Widely Tunable InP-on-silicon Lasers based on the Micro-Transfer Printing of Double-Ridge Coupons

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Abstract: We demonstrate the micro-transfer printing of III-V double-ridge active devices onto silicon photonics, realizing an integrated tunable laser with over 45 nm tuning range and 5 mW waveguide-coupled output power.

1. Introduction

Silicon photonics (SiPh) has emerged as a leading platform for developing compact, cost-effective, and highly scalable photonic circuits by leveraging the advancements in CMOS technology [1, 2]. For applications such as wavelength-division multiplexing (WDM) systems, coherent optical communications, and next-generation data center interconnects, there is a critical need for laser sources that offer wide spectral coverage. A promising approach is the micro-transfer printing, available under license from X-Celeprint Ltd, of III-V active devices onto SiPh chips. When combined with vernier filters and tunable reflectors, this technique has proven effective in producing widely tunable lasers on SiPh platforms [3–5]. While previous works focused on printing III-V coupons with a single semiconductor optical amplifier (SOA), this work employs a double-ridge SOA structure, encapsulated as one coupon. One ridge operates within the laser cavity, while the other serves as a booster amplifier.

This dual-function SOA architecture, along with the corresponding on-chip waveguide design, enables tunable lasers with narrow linewidth and broad spectral tuning. Integrating two amplifiers within a single III-V coupon enhances integration density and more effectively makes use of the expensive III-V source material.

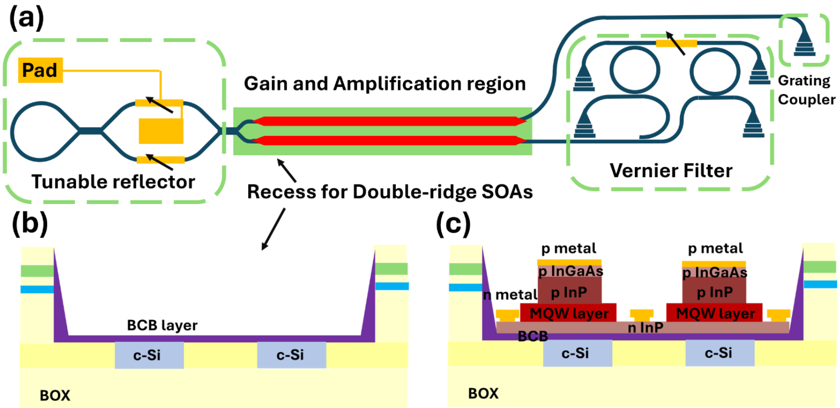

Fig. 1. (a) Schematic layout of the double-ridge laser cavity; (b) cross-sectional schematic of the SiPh chip with defined recesses; (c) cross-sectional schematic of the SiPh chip after transfer printing.

2. Design and fabrication

1.2 mm-long InP/InAlGaAs SOA waveguide structures were defined on InP epitaxial material. The III-V layer stack consisted of an n-InP contact layer, InAlGaAs quantum wells, barriers and separate confinement heterostructure (SCH) layers, a p-InP cladding layer, and an InGaAs contact layer. In contrast to conventional designs, we introduced a double-ridge structure on the III-V coupons. This approach involved defining a shared n-InP contact layer, followed by defining two InP/InAlGaAs active ridges on top of this layer using lithography and ICP etching. Each ridge was 3 μm wide and both ridges were spaced 20 μm apart, precisely aligning with the underlying silicon waveguides on the SiPh chip. The p-metal contacts for both ridges and the n-metal were deposited using standard III-V fabrication processes.

The silicon waveguide circuits were fabricated on IMEC's 400nm SiPh pilot-line platform. This platform features a 400 nm crystalline silicon (c-Si) device layer, and a complex back-end-of-line (BEOL) stack, including metal interconnect layers and exposed aluminum bond pads. Beneath the silicon waveguide, a 2 μm thick buried oxide (BOX) layer serves as an insulating layer, ensuring proper optical confinement and minimizing propagation losses. To accommodate the integration of the III-V devices, recesses were etched into the SiPh back-end (Figure 1b). A thin adhesive layer of benzocyclobutene (BCB), 100-150 nm thick, was applied to the SiPh chip surface to ensure high-yield printing.

Using a wafer-scale micro-transfer printer (Amicra Nano), eight double-ridge devices were simultaneously picked up with a PDMS stamps and transfer-printed into the designated recesses with high precision. Each ridge of the InP/InGaAs coupon was aligned to a corresponding silicon waveguide beneath it, ensuring effective optical coupling (Figure 1c).

Following placement, standard metallization processes were performed to form common p- and n-side electrode pads, effectively connecting the double-ridge active devices to the on-chip metal tracks of the SiPh platform. The microscope image of double-ridge devices in the SiPh wafer recesses after final metallization was shown in Fig 2(a).

