

Observation of Q-switching and mode-locking in two-section InAs/InP (100) quantum dot lasers around 1.55 μm

M.J.R. Heck, E.A.J.M. Bente, E. Smalbrugge, Y.S. Oei, M.K. Smit,
S. Anantathanasarn and R. Nötzel

COBRA Research Institute, Technische Universiteit Eindhoven
Postbus 513, 5600 MB Eindhoven, The Netherlands
m.heck@tue.nl

For the first time passive mode-locking in two-section quantum-dot lasers operating at wavelengths around 1.55 μm is reported. Pulse generation at 4.6 GHz from a 9-mm long device is verified by background-free autocorrelation, RF-spectra and real-time oscilloscope traces. The output pulses have a 7 nm optical bandwidth and are stretched in time and heavily up-chirped with a value of 20 ps/nm. From a 7 mm long device Q-switching is observed over a large operating regime. The lasers have been realized using a fabrication technology that is compatible with further photonic integration, and can perform the function of e.g. a mode-comb generator.

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. More advanced telecommunication coding technologies like optical code-division multiple-access (O-CDMA) systems also make use of short optical pulses [1]. 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.

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 [2]. The material of choice for fabricating these mode-locked laser diodes (MLLDs) is InP/InGaAsP, using either bulk or quantum well gain sections. The bandwidth of these MLLDs is however limited to between 1 nm – 5 nm [2,3].

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 having a bandwidth of 14 nm has been achieved with InAs-GaAs QD material operating at wavelengths around 1.3 μm [4]. In this work for the first time passive mode-locking of a two-section QD laser operating at wavelengths around 1.55 μm is presented.

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 [5]. 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 FP-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 and by reversely biasing the shorter gain section, creating a saturable absorber (SA). The devices are mounted on a copper chuck, p-side up. In this work we present the results of a device with a total length of 9 mm, with an SA section of 270 μm , showing mode-locking, and a 7-mm device, with an SA section of 350 μm , showing a large regime of Q-switching.

Experimental results

The 9-mm QD-laser has a lasing threshold current value 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 RF-spectrum at an injection current of 900 mA and an SA bias voltage of -1 V is shown. The first RF-peak at the fundamental frequency is 43 dB over the noise floor. Also the width of this peak is narrow, i.e. 0.57 MHz at -20 dB, as can be seen in Fig. 1(b). Moreover, the lower-frequency signal intensity around the DC-component in the spectrum is very low, i.e. in the order of the noise floor up to 5 GHz. Concluding it can be said that this RF-spectrum indicates clear and stable mode-locking.

The optical spectrum corresponding to this operating point 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 [5]. Clear, background-free pulses are observed with an autocorrelator after filtering the signal with a 1.2 nm optical bandpass filter (Fig. 3). The pulse duration of the filtered signal ranges from 6 ps up to 11 ps with increasing injection current. By tuning the filter over the full spectrum of the laser (about 10 nm, Fig. 2), clearly defined picosecond pulses are observed at all wavelengths. Thus the laser is mode-locked over this range and the full optical bandwidth is coherent over 10 nm.

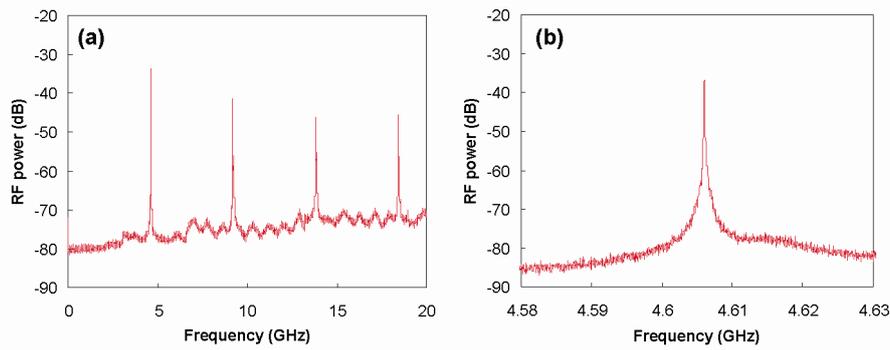


Fig. 1 (a) RF-spectrum obtained for a 9-mm device with 270- μm SA length. Injection current is 900 mA and SA bias voltage is -1 V. (b) Detailed view of the spectrum around the first RF-peak in (a). The electrical bandwidths used to obtain the spectra are 3 MHz and 50 kHz for (a) and (b) respectively

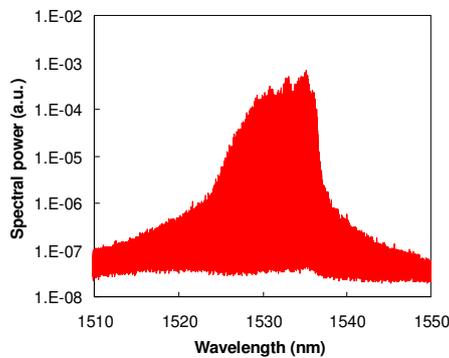


Fig. 2 Optical spectrum corresponding to Fig. 1. The optical bandwidth used to obtain the spectrum is 0.16 nm.

