A review of external cavity-coupled quantum dot lasers

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Abstract Since the external cavity quantum dot laser was first demonstrated, the performances have been improved in terms of operation temperature, output power, pulse generator and tuneability based on the naturally size fluctuation of quantum dot. Nowadays, the external cavity quantum dot sources have been successfully used in different absorption spectroscope techniques, in industry, biomedical and research. In this paper we reviewed the recent developments of quantum dot lasers operated in a grating-coupled external cavity system where a single frequency and wide tunable wavelength range were easily obtained by adjusting the grating angle. In all cases, we mainly stressed the significant progresses in understanding of basic optical and electronic properties to enable the importance steps forward. The prospects for further progress directed towards stability, mode-hoping-free tuning range, miniaturization and integration of the external cavity quantum dot lasers also reviewed.

Keywords External cavity system · Quantum dot laser · Tunable laser · Grating

1 Introduction

Self-assembled quantum dot (QD) as active regions of a laser diode has gained a lot of attentions due to its δ-like quantum state density, which displays some unique optical and

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electrical properties that are different in character to those of the corresponding quantum well (QW) lasers and bulk material lasers (Akiyama et al. 2002; Kovsh et al. 2003; Arakawa and Sakaki 1982; Liu et al. 1999). In recent years, successful growth techniques, such as solid-state molecular-beam epitaxy (SSMBE) (Joyce et al. 2002; Xie et al. 1995; Garcia et al. 1997; Kim et al. 2004), metal organic vapor-phase epitaxy (MOVPE) (Oshinowo et al. 1994; Heinrichsdorff et al. 1996, 1997; Jang et al. 2004; Anantathanasarn et al. 2006), chemical-beam epitaxy (Poole et al. 2009), and gas source molecular-beam epitaxy (GSMBE) (Chang et al. 2003; Paranthoen et al. 2001; Lelarge et al. 2005; Li et al. 2008), have been used to growth the QD materials. Good performances of QD lasers in terms of lower threshold current density, high quantum efficiency, high characteristics temperature and high wavelength stability have been obtained (Mi et al. 2005; Liu et al. 2006; Fathpour et al. 2004; Huang et al. 2001; Kloof et al. 2002; Shchekin and Deppe 2002; Kim et al. 2005; Alghoraibi et al. 2007; Saito et al. 2001; Jang et al. 2004; Li et al. 2009; Paranthoen et al. 2002). While, the QD lasers with internal cavity (Fabry-perot cavity) always emit their wavelength in multimode and are hard to achieve a single mode even if the cavity length of QD lasers is shortened. This undesirable characteristic has limited its applications in the fields of spectroscopy (Woodworth et al. 2001), biomedical (Olesberg et al. 2005), interferometer (Kuramoto and Fujii 2005) and wavelength-division-multiplexing (WDM) system (Tanaka et al. 2004).

To achieve a single frequency, distributed feedback (DFB) lasers, distributed Bragg reflector (DBR) lasers and their more advanced versions like sampled-grating DBRs (SG DBR) (Jayaraman et al. 1993) and superstructure grating DBRs (SSG DBR) (Tohmori et al. 1993), as well as vertical cavity surface emitting lasers (VCSEL) (Yang et al. 2005; Ustinov et al. 2001), have been performed. However, these kinds of lasers can be tuned over only a limited spectral range by changing injection current or operation temperature. Recently, an important grating-coupled external cavity (EC) system has been invented to obtain a wide spectral tunable range. The multi-quantum-well laser as light source has been successfully applied to the interesting system and a wide tuning range of 240 nm at 1.55 μm has been reported. However, extremely large current density, e.g., 33 KA/cm^2 (Tabuchi and Ishikawa 1990) had to be applied in order to achieve the tuning range. In contrast, EC taken quantum dot lasers as light source are able to operate at relatively much lower current density and simultaneously maintain a broad wavelength tuning range. A wide wavelength range of 201 nm has been obtained in GaAs based QD laser diode with a maximum injection current density of 2.87 KA/cm^2 (Varangis et al. 2000). This good performance is due to unique features of the QD material, i.e., low density of states and broad gain profile. Random size distribution of QD naturally results in a broad gain profile which is the key factor for broadly tunable lasers. Low state density of QD leads to rapid filling of the energy levels and consequently allows the wide gain profile to be utilized under the condition of low operation current (Varangis et al. 2000; Chen et al. 2011). Although, the recent developments of external cavity semiconductor lasers (Mroziewicz 2008) and quantum cascade lasers have been summarized (Hugi et al. 2010). There is no detailed report about the progresses of grating-coupled external cavity quantum dot laser (ECQDL).

In this paper, we reviewed the recent development of ECQDL based on the significant QD lasers, covering the 1.3 μm InAs/GaAs system and 1.55 μm InAs/InP systems. The famous EC system of Littrow configuration and Littman–Metcalf configuration and mode selection theory of blazed grating with a high reflective index were introduced. The performances of ECQDL, such as the wavelength tunable range, output power, threshold current density, quantum efficiency and operation temperature, were summarized. Wavelength tunability is one of the main important parameter of QD laser diode and special attention will be paid to this particular properties. At the same time, we also predict future progresses of ECQDL.

