Silicon Micro-Ring Weight Stabilization with Nonlinear Self-Heating

Joshua C. Lederman[1], Simon Bilodeau[1], Eli A. Doris[1], Eric C. Blow[2, 1], Bhavin J. Shastri[3], Paul R. Prucnal[1]

[1] *Department of Electrical and Computer Engineering, Princeton University, Princeton, NJ 08544, USA*
[2] *NEC Laboratories America, Princeton, NJ 08540, USA*
[3] *Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada*

Abstract: Micro-ring resonators can tunably weight wavelength-division-multiplexed signals, but they face high sensitivity to temperature. In this work, we take advantage of micro-ring self-heating to experimentally stabilize a silicon micro-ring weight, nearly halving its thermal sensitivity.

1. Introduction

A broadcast-and-weight photonic system performs linear combination of a set of wavelength-division-multiplexed (WDM) signals, with application to radio-frequency (RF) interference cancellation and photonic neural networks [1, 2]. Such a system uses micro-ring resonators (MRRs) to apply tunable weights to each wavelength of light, with the weight applied a function of the wavelength-dependent intensity buildup in the micro-ring. On the silicon-on-insulator (SOI) platform, the weight is typically tuned by changing the temperature of the micro-ring using an embedded heater. Such a temperature change produces a refractive index change due to the thermo-optic effect in silicon, in turn resulting in a shift in the resonant wavelength due to the sensitivity of micro-rings to refractive index variation [3].

The thermal sensitivity of micro-ring weights is a double-edged sword; while it provides a simple and effective way of fully tuning the weights, it also makes the weights susceptible to environmental temperature variation and other on-chip heat sources (such as the heaters of adjacent micro-rings). Reducing the micro-ring quality factor can lower this sensitivity by widening the resonance, at the cost of either increased optical cross-talk or a reduced maximum number of WDM signals. Instead, we take advantage of negative feedback associated with nonlinear self-heating in silicon micro-ring resonators to stabilize a micro-ring weight with respect to temperature without any impact on instantaneous resonance shape.

2. Micro-Ring Self-Heating

1550 nm light can be absorbed in silicon via intensity-dependent two-photon absorption, resulting in the generation of free carriers which cause further absorption (free carrier absorption). In both cases, carriers can fall back to the valence band, generating heat that raises the silicon refractive index and red-shifts resonances. This effect is particularly strong in MRRs due to the resonant buildup of optical intensity [4].

We consider an operating wavelength slightly to the "blue" side (the short-wavelength side) of a resonance near 1550 nm, with the system in steady state. A perturbation of additional applied heat causes a red-shift of the resonance, reducing the optical intensity buildup as the resonant wavelength and operating wavelength diverge. This in turn, results in reduced optical absorption and self-heating, *counter-acting* the perturbation—negative feedback. (Conversely, if we operated to the "red" side of the resonance, the feedback would be positive.) This negative feedback has the effect of reducing the impact of heat perturbations, stabilizing the micro-ring weight.

3. Experimental Setup

Our experimental setup is diagrammed in Fig. 1a. We create a simple one-MRR broadcast-and-weight system using a single integrated SOI add-drop MRR and an external set of balanced photodetectors (PDs). Input optical power is controlled by a variable optical attenuator (VOA), and the input source signal is a pure 950 MHz tone produced by a continuous wave generator (CWG) and modulated by a Mach-Zehnder modulator (MZM) with quadrature biasing. The DC component of the modulated signal, tunable by the VOA, controls the level of self-heating. Source-measurement units (SMUs) control the MRR heater current and measure the DC output signal, while an oscilloscope monitors the AC signal. The applied weight is the normalized amplitude of the 950 MHz component of the AC output signal.

