# Precision Tunable Silicon Compatible Microring Filters

Reja Amatya, *Student Member, IEEE*, Charles W. Holzwarth, Henry I. Smith, *Fellow, IEEE*, and Rajeev J. Ram, *Senior Member, IEEE*

***Abstract*—Microring resonators can be used as passband filters for wavelength-division demultiplexing in electronic-photonic integrated circuits. For applications such as analog-to-digital converters, the resonant frequency of the filter has to be held at a certain value to allow minimum timing errors in the sampling of the signal. Thermal tuning is used to compensate for any fabrication errors or environmental temperature fluctuations that might lead to a shift in the resonant frequency. With an optimized heater design, we demonstrate efficient on-chip thermal tuning for a second-order silicon-rich silicon nitride microring resonator at 80 $\mu$W/GHz. A closed-loop feedback circuit controls a resistive heater which is also used as a temperature sensor to maintain the resonant frequency within 280 MHz of the target value.**

***Index Terms*—Microring resonator, silicon nitride, thermal tuning.**

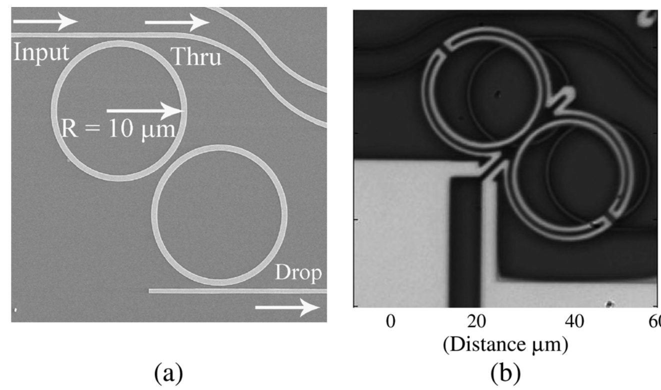


Fig. 1. (a) SEM picture of a second-order ring resonator; (b) micro-heater.

## I. Introduction

The versatility of microring resonators make them a suitable component for many optical systems [1]. The microrings fabricated with high-index-contrast materials such as silicon, silicon nitride (SiN), and silicon dioxide ($SiO_2$) ensure strong modal confinement and low bending loss, making them attractive for optical systems [2]. Because of the low material loss and compatibility with current complementary metal–oxide–semicondcutor (CMOS) technology, these resonators can be used in applications involving wavelength switching such as signal processing.

In this work, the microring resonators are used as tunable filters for wavelength-division demultiplexing (WDM) during optical sampling for a photonic enhanced analog-to-digital converter (ADC) [3]. The second-order filters [Fig. 1(a)] are fabricated with silicon-rich SiN $(n = 2.2)$ cores, and $SiO_2$ as a lower cladding and hydrogen silsequioxane (HSQ) as the upper and side cladding. With the use of an optimized annealing process, HSQ and $SiO_2$ have comparable, low refractive indices of 1.442 and 1.444 at 1.55 $\mu$m [4]. Due to the high index contrast the single-mode waveguides have submicron dimensions. The design details for the filter can be found in [5]. The ring diameter of 20 $\mu$m, with the group index of 2.29, gives a large free-spectral range (FSR) of 26 nm. The rings are designed such that the passband has a 3-dB bandwidth of 25 GHz. A low drop loss of 3.1 dB and crosstalk of less than 30 dB has been obtained for these ring resonators.

For a ring resonator, any fabrication error in the filter can shift the resonant wavelength $(\lambda_0)$ which depends on its radius $(r)$ and the effective index $(n_{\mathrm{eff}})$ [6]. Apart from the dimensional errors during fabrication, other factors can also shift the resonant wavelength. One of the main causes is the temperature variation of the filter which affects the refractive index. If there is any disturbance in the resonant wavelength, the filter needs to be tuned to compensate. One can obtain the change in the wavelength of the filter by changing its effective index [7] as given by

$$\frac{\Delta\lambda}{\lambda_0} = \left|\frac{\Delta n_{\mathrm{eff}}}{n_{\mathrm{group}}}\right|. \quad (1)$$

The change in the wavelength is related to both the effective index and the group index $(n_{\mathrm{group}})$ of the waveguide. Environmental temperature changes around the device can cause unwanted shifts in the resonant wavelength. However, deliberate temperature variation can be utilized to externally tune and control the filter response.

## II. Thermal Tuning

The thermooptic effect is utilized for tuning, where the resonant frequency is trimmed by changing the effective index of the ring. Highly efficient thermal tuning has been observed in first-order polymer rings due to their low thermal conductivity

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R. Amatya and R. J. Ram are with the Department of Electrical Engineering and Computer Science, Research Laboratory of Electronics, Microsystems Technology Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: ramatya@mit.edu).

