Initialization and Stabilization of Microring Resonators for Next-Generation Silicon Photonic Interconnects

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Abstract— **The bandwidth bottleneck looming for traditional electronic interconnects necessitates the use of optical communications, as realized through the CMOS-compatible silicon nanophotonic platform. Within the silicon photonics platform, silicon microring resonators have received a great deal of attention for their ability to implement the critical functionalities of an on-chip optical network while offering superior energy-efficiency and low footprint characteristics. However, silicon microring-based structures have a large susceptibility to fabrication errors and changes in temperature. Integrated heaters that provide local heating of individual microrings offer a method to correct for these effects, but no large-scale solution has been achieved to automate their tuning process. In this context, we present the use of dithering signals as a method to automatically tune and stabilize microring resonators. We show that this technique can be manifested in low-speed analog & digital circuitry, lending credence to its ability to be scaled to a complete photonic interconnection network.**

I. INTRODUCTION

Growing bandwidth needs are motivating the replacement of traditionally electronic links with optical links for applications as diverse as data centers, supercomputers, and fiber-optic access networks. For applications such as these, the silicon photonics platform has received wide attention because of its ability to deliver the necessary bandwidth, and by leveraging its CMOS-compatibility, at a potential economy of scale. In particular, silicon microring resonator based devices exhibit leading metrics on size density, energy-efficiency, and ease of wavelength-division-multiplexed (WDM) operation [1].

Fig. 1 illustrates a portion of an envisioned microring-based photonic network that would be used for transcribing electrical data signals into the optical domain, transmitting and routing them as necessary, and converting the optical signals back to the electrical domain at the termination of the link. The beginning of the link consists of a multi-wavelength laser source. These laser wavelengths are individually modulated by cascaded microring modulators in a multiplexed configuration. The entire set of signals can be routed as necessary by microring-based switches. Finally, they are received by a microring array that demultiplexes the individual signals before receiving them on independent photodetectors.

The basic configuration of Fig. 1 is but one of a myriad of proposed possibilities for photonic networks enabled by microring-based devices, with more complex network designs fully leveraging the unique capabilities of microrings [2]. However, these proposed microring-based photonic networks will never come to commercial realization unless the issues that plague microrings are resolved. Specifically, the relatively high thermo-optic coefficient of silicon combined with the wavelength selectivity of microring resonators lends them susceptible to changes in temperature and laser wavelength. The dominant method to resolving this problem uses energy-efficient integrated heaters to tune and stabilize the microring resonance to the laser wavelength [3]. While demonstrations of manual tuning validate the functionality of these heaters, for commercial implementations an energy-efficient and scalable solution to lock and stabilize microring resonators is required.

There have been several attempted solutions for wavelength locking and thermally stabilizing microring resonators [4-7]. However, no prior demonstrated system has satisfied all required criteria, that is, a system that is low-cost and energy-efficient, does not require additional photonic structures, is compatible with WDM implementation, immune to

