Low-Power Optical Interconnects based on Resonant Silicon Photonic Devices: Recent Advances and Challenges

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ABSTRACT

The progressive blooming of silicon photonics technology (SiP) over the last decade has indicated that optical interconnects may substitute the electrical wires for data movement over short distances in the future. A key enabler is the resonant structures that can participate in both modulation and demultiplexing of a high throughput wavelength division multiplexed (WDM) photonic link. The optical and electro-optical properties of such devices are subject to various design considerations, operation conditions, and optimization procedures. We present recent technological advances in photonic links based on resonant structures and highlight the key challenges that must be overcome at a large scale. Furthermore, we discuss how the design space of these resonant devices, down to the geometrical parameters and fabrication errors, can affect the performance and reliability of a photonic link.

CCS CONCEPTS

• **Applied computing → Physical sciences and engineering**; **Computer-aided design**; • **Computing methodologies → Modeling and simulation**; **Model development and analysis**;

KEYWORDS

Silicon photonics; microring resonators; optical amplitude modulation; optical interconnect; optical power penalty; wavelength division multiplexing

ACM Reference Format:
Meisam Bahadori and Keren Bergman. 2018. Low-Power Optical Interconnects based on Resonant Silicon Photonic Devices: Recent Advances and Challenges. In *GLSVLSI '18: 2018 Great Lakes Symposium on VLSI, May 23–25, 2018, Chicago, IL, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3194554.3194606

1 INTRODUCTION

Silicon Photonics (SiP) platform has been the subject of intensive research for more than a decade now and its prospects continue to emerge as it enjoys the maturity of CMOS manufacturing industry [2]. SiP foundries all over the world [27] and particularly in the US (AIM Photonics) have been developing reliable photonic design kits (PDKs) that include fundamental SiP building blocks such as wavelength selective modulators and tunable filters. Microring resonators (MRR) are hailed as the most compact devices that can perform both modulation and demodulation in a wavelength division multiplexed (WDM) transceiver design [9]. Although the use of WDM can reduce the number of fibers carrying data, it also makes the design of transceivers challenging [24]. It is probably acceptable to achieve compactness at the expense of somewhat higher transceiver cost and power consumptions. Nevertheless, these two metrics should remain close to their actual values [61] for Datacom applications. An increase of an order of magnitude is clearly not acceptable. For example costs relative to bandwidth for an optical link in a data center interconnect will have to decrease from the current ~$5/Gbps down to <$1/Gbps [1, 3]. Additionally, the transceiver itself must remain compact.

Silicon does not exhibit optical absorption at wavelengths in the vicinity of 1550 nm (a transparent material) and has an indirect bandgap. Therefore, silicon-based MRR modulators are designed based on the "electro-refraction" principle [47]. In this type of modulators, the refractive index of the material (silicon) is alternatively changed by applying an electrical signal, resulting in a different optical path length for "0" bits and "1" bits. In 1987, Soref *et al.* [51] characterized how the optical properties (index and absorption) of Silicon change by injecting charge carriers into an undoped sample or by extracting carriers from a doped sample. Although this phenomenon, called the plasma dispersion effect, is fast enough to enable Gb/s modulation speed [58], it still provides a weak perturbation of the refractive index. In addition, unlike the thermo-optic effects [5], the optical absorption of Silicon is also affected through the plasma dispersion effect. In return, electro-refractive modulators are relatively easy to fabricate, robust, and broadband. In contrast to electro-absorptive modulators (EAM) [16], they do not require the presence of Germanium or another absorbing material in the silicon-on-insulator (SOI) fabrication process.