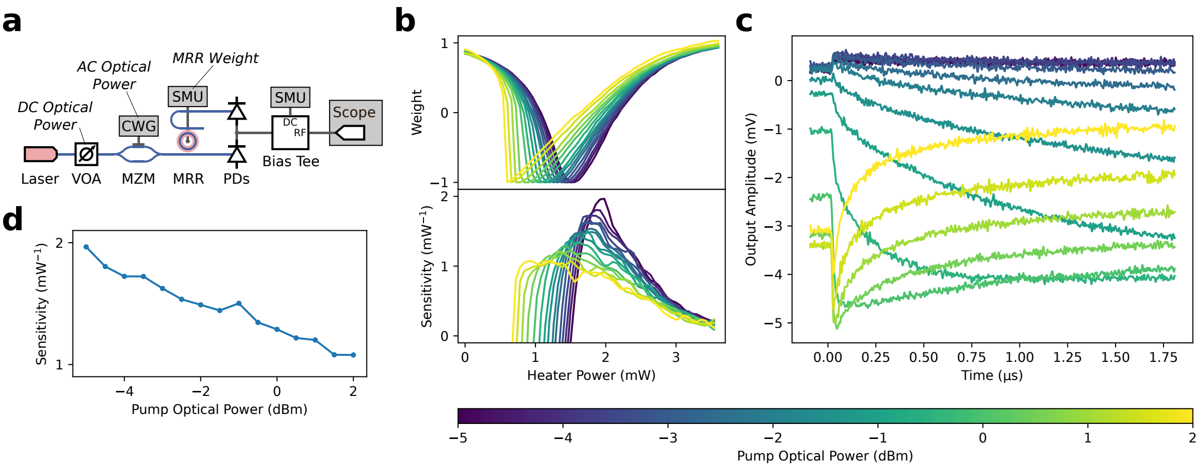

Fig. 1. Experimental setup and results. (a) Diagram of the experimental setup (optical and RF amplifiers and filters not shown). (b) MRR weight and thermal sensitivity. (c) Transient behavior of the output signal in response to a 1.3 dB optical step function. (d) Maximum thermal sensitivity.

4. Results

Fig. 1b shows the weight applied by the MRR and the sensitivity of that weight to variations in heater power as a function of heater power and pump optical power. The weights are normalized to the maximally on-resonance position (corresponding to a weight of -1). As optical power scales, absorption in the MRR increases, providing an internal source of heat. The fully on-resonance position is therefore achieved with reduced external heating. The maximum sensitivity of the micro-ring weight to heat perturbations, shown in Fig. 1d, is nearly halved at the highest input power as compared to the lowest input power as a result of the stabilization effect.

We require that the self-heating effect be slow relative to the period of the input signal to ensure the resonance position does not shift in time to the AC component of the pump optical intensity, distorting the signal. We evaluate the time constant of self-heating by measuring the transient system behavior in response to a 1.3 dB optical step function at various center pump optical powers, with the ring heated to operate in the positive-feedback (high-sensitivity) region to strengthen the effect. As shown in Fig. 1c, there is an initial sharp jump in measured output intensity in response to the increase in input intensity, followed by a gradual relaxation as the resonance shifts to its steady-state position under the influence of self-heating. Relaxation occurs with a time constant in the 100s of ns, suitable for input signals above 10 MHz.

5. Discussion

WDM photonic computing systems offer improved interconnect efficiency and reduced chip area in comparison to the alternative coherent architecture, and MRRs are crucial to enabling these benefits. The thermal sensitivity of MRRs represents a major disadvantage of the WDM architecture that has limited its application, as environmental thermal stability cannot be guaranteed in typical operating conditions. In this work, we demonstrate a novel mechanism to significantly reduce the thermal sensitivity of MRRs. We anticipate optimization of the MRR design would enable further reductions in MRR sensitivity.

References

1. C. Huang, S. Fujisawa, T. F. de Lima, A. N. Tait, E. C. Blow, Y. Tian, S. Bilodeau, A. Jha, F. Yaman, H.-T. Peng, H. G. Batshon, B. J. Shastri, Y. Inada, T. Wang, and P. R. Prucnal, "A silicon photonic–electronic neural network for fibre nonlinearity compensation," *Nature Electronics*, vol. 4, no. 11, pp. 837–844, Nov 2021.
2. W. Zhang, A. Tait, C. Huang, T. Ferreira de Lima, S. Bilodeau, E. C. Blow, A. Jha, B. J. Shastri, and P. Prucnal, "Broadband physical layer cognitive radio with an integrated photonic processor for blind source separation," *Nature Communications*, vol. 14, no. 1, p. 1107, Feb 2023.
3. T. F. de Lima, E. A. Doris, S. Bilodeau, W. Zhang, A. Jha, H.-T. Peng, E. C. Blow, C. Huang, A. N. Tait, B. J. Shastri, and P. R. Prucnal, "Design automation of photonic resonator weights," *Nanophotonics*, vol. 11, no. 17, pp. 3805–3822, 2022.
4. M. Novarese, S. R. Garcia, S. Cucco, D. Adams, J. Bovington, and M. Gioannini, "Study of nonlinear effects and self-heating in a silicon microring resonator including a shockley-read-hall model for carrier recombination," *Opt. Express*, vol. 30, no. 9, pp. 14 341–14 357, Apr 2022.