

# Silicon-photonic PTAT Temperature Sensor for Micro-ring Resonator Thermal Stabilization

Saman Saeedi and Azita Emami

California Institute of Technology, Pasadena, California 91125, USA, [saman.saeedi@caltech.edu](mailto:saman.saeedi@caltech.edu)

**Abstract** *This paper presents thermal stabilization of micro-ring resonator modulators through direct measurement of ring temperature using a monolithic PTAT temperature sensor. The measured temperature is used in a feedback loop to adjust the thermal tuner of the ring.*

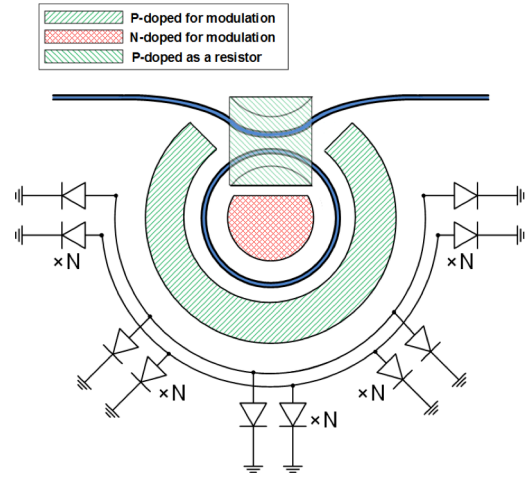
## Introduction

Compact, low-power and high-speed electro-optic modulators (EOM) are one of the key components in realization of chip-to-chip optical signalling. Resonant structures such as micro-ring modulators are promising candidates due to their compact size and low power consumption. As the resonance wavelength is susceptible to temperature fluctuations, resonant modulators require thermal tuning. Sophisticated techniques and circuitry have been proposed to stabilize the temperature fluctuations in ring resonator modulators<sup>1-3</sup>. These techniques require extra optical power<sup>1</sup> on the silicon-photonic chips, complex circuitry<sup>2</sup> or extra fabrication steps and do not fit standard CMOS process flows<sup>3</sup>. As an alternative method, micro-ring modulators with integrated temperature sensor and resistive heater have been proposed to enable thermal compensation<sup>4</sup>. However, these efforts relied on a single diode, which is prone to process variation. Also temperature gradients induced by the heater or ambient thermal sources can cause large error in a single isolated sensor. In this paper, we propose thermal tuning through a monolithic distributed Proportional To Absolute Temperature (PTAT) sensor. Linear operation of the temperature sensor with and without operational heater is demonstrated over 125°C. Using a temperature feedback loop, the micro-ring modulator is shown to operate at 20Gb/s in presence of emulated temperature fluctuations.

## Design and Analysis of PTAT Sensor

The basic principal behind the PTAT temperature sensor is that difference between voltage drop of two forward-biased diodes, operating at different current densities, is linearly

proportional to absolute temperature. Starting



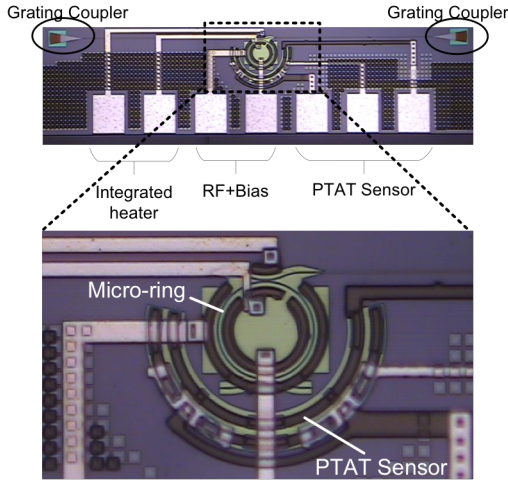
**Fig. 1:** Proposed structure of ring resonator with integrated heater and PTAT temperature sensor

from a simple diode equation, diode current ( $I_D$ ) vs voltage ( $V_D$ ) is approximated to be

