# Heterogeneous integration of III-V materials on Silicon photonic platforms: In the quest for high power, single-longitudinal mode and widely tuneable on-chip laser diodes

***Student Paper***

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## ABSTRACT

On-chip light sources and amplifiers are meant to be key components for next generation datacentres and long haul telecommunications managing large amounts of data within the Terabyte and Zetabyte range. To successfully deploy them, high-power, narrow linewidth and widely tunable compact lasers are needed to allocate multiple parallel data channels with optimum performance and low energy consumption. In this perspective, we demonstrate compact heterogeneous tunable laser diodes integrated on a 200-mm silicon photonics platform. It provides 5 dBm of optical fiber-coupled power in a wafer-testing configuration with a current density threshold of 1.7 kA/cm$^2$ , a differential resistance below 6 Ω at the nominal bias point and a tunable range of 60 nm within the C-band of telecommunications. Moreover, the small device footprint of ~1 mm$^2$, the large scalability heterogeneous III-V-on-SOI integration and the maturity of the fabrication processes make these lasers a compelling solution for competitive future wavelength-division-multiplexing solutions.

**Keywords**: Heterogeneous integration, silicon photonics, lasers, optical links, datacentres, telecommunications.

## 1. INTRODUCTION

Over the last few years, optical communications have experienced an enormous transformation and great progress, driven by the continuous need to meet the requirements of the massive data exchange rates in nowadays datacentres or long haul communications underpinning the digital world [1]. Further than that, the imminent deployment of new applications and hyper-connected networking architectures such as the 5G network, the Internet of things or the laser detection and ranging (LIDAR) systems for autonomous vehicles will surely increase the need for efficient, high-bandwidth, low power consuming and densely packed optical systems. Mass-volume fabrication of compact systems with small form factors is often seen as an appealing solution to reach that goal [2]. In this regard, silicon photonics provides an ideal platform, as it enables high-level integration of photonic devices and circuits with competitive performance, allowing the emergence of Photonic Integrated Circuits (PICs) with complex and multifunctional architectures [3, 4].

The demonstration of compact on-chip lasers compatible with the silicon photonics technology has been one of the burning challenges motivating an intense research on heterogeneous integration [4]. High-speed monolithic modulators and sensitive photodetectors are nowadays readily available in most of the Si foundries [5], but lasers have been the missing enabling device for optical transceivers to become a reality in silicon photonics. Hybrid devices combining InP gain-chips with passive silicon photonics external cavity circuits in a butt-coupling configuration are often used as an alternative solution and they demonstrate performances well in line with the specifications of the system demands [6]. Although impressive progress has been done in that regard, alignment of the two chips remains complex. It often takes place in a lab environment using in-house alignment techniques and costly packaging processes. This overhead is acceptable for prototyping but it has prevented the main industrial stakeholders from a massive exploitation of these devices. Nevertheless, with the advent of the heterogeneous integration of III-V materials on top of mature silicon photonic front-end wafers, the interest for this technology has exploded due to the possibility to implement on-chip optical interconnects using large-scale CMOS processes, giving access to low-cost and highly performing solutions for such miniaturized lasers [3].

In this work, we present our recent advancement on widely tunable heterogeneous III-V-on-Si laser diodes for datacom and telecom applications. Devices have been fabricated in a 200-mm silicon photonics platform. Our lasers easily achieve 5 dBm of optical fiber-coupled power across the wafer with a threshold current density of 1.7 kA/cm$^2$, a differential resistance below 6 Ω and a wavelength tunability over 60 nm.

