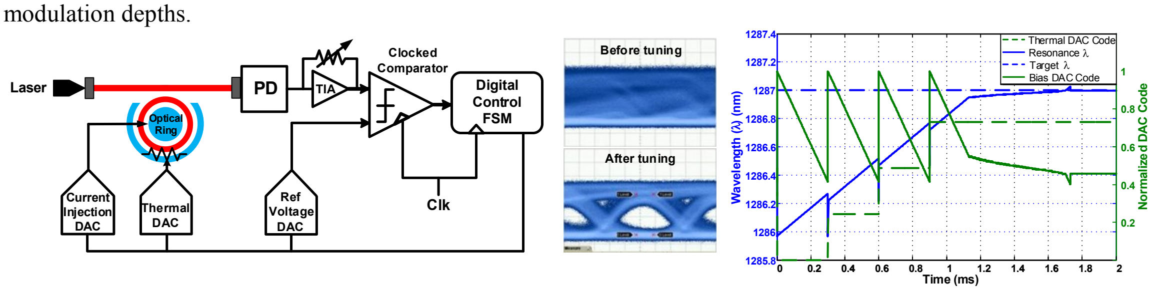
Efficiency Modeling of Tuning Techniques for Silicon Carrier Injection Ring Resonators

Alex Titriku[1*], Cheng Li[2], Ayman Shafik[1] and Samuel Palermo[1],
[1]Texas A&M University, College Station, TX 77843, USA, [2]HP Labs, Hewlett-Packard Company, Palo Alto, CA, 94304, USA
**e-mail address: akntitriku@tamu.edu*

Abstract: Modeling of carrier injection ring resonator devices with common thermal tuning and a new dual-bias/thermal scheme reveals that the latter scheme offers ~50% improvement in power with small variations and close to 16X speed improvement.

1. Introduction

Silicon photonic interconnects based on ring resonator devices offer an attractive substitute to traditional electrical interconnects due to the negligible frequency-dependent channel loss and high bandwidth density offered via wavelength-division multiplexing (WDM) [1]. An important issue is that the resonant wavelength of these high-Q devices is sensitive to fabrication and temperature variations, prompting the need for dynamic tuning [2]. Resonance wavelength tuning can be achieved by adjusting the ring resonator's refractive index thermally, electrically, or by employing both techniques. However, this tuning comes with both costs in power, with [3] reporting an addition of up to 4pJ/bit to the total link power at a data rate of 25 Gb/s with thermal tuning, and speed, with devices displaying ~100µs thermal time constants. This motivates investigation into alternative tuning schemes which improve both power efficiency and tuning speed. In this work, modeling results are presented which compare these important metrics between the common thermal tuning approach and a newly proposed dual-loop scheme which leverages both bias and thermal tuning for carrier-injection ring modulators, which provide large refractive index changes and high modulation depths.



(a) (b) (c)

Fig. 1. (a) Dual bias/thermal tuning block diagram (b) eye diagram before and after tuning (c) coarse-fine dual loop tuning with large offset.

2. Tuning Techniques

The two common tuning methods considered are thermal and bias (current injection) tuning. Thermal tuning is achieved by varying current through a heater near the ring resonator, causing an increase in the refractive index of the silicon and the resonant wavelength to red shift. Bias tuning involves varying the DC forward-bias current that is applied to the ring, changing the carrier density to decrease the refractive index and blue-shift the resonant wavelength. This provides flexibility and the potential for a very fast tuning mechanism [4]. Although thermal tuning generally covers a wider tuning range than bias tuning due to limitations in the bias range and increased loss, thermal tuning typically consumes more power and is slower due to large thermal time constants.

A hybrid tuning technique, denoted as "dual-loop tuning" involves a smart mix of bias and thermal tuning to take advantage of the thermal tuning large range and the bias tuning fast speed. Two dual-loop tuning approaches are proposed. The first "simple" approach involves starting the tuning with the bias loop and relinquishing control to a fine resolution thermal loop to complete the tuning if the bias loop is not successful. This allows for rapid tuning within the bias loop range and minimum power consumption when the thermal tuning is activated. The second "coarse-fine" method involves taking coarse thermal steps equal to the bias tuning range and fine tuning with bias until a successful lock is achieved. This allows for a dramatic increase in tuning speed with even large variations, at the cost of some power overhead due to the different bias/thermal tuning directions. A simplified block diagram of the dual-loop tuning system is shown in Fig. 1(a), with the experimental eye diagrams of Fig. 1(b) verifying the functionality of the closed-loop scheme in bias-only mode. The simulation results of Fig. 1(c) demonstrate correct operation of the coarse-fine dual loop method in the presence of a large ring mismatch, where a coarse thermal step in tandem with a fine bias control is used to achieve successful tuning.