$$V_D = \frac{nKT}{q} \ln\left(\frac{I_D}{I_s}\right) \quad (1)$$

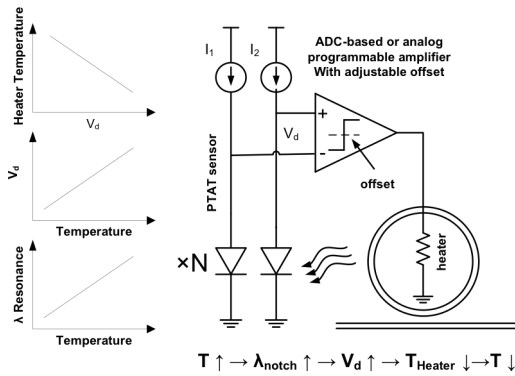
where  $K$  is the Boltzmann constant,  $T$  is the absolute temperature,  $q$  is the charge of electron,  $I_s$  is the reverse bias saturation current and  $n$  is fabrication constant typically between 1 and 2. Two forward-biased diodes with different sizes will have a voltage difference of

$$\begin{aligned} V_{D21} &= V_{D2} - V_{D1} = \frac{nKT}{q} \left( \ln\left(\frac{I_{D2}}{I_{s2}}\right) - \ln\left(\frac{I_{D1}}{I_{s1}}\right) \right) \\ &= \frac{nKT}{q} \ln\left(N \frac{I_{D2}}{I_{D1}}\right) \end{aligned} \quad (2)$$



**Fig. 2:** Die micrograph of the fabricated micro-ring modulator with integrated heater and PTAT temperature sensor

where  $N$  is the ratio of diodes (i.e. ratio of their reverse bias saturation currents). The slope of the PTAT sensor can be engineered using the ratio of reverse bias saturation currents and ratio of currents fed to each diode. In this design, the ratio of currents is 4 and  $N=5$  resulting in a factor of 20. For a given voltage sensitivity, it is desirable to maximize the slope of PTAT sensor to achieve higher accuracy in temperature readings. However, if the difference in currents becomes too large, the difference between voltage-drops across the parasitic resistances of diode contacts error. Fig. 1 shows the conceptual structure of the proposed micro-ring with monolithic PTAT sensor. In this structure the heater is placed under the coupler while the rest of ring's perimeter is used for modulation. The PTAT temperature sensor is distributed around the ring using pairs of PN junction to avoid temperature error in presence of temperature gradients. The device is designed in IME platform through OpSIS, which enables interconnection of distributed PTAT temperature



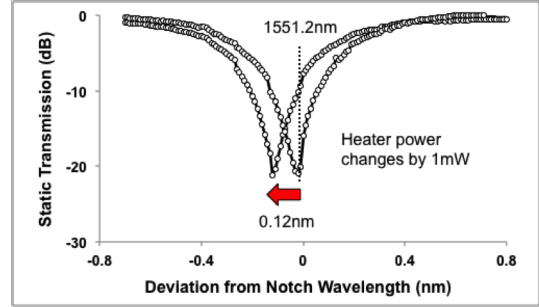
**Fig. 3:** Concept of a feedback loop to stabilize micro-ring's temperature

sensor using two metal layers<sup>5</sup> (Fig. 2).

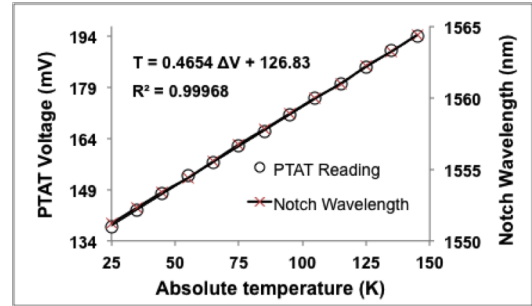
The PTAT temperature sensor can be used in a feedback loop to stabilize temperature of the micro-ring (Fig. 3).

