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High-speed Hybrid Silicon Microring Lasers

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Abstract—We report on low power consumption, high direct modulation speed performance of compact hybrid silicon microring lasers. By integrating a novel thermal shunt, device joule heating is significantly reduced, leading to low threshold, high continuous wave (cw) lasing temperature as high as 105 °C. A 3 dB bandwidth of 7.8 GHz is measured and 12.5 Gbps eye diagram is obtained.

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I. INTRODUCTION

Photonic links are widely believed to be the most promising solution to replace conventional metal interconnects for lower power consumption and larger data bandwidth, and thus enable complementary metal-oxide semiconductor (CMOS) integration to continue following the projection of Moore's Law. Advanced CMOS technology tends to choose the most cost effective approach to build such a photonic interconnect system on silicon (Si), the flagship material in the past half century CMOS history. Rapid advances in silicon photonics recently are being driven by a combination of a need for more complex, higher functionality and lower cost photonics integrated circuits, but also by pin count and power limits for communications, as summarized in the International Technology Roadmap for Semiconductors (ITRS) [1]. Among a variety of efforts in key photonic components and overall system studies, enormous focus has been enabling a practical light source, i.e., diode laser, preferable on Si [2].

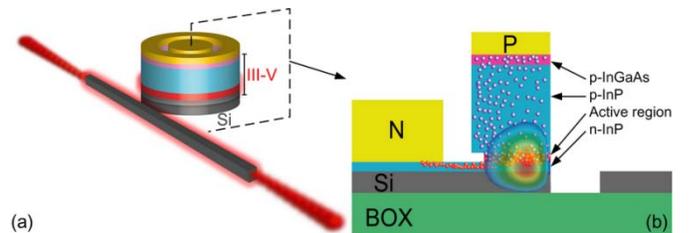
After decades of research in improving light emission efficiency in the indirect bandgap Si and monolithically growing direct-bandgap III-V compound semiconductor materials on Si, people still have not been able to build a Si-based laser robust enough for practical application, i.e., continuous wave (cw) operation at room temperature or higher, reasonable threshold and output power, decent lifetime. So in industry, the most traditional approach is to take prefabricated III-V lasers or amplifiers and die bond these elements onto a passive planar lightwave circuit (PLC). However, lower manufacturing efficiency, high component cost, low integration level and large chip size can diminish the advantages of photonic interconnects to their counterparts.

A new hybrid platform was recently developed to overcome those pitfalls by transferring high-quality thin III-V epitaxial layers onto the Si-on-insulator (SOI) substrate [3]. This approach brings optical gain and other optical functionalities from direct-bandgap III-V material to this Si substrate [4]. In a

span of less than 10 years, high-performance lasers, amplifier, modulator, photodetectors, buffers, and hybrid photonic integrated circuits have been demonstrated [5]. Among those devices, a compact hybrid microring laser [6] with low threshold current is particularly attractive to HP's technology roadmap to build a photonic interconnect system for our next-generation data center business.

II. DEVICE DESIGN AND EXPERIMENTAL RESULTS

Fig. 1 shows the schematic structure of such a hybrid microring laser in (a) and its cross-section in (b). Thin direct-bandgap III-V compound semiconductor epitaxial layers are transferred onto the SOI substrate to provide optical gain. A circular ring shape resonator is fabricated from III-V to Si through a self-aligned process [6]. A standard diode laser p-i-n junction, p-InP-active region-n-InP, composes of the III-V epitaxial layer structure as labelled in Fig. 1(b). Electrons and holes are injected into this diode when applying a bias between metal contact P and N. Those electrons and holes recombine radiatively in the active region to emit photons, which converts



(a) (b)
Fig. 1. Schematic of compact hybrid III-V-on-Si microring resonator laser with Si bus waveguide (a) and its cross-section with simulated fundamental TE mode profile (b).

most of the electrical energy into optical energy. The active region in this work is designed to emit photon around 1310 nm wavelength window. Underneath Si and III-V section form a hybrid waveguide structure to support possible optical modes. A simulated fundamental optical mode in Fig. 1(b) overlaps with the active region to receive optical gain. When injected electrical energy reaches certain level to enable accumulated optical gain high enough to overcome the total optical loss in the cavity, lasing will occur in this microring resonator. When placing a waveguide, called bus waveguide, close to the ring resonator, a fraction of power in the ring resonator can be coupled out for dedicated application.

