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Low repetition rate and broad frequency tuning from a grating-coupled passively mode-locked quantum dot laser

H. C. Cheng,[a)] Q. Y. Wu, C. H. Pan, C. P. Lee, and G. Lin
Department of Electronics Engineering and Institute of Electronics, National Chiao-Tung University, 1001 University Road, Hsinchu 30010, Taiwan

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Passively mode-locked quantum dot lasers with a grating-coupled external cavity arrangement are investigated. A broad repetition-rate tuning range of fundamental mode-locking from 2 GHz to a record-low frequency of 79.3 MHz is achieved with selecting the wavelength at 1.28 μm. A narrow RF linewidth of ~25 Hz and an intrinsic linewidth as low as 0.15 Hz are also obtained. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4833025]

Mode-locked semiconductor lasers are routinely used to generate picosecond or sub-picosecond optical pulses.[1] In the recent decade, much attention was given to semiconductor lasers with quantum dots (QD) active media because of their unique properties such as the delta function like density of states, fast carrier dynamics, low threshold current, low noise, and potential low wavelength chirp.[2] Sub-picosecond pulses with low phase noise and timing jitter at repetition rates from GHz to hundreds of GHz have been demonstrated for monolithic mode-locked QD lasers.[3] While most of these mode-locked signals are operated at very high frequencies, mode-locked lasers that are capable to work at low frequencies are also of interest for nonlinear imaging and bio-photonics applications.[4,5] With an external cavity, passively mode-locked semiconductor lasers with pulse repetition rates down to the hundreds of MHz range have been reported. The external cavity configuration offers advantages such as convenient tuning of wavelength and repetition rate and intra-cavity dispersion compensation. However, due to the short carrier lifetime (~1 ns),[6] it is very difficult for a passively mode-locked QD laser to generate pulses with a repetition rate below 1 GHz. When the cavity round-trip time is longer than the carrier lifetime, amplified spontaneous emission could build up and lead to instabilities or harmonic mode-locking (multiple-pulse circulating in the cavity).[7] In recent investigations, external cavity passively mode-locked QD lasers with repetition rates of 310 MHz and 191 MHz have been demonstrated,[7,8] and a very narrow radio-frequency (RF) linewidth of ~30 Hz was obtained. In this paper, with the use of a low threshold QD laser within a grating-coupled external cavity arrangement, we demonstrate passive mode-locking with a record-low repetition rate of 79.3 MHz.

The QD laser sample used in this work was grown on an (001) n^+-GaAs substrate by a Veeco Gen II molecular beam epitaxy system. The active region consisted of five InAs-QD layers. They were placed in the center of a 520 nm-thick GaAs waveguide, which was sandwiched between two 1.4 μm-thick $Al_{0.4}Ga_{0.6}As$ cladding layers. Each QD layer was capped with a 4 nm-thick $In_{0.15}Ga_{0.85}As$ strain-reducing layer and separated by a 45 nm-thick GaAs spacer. The dot density was around $2 \times 10^{10}/cm^2$. The chip was then fabricated into two-section superluminescent diodes with a J-shape structure, where the waveguide in the gain section was bent and terminated at an angle of 7°. The device had a 5-μm-wide and dry-etched ridge waveguide with a total chip length of 2.5 mm and an absorber-to-gain length ratio of 1:7. The facet at the gain-section side was antireflection coated, and light was coupled to a 1200 grooves/mm diffraction grating by using an aspherical lens, which had a numerical aperture as high as 0.68. The mirror at the absorber side was formed by cleavage without any coating. The arrangement of the external-cavity mode-locked laser is shown in Fig. 1.

In this experiment, the operating wavelength was 1280 nm, which was selected by the first order diffraction of the grating. The repetition rate of the mode locked pulses was tuned by adjusting the cavity length. For low frequency operations, when very long cavities (>1 m) were needed, a mirror was inserted in the optical path for easy adjustment of the cavity length. The device was kept at 20 °C by using a thermoelectric cooler. The threshold current density was smaller than 150 A/cm^2 for all the cavity lengths. The output light from the absorber side was collected and analyzed.

In our setup, the frequency of the mode-locked pulses was continuously tunable. The operation region of the fundamental mode-locking relative to the biasing condition became narrower when the cavity length increased. Nevertheless, a continuous tuning for stable mode-locking from 79.3 MHz to 2 GHz was achieved. The corresponding

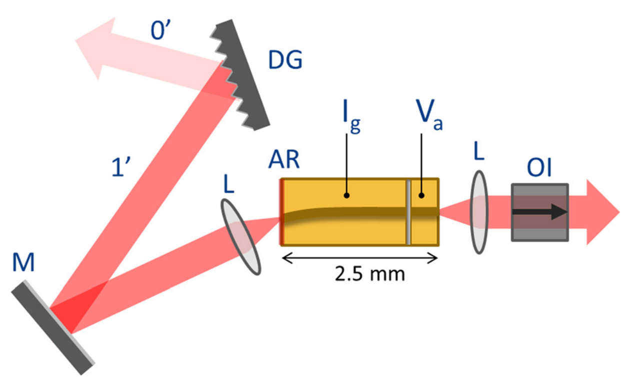

FIG. 1. The arrangement of the external-cavity passively mode-locked QD laser (DG: diffraction grating, AR: antireflection coating, L: lens, M: mirror, OI: optical isolator).

