# Maximizing the Thermo-Optic Tuning Range of Silicon Photonic Structures

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Tymon Barwicz
IBM



Franz Kärtner
Center for Free-Electron Laser Science

# Maximizing the Thermo-Optic Tuning Range of Silicon Photonic Structures

F. Gan, T. Barwicz, M. A. Popović, M. S. Dahlem, C. W. Holzwarth, P. T. Rakich, H. I. Smith, E. P. Ippen and F. X. Kärtner

Research Laboratory of Electronics, Massachusetts Institute of Technology,
77 Massachusetts Ave, Cambridge, MA 02139 USA, email: fuwan@alum.mit.edu

**Abstract**: We demonstrate 20nm thermo-optic tuning in silicon microring resonators with 16nm free spectral range (FSR), the largest reported full-FSR thermal tuning, with a tuning efficiency of 28μW/GHz, enabling telecom microphotonic tunable filters.

**Keywords**: Thermal tuning, silicon microring resonator filter

## 1. Introduction

Thermo-optic tuning has been widely used on microring filters because it can induce large refractive index changes without optical loss. A large tuning range is necessary to enable microring filters to operate over the whole C-band. This is important in chip-scale microphotonic reconfigurable optical add-drop multiplexers (R-OADMs). To our knowledge, the largest thermal tuning range reported in the literature is 16nm with an efficiency of 27μW/GHz. This has been achieved in InP/InGaAsP microrings with polymer waferbonding [1]. The low thermal conductivity of the polymer undercladding enhances the tuning range but hinders the tuning speed.

Here we demonstrate the largest reported full-FSR thermal tuning in silicon photonics. A thermo-optic tuning range of 20nm is demonstrated with an efficiency of 28μW/GHz on silicon microring resonators with 16nm FSR.

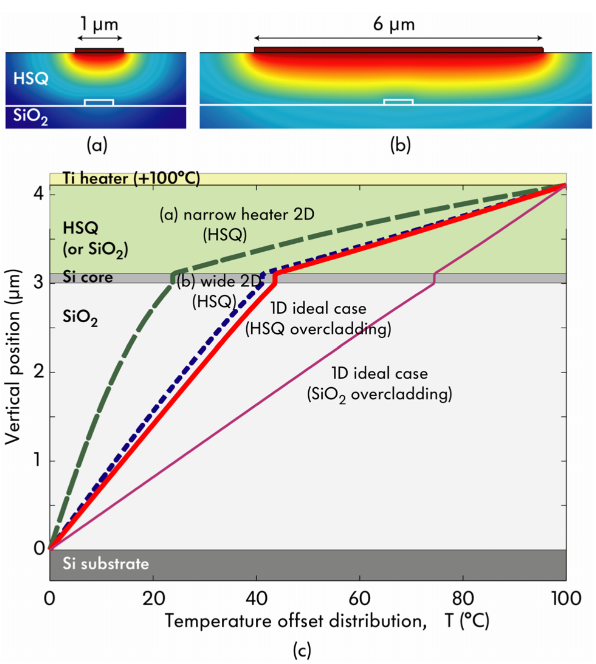


**Fig. 1. (a) Narrow 2D heater, (b) wide 2D heater, (c) temperature distribution vertically across Si-waveguide for 1μm narrow heater (dashed), 6μm wide heater (dotted), 1D ideal heater (red solid) and 1D ideal heater with $SiO_2$-cladding (purple solid).**

Novel heater structures were designed to maximize tuning range by minimizing the temperature difference between the resonator and the heater at a distance that avoids optical loss. We argue that the heater temperature is the tuning limiting parameter. Metal heaters cannot be made arbitrarily thick because of fabrication constrains. Hence, the current density cannot be decreased arbitrarily and the electromigration sets a limit on the operating temperature of the heater. A rise time of 7μs and a fall time of 14μs have been achieved enabling R-OADMs applications

## 2. Thermal Device Design

The heaters were designed to maximize tuning range and cover the full resonator FSR, which is chosen to span half of the C-band. Using an FSR doubling geometry [2], the filter's operating wavelength range can span the entire C-band. A wide tuning range is achieved by making the heat injection surface (heaters) approximate a 1D heat flow in the vertical through-the-ring direction. As shown in Fig.1(a-b), a narrow heater provides a more "diffracting" heat flow than a wide heater. In Fig.1(c), we note that the quasi-1D heat flow of a 6μm-wide heater (blue dotted) enables a larger temperature at the waveguide for a given heater temperature than the narrow heater (green dashed). A hydrogen silsequioxane (HSQ) uppercladding was chosen in our devices for its excellent gap-filling and self-planarization capabilities. An $SiO_2$ uppercladding, however, can further enhanced the tuning efficiency by 80% due to the higher thermal conductivity of $SiO_2$ with respect to HSQ.

