An Interior-Ridge Silicon Microring Switch with Integrated Thermal Tuner

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Abstract: A 1-by-2 compact injection-based switch is reported utilizing interior-ridge ring resonators, demonstrating nanosecond-scale switching speed, single-mode, low-loss (0/1.3dB for thru/drop port) with efficient integrated thermal tuner (7.25μ W/GHz). **OCIS codes:** (130.4815) Optical switching devices; (130.3120) Integrated optics devices; (200.6715) Switching.

1. Introduction

Silicon photonics [1] has been proposed as a promising solution to increase bandwidth and improve power efficiency in both inter-core and memory access. In such on-chip communication systems, switching is a critical functionality allowing for the turning on/off and directing large amounts of data throughout different destinations. While thermo-optics [2] has been widely used in the design of integrated switches, the electro-optic effect [3-6] is generally preferred for its nanosecond-scale switching performance. Previously, optical switches have been demonstrated in both resonant based (microring [3] or microdisk [4]) devices and Mach-Zehnder structures [5]. Resonant based devices are preferred for their compact size and adaptability to wavelength division multiplexed (WDM) systems. However, a single-mode ridge-waveguide microring switch consumes as much as 17.4mW [3]. The switching power consumption stems from the large footprint of the resonator (~800µm²), limited by the low confinement of the ridge waveguide. The radial silicon ridge exhibits only a weak outer boundary condition to confine light [6]. The confinement is maximized with the introduction of a hard outer wall in microdisk resoantors, which enables a compact footprint ($\sim 72 \mu m^2$) and low power operation of $\sim 1 mW$ [4]. However, the multi-mode nature of the microdisk resonator introduced spurious modes within the spectral range, not ideal for the WDM systems. In addition, the resonance of the switch needs to be tunable to compensate thermal and wafer-scale variations [7]. A single mode, compact and low-power switch with an integrated thermal tuner is desired for an efficient and scalable solution.

Here, we demonstrate an interior-ridge silicon microring switch with an integrated thermal tuner. The tight mode confinement, enabled by the hard outer wall, enables compact size ($\sim 28\mu m^2$), which exhibits a 4.2THz free-spectral-range (FSR). The interior ridge design eliminates high order modes and gives flexibility of adding multiple electrical contacts inside the cavity without introducing excess loss [6]. This enables introduction of multiple longitudinal P-I-N junctions and a joule heater (e.g. resistor) within a compact radius of $3\mu m$. The integrated heater shows a high tuning efficiency of $7.25\mu W/GHz$, capable of compensating for wafer-scale resonance variations at low power budget [7]. The switching time is 1.73ns (rise time 1.12ns and fall time 0.61ns), limited by the body silicon free-carrier lifetime. Optical error-free data transmission/switch at 10Gbit/s pseudo-random bit-stream (PRBS) are demonstrated in both states with >15dB on/off extinction ratio and zero bit-error-rate (BER) power penalty.





Fig. 1. (a) Schematic of the interior-ridge based tunable switch. (b) Scanning electron micrograph (SEM) of the fabricated device. (c) Transmission spectra of the switch, showing uncorrupted FSR of 4.2THz.

Fig. 1(a) shows the schematic of the proposed tunable ring switch with a 3µm radius. The ring consists of two different thickness of silicon layer (220nm for full height and 110nm for ridge etch). P and N doped silicon are interleaved with each other around part of the ring resonator, forming P-I-N junctions, necessary to achieve high-speed switching functionality. On the other part of the ring, P doping is implanted to form an integrated heater inside the resonator. Two metal layers (M1 and M2) are utilized in the device. The P-I-N junctions are connected out through second metal layer (M2) while integrated thermal tuner is connected out through first metal layer (M1). The gap between the waveguide and ring resonator is 150nm, with a filter bandwidth of ~60GHz to allow for switching of high-speed data rate.

The proposed structure was fabricated on a 300mm SOI wafer with a 220nm device layer using 193nm optical immersion lithography. P-I-N junctions are introduced by P and N type doping at concentrations of $\sim 1 \times 10^{18}$ cm⁻³ to intrinsic silicon and interior P+ and N+ contacts with doping concentrations at a level of $\sim 1 \times 10^{20}$ cm⁻³. The interior ridge microring, together with 400nm wide bus waveguide, ensures single-mode coupling into the microring resonators [6]. Fig. 1(b) shows a scanning electron micrograph (SEM) of the fabricated device after dry etching to remove the top SiO₂ cladding. With no bias voltage applied on the device, the transmission spectra of both thru port and drop port are shown in Fig. 1(c), demonstrating a spur-free FSR of 4.2THz. This allows for the incorporation of multi-wavelength channels by changing the radius of resonators, making it suitable for wavelength division multiplexing (WDM) applications.



