A High-Q Tunable Interior-Ridge Microring Filter

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Abstract: A tunable interior-ridge microring filter is demonstrated with a high quality factor of 1.5×10^5, while achieving a thermal tuning efficiency of 5.5μW/GHz. The filter demonstrates a record low insertion-loss <0.05dB over an uncorrupted 4-THz free-spectral-range.

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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 comb and filter resonances. However, the alignment will be distorted due to the wafer-scale dimensional errors and the temperature fluctuations, necessiating high-speed active thermo-optic control of microring filters. The challenge is to implement such control efficiently and rapidly for enabling reconfigurable networks as well as tracking the dynamic processor activity. For this purpose, metal and silicon heaters have been implemented. The metal heaters, buried in or placed over the SiO_2 cladding, achieve the highest temperature change within the metal and not inside the silicon core. This limits the thermal tuning efficiency and speed while increasing the channel-to-channel thermal crosstalk. On the contrary, the silicon heaters, formed using ion implantation, and directly integrated within the silicon microring enable direct, efficient, and high-speed tuning due to the combination of lower heat capacity and reduced thermal conductance [1,2]. The integrated and well isolated silicon heaters achieve rapid (τ~1-2.2μs) and highly efficient thermal tuning (Δf ~ 4.4-3.3μW/GHz) [1,2]. However, the integrated silicon heaters tend to be highly resistive (R_s>2kΩ) compared to their metal counterparts, and require high voltages to operate. More importantly, the interaction between doped silicon and optical mode limits the quality factor of the resonators ($Q_i<10^4$), thereby introducing a significant filter insertion loss (>1dB).

Here, we demonstrate an interior-ridge microring resonator with a novel optical and electrical design that eliminates the aforementioned drawbacks of tunable filters with directly integrated silicon heaters. The 3-μm radius interior ridge microring resonator demonstrates a quality factor of 1.5×10^5, limited mainly by the line edge roughness, while achieving a low-resistance (1kΩ) integrated silicon heater with a thermal tuning efficieny of 5.5μW/GHz. The resonator is used to operate as a 75GHz 3dB bandwidth filter. The filter demonstrates a record low

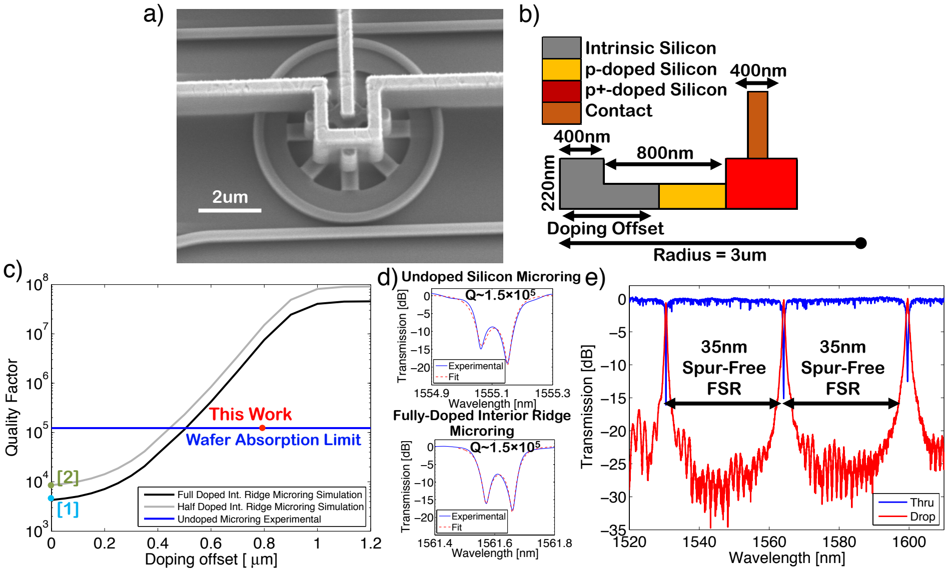

Figure 1 – (a) Scanning electron microscope image of the 3-μm radius interior-ridge microring filter. (b) The crossection of the interior-ridge microring filter. (c) The simulated and measured quality factor values as a function of doping offset. (d) The fit and the measured spectrum of an undoped silicon microring resonator and a fully-doped interior-ridge resonator, showing the background absorption limited quality factor 1.5×10^5. (e) The measured spectrum of a fully-doped interior-ridge filter, showing an uncorrupted 35-nm or 4-THz free-spectral-range (FSR).

insertion loss <0.05dB, owing to its high internal quality factor, over an uncorrupted 35nm (4THz) free-spectral range.

