A grating-coupled external cavity InAs/InP quantum dot laser with 85-nm tuning range*

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The optical performance of a grating-coupled external cavity laser based on InAs/InP quantum dots is investigated. Continuous tuning from 1391 nm to 1468 nm is realized at an injection current of 1900 mA. With the injection current increasing to 2300 mA, the tuning is blue shifted to some extent to the range from 1383 nm to 1461 nm. By combining the effect of the injection current with the grating tuning, the total tuning bandwidth of the external cavity quantum-dot laser can reach up to 85 nm. The dependence of the threshold current on the tuning wavelength is also presented.

Keywords: quantum dot, external cavity, tunable laser

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1. Introduction

The development of a flexible, high power, broadband-tunable external-cavity (EC) laser has always been popular owing to its wide range of applications, such as spectroscopy,[1–3] interferometry,[4] optical coherence tomography (OCT),[5–8] and wavelength-division-multiplexing (WDM) systems.[9,10] EC lasers based on self-assembled quantum dots (QDs) with large tuning bandwidth are expected to meet the requirements for tunable light sources. For a grating-coupled external cavity system, the tuning bandwidth is mainly determined by the gain spectrum width of the active gain medium. The self-assembled QDs[11–14] fabricated in heteroepitaxial systems such as InAs/GaAs and InAs/InP have shown great promise for being used as the gain medium of broadband light emitting devices, such as superluminescent diodes,[15,16] broadband laser diodes,[17] and tunable EC lasers.[18,19] First, the characteristics of size inhomogeneity, naturally occurring in self-assembled QDs grown in the Stranski–Krastanow mode, are beneficial to broadening the gain spectrum. Secondly, due to the low density of the states in the QD ground state, the optical gain of the QD ground state is saturated easily, which means that the excited states can be filled under a relatively low current density. For GaAs-based In(Ga)As QDs, its working wavelength is in the range of 0.9–1.3 μm.[20–23] However, the In(Ga)As QD material based on an InP substrate allows emission wavelength in the range of 1.2–2 μm.[24–26] Up to now, many investigations have been devoted to the InAs/GaAs QD EC lasers. In those investigations, using GaAs based QDs as the gain medium, EC lasers working in the wavelength range of 1–1.3 μm have been demonstrated in the past few years.[27–31] A tuning range of 110 nm at a bias of 458 A/cm^2 was obtained and the facet anti-reflection (AR) coating extended the tuning range to 150 nm;[28] in addition, the tuning range of 130 nm (from 1160 nm to 1290 nm) under an injection current density of 0.9 kA/cm^2 was realized.[32] By exploiting the chirped multilayer QD structure, more than 200 nm tuning range with ∼200 mW maximum output power was reported in our previous paper.[33] To the best of our knowledge, for the InAs/InP QD EC laser, only a few reports are devoted to the discussion of the performance of the device. For example, the device with a 166-nm tuning range emitting around 1.6 μm with a threshold current density less than 8 kA/cm^2 was reported, however, the average output power of their EC laser was only a few μW.[34] A tuning range of 98 nm (from 1618 nm to 1716 nm) with a maximum output power of about 7 mW has been reported.[35]

In this paper, an InP-based InAs QDs gain device is fabricated. The free-running property of the device is investigated. The grating-coupled EC laser based on the InAs/InP QD gain device is demonstrated. The effect of the injection current on the tuning property is investigated. The system demonstrates a continuous tuning range of 77 nm (from 1391 nm to 1468 nm) at an injection current of 1900 mA. With the increase of the injection current, the long and the short tuning wavelength limits are both blue shifted to some extent.

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2. Experiment

The epitaxial structure for the gain device in this experiment was grown in an Aixtron metal-organic chemical vapor deposition (MOCVD) system on an n-type InP (100) substrate. The undoped active region of the device contained five InAs QD layers of 2 monolayers (MLs) separated from each other by a 50-nm-thick InGaAsP layer (lattice matched with the InP substrate and with 1.15-μm emitting wavelength), which were embedded in the quaternary InGaAsP waveguide. The waveguide was surrounded by a 1.5-μm-thick n-InP bottom cladding layer and a 1.5-μm-thick p-InP top cladding layer. The latter was covered with a cap of 150-nm-thick p^+-InGaAs layer in order to form a good Ohmic contact with the top metal. The epitaxial wafer was patterned by dry etching into a ridge waveguide gain device with a stripe width of 5 μm. The device was cleaved at the cavity length of 4 mm and mounted p-side down on a copper heat sink. The two facets of the device were both uncoated.

