Quantum-dot external-cavity passively mode-locked laser with high peak power and pulse energy

Y. Ding, D. I. Nikitichev, I. Krestnikov, D. Livshits, M. A. Cataluna and E. U. Rafailov

Abstract: An InAs quantum-dot external-cavity passively mode-locked laser with an operation wavelength of 1.27 μm is demonstrated, based on a two-section quantum-dot superluminescent diode with bending ridge waveguide and a 96% output coupler. Stable mode-locking with an average power up to 60 mW was obtained at a repetition frequency of 2.4 GHz. This performance corresponds to a 25-pJ pulse energy obtained directly from the oscillator, which represents a 55-fold increase in the pulse energy when compared to the current state-of-the-art for semiconductor lasers. At a repetition frequency of 1.14 GHz, picosecond optical pulses with 1.5-W peak power are also demonstrated, representing the highest peak power achieved from an external-cavity laser at the 1.3 μm waveband, without the use of any pulse compression or optical amplification.

Introduction: High-power, electrically-pumped mode-locked semiconductor lasers generating picosecond pulse trains have been regarded as potentially suitable for a wide variety of applications, such as optical clocking, telecommunications, nonlinear optics and biomedical applications [1-3].

Mode-locked lasers based on quantum-dot (QD) materials present a number of significant advantages such as ultrafast absorption recovery, broad gain bandwidth and low threshold current density. This latter characteristic, together with low optical losses, enables the fabrication of long-cavity and extremely high wall-plug efficiency lasers [4-6].

External-cavity configurations are usually used to decrease the repetition rate beyond the limits of what is achievable with monolithic mode-locked lasers [7-9]. Furthermore, tunable operation [2, 10] or appropriate dispersion compensation for pulse narrowing may be implemented in the external-cavity configuration by the introduction of appropriate optical elements [8].

A quantum-dot external-cavity passively mode-locked laser (QD-ECMLL) at 1.27 μm was demonstrated for the first time in [7], with a repetition frequency of 5 GHz. A peak power of 1.22 W (and pulse energy of 1.46 pJ) was demonstrated after optical amplification and pulse compression of the pulses generated by the external-cavity laser oscillator [7]. In our previous report [9], repetition rates from 350 MHz to 1.5 GHz, with average output power of up to 27 mW (860 MHz) at 1.2 μm were achieved by external-cavity quantum-dot lasers incorporating a separate quantum-dot semiconductor saturable absorber mirrors (SESAMs). In a more recent investigation [8], external-cavity mode-locking of a quantum-dot laser is demonstrated with record-low repetition-rates of 310MHz, albeit with a modest pulse-energy of ~0.45 pJ (which was shown to be independent of the repetition rate). The highest peak power achieved after intra-cavity pulse compression was 0.41W [8].

In this letter, we demonstrate a high-peak-power 1.27-μm QD-ECMLL without the use of any pulse compression and optical amplifier. Optimal pulse performance was observed at a repetition frequency of 1.14 GHz (~13-cm total optical cavity length), resulting in an average power of 23.2 mW and peak power of 1.5 W with a pulse duration of 13.6 ps. This represents the highest peak power achieved for 1.3-μm waveband ECMLLs. Stable mode-locking with an average power up to 60 mW was also obtained at a repetition frequency of 2.4 GHz, which corresponded to a 25-pJ pulse energy - a 55-fold increase in the pulse energy when compared to the demonstration in [8].

Experimental results: The QD chips were grown by molecular beam expitaxy (MBE) on an n^+-GaAs (100) substrate which contained 10 layers of self-assembled InAs/GaAs quantum dots. The two-section superluminescent diode (SLD) chip used for this study consists of a gain section and a saturable absorber section. The waveguide in gain section is bended and terminated at an angle of 7° relative to the cleaved facet, in combination with antireflection (AR) coating (R~10^{-5}), to minimize the back reflection from the front facet. The back facet was high-reflection (HR) coated with a reflectivity of about 95%. The total chip length is 4 mm with a 600-μm-long saturable absorber (SA) section (15% SA to length ratio). The chip was kept at 20 °C using thermoelectric cooler control. The thermal rollover was not observed even at an injection current of 500 mA. An output coupler (OC) of 96% transmissivity was used for external cavity facet. A collimating aspherical lens with a numerical aperture of 0.55 was used to couple light to and from the chip. The inclusion of an intra-waveguide saturable absorber in this work as opposed to the SESAM configuration previously demonstrated in [9] imparts more robustness and ease of alignment to the laser cavity. The output beam was focused onto a single-mode fibre splitter and input autocorrelator, radio-frequency (RF) spectrum analyzer and optical spectrum analyzer for measurements. The simplified optical scheme is shown in Fig. 1.

