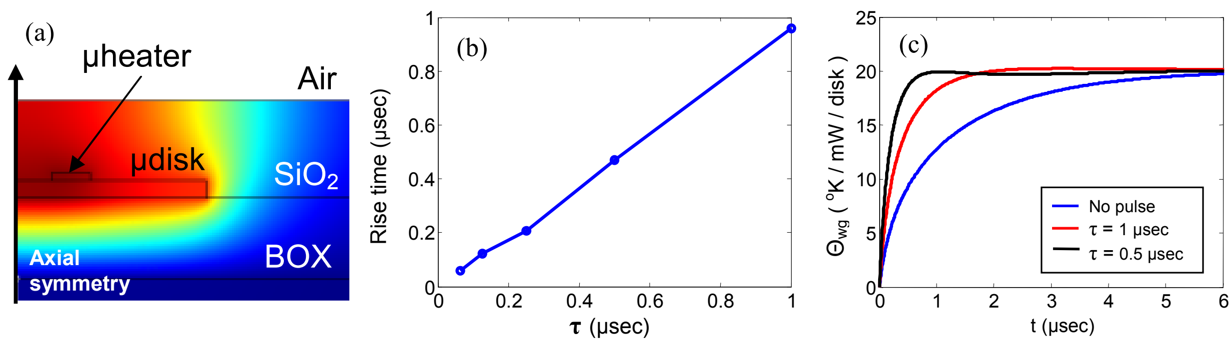

Fig. 2. ((a) Distribution of temperature at the cross-section of a 5µm diameter microdisk on SOI with the heater on the Si slab. (b) Rise time vs. intial pulse-width. (c) temperature rise in microdisk in (a) for the cases with no initial pulse, 0.5 µsec and 1 µsec wide initial pulses.

In conclusion, we observed that the intrinsic slow reconfiguration speed of micro-heaters can be improved in conventional architectures by adding a high-energy initial pulse to the tuning signal. Using the experimental data for the step-response of the system, rise-time of the heater is reduced from 4.5 µsec to approximately 0.94 µsec. Also, a new tuning architecture is proposed based on micro-disk resonators in which we take advantage of the high thermal conductivity of Si slab to reduce the reconfiguration time to as low as 50 nsec. The shortcoming of this pulsed-signaling technique is that differential architectures should be used, because the speed of cooling of the device cannot be improved using the same technique. We will elaborate on the performance and the technical consequences of the differential architecture in the presentation.

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