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Thermal Stabilization of Micro-ring Modulator using a Monolithically Integrated Analog Feedback Circuit

(Student paper)

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We present an on-chip analog feedback circuit to stabilize the micro-ring modulator operation against temperature fluctuations, implemented in monolithic 45 nm CMOS-Silicon-Photonics (Si-Ph) 300 mm platform. Measured data confirms the feedback circuit's ability to stabilize the micro-ring modulator.

Keywords: *Micro-ring modulator, High-speed, Integrated photonics, Monolithic SiPh CMOS*

INTRODUCTION

The silicon micro-ring resonator (MRR) is a basic building block to realise more advanced devices like wavelength selective filters[1], high speed modulators[2], single photon generators[3] and many more. Silicon micro-ring modulators (MRM) are becoming a fundamental device to enable high speed, low-footprint and energy efficient transceiver systems. However, the operating wavelength range of these modulators is smaller than 100 pm, owing to their resonant operation. The temperature dependent wavelength resonance makes the micro-ring modulator inoperable in thermally volatile environments.

An active thermal stabilization circuit can keep the resonance wavelength of the micro-ring modulator locked with respect to the laser beam. Such a system can detect the shift in MRM's resonant wavelength in real time and give feedback to the heater element, to heat the MRM accordingly, in order to bring the resonant wavelength back to its intended operating condition. Many techniques have been used in the past to realize such systems. Most of those techniques involved a digital closed loop thermal feedback circuit[4,5,6]. In this work, we are demonstrating for the first time an on-chip analog feedback circuit, to monitor and stabilize the resonant wavelength of the MRR suitable for dense wavelength division multiplexing (DWDM) applications, integrated in a monolithic SiPh-CMOS platform.

CIRCUIT ARCHITECTURE

High bandwidth optical transceivers based on the ring devices require efficient and compact thermal stabilization circuitry. The small footprint of the thermal control block is becoming one of the most critical parameters for DWDM application operating at 8 or more wavelengths. Fig. 1a shows the proposed analog feedback circuit to stabilize the resonant wavelength of the MRM. Fig. 1b shows the layout image of the analog thermal stabilization circuit integrated with the MRM in add-drop configuration. The image of the layout of the analog thermal stabilization circuit integrated with the MRM in add-drop configuration is presented in Fig 1b. The total footprint of the circuit along with the decoupling capacitors is 200 µm X 220 µm which shows the ultra-compact nature of the circuit.

The Germanium photodiode operating in reverse bias mode, senses the optical power from the MRM's drop port. A micro-ring modulator of 7.5 µm radius, optimized for 56 Gbaud data rate operation, is a GF 45nm CMOS Si-Ph standard PDK library component, with approximately 5% coupling power at the drop-port. The MRM has a built-in undercut heater implemented as four silicide resistors - two inside and two outside. The thermal tuning efficiency of the MRM heater is achieved with silicon undercut and provides improved thermal isolation. The photodetector output is converted to a voltage by the transimpedance amplifier (TIA) and compared with the reference voltage V_{ref} using a difference amplifier (DIFFAMP). The TIA has been designed with optimized gain to sense very subtle changes of optical power around the MRM resonance wavelength. While the 45nm CMOS Si-Ph monolithic platform with RF grade transistors is optimized for 56 Gbaud transceiver application[7], both the TIA and the DIFFAMP operate at much lower speed that is defined by the thermal time constant of the ring heater.

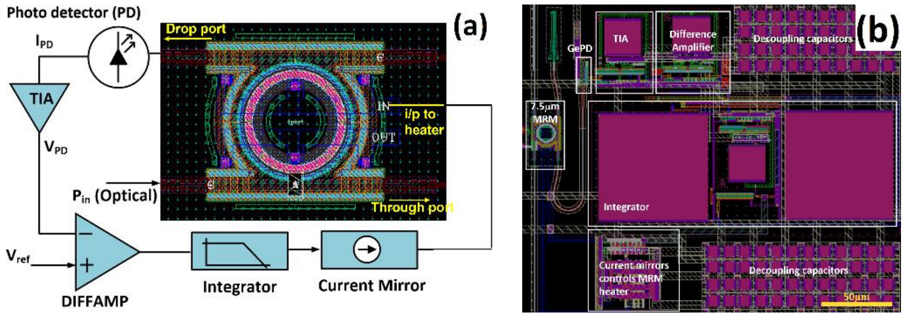

Fig. 1. (a) Block diagram of the add-drop MRM integrated with analog feedback circuit, (b) an image of the analog thermal stabilization circuit (200 µm x 220 µm) and its building blocks.

The resultant error signal from the DIFFAMP is fed to the integrator circuit. The integrator time constant has been set to be comparable with the time constant of the integrated heater thermal response to properly track the MRM resonance changes. The integrator voltage controls the output current of the current mirror circuit which is fed to the heater port.

The reference voltage, set via external pad in this circuit implementation, defines the locking position around the MRM resonance. In the subsequent circuit architecture V_{ref} is set on-chip using a peak-detector circuit. At the circuit boot-up, due to the initial difference between V_{ref} and V_{PD} the integrator voltage starts building up delivering higher and higher power to the MRM heater via current mirrors. When the MRM warms up and shifts its resonance closer to the operating wavelength the V_{PD} starts increasing. When the error signal from the DIFFAMP gets smaller the thermal tuning circuit reduces the rate of the electrical power that is delivered to the MRM heater thus slowing down the warming up process. For the scenario, when $V_{PD} = V_{ref}$, the comparator voltage becomes zero and a fixed current is forced via the thermal resistor keeping the ring resonance wavelength locked. Any further thermal fluctuations resulting in MRM resonance drift are compensated via increase or decrease of the current controlled by the analog feedback control loop.