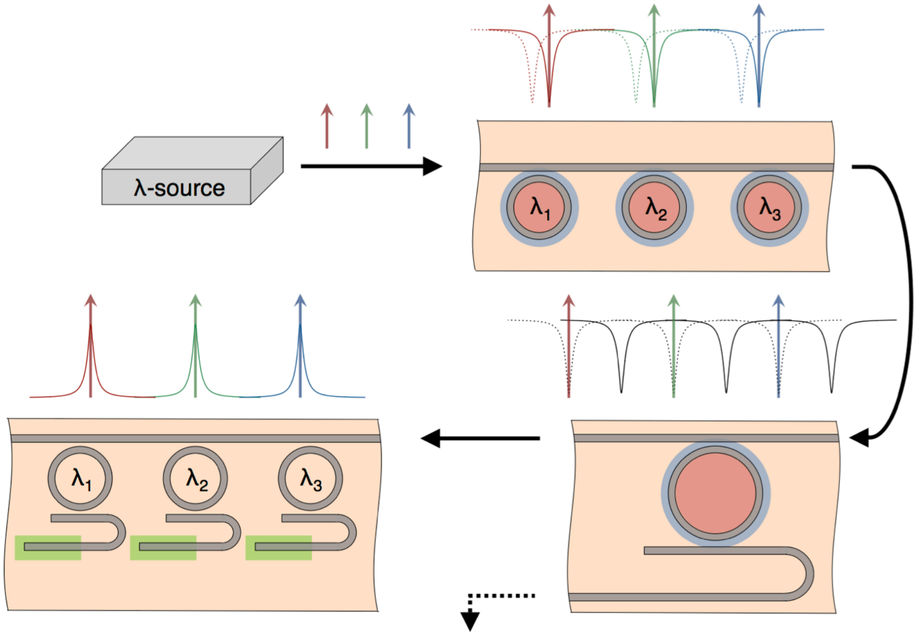

Fig. 1: An optical link composed of microring-based devices. A wavelength source (λ-source) is modulated by multiplexed microring modulators (utilizing fast carrier-induced resonance shifts). A microring switch can then route the entire set of signals appropriately before it is received by a demultiplexing microring array.

fluctuations in the optical power, and implementable for either passive microring resonators or active components such as microring modulators.

Recognizing the limitations of traditional techniques in addressing the above listed criteria, we have pioneered a novel method of locking and stabilizing microring resonators. The underlying principle of our method is to use dithering signals to break the symmetry of the microring resonator [8]. Specifically, the use of a dithering signal can generate the anti-symmetric error signal that is critical for use in electrical feedback controllers.

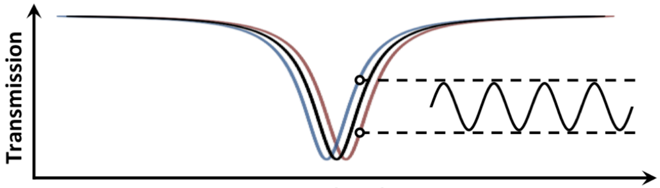

Fig. 2: A small dither signal, applied thermally to the microring resonator, results in a small modulation of the optical signal.

Fig. 2 illustrates dithering (applied thermally), whereby a small modulation is applied to the local temperature of the microring in order to produce a small modulation of the optical signal. The generated optical modulation will either be in-, or out-of-phase with the driving signal, depending on which side of the resonance the laser wavelength is positioned. By mixing the modulated optical signal with the driving dithering signal this information can be recovered as shown in eq. (1), where f_D is the frequency of the dithering signal, and ϕ is the relative phase (0 or π) of the modulated optical signal.

$$\cos(f_D t)\otimes\cos(f_D t+\phi)=\frac{1}{2}[\cos(2f_D t+\phi)+\cos(\phi)] \qquad (1)$$

The higher harmonic can be filtered, leaving the sign of the DC component {cos(ϕ) term} as an indication of the location of the resonance relative to the optical signal. The end product of this process is the desired anti-symmetric error signal

II. DEVICE & EXPERIMENTAL SETUP

The device we used to proof our method is illustrated in Fig. 3, and consists of a 15-µm radius depletion-mode silicon microring modulator. A thin film titanium-based heater is situated directly above the microring, separated from the microring by 1 µm of oxide. The drop port of the microring terminates in a defect-enhanced silicon photodiode, enabling the monitoring of the optical power dropped into the microring [9].

The off-chip electronics implementing the thermal dithering system are shown in the dashed box of Fig. 3. The electronics consist of low-speed (< 20-MHz bandwidth) analog ICs. A 1-kHz square-wave is used for the dithering signal, as a square waveform is easier to synthesize electronically than a sinusoidal waveform, and results in a larger DC component when mixed. The dithering signal is chosen to be higher in frequency than the thermal fluctuations it is monitoring.