Fig. 1 Schematic diagrams of the External cavity based on the most famous Littrow configuration and the Littman–Metcalf configuration, which are made up of three main elements, including a gain element, a collimating lens and a grating. **a** Littrow configuration and **b** Littman–Metcalf configuration
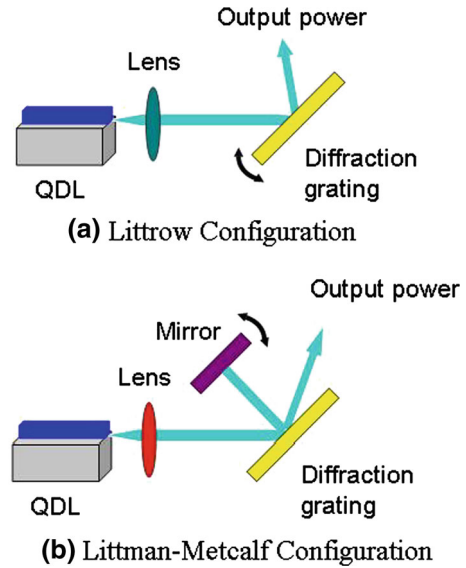
2 The basics of external cavity

Up to now, lots of EC structure, i.e. high reflective-index mirror, electro-optic filter (Ménager et al. 2000; Levin 2002), acousto-optic filters (Coquin and Cheung 1988; Takabayashi et al. 2004) and etalon plus wavelength selective mirror, have been carried out on the semiconductor laser. While, grating-coupled EC system is a widely used technique to alter a free running semiconductor laser into a tunable single mode. In general, the external cavity system is made up of three main elements, including a gain element (in our case the gain element is QD laser chip), a collimating lens and a grating which acts as a wavelength filter element within the system. The EC structure is usually based on the Littrow configuration and the Littman–Metcalf configuration, as shown in the Fig. 1. In Littrow configuration, there contains a collimating lens and a diffraction grating as the end mirror, as shown in Fig. 1a. The diffracted beam provides optical feedback to the laser diode chip, which has a naturally as-cleaved facet or an anti-reflection coating on the right-hand side. The emission wavelength can be tuned by rotating the diffraction grating. A disadvantage is that this also changes the direction of the output beam, which is inconvenient for many applications. In the Littman–Metcalf configuration shown in Fig. 1b, the grating orientation is fixed, and an additional mirror is used to reflect the diffraction beam back to the laser diode. The wavelength can be tuned by rotating that mirror. This configuration offers a fixed direction of the output beam, and also tends to exhibit a smaller linewidth, as the wavelength selectivity is stronger. A disadvantage is that the first-order reflection of the beam reflected by the tuning mirror is lost, so that the output power is lower than that for a Littrow configuration laser.

The diffraction grating plays an important role in the EC system to select a single frequency. For ECQDL system, the blazed grating was normally applied to adjust the lasing mode. Like standard diffraction gratings, blazed gratings diffract incoming light using a series of grooves. However, in blazed gratings the grooves have been manufactured such that they form right angles with a specified "blaze angle," which is the angular distance from the surface normal of the diffraction plate. The magnitude of the blaze angle determines the wavelength at which

the grating will be most efficient. The lasing wavelength is determined by the centre of the grating dispersion curve, which is given by the well-known grating equation,

$$m\lambda = d(\sin\theta_i + \sin\theta_m) \qquad (1)$$

where θ_i is the angle of incident (relative to the grating normal), θ_m is the angle of diffraction order, d is the grating period, m is the diffraction order (usually a small integer $0, \pm1, \pm2\ldots$), λ is the diffraction wavelength, which can be adjusted by the change of angle of incident light. However, the actual operating process is different because the selective wavelength is tuned by different method in Littrow configuration and Littman–Metcalf configuration (Mroziewicz 2008).

3 The achieved parameters of ECQDL system

3.1 InAs/InP ECQD laser

Self-assembled InAs QD lasers based on the InP substrate are of considerable interest as they can offer potential applications in the fiber optical communication system of 1.55 μm. With the progress of growth techniques, high densities of 10^{10} cm^{-2} on the InP(100) substrates (Li et al. 2008) and 10^{11} cm^{-2} on the InP(311) substrates (Caroff et al. 2005) have been demonstrated. However, size fluctuation is the naturally properties of QD grown by the Stranski-Krastanaov mode (Anantathanasarn et al. 2006; Paranthoen et al. 2001; Li et al. 2008; Alghoraibi et al. 2007), as shown in the Fig. 2a. Although, the size fluctuation of QD can generally be controlled by the growth equipments and growth procedures. Such unavoidable size fluctuation always brings about a wide electroluminescence (EL) spectrum, as shown in the Fig. 2b. This feature of QD gain chip is a very interesting in the EC system because it is the foundation to achieve a wide wavelength tunable range. For a normal QD gain laser diode, the lasing processes are generally regarded as that the EL spectra narrow gradually and the peak wavelength shifts to higher energy side with the increase of injection current and finally emits its lasing spectrum at higher energy side of EL spectrum. The spectra of as-cleaved facet laser always exhibited multimode lasing and the lasing spectra gradually broadened with increasing applied current. These unique properties are normally to the QD laser diode because lots of QD can capture the carriers in a lager current and provide a wide gain profile, which has been observed in the references (Mi et al. 2005; Liu et al. 2006; Fathpour et al. 2004; Huang et al. 2001; Kloof et al. 2002; Shchekin and Deppe 2002; Kim et al. 2005). However, when this gain chip applied to the ECQDL system based on the Littrow configuration, a single mode was obtained at a special angle of blazed grating and a wide wavelength tunable range was performed by rotating blazed grating, as shown in the Fig. 2c. A tunable range of 70 nm was achieved by adjusting the angle of grating, as shown in the inset of Fig. 2c. The tunable range is a little wider than the linewidth of EL spectrum under a little below threshold current. This special property is attributed to the size non-uniform distribution of QD and the high reflection from the blazed grating.