### Measurements

The prototype was fully characterized via both DC and high-speed measurements. The DC



(a)

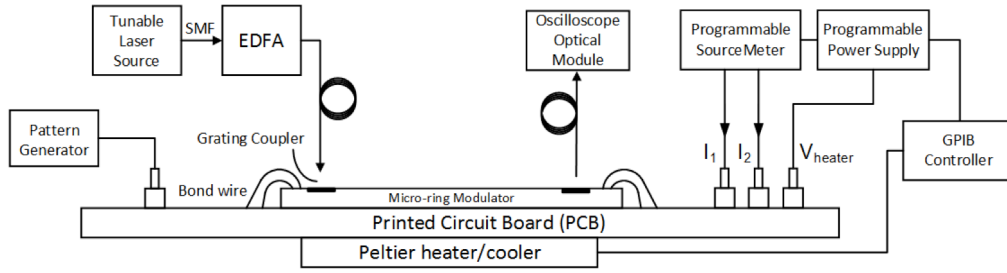


(b)

**Fig. 4:** (a) Static transmission and heater tunability of the micro-ring (b) PTAT voltage and notch wavelength vs temperature

characteristics of the micro-ring is shown in Fig. 4 (a). The full-width half-maximum of the transmission spectra is measured to be 0.33nm resulting in a Q of around 4700. Tunability of the ring is measured to be 0.12nm/mW. In order to characterize the performance of the PTAT sensor, a heater is attached to the die and the difference between diode voltages versus temperature is measured. For every wavelength the corresponding notch wavelength is also measured. Fig. 4 (b) illustrates these measurements and the linear equation fitted to predict the temperature from PTAT readings.

Functionality of the micro-ring modulator is first verified without ambient thermal noise. An RF probe is used to modulate the micro-ring and optical probes are used for carrying CW beam of laser to the input grating coupler and from output grating coupler. A high-speed PRBS-15 sequence is then used with a reverse bias of -3.5V and peak-to-peak modulation depth of 5.5V



**Fig. 5:** Measurement setup with induced thermal fluctuations and temperature stabilization feedback loop

at 10Gb/s and 20Gb/s. The micro-ring achieves up to 20Gb/s of data rate with an extinction ratio of 4dB.

Fig. 5 shows the measurement setup for high-speed measurements of the modulator. A peltier thermoelectric cooler is used to emulate temperature fluctuations of the ring. The peltier cooler provides a maximum temperature difference of 47°C from a maximum current of 5A. The peltier cooler's current is modulated with a 1Hz square wave such that the temperature of the ring changes by 3.2°C every second. A feedback loop is formed using two GPIB programmable SourceMeters connected to the PTAT sensor and a programmable power supply connected to the integrated heater. The SourceMeters provide constant currents for the PTAT sensor and are used to read the voltage difference between the two diodes. The voltage reading is used to measure the temperature of the micro-ring and the integrated heater's voltage is tuned to keep the ring temperature constant.

Fig. 6 (a) and (b) shows this current and the corresponding voltage of the integrated heater produced by the feedback loop. The primary limit in demonstrating higher bandwidth of the

Fig. 6 (c) and (d) show the output optical eye diagram in presence of emulated ambient temperature noise without and with temperature stabilization feedback loop.

### Conclusion

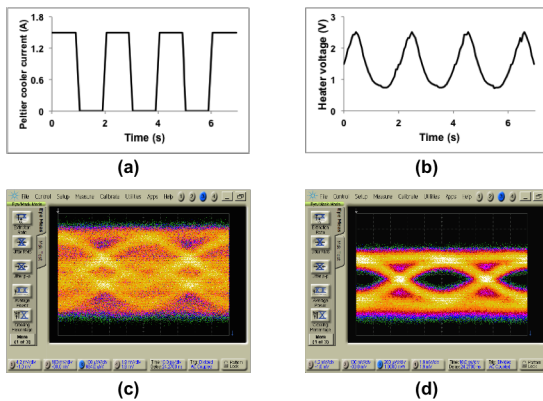
A compact micro-ring modulator with integrated heater and monolithic PTAT temperature sensor is presented. Total active area of the micro-ring including PTAT sensor (not including pads) is 100μm×100μm. Linearity of the PTAT sensor is verified over 125°C. A temperature stabilization loop is demonstrated to compensate ambient thermal noise. The closed-loop system operates at data-rates up to 20Gb/s when external temperature fluctuations are present.

### Acknowledgements

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**Fig. 6:** (a) Peltier heater/cooler supplied current (b) integrated heater voltage provided by the feedback loop (c) output optical eye diagram without thermal tuning feedback (d) with thermal tuning feedback.

feedback loop is in the speed of emulated thermal fluctuations and not the PTAT sensor.