C. W. Holzwarth is with the Research Laboratory of Electronics, Department of Material Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

H. I. Smith is with the Department of Electrical Engineering and Computer Science, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

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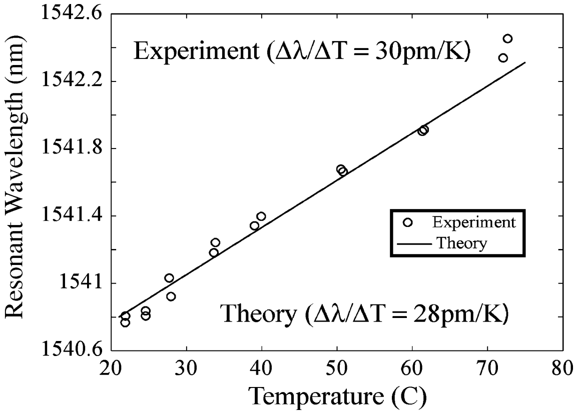


Fig. 2. Thermal tuning of microring resonator with an external heater.

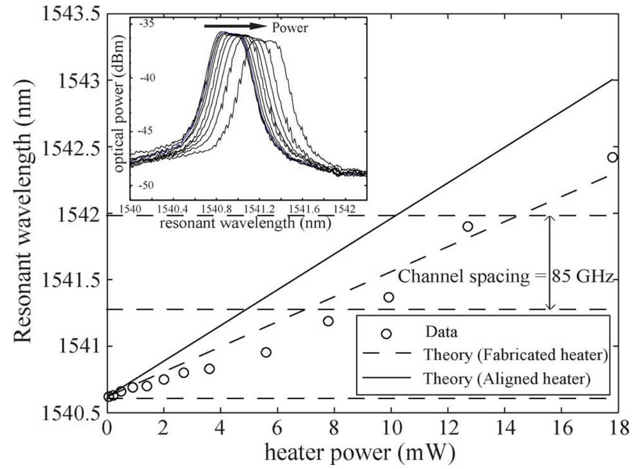


Fig. 3. Thermal tuning with on-chip heater. Inset shows shift in the filter response at the drop port for various electrical power.

and high thermooptic coefficient. The lowest tuning power of 26 $\mu$W/GHz has been achieved for InP–InGaAsP microrings fabricated with wafer-bonding using polymer [benzocyclobutene (BCB)] [8]. Vertically coupled first-order microrings made of polyimide have been tuned with 50 $\mu$W/GHz, showing the total tuning of 9.4 nm [9]. Incorporation of a silicon-based waveguide has a distinct advantage for the integrated photonic circuit application, as current CMOS processing can be readily utilized. A first-order silicon microring has been tuned with a power of 28 $\mu$W/GHz with a large tuning range of 16 nm [10]. However, wavelength stability as well as power efficiency for tuning are more important metrics than the total tuning range for the application of interest. A distinct disadvantage of working with silicon is the stringent need for temperature stability. Due to the larger thermooptic coefficient of silicon, the resonant wavelength is very susceptible to temperature change. While SiN has a lower thermooptic coefficient compared to silicon, the lower temperature dependence offers greater wavelength stability, allowing a trade-off between tuning power and temperature stability. Previously, a single SiN ring has been tuned within a range of 20 pm/K with a tuning power of 400 $\mu$W/GHz [11]. With improved heater design compared to [8] and [9], we demonstrate efficient thermal tuning for silicon-rich SiN second-order filters using a total tuning power of 80 $\mu$W/GHz.

At 1.55 $\mu$m, the thermooptic coefficients for SiN and $SiO_2$ are $4 \times 10^{-5}$ K$^{-1}$ and $1.5 \times 10^{-5}$ K$^{-1}$, respectively. As the temperature of the ring changes, the refractive index of both the core and the cladding material changes which causes the shift in the resonant wavelength for the ring structure [7]

$$\frac{\Delta\lambda}{\Delta T} = \left|\frac{\lambda_0}{n_{\text{group}}}\left(\frac{\Delta n_{\text{eff}}}{\Delta n_{\text{core}}}\frac{\Delta n_{\text{core}}}{\Delta T} + \frac{\Delta n_{\text{eff}}}{\Delta n_{\text{clad}}}\frac{\Delta n_{\text{clad}}}{\Delta T}\right)\right|. \quad (2)$$

For a SiN core, HSQ upper cladding, and $SiO_2$ lower cladding, the theoretical tuning range is 28 pm/K (3.55 GHz/K). The tuning range of 30 pm/K is measured for the SiN rings with external heaters (Fig. 2).