The cavity length of QD gain chips always plays an important role in the wavelength tunable range and output performance of ECQD system. Three QD gain chips consisted of same active region, but in different length of 1.3, 1.5 and 2.0 mm, were applied into EC system. When the length of QD gain chips decreases from 2.0 to 1.3 mm, the maximum-tunable-wavelength ranges increases from 57 to 105 nm, as shown in the Fig. 3. Obviously, as the length of QD gain chips shortened, the tunable wavelength shifts toward high energy side of EL spectrum and possibly exhibits a wider tunable wavelength range. Such similar

Fig. 2 **a** Three-dimensional AFM image of uncapped InAs QD on the lattice matched InGaAsP with InAs thickness of 3.0 ML. The scaling size is 3 µm × 3 µm. **b** EL spectra of a free-running QD laser (cavity size of 1.5 mm × 8 µm) at an injection current of 140 mA. **c** Lasing spectra of the external cavity quantum dot laser in the littrow configuration. A tunable range of 70 nm was obtained by rotating the grating shown in the *inset* of **c**
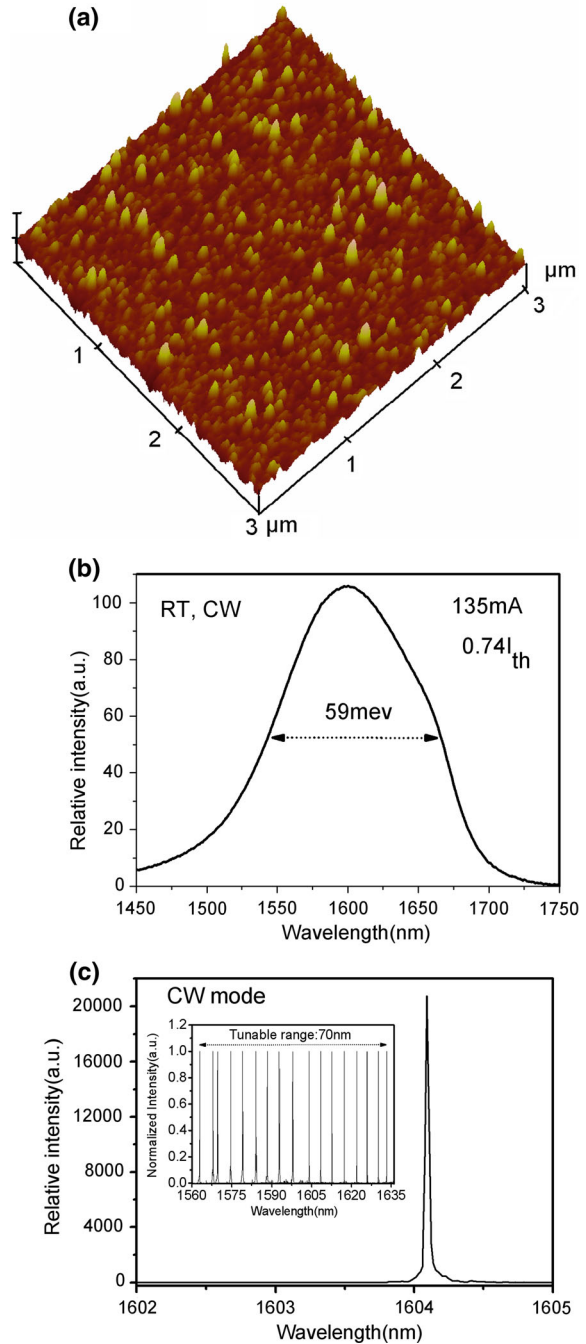
properties have been obtained in Allen et al. (2006). This special property is considered to come from the cavity loss from different QD gain chips. As the cavity length of QD gain chips shortened, the facet loss in average cavity length of chips increased, which helpfully decrease

