A broadband external cavity tunable InAs/GaAs quantum dot laser by utilizing only the ground state emission*

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A broadband external cavity tunable laser is realized by using a broad-emitting spectral InAs/GaAs quantum dot (QD) gain device. A tuning range of 69 nm with a central wavelength of 1056 nm, is achieved at a bias of 1.25 kA/cm^{2}only by utilizing the light emission from the ground state of QDs. This large tunable range only covers the QD ground-state emission and is related to the inhomogeneous size distribution of QDs. No excited state contributes to the tuning bandwidth. The application of the QD gain device to the external cavity tunable laser shows its immense potential in broadening the tuning bandwidth. By the external cavity feedback, the threshold current density can be reduced remarkably compared with the free-running QD gain device.

Keywords: quantum-dot, tunable laser, external cavity, broadband tuning
PACC: 8116D, 4260, 7845

1. Introduction

The broadband tunable laser is an important kind of coherent light source for a wide range of applications, such as spectroscopy,[1,2] biomedical,[3,4] and dense wavelength-division multiplexing (DWDM).[5] The tuning range is one of the most important features for tunable lasers. The grating-coupled external cavity tunable laser (ECTL) benefits from its broadband tuning range, owing to the wide tunability of the grating rotation angle. The tuning band of ECTL depends mainly on the optical gain spectrum width of the gain device. For a quantum-well (QW) gain device, because of its narrow gain characteristic, the broadening of its gain spectrum typically relies on the introduction of higher order transitions[6,7] or asymmetric multiple QW structure.[8−11] However, due to the higher saturated gain of the ground state in QW, a high pump level (generally more than 10 kA/cm^2) is needed for the realization of large tuning range, which restricts its real applications. Although asymmetric multiple QW structure is effective to extend the tuning range, irregular gain spectrum shape induced by the gain overlap of different QW layers usually leads to a large change of the threshold current and output power across the wavelength tuning range. Besides, the pump level is also very high and it is still not suitable for real applications.

The self-assembled quantum dot (QD)[12,13] material is beneficial to the characteristic of size inhomogeneity naturally occurring in Stranski–Krastanow growth, and thus it is suitable for the realization of broadband emission.[14,15] It has successfully been used to fabricate broadband superluminescent diodes (SLDs).[16−19] On the other hand, due to the lower saturated gain of the ground state and the phonon bottle-neck effects[20] for QDs the excited states can be filled at a fairly low pump current density, which will further increase the emission spectrum width. ECTLs using QDs as a gain medium have been demonstrated in the most recent few years.[21−28] The largest tuning range of 201 nm covered by the light emission from the ground to the excited state of QDs has been investigated[23] while the output power was not mentioned. By means of intentional inhomogeneous broadening according to the design of asymmetric multi-layer QDs, 160 nm tuning bandwidth and 200 mW output power have been realized simultaneously.[28] However, the 160 nm tuning range was not realized at the same injection current.

In the present paper, using InAs/GaAs QD mate-

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rial with broadband emission characteristic as a gain medium, a grating-coupled broadband ECTL with 69 nm tuning range is achieved only by utilizing the light emission from the ground state of QDs. It is also demonstrated that threshold current density can be reduced remarkably from 1.33 kA/cm^2 for the free-running QD gain device to 0.58 kA/cm^2 for the ECTL with the external grating feedback near 1075 nm.

2. Experiment

The epitaxial structure of the QD gain device used in this study is grown on n-GaAs (001) substrate by a Riber 32P solid-source molecular beam epitaxy machine. The active region consists of five layers of InAs QDs which are capped by 7 monolayers (MLs) of $In_{0.14}Ga_{0.86}As$. 18 nm thick GaAs spacer layers are used to separate the five QD layers from each other. The active layer is embedded in a 100 nm thick GaAs waveguide. The deposition amount of InAs is 2.1 ML per layer with a growth rate of 0.1 ML/s. No growth interruption was inserted during or at the end of the InAs growth period, so that QDs with large size dispersion could be formed. Next to the GaAs waveguide, graded index-separating confinement heterostructure is grown. The n- and the p-type cladding layers are made of 1.5 μm $Al_{0.5}Ga_{0.5}As$ material. Finally, a 300 nm thick p^+-GaAs cap layer completes the structure. The QD gain device is fabricated in the form of a ridge waveguide with a length of 1 mm and a stripe width of 120 μm. It is mounted epitaxial-side down on a copper heat sink. No antireflection coating is deposited on the facets.