A test chip (2 mm $\times$ 5 mm) is mounted on a copper block with a thermoelectric component. Thin-film titanium heaters (thickness $= 100$ nm, width $= 800$ nm) are fabricated on top of the cladding to locally change the temperature of the resonator. The upper cladding of 1.5 $\mu$m ensures optical isolation for the resonator from local metal heaters on top. The temperature coefficient for the titanium metal with a thin layer of gold on top is measured to be 0.0012 K$^{-1}$. The gold layer prevents oxidation of titanium.

The experimental thermal tuning data as shown in Fig. 3 indicates the tuning power requirement of 80 $\mu$W/GHz for the second-order filter. During the fabrication of the heater, there was a misalignment of 5 $\mu$m between the heater and the actual waveguide underneath. Due to nonuniform heating, the passband of the filter broadens (0.2 nm) which results in two peaks within the passband at higher temperature. The thermal simulation with the misalignment of the heater shows a drop in the tuning efficiency by nearly 25%, which is comparable to the difference observed in the tuning power. The temperature profile of the heater as well as the ring filter is simulated with finite-element thermal simulation (FEMLAB). From simulations, the average thermal impedance of the ring with the heater on top is 4800 K/W, but with the fabricated heater, the impedance drops to 3570 K/W. The thermal impedance of various heaters were characterized using the 3-$\omega$ method [12]. The demonstrated tuning power is a 5$\times$ reduction for a SiN ring resonator.

## III. Temperature Control Circuit

An on-chip heater is run by a temperature controller feedback circuit which helps in maintaining a steady temperature against environmental temperature perturbations. In [13], two bands of thin metal are fitted within the circumference of a large ring (diameter $\sim 4$ mm) to work as a heater and a temperature sensor for thermal tuning. Here, due to size constraints for microring resonators, a single resistive element is used both as a heater and as a temperature sensor. The circuit we employ monitors the temperature of the heater by monitoring its resistance as a measure of the filter temperature. Another temperature control alternative was to put the sensor on the edge of the heater, but this approach can give inaccurate temperature readings due to thermal crosstalk between nearby resonators within a filterbank. A circuit that switches between sensing the temperature and heating the resistive element requires precise ADCs to buffer and are limited when scaling with the tuning speed. Our control circuit works on the principle of the Wheatstone bridge, where the circuit senses the change in the resistance of

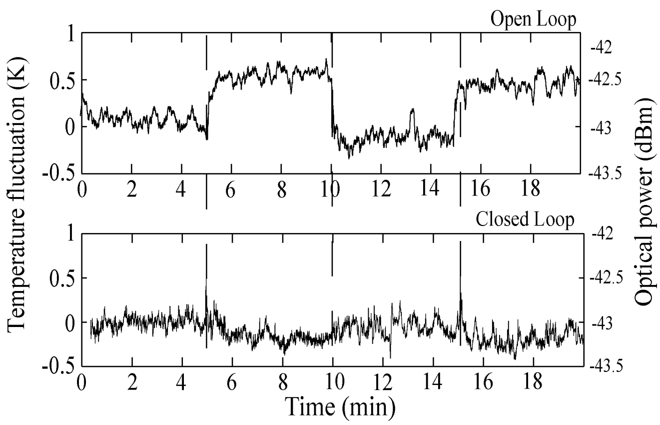


Fig. 4. Thermal control achieved within 80 mK of the absolute value for the second-order ring resonator using feedback control loop.

the heater induced by the temperature change, thus allowing us to sense and heat at the same time. The feedback circuit utilizing a proportional-integral-derivative (PID) controller tries to maintain the overall balance between the voltages of the heater and the set resistor such that the error in the voltage difference measured by an instrumentation amplifier is minimized. A two-color lock-in technique is used for the thermal stability measurement. For the experiment, the two optical signals ($\lambda_1 = 1541.2$ nm, and $\lambda_2 = 1542.2$ nm) from two laser modules are coupled into the waveguide using a polarization-maintaining coupler. One of the optical wavelengths is taken to be at the steepest slope in the passband of the filter and the other signal is taken as the reference, away from the passband. Both the signals are externally modulated with two phase-locked function generators at different frequencies ($\omega_1 = 5$ KHz, and $\omega_2 = 35$ KHz), and measured through a photodetector and a lock-in amplifier in the dual-harmonic mode. Any variation due to the fiber coupling misalignment over a certain time period is the common noise factor in both the signals measured by the lock-in amplifier, which is cancelled by subtraction and the residual intensity deviation is due to the thermal fluctuation of the filter. The laser fluctuation is negligible in this experiment with an average drift of 0.28 pm over an hour. This drift corresponds to 10-mK temperature variation which is the limiting factor for the stability measurement. The experiment was done on a commercial athermal WDM filter to validate the technique.