Fig. 3 The maximum tunable wavelength ranges were obtained by different cavity length of QD gain chips under CW mode. All QD gain chips have cavity width of 6 μm and the active regions were composed by five-stacked InAs layers with thickness of 3.5 MLs
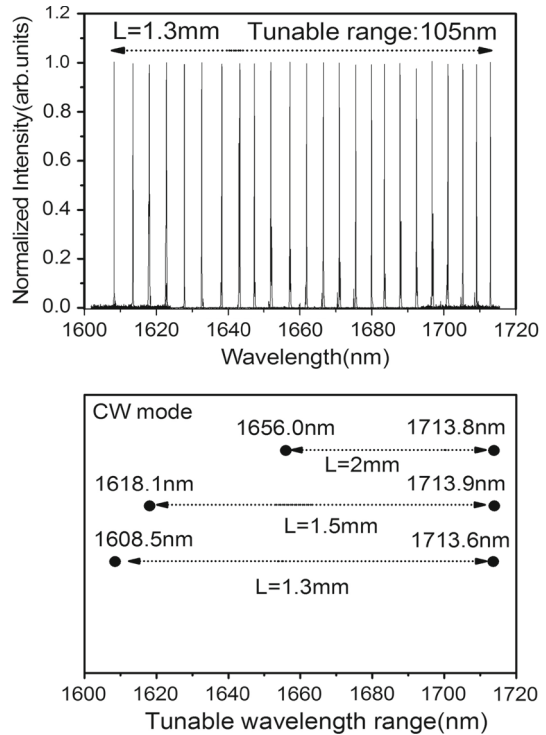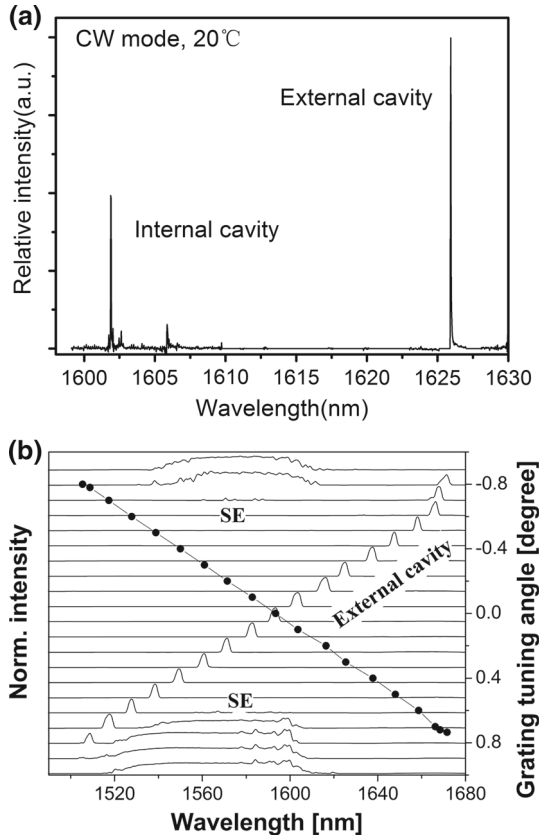

the probability of the internal cavity lasing from QD gain chips. So, a larger injection current can be applied to QD gain chips and meantime maintains no any lasing from internal cavity modes. Under higher amplitude of applied current, more carriers will fill into higher states of the QD gain chips and a wider EL spectrum can be easily obtained. These are origin of wider tunable ranges. However, when the QD gain chips with longer cavity length were applied to the EC system, the wavelength always shows a small tunable range. These can be explained by that longer length of QD gain chips have a large number of QD in the active region and can easily provide enough gain to drive internal cavity modes lasing, which limit their tunable range in EC system. So, to pursue simply a wider tunable range in the EC system, a shorter cavity length of QD chips is considered to be an efficient way. Up to now, the maximum tunable range of 110 nm based on InAs/InP QD gain chip with a cavity length of 1 mm has been achieved by Allen et al. (2006). Although, shorter cavity length of QD gain chips can be easily performed a maximum tuneability in EC system, the increased loss of QD chips largely degrades the output performance because the most parts of input power converts into phonon in the active region of QD chips and then decreases quantum efficiency. On the other side, the external cavity length dependence of maximum tuneability in QDEC system was investigated by changing the length from 50 to 300 mm in the steps of 50 mm. We found that the length of external cavity (the total distance from the back side of QD gain chips to the blazed grating) had a little impact on the tunable wavelength range of ECQDL.

To achieve a wider tuneablity and meanwhile maintain good quantum efficiency in the ECQD system, longer cavity length of QD gain chips are the better choices. While, the crucial points by taking such QD gain chips are that the lasing from the internal cavity modes should be prevent completely. It is well known that the ECQDL system is composed of an internal

cavity (Fabry-perot cavity) of the QD gain chip and a grating-coupled external cavity system. There always exists a competition between the external cavity lasing modes and the gain chip lasing modes. Therefore, the ECQDL can emit double lasing wavelength simultaneously when the injection current reaches threshold current of internal cavity of gain chips and the EC system, as shown in Fig. 4a. This property has also been observed in the article (Allen et al. 2006). Generally, internal cavity lasing modes of QD gain chip are undesirable when the ECQD laser is applied to some special system, i.e. absorption spectroscope of atom, gas detection system and biomedical system because they always emits multimode wavelength, which leads to interfere with ECQDL applications. To eliminate the lasing spectrum from the internal cavity of QD gain chips, an improved method is that a higher reflection layer is coated on one facet of QD gain chips to improve efficiency and an antireflection layer deposits on the other facet to obtain a broad gain spectrum. The facet of QD gain chips deposited an antireflection layers tremendously increase the loss of internal cavity, which helpfully inhibits the lasing spectrum from internal cavity even if the injection current has a large amplitude. Meanwhile, this method has another merit to bring about a wide tunable range because the carries can fill to higher state (the first excited state and/or second excited state) and provide a wider gain profile. By taking this method, Ortner et al. (2006) has been reported on an InAs/InP ECQDL diode with maximum wide tunable range of 166 nm, as shown in Fig. 4b. At the same time, a good output performance is simultaneously obtained.