2 SILICON PHOTONIC LINKS

A photonic link is by definition equipped with a transmit unit (Tx) and a receive unit (Rx). The link architecture based on an integrated photonic platform such as Silicon Photonics can be envisaged as the ones presented in Fig. 1 [7, 10]. The Tx requires input optical power in the form of serialized/combined optical wavelengths. Each wavelength provides one channel of optical data. One convenient solution is to use a multi-wavelength laser source such as a comb laser source [11]. The optical power is then injected into the Tx using vertical grating couplers or edge couplers. This process inflicts optical loss and is unavoidable. Grating couplers with

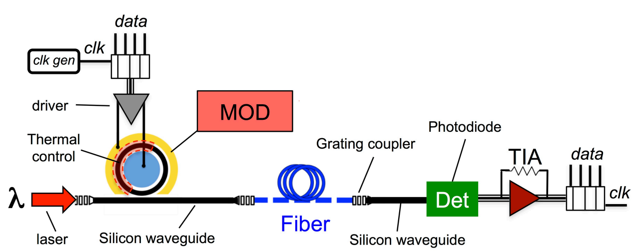
GLSVLSI '18, May 23–25, 2018, Chicago, IL, USA

ACM ISBN 978-1-4503-5724-1/18/05…$15.00
https://doi.org/10.1145/3194554.3194606

more than 75% coupling efficiency [54] and less than 4 dB loss [26] have already been demonstrated.

The architecture in Fig. 1(b) consists of cascaded microring modulators. Each modulator is designated to a specific wavelength through thermo-optic tuning of its resonance, while modulating light through fast charge carrier based electro-optic effects in silicon. The output data streams of all modulators are combined and multiplexed inside the bus waveguide and extracted from the Tx unit into a carrier fiber through another optical coupler. As can be seen in Fig. 1(b), multiplexing of optical channels in a transmitter architecture based on MRR modulators is achieved at no additional cost because of the wavelength-selective property of MRRs.

The Rx unit is equipped with a wavelength demultiplexer since WDM scheme is used [6]. Light from each channel, accompanied by optical crosstalk [8], is incident on a photodiode, which is then converted to electrical current. The electrical current is converted to electrical voltage signal and amplified and finally deserialized to recover each individual electrical data stream. Although inclusion of a clock-and-data recovery (CDR) module is a common choice for the Rx units, forwarded clock schemes have also been proposed for MRR-based links [18].



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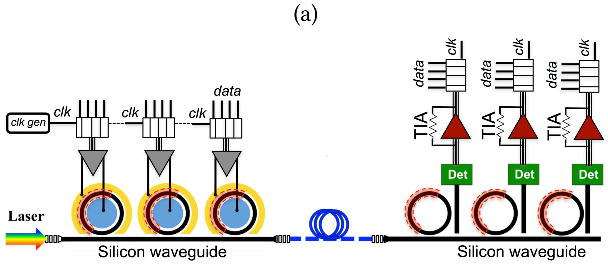
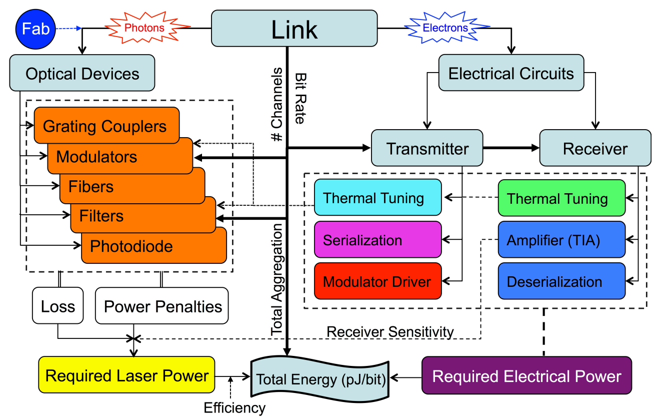


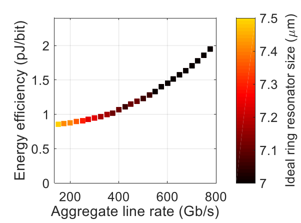
(b)

Figure 1: (a) Structure of a single-λ photonic link with a microring modulator at the transmitter and no spectral filtering at the receiver. (b) Anatomy of a WDM link based on microring resonators. Multiplexing of wavelengths is easily achieved due to the wavelength-selective nature of MRRs. Spectral filtering is required at the receiver to select individual channels.