The average thermal deviation of 145 mK is measured for the intensity fluctuation at the drop port during open-loop operation (no feedback). With closed-loop feedback, the thermal deviation of less than 80 mK is achieved for the ring filter, which is equivalent to the frequency variation of 280 MHz. Currently, the performance of the temperature control circuit is limited by the Johnson noise of the instrumentation amplifier which limits the temperature stability for a SiN ring with Ti heater to 67 mK. The electrical noise of the circuit sets the minimum measurable voltage difference, the temperature coefficient of the heater sets the thermal sensitivity, and the thermooptic coefficient of the waveguide determines the wavelength stability. Using SiN rings instead of Si rings gives us better wavelength stability. Similarly, using high-temperature coefficient material such as Pt for heater would give us better temperature stability.

Another set of experiments is done to show the thermal stability of the system where an external temperature perturbation is introduced by shining a white light source on the sample. When the light is on, a temperature variation of 1 K is introduced to the filter chip. With the closed-loop feedback, the temperature variation is reduced to an average fluctuation of 80 mK (Fig. 4). The speed of the feedback circuit to compensate for the temperature perturbation is in the order of a few tens of milliseconds, which is roughly equivalent to the thermal time constant of the structure. Thus, with the PID controller circuit, we demonstrate the temperature control of the microring resonator to within 80 mK of its absolute value.

## IV. Conclusion

We have demonstrated thermal tuning for a second-order SiN microring resonator with a low power consumption of 80 $\mu$W/GHz. We have used the same on-chip resistive element as the heater and also as the temperature sensor. With the PID temperature controller circuit, we show the stability of the microring resonator to 80 mK giving the resonant frequency stability of 280 MHz, which is approximately 1 part in 8000 of the FSR for the filter.

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## References

[1] R. A. Soref, "Silicon-based optoelectronics," *Proc. IEEE*, vol. 81, no. 12, pp. 1687–1706, Dec. 1993.
[2] B. E. Little, "Advances in microring resonators, Invited Talk," presented at the Integrated Photonics Research Conf., Washington, DC, 2003.
[3] F. X. Kaertner, R. Amatya, G. Barbastathis, H. Byun, F. Gan, C. W. Holzwarth, J. L. Hoyt, E. P. Ippen, O. O. Olubuyyide, J. S. Orcutt, M. Park, M. Perrott, M. A. Popovic, P. T. Rakich, R. J. Ram, H. I. Smith, M. Geis, M. Grein, T. Lyszczarz, S. Spector, and J. U. Yoon, "Silicon electronic photonic integrated circuits for high speed analog to digital conversion," in *3rd IEEE Int. Conf. Group IV Photonics*, 2006, p. 3.
[4] C. W. Holzwarth, T. Barwicz, and H. I. Smith, "Optimization of hydrogen Silsequioxane films for photonic applications," presented at the EIPBN, Denver, CO, 2007.
[5] T. Barwicz, M. A. Popovic, P. T. Rakich, M. R. Watts, H. A. Haus, E. P. Ippen, and H. I. Smith, "Microring-resonator-based add-drop filters in SiN: Fabrication and analysis," *Opt. Express*, vol. 12, no. 7, pp. 1437–1442, 2004.
[6] R. Marz, *Optical Waveguide Theory*. Boston: Artech House, 1995.
[7] M. Popovic, "Theory and Design of High-Index-Contrast Microphotonic Circuits," Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 2008.
[8] I. Christiaens, D. Van Thourhout, and R. Baets, "Low-power thermo-optic tuning of vertically coupled microring resonators," *Electron. Lett.*, vol. 40, no. 9, pp. 560–561, Apr. 2004.
[9] Y. Kokubun, "Wavelength selective integrated device by vertically coupled microring resonator filter," *IPAP Books 2*, pp. 303–316, 2005.
[10] F. Gan, T. Barwicz, M. A. Popovic, M. S. Dahlem, C. W. Holzwarth, P. T. Rakich, H. I. Smith, E. P. Ippen, and F. X. Kartner, "Maximizing the thermo-optic tuning range of silicon photonic structures," in *Proc. Photonics in Switching*, San Fransisco, CA, 2007.
[11] D. H. Geuzebroek, E. J. Klein, H. Kelderman, F. S. Tan, D. J. W. Klunder, and A. Driessen, "Thermally tunable, wide FSR switch based on micro-ring resonators," in *Proc. Symp. IEEE/LEOS Benelux Chapter*, Amsterdam, The Netherlands, 2002.
[12] R. Amatya, C. W. Holzwarth, F. Gan, M. A. Popovic, F. X. Kaertner, H. I. Smith, and R. J. Ram, "Thermally tunable, micro-ring resonators," in *Proc. Conf. Lasers and Electro-Optics (CLEO)*, Baltimore, MD, 2007.
[13] P. Heimale, P. Katila, J. Aarnio, and A. Heinamaki, "Thermally tunable integrated optical ring resonator with poly-Si thermistor," *J. Lightw. Technol.*, vol. 14, no. 10, pp. 2260–2267, Oct. 1996.