

Low threshold current and widely tunable external cavity lasers with chirped multilayer InAs/InGaAs/GaAs quantum-dot structure

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Abstract: Low threshold and widely tunable InAs/GaAs quantum-dot lasers are implemented with grating-coupled external-cavity arrangement. Throughout the tuning range of 130 nm, from 1160 to 1290 nm, the threshold current density is not more than 0.9 kA/cm² and no noticeable threshold jump is observed. For a shorter-cavity device, the injection current is kept at a record low value of 90 mA but the tuning range is further extended to 150 nm, from 1143 to 1293 nm. The effect of cavity length on the tuning characteristics is discussed and the strategy for design and optimization of multilayer quantum-dot structure is also proposed.

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OCIS codes: (140.3600) Lasers, tunable; (140.5960) Semiconductor lasers; (140.2020) Diode lasers; (250.5590) Quantum-well, -wire and -dot devices; (140.0140) Lasers and laser optics; (140.3410) Laser resonators.

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1. Introduction

The subject of widely tunable external cavity lasers (ECLs) has always been popular because of its applications in various scientific fields, such as fiber-optic communications based on wavelength-division multiplexing (WDM) [1] and medical diagnosis of optical coherence tomography (OCT) [2]. Furthermore, the usage of 1.3 μ m wavelength band benefits from not only lowest dispersion in optical fiber but also minimal absorption and scattering in human tissues [3]. Several successes have been achieved for grating-coupled ECLs with quantum-well (QW) gain media [4–6]; however, very high current density should be injected to populate carriers in the lowest ($n = 1$) as well as higher ($n \geq 2$) energy state for broadband tuning. The maximum tuning range achieved for InP-based QW ECLs of 1.3- μ m range is 160 nm under injection current of 400 mA (64 kA/cm²), which falls below 120 nm under 100 mA (16 kA/cm²) [6].

In contrast, ECLs with quantum-dot (QD) gain media are well-suited for low-threshold and broad spectral tuning due to their unique features of larger inhomogeneous broadening as well as lower ground-state saturation gain [7–10]. For GaAs-based InAs QD ECLs, the earliest records were 150-nm tuning at a maximum bias of 200 mA (1.1 kA/cm²) [7] and 201-nm tuning at a maximum bias of 400 mA (2.87 kA/cm²) [8]; nevertheless, the long-wavelength side is not more than 1.25 μ m. Besides, an unnegligible threshold jump is observed around the transition between ground-state (GS) and excited-state (ES) emissions in the single-layer In(Ga)As QD laser [7,8]. The recent demonstration of 110-nm tuning (1141.6–1251.7 nm) under low injection current density of 458 A/cm² (1.1 A) was realized in as-cleaved broad-area device of 120- μ m width [9]. Another latest record of 130-nm tuning (1174–1304 nm) at elevated temperature of 30 °C under injection current of 300 mA (1.5 kA/cm²) was achieved by QD gain chip with bent-waveguide design incorporated with output coupler configuration [10].

In this paper, we present grating-coupled ECLs with chirped multilayer QDs of 1.3 μ m wavelength range. High performance ridge waveguide lasers of 5- μ m width are fabricated for the investigation. A continuous tuning of 130 nm (1160–1290 nm) is achieved for a 2-mm length device at low injection current density of 0.9 kA/cm² and extended tuning of 150 nm (1143–1293 nm) is demonstrated for a 1.5-mm length device at record low current injection of 90 mA. This is advantageous to low-power applications which produce less heat. Moreover, the effect of cavity length on tuning characteristics is discussed. We also propose the strategy to further extend the tuning range without much sacrifice of the tuning threshold.

