Integrated Thermal Stabilization of a Microring Modulator

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Abstract: An integrated silicon photodiode and heater are used to thermally stabilize a microring modulator, interfacing with external feedback circuitry to provide error-free microring modulator operation under thermal fluctuations that would normally render it inoperable.
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Growing bandwidth needs have presented the need for optical communication at scales and distances smaller than previously precedented, motivating the use of optical links for such scenarios as rack-to-rack links in data centers, board-to-board interconnects, and ultimately for use in multi-core processors [1]. However, at these smaller scales, optical links are only feasible if they can be realized in a small footprint and energy-efficient manner. For this reason, the silicon photonics platform, with its ability to manifest CMOS-compatible photonic devices, is promising for use in next-generation optical links. Within the silicon photonics platform, microring-based devices have been shown to push the boundaries on the aforementioned metrics of size and energy efficiency.

However, as the high-performance functionality of both passive and active silicon microring-based devices have continued to be demonstrated, concerns have grown over the suitability of these devices for use in thermally volatile environments. The high thermo-optic coefficient of silicon, combined with the resonant nature of the microring-based devices, lends the operation of said devices susceptible to thermal fluctuations of only a few kelvin (K) [2]. Attempts to resolve the thermal sensitivity of passive and active microring-based devices have been focused on creating thermally insensitive structures [3,4] or dynamic feedback systems [2,5]. In particular, it has been shown that using a feedback system, a microring modulator can maintain error-free performance under thermal fluctuations that would normally render it inoperable [2]. A feedback system thermally stabilizes the microring modulator by monitoring the temperature, either directly or indirectly, and then adjusting the local temperature of the modulator using an appropriate mechanism. In the cited demonstration [2], changes in the temperature of the microring modulator were inferred by monitoring the mean power of the microring-modulated signal using an off-chip photodetector. To complete the feedback system, the bias current was varied to provide the necessary temperature adjustment in the localized region of the microring modulator.

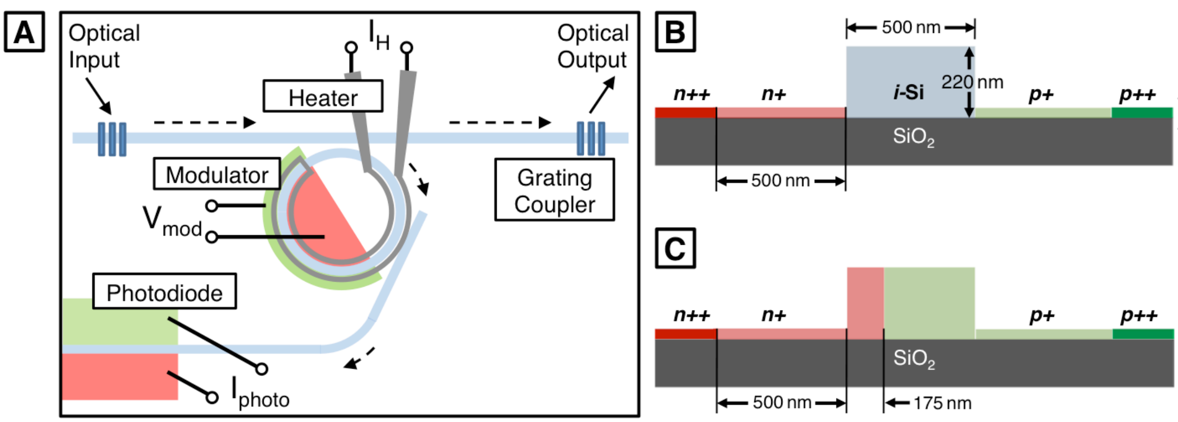

Figure 1: (a) Schematic of the integrated device (not to scale). Waveguide geometry and doping profile for the **(b)** silicon photodiode and **(c)** depletion-mode microring modulator.

