Ultra-Dense III-V-on-Silicon Nitride Frequency Comb Laser

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Abstract *A heterogeneously integrated III-V-on-silicon nitride mode-locked laser is demonstrated. The device is fabricated by microtransfer printing an InP/InAlGaAs-based multiple-quantum-well coupon. A dense comb with a 755 MHz repetition rate, a 1 Hz ASE limited RF linewidth and a 200 kHz optical linewidth is achieved.*

Introduction

Comb sources on a photonic chip have gained considerable interest in recent years for their potential in various domains, including optical ranging, microwave photonics, spectroscopy, time- and frequency metrology[1],[2]. While platforms such as quantum cascade lasers (QCLs), electro-optic and Kerr combs have shown impressive developments, their use in a number of applications remains elusive because of their large line spacing, limited number of usable comb lines and integration challenges[3]–[6]. In particular the concept of dual-comb spectroscopy in the gas-phase has proven difficult because of the need for ultra-dense optical frequency combs[3],[7]. As most gasses have absorption features with a linewidth on the order of a GHz, comb sources with a line spacing $<$1 GHz are in high demand to accurately sample the spectra without the need for interleaving[3],[8]. Mode-locked laser comb sources offer an attractive platform for such applications as they can provide comb spectra with ultra-narrow line spacing. Moreover, these devices allow for high conversion efficiencies and can be electrically pumped, omitting the need for an external optical pump source[9]. Due to the high waveguide losses of monolithic III-V, InP, and III-V-on-Si platforms and the difficulties with heterogeneous integration, current state-of-the-art integrated passively mode-locked lasers fail to demonstrate comb spectra with sub-GHz repetition rates[8],[9].

In this work, we leverage the ultra-low losses of silicon nitride (Si_3N_4) to build a heterogeneously integrated III-V-on-Si_3N_4 mode-locked laser (MLL) with a record-low repetition rate of 755 MHz. The technique of microtransfer printing is used to integrate an InP/InAlGaAs based multiple-quantum-well (MQW) semiconductor optical amplifier (SOA) on an ultra-low-loss silicon nitride waveguide platform, hence enabling wafer scale manufacturing. Excellent noise performance is achieved, such as an ASE limited RF linewidth of 1 Hz and an optical linewidth of 200 kHz.

Design and fabrication

A schematic of the MLL is depicted in Figure 1(a). An extended ring cavity geometry was employed, consisting of two 10 cm Si_3N_4 spirals, deposited by means of low-pressure chemical vapor deposition on top of a silicon-on-insulator (SOI) wafer. The Si_3N_4 waveguides were defined using deep-UV lithography and have a width of 2 µm and a height of 330 nm. To enable heterogeneous integration, a recess is locally etched in the 4.2 µm silicon oxide (SiO_2) top cladding. A two-stage taper structure is employed to bridge the large index difference and ensure efficient coupling of light from the Si_3N_4 to the III-V stack: first from the Si_3N_4 waveguide to a silicon waveguide underneath, and subsequently to the III-V waveguide. A microscope image of the two-stage taper with transfer printed coupon is shown in Figure 1(b). The III-V InP/InAlGaAs layer stack is described in detail in Reference [10].

Heterogeneous integration

For the heterogeneous integration of the III-V amplifier in the recess on the passive chip, the microtransfer printing technique is used[10]–[12]. It is based on the kinetically controlled adhesion of an elastomeric stamp to pick pre-processed devices from their source substrate and print them on a target photonic integrated circuit. In contrast to bonding techniques, microtransfer printing allows to integrate a III/V coupon in a recess. Moreover, this approach allows massively parallel integration, enabling wafer-scale manufacturing. After transfer printing, the coupon is post-processed to