Light-current (*L-I*) characteristics of SLD chip without external feedback and of the external-cavity laser (~13-cm total optical cavity length) with reverse-bias of 0 V and 7.2 V on the absorber are shown in Fig. 2. Superluminescent power of 17.2 mW was obtained at a forward current of 500 mA applied on the gain section. The secondary-derivation curve of SLD shows a negligible peak, which hints an effective suppression of back reflection.

For the external-cavity laser, strong hysteresis was observed for 7.2-V reverse bias (hysteresis loop of 45 mA width), which indicates the non-linear saturation of the QD absorber section. The inset in Fig. 2(b) shows the 6.4-ps pulse generated under 7.2-V reverse bias and 315-mA forward current where just the bifurcation point of hysteresis is. Probably for this reason, the repetition frequency was fixed at 5th order harmonic (5.7 GHz) with a good stability, instead of fundamental mode. Nevertheless, it is important to refer that the fundamental mode at 1.14GHz and its harmonics could still be observed as well, albeit with lower signal-to-noise ratio than the 5th harmonic, indicating the coexistence of fundamental and harmonic mode-locking at this point. Such tendency for shifting from a fundamental to a harmonic mode-locking regime has also been previously observed and modelled [8, 11].

Under a forward bias current of 500mA, a continuous wave (CW) output power of nearly 100 mW was attained with an applied reverse bias of 0 V, while for mode-locked operation under a 7.2 V reverse bias, an average power of about 35 mW was achieved. It should be noted that in this *L-I* curve, not all the represented different points for the average power under mode-locked operation correspond to the optimum fundamental mode-locking conditions, and therefore, a mixture of fundamental mode-locking and high-order harmonic mode-locking may be existent, particularly for higher injection current. The higher forward bias in the gain section leads to an earlier and more complete gain recovery time, which in combination with the relatively long pulse roundtrip time in the long cavity, could lead to the appearance of multiple pulses in a wider net gain window. In fact, the superlinear behaviour of the *L-I* curve for 7.2-V reverse bias above 375 mA in Fig. 2(b) is indicative of the increasing proportion of higher-order harmonic modes, given that the average power is proportional to the pulse repetition rate. In order to investigate the pulse characteristics at higher current levels, the external cavity laser alignment was optimised for each operating point in order to achieve robust fundamental mode-locking – at the expense, however, of a drop in average power of the order of a few mW. For gain current values equal and above 330 mA, robust fundamental mode-locking was achieved after optical feedback adjustment, with the corresponding RF peak exhibiting a signal-to-noise-ratio in excess of 50 dB.

In Figure 3, the autocorrelation, optical and RF spectra are represented for the 13.6-ps pulse generated under 7.2-V reverse bias and 457-mA forward current. Under these operating conditions, 1.5-W peak power and 23.2-mW average power were achieved, for a 1.14-GHz repetition frequency, corresponding to 20.4-pJ pulse energy. Time-bandwidth product (TBP) of 3.02 can be calculated taking into account the mode-locking lasing wavelength of 1274 nm with 1.2-nm full width at half maximum (FWHM). Remarkably, a minimum TBP of 1.01, only 2.3 times the Fourier limit, was obtained under 7.2-V reverse bias and 330-mA forward current with a pulse duration of 8.4 ps.

In Figure 4, the dependence of the peak power, average power, and pulse duration with forward current is depicted, for a fixed reverse bias of 7.2 V, and under the fundamental mode-locking conditions. As shown in Figure 4, both the pulse duration and average power increased with increasing gain current. On the other hand, the peak power changes little even if under a high drive current.