Figure 2(a) depicts the inter-relations of optical and electrical parts of a link to target a specific throughput and energy/bit metric. A link design problem can be formulated in several ways: 1) Maximizing the total throughput (aggregated bandwidth) of the link by finding the best combination of number of channels and data rate per channel for a given optical power budget; 2) minimizing the energy/bit metric for a given throughput; 3) maximizing the throughput for a given energy/bit metric. In [9], we showed that a silicon photonic link under ideal electronics circuitry can provide up to 2 Tb/s of aggregation. However, later on we included more realistic models for the modulator drivers and TIAs based on 65nm CMOS node and concluded a maximum supported throughput of 1.6 Tb/s for the best energy/bit metric (~1.5 pJ/bit) [7]. In a more recent work, we added an optimization of the microring resonators based on realistic fabrication limitations (e.g. the coupling gaps are in the range of 100nm–400nm) and found out that the maximum supported bandwidth is limited to less than 1 Tb/s [10]. Figure 2(b) shows the result of optimization of the link for various throughput targets and Fig. 2(c) shows the breakdown of the calculated energy/bit metrics. This shows that both electronic and photonic components play a significant role in determining the capacity of a silicon photonic link.



(a)



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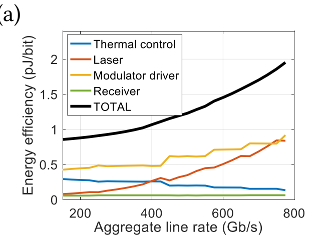


(c)

Figure 2: (a) Diagram of electrical and optical interplays for designing and analyzing a photonic link. Both electronics and photonics play important parts in the energy consumption of the link (in units of pJ/bit). (b) A recent example of optimizing an MRR-based silicon photonic link for various throughputs. (c) Breakdown of energy consumption of a link for various aggregations.

3 MICRORING MODULATORS

In 2005, it was first demonstrated that silicon MRRs can provide adequate phase shift by taking advantage of the plasma dispersion effect (PN or PIN diode). The device had a compact footprint (12 μm diameter) while achieved more than 10 dB of extinction ratio with a low insertion loss [59]. Since then, many researchers have proposed various modulator designs based on MRRs for low-power and high-speed modulations. MRRs with free spectral range as large as 22 nm (diameter <10 μm) have been demonstrated for dense WDM systems, capable of operating at 15 Gb/s [50]. Dynamic energy consumptions as low as 7 fJ/bit have been demonstrated for an MRR operating at 25 Gb/s with 1 V peak-to-peak drive voltage [23]. In 2013, the first 50 Gb/s modulation at 1.96 V peak-to-peak drive voltage for a silicon racetrack MRR was demonstrated [4]. In order to enhance the modulation efficiency and reduce the effective junction capacitance, MRRs with ZigZag [56] and interdigitated [43] junctions have been proposed. MRRs have also been used for higher-order amplitude modulation formats such as four-level pulse amplitude modulation (PAM4) [48] at 80 Gb/s and PAM8 at 45 Gb/s [15], with a power consumption of 7 fJ/bit and 1 fJ/bit, respectively. Due to the nonlinear spectral response of MRR, a single PN phase shifter requires unequal voltage steps to realize a high-order PAM. To resolve this, designs with two separate phase shifters embedded in one MRR have been proposed [42]. Phase modulation such as binary phase shift keying (BPSK) at 10 Gb/s has also been realized with MRRs [25]. Table 1 provides a summary of recent notable demonstrations of microring modulators.

Table 1: Notable demonstrations of SiP microring modulators.

