Wavelength-tunable prism-coupled external cavity passively mode-locked quantum-dot laser*

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A wavelength-tunable mode-locked quantum dot laser using an InAs/GaAs quantum-dot gain medium and a discrete semiconductor saturable absorber mirror is demonstrated. A dispersion prism, which has lower optical loss and less spectral narrowing than a blazed grating, is used for wavelength selection and tuning. A wavelength tuning range of 45.5 nm (from 1137.3 nm to 1182.8 nm) under 140-mA injection current in the passive mode-locked regime is achieved. The maximum average power of 19 mW is obtained at the 1170.3-nm wavelength, corresponding to the single pulse energy of 36.5 pJ.

Keywords: quantum dot, mode-locked laser, prism-coupled external cavity, tunability

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1. Introduction

External-cavity (EC) passively mode-locked quantum dot (QD) lasers are excellent candidates for generating ultra-short pulses, due to QD lasers' inherent merits of low threshold current density,[1–3] temperature insensitivity,[4–6] and ultra-fast carrier dynamics.[7–9] The broad gain spectrum due to the inherent dot size fluctuation during the growth process of self-assembled QDs is very promising for the development of broadly tunable laser[10–21] and broadly tunable high-power picosecond source.[22,23] Furthermore, EC configurations of such lasers offer some useful features when compared to monolithic devices. For instance, monolithic mode-locked lasers' inability to generate relatively low repetition-rate pulses can be remedied easily by EC mode-locked lasers, since the EC configuration greatly extends the cavity length of the laser system. Appropriate optical elements can be introduced to realize wavelength tuning and dispersion compensation for pulse narrowing. In this context, broad wavelength tunability from an InAs/GaAs QD pulse laser has been reported using diffraction grating techniques. Kim *et al.* reported the first wavelength-tunable grating-coupled mode-locked EC QD laser in 2006; it demonstrated a continuous optical spectrum tuning range of 30 nm–50.5 nm from ground-state and excited-state passive mode-locking, respectively.[21] The widest tunability range was demonstrated in Ref. [22], where the gain chip used in the grating coupled external cavity was based on a QD structure that consisted of 10 non-identical InAs/GaAs QD layers. Owing to the inherent broad gain and absorption bandwidth afforded by QD structures, a broad (136.5 nm) wavelength tunability in a passive mode-locked regime has been demonstrated.

In this letter, we demonstrate a tunable mode-locked EC QD laser using the dispersion prism as the tuning element, instead of the traditional blazed grating. The former offers some advantages compared with the latter. First, the light loss caused by the prism is smaller and ensures a higher output power than the blazed grating. Second, the narrowing effect of the spectral width of the EC mode-locked laser with the prism is reduced significantly because of its relatively low light dispersion, resulting in a reduction in the broadening of the laser output optical pulse duration. By using a gain device with self-assembled InAs/GaAs QDs as its active region, we present 45.5-nm wavelength tunability between 1137.3 nm and 1182.8 nm in the mode-locked regime from the prism-coupled mode-locked EC QD laser. The maximum average power of 19 mW is achieved at the wavelength of 1170.3 nm at room temperature.

2. Experiment

The tunable mode-locked EC QD laser, as shown in Fig. 1, was realized by employing a simple linear EC configuration, incorporating a QD gain device, a collimating lens, a focusing lens, a SESAM and an equilateral prism as the dispersion element. The detailed description of the scheme of the epitaxial structure of the QD gain device can be found in our previous papers.[24,25] Then the QD epitaxial chip was processed to fabricate the gain device, using standard photolithography and a wet etching process. The gain device had a ridge waveguide structure with a waveguide width of 5 μm and a device length of 1.5 mm. Both facets were coated: a single $\lambda/4$

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SiO_2 anti-reflection (AR) layer designed to minimize the reflectivity at 1.16 μm was deposited on one facet; SiO_2/Ta_2O_5 double layers were deposited on the other facet with designed reflectivity of 20% at the same wavelength. Finally, the gain device was mounted epitaxial-side down on a copper heat sink.

Light emission from the AR-coated facet was coupled into the EC using an 8-mm focal-length collimating lens, and then passed through the prism, and finally focused onto the SESAM using another 8-mm focal-length focusing lens. The saturation fluence of the SESAM (Batop SAM-1150-6) was around 60 μJ/cm^2 and the reflectivity exceeded 94% for wavelengths ranging from 1.11 μm to 1.19 μm. As the SESAM was fixed, the light through the prism had a deflection angle of a certain value (a calculated deflection angle fixed at 63°), the different wavelengths of light were matched to the deflection angle by rotating the prism, and hence the wavelength tuning was achieved. Mode-locked pulses were detected by a high-speed InGaAs photodiode detector whose output signal was connected to a radio-frequency (RF) spectrum analyzer with a bandwidth of 3 GHz. Measurements of emission spectrum, light power, and RF spectrum were all performed under continuous-wave (CW) current injection at room temperature. In this work, the power value measured by the pyro-electric probe is the average power of the mode-locked pulses, not the peak one.

