Ultra-Long Cavity Hybrid Silicon Mode-locked Laser Diode Operating at 930 MHz

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Abstract: An integrated 9-cm cavity hybrid silicon laser that is fundamentally mode-locked at 930 MHz is presented. The laser outputs chirped 200-ps pulses at 1.1-ns repetition rate. Harmonic mode-locking up to the 8^{th} harmonic is shown, with 35-ps pulses at the 3^{rd} harmonic.

OCIS codes: (130.0250) Optoelectronics; (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers

1. Introduction

Mode-locked laser diodes (MLLDs) can be used as stable, robust and low-cost pulse sources for applications such as optical fiber communications, bio-medical imaging and metrology. Repetition rates for monolithic MMLDs are typically between 5 – 50 GHz due to the cavity sizes in the order of millimeters [1]. However for many applications, lower repetition rates are desirable. For example in nonlinear microscopy and spectroscopy, pulse peak power is essential for high signal to noise contrast and imaging quality [2]. Lower repetition rates of the MLL allow for larger energy per pulse and hence larger pulse peak power. Furthermore it has been proven theoretically and experimentally that harmonic mode-locking of long cavity lasers results in lower phase noise for the output pulses as compared to fundamental mode-locking of a short cavity [3]. Hence a MLLD with a long cavity is very promising for low-timing jitter applications.

Typically fiber optics or external free-space cavities are used to increase the cavity of a MLLD. Also EDFA-based mode-locked lasers are widely used. However for reasons of cost, size, stability and energy-efficiency, integration of a low repetition rate MLLD on a single chip is an attractive and promising option.

Recently the hybrid silicon platform has appeared as a promising candidate for realizing such MLLDs [4]. In this technology passive waveguiding structures are realized as silicon-on-insulator (SOI) rib waveguides and active, i.e. gain, elements are realized by selectively bonding III/V-based multiple quantum well epitaxial layer to the top of the silicon waveguide. The light in the waveguide can then evanescently couple to the III/V region as schematically depicted in Fig. 1(a). This technology has some significant advantages over the Indium Phosphide-based material platform, i.e. the technology generally used to realize lasers and MLLDs that operate around wavelengths of 1.55 µm. Since the SOI passive waveguide losses can be as low as 0.1 – 0.5 dB/cm (as opposed to ~1 dB – 3 dB/cm for typical InP-based waveguides) ultra-long integrated (on-chip) cavities become possible. Furthermore two-photon absorption is around two orders of magnitude lower in silicon waveguides as compared to InP [5]. This allows for higher power densities and consequently higher pulse peak powers in the waveguide. A final point is that by changing the width of the silicon waveguide in the gain sections, the confinement with the quantum wells can easily be changed. High-saturation power amplifiers can be made by lowering the confinement, which will also minimize non-linear gain compression. Both are beneficial for MLLD performance.

In this paper we present an ultra-long cavity mode-locked laser diode (ULC-MLLD) fully integrated using the hybrid silicon platform. We demonstrate fundamental mode-locking at 930 MHz, which is about five times lower than the state-of-the-art. The cavity length of around 9 cm is to our knowledge the longest ever reported for an integrated MLLD.

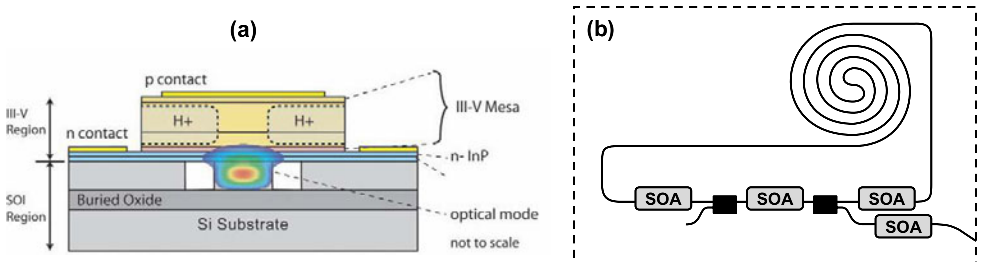

Fig. 1. (a) Schematic of the hybrid silicon amplifier cross-section [5]. (b) Schematic of the ULC-MLLD indicating the waveguides (black solid lines), couplers (black boxes) and chip boundary (dashed). The SOAs (grey) are realized as shown in (a).

