Passively mode-locked quantum dot laser diodes at 1.53 μm with large operating regime

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Abstract. *Passive mode-locking in two section InAs/InP (100) quantum dot lasers emitting around 1.53 μm is observed over a large operating regime. For absorber voltages of 0 V down to -3 V and for amplifier currents of 750 mA up to 1 A the fundamental RF-peak is over 40 dB above the noise floor.*

Introduction

Sources of picosecond or femtosecond optical pulses with a wavelength around 1550 nm have many applications in optical telecommunications. They can be used as pulse sources for time-domain multiplexed systems and as synchronized pulse sources or multi-wavelength lasers for wavelength-division multiplexed systems. Moreover the optical spectrum is a frequency comb and may be used in e.g. arbitrary pulse generation. An important requirement for many of these applications is a broad coherent optical bandwidth of the output of the source, which may well exceed 1 THz. Also the operation regime should be robust for practical implementation.

For reasons of stability, compactness, and fabrication costs, mode-locking of semiconductor laser diodes is an attractive option for generating picosecond pulses at 1.55 μm [1]. The material system of choice for fabricating these mode-locked laser diodes (MLLDs) is InP/InGaAsP, using either bulk or quantum well gain material. The bandwidth of these MLLDs is however limited to between 1 nm – 5 nm [1,2].

Quantum dot (QD) gain material is promising for the application in MLLDs due to its broad gain spectrum. Sub-picosecond pulse generation down to 0.4 ps with a bandwidth of 14 nm has been achieved with InAs/GaAs QD material operating at wavelengths around 1.3 μm [3]. These lasers are shown to have robust operating regimes [4].

In this paper a study of the ranges for absorber voltage and amplifier current for passive mode-locked operation of 4.6-GHz monolithic two-section InAs/InP (100) QD lasers is presented. These devices operate at wavelengths of around 1.53 μm. Some first results have been published in [5].

Design and fabrication

The QD laser structure is grown on n-type InP (100) substrates by metal-organic vapor-phase epitaxy (MOVPE), as presented in [6]. In the active region five InAs QD layers are stacked. These are placed in the center of a 500 nm InGaAsP optical waveguiding core layer. The bottom cladding of this laser structure is a 500-nm thick n-InP buffer and the top cladding is a 1.5-μm p-InP with a compositionally graded 300-nm p-InGaAs(P) top contact layer. This layerstack is compatible with a butt-joint active-passive integration process for possible further integration.

Two-section Fabry-Pérot-type laser devices have been designed and realized. The ridge waveguides have a width of 2 μm and are etched 100 nm into the InGaAsP waveguiding

layer. To create electrical isolation between the two sections, the most highly doped part of the p-cladding layer is etched away. The waveguide and isolation sections are etched using an optimized CH_4 / H_2 two-step reactive-ion dry etch process. The structures are planarized using polyimide. Two evaporated and plated metal pads contact the two sections to create two contacts. The backside of the n-InP substrate is metallized to create a common ground contact for the two sections.
The structures are cleaved to create the mirrors for the FP cavity. No coating is applied. The two-section devices are operated by forward biasing the longer gain section, creating a semiconductor optical amplifier (SOA) and by reversely biasing the shorter gain section, creating a saturable absorber (SA). The devices are mounted on a copper chuck, p-side up, which is kept at a temperature of 10 ˚C. The total length of the devices is 9 mm. In this paper we study two two-section devices with SA lengths of 270 µm and 540 µm respectively. A 9-mm one-section device (i.e. an SOA with cleaved mirrors), fabricated on the same wafer, is used for reference purposes.

Experimental results

The laser with a 270-µm SA section has lasing threshold current values of 660 mA to 690 mA for SA reverse bias voltages of 0 V to -4 V respectively. Passive mode-locking is first studied by recording the electrical power spectrum using a 50-GHz photodiode and a 50-GHz electrical spectrum analyzer. The RF-spectra obtained for this laser show clear peaks at the cavity roundtrip-frequency of 4.6 GHz. In Fig. 1 the height of these RF-peaks over the noise floor is given as a function of the operation parameters, i.e. the SA bias voltage and the SOA injection current. A large, robust operating regime with RF-peak heights over 40 dB is found for values of the injection current of 750 mA up to 1.0 A and for values of the SA bias voltage of 0 V down to -3 V.