The optical signal, modulated by the thermal dithering, generates a photocurrent on the integrated silicon photodiode. The photocurrent is converted to a voltage using a transimpedance amplifier (TIA), and then furthered amplified. An analog mixer IC (AD 633) is used to then mix the amplified signal with the driving dithering signal. A low-pass RC filter is used to suppress the AC component of the mixed product. A proportional-integral-derivative (PID) feedback controller then uses the processed signal as an error signal to determine the drift of the microring and apply an appropriate correction to the heater [7].

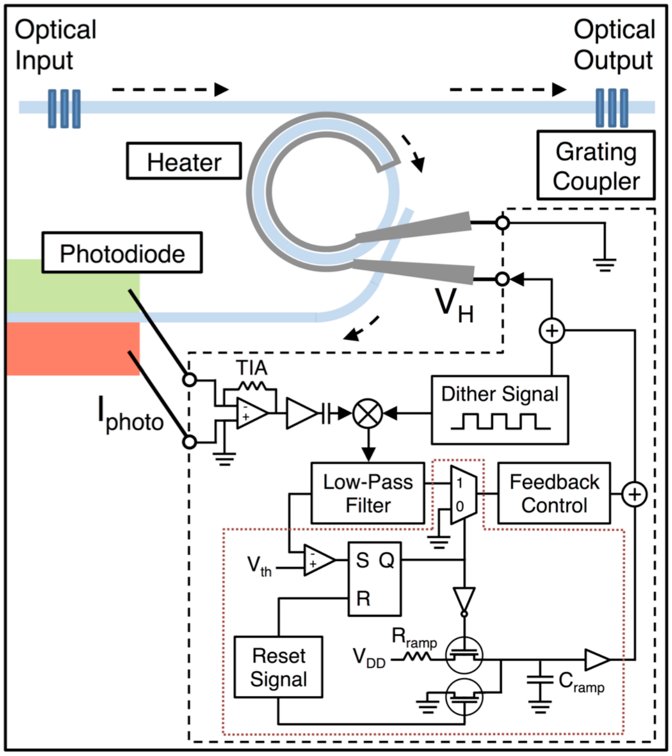

Fig. 3: The device used in this experiment (not to scale). The off-chip electronics interfacing with the integrated photonic elements are shown in the dashed box. Highlighted in red is the circuitry devoted to wavelength locking.

The use of the thermal dithering signal has the consequence of reducing the extinction ratio of the microring resonance. In Fig. 4, the simulated and measured resonances of the microring resonator (Q of ~14,000) are plotted for square-wave thermal dithering signals of magnitude 0.1 K and 0.2 K. A larger thermal dither will result in a larger reduction of the extinction ratio. For thermal dithering of magnitude 0.1 K and 0.2 K the reduction in extinction ratio was measured to be 1.9 dB & 4.8 dB, respectively. Simulations produced identical results (Fig. 4).

While a larger thermal dither results in a larger reduction in extinction ratio, it has the advantage of producing a stronger error signal. Fig. 5 plots the simulated and measured waveforms of the error signal generated from mixing the dithering signal with the generated signal, and then subsequently filtering to the DC component (as shown schematically in Fig. 3).

The error signal generated in Fig. 5 is valuable because it breaks the symmetry of the microring resonance. The anti-symmetric response clearly distinguishes between the red and blue sides of the microring resonance. Furthermore, the zero crossing of the monotonic slope is located at the resonance point of minimum transmission. Hence, a feedback system can easily stay locked to the zero crossing in order to match the laser wavelength with the microring resonance.

While a larger error signal makes the system more robust against noise, we found that the smaller 0.1 K dithering signal generated a sufficient error signal for locking and stabilizing the microring resonator.