In the ECQDL system, the threshold current density (J_{th}) is usually lower than that of the free-running QD laser diode at almost all the lasing wavelength in the tuning range. The special properties from ECQDL are attributed to the selective feedback from grating, which decreases the loss of as-cleaved facet because the grating diffraction intensity from the zero order and first-order occupies the main rate of the total diffraction intensity. It is well known that the lasing conditions for a normal QD laser obey the following equation:

$$g_{th} \geq \alpha = \alpha_i + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) \tag{2}$$

where g_{th} is the threshold of gain profile of QD laser, α is the total loss, α_i is the internal loss of QD laser diode, which is determined by the materials in the active region, L is the cavity length of QD gain chips, R_1 and R_2 are reflectivity of the facet on both side. For a normal InP-based QD gain laser, the reflectivity as-cleaved facet is approximately 0.32. When a QD gain laser drove by injection current obtain enough gain profile to overcome the total loss, the lasers start lasing at the so-called threshold current (J_{th}). While, when the QD gain laser as-cleaved facet without coating was applied into grating-coupled EC system, one side of facet maintains a reflectivity of 0.32. While the other side of the reflectivity (being near to the grating) increase and reach the diffraction efficiency of grating, which is larger than the value of as-cleaved facet of 0.32. The diffraction efficiency is mainly determined by the grating and normal above 0.8. Comparison with the QD gain chips, the loss from the last term of Eq. (2) decreases and further decreases the threshold current density. On the other side, the J_{th} in EC system is greatly dependent on the gain profile of QD gain chips, as shown in the Fig. 5a. At the maximum gain profile, the J_{th} in EC system exhibits the smallest value because the QD gain chip can easily obtain the gain to overcome the loss and then a small threshold current is achieved. However, in the long wavelength regime, the J_{th} increases gradually and finally exceeds the value of QD gain chip itself. The feature is considered by the decrease density of QD, which causes the gradual decrease in the material gain available of QD laser and a larger injection current is needed. While, in short wavelength regime, the density of ensemble QD is higher, under a fixed injection current the occupation probability of these states decrease, causing a decline of the QD laser gain profile. By further increasing the injection current, the carriers fill to higher state and push the tuning range to short wavelength. These are the reasons the increase of threshold current density and blue-shift wavelength. At the same time, the J_{th} of ECQDL diodes also is relative to the size of QD gain chips, as shown in the Fig. 5b. When the size of QD gain chips increased, the J_{th} has a little decrease. This performance can be explained by the loss decreases and less gain is required to achieve the gain-length product required for threshold current by the increase of cavity length. The tuning wavelength also shifts to longer wavelength side as the cavity length of QD gain chips increased. A possible explanation for this behavior is that more QD states per cavity unit length become available, thus resulting in a larger number of recombination channels for electron-hole pairs contributing to the material gain. By the increase of the cavity width of QD gain chips, the threshold density can be a little decrease, while, the tunable range reduces. So, the choice for actual applications should be made by the requirements.

The output power is also another important parameter of ECQDL and is close connection with the position of lasing spectrum. Figure 6a is the output power as a function of injection current at a different wavelength regime (Chen et al. 2011). The size of QD gain laser based on the InAs/InP material system is 1.5 mm × 8 µm and has an as-cleaved facet. At a wavelength of 1,603 nm being near to the gain maximum profile of QD chip, the ECQD laser exhibits a maximum output power of 24 mW under CW mode. When the wavelength is tuned to longer wavelength regime of gain spectrum and arrives to 1,620 nm, the output power decreases