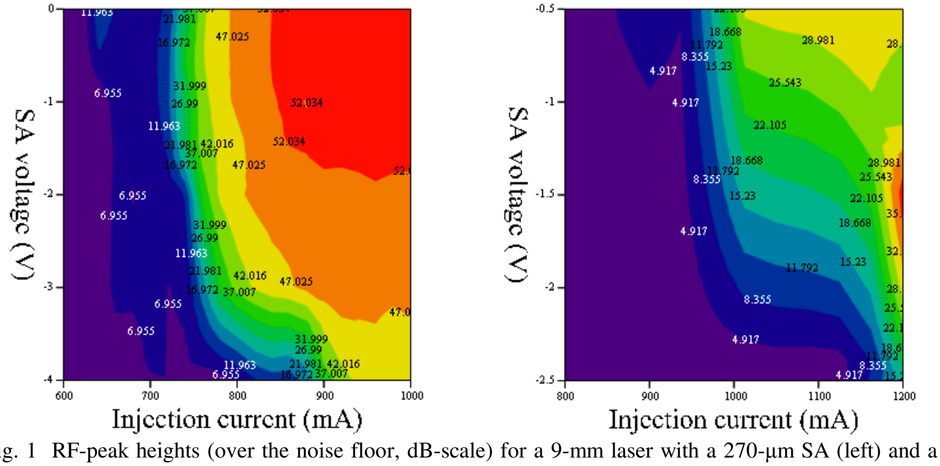

Fig. 1 RF-peak heights (over the noise floor, dB-scale) for a 9-mm laser with a 270-µm SA (left) and a 540-µm SA (right). The electrical bandwidth used to obtain the RF-spectra is 50 kHz. An external SOA was used before the 50-GHz photodiode to boost the optical output power of the 270-µm laser by about 6 dB – 7 dB. The 540-µm laser was directly connected to the photodiode, without an SOA.

The width of this RF peak is narrow, i.e. 0.57 MHz at -20 dB (for I_{SOA} = 900 mA and V_{SA} = -1 V). Also the position of this RF-peak, which is centered around 4.599 GHz, is stable within 3 MHz for the operating regime mentioned above. In MLLDs based on bulk gain material minimum RF-linewidths of 2.5 MHz at -20 dB have been reported, with a stability of the roundtrip frequency of about 50 MHz over their operating regime [2]. So a clear improvement of the 'longer term' laser stability is observed by using QD gain material instead of bulk gain material.

The laser with a 540-μm SA section has lasing threshold current values of 830 mA to 910 mA for SA reverse bias voltages of -0.5 V to -2.5 V respectively. This increase of the threshold current as compared to the 270-μm laser is caused by the increased SA length and the correspondingly increased absorption in the laser cavity.

The RF-spectra obtained for this laser show that mode-locking only sets in at relatively high values of the injection current, i.e. around 1.0 A. For the SA bias voltages of -2.0 V down to -2.5 V mode-locking sets in close to 1.2 A. This is the upper limit for our measurement setup, since above this value of the injection current the detrimental effect of the device heating causes the output power to drop.

For comparison we studied the 9-mm one-section QD-laser. The threshold current of this device is 380 mA. The electrical spectrum shows no distinct peak at the roundtrip frequency. This can be expected based on the well-known mechanisms of passive mode-locking in laser diodes with bulk or quantum-well gain material, where the SA plays a crucial role [1,2]. However one-section quantum-dash lasers emitting at 1.56 μm have been reported to show passive mode-locking, without the aid of an SA [7].

Timing jitter has been studied by evaluating the single-sideband phase noise signal around the fundamental RF-peak, using an integration interval of 10 kHz - 80 MHz. The timing jitter has been evaluated for the 270-μm SA device at a fixed injection current of 900 mA. The value is (35±3) ps for a low SA bias voltage of -0.5 V and increases slightly to (39±3) ps for an SA bias voltage of -2 V. For the 540-μm SA device (evaluated at 1100 mA) this increase of the timing jitter is larger, going from (36±4) ps to (53±7) ps for SA bias voltages of -0.5 V and -2 V respectively. We note that the mode-locking in the 540-μm device is weaker, as can be seen in Fig. 1.