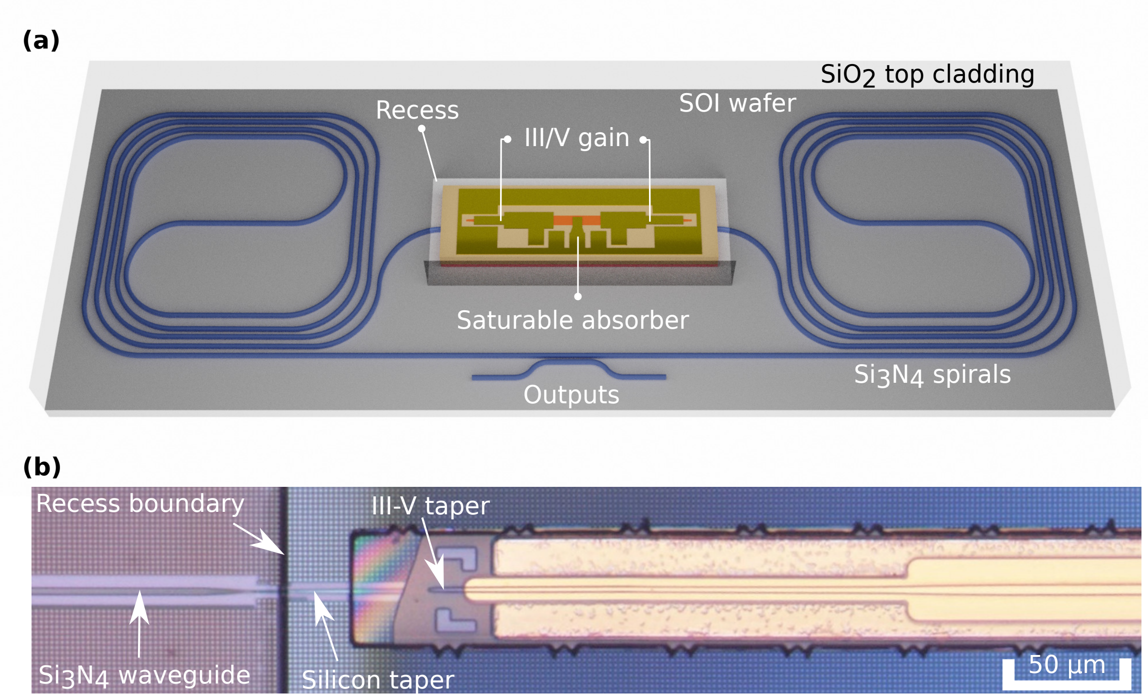

Fig. 1: (a) Schematic of the extended ring cavity mode-locked laser with Si_3N_4 spirals and InP/InAlGaAs-based amplifiers with saturable absorber. The recess for microtransfer printing the III/V coupon is indicated. (b) Microscope image of the transfer printed coupon on top of the taper structure.

isolate a saturable absorber (SA), vias are etched to access the n-InP layer and electrical contacts are added. The SA has a length of approximately 34 µm whereas the amplifiers have a length of 600 µm SOA at each side.