In this demonstration, we further the results of [2] by showing that the optoelectronic components that comprise the feedback system can be integrated onto a single device using CMOS-compatible processes and materials. The enabling technology of this integration is the use of a defect-enhanced silicon photodiode [6]. Such devices have been demonstrated as effective high-speed optical receivers, but an additional utility lies in their use as in-situ power monitors for silicon photonic devices [7]. Positioned on the drop-port of the microring modulator, the silicon photodiode is utilized as the photoreceiver needed to monitor the mean power of the modulated signal. This configuration avoids the use of a power tap and is compatible with the WDM arrangement of microring modulators, where several microrings are cascaded along the same waveguide bus.

The device layout is shown in Fig. 1a, and consists of a depletion-mode microring modulator, with a thin film heater directly above it, and a defect-enhanced silicon photodiode on the drop-port. Holographic gratings are employed to facilitate coupling of *C*-band wavelengths into and out of the chip. The ring is 15 µm in radius. The cross-section of the photodiode and modulator are shown in Fig. 1b and 1c, respectively. The waveguides are 500 nm wide and 220 nm in height, and etched to a depth of 170 nm. The modulator is formed of an $n^{+}p$ junction that is offset by 75 nm from the center of the waveguide, taking up one-half of the ring circumference. The thin film heater is formed of a titanium-based layer, separated from the active layer by 1 µm of oxide. The photodiode is 500 µm long, and consists of a p-i-n junction formed laterally on the waveguide. Sensitivity to sub-bandgap wavelengths was provided by a masked phosphorus implantation followed by a low temperature anneal.

In our experimental setup (Fig. 2a), a pulsed-pattern-generator was used to generate a 5 Gb/s non-return-to-zero (NRZ) 2^{31}-1 pseudo-random-bit-sequence (PRBS) electrical signal. This electrical signal was amplified to 5 V_{pp} and biased at -2.5 V to drive the microring modulator using high-speed electrical probes. A separate set of low-speed electrical probes was used to contact the heater and silicon photodiode. A CW tunable laser was set to TE polarization before being launched into the grating coupler with a power of 4 dBm. The microring-modulated 5 Gb/s optical signal was recovered from the exit grating coupler for bit-error-rate (BER) measurements and eye diagrams.

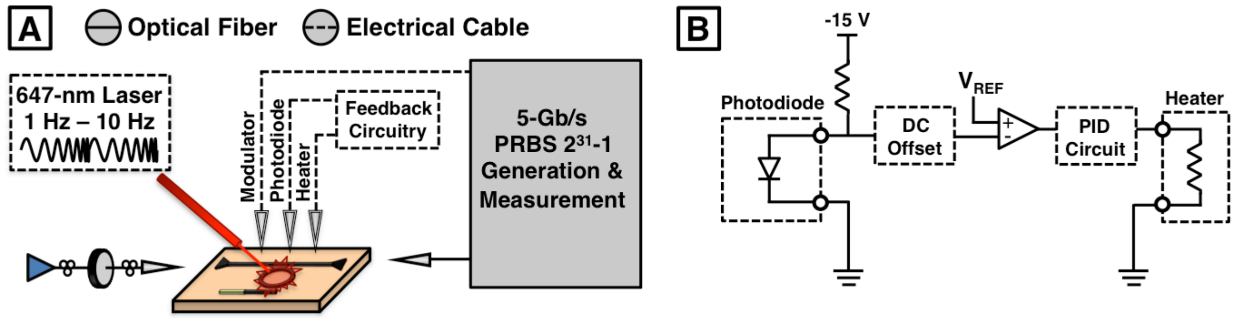

Figure 2: (a) Experimental Setup. **(b)** Circuitry comprising feedback system. Included in the schematic are the on-chip components.

As illustrated in Fig. 2a, a visible laser at a wavelength of 647 nm was vertically aligned above the microring modulator. The power of the visible laser was internally modulated with a 1-10 Hz sinusoid, thereby imprinting a 1-10 Hz sinusoidal thermal fluctuation of magnitude 1.5 K in the localized region of the microring modulator [2]. While the magnitude of the thermal fluctuation was relatively minor, our results show that this was enough of a thermal fluctuation to render the microring modulator inoperable, hence providing a sufficiently thermally volatile environment to demonstrate the functionality of the integrated feedback system.