A multi-wire structure heater was designed as shown in Fig.2. The electrical power dissipated at the heater can be explicitly expressed as

$$p = \frac{V^2}{R} = VA\frac{V}{\rho L} \quad [1]$$

where V is the applied voltage, ρ is the metal resistivity,and A and L are the heater wire cross-section and length, respectively. Eq.(1) indicates that a larger cross-section leads to a smaller current density J=V/ρL at the same power level. The wire height was chosen to be 0.1μm, the width to be 0.8-1μm, and the gap between wires to be 0.8μm to allow

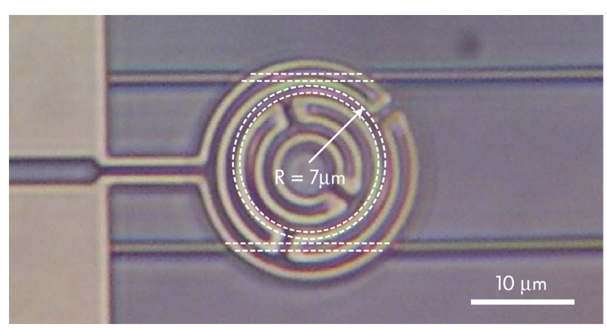


**Fig. 2. Optical micrograph of fabricated heater above tunable silicon microring resonator filter.**

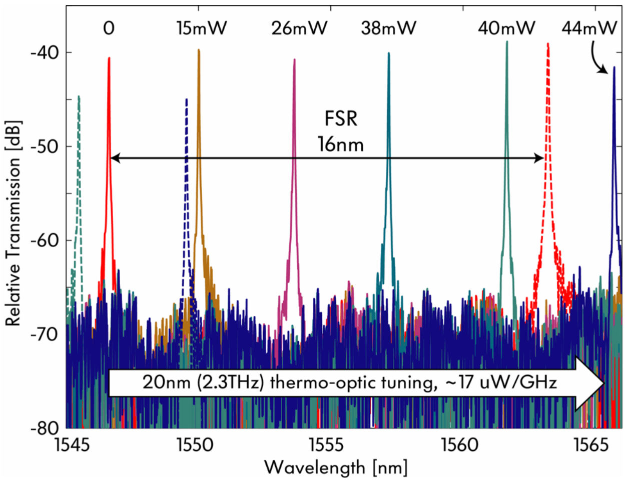


**Fig. 3. Drop-port transmission spectra for different tuning powers, showing a large tuning range of 20nm which exceeds the 16nm FSR of the resonator.**

fabrication with contact photolithography. These dimensions lead to a total wire length of about 250μm, a ring-heater width of 8μm, and heater diameter of 20μm. Ti was chosen for heater wires because its resistivity leads to a relatively low current density and no serious electromigration happens at the high heater temperatures (~500°C) necessary for full 16-nm FSR tuning.

## 3. Experimental Results

The optical micrograph of the tunable microring resonator filters is shown in Fig. 2. A ring-waveguide cross-section of 600x106nm was chosen for its reduced sensitivity to dimensional variations and sidewall roughness in comparison to conventional cross-sections [4]. The microrings have a 7μm radius. A 3-μm-thick $SiO_2$ undercladding was chosen to prevent optical power from leaking into the Si-substrate. The heater wires were placed about 900nm above the top surface of the waveguides to reduce optical loss due to metal heater wires. The Ti heaters were covered with a 100-nm-thick sputtered $SiO_2$ to hinder heater oxidation at operating temperatures (up to ~500°C).