Measurements

The MLL was characterized on a Peltier temperature-controlled stage, which kept the device substrate at a constant temperature of 15°C. A PGSGP probe was used for biasing, where the P-contacts were used to power the amplifiers and the S-contact was used to reverse bias the saturable absorber. Light was extracted with a single-mode fiber using a Si_3N_4 grating coupler. Passive mode-locking at the fundamental frequency was found to occur at an SA reverse bias voltage of -2.9 V with a -0.499 mA SA current, and an amplifier bias of 1.88 V with a 75 mA injection current. The optical power in the fiber was measured to be around -24 dBm, corresponding with an on-chip power of approximately 126 µW when the grating coupler losses are taken into account. Although it has been shown that 10 µW of optical output power suffices to perform gas-phase dual-comb spectroscopy, larger output powers could be obtained by using longer amplifiers. Figure 2(a) shows the electrical spectrum of the MLL at the aforementioned bias point, obtained with a Agilent N9010A Electrical Spectrum Analyzer (ESA) with a 300 kHz resolution bandwidth. A flat, densely-spaced comb spectrum is achieved with a record-low repetition rate of 755 MHz. To the best of our knowledge, this it the lowest reported repetition rate for any integrated passively mode-locked laser, enabling an unprecedented resolution for chip-based spectroscopic applications. Note that the roll-of of the RF comb at high frequencies is a consequence of the 30 GHz bandwidth limitation of the transimpedance amplifier of the photodetector. Furthermore, the repetition frequency signal was measured with a 100 Hz RBW, revealing a narrow -10 dB RF linewidth of 100 Hz. The optical spectrum of the MLL was measured with an Optical Spectrum Analyzer (OSA) with a 30 pm resolution and is depicted in Figure 2(b). A 10-dB optical bandwidth of 3.27 nm is achieved, corresponding with over 500 densely and evenly spaced comb lines. The capacity to produce such dense combs on-chip with hundreds of lines and sub-GHz linespacing is unmatched by other comb generation techniques such as QCLs, electro-optic combs and Kerr microcombs. Moreover, the spectrum of a mode-locked laser does not suffer from a strong central optical pump signal as is often the case with competing techniques. The optical linewidth was characterized by beating the MLL output with a Santec tunable laser (60 kHz),

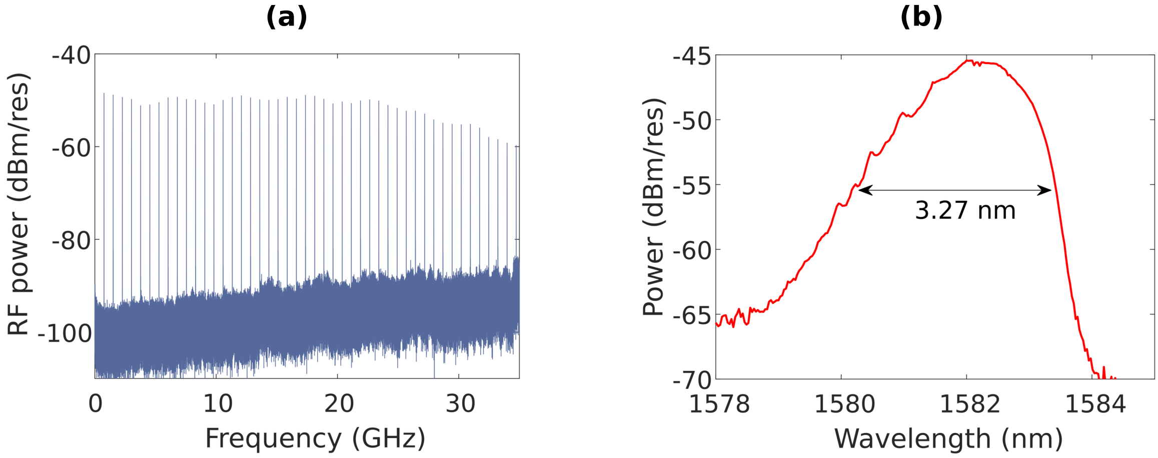

Fig. 2: (a) RF spectrum of the generated pulse train at the chosen operating point. The RBW is 300 kHz. (b) Optical spectrum measured with a 30 pm resolution. A 10-dB optical bandwidth of 3.27 nm is measured.

resulting in a heterodyne beatnote with a 200 kHz optical linewidth. Finally, single-sideband phase-noise measurements were carried out, showing a record-low 1 Hz ASE limited RF linewidth.

Conclusions

We have demonstrated a heterogeneously integrated III-V-on silicon nitride mode-locked laser with a record-low repetition rate of 755 MHz and unprecedented noise performance such as a fundamental RF linewidth of 1 Hz and an optical linewidth of 200 kHz. The device was fabricated by microtransfer printing an InP/InAlGaAs-based multiple-quantum-well coupon on a low-loss silicon nitride platform, enabling wafer scale manufacturing. Such an electrically pumped low-noise ultra-dense frequency comb source is highly desirable in a number of applications, for example in high-resolution spectroscopy.

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