A 10Gb/s, 342fJ/bit Micro-Ring Modulator Transmitter with Switched-Capacitor Pre-Emphasis and Monolithic Temperature Sensor in 65nm CMOS

Saman Saeedi[1,2], and Azita Emami[2]
[1]Oracle Labs, Redwood Shores, CA, Email: saman.saeedi@oracle.com and [2]California Institute of Technology, Pasadena, CA

Abstract

In this work, a CMOS-SiPh optical transmitter based on carrier-injection ring modulators is presented. It features a novel low-power switched-capacitor-based pre-emphasis that effectively compensates the modulator bandwidth limitation. A wavelength stabilization technique via direct measurement of ring temperature using a monolithic PTAT sensor is also presented. The optical transmitter achieves energy efficiency of 342fJ/bit at 10Gb/s and the wavelength stabilization circuit consumes 0.29mW.

Keywords: CMOS, transmitter, silicon photonics, micro-ring, resonator, pre-emphasis, thermal tuning

Introduction

Electro-optic modulators (EOM) that are CMOS-compatible, compact and low power are essential elements in realization of chip-to-chip optical signaling. Carrier injection micro-ring modulators (MRM) are one of the promising candidates [1], [2]. Compared with carrier depletion MRM, they can operate with higher extinction ratio and with CMOS-compatible drive voltages. However, the speed of carrier-injection rings is limited to slow carrier dynamics and necessitates pre-emphasis to compensate their nonlinear transient behavior. Both types of MRMs are also susceptible to temperature variations and need wavelength stabilization loops. In this paper we present a hybrid-integrated CMOS-SiPh transmitter that tackles these challenges. A novel low-power switched-capacitor-based (SC) pre-emphasis technique that effectively compensates the modulator bandwidth limitation is proposed. A feed-forward bias-based wavelength stabilization technique via direct measurement of ring temperature using a monolithic PTAT temperature sensor is also presented.

Principles of Operation

Carrier-injection MRMs are inherently slow and limited by

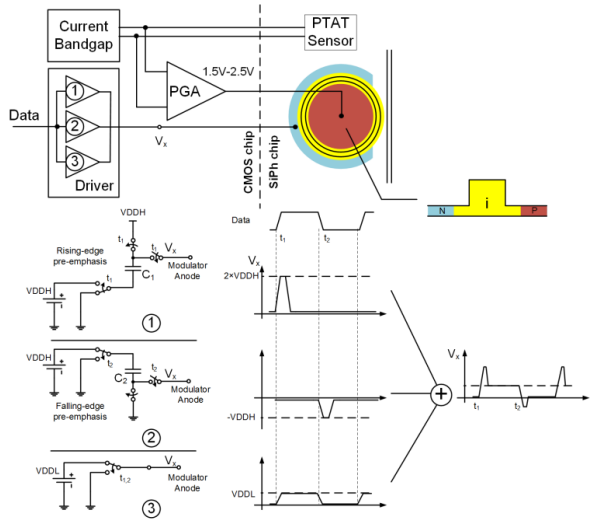

Fig. 1 Top-level block diagram of the transmitter.

recombination lifetime of carriers in the intrinsic region of the p-i-n junction (Fig. 1). Nonlinear pre-emphasis has proven to be an effective way of reducing carrier dynamic rise-time and fall-time [1], [2]. By increasing the pre-emphasis voltage, rise-time/fall-time is shortened and higher data-rate is achievable. Prior pre-emphasis techniques relied on stacked output drivers that are highly power-inefficient and have a maximum pre-emphasis voltage drive of 2×VDDL, where VDDL is the thin-oxide transistors' voltage. In this work, we use a low-power SC-based pre-emphasis technique that can boost the output voltage to 4×VDDL. A top-level block diagram of the transmitter with proposed SC-based pre-emphasis technique is shown in Fig. 1. The driver consists of three main elements, a conventional voltage driver and two pre-emphasis blocks for rising and falling data edges. There are two voltage levels required for operation of this scheme, VDDL=1V, set by the standard thin-oxide transistors' voltage and VDDH=2V. The conventional voltage driver provides a steady state voltage to keep the junction in forward bias when needed. The two pre-emphasis blocks work by first accumulating charge on C_1 and C_2 up to VDDH. Subsequently, these capacitors are switched so that for the rising-edge pre-emphasis the output is at 2×VDDH and for falling-edge pre-emphasis the output is at -VDDH. The charge on these capacitors is used as pre-emphasis to inject and extract charge from the intrinsic region of the junction.