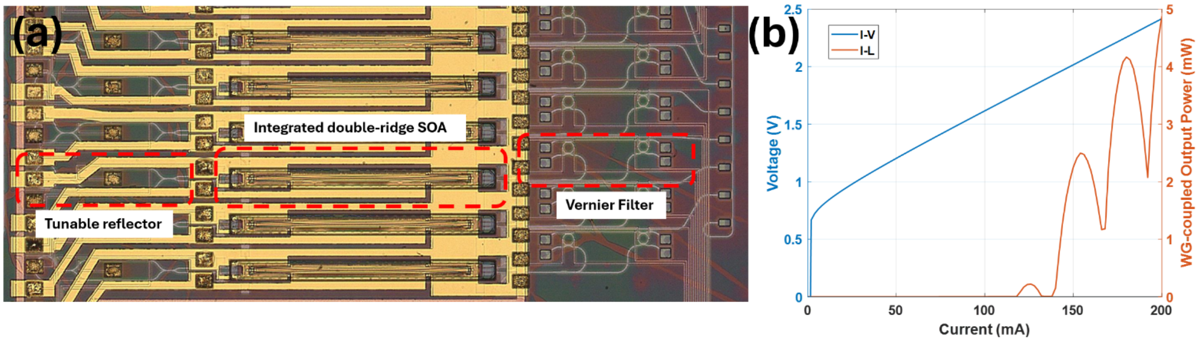

Fig. 2. (a) Microscope image of double-ridge devices in the SiPh wafer recesses after final metallization; (b) Light-current-voltage (LIV) characteristics of the double-ridge laser at 20°C.

3. Characterization and Discussion

The fabricated InP/InGaAs double-ridge lasers were characterized using a temperature-controlled stage, stabilized at 20 °C. Fig. 2(b) shows the light-current-voltage (LIV) characteristics of the double-ridge laser, which exhibited a differential resistance of 8.1 Ω (both SOAs in parallel). Lasing is obtained when the conbined drive current through both SOAs exceeded 120 mA. The waveguide-coupled (WG) output power reaches 5 mW when the drive current is increased to 200 mA, at a stage temperature of 20°C. This high output power is achieved by integrating both laser gain and optical amplification within a single III-V device.

The laser's tuning mechanism relies on a vernier filter that incorporates two thermally tunable micro-ring resonators with slightly different diameters, enabling a wide spectral tuning range. In addition, a thermally tunable Sagnac loop mirror and phase shifter were employed to optimize the reflectivity of the output-coupling mirror, enhancing both tuning precision and output power. As a result, the laser achieved a broad tuning range from 1530.0 nm to 1577.2 nm, spanning over 45 nm as shown in Fig. 3(a). The instantaneous linewidth at different wavelengths is shown in Fig. 3(b), with a narrow linewidth of 3.93 kHz at 1540.8 nm, confirmed by the frequency noise spectrum in Fig. 3(c), as measured using an OE4000 laser phase noise analyzer system. Such a narrow linewidth is advantageous for applications requiring high spectral purity and coherence, including coherent optical communications and sensing.

4. Conclusion

We demonstrate the heterogeneous integration of III-V double-ridge active devices onto a SiPh platform, forming a widely tunable laser via micro-transfer printing. The double-ridge structure enables simultaneous laser gain and

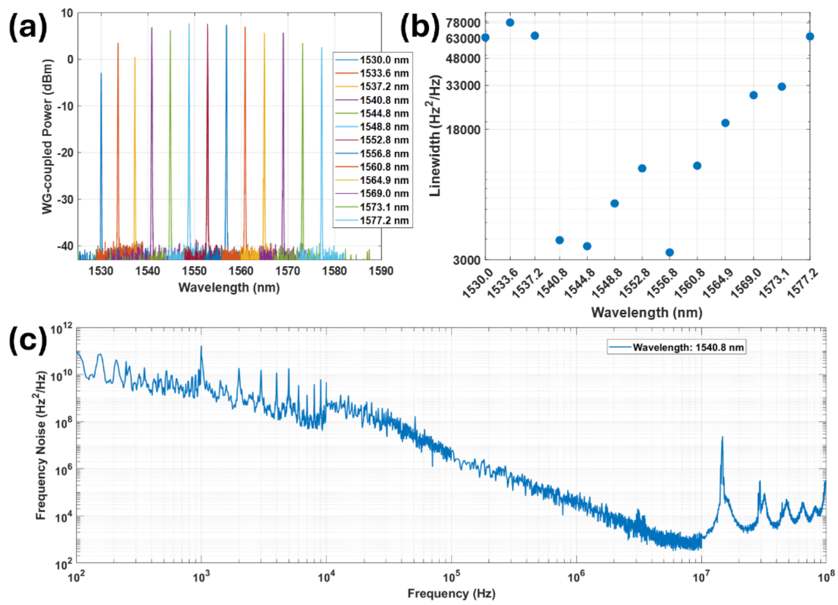

Fig. 3. (a) Optical spectrum of the widely tunable laser; (b) linewidth corresponding to each wavelength; (c) frequency noise spectrum of the laser at 1540.8 nm.

external amplification, achieving high-density integration. After amplification within the same device, the WG-coupled output power reaches 5 mW, with a linewidth as low as 3.93 kHz and a tuning range of over 45 nm. Our results demonstrate the potential to achieve a highly-integrated, narrow-linewidth tunable laser offering wide spectral coverage for advanced photonic integrated circuits.

5. Acknowledgement

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