Fig. 5 **a** EL spectra of a free-running QD laser (cavity size of 1.5 mm × 8 μm) at different injection currents and the threshold current density versus tunable wavelength. The *dashed vertical lines* mark the wavelength tuning range achieved by external cavity feedback in Littrow configuration (from Chen et al. (2011)). The *horizontal line* marks the threshold current density of QD gain chip under the same operation. **b** Threshold current density as a function of laser wavelength for different QD laser lengths and widths as denoted by the *different symbols*. The maximum injected current has been set to 900 mA. The measurements were carried out on the current with a 1 % duty cycle at a frequency of 1 kHz (from Ortner et al. 2006)
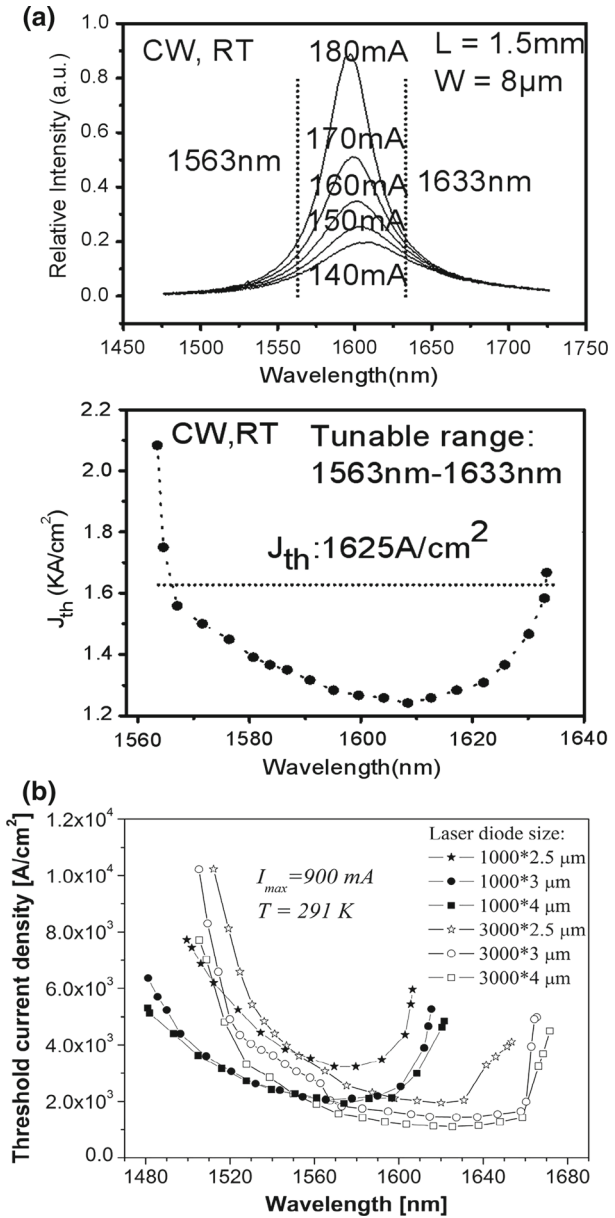
quickly and emits only 2.5 mW. The same trend has been observed in the short wavelength of gain spectrum. It is obviously seen that the output power of ECQDL is greatly dependent on the shape gain spectrum of QD gain chips and the maximum power always happens to the peak of QD chips of gain profile. The special properties have also been demonstrated in the InAs/GaAs based QD gain chips, as shown in the Fig. 6b (Lv et al. 2010). Actually, the gain spectrum of QD chips reflects the density of assembled QD in the active region, which means that there, has the maximum number of dots contribution to the output power at the peak of gain spectrum and performs a higher output power. On the other hand, the
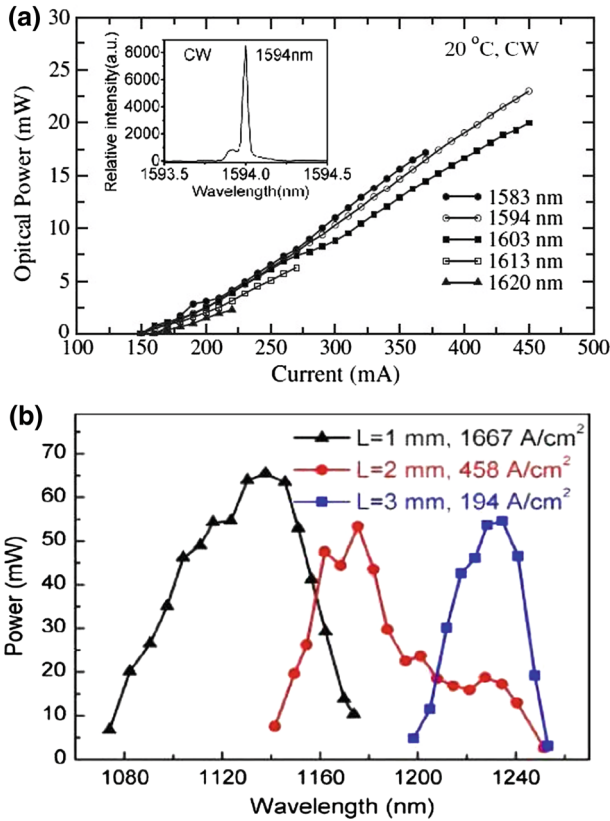
Fig. 6 **a** L–I curve of the ECQDL at different operation wavelengths. The size of QD gain laser based on the InAs/InP material system is 1.5 mm × 8 μm and has an as-cleaved facet (from Chen et al. 2011). **b** Output power of the ECQD lasers based on the InAs/GaAs QD gain chips as a function of tuning wavelength in different cavity length. All QD gain chips have no coating on the facets. For the L = 1 mm device, the injection is pulsed mode and the output power is the peak one (from Lv et al. 2010)

selective grating inhibits the internal cavity of QD gain laser lasing modes, which makes the ECQD laser operating at higher injection current. When the lasing wavelength was tuned to the lower energy side of the gain profile, the quantum efficiency decreased. The decreased quantum efficiency caused by the low carrier capture efficiency due to the limited density of states at the low energy side degraded the performances of output power (Ortner et al. 2006). At the same time, lasing from the FP cavity of QD laser was observed in a relatively early stage, which limited the maximum optical power recorded at low energy side wavelengths. In the short wavelength regime, the decreased output power is due to the larger density of state of QD gain laser, which possibly decreases quantum efficiency.

