Heterogeneously integrated III/V-on-SiN mode-locked laser using two-step micro-transfer printing

S. Poelman,[1, 2] T. Reep,[1,2] M. Billet[1,2] and B. Kuyken[1,2]

[1] Photonics Research Group, INTEC, Ghent University – imec, Technologiepark-Zwijnaarde 126, 9052 Ghent, Belgium

[2] Center for Nano- and Biophotonics (NB-Photonics), Ghent University, Technologiepark-Zwijnaarde 126, 9052 Ghent, Belgium

We demonstrate a low repetition rate mode-locked laser using heterogeneous integration of a III/V semiconductor amplifier on a passive silicon nitride extended cavity. The long extended cavity needed to achieve a low repetition rate is created using electron beam lithography on a 300 mm silicon nitride sample. The versatile integration technique of micro-transfer printing is used to integrate not only the III/V amplifier, but also a silicon interposer layer which is needed to facilitate efficient coupling from the silicon nitride to the III/V material. In this work we show these lasers offer a wide range of operation, including fundamental (3 GHz), second and third harmonic mode-locking with output powers close to 1 mW in the fiber. We also show 10 dB optical bandwidths exceeding 20 nm and pulse widths of a few picoseconds. These results show that using this two-step integration approach we can make mode-locked lasers with good performance, and a promising outlook for their use in applications such as dual-comb spectroscopy.

Introduction

Integrated frequency comb sources have gained ever more interest in recent years, as researchers are able to generate very short pulses with fixed repetition frequencies, but replacing the more common and bulky fiber- and solid state lasers by integrated solutions. This opens up a lot of opportunities for numerous potential applications such as telecommunication, light detection and ranging (LIDAR) [1] and spectroscopy [2]. One way of creating integrated low repetition rate frequency combs is by means of mode-locked lasers. Several mode-locked lasers have been demonstrated in recent years, by heterogeneous integration of III-V semiconductor optical amplifiers (SOAs) on passive silicon nitride platforms [3][4][5]. Heterogeneous integration enables to combine the low propagation losses and wide transparency range from a passive silicon nitride platform, with the gain properties of a III-V material such as indium phosphide.
In this work we utilize the versatility of micro-transfer printing to heterogeneously integrate not only the SOA, but also an intermediate silicon layer, which is needed to facilitate efficient evanescent coupling from the silicon nitride to the III-V material. With this method we fabricate a 3 GHz repetition rate mode-locked laser with a wide range of operating points.

Design and fabrication

The demonstrated mode-locked lasers has a Fabry-Perot topology, creating a colliding-pulse configuration. The long extended cavity was created using two 2 cm long low-loss SiN waveguide spirals and 2 Sagnac reflectors as the mirrors. Centrally placed in the cavity is the 2.5 mm long semiconductor optical amplifier. A microscope figure of the fabricated devices is shown in Figure 1.