2. Device design and realization

A schematic of the ULC-MLLD is shown in Fig. 1(b). Two 1200-µm semiconductor optical amplifiers (SOAs) and one 800-µm (center) are located inside the 9-cm ring cavity to provide the gain of the laser. Two multi-mode interference (MMI) couplers are used to couple out 50% of the light inside the cavity, at the expense of a total of 6-dB loss. Booster SOAs are located at the output waveguides, which have a 7° angled facet and an anti-reflection coating for minimizing reflections back into the laser cavity. The size of the chip is 0.6 × 1 cm^2.

The device fabrication and realization are equal to the one presented by Park et al. [6] and we refer to this paper for further details. The SOI passive waveguide loss is around 1.7 dB/cm and the SOA maximum gain is around 6 dB for the 800-µm SOA and 8 dB for the 1200-µm SOA, limited by the heating of the device. The laser is operated at injection currents of 280 mA and 160 mA for the 1200-µm and 800-µm SOAs respectively. A lensed fiber is used for collecting the output light. Under continuous-wave operation the device lases at 1575 nm. Output power is around -9 dBm (-18 dBm in fiber with an estimated 9-dB coupling loss). The optical linewidth is less than 7 MHz as measured by a heterodyne technique.

3. Active mode-locking

We actively mode-lock the device by applying an RF-bias to the 800-µm center SOA inside the laser cavity. The optical spectrum around 1575 nm broadens to about 0.1 nm when 12 dBm of RF-power at 927 MHz is applied. A second group of modes is visible around 1578 nm, at -30 dB of the main group of modes, as can be seen in Fig. 2(a).

The output of the laser is amplified by an L-band amplifier and a 50-GHz photodiode is used to record the RF spectrum, using a 50-GHz electrical spectrum analyzer (ESA). The spectrum shows a distinct comb of modes at an RF-power of 20 dBm, as shown in Fig. 2(b). A supermodulation with a period of around 15 GHz is visible over the RF mode-comb. The harmonics show a side-peak at ~60 MHz higher frequency, which rises at the expense of the main peaks for increasing frequency. We hypothesize that these side-peaks arise as a result of the small group of modes around 1578 nm, which travel at a different group velocity and are likely not locked (synchronized) with the main group of modes. The interference between these two groups of modes might explain the 15-GHz supermodulation as shown in Fig. 2(b). A close-up of the first harmonic in Fig. 2(c) shows additional sidebands around 0.7 – 0.8 MHz.

The single side-band phase noise is plotted in Fig. 3(a). Up to around 30 kHz, the phase noise of the synthesizer dominates. To verify pulse generation, we use a digital component analyzer with an optical input with 53-GHz bandwidth. Pulses with a duration of about 200 ps and a 1.1 ns period are clearly visible. Given the optical bandwidth of 0.1 nm the pulses are highly chirped, probably due to the dispersive 9-cm cavity.

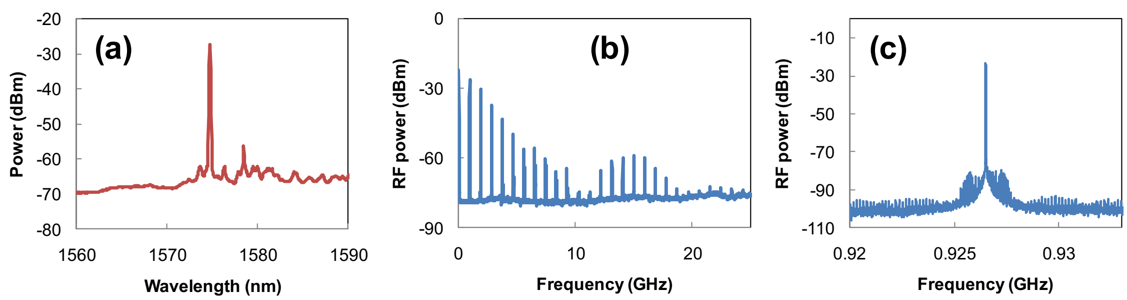

Fig. 2. (a) Optical spectrum at 12 dBm RF-power at 927 MHz. The optical bandwidth used is 0.06 nm. (b,c) RF-spectra obtained at 20 dBm RF-power. The spectrum analyzer resolution bandwidths in (b) and (c) are 5 MHz and 10 kHz, respectively.

4. Harmonic mode-locking

In Fig. 3(c) the small-signal modulation response of the ULC-MLLD is shown. As can be seen clear resonance peaks are observed around 0.9 GHz and the higher harmonics. This shows the potential for harmonic mode-locking. In Fig. 4(a) the RF-spectra for locking at the 2nd, 3rd, 4th and 8th harmonic are shown. The spectra were optimized for minimization of the supermodes, i.e. the modes in between the harmonics. As can be seen the supermodes can be suppressed to around -30 dB of the locking frequency for the 2nd, 3rd and 8th harmonic locking. Locking at the 4th harmonic shows a more limited supermode suppression.