While reducing the reverse bias to values as low as 1.4 V, stable mode-locking could still be observed. An average power up to 60 mW (corresponding to 25-pJ pulse energy) was obtained at a repetition frequency of 2.4 GHz with 1.4-V reverse bias and 375-mA forward current - however, for these operating conditions, a broad pulse with 44-ps duration (not shown here) was generated. For different external cavity lengths, the average power was found to be approximately proportional to the repetition frequency. The constant pulse energy required to saturate the absorber is independent of repetition rate under certain operation conditions, which is consistent with the conclusions from [8].

Conclusions: Electrically pumped 1.27-µm QD-ECMLL with peak power of 1.5 W and average power of 23.2 mW at a repetition frequency of 1.14 GHz are achieved without the use of any pulse compression and optical amplifier. Stable mode-locking with an average power up to 60 mW, corresponding to 25-pJ pulse energy was also obtained at a repetition frequency of 2.4 GHz. The minimum TBP of 1.01 was obtained with the pulse duration of 8.4 ps.

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References

1 Kuramoto, M., Kitajima, N., Guo, H., Furushima, Y., Ikeda, M., Yokoyama, H.: “Two-photon fluorescence bioimaging with an all-semiconductor laser picoseconds pulse source,” *Optics Lett.,* 2007*,* **32**, 2726

2 Kim, J., Delfyett, P.J.: “Interband optical pulse injection locking of quantum dot mode-locked semiconductor laser”, Optics Express, 2008, **16**, 11153

3 Thompson, M. G., Rae, A., Xia, M., Penty, R. V., and White, I. H.: “InGaAs Quantum-Dot mode-locked laser diodes,” *IEEE J. Sel.Top. Quantum Electron.*, 2009, **15**, 661-672

4 Rafailov, E.U., Cataluna, M. A., and Sibbett, W.: “Mode-locked quantum-dot lasers”, *Nature Photonics*, 2007, **1**, pp 395-401

5 Huang, X.D., Stintz, A., Li, H., Lester, L.F., Cheng, J., Malloy, K.J.: “Passive mode-locking in 1.3 µm two-section InAs quantum dot lasers”, *Appl. Phys. Lett.*, 2001, **78**, 2825-2827

6 Gubenko, A., Livshits, D., Krestnikov, I., Mikhrin, S., Kozhukhov, A., Kovsh, A., Ledentsov, N., Zhukov, A., Portnoi, E.: "High-power monolithic passively modelocked quantum-dot laser", *Electron. Lett.*, 2005, **41**, pp 1124-1125

7 Choi, M.T., Lee, W., Kim, J.M., Delfyett, P.J.: "Ultrashort, high-power pulse generation from a master oscillator power amplifier based on external cavity mode locking of a quantum-dot two-section diode laser", *Appl. Phys. Lett.*, 2005, **87**, 221107

8 Xia, M., Thompson, M.G., Penty, R.V., White, I.H.: "External-Cavity Mode-Locked Quantum-Dot Lasers for Low Repetition Rate, Sub-Picosecond Pulse Generation", *2008 CLEO/QELS*, 2008, **1-9**, pp: 1137-1138

9 McRobbie, A.D., Cataluna, M.A., Zolotovskaya, S.A., Livshits, D.A., Sibbett, W., Rafailov, E.U.: "High power all-quantum-dot-based external cavity modelocked laser", *Electron. Lett.*, 2007, **43**, pp 812-813

10 Kim, J., Choi, M., and Delfyett, P.J. : "Pulse generation and compression via ground and excited states from a grating coupled passively mode-locked quantum dot two-section diode laser", *Appl. Phys. Lett.*, 2006, **89**, 261106

11 Viktorov, E. A., Mandel, P., Kuntz, M., Fiol, G., Bimberg, D., Vladimirov, A. G. and Wolfrum, M.: "Stability of the mode-locked regime in quantum dot lasers", *Appl. Phys. Lett.*, 2007, **91**, 231116

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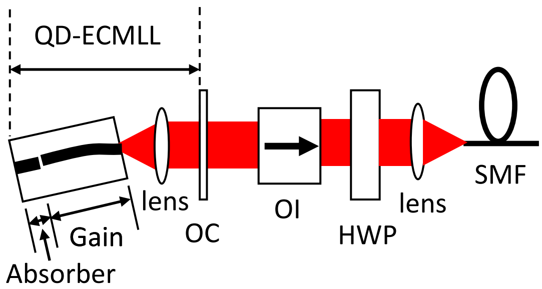
Figure captions

Fig. 1 Configuration of an QD-ECMLL and the experimental setup. OC: output coupler (R=4%); OI: optical isolator; HWP: half wave plate; SMF: single-mode fiber.