A Littrow configuration is constructed in the external-cavity tuning experiment. A 1200 lines/mm diffraction grating blazed at 1060 nm is employed and its diffraction efficiency in the first order is about 70%. The emission from one facet of the QD gain device is nearly collimated by using an aspherical lens. By rotating the grating, the emission with selected wavelength can be diffracted back. The measurements of emission spectra and output power are performed on the other facet of the QD gain device. The spectral resolution is about 0.9 nm. The QD gain device is operated at room temperature (RT) in pulsed injection with 1 kHz repetition rate and 30 μs pulse width (3% duty cycle) for the spectral and power measurements.

3. Results and discussion

The free-running QD gain device is examined before being located in the Littrow setup. Figure 1 shows the RT electroluminescence spectra of the free-running QD gain device under different injection levels with a 1 kHz repetition rate and 3% duty cycle. At a bias of 0.25 kA/cm^2 the spontaneous emission spectrum shows a single-peak emission from the QD ground state, with a 100-nm full width at half maximum. With the injection level increasing to 1.33 kA/cm^2, the device starts the ground-state lasing at around 1040 nm. Upon the increase of the pump level to 2.5 kA/cm^2, the lasing spectrum covers the wavelength range from 1001 nm to 1086 nm (−20 dB bandwidth). The broad lasing spectrum is mainly attributed to the large inhomogeneous size distribution of InAs QDs, induced by the continuous and relatively fast dot growth. Due to the lack of antireflection coatings on both the facets of the gain device and the sufficient gain of the QD ground state produced by the higher dot density, lasing from the excited state of QDs does not appear at this injection level.

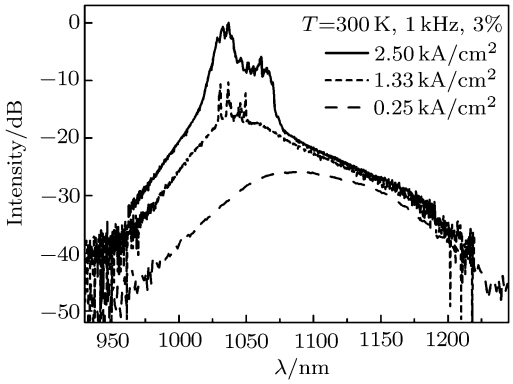


Fig. 1. Electroluminescence spectra of the free-running InAs/GaAs QD gain device under different injection levels.

The tuning characteristics under 1.25 kA/cm^2 pulsed injection (1 kHz and 3%) of the InAs/GaAs QD ECTL are shown in Fig. 2. A tuning bandwidth of 69 nm, covering a wavelength range from 1021 nm to 1090 nm contributed only by the ground state of QDs, is achieved. Across the tuning range, the peak intensity at 1065 nm is 11.4 dB higher than that at 1090 nm. The amplified spontaneous emission suppression ratio is 15–23 dB. The lasing linewidth is no more than 2 nm. It can be seen from the figure that double peaks appear in the lasing spectra and they are possibly due to the multi-spatial modes in the broad-area QD gain device.[22] When the laser wavelength is

tuned close to the extremes, small emission peaks in a range of 1025–1065 nm originating from the Fabry–Pérot (FP) cavity resonance of the free-running QD gain device can be observed. When the external cavity resonance is tuned near the gain peak (see Fig. 1), the external cavity lasing mode dominates the spectrum and the inner-FP cavity resonance can be suppressed well.

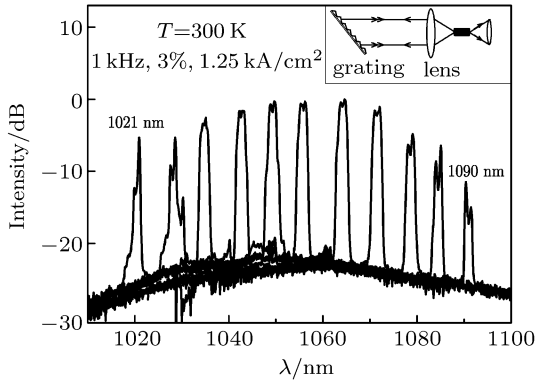


Fig. 2. Lasing spectra of grating-coupled InAs/GaAs QD ECTL at a bias of 1.25 kA/cm^2. The inset shows the experimental setup (Littrow configuration).