Fig. 4(b) shows the time-domain trace of the laser output operated at the third harmonic. Pulses with a duration of 30 – 40 ps can be observed. Also trailing pulses at around 120 ps of the main pulse can be observed. We note that the 18th harmonic is relatively strong when the laser is operated at its 3rd harmonic (Fig. 4(a)), which is in agreement with this observation of trailing pulses at around 1/3 of the pulse period. We ascribe the appearance of this trailing pulse to the locking and synchronization of the second group of (optical) modes.

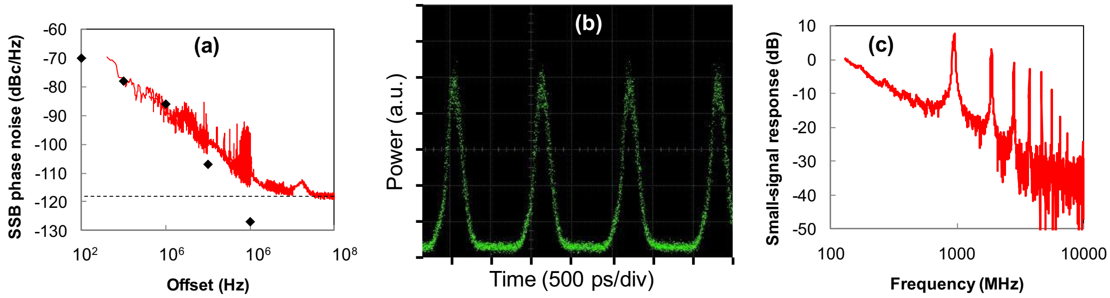

Fig. 3. (a) SSB phase noise plot of the first harmonic at 20 dBm RF power (red). The RF synthesizer phase noise (black diamonds) and analyzer noise floor (dashed line) are also indicated. (b) Time-domain trace obtained with a 53-GHz digital component analyzer. (c) Small-signal response of the free-running (continuous-wave) laser as measured by a 20-GHz Lightwave Component Analyzer. Signal is normalized to the lowest-frequency response.

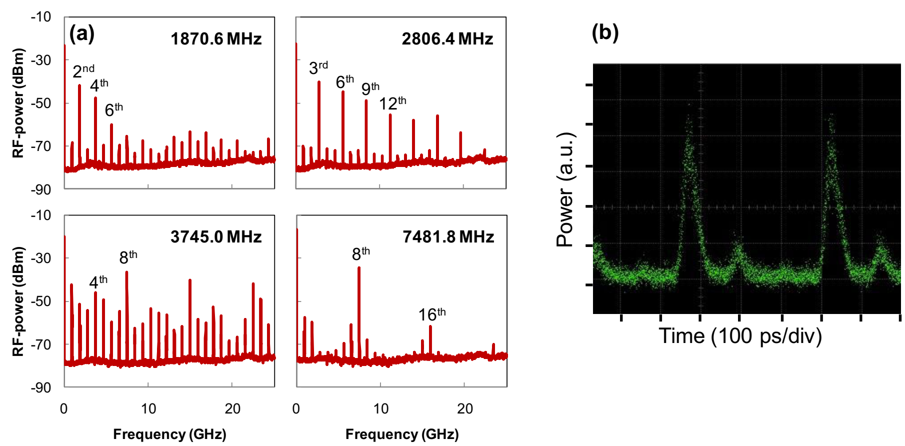

Fig. 4. (a) RF-spectra obtained at 20 dBm injection at the indicated frequency and with a bandwidth of 5 MHz. (b) Time-domain trace obtained at an injection frequency of 2807 MHz.

5. Conclusion

For the first time sub-GigaHertz mode-locking is shown in an integrated laser diode. The ULC-MLLD operates at 930 MHz under fundamental and active mode-locking and outputs chirped pulses with a 200-ps duration. Harmonic mode-locking up to the 8th harmonic is also shown. We hypothesize that the stability of operation is limited by the appearance of optical modes which are not locked and not synchronized with the main group of modes.

The laser can be further optimized by adding an intracavity bandpass filter, such as an arrayed waveguide grating (AWG) based filter, to filter out the non-synchronized optical modes. Furthermore a decrease in cavity losses, which is feasible in the hybrid silicon technology, will decrease the phase noise and allow mode locking at even lower frequencies, down to 100 MHz. An intracavity etalon, e.g. a ring-resonator based filter, can suppress the supermodes in harmonic mode-locking and increase the stability of the output. Consequently, significantly improved performance should be possible.

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