AIP Applied Physics Letters

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Citation: Applied Physics Letters **101**, 121107 (2012); doi: 10.1063/1.4751034
View online: http://dx.doi.org/10.1063/1.4751034
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/101/12?ver=pdfcov
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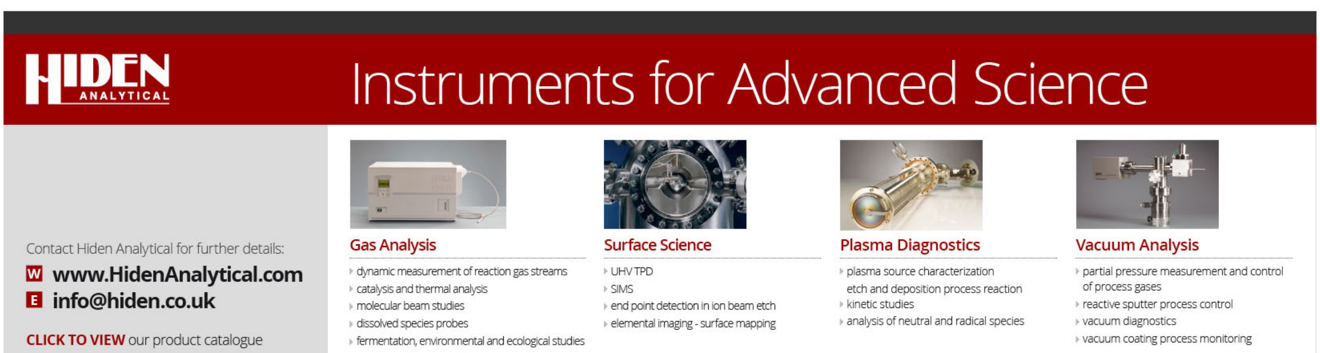

Broad wavelength tunability from external cavity quantum-dot mode-locked laser

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(Received 15 May 2012; accepted 23 August 2012; published online 18 September 2012)

Broadband wavelength tunability over 136 nm (between 1182.5 nm and 1319 nm) of picosecond pulses in passive mode-locked regime is demonstrated in a multi-section quantum-dot laser in external cavity configuration at room temperature. The maximum peak power of 870 mW with 15 ps pulse duration was achieved at 1226 nm wavelength. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4751034]

In recent years, quantum dot based mode-locked lasers have shown great development as next generation of compact ultrashort pulses sources due to the discrete nature of the density of states.[1] Modern technologies of quantum-dot (QD) growth enable a high degree of control over the emission spectrum of QD devices, which can be tailored for different applications, such as a broadly tunable laser.[2–8] For example, monolithic multi-section lasers incorporating 5 QD layers have shown the wavelength tunability from 1004.3 nm to 1029.1 nm, controlled by different injection currents to the multiple sections.[3] The chirped multiple QD based mode-locked monolithic lasers have recently demonstrated electronically controlled 45 nm wavelength sweep range.[7] Alternatively, external-cavity diode lasers incorporating multiple chirped QD layers and bent waveguide have been also demonstrated impressive tunability ranges (up to 202 nm) with nearly 500 mW maximum output power under continuous-wave operation.[2] In this context, grating coupled 10 QD-layer passive mode-locked laser demonstrated a continuous optical spectra tuning range of 30 nm-50.5 nm from ground-state and excited-state passive mode-locking, respectively.[9] In this paper, we present 136.5 nm wavelength tunability between 1182.5 nm and 1319 nm in mode-locked regime from a curved two-section QD laser. The maximum peak power of 870 mW was achieved at 1226 nm wavelength at room temperature. The presented work demonstrates significant improvement in mode-locked devices by offering a broad spectral tuning, which is of great interest for many applications ranging from biophotonics[10] and medicine[11] to telecommunication[12,13] and material processing.[14]

The investigated two-section laser with a ridge-waveguide structure was fabricated from a QD wafer whose active region consists of 10 non-identical InAs QD layers grown on GaAs substrate by molecular beam epitaxy. They were covered by non-identical InGaAs capping layers, incorporated into $Al_{0.35}Ga_{0.65}As$ cladding layers as fully explained in Ref. 2. These 10 layers were made up of 3 groups of QDs with different photoluminescence peak positions (at 1211 nm, 1243 nm, and 1285 nm). As a result of this QD structure design, continuous wavelength tuning between the ground and excited-state optical transitions of the different QD groups was demonstrated.