Structure	Bit rate (Gb/s)	Modulation Format	Extinction Ratio (dB)	Year	Ref.
MRR-PIN	12.5	NRZ	>9	2007	[58]
MRR-PIN	15	NRZ	NA	2016	[50]
MRR-PN	25	NRZ	>5	2011	[23]
MRR-PN	40	PAM4	NA	2017	[42]
MRR-PN	25	NRZ	4.5	2012	[57]
MRR-PN	44	NRZ	3.01	2012	[56]
MRR-PIN	50	NRZ	4.58	2013	[4]

4 MICRORING FILTERS

The use of cascaded MRR modulators at the transmitter to achieve WDM signaling mandates the presence of a wavelength demultiplexer at the receiver end. As shown in Fig. 1(b), MRRs in the form of add-drop structures are capable of performing wavelength demultiplexing due to their wavelength selective spectral response. Based on the desired passband and the rejection ratio of the filter, first-order [8, 12–14] or higher-order [19, 32, 46, 55] add-drop filters are used. Higher order filters provide a better rejection ratio but suffer from a higher loss in their passband.

Recently we showed that it is possible to perform an optimization on the add-drop filters to minimize the optical power penalty of the demultiplexing array [6]. Such optimization of microrings requires a deeper understanding of how these structures operate. MRRs in a demux array are subject to multiple physical and optical constraints. For example, the radius must be large enough to prevent undesired high bending losses [19], but not too large in order to avoid interference of other resonances in the optical bandwidth of interest. Moreover, the 3dB optical bandwidth of a ring used in a WDM add-drop configuration should be large enough to accommodate the bandwidth of the optical signal to be dropped. A too narrow bandwidth will result in heavy, and undesired, truncation of the signal spectrum, thus distortions [9] (truncation power penalty). However, a too large bandwidth can cause a severe optical crosstalk problem (crosstalk power penalty) if the channel density is high [8, 19, 39].

Under these multiple constraints, the selection of an MRR with right parameters is not a straightforward and easy task. For example, a larger radius results in a strong coupling of the ring to the waveguides while at the same time it results in a smaller optical loss of the ring. Furthermore, in some cases no realistic MRR matching all the requirements exists. In order to characterize the design space of MRR filters, recently we developed accurate compact models [49] that incorporate the effect of physical dimensions (width, height, gap size, radius) on the optical response of first order and higher order structures. Such compact models allow us to characterize the design space of a first-order MRR as shown in Fig. 3. In Fig. 3(a), we calculate the contours of optical loss in the passband of the filter and gray out losses worse than 1 dB. In Fig. 3(b), the maximum extinction of the filter outside of its passband is calculated and the values greater than -30 dB are ruled out. In Fig. 3(c), the optical bandwidth of the passband is plotted and the region from 10 Ghz to 50 Ghz is selected. Finally, the design space shown in Fig. 3(d) is obtained by overlaying the contours of all the parameters. The center point of the design space corresponds to a radius of 9 μm and coupling gaps of 180 nm. The center point still

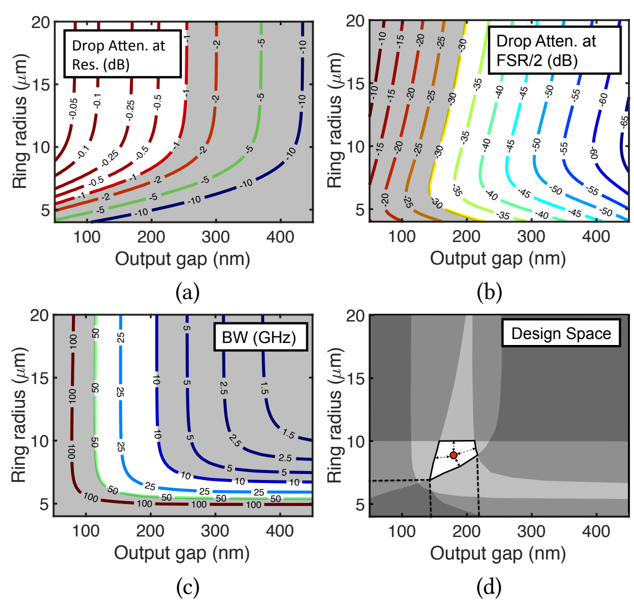


Figure 3: Design space exploration of silicon-based first-order MRR. (a) Contours of optical loss in the passband. (b) Contours of rejection ratio outside of the passband. (c) Optical bandwidth. (d) Design space. Output gap refers to the distance between the ring and the drop waveguide.