a)Electronic mail: u890851@alumni.nthu.edu.tw

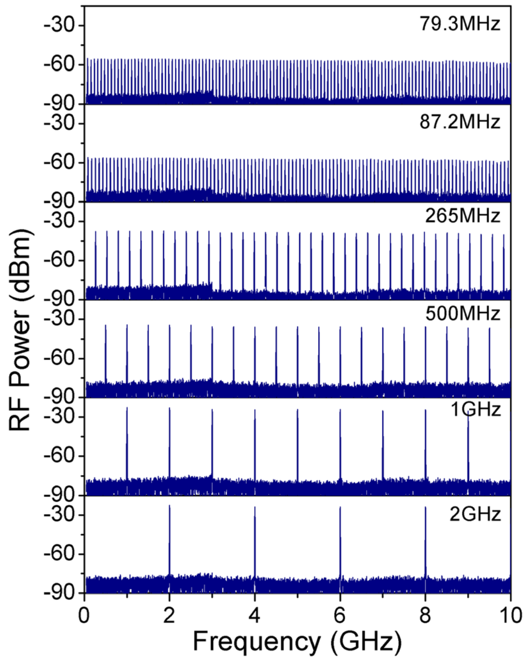

FIG. 2. RF spectra of the photocurrent of the mode-locked laser with the repetition frequency varied from 79.3 MHz to 2 GHz. The operation condition is 55 mA and −3 V for all the frequencies.

external cavity length was from 188 cm to 6.6 cm. The RF spectra of the mode-locked signals at six different repetition rates are shown in Fig. 2. Throughout the tuning operation, the device was kept at an identical bias condition, which was 55 mA for the gain current and −3 V for the absorber bias. The spectra were displayed with a 10-GHz span. The uniform and large number of harmonics in the RF spectrum indicates the high quality of mode-locking operation throughout the tuning range. The repetition frequency of 79.3 MHz is the lowest repetition rate achieved to date for any passively mode-locked semiconductor laser. It corresponds to a cavity's roundtrip time of 12.6 ns, which is more than ten times the typical carrier lifetime in semiconductor QDs.[6]

The corresponding optical spectra at various repetition frequencies are shown in Fig. 3, and the inset shows the spectra at a smaller wavelength span but with a higher resolution of 0.05 nm. The lasing wavelength, selected by the diffraction grating, was centered at 1280 nm. The spontaneous emission background is about the same for all spectra, but the output power is proportional to the repetition rate, which agrees with what has been reported before.[7,8] The full width at half maximum (FWHM) of the optical spectrum is around 0.176 nm, which is about the same for all repetition rates at the operation condition of 55 mA and −3 V. The FWHM of the optical spectrum corresponds to a bandwidth around 32 GHz which limits the minimum pulse width of around 10 ps for a squared hyperbolic secant ($sech^2$) shape pulse.

We have studied the repetition-rate tuning for different center wavelengths. The broadest tuning range was obtained at 1280 nm, which corresponds to the point that the laser had the lowest threshold current and the spontaneous emission was minimized. Because of the use of a diffraction grating, only a small portion of spontaneous emission can be coupled back to the active medium. So, the instability induced by

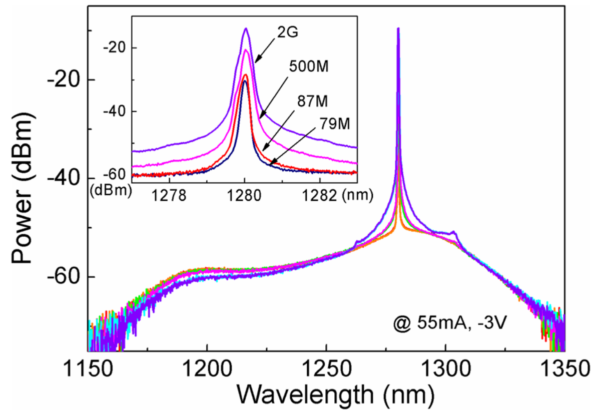

FIG. 3. Optical spectra of the mode-locked laser with the fundamental repetition frequency varied from 79.3 MHz to 2 GHz. Inset: optical spectra with a small span and a resolution of 0.05 nm (the FWHMs are 0.176, 0.176, 0.176, and 0.174 nm for the repetition rates of 79.3 MHz, 87 MHz, 500 MHz, and 2 GHz, respectively).

amplified spontaneous emission is minimized, and stable mode-locking with wide tuning range can be achieved.