2. Experimental details

The laser structure is grown by molecular beam epitaxy on (100) oriented Si-doped GaAs substrate. The QDs are self-assembled using Stranski-Krastanov growth method. The nominal thickness of InAs QD is 2.6 ML and the single-layer dot density is about 5×10^{10} cm⁻². To change the peak wavelength of QD emissions, InGaAs strain-reducing layer (SRL) of different thickness is deposited immediately after the dot formation. The In composition is fixed at 0.15 in this work. Figure 1 shows the dependence of room temperature (RT) photoluminescence (PL) for the ground-state (GS) and excited-state (ES) emission peaks of a

single InAs QD layer as function of the thickness of capped $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ SRL (d). The data points are based on our separate growth and measurement as well as published results in Ref [11]. Between 0 and 5 nm, the PL peak wavelengths are fitted by the following expressions,

$$\lambda^{GS}(d) = (1150 + 38 \times d - 2.0 \times d^2) \pm 10 \text{ (nm)} \quad (1)$$

$$\lambda^{ES}(d) = (1088 + 31 \times d - 1.3 \times d^2) \pm 10 \text{ (nm)} \quad (2)$$

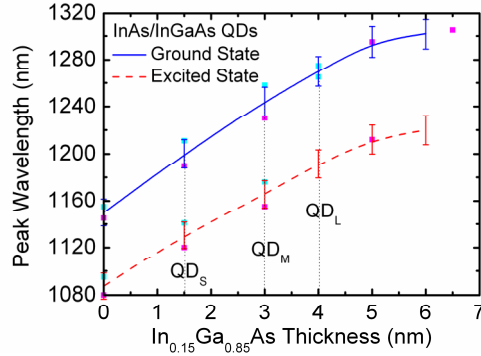


Fig. 1. RT PL for the GS and ES emission peaks of a single QD layer as function of the thickness of InGaAs SRL.

The active region consists of 10 layers of self-assembled InAs QDs which are capped by $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ SRL of varying thickness and spaced by GaAs of 33 nm. Three chirped wavelengths of longer, medium, and shorter wavelength range, with stacking numbers of 4, 3 and 3 layers and designated as $4 \times \text{QD}_L$, $3 \times \text{QD}_M$ and $3 \times \text{QD}_S$, are designed with InGaAs SRL thickness of 4, 3 and 1.5 nm, respectively. From Eq. (1) and (2), the GS/ES emission peaks are calculated to be 1270/1191, 1246/1169 and 1202/1132 nm for longer, medium and shorter wavelength QD-stacks, respectively. Also bear in mind that the experimental data may have uncertainty of ± 10 nm due to wafer non-uniformity as well as calibration factor of thickness and composition. The detail crystal growth can be found in [12].

The wafer is patterned by wet etching into ridge waveguides of 5- μm width. As-cleaved laser bars with different cavity lengths are first evaluated by standard light-current-voltage (L - I - V) and spectrum measurement. They are left unpacked for probe characterization under continuous-wave operation at RT of 20 °C. Since the cleaved mirror may create double-cavity effect in the following external cavity experiment, the front facets of laser bars are deposited with broadband multilayer anti-reflection (AR) coating ($R < 1\%$ from 1050 nm to 1350 nm). The rear facets are deposited with high-reflection (HR) distributed Bragg reflector coating ($R > 99\%$) to reduce cavity loss as well as form the end mirrors of ECLs.

Three coated QD lasers of 1.5, 2.0 and 3.0 mm in length are then investigated by grating-coupled external-cavity arrangement in the Littrow configuration [13]. Figure 2 shows the experimental setup. The optical feedback is provided by first-order diffraction from one external grating with a groove density of 1200 lines/mm and blazed wavelength of 1.0 μm . To collect the wide angle emission from edge emitter with thick active region, collimation lens with high numerical aperture of 0.68 is utilized. The zeroth-order light diffracted from the grating is coupled via a multimode optical fiber into an optical spectrum analyzer (Ando AQ6315E) at a resolution of 0.05 nm. Maximum optical feedback is achieved by tilting the grating with proper vertical angle until the lowest threshold current is reached.