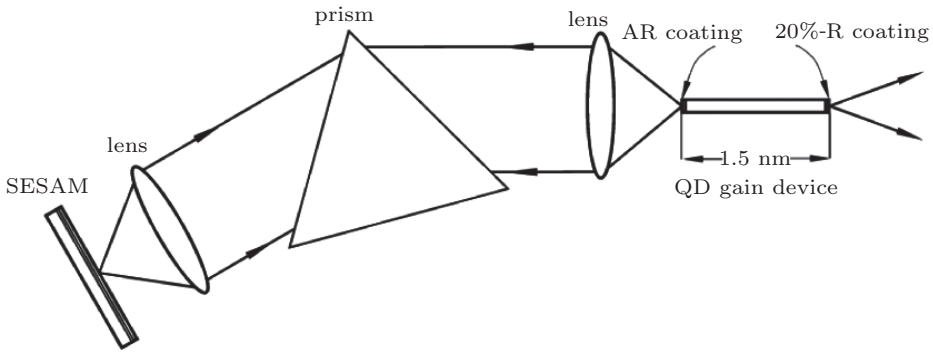


Fig. 1. Configuration of the mode-locked EC QD laser.

3. Results and discussion

A fundamental mode-locking wavelength tuning range of 40.9 nm (1141.9 nm–1182.8 nm) is achieved for the mode-locked EC QD laser under 120-mA current applied to the gain device, and an extended tuning of 45.5 nm (1137.3 nm–1182.8 nm) is demonstrated at the current injection of 140 mA, as shown in Fig. 2. The full-width at half maximum (FWHM) of the optical spectra of the laser varies between 1.2 nm and 2.6 nm across the tuning range, which is smaller than the feedback bandwidth (2.8 nm) of the prism. This proves that the prism used in the laser could not result in spectrum narrowing. The tuning bandwidth of the mode-locked EC QD laser is mainly affected by the reflection bandwidth of SESAM and operating current. The reflection bandwidth of SESAM is 1110 nm–1190 nm, so the tuning bandwidth of the mode-locking is limited in this range.

In Fig. 3, the RF characteristics for one representative operation wavelength of 1166.2 nm are presented. The repetition rate of 520 MHz is realized for the EC optical length. The −3-dB RF linewidth of 23 kHz is obtained and the signal-to-noise ratio in the RF spectra is larger than 30 dB, showing the low noise and robust stability for mode-locked operation, as shown in Fig. 3(b).

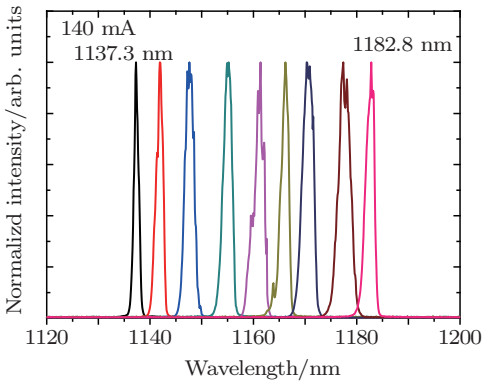


Fig. 2. (color online) Optical spectra of the wavelength-tunable EC mode-locked QD laser under 140-mA current applied to the gain device.

From the *P–I* measurements at different tuning wavelengths, we obtain the dependence of the threshold current and of the output power on the lasing wavelength, as shown in Fig. 4. The lowest threshold current of 52 mA is obtained at a lasing wavelength of 1170.3 nm; meanwhile, the average power of the mode-locked pulses reaches a maximum value of 19 mW, corresponding to the single pulse energy of 36.5 pJ. Compared to the average power of 20 mW of the mode-locked pulses in the mode-locked EC QD laser with a SESAM employing the same QD gain device without the prism at the same wavelength and with the same injection current in our previous paper,[26] the output power is only slightly reduced due to the introduction of the prism, indicating that the dispersion prism

has not induced a significant degree of light loss.