A background-free intensity autocorrelator (Femtochrome, FR-103XL) was used to measure the pulse width of the mode-locked laser. Figure 4 shows the autocorrelation traces and the $sech^2$-fitting curves. The external cavity length was fixed at 171 cm, which corresponds to a fundamental repetition frequency of 87.2 MHz. The laser was then operated at a fixed gain current of 55 mA while the absorber bias varied from −0.5 V to −3 V. Two groups of traces can be clearly seen in the figure. It is due to a switching from the harmonic mode-locking (the upper group) to the fundamental mode-locking (the lower group) when the reverse bias increases. So the traces of upper group were obtained from pulses that had repetition frequencies multiples of the fundamental frequency. It should be noted that when the laser is mode-locked at the fundamental frequency of 87.2 MHz (the lower group), the average output power is only around 25 μW which is very low and was obtained with careful measurement. The occurrence of the harmonic mode-locking could lead to higher signal intensity on the autocorrelator because the higher integrated intensity for

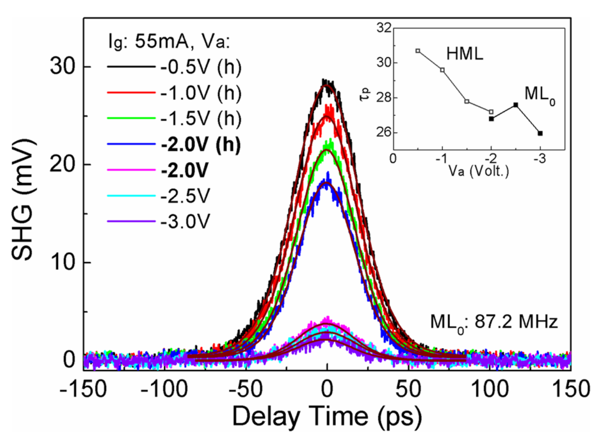

FIG. 4. Autocorrelation traces of the mode-locked pulses with the absorber bias varied from −0.5 V to −3 V. The fundamental repetition frequency is 87.2 MHz. Inset: the $sech^2$-fitted pulse width as a function of the absorber bias.

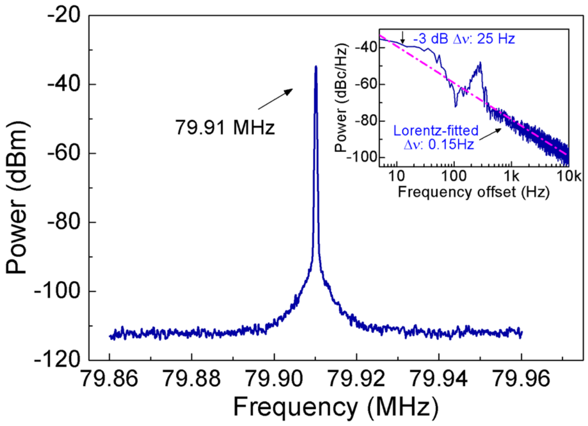

FIG. 5. RF spectrum of the pulses with a repetition rate of 79.91 MHz (RBW: 300 Hz, VBW: 30 Hz). Inset: single-sideband phase noise spectrum with a Lorentz-fitted curve (RBW: 10 Hz, VBW: 3 Hz).

the higher repetition rate even when the pulse peak power is similar. Bistability between the fundamental and the harmonic mode-locking was observed at an absorber bias of −2 V, but there is no significant change in the pulse width for them. The fitted pulse width as a function of the absorber bias is shown in the inset, and the minimum pulse width is around 26 ps at −3 V.

Mode-locked QD lasers have been regarded as low-noise sources owing to the low optical confinement factor and reduced amplified spontaneous emission.[9,10] Because only a very small portion of the optical cavity is occupied by the active medium, external-cavity mode-locked lasers also potentially have lower phase noise and timing jitter compared to monolithic mode-locked lasers if the mechanical instability can be minimized.[11] In this work, the quantum dot lasers used had low threshold currents. So by putting these lasers in the grating coupled external cavity configuration, the influence of spontaneous emission, which is one of the major sources of the phase noise, could be significantly reduced. Fig. 5 shows the RF spectrum of the first harmonic with a repetition-frequency of 79.91 MHz. A large dynamic contrast can be observed. To investigate the RF linewidth, a higher resolution of the spectrum analyzer with a resolution bandwidth (RBW) of 10 Hz and a video bandwidth (VBW) of 3 Hz was used. The inset shows the single-sideband phase noise spectrum with the frequency axis offset by the carrier frequency. The typical −20 dBc/Hz per decade roll-off is observed. With a Lorentz-fitting in this range, the intrinsic phase noise could lead to a RF linewidth as low as 0.15 Hz. However, mechanical instability of the setup dominated the noise in this experiment and broadened the −3 dB linewidth to ∼25 Hz. Nevertheless, the RF linewidth is still very small. With reduced mechanical instabilities, a further reduction of the RF linewidth would be expected.

In conclusion, we have investigated the repetition-rate tunable grating-coupled external-cavity passively mode-locked QD laser. A broad frequency-tuning range from 79.3 MHz to 2 GHz was achieved in an identical operation condition. The repetition rate of 79.3 MHz is the lowest ever achieved for any passively mode-locked semiconductor lasers. A narrow RF linewidth of ∼25 Hz and an intrinsic RF linewidth as low as 0.15 Hz were also obtained. The results largely extend the lower limit of the repetition rate of passively mode-locked QD lasers and suggest a noteworthy prospect for applications with ultrafast pulses of MHz to GHz repetition rates.

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