Implementation and Measurements

Fig. 2 shows the schematic circuit details of the SC-based pre-emphasis technique. A 2V pulsed-cascode stage, similar to

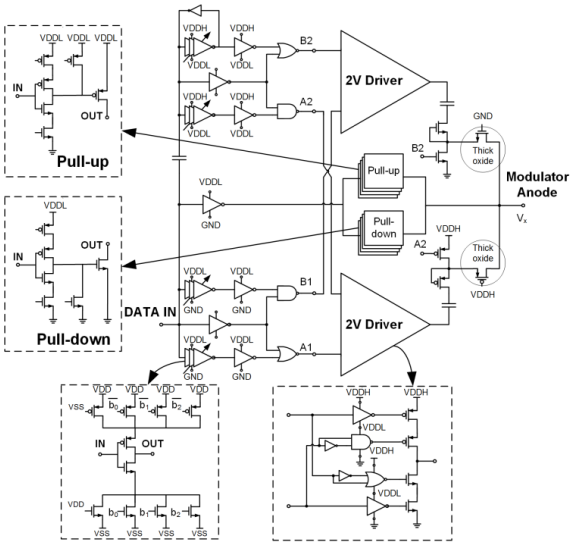

Fig. 2 Schematic circuit details of the proposed MRM driver with switched-capacitor-based pre-emphasis.

[1], is used to charge capacitors C_1 and C_2. Tunable delays are used to adjust the charge time and therefore strength of the pre-emphasis. A voltage driver with digitally adjustable pull-up and pull-down strengths is incorporated to maintain the junction in forward bias region and in off region according to the data. Fig. 3 shows optical measurement results of the transmitter. The static transmission of the MRM shows a

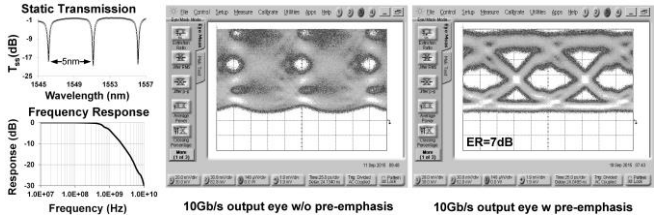

Fig. 3 Measured characteristics of the MRM and output optical eye diagram of the optical transmitter with and without pre-emphasis.

quality factor (Q) of ~6000 and free spectral range (FSR) of 5nm. The measured optical frequency response of the MRM in forward-bias shows a -3dB bandwidth of about 900MHz. When a 10Gb/s, PRBS 2^7-1 data stream is transmitted the output optical eye is completely closed without pre-emphasis. Enabling pre-emphasis opens the eye to have 7dB extinction ratio. The transmitter consumes 3.42mW resulting in per-bit energy of 342fJ/b.

Another challenge for robust operation of MRMs is their sensitivity to temperature fluctuations. Previously reported wavelength stabilization techniques, such as output optical power feedback using bias voltage [1] or heater [3] require extra optical power on the silicon-photonic chips and have excessive power overhead. In this work, we propose wavelength stabilization by direct measurement of temperature through a monolithic distributed PTAT sensor. Fig. 4 shows the schematic block diagram of the feed-forward bias-based wavelength stabilization technique and the SiPh MRM with on-chip PTAT temperature sensor. The monolithic PTAT temperature sensor, used for directly measuring the temperature of the ring, is described in [4]. In [4], the PTAT temperature sensor operation was demonstrated in a carrier-depletion MRM with heater-based wavelength stabilization and without using a CMOS chip. In this work, the PTAT sensor works by measuring the voltage difference between two diodes with different current densities. The PTAT voltage is then applied to an on-chip programmable gain amplifier (PGA) implemented in the CMOS chip. This PGA sets the bias voltage of the MRM. As calculated in Fig. 4, a gain of 5-10 (depending on β_{Temp} and variation of currents) cancels the temperature dependency of MRM's notch wavelength. The PTAT sensor currents, I_1 and I_2, are provided by the CMOS chip using a current bandgap circuit. Measurements verify that these currents vary less than 5% in a range of 25-150°C. Note