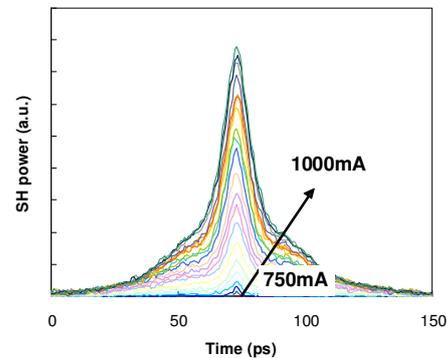


Fig. 3 Autocorrelator traces (second harmonic power given) obtained with a 1.2 nm optical bandpass filter. Injection current is varied from 750 mA up to 1.0 A and SA bias voltage is -1 V. The filter is set at 1534 nm.

The 7-mm QD-laser, having an SA section of 350 μm , has a threshold current of 700 mA up to 775 mA for SA bias voltages of 0 V down to -3 V respectively. In this device large regimes of Q-switching have been observed at an SA bias voltage of -3 V. The RF-spectra for frequencies up to 5 GHz are plotted in Fig. 4(a). Three regimes of Q-switching can be identified, with RF-peak spacings of approximately 32.5 MHz, 153 MHz and 390 MHz with increasing injection current. The increase in the oscillation frequency with increasing injection current is in agreement with the observation in [6]. Q-switching has been verified by recording the optical output with a 6-GHz bandwidth oscilloscope and a 45-GHz photodiode. The traces are shown in Fig. 4(b) and are obtained with values for the injection current corresponding to the three regimes of Q-switching in Fig. 4(a). The pulse repetition rates corresponding to the RF-peak spacing are 31 ns, 6.5 ns and 2.6 ns respectively for increasing injection current. These repetition rates are in agreement with the oscilloscope traces in Fig. 4(b). So concluding we can say that passive Q-switching in QD-lasers has been shown.

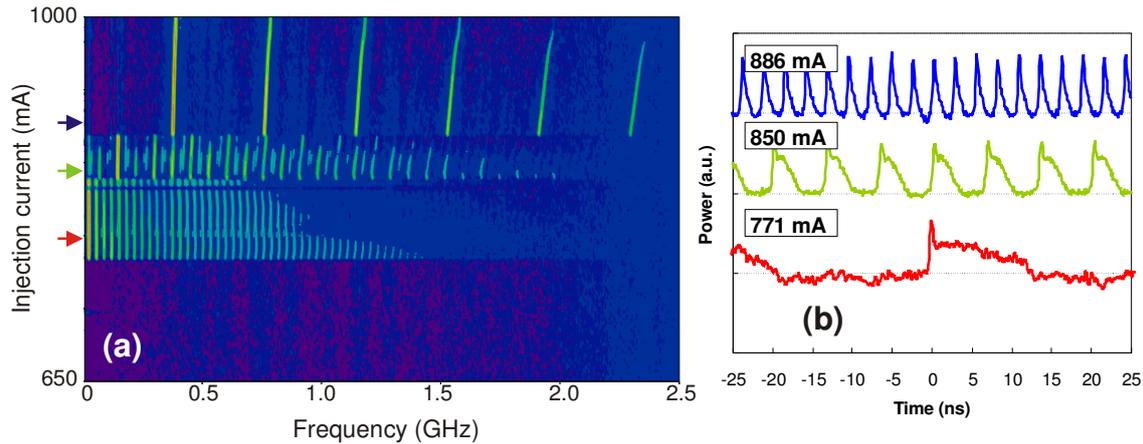


Fig. 4 (a) RF-spectra (3-MHz bandwidth resolution), color coded from low intensity (blue) to high intensity (red) obtained with a 7 mm device with 5% SA length and an SA bias voltage of -3 V. (b) Oscilloscope traces obtained for different injection currents corresponding to the three different regimes of Q-switching shown in (a) as indicated by the arrows. Traces have been offset for clarity, i.e. the dotted lines represent the respective 0-levels.

Conclusions

For the first time passive mode-locking in two-section QD-lasers operating around $1.55 \mu\text{m}$ is observed. The 4.6 GHz output pulses are elongated and heavily up-chirped. The optical bandwidth is broad, i.e. 6 – 7 nm, and shown to be coherent over its full range.

Our results indicate that the dynamics in these lasers are significantly different from their bulk and quantum-well counterparts and also from those published for $1.3 \mu\text{m}$ InAs/GaAs QD-lasers. The origin of the observed dynamics of the lasers presented here is not understood yet. Most probably the laser behavior is related to the not well-known dynamics governed by the energy level structure and spectral inhomogeneous aspects in the $1.55 \mu\text{m}$ QD gain material.

Also large regimes of Q-switching have been observed in a 7-mm device, having a longer SA length and a higher SA bias voltage.

The 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, and applications like an integrated O-CDMA encoder become possible.

This work was supported by the Netherlands Foundation of Scientific Research (NWO), the Dutch Technology Foundation STW through a Valorization Grant, and by the Dutch Ministry of Economic Affairs through the NRC Photonics Grant and the “Towards Freeband Communication Impulse” technology program.

References

- [1] C. Ji et al., *IEEE J. of Sel. Top. Quant. Electron.*, vol. 11 (2005), pp. 66-77.
- [2] R. Kaiser and B. Hüttl, *IEEE J. of Sel. Top. Quant. Electr.* vol. 13 (2007), pp. 125-135.
- [3] Y. Barbarin et al., *Optics Express*, vol. 14 (2006), pp. 9716-9727.
- [4] E.U. Rafailov et al., *Appl. Phys. Lett.*, vol. 87 (2005), 081107.
- [5] S. Anantathanasarn et al., *Appl. Phys. Lett.*, vol. 89 (2006), 073115.
- [6] E.A. Viktorov et al., *Conference on Lasers and Electro-optics Europe, CLEO (2007)*, paper IG6.