The Littrow configuration, which was similar to that in our previous study,[18,19] was used in the EC tuning experiment. The light emission from one facet of the QD device was collimated by using an aspherical lens with a numerical aperture of 0.5, and then was fed back by a 600-groove/mm grating in the first diffraction order. By rotating the grating, the resonance wavelength was selected. The emission spectrum and output optical power were measured from the other facet of the QD device under a pulsed injection current at a repetition rate 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 pyroelectric probe divided by the 3% duty cycle.

3. Results and discussion

Figure 1 shows the light power–injection current (P–I) curve and the normalized emission spectra of the free-running QD device (not mounted in the EC system) at different injection levels. A maximum output power of 7.8 mW under 2.5-A injection is obtained. At a low injection level of 10 mA, the peak of the emission spectrum is centerd at 1621 nm with a full width at half maximum (FWHM) of 172 nm and the QD ground-state (GS) transition dominates the emission spectrum. With the injection current increasing, the GS emission is gradually saturated and the excited-state (ES) emission of the QD becomes notable. A spectrum bandwidth of 187 nm is observed at 100-mA injection current, to which the contributions are made by both the GS and the ES transitions of the self-assembled QD. At the injection level of 400 mA, the peak of the emission spectrum is around 1515 nm with an FWHM of 146 nm. The emission spectrum from the device is dominated by the spontaneous radiation at a low injection level. For the injection currents of 800 mA and 1100 mA, the FWHMs of the emission spectra are 98 nm and 88 nm, respectively, and the ES emission peaks of the two spectra shift to 1470 nm and 1453 nm, respectively. With the injection level increasing, the bandwidth of the spectrum gradually becomes narrow and the emission peak is blue shifted, which could be attributed to the fact that the QD ground state tends to be saturated and the higher energy states are filled simultaneously at a relatively high injection current. Another possible reason that makes the spectrum narrow could be the increase of the stimulated radiation when the current is high enough. Eventually at 1700-mA injection current, the free-running device lases at the wavelength of 1421 nm due to the excited state of QDs where the optical gain exceeds the internal and mirror losses.

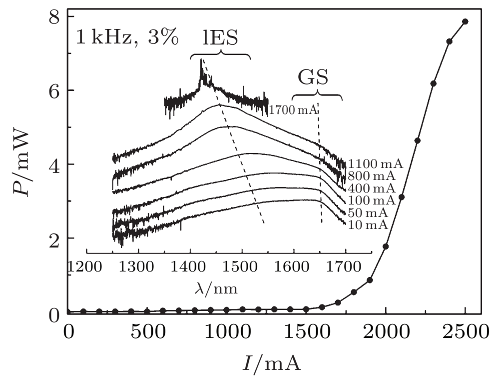

Fig. 1. The P–I curve of the free-running InAs/InP QD device in pulsed injection mode at room temperature. The inset shows the normalized emission spectra of the free-running QD device under different injection levels with the logarithmic sale in the spectral intensity. Some of the spectra are shifted vertically for clarity. The dashed lines denote the transitions from the ground and the first excited states.

The QD gain device is mounted in the Littrow EC system to investigate its tuning properties. Figure 2 shows a series of tuning spectra of the EC laser under 1900-mA pulsed injection (1 kHz and 3%). For the EC laser, a tuning bandwidth of 77 nm, from 1391 nm to 1468 nm, as contributed only by the excited state of the QDs, is realized. The light gain of the laser due to the QD ground state is not enough to compensate for the total cavity loss, so the external-cavity laser does not achieve lasing in the longer wavelength region. When the tuning is close to the long or short wavelength limit, the gain at the external cavity resonance decreases and the inner Fabry–Pérot (FP) resonance peak appears, whose position remains unchanged. Around the tuning center, the inner FP lasing of the free-running laser is suppressed well due to the high feedback from the grating.

Figure 3 shows the tuning spectra of the EC laser under a pulsed current of 2300 mA, the tuning bandwidth is 78 nm (from 1383 nm to 1461 nm). With respect to the case of 1900-mA injection current, both the long and the short tuning wavelength limits under the 2300-mA injection current are blue shifted to some extent. In other words, with the pump level of the laser increasing, the tuning extends towards the short-wavelength region, while in the long-wavelength region, the EC laser loses the ability to lase. This tuning bandwidth extension to the short wavelength side is due to a large light gain in higher energy states that have been filled by more carries under a higher injection current.[18] In addition, a relatively large pump current leads to a strong inner FP lasing mode, which competes with the EC mode and consequently restricts the tuning ability in the long-wavelength region. By combining the effect of the injection current (Figs. 2 and 3) with the grating tuning, the total tuning bandwidth of the external cavity quantum-dot laser can reach up to 85 nm. It can be concluded that a larger tuning bandwidth would be realized if the FP lasing from the QD device itself is inhibited. Facet coating will be performed in the following study to suppress the FP lasing.