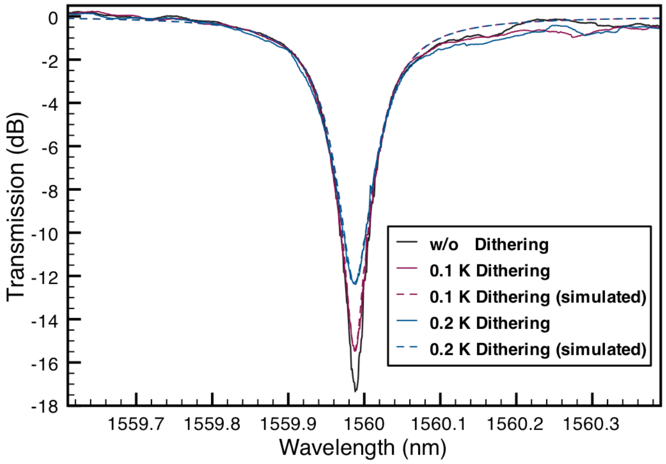

Fig. 4: The microring resonance as it is subjected to thermal dithering signals of varying magnitude (simulations in dashed).

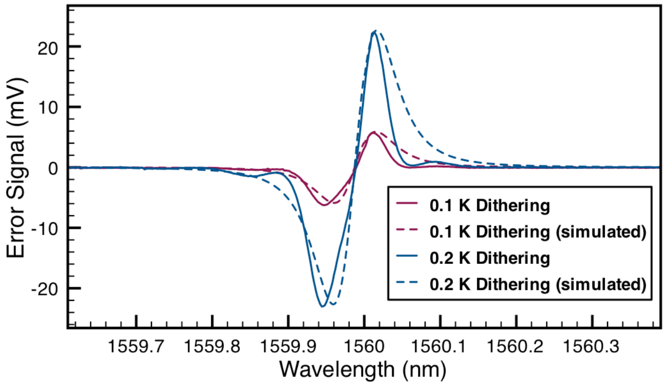

Fig. 5: The generated electrical response (for use as the error signal) for thermal dithering signals of varying magnitude (simulations in dashed).

III. WAVELENGTH LOCKING

The first objective in our control system is to establish the initial lock between the wavelength of the laser source and the wavelength of the microring resonator. Denoted as wavelength locking, this is a critical functionality as in any given system the laser and microring will be initially offset in wavelength due to errors in fabrication or changes in the ambient temperature.

The dashed red box of Fig. 3 indicates the additional electronic circuitry needed to implement the wavelength locking. The functionality of this circuitry is succinctly described in the state diagram of Fig. 6. A simple reset signal is used to trigger the voltage ramping on the integrated heater. As the microring is tuned to the laser wavelength the error signal will trip the system into the hold state, in which the feedback controller is activated and the microring is locked and stabilized against further drifts in temperature or laser wavelength. Additional logic can be added to reset and re-attempt the wavelength locking should it fail on its initial attempt.

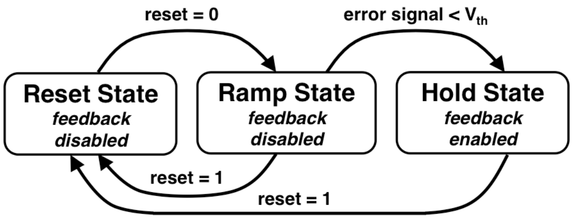

Fig. 6: A state diagram describing the functionality of the wavelength-locking circuitry (dashed red box, Fig. 3)

The wavelength scans in Fig. 7 demonstrate the system locking a passive microring resonator to a laser. Initially, the microring resonance is at ~1559.2 nm, and the laser is offset at ~1560 nm. Over the course of 50 s, the microring is tuned higher in wavelength until the system detects the error signal and establishes the lock. To record the optical traces of Fig. 7, the ramp speed (rate at which the tuning occurs) of the system was drastically reduced, such that the wavelength locking would occur over the course of seconds. In subsequent trials, we increased the ramp speed to achieve wavelength locking in the ~ms time frame. In future implementations, the speed of the dithering signal can easily be increased to >1 MHz to allow the wavelength locking to occur in the ~µs time frame. At that point, the fundamental limits on the speed of the wavelength locking will be determined by the initial offset between the microring resonance and the laser wavelength, and the rate at which the integrated heater can tune the temperature of the resonator.