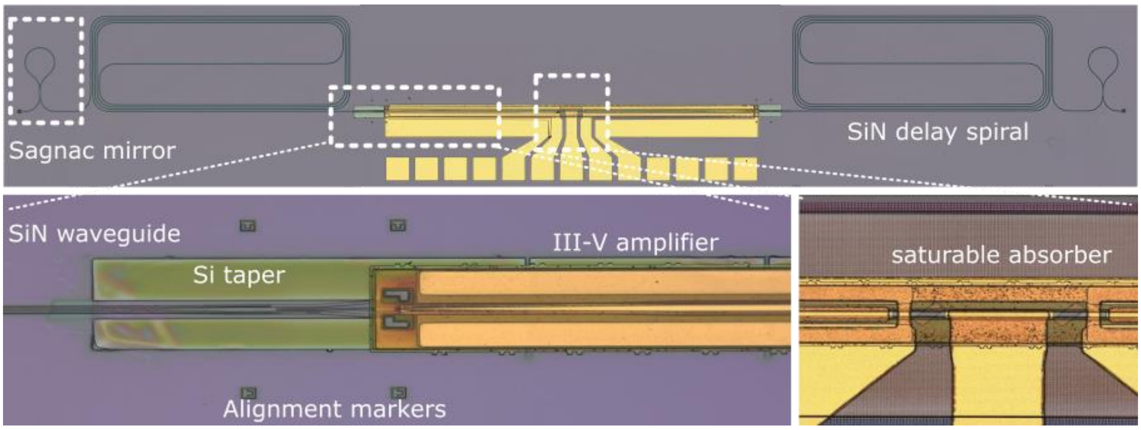

Figure 1: Microscope picture of the 3 GHz mode-locked laser with a colliding pulse Fabry-Perot configuration (top). Zoomed in views of the transition section between SiN, Si and the III-V amplifier, as well as an image of the isolated section in the amplifier, forming the saturable absorber.

All of the passive circuits are patterned using electron beam lithography and etched using reactive ion etching. A 35 nm aluminum oxide etch stop layer is deposited using atomic layer deposition to protect the silicon nitride layer during the subsequent processing steps. The heterogeneous integration of both the silicon interposer layer and the III-V SOA is done through micro-transfer printing, which is a versatile heterogeneous integration approach enabling the transfer of thin-film devices of different source materials on various target platforms. For a detailed overview of the micro-transfer printing technique we refer to [6]. In the first transfer printing step, 400 nm thick silicon slab coupons are transferred to the center of silicon nitride cavity. Electron beam lithography is used to create taper structures and a waveguide, which enable efficient evanescent coupling from and to the silicon nitride waveguide and a hybrid guided mode respectively. In the second transfer printing step the InP-based multi-quantum well SOA is transferred on top of the interposer silicon coupon. This amplifier already contains a saturable absorber, by means of a 100 µm section which is isolated from the remainder of the amplifier. The fabrication process is concluded with a metalization step, which creates the contact pads to bias the amplifier and saturable absorber sections.

Measurement results

The mode-locked laser device was characterized by biasing the amplifier and saturable absorber using two Keithley source measure units, while being kept thermally stable at 18°C using a thermoelectric cooler. The light from the laser could be captured from either of the output grating couplers, with no notable difference between the two. The grating couplers had a loss of about 8 dB per coupler. While on-chip implementations of mode-locked lasers used to have very limited operating points, recent advances to the SOA and intermediate layer designs have led to much broader regions of operation [4]. While those results were obtained on a dedicated platform, we could get similarly broad operating regimes using our in-house fabricated mode-locked lasers. By sweeping the amplifier current bias and saturable absorber reverse bias, we could obtain maps of operating regimes, containing fundamental, and higher harmonic mode-locking as shown in Fig. 2. These operating regimes were distinguished by inspecting the optical and RF spectra for each bias condition. Similarly maps were obtained of the optical output power (measured in the fiber), the optical 10 dB bandwidth of the frequency combs and the RF peak power, shown in figures 2(b), 2(c) and 2(d) respectively.

