L-Shaped Resonant Microring (LRM) Filter with Integrated Thermal Tuner

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Abstract: A new filter, an L-Shaped Resonant Microring (LRM), is introduced in the application of a highly efficient (3.3-µW/GHz) thermal tuner that enables electrical contact while maintaining single-mode operation and a large 4-THz spur-free FSR.

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (230.7370) Waveguides

1. Introduction

Silicon photonics enables wavelength division multiplexed (WDM) networks to be efficiently and cost effectively implemented on chip with potential for multi-terabit/s communication links. The multiplexing and demultiplexing operations are performed by microring-based filters which require tight alignment between the laser line and filter resonances, which drift by process/wafer variations and dynamic temperature fluctuations. Therefore, high-speed thermo-optic control of microring filters is necessary in silicon photonic communication links [1]. The challenge is in implementing such control efficiently. Without using complex undercut etch processes [2], the most efficient thermo-optic tunable filter to date have been demonstrated with a 4.4 µW/GHz tuning efficiency, 1µs thermal time constant and a FSR of 5.6 THz [3]. For a WDM link with ± 20^0C variation due to processor activity, thermal tuning will consume ~1.2 mW [2] and ~1.8 mW [3] power as opposed to an integrated microdisk modulator with a 3 fJ/bit performance and a power consumption of 30 µW at a data rate of 10 Gb/s [4]. Therefore, it is essential to introduce new resonators. Additionally, high-speed thermal tuning can enable reconfigurable networks as well as track the dynamic processor activity. However, the buried oxide thickness around microring filter is favoring either thermal tuning efficiency or speed.

In this paper, we introduce a new class of filters, L-shaped resonant microrings (LRM), which allow for both hard outer walls and single mode propagation while enabling interior electrical contacts without inducing radiation or scattering. Thus, LRM filters can directly integrate a heater within the resonator and minimize the thermal capacitance and maintain a compact size and an uncorrupted FSR. Here, we demonstrate a 6-um diameter LRM filter with high efficiency (3.3 µW/GHz), high-speed (1.6 µs) thermal tuning and record low thru-to-drop power penalty (<1.1 dB) over the 4 THz FSR.

2. Design and Experimental Results

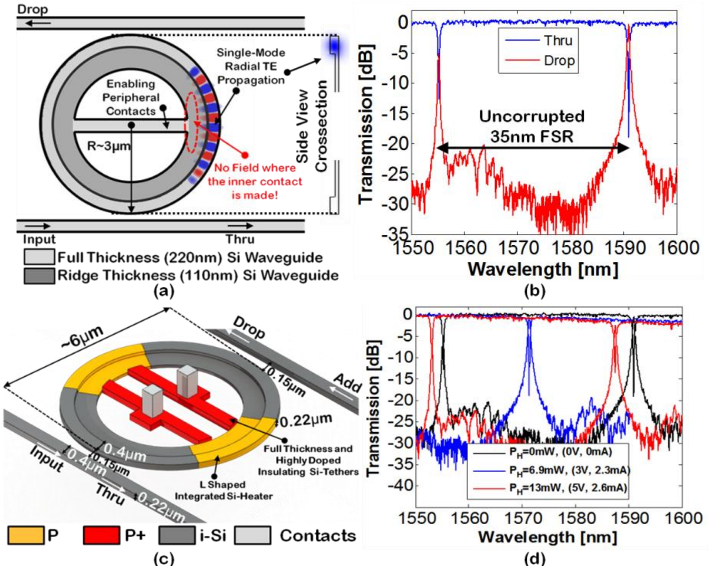

Figure 1 – (a) FD-TD simulation of a LRM resonator, (b) Measured spectrum of a fabricated LRM filter, showing uncorrupted 4 THz FSR on thru and drop ports, (c) 3D sketch of the proposed LRM filter with integrated heater and insulating tethers, (d) Demonstration of thermal tuning of full FSR with a 13mW heater power and a 5V drive voltage.

The LRM filter has a L-shaped waveguide crossection, formed by an internal ridge etch of a wide micro-ring/ -disk. The thickness of the inner ridge and width of the microring is optimized for single mode operation [5], thus the coupling region does not require a complicated waveguide geometry or phase matching. Since the radial TE mode is confined at the edge of the LRM, lossless contacts can be introduced to the periphery of the interior ridge without inducing scattering or radiation as shown by the Finite Difference Time Domain (FD-TD) simulation in Fig. 1a. For a compact (4.2 μm diameter) LRM resonator with a 220nm thick and 110nm ridge silicon waveguide, a cylindrical mode solver is predicting single mode operation with a high quality factor ($Q>10^5$) and large spur-free FSR (>5 THz).

A LRM filter is designed and fabricated as illustrated in Fig. 1c. Thru and drop spectrum of the fabricated LRM filter, showing single-mode operation and an uncorrupted FSR of 4 THz, is measured using tunable CW laser (Fig. 1b). Integrated heaters are introduced by *p* type doping concentration of 1×10^{18} cm^{-3} in the L-shaped waveguide. The thermally conductive vias/contacts are required to be insulated from the integrated heater for enabling low-power and rapid thermal tuning. This is achieved by contacting the integrated heater with narrow heavily doped (*p*+ type doping concentration of 1×10^{20} cm^{-3}) silicon waveguide tethers (Fig. 1c). The resistance of the integrated heater is ~1.3kΩ and ~2kΩ for an applied voltage of below and above 3V, respectively.