The microring filters were designed with a 16nm free spectral range (FSR) to cover half of the C-band. The loss Q's were measured to be, as designed, ~250k and ~130k without and with a Ti heater present, respectively. This corresponds to a propagation loss in the rings of ~2-2.5 dB/cm and ~4.5 dB/cm, respectively. The wide tuning range and FSR are shown in the drop-port transmissions of the fabricated single-ring filters (Fig. 3). A direct tuning of 20nm is shown, which is the largest single-resonator tuning reported in silicon. The tuned wavelength shifts by 10nm with an average tuning efficiency of ~28μW/GHz and shifts by 20nm with an average efficiency of ~17μW/GHz. The slope of the resonance wavelength shift in terms of electrical power becomes larger at higher electrical power. This is a consequence of the increase of the Si thermo-optic coefficient with the temperature [5].

As shown in Fig. 4, the time response was measured by applying a square-wave voltage on a heater placed on the arm of the Mach-Zehnder interferometer (MZI). The heater changes the temperature at one arm and induces a phase difference between the two arms of the MZI. This MZI heater

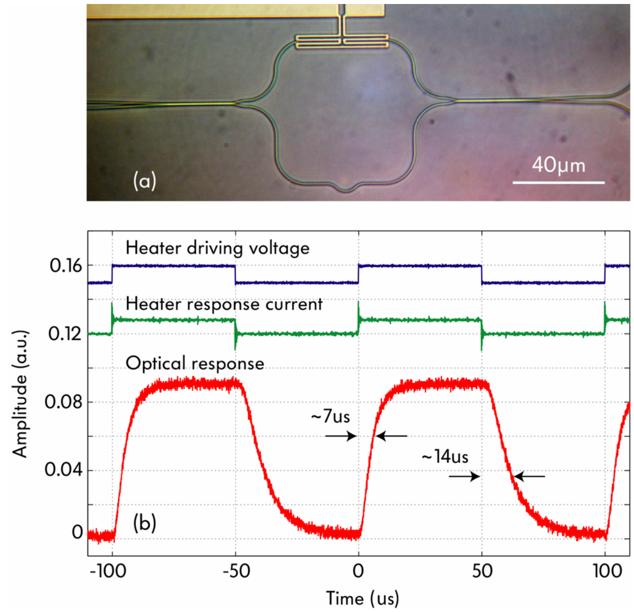


**Fig. 4. (a) Mach-Zehnder interferometer with a heater, (b) time response with 7μs rise time and 14μs fall time.**

has the same cross-section as the microring heater discussed above. As there is no significant delay between the current and the input voltage in Fig. 4b, the driving circuits don't contribute notably to the switching speed and the measured time response is mainly from the heat flow process in the devices. The rise and fall times are 7μs and 14μs, respectively. This response time enables applications of these heaters to R-OADMs.

## 4. Conclusions

We demonstrated the largest thermo-optic tuning of microphotonic resonators demonstrated to date, 20nm, (and the largest full-FSR tuning over 16nm) using silicon microring resonators. Design and experimental confirmation of our approach to wide tuning was described. A switching rise time of 7μs and a fall time of 14μs were obtained enabling widely tunable and reconfigurable telecom.

## 5. Acknowledgments

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## 6. References

[1] P. Rabiei and W. H. Steier: "*Low-power thermo-optic tuning of vertically coupled microring resonators*", Electronic Letters Vol. 40 No. 9, April 2004.
[2] M. A. Popović *et al.*, Universally balanced photonic interferometers, *Opt. Lett.* 31, 2713 (2006).
[3] M. A. Popović, et al., Tunable, Fourth-Order Silicon Microring-Resonator Add-Drop Filters, 33rd European conference and Exhibition on Optical Communication, Berlin, Germany, 2007.
[4] M. A. Popović *et al.*, Global Design Rules for Silicon Microphotonic Waveguides: Sensitivity, Polarization and Resonance Tunability, *in Conf. Lasers and Electr-Opt. (CLEO)*, Long Beach, USA, paper CTuCC1 (2006).
[5] J. A. McCaulley *et al.*, Temperature dependence of the near-infrared refractive index of silicon, gallium arsenide, and indium phosphide, Vol.49, No.11, *Physical Review B*, 1994.