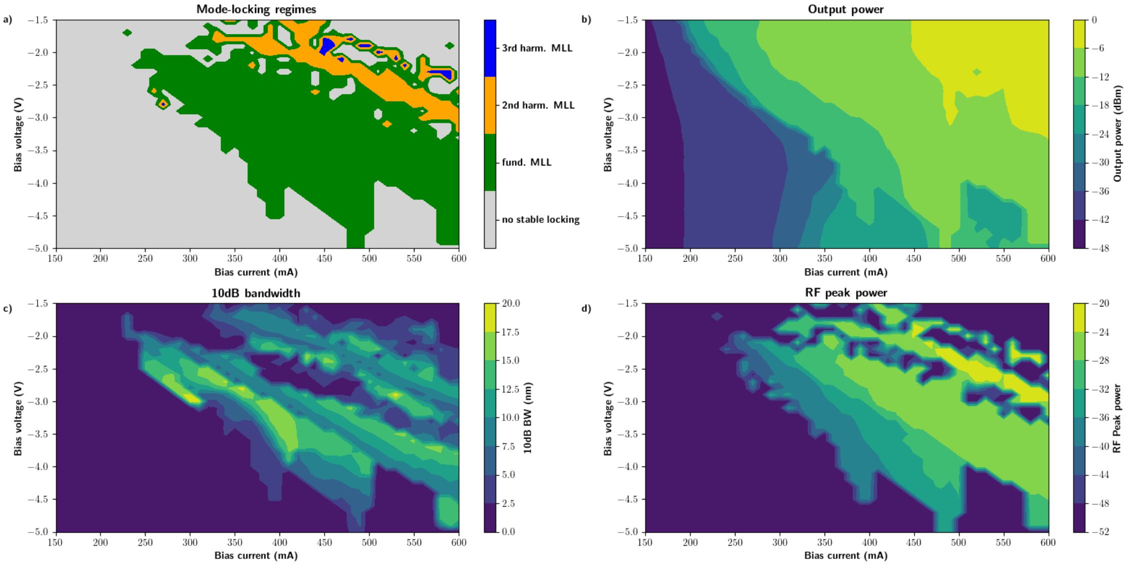

Figure 2: (a) Map of different mode-locking regimes for a range of amplifier bias currents and saturable absorber reverse bias voltages. The regimes are divided according to their mode-locking operation. Maps of the (b) optical output powers, measured in the fiber, (c) optical 10 dB bandwidth of the comb spectrum and (d) RF power of the fundamental peak of the RF spectra, all obtained for the biasing conditions corresponding with (a).

Inspection of these maps shows that we can obtain a wide range of operating points, with relatively high output powers up to 1 mW and 10 dB optical bandwidths of 20 nm. These maps are however not unique, as some hysteresis was noted and the mode-locked laser operation varied depending on the sweep direction.
Figure 3 shows the optical and RF spectrum for one of the operating points (amplifier bias: 450 mA, SA reverse bias: -3.0 V). The optical spectrum is ~15 nm wide and relatively flat. While the individual comb lines cannot be resolved by the optical spectrum analyzer, it can be easily calculated that this spectrum contains over 600 lines, making it very interesting for applications such as dual-comb spectroscopy. The ripple on the spectrum is suspected to be a result of roughness in the silicon tapers which could be mitigated in future runs by changing the etching process. The RF spectrum confirms the mode-locking operation, showing distinct lines at ~3 GHz and the higher harmonics with a signal-to-noise ratio of >30 dB.

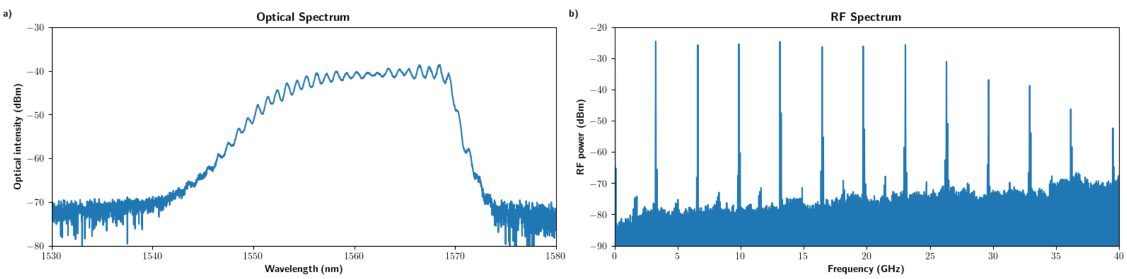

Figure 3: (a) Optical spectrum and (b) RF spectrum of a fundamental mode-locking operating point (450 mA, -3.0 V)

Conclusion and Outlook

In this work we utilized the versatility of micro-transfer printing to create a heterogeneously integrated mode-locked laser, with a wide range of operation. This gives a promising outlook for their use in (dual-comb) applications such as LIDAR and spectroscopy. Furthermore, we can achieve performance which is close to similar demonstrations on dedicated platforms. This shows that this approach is an ideal candidate for fast prototyping and experimenting with integrated (mode-locked) sources.

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