One intrinsic challenge in this platform, however, is efficient heat dissipation because thick (1 μm typically) buried oxide

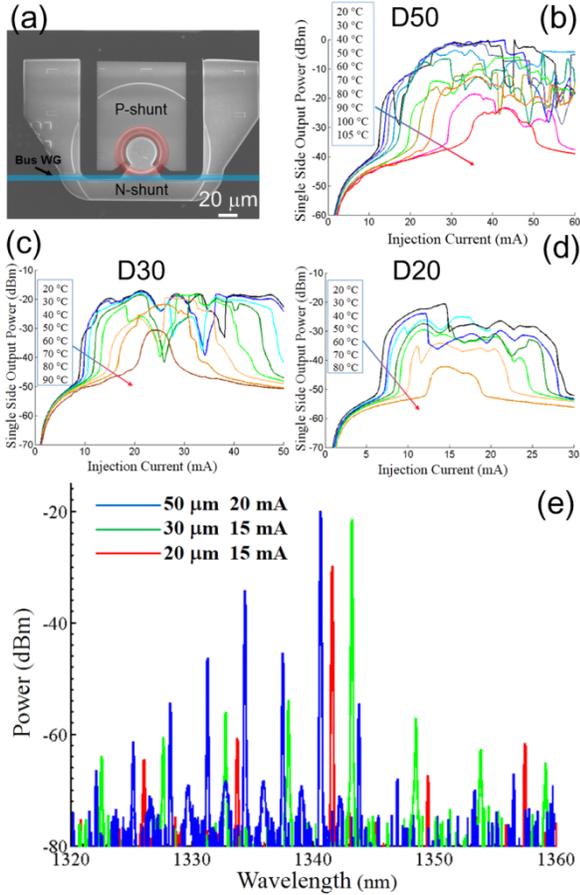


Fig. 2. Top-view SEM image of a fabricated $D=50 \mu\text{m}$ device whose hybrid microring resonator and Si bus waveguide are highlighted in red and blue, respectively; (b)-(d): temperature-dependent, cw LI characteristic of $D=50$, 20 and $20 \mu\text{m}$ devices with their spectra in (e).

layer (BOX) in SOI wafer blocks most of heat from heat source, the diode junction, to the Si substrate [7]. Excessive heat in the laser diode reduces the efficiency of electrical carrier radiative recombination, i.e., photon carrier density. Consequently, the devices suffer from higher laser threshold, lower output power and degraded direct modulation bandwidth [8].

In this work, we implemented a novel thermal shunt design to "ground" the heat generated in III-V junction to the Si substrate through BOX layer via metal shunts [9-11]. The detailed thermal shunt design and fabrication process can be found at [10]. Fig. 2(a) is a top-view scanning electron microscope (SEM) image of a fabricated device. The hybrid microring resonator with $50 \mu\text{m}$ in diameter and a Si bus waveguide are highlighted in red and blue, respectively. Figs. 2 (b)-(d) are typical temperature-dependent, continuous-wave (cw) light-current (LI) characteristic of devices in 50, 30 and $20 \mu\text{m}$ diameters, respectively. The temperature here is referred to temperature set at the copper testing stage where devices sit on with III-V side up. At $20 \text{ }^\circ\text{C}$, low thresholds of 12.3, 8.8, 5.8 mA are observed for diameter $D=50$, 30 and $20 \mu\text{m}$, respectively. A record-high cw lasing stage temperature of $105 \text{ }^\circ\text{C}$ is achieved in the $D=50 \mu\text{m}$ device in Fig. 2(b), $35 \text{ }^\circ\text{C}$ higher than the devices without thermal shunt (data not shown). Smaller devices whose series resistance is higher tend to heat up more quickly. Despite of that, $D=30$ and $20 \mu\text{m}$ devices can

still lase up to 90 and $80 \text{ }^\circ\text{C}$, respectively. This makes them very appealing to be low-power consumption light sources in a photonic interconnect system which may work in an elevated temperature environment, such as, data centers.