3.2 InAs/GaAs ECQD laser

Comparison with InAs/InP QD gain laser diode, InAs QD based on GaAs substrate shows a relative small size of QD distribution because of a larger lattice mismatch between the InAs and GaAs. This property leads the InAs/GaAs QD lasers to emit their wavelength in another important fiber optical communication window of 1.3 μm. In the past few years, good performances of the Fabry-perot of QD laser have been achieved (Shchekin and Deppe

Fig. 7 The maximum tunable range obtained in different lasers. Sample A has a maximum range of 150 nm (reproduced from Yang et al. 2010). Sample B has a maximum range of 201 nm (reproduced from Varangis et al. 2000). Sample C has a maximum range of 155 nm (reproduced from Li et al. 2000). Sample D has a maximum range of 110 nm (reproduced from Nevsky et al. 2008)
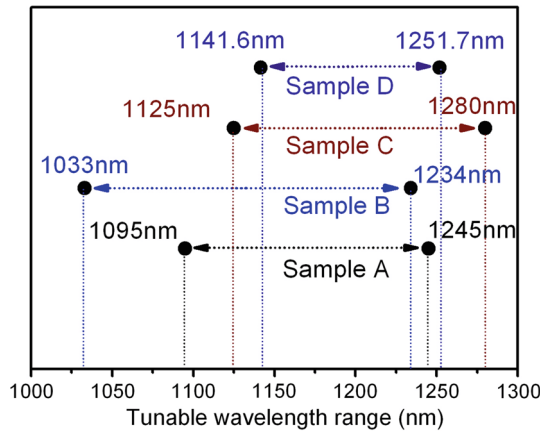

2002; Yang et al. 2010). While, when the InAs/GaAs QD gain lasers applied to the EC system, these lasers exhibit the same properties as that of observed in the InAs/InP QD gain laser diode. By fabricating a high reflection and antireflection on the as-cleaved facet of InAs/GaAs QD lasers, P. M. Varangis et al obtained a wide tuning range of 201 nm under pulse mode. The maximum threshold current density was only 2.87 KA/cm^2, which is approximately 10 times lower than the bias required for tuning quantum well lasers across similar range (Tabuchi and Ishikawa 1990). The maximum tunable wavelength ranges have been achieved recently (Varangis et al. 2000; Lv et al. 2010; Li et al. 2000; Nevsky et al. 2008), as shown in the Fig. 7. The output power performance was also carried out on the InAs/GaAs ECQDL and a high power of 65 mW was obtained under CW operation mode by Lv et al. (2010). The output power performance is as same curve as the gain profile. The maximum output power happened to be the wavelength in the gain peaks.

In the ECQDL setup, it is very important to minimize as much as possible the effective reflective of the gain elements, which can be attained by fabrication of devices with a particular angle of the facet. Basically, two kinds of waveguide structure designs were reported as a bent ridge waveguide gain chip and a title ridge waveguide QD optical amplifier, respectively (Fedorova et al. 2010). When a super-luminescent (SL) InAs/GaAs QD chip with a bent waveguide gain was applied to the ECQD system, a broad gain is obtained because the laser chip can not lase even at a larger injection current. This property is very suitable for achieving a wide wavelength tunable range. Under CW operation mode, a wide tunable range of 202nm was obtained, which cover the ground state and excited state of InAs/GaAs SL gain laser chip, as shown in the Fig. 8 (Fedorova et al. 2010). The output power arrived to 480 mW and a side-mode suppression ratio was greater than 45 dB in the central part of the tuning range (Fedorova et al. 2010). While, this kind of QD gain laser has a larger threshold current than that of normal QD gain laser diode because of its special waveguide structure, which greatly decreases the quantum efficiency. Therefore, a larger current is needed to drive the ECQD super-luminescent laser chip lasing and the current density increases.

3.3 ECQD mode-locked laser

Mode-locking laser is a technique in optics by which a laser can be made to produce pulse of light of extremely short duration, on the order of picoseconds (10^{-12} s) or femtoseconds (10^{-15} s). Methods for producing mode-locking in a laser may be classified as either active or passive. Active methods typically involve using an external signal to induce a modulation of