## 2. Widely tunable lasers

The tunable laser diodes studied in this work are formed by a III-V gain material containing multiple quantum wells and a passive external cavity entirely defined in the silicon wafer. Wafer bonding of unprocessed InP wafers on already processed Si photonics wafers followed by several etching steps and metallization is performed to define the heterogeneous III-V-on-Si lasers. Asymmetric cavity feedback is defined with Sagnac mirrors. A Vernier filter composed by two racetrack ring resonators containing thermal heaters is used to coarsely tune the laser emission wavelength according to the maximum free spectral range (FSR) of the filter. Fine wavelength tuning is obtained with an additional phase shifter located outside the Vernier filter. Vertical grating couplers are employed to enable rapid wafer testing of devices. Further details on the design and fabrication of such lasers can be found in ref. 3.

Figure 1(a) shows a representative static characteristic of a tunable laser diode, with a threshold current density value of 1.7 kA/cm$^2$, a maximum fiber-coupled optical power exceeding 3 mW (i. e. 5 dBm) and single-longitudinal mode emission with a side-mode suppression ratio (SMSR) exceeding 40 dBm. The multiple kinks observed correspond to mode hops between adjacent lasing modes. This is due to the temperature rise in the III-V part of the laser being higher than in the silicon, where the external Vernier filter is defined. This fact is represented in one of the insets of figure 1(a) (at the right-hand side), where two different lasing modes corresponding to a different laser injection current are superimposed, showing an evident wavelength red shift. In addition, the optical power-versus injected current density curve is represented with segments of different colours corresponding to each lasing mode. Figure (b) displays the typical Voltage-current density characteristic of the diode laser, with an onset voltage value of around 0.7 V and an almost linear behaviour of the leakage current. We observe a slope diminution from 4.5 kA/cm$^2$ on, followed by an irregular behaviour for injected current density values close to 6 kA/cm$^2$. This behaviour is attributed to the activation of non-negligible thermal effects and to charge accumulation within the laser diode. Figure 1 (c) shows the measured differential resistance evolution as a function of the injected current density. As can be seen, the differential resistance rapidly decreases until values below 6 Ω, in agreement with the onset of lasing, and then remains almost constant until 4.5 kA/cm$^2$. The measurement becomes noisy and slightly chaotic beyond this value, in agreement with the onset of thermal and charging effects in the laser diode.

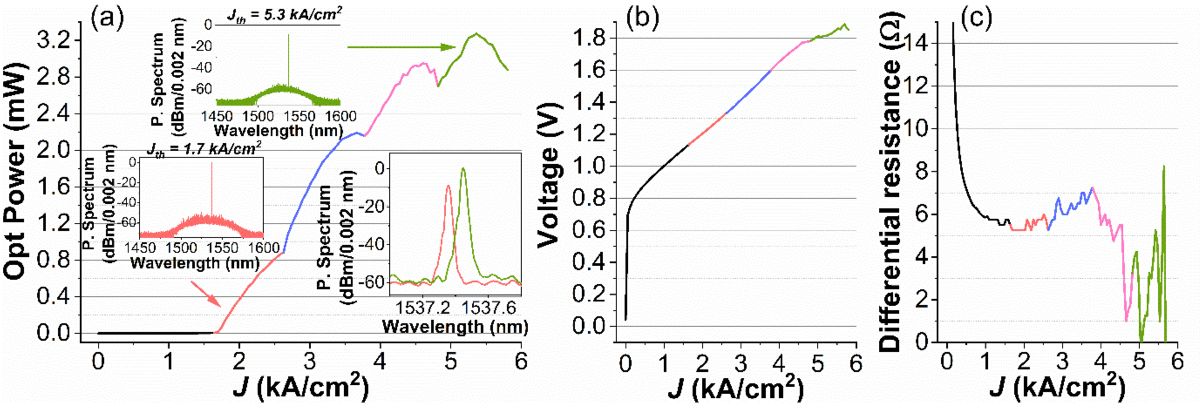

Figure 1. Static optoelectronic characteristic of an integrated tunable lasers. The current density range for different lasing modes is highlighted with different colours to ease the correspondence between the different curves: (a) Single-mode fibre-coupled optical power as a function of the injected current density in the laser. Insets on the left-hand side show the measured laser spectrum for low current density values after the threshold (magenta curve) and for high current density values close to the optical power saturation point (green curve). Right-hand inset compares the emission spectrum for the two spectra, showing different lasing modes. Votage-current density (b) and differential resistance-current density (c) curves of a tunable laser.