Fig. 2(e) is characteristic spectra for devices in three dimensions above. The free spectral range (FSR), which is the separation between two allowed wavelengths in a ring resonator cavity, for $D=50$, 30 and $20 \mu\text{m}$ rings are 3.11, 5.18 and 7.81 nm , respectively. Over 50 dB extinction ratio is obtained in all devices. While they lase at multiple resonance wavelengths, particularly for $D=50 \mu\text{m}$ one due to smallest FSR, over 15 dB side-mode suppression ratio still makes it feasible for WDM application.

III. DYNAMIC MEASUREMENT RESULTS AND DISCUSSION

With the help of reduced device heating from efficient thermal shunt design, devices now can operate at higher direct modulation bandwidth. Fig. 3(a) is a comparison of small-signal direct modulation response for two devices with the same dimension of $D=50 \mu\text{m}$, same injection current of 25 mA and similar output power. The one with thermal shunt shows a 3 dB bandwidth of 5.5 GHz while bandwidth for the other one without shunt is only 3 GHz. Fig. 3(b) is the same measurement on the device with thermal shunt at different

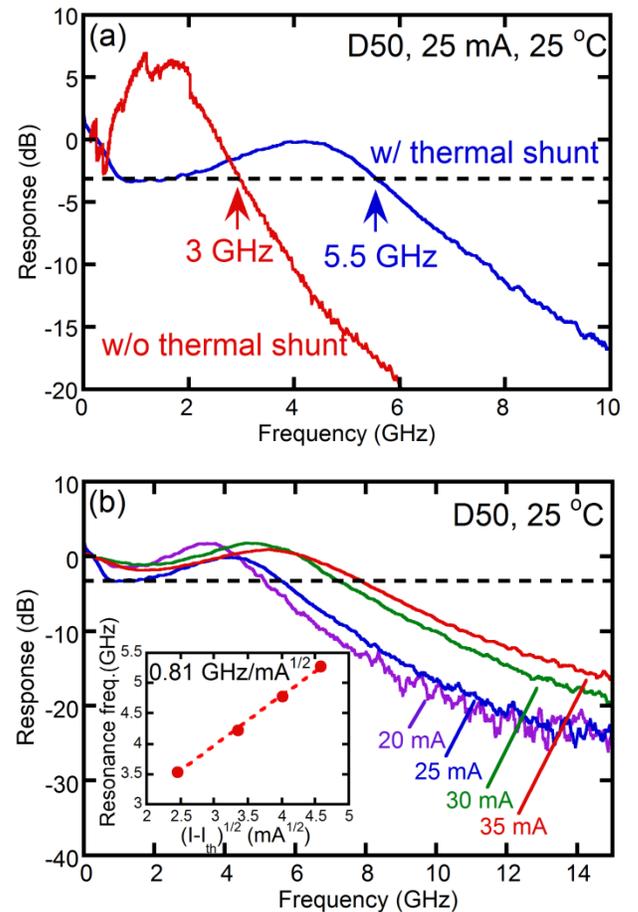


Fig. 3. (a) Measured small-signal responses for $D=50 \mu\text{m}$ devices at 25 mA injection current with and without thermal shunt design, and (b) small-signal response for thermal shunt microring laser at 20 to 35 mA injection current. Inset: resonance frequency as a function of square root of DC injection current.

injection current. Higher injection current, corresponding to higher output power (before thermal rollover), leads to larger bandwidth, which is expected. A maximum bandwidth of 7.8 GHz is observed at 35 mA injection current. Fig. 3(b) inset is a plot of resonance frequency vs. square root of DC injection current, showing expected linear dependence. The slope is 0.81 GHz/mA^{1/2}, 3X better than previously demonstrated hybrid Si DBR lasers [12].