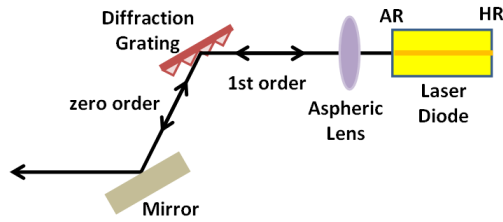


Fig. 2. The arrangement of external cavity laser in Littrow configuration.

3. Results and discussion

We first present the material gain characteristics of this novel chirped QD gain media. Due to the limited saturation gain of QDs, the lasing emissions switch between different energy states and exhibit a sudden change of peak wavelength in the varying-cavity-length measurement of as-cleaved devices. Figure 3 shows the modal gain and lasing wavelength as function of threshold current density for investigated chirped QD lasers. Based on the gain-current analysis [12] along with the empirical fitting formula [14], the switched transitions from GS-QD_L to ES-QD_L at cavity length of 0.75 mm are associated with emissions from GS-QD_L to ES-QD_L. The fitted GS saturated gain is 16.8 cm⁻¹ for 4 layers of QD_L or 4.2 cm⁻¹ per layer of QD_L, which fits very well in the reasonable range of 3~5 cm⁻¹. The effect of QD_M and QD_S on the modal gain is not visible in the gain-current analysis and should be accessed by spectral gain measurement.

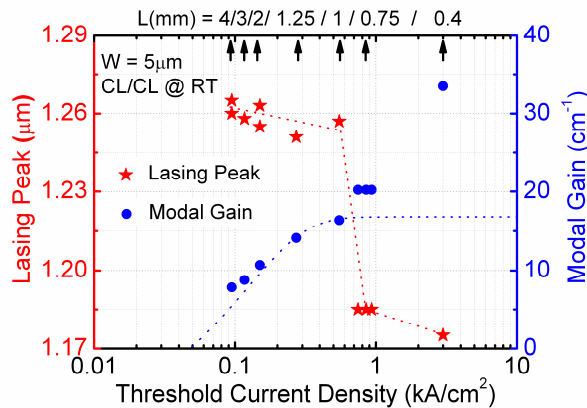


Fig. 3. Modal gain and lasing wavelength as function of threshold current density for chirped multilayer QD lasers.

Figure 4(a) shows the L - I - V characteristics of solitary AR/HR coated QD lasers for three cavity lengths of 1.5, 2.0 and 3.0 mm. For 2-mm emitter, the threshold current density increases from 15 to 75 mA (0.15 to 0.75 kA/cm²) and the free-running lasing peak switches from 1260 to 1180 nm as shown in Fig. 4(b). Also seen in Fig. 4(b), a rather flat and broad spontaneous emission spectrum is observed between the two stimulated emission peaks, which implies a smooth change in tuning threshold across this region. The 1.5-mm emitter, with coated threshold of 100 mA (1.33 kA/cm²), also switches lasing from 1260 to 1180 nm. Yet the 3-mm emitter does not switch its lasing wavelength around 1260 nm as its cavity is longer enough so that the total loss is still less than the saturated gain of GS-QD_L. Its coated threshold increases slightly to 50 mA (0.33 kA/cm²).

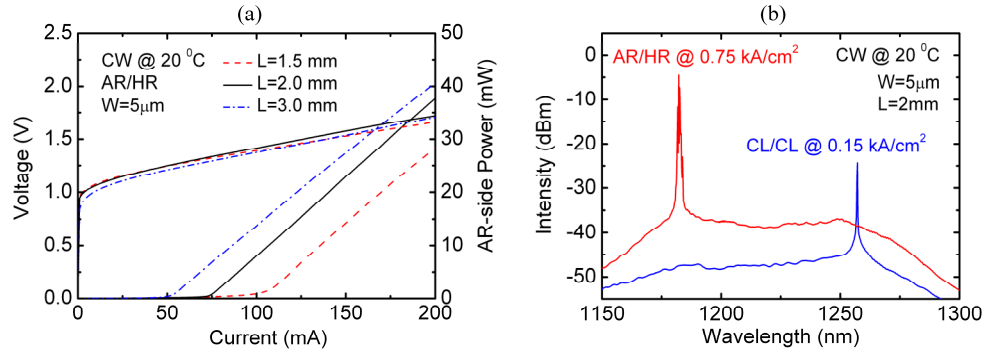


Fig. 4. (a) L - I - V characteristics of solitary AR/HR coated QD lasers for three cavity lengths of 1.5, 2.0 and 3.0 mm. (b) The threshold lasing spectrum for 2-mm QD emitter before and after facet coatings.