Figure 2(a) shows a representative tuneability map of a tunable laser diode. The y- and x-axes show the injected current in each of the two heaters that compose the Vernier filter. The measured lasing emission wavelength is represented by the colour bar, with values comprised between 1500 nm and 1560 nm, i. e a tuning range of 60 nm. As a criterion, only the measured spectra showing an SMSR > 40 dB are coloured, whereas the ones with SMSR < 40 dB have been depicted in black. To better illustrate the spectral tuneability of the laser diode, figure 2(b) shows the evolution of wavelength of emission as a function of the injected current in the heaters for the current density range indicated by the white cross in figure 2(a). A step-like behaviour is observed, corresponding to the coarse tuning of the external filter. It is worth noting that continuous wavelength tuning is achievable by combining the two heaters and the phase shifter.

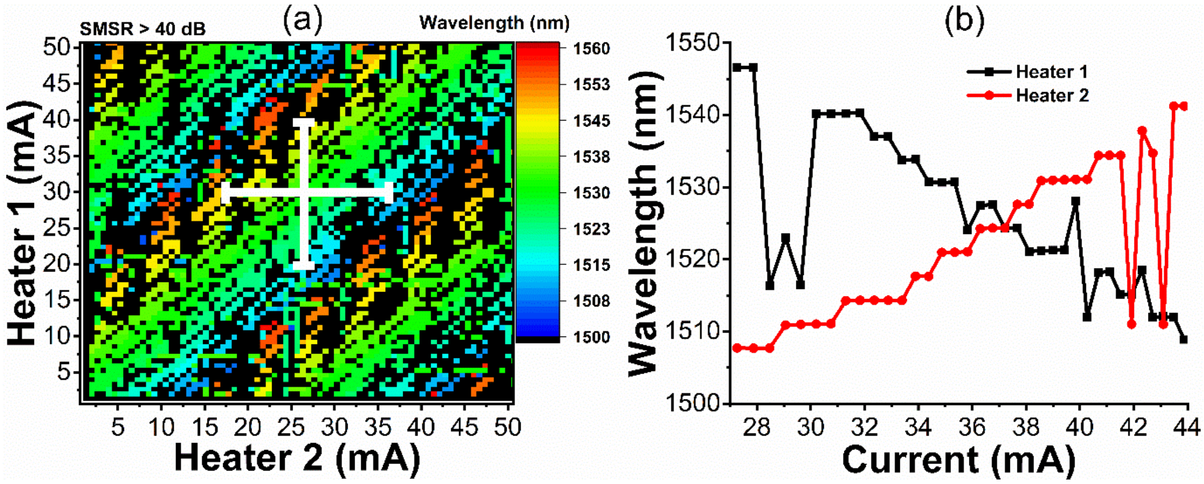

Figure 2. (a) Colour map of the spectral tunability of the integrated laser. (b) Evolution of the laser spectral wavelength as a function of the injected current in each of the thermal heaters comprising the Vernier filter. The curves correspond to the data marked with a white cross in figure (a).

## 3. CONCLUSIONS

In this work, we present our latest work on the demonstration of compact widely tuneable heterogeneous laser diodes on 200-mm Si platform. Devices show good optoelectronic properties, with a threshold current density of 1.7 kA/cm$^2$, a differential resistance below 6 Ω, maximum fiber-coupled optical power of 5 dBm, an SMSR > 40 dBm and a wavelength tuneability of 60 nm. The total device footprint is approximately 1 mm$^2$, including the external Si cavity. These results pave the way towards low-cost, energy-efficient and easily scalable compact lasers suitable for applications requiring high spectral efficiency and demanding optical power budget.

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