3. Tuning Efficiency Comparison

In order to evaluate the tuning power efficiency and speed of the aforementioned wavelength stabilization techniques, a Matlab-based tuning model is developed. WDM systems employing between 5-20 rings with a 3.7THz free spectral range (FSR) [3] are modeled. These rings are designed with an 80GHz channel spacing to match an assumed comb

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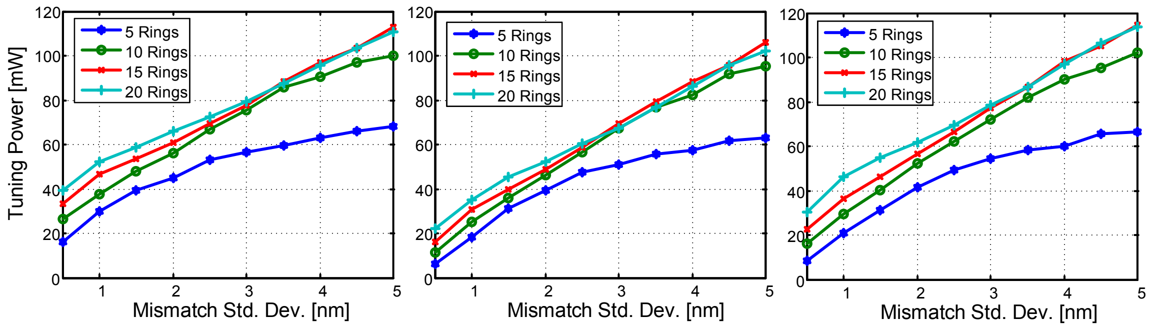
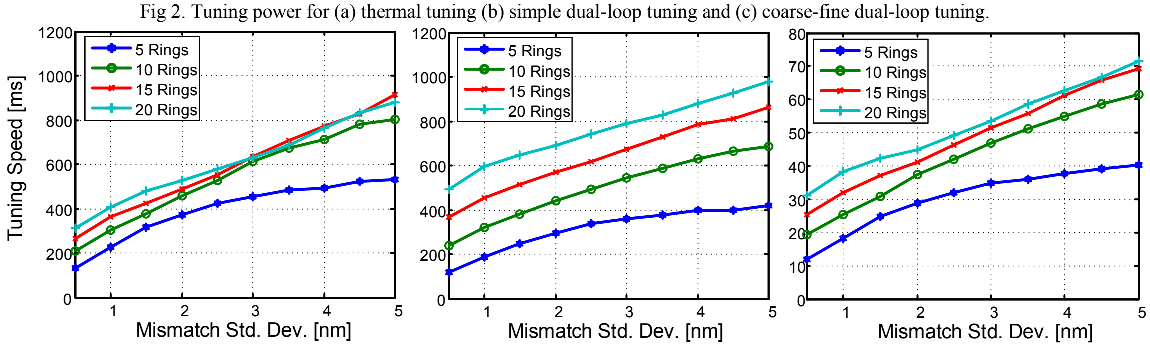
laser source. In lieu of tuning a specific ring to an assigned wavelength, ring shuffling is employed to allow tuning to the nearest available wavelength [1]. The bias tuning is modelled with a 6.8 μW/GHz efficiency and 0.28nm range [5], while the thermal tuning is assumed to have 10 μW/GHz [2], a 77μs time constant [3], and sufficient tuning range to cover 5nm$_{rms}$ variation. A 1MHz finite state machine controls both the bias and thermal tuning.



(a) (b) (c)

Fig 2. Tuning power for (a) thermal tuning (b) simple dual-loop tuning and (c) coarse-fine dual-loop tuning.



(a) (b) (c)

Fig 3. Tuning speed for (a) thermal tuning (b) simple dual-loop tuning and (c) coarse-fine dual-loop tuning.

As shown in the tuning power versus wavelength mismatch results of Fig. 2, thermal tuning consumes the most power for smaller mismatch standard deviations (<2.5nm), with 33% and 12% more power relative to the simple and coarse-fine dual-loop tuning, respectively, for a 20 ring system with 1nm$_{rms}$. Note that the power overhead of the coarse-fine approach relative to the simple dual-loop scheme due to the different bias/thermal tuning polarities is observable at small mismatch values. With larger mismatches, all schemes display similar performance due to the thermal tuning power dominating. The potential of the coarse-fine dual-loop technique is highlighted in the Fig. 3 tuning speed results, with as much as a 16X improvement in speed observed at the same resolution due to the fine tuning achieved with the high-speed bias tuning. Due to only a single bias sweep with the simple dual-loop approach, its tuning speed is similar to thermal-only tuning.

4. Conclusion

Resonance wavelength sensitivity to process and temperature variations is a major obstacle in the deployment of ring-resonator based nanophotonic interconnects. This necessitates innovative tuning systems with high efficiency and acceptable tuning times. A new dual-bias/thermal tuning system was proposed and compared against conventional thermal tuning for carrier injection ring resonators. This dual-loop tuning scheme allows for dramatic improvements in power efficiency with small variations and tuning speed over a wide variation range, providing the potential for rapid tuning of large ring count systems with minimal power overhead.

Acknowledgment

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