Broadband tunable external cavity laser using a bent-waveguide quantum-dot superluminescent diode as gain device*

Wu Jian(吴 剑)[a], Lü Xue-Qin(吕雪芹)[a], Jin Peng(金 鹏)[a]†,
Meng Xian-Quan(孟宪权)[b], and Wang Zhan-Guo(王占国)[a]

[a] *Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, Beijing* 100083, *China*

[b] *Key Laboratory of Artificial Micro- and Nano-structures of Ministry of Education and School of Physics and Technology, Wuhan University, Wuhan* 430072, *China*

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A broadband tunable grating-coupled external cavity laser is realized by employing a self-assembled InAs/GaAs quantum-dot (QD) superluminescent diode (SLD) as the gain device. The SLD device is processed with a bent-waveguide structure and facet antireflection (AR) coating. Tuning bandwidths of 106 nm and 117 nm are achieved under 3-A and 3.5-A injection currents, respectively. The large tuning range originates essentially from the broad gain spectrum of self-assembled QDs. The bent waveguide structure combined with the facet AR coating plays a role in suppressing the inner-cavity lasing under a large injection current.

Keywords: quantum dot, external cavity laser, broadband tuning

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1. Introduction

Tunable external cavity (EC) laser, an important kind of coherent light source, can find applications in many areas, such as spectroscopy,[1−4] gas detection,[5] interferometry,[6] and optical coherence tomography (OCT) measurement.[7,8] For an EC laser, a large tuning bandwidth is always expected to meet the requirements for some applications. Since the tuning bandwidth relies mainly on the width of the optical gain spectrum of the active gain device used in the EC laser, a feasible way to extend the tuning ability is to use gain device with a wider gain spectrum. Recently, self-assembled quantum dots (QDs) have been used as an active media for fabricating superluminescent diodes (SLDs)[9−17] and broadband emitting laser diodes,[18,19] owing to the QDs' broadened spectral width, which is induced by the naturally-formed size inhomogeneity in their Stranski–Krastanow (SK) growth. Moreover self-assembled QD gain devices have also been used in the tunable EC lasers.[20−30] It has been shown that self-assembled QDs are suitable for realizing broadband tuning. On the one hand, the size inhomogeneity of the self-assembled QDs can broaden the width of the gain spectrum.[9,31] On the other hand, the relatively low density of state (DOS) of the QD ground state (GS) leads to much easier saturation of the optical gain in the state.[32−34] As a result, excited states (ESs) can be filled by carriers under a relatively low pump level, causing one or more of the ESs as well as the GS to emit simultaneously. The two factors jointly make the wide and continuous wavelength coverage of the QD optical gain spectrum possible, which is conducible to the realization of broadband tuning. A tuning range of 201 nm at an injection bias of 2.87 kA/cm^2 has been reported.[20] In addition, the effective lasing suppression of the inner Fabry–Pérot cavity resonance is a crucial factor for broadband tuning. It allows the gain device to populate in higher energy states in the EC without inner-cavity lasing so that the tuning can be expanded to the short-wavelength side. Both the J-shape bent-waveguide structure[35] and facet antireflection (AR)[20,21] coating are usual means for the lasing suppress. In our previous studies, by using

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†Corresponding author. E-mail: pengjin@red.semi.ac.cn

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broad-area QD gain devices without any lasing suppress means, tuning ranges of 69 nm[28] and 110 nm[29] were achieved.

In the present paper, we fabricate an SLD device using the self-assembled InAs/GaAs QDs as its active region. By using the J-shape bent-waveguide structure and the facet AR coating, effective lasing suppression is realized for the free-running SLD device. No lasing occurs even when the injection current is increased up to 4 A. Then a Littrow grating-coupled EC laser is constructed with using the QD SLD as the gain device. Tuning ranges of 106 nm and 117 nm are achieved under 3-A and 3.5-A injection current, respectively.

2. Experiment

The epitaxial structure of the QD gain device used in this experiment was grown on an n-GaAs (001) substrate by a Riber 32P solid-source molecular beam epitaxy machine. The active region contained ten layers of self-assembled InAs QDs, each of which was covered by a 2-nm thick InGaAs cap layer and separated from the adjacent QD layers by GaAs spacer layer. The active region was embedded in a 120-nm GaAs waveguide layer. Below and above the waveguide were 1.5 μm n-type and 1.5 μm p-type $Al_{0.5}Ga_{0.5}As$ cladding layers, respectively. Finally, a 300-nm thick p^+-GaAs layer was capped as an Ohmic contact layer. Then the QD epitaxial chip was processed to fabricate the gain device of a J-shape bent-waveguide structure.[35] The main structural parameters are shown in Fig. 1(a). The gain device was mounted epitaxial-side down on a copper heat sink. A single $\lambda/4$ SiO_2 AR layer designed for minimum reflectivity at 1.19 μm was deposited on the bent-waveguide facet; while the straight-waveguide facet remained as-cleaved.