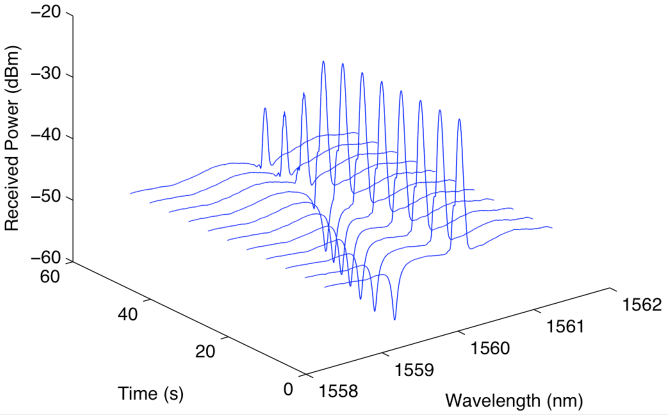

Fig. 7: Optical traces show the microring resonance being tuned and wavelength locked to a laser source.

Fig. 8 shows an oscilloscope measurement of the heater voltage, offering another perspective on the wavelength locking process. Here, the ramp speed has been decreased to allow locking in the ~ms regime. From 0 to ~10 ms the heater voltage is maintained at 0 V, as the system is in the reset state. At 10 ms, the system is triggered, thereby ramping the voltage to tune the microring resonator closer to the laser wavelength. When the heater voltage is ~2.5 V, the microring and laser are aligned in wavelength, and the presence of the error signal triggers the system to stop ramping the voltage and to finalize the lock.

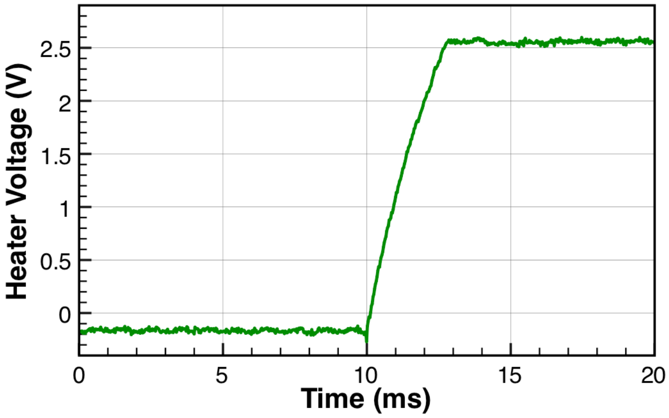

Fig. 8: Oscilloscope trace of the heater voltage as the microring is wavelength locked to the laser source.

IV. THERMAL STABILIZATION

The wavelength locking method we have demonstrated serves to initialize the microring-based photonic link. Once the link has been initialized, it is necessary to guard it against thermal fluctuations. Conventionally, to maintain the local temperature of the microring, the heat generated by the integrated heater is increased or decreased in response to decreases or increases in the ambient temperature [7].

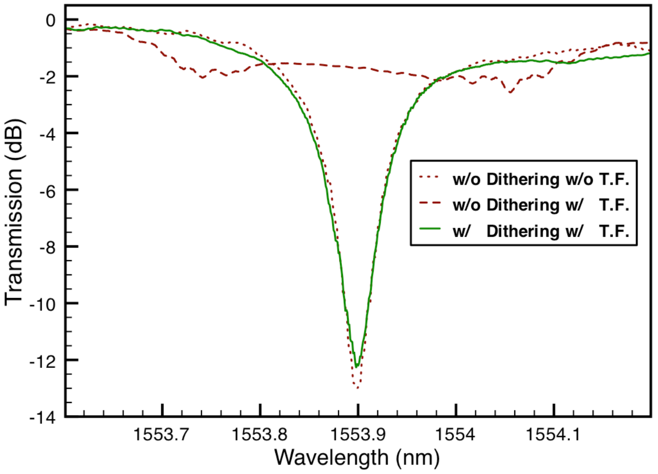

Fig. 9: The microring resonance when subjected to thermal fluctuations (T.F.), with and without the dithering & feedback system implemented.