We then present the tuning characteristics of QD ECLs. Because the AR coating is not low enough to inhibit the lasing emissions, the suggested operation current is either slightly below or at least not well above the threshold current density of solitary coated devices in order to avoid the competition from free-running lasing modes of original FP emitter. Figure 5 shows the wavelength tuning for 2-mm-long QD emitter under 100 mA by manually rotating the diffraction grating. The lasing peaks are corresponding to the resonance of the external cavity and its spectral linewidth is less than 0.5 nm. Almost across the tuning range of 130 nm, from 1160 to 1290 nm, the peak intensities are about 35 dB higher than their side mode emissions. The lasing linewidth can be further reduced by packaging the laser devices and enclosing the entire external cavity with acoustic and thermal isolation [15].

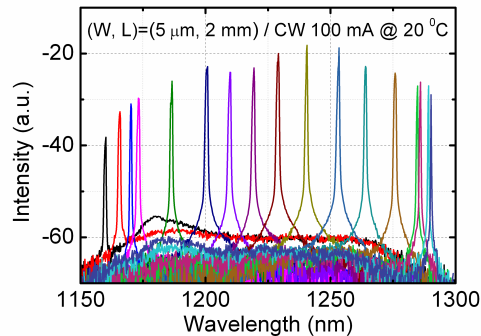


Fig. 5. Lasing spectra of 2-mm QD ECL, tuned across 1160-1290 nm wavelength at constant current of 100 mA.

Figure 6 shows the threshold current and threshold current density of tunable QD ECLs as function of tuning wavelength for three cavity lengths. The minimum threshold currents are achieved around 1260 nm where as-cleaved emitters exhibit their spectral gain peaks. It is worthy to mention that the threshold current increases almost monotonically from minimum-threshold wavelength toward longer and shorter wavelengths with no significant jump in threshold current. The spectral gain dip between the GS and ES, which is prominent in conventional unchirped QD structure [7,8], is now unobvious or absent in our chirped multilayer QD structure. The tuning range of 3-mm ECL is only 63 nm (from 1218 to 1281 nm) with maximum threshold near its solitary threshold current, while the 1.5-mm ECL can tune across 150 nm (from 1143 to 1293 nm) under maximum threshold current of 90 mA (1.2 kA/cm^2), which is a little below its solitary threshold current. The short-wavelength and long-

wavelength ends are therefore limited by mode competitions from free-running lasing modes of internal Fabry-Perot (FP) emitter.

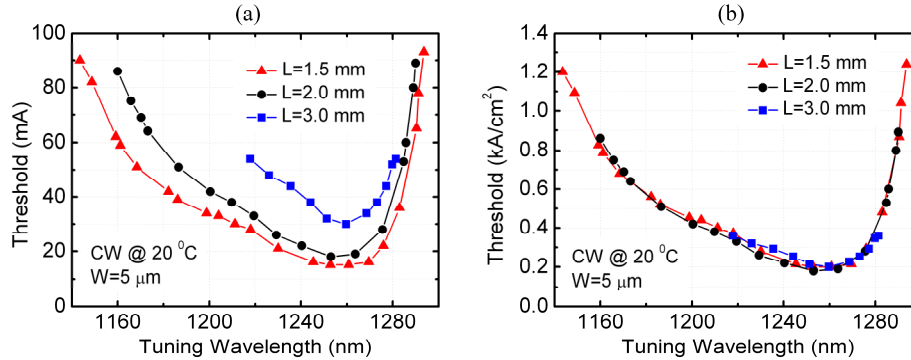


Fig. 6. (a) Threshold current and (b) threshold current density of QD ECLs as function of tuning wavelength for three cavity lengths of 1.5, 2.0 and 3.0 mm.