The Littrow configuration, shown in Fig. 1(b), was used in our EC tuning experiments. A 1200-grooves/mm grating, blazed at 1060 nm with about 70% diffraction efficiency in its first order, was employed. The external cavity length was about 12 cm. The light emission from the bent-waveguide facet was collimated by an aspherical lens and then was diffracted back with selected wavelengths from the grating. The emission from the as-cleaved straight-waveguide facet was taken as the output of the EC laser. Measurements of emission spectrum and light power were performed under pulsed current injection at a repeated frequency of 1 kHz with a 3% duty cycle at room temperature. In this paper, the power value is presented as the peak power, which is deduced from the average one measured with a pyro-electric probe, divided by the 3% duty cycle.

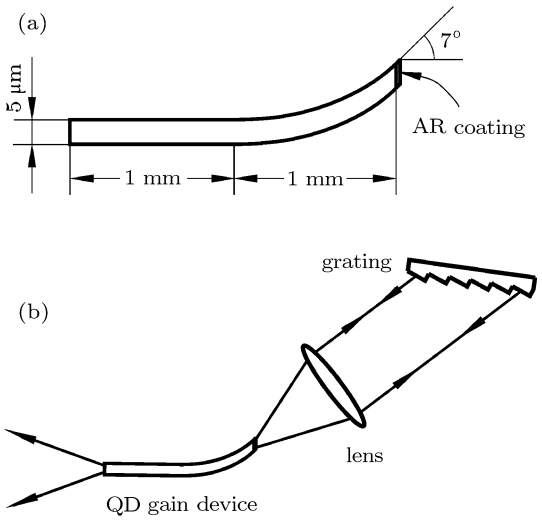


Fig. 1. Sketches of (a) the quantum dot gain device waveguide structure and (b) the Littrow configuration used in the external-cavity tuning experiment. Antireflection (AR) coating is used on the bent-waveguide facet.

3. Results and discussion

Before performing the EC tuning experiment, electroluminescent (EL) spectra and light power–current (P–I) property of the free-running QD gain device are measured first. Figure 2(a) shows a comparison between the P–I curves measured from the bent-waveguide facet and from the straight-waveguide facet respectively. It is found that the power output from the bent-waveguide facet is much larger than that from the straight-waveguide facet when the injection current is more than 2.5 A. For example, under 3.2-A injection, an power output of 30 mW from the bent-waveguide facet is obtained while the power output from the straight-waveguide facet is only 5.9 mW. This is because the device has a small retro-reflectivity at the bent-waveguide facet and the facet AR coating makes the reflectivity even smaller. However, the retro-reflectivity of the straight-waveguide facet is still large (∼30%) as the facet remains as-cleaved. Therefore, the light emitted from the bent-waveguide facet can experience double-path amplification while the light emitted from the straight-waveguide facet can experience only single-path amplification.[35] Besides, the higher reflectivity of the straight-waveguide facet causes larger loss of the light output than that

of the bent-waveguide facet. As a result, the bent-waveguide facet has larger power output than the straight-waveguide facet. In addition, the P–I curves show obvious kinks. This is attributed to the sequential carrier filling in the energy states of the self-assembled QDs.