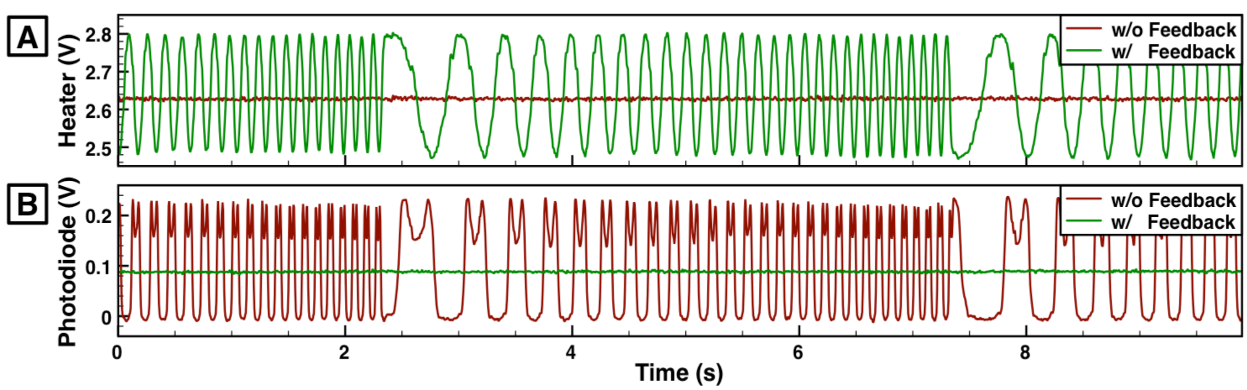

Figure 3: Oscilloscope measurements (with and without the feedback system) of the **(a)** voltage applied to the heater, and the **(b)** voltage generated from the photodiode (following the transimpedance resistance and DC offset) measuring the mean modulation power.

As Fig. 2a shows, the operation of the feedback system occurs independent of the high-speed operation of the microring modulator. Fig. 2b outlines the feedback circuitry, including the interface between the circuitry and the on-chip integrated photodiode and heater. As previously mentioned, the silicon photodiode is used to ascertain changes in the mean power of the modulated optical signal. The photodiode is reversed biased in series with a resistor at -15 V. The transimpedance voltage generated from this arrangement is offset by a set DC voltage, and then compared to a reference voltage using an instrumentation amplifier. The resultant error signal is fed into an analog proportional-integral-derivative (PID) control circuit. The PID circuit generates a feedback signal that is used to change the voltage on the integrated heater. In this manner, the integrated heater dynamically reduces current (cools down) in the presence of high ambient temperatures and increases current (heats up) in the presence of low ambient temperatures, thereby maintaining the temperature of the microring modulator at a set operating temperature throughout the duration of the thermal fluctuations inflicted by the visible laser.

The dynamic adjustment of the heater voltage is seen in the oscilloscope trace of Fig. 3a. Without the feedback circuit, the heater voltage is set at a constant 2.6 V (an arbitrary voltage), whereas, with the feedback circuit, the voltage is swung dynamically between 2.5 V and 2.8 V to correct for the thermal fluctuations. The effect of this action can be seen in the transimpedance voltage from the photodiode (Fig. 3b), which was used to measure the mean power of the optical signal for our feedback system. Without the feedback circuit the mean power fluctuates in correspondence with the thermal fluctuations. The feedback system locks the mean power to the set reference, ensuring that the modulation is maintained throughout the duration of the thermal fluctuations.