As regard to the 2-mm ECL, the maximum threshold current of 2-mm ECL is no more than 90 mA (0.9 kA/cm^2) across the 130 nm tuning range; nonetheless, the maximum threshold at tuning-wavelength ends is about 1.2 times its solitary threshold current of 75 mA. The mechanism is two fold. First, the grating-forced operation can suppress the internal FP emissions within spectral width of homogeneous broadening [8,16]. The 20-nm separation between our measured short-wavelength end (1160 nm) and the solitary lasing peak (1180 nm) is safely within the homogeneous broadening (typically 10–20 meV) [17,18]. Second, simultaneous lasing conditions can be met for both free-running peak wavelength of internal FP cavity and long-wavelength end of external cavity; however, the ECL lasing at long-wavelength end can suppress the internal FP lasing due to depletion of ES carriers by relaxation to GS [19,20]. We also investigate the temperature dependence on QD ECL tuning for 2-mm emitter. At cooled heatsink temperature of 10 °C, the tuning range is slightly reduced to 126 nm, from 1157 to 1283 nm. At elevated heatsink temperature of 30 °C, the tuning range is slightly enhanced to 133 nm, from 1163 to 1296 nm, which is consistent to the observation in Ref [10]. The small temperature rise causes thermal excitation of carrier in the higher energy states out of the QDs into the wetting layer, which results in spectral broadening as well as red-shits of spectral peak.

To further extend the tuning range, one could apply an ultralow reflectivity coating ($R < 0.1\%$) or incorporate a tilted-waveguide design; however, the expense is higher injection current density. The alternative strategy is through the epitaxial design and optimization of the multilayer QD structure. It is summarized in this work that the 130-nm tuning (1160–1290 nm) covers light emissions from GS-QD_L, GS-QD_M, GS-QD_S, ES-QD_L and ES-QD_M, while the 150-nm tuning (1143–1293 nm) covers those from all six energy states, both GS and ES of QD_L, QD_M and QD_S. Therefore, it is proposed to change the thickness of InGaAs SRL, say 5, 3 and 1 nm for three chirped wavelength of QD_L, QD_M and QD_S or one can introduce the fourth QD layers of even shorter wavelength. The last degree of freedom for optimization is the number of stacking layers for each chirped wavelength.

4. Conclusions

Low threshold and widely tunable InAs/InGaAs/GaAs QD lasers are implemented with external-cavity arrangement in Littrow configuration. The broad and flat gain spectra are achieved in the chirped multilayer QD gain media. Across the tuning range of 130 nm (1160–1290 nm), no noticeable threshold jump is observed and the maximum threshold current density is not more than 0.9 kA/cm^2 for 2-mm QD ECL. The tuning range is further extended to 150 nm (1143–1293 nm) for 1.5-mm QD ECL under record low threshold current of 90 mA. We discuss the effect of cavity length on tuning characteristics of tuning range and

tuning threshold. With clever choice of cavity length, the short-wavelength and long-wavelength tuning ends are optimized under injection current even slightly above the threshold current of solitary device. We also propose the strategy to further extend the tuning wavelength without sacrificing its tuning threshold. It can be easily implemented by the epitaxial growth design through optimization of QD-stacks of three or more chirped wavelengths, each with separate number of stacking layers.

Acknowledgments

The authors would like to thank the Union Optronics Corporation (UOC) for broadband AR coatings. They are also indebted to K. F. Lin of Industrial Technology Research Institute (ITRI) for device fabrication. The growth of QD laser structure is credited to Innolume GmbH in Dortmund, Germany. This work was supported by the Ministry of Education under the Aiming for the Top University and Elite Research Center Development Plan as well as the National Science Council Project under the contract number NSC 100-2221-E-009-021.