A WDM Silicon Photonic Transmitter based on Carrier-Injection Microring Modulators

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Abstract: We present a 5 x 10 Gbps WDM silicon photonic transmitter based on carrier-injection type microring modulators. Resonant wavelengths can be adjusted by both thermal heaters and bias tuning.

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Silicon photonics technology provides a scalable alternative to meet both high-bandwidth and low-power requirements for future high-performance computing systems [1]. Microring resonators with slightly different radii can be easily cascaded to a single waveguide to form wavelength division multiplexing (WDM). Fig. 1 (a) shows a schematic of a WDM CMOS photonic link. Carrier-injection-based microring modulators can be driven by small voltage swings to achieve large modulation because of the large current flow above threshold. Due to its inherent slow diffusion time, however, pre-emphasized driving signals are required for high-speed operation [2]. To tune the resonance of the microrings to the input laser wavelength and compensate for any thermal drifts, a tuning scheme is also required. In this work, we demonstrate a 50 Gbps silicon photonic WDM transmitter based on carrier-injection microring modulators. Both thermal tuning and bias tuning circuits are included to adjust the resonant wavelength of the microring. A digital-controlled circuitry in a 2Vpp CMOS driver is implemented for automatic wavelength locking. This represents an important step towards a fully integrated WDM CMOS photonics link.

Fig. 1(b) shows a fabricated 5-channel photonic transceiver with transmitters on the upper-half and receivers on the lower-half. Vertical fiber-to-chip grating couplers are used to provide optical input and output access. The basic element of each channel consists of a microring resonator with an integrated Ge waveguide photodiode at its drop port and an integrated heater close to the ring waveguide, as shown in Fig. 1 (c). Two layers of metal implemented by a standard damascene process facilitate the complex metal routing. The total footprint of the photonic transceiver is currently limited by the flip-chip bonding pads and the matching CMOS circuits at 65 nm technology nodes. The microring resonators with a variety of radii around 5 μm generate a series of WDM channel, and support more than 20 channels with 80 GHz spacing at 1.3 μm wavelengths. Optical transmission spectrum of a microring resonator in Fig. 1 (d) exhibits a quality factor of 12,000 with an on/off extinction ratio of 18 dB.

In the previous proof-of-concept single channel demonstration [3, 4], the high-speed performance of the transmitter was limited by unexpected high contact resistance of the photonic device and long bonding wires. There was also no drop port incorporated with the microring. Here we tailor the photonic device to meet the needs for WDM transceivers. By driving the microring modulators with external pre-emphasized electrical signals at 10 Gbps (Fig. 2 (a)), we demonstrate that the optical output signals at all five channels have a clear eye opening with healthy margin (Fig. 2 (b-f)). We also demonstrate a 12.5 Gbps operation in Fig. 2 (g). A 2Vpp CMOS driver wirebonded to the microring shows 9 Gbps operation with energy efficiency of 473 fJ/bit.

A local heater is implemented by doping silicon at the same step as the p-i-n junction formation to provide wide range red-shift. A sheet resistance of around 800Ω/□ is achieved in a 50 nm silicon slab layer. Fig. 3 (a) shows the resonance shifts in relation to various heater biases with a tuning efficiency of 23μW/GHz, or 44mW/FSR. Fig. 3 (b) describes the results of bias tuning, which serves as a complement to thermal tuning to blue-shift the resonant wavelength with better energy efficiency. We intentionally detune the input laser wavelength to -0.3nm of the microring resonance to exemplify the mismatch due to fabrication variations. A control loop for bias-based tuning circuits in a 2Vpp driver increases the anode voltage of the p-i-n diode to blue-shift the resonant wavelength due to accumulated free carriers in the ring waveguide with an efficiency of 6.8μW/GHz [3]. Optical power is monitored at the through port of the microring here, and thus a minimal optical power represents the optimal operating point. It monotonically decreases during the tuning process and remains at the minimal power level after the microring resonance locked to the laser wavelength. The CMOS circuits can also accommodate drop port monitoring. In order to realize a fully-integrated WDM CMOS photonics link, we use flip-chip bonding techniques to enable the chip-scale integration between CMOS and photonics chips. This can significantly reduce the form factor and improve the signal bandwidth at high data rates.