The QD device had a total length of 4 mm and a ridge waveguide width of 6 μm with 7° tilting from the normal direction of the cleaved facet in order to decrease reflectivity. AR coatings for the rear and front facets are $\sim 10^{-5}$ (angled facet) and 10^{-2}, respectively. The laser operated in external cavity configuration similar to Ref. 15. A reverse bias was applied to the section placed nearer to the back facet, thus forming a distributed saturable absorber with a total length of 800 μm (4:1 gain/absorber length ratio), while the gain section was forward-biased. The chosen external cavity length of 18.9 cm resulted in a fundamental mode-locking at 740 MHz. A diffraction grating with 1200 grooves/mm was used to provide the first order diffraction beam back to the laser. Such configuration in combination with the chirped QD structure grown on a GaAs substrate by molecular beam epitaxy allowed us to achieve a broad wavelength tuning range. The laser was kept at 20 °C by a Peltier cooler. The experimental setup is presented in Fig. 1. The pulse duration was measured by a non-collinear autocorrelator based on second-harmonic generation (Femtochrome FR103XL/IR). The mode-locking performance was further investigated with an RF spectrum analyzer (Rohde & Schwarz RSP FSP-40) in combination with a high-speed 29 GHz photodiode.

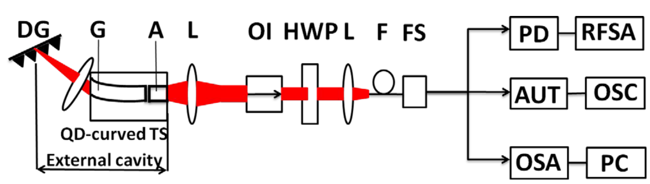

FIG. 1. Experimental setup for a passive mode-locked external cavity quantum dot (QD) curved two-section (TS) diode laser. DG: Diffractive grating, A: absorber section, G: gain section, L: lens, OI: optical isolator, HWP: haft wave plate, F: fibre, FS: fibre splitter, PD: photo diode, RFSA: RF spectrum analyzer, AUT: autocorrelator, OSC: oscilloscope, OSA: optical spectrum analyzer, PC: personal computer.

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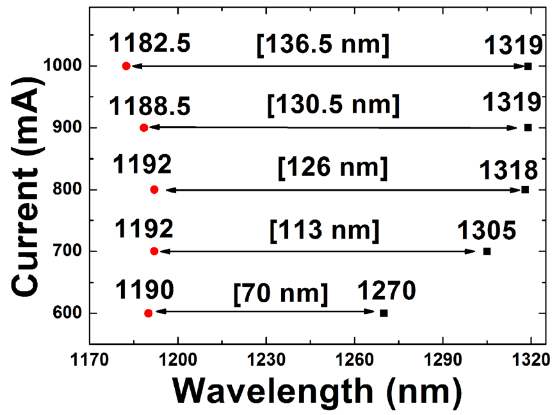

FIG. 2. Wavelength tuning range in mode-locked regime is presented for different applied gain current and 3 V reverse bias. The highest tuning range of 136.5 nm is achieved for gain current of 1 A.