2. Design and Experimental Results

The proposed microring filter, shown in Fig. 1-a, has an interior ridge etched out of a wide microring. The silicon layer thickness over a 2μm thick box oxide was 220nm and the interior ridge silicon thickness is timed-etched down to 110nm. Since the radial TE mode is confined at the outer edge of the microring, lossless contacts can be introduced to the periphery of the inner edge of the interior ridge without inducing scattering or radiation (see Fig. 1-a,b). In addition, the doping is offset from the edge of the microring, enabling the lossless introduction of directly contacted silicon heaters for the first time (see Fig. 1-b). The internal quality factor, shown in Fig. 1-c, is simulated using a finite-difference-cylindrical-eigenmode-solver for the interior-ridge microring cross-section in Fig. 1-b. Prior to this demonstration, state-of-the-art tunable microring filters [1,2] had a quality factor $<10^4$, which is partially compromised by the absorption loss of the doped silicon heaters. In order to maximize the quality factor and minimize the absorption loss, the periphery of the resonators were doped in patches rather than full coverage, thereby increasing the heater resistance. A 3μm radius interior ridge microring resonator with doping offset of >0.5μm is offered as a solution to this limitation. The proposed resonator was predicting a quality factor $>10^5$. In order to demonstrate the lossless direct integration, a 3μm radius fully-doped interior ridge resonator with a doping offset of 0.8μm is fabricated and the drop port is eliminated to measure the internal quality factor. The critical coupling occurs around a 300nm gap between the outer edge of the resonator and the 400nm wide bus waveguide. A quality factor of $Q\sim1.5\times10^5$, shown in Fig. 1-c,d, is measured for the doped interior-ridge microring resonator and compared to an adjacent 3μm radius undoped silicon microring resonator ($Q\sim1.5\times10^5$, shown in Fig. 1-c,d). The Q of the doped interior ridge microring resonator was limited mainly by the line edge roughness.

An interior-ridge micoring filter, fabricated as in Fig. 1-a, had a bus-to-ring and ring-to-drop gap of 150nm. Thru and drop spectrum of the fabricated filter, showing single-mode operation in Fig. 1-e and a free-spectral-range (FSR) of 35nm (~4THz), measured using a tunable CW laser. The filter full-width-half-maximum bandwidth was measured to be 75GHz. The integrated heaters were implanted to achieve a p-type doping concentration of 1×10^{18} cm^{-3} in the interior ridge waveguide. The thermally conductive vias/contacts were insulated from the integrated heater for enabling efficient and rapid thermal tuning. This was achieved by contacting the integrated heater with eight narrow heavily doped (p+ type doping concentration of 1×10^{20} cm^{-3}) tethers. The polarity of adjacent contacts is alternated to achieve 8 parallel connected heaters (each one is ~8kΩ resistance). This configuration minimized the equivalent resistance of the integrated heater down to 1kΩ.

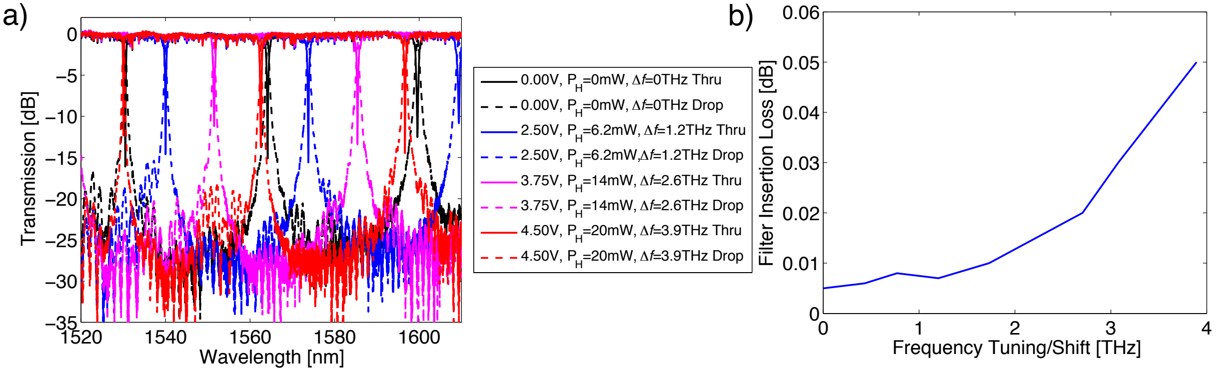

Figure 2 – (a) Thru and drop spectrum of the interior-ridge microring filter as a function of applied heater voltage. (b) The insertion loss of the interior-ridge microring filter as a function of frequency shift or thermal tuning.

The filter is thermo-optically tuned by applying a voltage across the integrated heater and the thru and drop spectrum was measured using a tunable CW laser (Fig. 2-a). Wavelength shifts of $\Delta\lambda\sim10$nm ($\Delta f\sim1.2$THz), $\Delta\lambda\sim22$nm ($\Delta f\sim2.6$THz) and $\Delta\lambda\sim34$nm ($\Delta f\sim3.9$ THz) were observed for heater powers of 6.2mW (2.5V), 14mW (3.75V) and 20mW (4.5V), respectively. These values correspond to a heater efficiency of ~5.5μW/GHz. The filter insertion loss, shown in Fig. 2-b, is measured to be <0.05dB for the tuning across the large FSR of the microring, owing to the high internal quality factor. This sets a milestone for the tunable silicon microring filter design.

3. Conclusions

We proposed and demonstrated an interior ridge microring filter with lossless integration of silicon heaters. The filter with low resistance silicon heaters achieved an efficient thermal tuning (5.5μW/GHz) while preserving a high internal quality factor of 1.5×10^5, which resulted in a record low insertion loss of <0.05dB over the wide spur-free 4THz FSR.

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4. References

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