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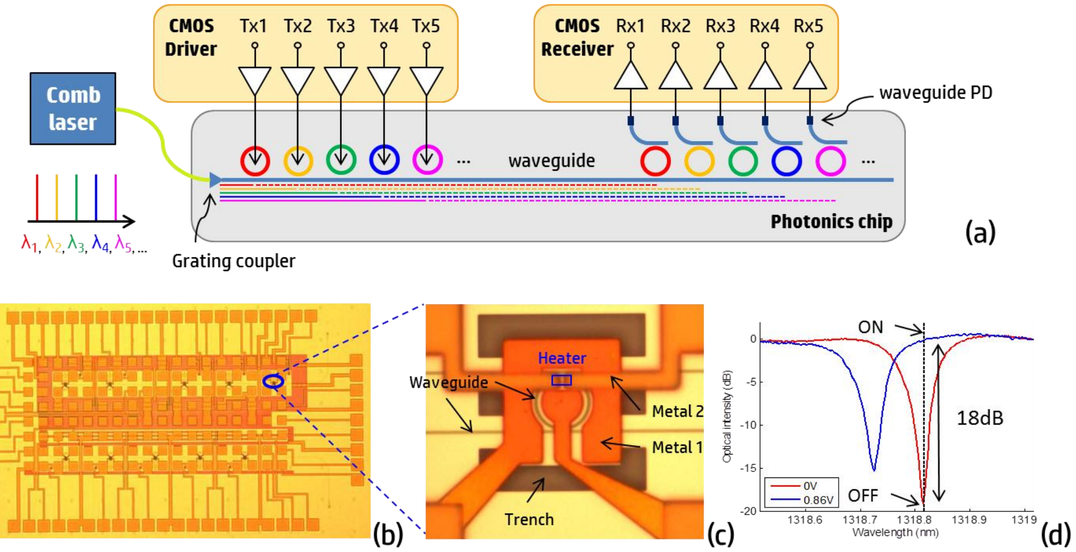

Fig. 1. (a) Schematics of a WDM CMOS photonic link. (b) A fabricated 5-channel silicon photonic transceiver. (c) Microscope image of a microring modulator. (d) Optical transmission of the microring modulator at 0V and 0.86V.

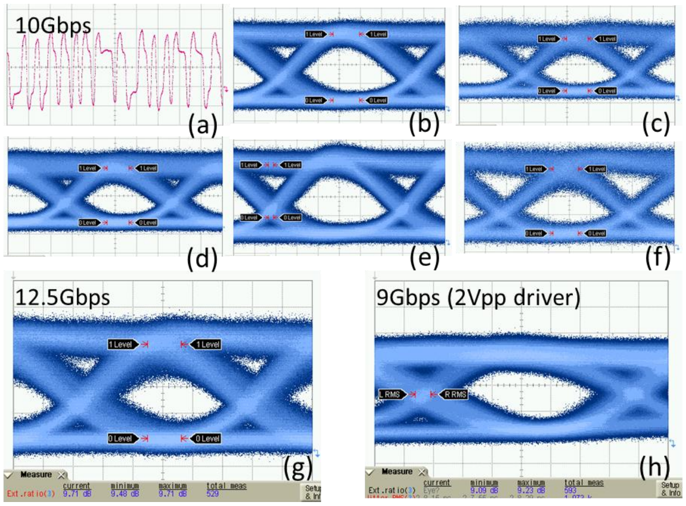

Fig. 2. Eye diagrams of (a) 10 Gbps pre-emphasis input signal, (b-f) 10 Gbps optical signal at five different channels, (g) 12.5 Gbps optical signal, and (h) 9 Gbps optical signal with a 2 Vpp CMOS driver.

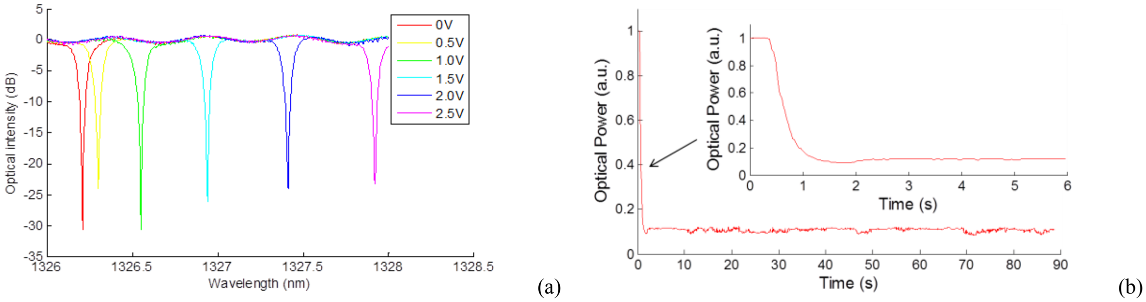

Fig. 3. (a) Microring transmission spectra at various heater biases. (b) Wavelength stabilization by CMOS circuitry. The optical power is monitored at the through port waveguide.

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