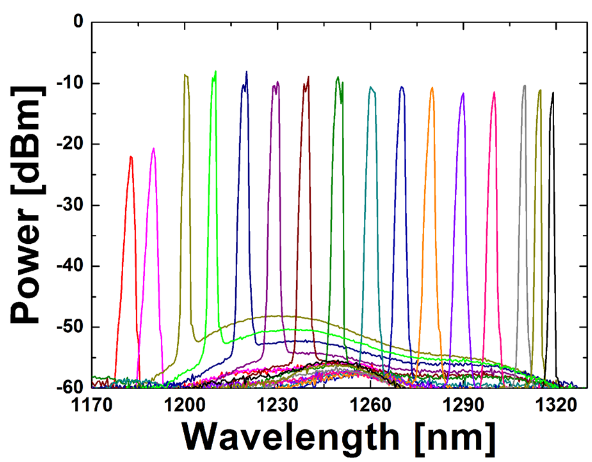

FIG. 3. Wavelength tunability in mode-locked regime from 1182.5 nm to 1319 nm at 3 V reverse bias and 1 A gain current.

The spectral characteristics were measured with an optical spectrum analyser (Advantest Q8383).

Broad wavelength tunability in mode-locked regime was achieved under varieties of bias condition: the gain current from 500 mA to 1 A and reverse bias from 1 V to 5 V by tuning the incidence angle of the grating. The highest wavelength tuning range of 136.5 nm from 1182.5 nm to 1319 nm was observed for gain current of 1 A and reverse bias of 3 V (Fig. 2). It is very important to stress that the lasing wavelength of 1319 nm is the longest lasing wavelength reported until now from a tunable mode-locked GaAs-based QD laser. Moreover, it should be emphasised that we observe a continuous wavelength tuning of over 136 nm due to non-identical QD layers structure in comparison to Ref. 9 where optical spectra tuning was achieved for ground-state from ~1265 nm to ~1295 nm and for excited-state from ~1170 to ~ 1220 nm.[9] As can be seen in Fig. 2, the tunability range in mode-locked operation was extended from 70 nm to 136.5 nm by increasing the gain current from 600 mA to 1 A under constant 3 V reverse bias. Optical spectra for broadest tuning regime for gain current of 1 A and reverse bias of 3 V are presented in Fig. 3.

Peak power and pulse duration dynamics for the laser output tuned across the 1182.5–1319 nm wavelength range under an applied constant current of 900 mA and reverse bias of 3 V are shown in Figs. 4(a) and 4(b). The pulse duration varied between 12.8 ps and 39 ps across the tuning range under a constant bias condition. The highest peak power of 532 mW was demonstrated at 1226 nm wavelength for such bias conditions (Fig. 4(a)). The autocorrelation trace presented in the inset of Fig. 4(b) corresponds to 21.7 ps Gaussian fitting pulse shape, which results in the deconvolved pulse duration of 15.3 ps achieved for 1226 nm wavelength. From the corresponding optical spectra, an effective spectral width of ~1 nm was determined and demonstrated a resulting time-bandwidth product of 3, suggesting that the pulses were still highly chirped.

Furthermore, pulse duration and peak power dynamics for fixed 1226 nm wavelength were investigated in more details, as depicted in Fig. 5. For a reverse bias applied to the absorber section changed between 3 V and 5 V and a gain current changed between 500 mA and 1 A. With the increased reverse bias applied to the absorber section the pulse duration become shorter which is well known effect due to a decrease in the relaxation time with increasing reverse bias.[16] The highest peak power of 870 mW was