The eye diagrams and BER measurements in Fig. 4 validate the performance of the feedback system. Without the thermal fluctuations, there is a negligible difference between operating the microring modulator without feedback (Fig. 4a), and with feedback (Fig. 4c), further confirmed by the BER measurements in Fig. 4e, which shows no incurred power penalty as a consequence of operating with the feedback system. As seen in Fig. 4b, subjection of the microring modulator to thermal fluctuations without a corrective feedback system will result in complete failure of the modulation. However, as can be seen in Fig. 4d, the feedback system can completely correct for the thermal disturbances, maintaining error-free modulation with a power penalty of 2.8 dB (in comparison to the back-to-back case of Fig. 4a).

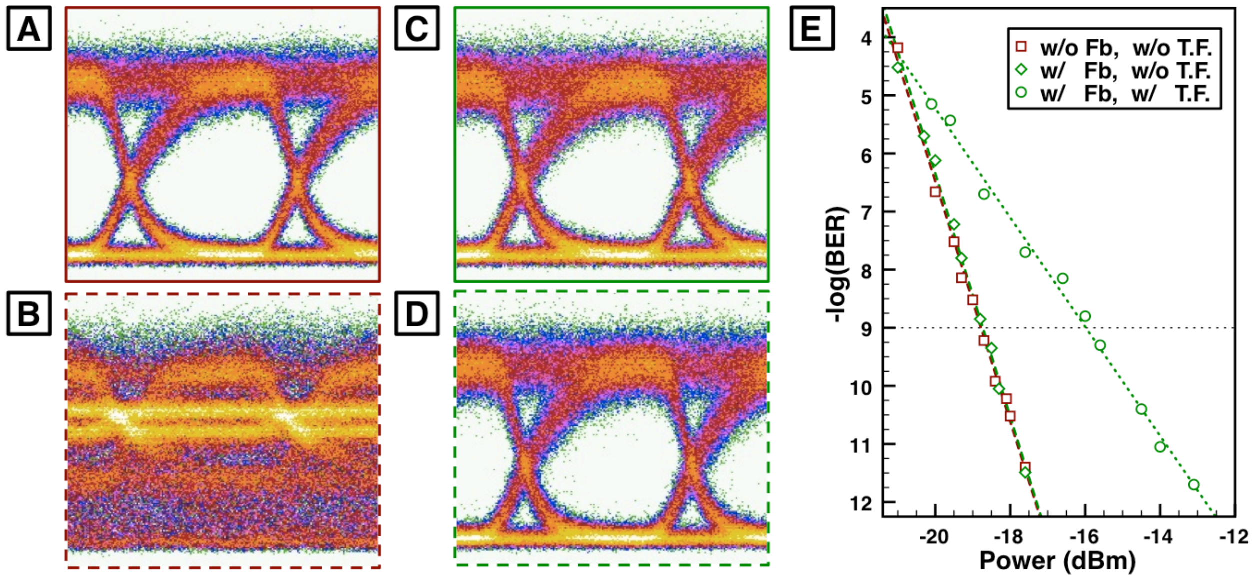

Figure 4: Eye diagrams of 5-Gb/s microring-modulated optical signal ***without*** the feedback (Fb) system in **(a)** a stable thermal environment, and **(b)** under thermal fluctuations (T.F.). Similarly, the microring modulation ***with*** the feedback system in **(c)** a stable thermal environment, and **(d)** under thermal fluctuations. **(e)** BER measurements corresponding to eye diagrams in (a), (c), and (d).

By leveraging the diversity of functionality found in the silicon photonics platform we have demonstrated a thermal stabilization solution that uses components integrated directly with a microring modulator. The demonstrated bit-rate transparent feedback system operates independently, and without disturbing, the high-performance optical modulation. While this demonstration stressed the basic functionality of the system, it has been shown that a heater closely integrated with the modulator can enable energy-efficient thermal tuning across a range of 60 K [8], lending plausibility to the ability of this system to completely adapt to the full range of temperatures that would be encountered in a microelectronics environment. The slow-speed (bandwidth < 20 MHz) analog electronics (op-amps & instrumentation amplifier) comprising the feedback system have the potential to be implemented in a low-energy integrated form with the integrated photonic components, providing a small-footprint, energy-efficient, WDM scalable, thermally stable microring modulator for use in next-generation optical links.

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