We also measured the large-signal direct modulation response of the same device at a constant injection current of 30 mA at 25 °C. The measurement setup is schematically shown in Fig. 4(a). 2⁷-1 Pseudo Random binary sequence (PRBS) electrical signal with a voltage swing of 1 V from the pattern generator was combined with a DC bias corresponding to 30 mA injection current in a Bias T and sent to the device. The output of the device was collected by a single-mode optical fiber and amplified by a semiconductor optical amplifier (SOA) at 1310 nm regime. To suppress amplified spontaneous emission (ASE) noise from SOA, a filter is required before the modulated signal was measured by the optical module of a digital communication analyzer (DCA). The clock between PRBS and DCA is synchronized in order to measure the eye diagram in DCA. Figs. 4(b)-(d) are measured eye diagram at 5, 10 and 12.5 Gbps, respectively. Open eye diagram is observed at all three data rates and the respective extinction ratio is 8.9, 8.6 and 7.9 dB, corresponding to respective power consumption is 13.2, 6.6 and 5.28 pJ/bit. The noise at "1" level is mainly from the stage temperature fluctuation between 25-27 °C because thermal electrical controller which was used for temperature-dependent LI measurement in Fig. 2 was not available at the moment of dynamic measurement here. Furthermore, the 1 nm optical filter bandwidth is not narrow enough to filter out most of the ASE noise, which also contributes to the noise in the eye diagram.

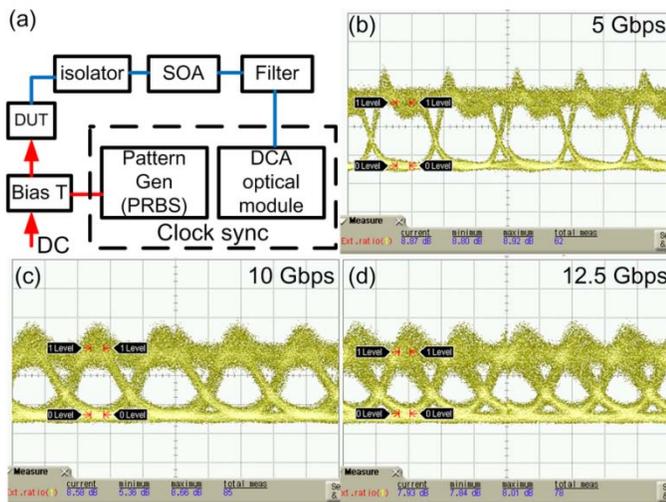


Fig. 4. (a) Schematic of large-signal measurement setup, and measured open eye diagrams for a D=50 μm device at 5 (b), 10 (c) and 12.5 Gbps (d) modulation rate.

IV. FUTURE WORK

In addition to further improve the thermal shunt process to increase output power in smaller size devices, we will integrate

a CMOS driver to drive and control hybrid lasers (array). Since a relatively high DC-biasing (~2V) of the microring laser is necessary to maintain the lasing status, an AC-coupled single-ended driver will be implemented that applies a ~1 V_{pp} output-swing on the laser anode while providing a tunable on-chip DC-bias. One problem with microring devices is that their resonance is sensitive to temperature variation and fabrication tolerances. Similar as the tuning circuits implemented for microring resonators [13], a closed-loop adaptation scheme is also necessary to tune the microring laser at correct output wavelength. This driver will be implemented in a standard CMOS process, and be wire-bonded to the microring laser in the future prototype.

V. SUMMARY

In summary, we have demonstrated compact, directly modulated hybrid microring lasers with decent power consumption. By drastically reducing the device joule heating via a metal thermal shunt design, we observed cw lasing at a record-high 105 °C stage temperature for 50 μm in diameter device, and 80 °C for 20 μm device. A 3 dB bandwidth of 7.8 GHz is measured and 12.5 Gbps eye diagram is obtained. The minimum power consumption is calculated to be 5.28 pJ/bit. We expect to apply the same design to a hybrid microring array which will be driven by a CMOS chip with a close-loop circuit for resonance wavelength tuning/locking. So this multi-wavelength high-speed transmitter can be very promising to be deployed into HP's "The Machine" for next-generation data center application [14].

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