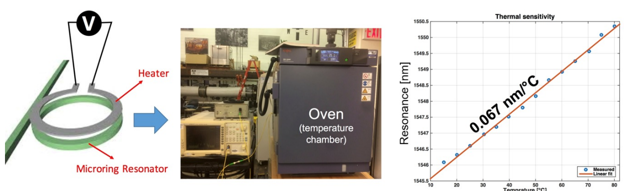
remains in the white zone even with the presence of small variations on the gap or radius.

5 CHALLENGES AT SCALE

Although the physical principles behind the operation of MRRs are well-known, a significant amount of engineering effort must be put together to make a MRR-based transceiver fully functional. Here, we briefly review four obstacles that negatively affect the optical performance of MRRs.

5.1 Thermal Sensitivity of MRRs

Thermal effects significantly change the optical behavior of silicon-based devices due to the strong thermo-optic coefficient of silicon material (dn_{Si}/dT = 1.8×10^{-4} K^{-1}) [20]. For very narrow-band optical devices such as MRRs, thermal susceptibility can be significantly detrimental, and requires accurate monitoring and control of the temperature to maintain desired behavior and performance over a long period of operation [17, 31, 60]. The resonance of a typical silicon MRR is shifted by ~10 Ghz (~0.07 nm) for each degree Kelvin change in the temperature of the MRR [34, 44]. A single degree of temperature variation is therefore sufficient to create significant spectral distortion of on-off keying (OOK) signals for dense wavelength-division multiplexing (DWDM) systems that employ the link architecture of Fig. 1(b). In order to experimentally verify the sensitivity of a silicon MRR as shown in Fig. 4(a), we put it inside a temperature chamber (oven) shown in Fig. 4(b) and tracked the resonance wavelength by increasing the tempearture (Fig. 4(c)). As expected, a linear relation between shift of resonance and temperature was observed indicating a thermal sensitivity of 0.067 nm/K of the resonance.



(a) (b) (c)

Figure 4: (a) Structure of an MRR with a microheater. (b) An oven hosting an MRR. (c) Measured shift of resonance as a function of temperature.

The popular solution for thermal control of MRRs is based on active thermal feedback control [40, 41] and consists of sending an electrical current through integrated metallic or doped-silicon based micro-heaters to induce Ohmic heating. This method of operation is based on the heat diffusion principle which is a rather slow process. The thermo-optic bandwidth of the heater-MRR structure is typically limited to 50–100 kHz. Recently, we investigated the main tradeoffs between the thermo-optic bandwidth (i.e., heating speed) and the thermo-optic efficiency (i.e., shift of resonance as a function of heater power, in units of nm/mW) for MRRs [5] and concluded that reaching a higher efficiency leads to a lower speed. The rise time and fall time of thermo-optic response typically falls on the order of micro-seconds. Such low speed response imposes challenges in real-time monitoring and wavelength locking of MRRs. On the plus side, the small thermo-optic bandwidth of the MRR can be utilized to actuate the heater with electrical digital signals such as pulse width modulation (PWM), hence eliminating the need for digital to analog converters [35].