The reference voltage is initially set mid-way from the maximum transmission. Initially, due to reduction in temperature, the resonant peak of the MRR shifts left to the initial resonant peak. Therefore, $V_{ref} - V_{PD} > 0$, and comparator voltage is non-zero. This increases the output current and heater voltage. Similarly, when the temperature increases, the proposed circuit reduces output current. Hence, the resonant peak is stabilized even though there is a change in temperature.

Fig. 1b shows the image of the layout of the analog thermal stabilization circuit integrated with the MRM in add-drop configuration. The Germanium photodiode is connected to the TIA having 5kOhms gain and 1GHz bandwidth which is further fed to the difference amplifier. The reference voltage V_{ref}, set via external pad in this circuit implementation, is fed to the other input of the difference amplifier. The integrator takes the output of the difference amplifier as the input as its output is fed to the current mirror which in turn gives the feedback to the microheater integrated with the MRM. The total footprint of the circuit along with the decoupling capacitors is 200 µm X 220 µm which shows the ultra-compact nature of the circuit.

A low V_{ref} value (as shown around point `A' in Fig. 2) represents off-resonance locking point. Point `A' corresponds to 15.1 mA of heater current which red shifts the MRM response indicated by the red dashed line in Fig. 2a. At point `A' drop port optical power is low since the MRM is operating far away from the resonating wavelength. It is further verified from the photocurrent versus V_{ref} plot shown in Fig. 2c. As the V_{ref} increases, the heater current reduces, thus enforcing wavelength locking near the left-hand side of the MRM resonance. Similar wavelength tracking is observed for points `B' and `C' on the plots which corresponds to 13.7 mA and 11.5 mA of heater current respectively. The correlation between Fig. 2a and 2c is prominent in determining the position where the wavelength is locked on the resonance curve. The analog thermal tuning circuit can lock the resonance at any point of the left-hand side of MRM resonance (the rising edge of the MRM drop port). Locking MRM resonance on this slope allows operating the micro-ring modulator at higher optical power even when the resonance response is nonlinear[8]. When the V_{ref} is higher than the maximum V_{PD} the feedback circuit cannot properly lock, and there will always be an offset voltage after DIFFAMP. We observe the heater current reducing after V_{ref} > 0.65V (marked as gray region in Fig. 2b and 2c).

RESULT AND DISCUSSION

The presented experimental data have been chosen to mimic a realistic scenario of wavelength locking requirement and to confirm circuit functionality. In this work we have chosen a manually set reference voltage (via external supply voltage). However, the V_{ref} can be set automatically by tightening its value to the peak detector circuit (with specific or tunable offset) that follows MRM drop port response during the pre-heating stage. Additionally, a variable TIA gain expands the range on optical power and enables complete automation of the thermal stabilization process.

At lower V_{ref} values the feedback circuit is pre-heating the MRM as shown around point `A'. Point 'A' corresponds to 15.1 mA of heater current which shifts the MRM response indicated by the red dashed line in Fig 2a. At point 'A' drop port response is low since the MRR is operating far away from the resonating wavelength.

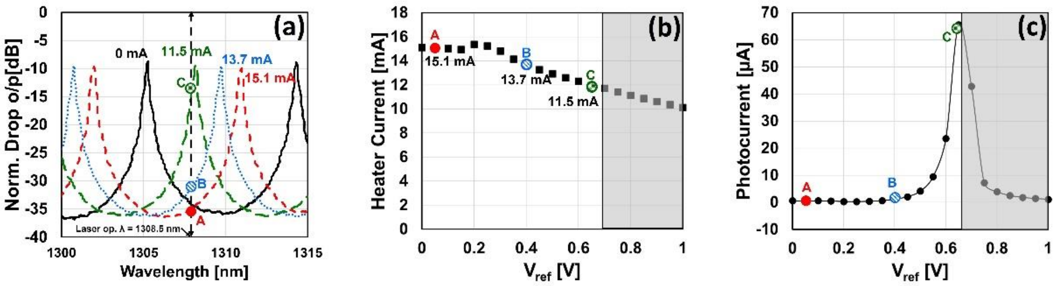

Fig. 2. (a) Normalized drop port output optical power (o/p) of the MRM for different micro-ring heater currents. The dashed vertical line shows the laser operating wavelength of 1308.5 nm, (b) steady-state MRM heater current for different values of V_{ref}. Points A, B and C correspond to MRM heater current of 15.1 mA, 13.7 mA and 11.5 mA, (c) the photodiode current w.r.t V_{ref} for λ = 1308.5 nm. The gray colour region demarcates the falling edge of the resonance.

CONCLUSION

In this paper we have reported a fully analog feedback circuit integrated monolithically with an MRM to stabilize its operation against any thermal fluctuations. Since we are using an analog feedback circuit instead of a digital feedback circuit, we managed to implement the circuit within a compact footprint of 200 µm X 220 µm. This enables locking of the micro-ring modulator resonance wavelength to the operating wavelength from an arbitrary set position for low power DWDM systems.

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