Figure 3 shows the threshold current density ($J_{\rm th}$) of the QD ECTL as a function of lasing wavelength. The external cavity light feedback makes the $J_{\rm th}$ decrease remarkably. The lowest $J_{\rm th}$ is 0.58 kA/cm^2 near 1075 nm, while for the free-running QD gain device the $J_{\rm th}$ is 1.33 kA/cm^2. The $J_{\rm th}$ decreases by 56%. However, Refs. [21] and [27], in which the free-running gain devices were also not coated, show that $J_{\rm th}$ decreases only by 10% and 12.8% respectively. Maybe this significant decrease is related to the simple Littrow external cavity configuration and the used gain device with broad-area. More light beams can be fed back to the gain device and $J_{\rm th}$ can decrease obviously. Due to the fact that the wavelength tuning is performed across the ground state of QDs, only one minimum of the $J_{\rm th}$ appears. Generally, two minima of $J_{\rm th}$ appear for the ECTLs in which the emissions from the ground and excited states are utilized simultaneously in the tuning process. Also, it is evident in the figure that $J_{\rm th}$ increases on both the sides of short and long wavelengths, and eventually the ECTL loses the ability to lase. This is related to the density-of-state (DOS) and the state occupation probability characteristic of QDs. The DOS of QDs is lower at longer wavelengths and the gain can saturate easily there. This restricts the tuning towards longer wavelengths. In a short wavelength regime, although the DOS is higher, for a given injection current the occupation probability of the state at a higher energy level decreases. This also results in a decrease of material gain and a tuning limitation towards short wavelengths.[26]

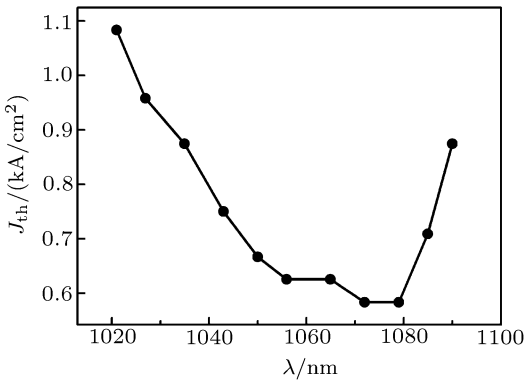


Fig. 3. Threshold current density of grating-coupled InAs/GaAs QD ECTL against lasing wavelength.

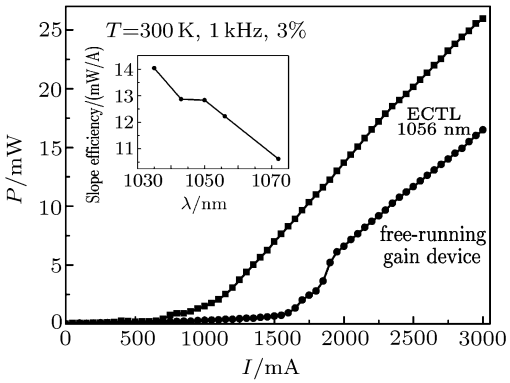


Fig. 4. Light output power–injection current (P–I) curve. The upper line corresponds to the ECTL tuned at 1056 nm, and the lower line to the free-running QD gain device. The inset shows the slope efficiency as a function of lasing wavelength.

Figure 4 shows a comparison of the light output power–injection current (P–I) curve at RT between the InAs/GaAs QD ECTL tuned at 1056 nm and the free-running QD gain device. The power value in the figure is peak power, which is deduced from the average one measured with a pyroelectric probe divided by the 3% duty cycle. The slope efficiency is calculated according to the P–I curve above its threshold. An output power of 25.9 mW is obtained under 2.5 kA/cm^2 current injection for the ECTL while it is 16.5 mW for the free-running QD gain device. The output power increases by 57% with using the external cavity light feedback. The inset shows the change of slope efficiency across the tuning range. It can be seen that the slope efficiency decreases with the tuning towards long wavelengths. This may be due to the carrier filling at the states at higher energy levels.[22]

Conversely, on the side of short wavelength, the higher DOS gives birth to a higher slope efficiency.

The tuning range can be extended by antireflection coating on the cavity facet. The decrease of the cavity facet reflectivity will extinguish the ground state lasing of the QD gain device. Therefore, the ECTL can work at higher injection levels and a shorter tuning wavelength corresponding to the excited states can be realized. Due to the lower DOS of the longer wavelength, the extension of the tuning range to longer wavelengths is limited. On the other hand, similar to the asymmetric multiple QW design in QW-ECTL, by using multi-layer QDs with different emission energies as gain media in the QD gain device, the tuning range can be further broadened.

4. Conclusion

Using self-assembled QDs with broadband emission characteristics as a gain medium, a continuous tuning range of 69 nm is realized in a grating-coupled InAs/GaAs QD ECTL only by utilizing the ground state. This large tunable range results from the inhomogeneous size distribution of QDs. It is also demonstrated that the external light feedback can reduce the threshold current density remarkably.

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