Fig. 2. (a) Transmission spectra of switch with different forward bias voltages on P-I-N junction. 10-to-90% rise (b) and fall (c) time of the switches for the P-I-N junction for the thru port, showing 1.12ns rise time and 0.61ns fall time, agreeing with the nanosecond-scale free-carrier lifetime.

To achieve a large frequency shift, we inject carriers into the P-I-N junction of the resonator. The change in carrier concentration introduces a refractive index change in silicon [4], resulting in a resonant frequency shift. Fig. 2(a) shows the transmission spectra of both through (thru) and drop ports of the switch with different bias voltages. With a forward bias voltage as low as 1.1V (leading to a 0.78mW electrical power consumption), a signal extinction ratio of more than 15dB in both thru and drop port is achieved. The drop port response shows an insertion loss of 1.3dB with no voltage applied, which is the loss inside the resonant cavity. This is due to the partial doping implants inside the cavity which lower its intrinsic quality factor (Q-factor). Compared to carrier depletion-based devices [4], injection-based devices enable higher carrier concentrations. But bandwidth of them are generally limited by the nanosecond free-carrier lifetime. By applying square wave with voltage swing from 0 to 1.1V, one can achieve the rise and fall time plots the rise and fall time plots of the thru port response, which are shown in Fig. 2 (b) and (c) respectively. The 10-to-90% rise time is around 1.12ns while the fall time is around 0.61ns. The difference between rise and fall time comes from the speed difference between carrier injection and depletion in doped silicon. The 3dB bandwidth of the filter is 59.5 GHz, indicating that it can switch even higher speed data across the device.

In order to test the response of the switch to data streams passing through it, data encoded with an external lithium niobate (LiNbO₃) modulator and non-return-to-zero (NRZ) on-off keying (OOK) using a pulse pattern generator (PPG) with 2^{31} -1 pseudo-random bit sequence (PRBS) were launched into the chip with 10Gbit/s data rate. The optical data were then received by an off-chip PIN photodiode and transimpedence amplifier (PIN-TIA) receiver with limiting amplifier and fed into the bit-error-rate test (BERT). The eye diagrams for three different cases – thru port off-resonance, switched thru port on-resonance and drop port on-resonance, are shown in the inset of Fig. 3(a). Wide-open eye diagrams are demonstrated. The bit-error-rate test curves of the switch are shown in Fig. 3(a). Error-free operations (bit-error-rate (BER)<10⁻¹²) are achieved for all functions, demonstrating no signal degradation passing through the switch.



Fig. 3. (a) Bit-error-rate test curves of the switch with external 10Gbit/s data rate for different bias and ports. (b) Transmission spectra of the switch with different voltages applied to the integrated heater. (c) Thermo-optic frequency shift as a function of integrated heater power. The tuning efficiency is extracted to be 7.25μ W/GHz from linear fitting.

To move toward wafer-scale production, the resonance non-uniformities inevitably associated with the fabrication process must be compensated for. Since resonance based switches works only around the resonant wavelength, an efficient tuning approach must be engineered. By employing an integrated thermal tuner, part of the device, which has a large overlap with the resonant mode, can be heated, thus leading to efficient resonant wavelength tuning. An Increase in temperature leads to an increase in the silicon refractive index, corresponding to a resonance shift to longer wavelength. Fig. 3 (b) shows the transmission spectra of the switch under different voltages applied to the integrated heater, where the resonant wavelength shifts without introducing extra losses to the drop port response. The relative resonant frequency shift and heater power relation is shown in Fig. 3(c). The resulting tuning efficiency is 7.25μ W/GHz, limiting the power necessary for compensating a 100GHz resonance frequency shift [7] to less than 1.0mW. Though our device utilize only first-order ring filter, it demonstrates comparable extinction ratio to high-order switches [3,4] demonstrated with only 1.1V forward bias applied. Though the slow roll-off of first-order filter can lead to larger crosstalk among adjacent frequency channels, by employing high-order switch design with integrated thermal tuner, higher extinction ratios and better crosstalk performance can be readily achieved inside the interior-ridge microring based design.

3. Conclusion

A 1-by-2 compact interior-ridge microring switch with integrated thermal tuner is successfully demonstrated for the first time. The compact size and nanosecond-scale switching speed make it a valuable component for large-scale photonics switching system. The single-mode operation ensures a 4.2THz spur-free FSR, making it a promising building block for dense WDM applications. Additionally, with the efficient thermal tuner (7.25 μ W/GHz) integrated, low power budget is predicted for compensating fabrication or temperature variations.

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