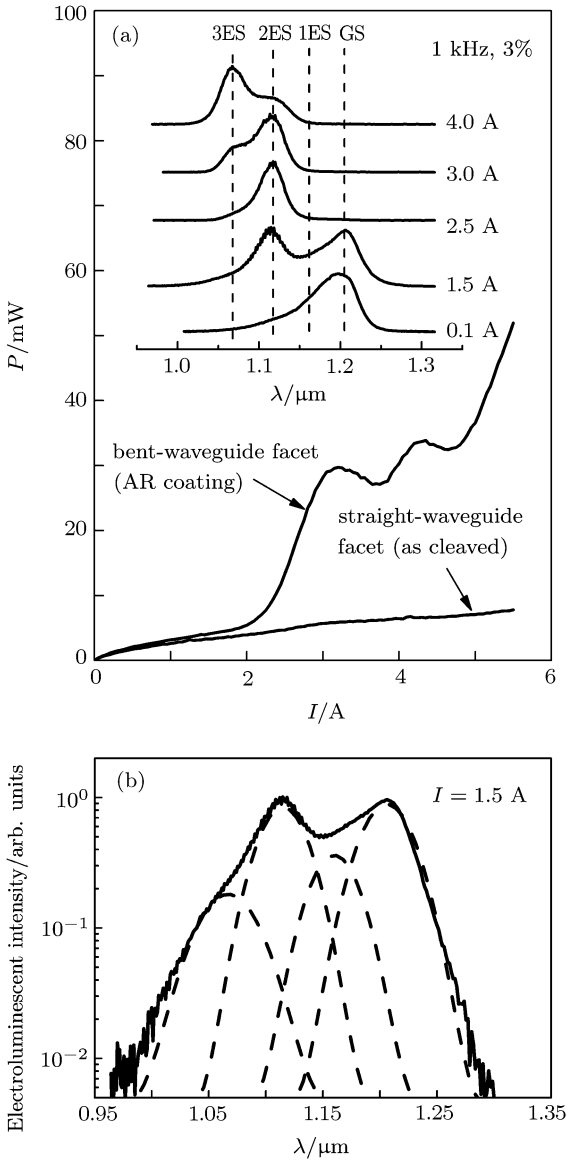


Fig. 2. (a) Light output power-injection current (P–I) curves measured from the bent-waveguide facet and the straight-waveguide facet of the free running QD gain device, respectively. The inset shows normalized electroluminescent spectra of the QD gain device under various injection levels measured from the bent-waveguide facet. The dashed lines denote the transitions from the ground state (GS), the 1st excited state (1ES), the 2nd excited state (2ES) and the 3rd excited state (3ES); (b) the electroluminescent spectrum under injection current 1.5 A and its Gaussian fittings.

The inset of Fig. 2(a) shows normalized EL spectra of the free-running QD gain device under various injection levels, measured from the bent-waveguide facet. Lasing does not occur even when the injection current is increased up to 4 A, showing a typical superluminescent behaviour for the self-assembled QD gain device. In our previous study,[28] broad-area straight waveguide structure showed less ability to suppress the inner-cavity lasing. So the J-shape bent-waveguide structure combined with the facet AR coating plays a role in effectively suppressing the inner-cavity lasing under such a large injection current. This is an important factor for the broadband tuning of an EC QD laser under relatively high injection level, under which the tuning can extend to the short-wavelength side further by populating the self-assembled QDs in their excited states (ESs).[29]

Under a relatively low (0.1 A) injection current, the emission spectrum has an asymmetrical single peak in the long-wavelength region, with a full width at half maximum (FWHM) of 68 nm. Multi-peak fitting presents that the spectrum can be decomposed into three Gaussian peaks (not shown here) which can be assigned to the GS, the 1st excited state (1ES) and the 2nd excited state (2ES) emission, respectively. Under the low pump level, the GS transition dominates the spectrum. With the increase of the injection current, more carries fill in the QD ESs, revealed by the increased proportion of the ES emission peaks in the short-wavelength region. Figure 2(b) shows the four-peak Gaussian fitting to the EL spectrum at 1.5-A current, giving the GS (1206 nm), the 1ES (1160 nm), the 2ES (1115 nm) and the 3ES (1067 nm) emission with nearly equivalent wavelength spacing. Under higher pump levels (more than 2 A), the emission from ESs dominates the spectrum and the emission peak from the GS almost disappears. This can be explained by the small DOS of the QD GS which saturates easily under a relatively low injection current. On the other hand, the possible phonon bottleneck effects[36] may cause longer relaxation time for the carrier (especially the electron) transition from the ES to the GS. Therefore, under relatively high pump levels, the superluminescent emission lifetime of carries filling into the ES may be shorter than the relaxation time from the ES to the GS for the carries, causing the insufficient supply of carries for the GS. For clarity, four dashed lines are used in Fig. 2(a) to denote the transition positions for the GS, the 1ES, the 2ES and the 3ES.