These values of the timing jitter are relatively large as compared to e.g. MLLDs based on bulk gain material [2]. Compared to the results obtained for the width of the RF-peak, which has a relatively small value of 0.57 MHz at -20 dB, we conclude that the 'short-term' jitter is relatively large in the QD-lasers and the 'long-term' jitter is relatively small as compared to bulk or quantum-well MLLDs.

A typical optical spectrum of a 9-mm two-section laser is given in Fig. 2. The spectrum is broad, i.e. 6 nm – 7 nm, as can be expected from the inhomogeneously broadened gain of QD-lasers [6]. As was already measured in [5], this output spectrum is coherent. However the output pulses of these lasers are very elongated, i.e. well over 100-ps duration, and heavily up-chirped, with a chirp value of about 20 ps/nm. In this paper we confirm this observation by compressing the pulses, using standard single-mode optical fiber (SMF). The second order dispersion of SMF is in the order of 16 – 20 ps/(nm·km), meaning that 1.0 – 1.2 km of SMF should be able to compensate the chirp of these pulses. In Fig. 3 the autocorrelator traces are shown for different lengths of SMF after the 270-μm SA laser output. As can be seen the pulse is compressed to a minimum duration with 1500 m of SMF. However the strong peak in the center indicates an increased compression of part of the pulse. This partial compression can either be caused by a non-linear part of the chirp (or higher order SMF-dispersion), or by the non-Gaussian shape of the optical spectrum (Fig. 2). No autocorrelator traces could be obtained without SMF [5].

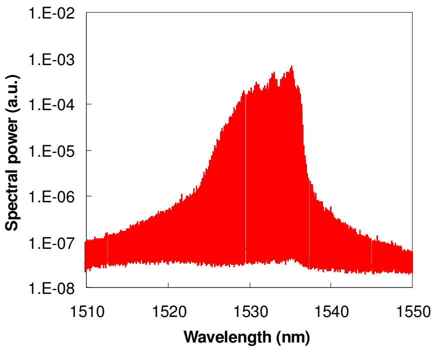

Fig. 2 Optical spectrum obtained for the 270-µm SA device. Injection current is 900 mA and SA bias voltage is -1 V. The optical bandwidth used to obtain the spectrum is 0.16 pm.

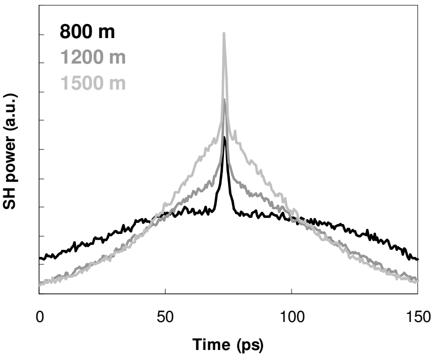

Fig. 3 Autocorrelator traces (second harmonic power given) obtained with a 270-µm SA device. Injection current is 900 mA and SA bias voltage is -1 V. The length of SMF between the device and the autocorrelator is indicated.

Conclusion

In this paper we have presented 4.6-GHz, two-section QD-lasers emitting around 1530 nm. Their operation is shown to be tolerant against variations in operation parameters. For a device with a 270-µm SA section, passive-modelocking with an RF-peak of 40 dB above the noise floor, was shown over a large operating regime of SOA injection currents of 750 mA up to 1.0 A and of SA bias voltages of 0 V down to -3 V. The variation of the roundtrip frequency within this operating regime is limited to below 3 MHz. This large and robust operating regime is essential for practical implementation of MLLDs.

The timing jitter values are relatively large, but the presence of an SA in the devices allows for possible hybrid mode-locking. This technique can severely decrease the timing jitter.

These QD-lasers have been realized with a fabrication technology that is compatible with further photonic integration. As such these devices can perform the function of e.g. a mode-comb generator in a complex photonic chip. The output spectrum is however not usable for ultrashort (sub-picosecond) pulse generation using common pulse compression techniques.

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