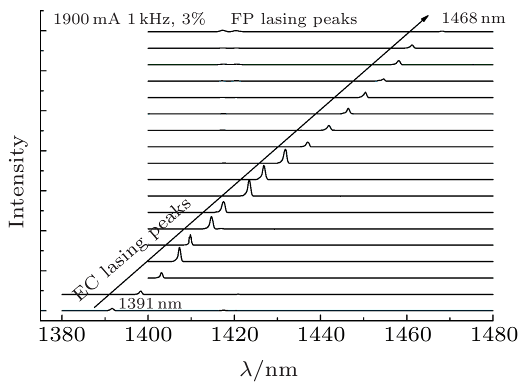

Fig. 2. Lasing spectra of the grating-coupled EC InAs/InP QD laser under 1900-mA current in pulsed injection mode at room temperature.

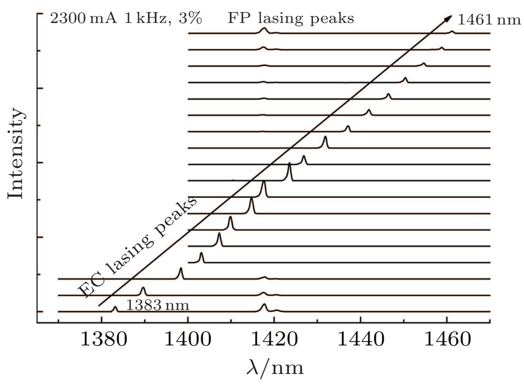

Fig. 3. Lasing spectra of the grating-coupled EC InAs/InP QD laser under 2300-mA current in pulsed injection mode at room temperature.

Figure 4 shows the threshold current ($I_{\rm th}$) of the EC laser obtained from the *P–I* measurement as a function of the tuning wavelength. The $I_{\rm th}$ increases gradually from the lowest threshold wavelength towards both long and short wavelength sides. In the long wavelength region, the smaller gain restricts the tuning limitation. The reduced occupation probability of the higher energy state results in a decline of the material gain and a tuning limitation towards the short wavelength.[19] A maximum output power of 7.8 mW is obtained at the tuning wavelength of 1423.5 nm for the EC laser under 2300-mA injection current.

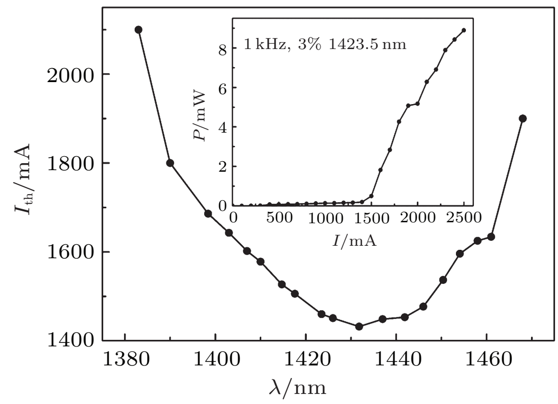

Fig. 4. Dependence of the threshold current on the tuning wavelength for the grating-coupled EC InAs/InP QD laser. The inset shows light output power–injection current (*P–I*) curve for the EC wavelength tuned at 1423.5 nm.

4. Conclusion

In this paper, an InAs/InP QD laser structure is grown by MOCVD. The QD device starts excited-state lasing at the wavelength of 1421 nm under an injection current of 1700 mA. The grating-coupled ECLs based on this uncoated QD laser diodes mounted in the Littrow configuration are demonstrated and characterized. A 77-nm tuning bandwidth under the 1900-mA injection is realized. With working current increasing to 2300 mA, the long and the short tuning wavelengths are both blue shifted to some extent. By combining the effect of the injection current with the grating tuning, the total tuning bandwidth of the QD device can reach up to 85 nm with a maximum output power of 7.8 mW. Further extension of the tuning bandwidth towards the longer wavelength region is possible by suppressing the FP lasing.

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