Fig. 2 Light-current characteristics of SLD chip without external feedback (a); and the external-cavity laser for 0-V and 7.2-V reverse-bias (b). Inset: 6.4-ps pulse recorded at a reverse bias of 7.2 V and forward current of 315 mA.

Fig. 3 Autocorrelation trace, optical spectrum, RF spectrum with 500-MHz span and 10-GHz span at reverse bias of 7.2 V and forward current of 457 mA.

Fig. 4 Peak power, average power and pulse duration versus forward current with 7.2-V reverse bias.



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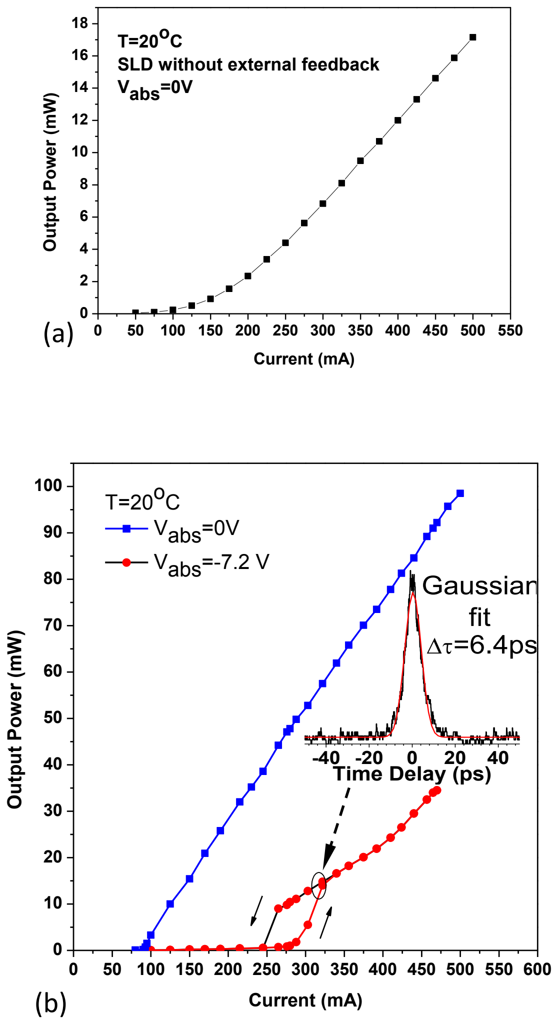

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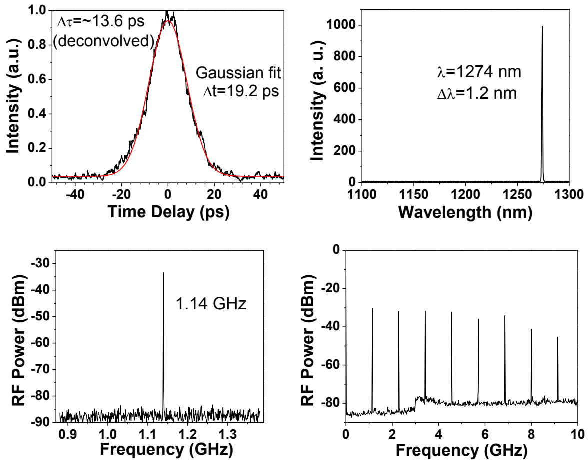

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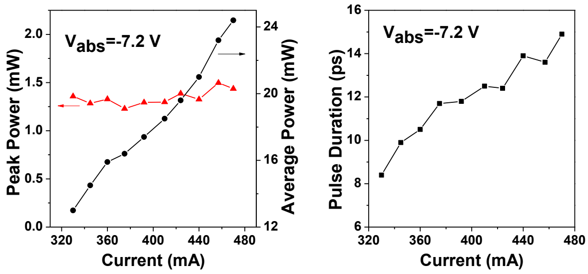

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