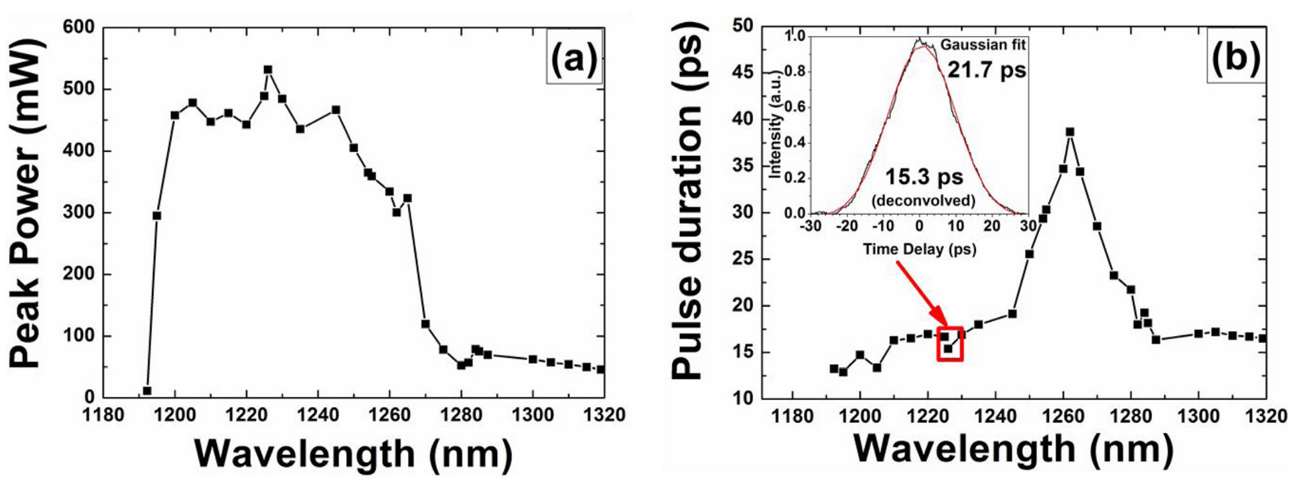

FIG. 4. (a) Dependence of peak power and (b) pulse duration with the emission wavelength in mode-locked regime for gain current of 900 mA and reverse bias of 3 V, inset: autocorrelation trace for 1226 nm.

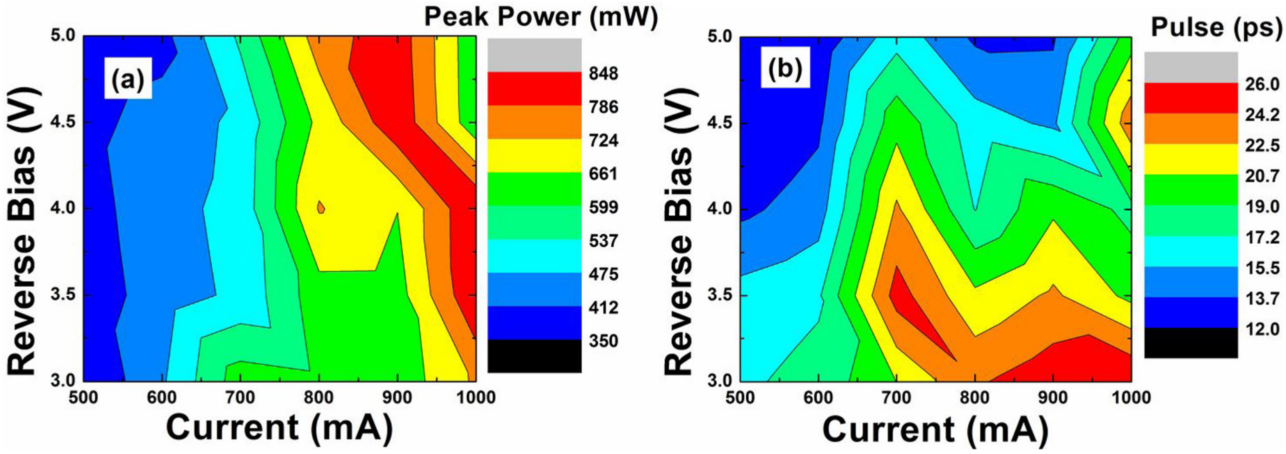

FIG. 5. (a) Dependence of peak power and (b) pulse duration with different bias conditions for 1226 nm wavelength. The highest peak power of 870 mW was achieved for current of 1 A and reverse bias of 4 V.