5.2 Self-heating and bistability of MRRs

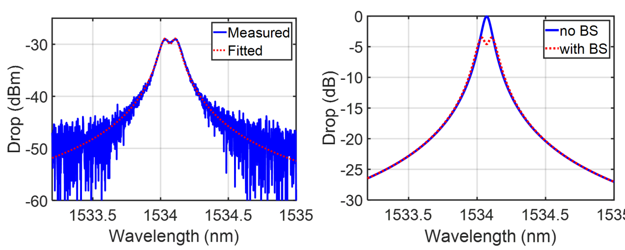
Due to the resonant nature of MRRs, there is a strong build-up of optical power inside the resonator. The enhancement of optical power is proportional to the finesse (Q-factor) of the resonator for a critically coupled MRR [33]. At the presence of such high optical power inside the ring, even a slight inherent absorption can lead to a noticeable change in the temperature of the ring which causes a thermal drift of resonance, hence deteriorating the optical OOK data. Although for the short period of a "1" bit (e.g., 100 pico-second for 10 Gb/s OOK) this effect is not tangible, for a long stream of consecutive "1" bits it poses a severe threat to the operation of both MRR modulators and filters. A recent transceiver design has clearly pointed out this problem [52] and proposed a thermal tuning algorithm based on the statistics of the data stream. It is worth noting that addition of more electronic circuitry for such algorithms will add-up to the overall energy consumption of the photonic link.

5.3 Fabrication variations and nonuniformity

The spectral parameters of an MRR such as resonance wavelength, free spectral range (FSR), and the optical bandwidth mainly depend on the geometrical properties of the MRR. It is quite known that current silicon photonic fabrication imposes variations on the dimensions of the waveguides (typically in the range of ~5 nm) [21] and the radius of the ring. This results in deviations of the resonance wavelength from the original design [36, 38] and requires thermal tuning, hence degrading the energy efficiency of the link. Furthermore, identical devices experience different variations based on their location on the silicon wafer (fabrication nonuniformity) [37]. Therefore, in order to predict the yield of the fabrication and include that in the optical budget of the link, a wafer-scale statistical model of the variations for the photonic devices should be developed [21, 29, 45]. Most likely, such statistical models vary from one silicon photonic foundry to another which may impose challenges on predicting the yield for a particular transceiver design. Unconventional designs such as multi-mode waveguides have been proven to mitigate the impact of fabrication variations on the resonance of MRRs [30].

5.4 Sidewall roughness and backscattering inside MRRs

Narrow-band spectral response of MRRs in conjunction with high-speed data streams puts stringent requirements on the design of MRRs for high-performance links. It has been shown that in applications where very narrow linewidths (i.e. Q > 10000) are required, even a slight roughness on the sidewalls of the ring will cause backscattering (BS) inside the ring [22, 28]. The effect of backscattering in MRRs is typically observed in the form of a splitting of the resonance in the spectral response of the ring [28]. Such spectral distortion adds extra complexity that further narrows down the design space of MRRs for minimizing power penalties. An increase of optical bandwidth (thus a decrease of the Q-factor) limits the attenuation of the high-frequency components of the dropped signals, but may lead to a truncated filtering shape that inflicts higher losses and spectral distortions on the central frequency components of the dropped signals. Figure 5(a) shows the spectral response of one of our fabricated add-drop MRRs exhibiting a significant resonance splitting. Figure 5(b) compares the simulated response of an MRR with and without the observed backscattering. A loss of 5dB in the passband is inflicted onto the optical data which can significantly impact the bit-error-rate of the optical link.



(a) (b)

Figure 5: (a) Measured spectral response of a first-order add-drop with strong backscattering (BS). (b) Simulated MRR with and without backscattering (BS).

6 CONCLUSIONS

Our recent studies indicate that silicon photonic links based on microring resonators can provide data aggregations in the range of 0.5–1 Tb/s at energy efficiencies in the range of 1.5–3 pJ/bit. While the design space of MRRs is not hard to explore for the optimum designs, significant amount of engineering effort still needs to accompany that to overcome challenges such as thermal sensitivity of MRRs, optical absorption and self heating, fabrication variations, and backscattering effects. The potential of silicon photonics for monolithic integration with CMOS electronics [53] is driving engineers to find the best solutions for all the problems that MRRs are facing.

ACKNOWLEDGMENTS

This work is supported in part by Air Force Research Laboratory (FA8650-15-2-5220), ARPA-E ENLITENED project (DE-AR00000843), and by Department of Energy under LLNS subcontract (B621301).

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