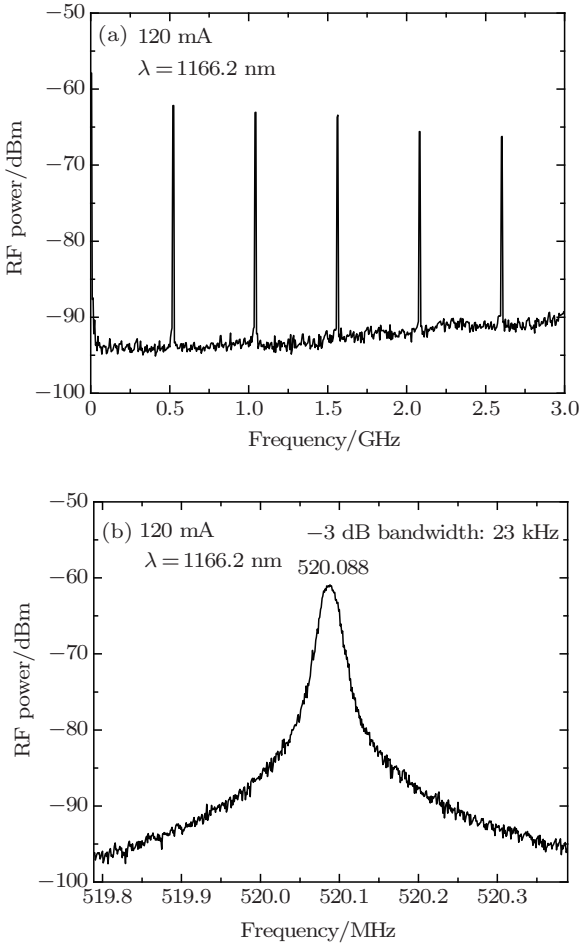


Fig. 3. RF spectral trace for mode locking under 120-mA current at 1166.2-nm wavelengths: (a) 3-GHz scan range, measured with a resolution bandwidth of 100 kHz; (b) 0.6-MHz scan range measured with a resolution bandwidth of 30 kHz.

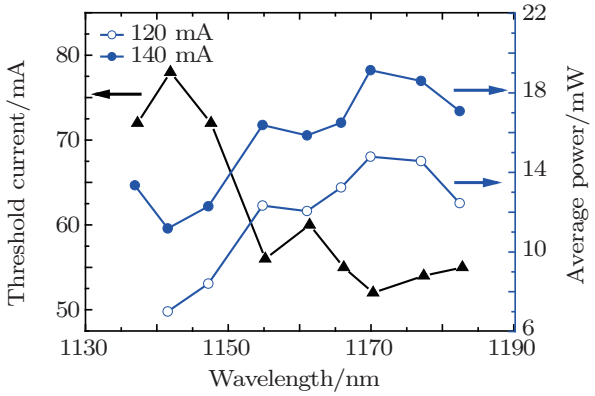


Fig. 4. (color online) Threshold current and average power under 120-mA and 140-mA injection currents, each as a function of the tuning wavelength of the mode-locked EC QD laser.

According to the calculation of the saturation parameter S in our previous paper,[27] we obtain saturation parameters S of the SESAM at different lasing wavelengths, as shown in Fig. 5. Typically, the SESAM operates with a saturation parameter S from 3 to 5[28] as marked in Fig. 5, since the mode-locked laser can produce the shortest pulse duration under such conditions.[26] The saturation parameters S of the SESAM at different lasing wavelengths and different injection currents are close to ideal.

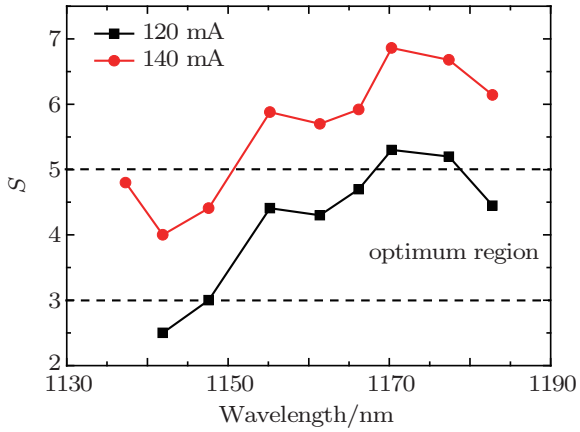


Fig. 5. (color online) Saturation parameters S of the SESAM at the different lasing wavelengths. The two dashed lines indicate the ideal operating range of the SESAM.

4. Conclusion

In conclusion, we demonstrate a wavelength-tunable mode-locked EC QD laser using the prism as the wavelength tuning element. A broad wavelength tuning range of 45.5 nm (from 1137.3 nm to 1182.8 nm) under 140-mA injection current in a passive mode-locked regime is achieved. The maximum average power of 19 mW is obtained at the wavelength of 1170.3 nm, corresponding to the single pulse energy of 36.5 pJ. The saturation parameters S of the SESAM at the different lasing wavelengths and the different injection currents are close to ideal. These results reinforce the view that as the tuning element, a dispersion prism outperforms a grating for a wavelength-tunable mode-locked EC laser due to lower optical loss and less spectral narrowing.

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