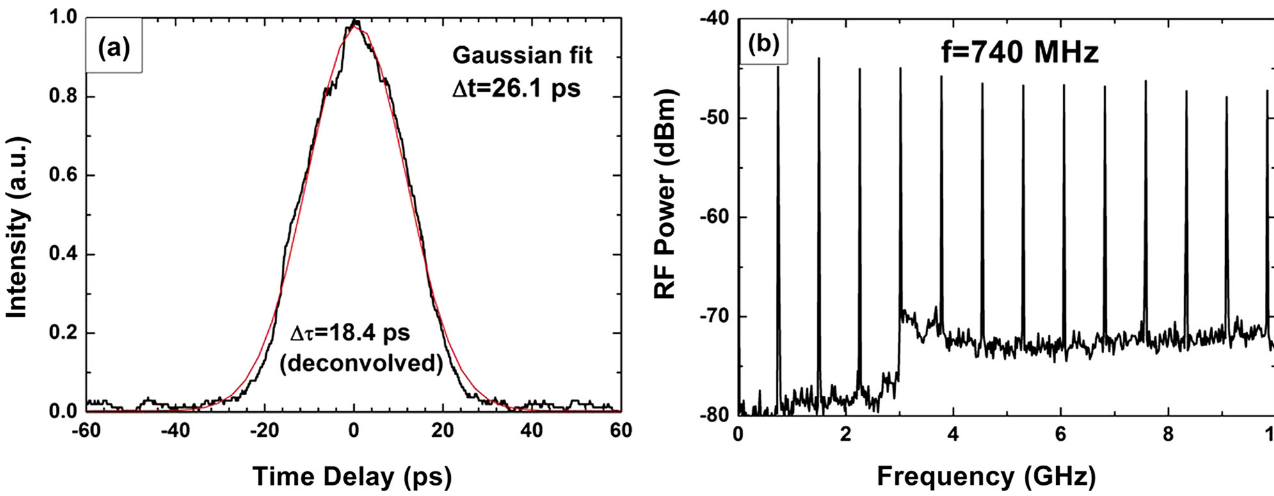

FIG. 6. (a) A measured autocorrelation trace (black) and Gaussian fitting (red) pulse shape of 26.1 ps resulting in deconvolved pulse duration of 18.4 ps. (b) RF spectrum for highest peak power regime at −4.5 V reverse bias and 1 A gain current for fundamental mode-locking regime of ∼740 MHz.

observed for 4 V and 1 A (grey region in Fig. 5(a)). As can be seen from Fig. 5(a), high peak power can be achieved with high forward current and relatively low reverse bias. Autocorrelation and RF spectrum are presented for this regime in Fig. 6. A measured Gaussian fitting pulse shape was 26.1 ps results in deconvolved pulse duration of 18.4 ps at a fundamental frequency of 740 MHz (Fig. 6(a)).

The large number of harmonics in the RF spectrum indicates the high quality of mode-locking as shown in Fig. 6(b). Time-bandwidth product of 4.4 for this regime was estimated using a 1.2 nm spectral width.

We observed stable fundamental mode-locking and harmonic mode-locking depending on the optical feedback. For sustaining a stable fundamental mode-locking, the high order harmonic mode-locking should be suppressed by low net gain which can be achieved by optimizing the optical feedback. The photocurrent in the absorber should be kept at 10-20 mA as was noted in the past.[15] Otherwise the harmonic mode-locking was achieved with the photocurrent up to 120 mA. An increase of optical feedback leads to an earlier and more complete gain recovery time, which in combination with the relatively long pulse roundtrip time leads to the appearance of harmonic mode-locking.

We demonstrated a broad (136.5 nm) wavelength tunability in a passive mode-locked regime from a multi-section QD laser in external cavity configuration, operating in the spectral range of 1182.5 nm–1319 nm. The pulse duration varied from 12.8 ps to 39 ps while the maximum peak power up to 870 mW was observed at 1226 nm wavelengths. Demonstrated tunable laser generating picosecond pulses represents a promising achievement for the development of a compact and low-cost room-temperature source which can be effectively used for varieties of applications including optical coherent tomography and generation of tunable visible light by second harmonic generation.[17]

The authors wish to acknowledge financial support from the EU FP7 programme through the FAST-DOT project (Contract No. 224338).

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