The EC properties were characterized by lasing spectrum and P–I curve measurements at various tun-

ing wavelengths. The EC lasing is formed between the grating and the straight-waveguide facet. The wavelength tuning is realized by rotating the grating. Shown in Fig. 3 is a series of lasing spectra of the EC QD laser tuned at different wavelengths under a 3-A injection current. A tuning bandwidth of 106 nm (1046 nm∼1152 nm), which covers the 1ES, the 2ES and the 3ES of InAs/GaAs QDs (refer to Fig. 2 and relative description in the text to obtain the QD energy states), is achieved. The QD GS does not contribute to the tuning mainly because of its low DOS. No inner-cavity lasing from the gain device itself is found in these spectra, showing the good suppression effect of the bent-waveguide structure and the facet AR coating on the inner-cavity mode. Some double peaks can be seen in the lasing spectra and they can be attributed to the multi-spatial modes in the QD gain device.[21]

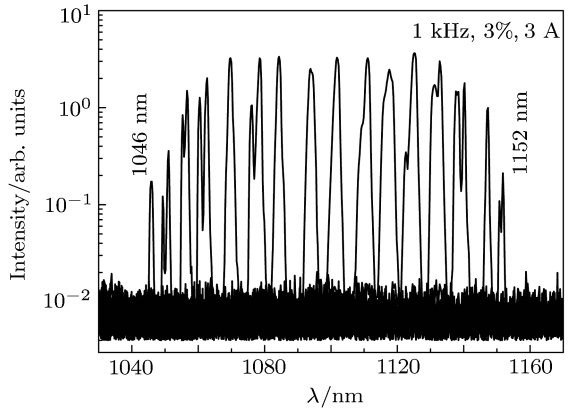


Fig. 3. Lasing spectra of the grating-coupled external-cavity quantum-dot laser under 3-A injection current.

From the P–I measurements at different tuning wavelengths, we obtain the dependences of the threshold current ($I_{\rm th}$) and the output light power on lasing wavelength as shown in Fig. 4. The lowest threshold current of 2.04 A is obtained at a lasing wavelength of 1125 nm. Towards both the long- and the short-wavelength sides of the tuning, the threshold current increases. The increasing of $I_{\rm th}$ towards the long-wavelength side is attributed to the low DOS and the random filling in the QDs. However, towards the short-wavelength side, the increasing of $I_{\rm th}$ is because of the useless carrier filling into the states that are lower than the lasing state. So for further tuning to the short-wavelength side, higher injection level is needed.

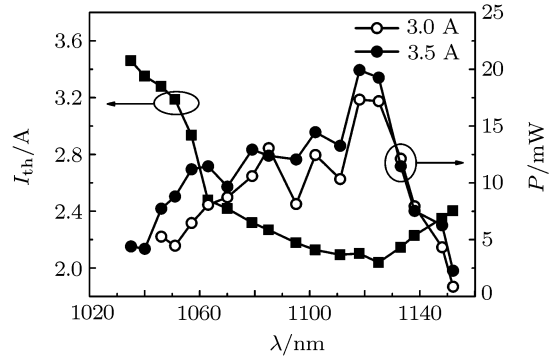


Fig. 4. Threshold currents and power outputs under 3-A and 3.5-A injection current each as a function of the tuning wavelength of the external-cavity quantum-dot laser.

Under the 3.5-A injection, a 117-nm (1035 nm ∼ 1152 nm) tuning range, which is larger than that under the 3-A injection, is obtained. The enhancement of the tuning range under higher injection is contributed to by the tuning extension to the short-wavelength side, while remains the same on the long wavelength side. It is shown that the increase of the injection current can extend the tuning range towards the short wavelength side. As mentioned above, this is mainly because the high energy levels of the QDs can be filled by more carries and the blue shift of the gain spectrum occurs when the current increases. Consequently, it causes an increased gain in the short wavelength region, benefiting the lasing at short wavelengths. However, merely increasing the pump level cannot obviously extend the tuning range towards longer wavelengths as the gain in the long wavelength region saturates easily due to the small DOS of QD low energy levels. Only a reduction in total cavity loss or a longer gain region can extend the tuning range on the long wavelength side in some manner.[21]

It should be mentioned that the EC laser has a high threshold current density as compared with that using broad-area QD gain device.[29] There is no assured reason we can give at present. It may be caused by the bent-waveguide structure itself, the un-optimized device processes, or some other factors. Next, some experiments will be done for reducing the threshold current.

4. Conclusion

A QD superluminescent diode with bent-waveguide structure and facet AR coating process is fabricated and characterized. A 30-mW power output from the bent-waveguide facet and an emission spectrum of 46-nm FWHM are obtained under 4-A injection current, showing the typical property of superluminescence. It reveals that bent-waveguide structure and facet antireflection coating process can pro-

hibit lasing effectively. The QD SLD is used in a Littrow structure to build a tunable EC QD laser. The EC tuning properties are evaluated by using P–I and spectral measurements. EC tuning bandwidths of 106 nm and 117 nm are achieved under 3-A and 3.5-A injection currents, respectively. It is shown that the effective suppression of the inner-cavity lasing is an important factor for broadband EC tuning.

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