To implement this, the thermal dithering system was cascaded with a feedback system (as schematized in Fig. 3) to thermally stabilize the microring resonator. To test the system, 10-Hz sinusoidal thermal fluctuations of magnitude 3 K were generated using an external visible laser [10].

In order to verify the thermal stabilization, wavelength scans were performed of a resonance adjacent in wavelength to the resonance that the thermal dithering & feedback system was locked to (Fig. 9). As Fig. 9 shows, with the thermal dithering & feedback system implemented, the microring resonance stays locked to the laser wavelength, with the dynamic tuning of the heater counteracting the thermal fluctuations inflicted on the microring.

V. CONCLUSION

The demonstrated system has been shown to be able to effectively initialize and thermally stabilize individual microring resonators. The thermal stabilization is projected to be effective up to the tuning range of the microring (>50 K), hence enabling the use of microring resonators within thermally volatile microelectronic environments.

The novel use of thermal dithering to generate the error signal has the advantage of giving the feedback system immunity to power fluctuations (the zero crossing of the error signal will stay constant). This renders the system robust against fluctuations in the received power, and immune to fabry-perot artifacts in the optical path. Additionally, the use of low-speed analog and digital ICs in the experimental implementation lends credibility to the system's ability to scale in an energy-efficient manner to the multiple microring resonators that comprise a WDM photonic interconnect. Thus, the fabrication offset and thermal issues that currently plague microring resonators can be resolved in future commercial implementations, allowing them to be manifested in a variety of applications for the purpose of delivering magnitudes of order greater interconnect bandwidth than available with traditional electronic interconnects.

ACKNOWLEDGEMENTS

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REFERENCES

[1] A. V. Krishnamoorthy *et al.*, "Computer systems based on silicon photonic interconnects," *Proc. IEEE* **97**, 1337-1361 (2009).

[2] J. Chan *et al.*, "Chip-Scale Photonic Architectures using Wavelength-Selective Spatial Routing for High-Performance Interconnection Networks," *Proc. TECHCON* (2011).

[3] J. E. Cunningham *et al.*, "Highly-efficient thermally tuned resonant optical filters," *Optics Express* **18**(18), (2010).

[4] E. Timurdogan *et al.*, "Automated Wavelength Recovery for Microring Resonators," *Proc. CLEO* (2012).

[5] W. A. Zortman *et al.*, "Bit error rate monitoring for active wavelength control of silicon microphotonic resonator modulators," *IEEE Micro* **33**(1), (2013).

[6] J. A. Cox *et al.*, "Integrated control of silicon-photonic micro-resonator wavelength via balanced homodyne locking," *Proc. CLEO* (2013).

[7] K. Padmaraju *et al.*, "Integrated thermal stabilization of a microring modulator," *Optics Express* **21**(12), (2013).

[8] K. Padmaraju *et al.*, "Microring Resonance Stabilization using Thermal Dithering," *Proc. IEEE Optical Interconnects* (2013).

[9] D. F. Logan *et al.*, "Monitoring and Tuning Micro-Ring Properties Using Defect-Enhanced Silicon Photodiodes at 1550 nm," *IEEE Photon. Technol. Lett.* **24**(4), 261-263 (2011).

[10] K. Padmaraju *et al.*, "Thermal Stabilization of a microring modulator using feedback control," *Opt. Express* **20**(27), 27999-28008 (2012).