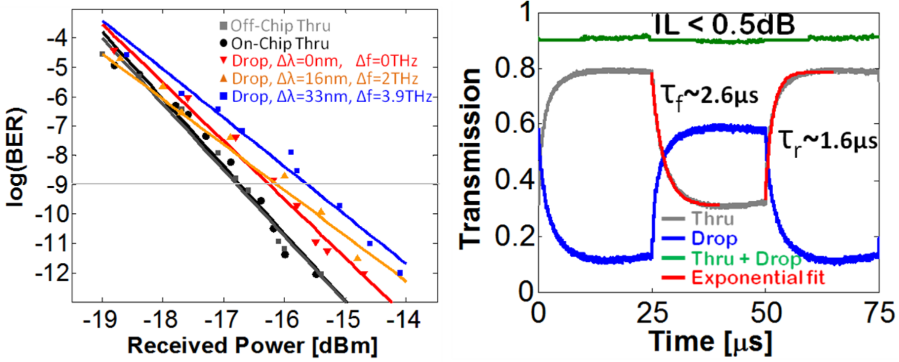

Figure 2 – Bit Error Rate (BER) curves measured for the thru and drop ports of the LRM filter at different thermo-optic resonance shifts. to the BER curve of off-chip thru (bypassing the chip) is measured for comparison (left), temporal response of the thru and drop ports of the LRM filter, excited by 20kHz 0.15V square-wave drive, fit to a 2.6μs exponential decay and a 1.6μs rise thermal time constant (shown in red), the insertion loss of the LRM filter is <0.5dB.

The LRM filter is thermo-optically tuned by applying a voltage across the integrated heater and thru and drop spectrum of is measured using tunable CW laser (Fig. 1d). Wavelength shifts of 16 nm (~2 THz) and 33 nm (~3.9 THz) is observed for a heater power of 6.9 mW (3V) and 13 mW (5V), respectively. These values correspond to a heater efficiency of 3.45 μW/GHz and 3.33 μW/GHz, respectively and ~1.3 mW heater power for a temperature variation of ± 20^0C. Power dissipation of the proposed LRM filter, fabricated on thick SOI process, is comparable to the undercut process [2].

An external $LiNbO_3$ Mach-Zehnder modulator, driven with a non-return-to-zero-on-off-keying (NRZ-OOK) signal encoded with pseudo-random-bit-sequence (PRBS) data with a pattern length of $2^{31}-1$, and a data rate of 13 Gb/s, was used to quantify data transmission and routing performance of the LRM filter. Bit error rate (BER) was measured for off-chip (bypassing the chip), on-chip thru port (off-resonance) of the LRM filter, and drop port (on-resonance) at an applied voltage of 0V (Δλ=0nm), 3V (Δλ=16nm) and 5V (Δλ=33nm) across the LRM filter as shown in Fig. 3, left. The power penalty between on- and off-chip thru is recorded as <0.1dB and between on-chip thru and drop port is 0.5dB, 0.7dB, and 1.1dB for the applied voltage of 0V (Δλ=0nm), 3V (Δλ=16nm) and 5V (Δλ=33nm).

The temporal response of the LRM filter was measured by driving the LRM filter with a square-wave at a frequency of 20 KHz and 0.15 Vpp, and observing the thru and drop port intensity of a laser probe at λ ~ 1555nm (Fig. 3, right). The thru port intensity is in good agreement with an exponential decay (τ_f ~2.6μs) and rise (τ_r ~1.6μs) fit, shown with red lines in Fig. 3, right. Insertion loss of the LRM filter (<0.5 dB) is determined from the total intensity of the thru and drop ports with respect to transmission one.

3. Conclusions

We proposed and demonstrated an L-shaped resonant microring filter with integrated heater successfully. The LRM filter achieved efficent (3.3μW/GHz) and high-speed (τ_f ~1.6 μs) thermal tuning and maintained signal integrity with record low thru to drop power penalty (<1.1 dB) over the 4 THz FSR and <0.5dB insertion loss. LRM resonators can be used to form on-chip modulators, suspended microrings and phase shifter elements.

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4. References

[1] E. Timurdogan, *et al.*, "Automated Wavelength Recovery for Microring Resonators," *CLEO*, 2012
[2] J. S. Orcutt, *et al.*, "Nanophotonic integration in state-of-the-art CMOS foundries," *Optics Express*, Vol. 19, Issue 3, 2011
[3] M. R. Watts *et al.*, "Adiabatic Resonant Microrings (ARMs) with directly integrated Thermal Microphotonics," *CLEO*, 2012.
[4] M. R. Watts *et al.*, "Vertical junction silicon microdisk modulators and switches", *Opt. Exp.* 19, 21989–22003 (2011).
[5] J. Song *et al.*, "Thermo-optical tunable planar ridge microdisk resonator in silicon-on-insulator," *Opt. Exp.* 19, 11220-11227 (2011).