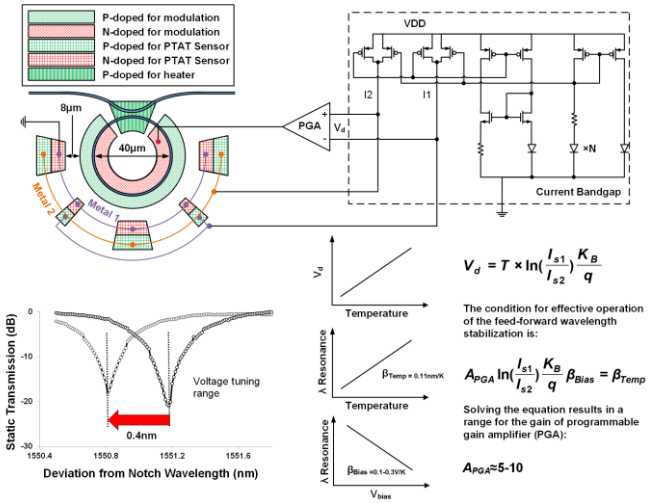

Fig. 4 Schematic of the feed-forward bias-based wavelength stabilization technique. Measured MRM resonance versus bias.

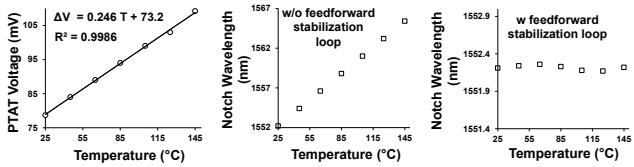

Fig. 5 Characteristics of the PTAT sensor and MRM's resonance wavelength w and w/o wavelength stabilization.

that process and voltage variation can be compensated by adjusting gain of the programmable gain amplifier (PGA). Fig. 5 shows measured operation of the feed-forward bias-based wavelength stabilization technique. First, the temperature dependency of the MRM's resonance wavelength is measured to be about 0.11nm/K. The linear operation of the PTAT sensor is independently verified from 25°C to 150°C. Next, the optimal PGA gain is found to be 8.2 to make the notch wavelength temperature-independent. The maximum tuning power is 290µW for a resonance wavelength range of 0.4nm. In order to cover the complete FSR, this technique can be used as a fine-tuning in combination with heater-based thermal control as coarse-tuning [5].

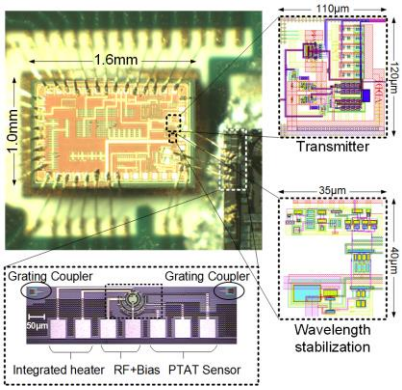

Fig. 6 CMOS and SiPh chip micrographs.

TABLE I
TRANSMITTER PERFORMANCE SUMMARY

Electronics technology	65nm CMOS
TX data-rate	10Gb/s
Extinction ratio	7dB
Tuning power consumption	0.29mW
Active area	0.15mm^2
TX energy/bit	342fJ/b

Conclusion

The optical transmitter CMOS chip is fabricated in a 65nm bulk process and the silicon photonic device is fabricated in OpSIS IME-5 process. The silicon photonic MRM with integrated PTAT sensor is connected to the CMOS chip through wirebonds as shown in Fig. 6. The optical transmitter achieves energy efficiency of 342fJ/bit at 10Gb/s. The feed-forward bias-based wavelength stabilization circuit consumes 0.29mW. Table 1 summarizes the system performance and compares it to prior art.

Acknowledgement

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References

[1] C. Li, et al, *ISSCC Dig. Tech. Papers*, pp. 124-125, Feb. 2013.
[2] Y. Chen, et al, *ISSCC Dig. Tech. Papers*, pp. 402-404, Feb. 2015.
[3] H. Li, et al, *ISSCC Dig. Tech. Papers*, pp. 410-411, Feb. 2015.
[4] S. Saeedi, et al, Optics Express, Aug 2015, pp. 21875-21883.
[5] C. Chen, et al, *OI Dig. Tech. Papers*, pp. 121-122, May. 2014.