Fig. 8 Spectra of the QD-EC diode with the gain chip, tuned across the 1,122.5–1,324.5 nm wavelength range, under an applied constant current of 1.7 A. The gain chip ridge waveguide has a width of 5 μm and length of 4 mm, and is angled of 5° with respect to the normal to the back facet. The front facet was coated by anti-reflective coatings. The optical spectra obtained by tuning this laser across the 1,122.5–1,324.5 nm wavelength range (from Fedorova et al. 2010)
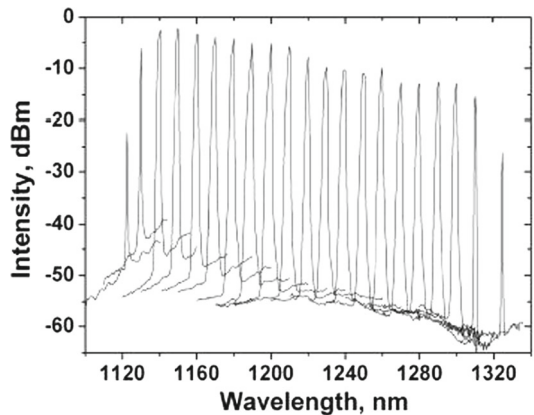
the intra-cavity light. Passive methods do not use an external signal, but rely on placing some element into the laser cavity which causes self-modulation of the light. The QD lasers owning to its discrete nature of the density of states have been considered to be next generation of compact ultra short source, which has very important application in the fields of medicine (Wardle 2009), telecommunication (Attygalle et al. 2003; Keeler et al. 2003) and material processing (Steen and Mazumder 2010). Although, self-mode locked pulse of light has been found from a monolithic chip and a frequency of 92.5 GHz based on InP substrate QD laser diode has been obtained (Liu et al. 2008), the mode-locked QD laser are usually fabricated into two sections on a monolithic chip. One section took role of gain element by applying forward current on this element to drive the laser emitting light. The other one is the saturable absorber, which will selectively absorb low-intensity light and transmit light which is of sufficiently high intensity. The mode-locked QD based on the two sections structure has recently been demonstrated a 50 nm wavelength bistability (between 1,245 and 1,295 nm) with output power up to 25 and 17 mW (Nikitichev et al. 2011). Recently, Hoffmann et al. (2011) have demonstrated femtosecond vertical external cavity surface emitting laser based on self-assembled InAs/GaAs QD gain layers. The mode-locked laser has a good output performance and exhibits more than 1 W of average output power with 784-fs pulse duration at a repetition rate of 5.4 GHz. While, these kinds of lasers can not achieve a large scale wavelength tuning, which limit their applications.

The ECQD mode-locked laser is taken QD mode-locked laser as gain light source in the EC system. The wavelength tuning is realized by rotating the diffraction angle of grating. By taking this method, broad wavelength tenability of 136.5 nm (between 1,182.5 and 1,319 nm) has been achieved on the GaAs based QD mode-locked laser (Nikitichev et al. 2012). At the same time, the peak power of 532 mW was obtained at the wavelength of 1,226 nm. The pulse duration of 15.3ps was also demonstrated in this wavelength region, as shown in the Fig. 9 (Nikitichev et al. 2012).

4 Prospects for further progress

4.1 New QD laser materials

A major advantage of the EC configuration is that it may be employed regardless of the material and cavity size from which we make the lasers. This feature enables to build lasers
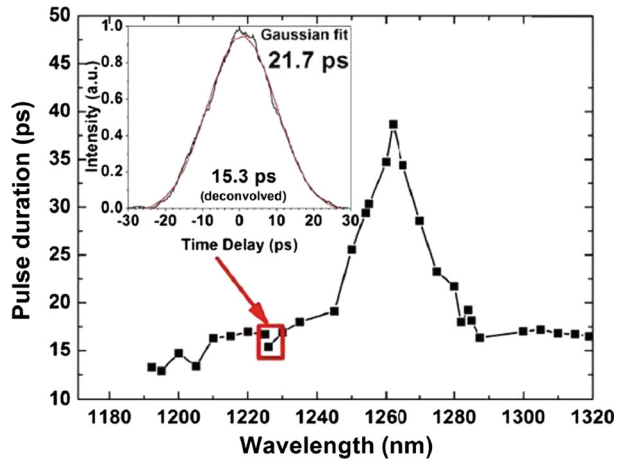
emitting in very wide wavelength range that is limited only by the availability of the gain chips. Up to now, a great number of ECQDL emitting within the near-infrared wavelength range of 1.3 µm based on the GaAs substrate and 1.55 µm on the InP substrate have been described as indicated in the preceding sections but there is still an effort being put into development of new materials and structures that would expand the spectral limits towards both visible wavelength and far-infrared. In the visible region, although the bulk laser and quantum well laser have been achieved (Lonsdale et al. 2002), there is a little report about the QD laser achieved in this wavelength region because the self-assembled growth mode can hardly obtain a small size of QD. In the far-infrared wavelength region, especially for the range of 3–5 µm, the interband quantum cascade lasers based on the GaSb substrates have been successfully achieved and shown very good performances at room temperature. However, these kinds of lasers contain hundreds of quantum wells and barriers, resulting complicated material growth procedures. Especially, the thickness and component of each quantum well and barrier should be precision control when these materials are fabricated. Such little imperfections may increase the cost. Due to the unique characteristics of QD gain chips, a new materials system of InAsSb/InP covering their wavelength in these regions is considered to be another choice (Cornet et al. 2005). Recently, good performance of QD laser in a wavelength of 2 µm has been obtained (Qiu et al. 2004). These kinds of QD laser are expected to achieve a longer wavelength in the ECQDL system.

4.2 Stability and mode-hoping-free tunability

A single frequency from ECQDL system has very important applications in many fields as described in the preceding sections. However, the stability of ECQDL are one of most the properties in the actual applications. The stability is greatly dependent on the operating environment, such as operation temperature and the ability of vibration. When the operation temperature increased, the thermal effect always results the changes of cavity size of QD gain lasers and the period of gratings, which always leads to the mode hopping of ECQDL. These features are undesirable when the lasing spectrum is needed to have a high resolution (for example, the ECQDL is applied to detect the gas and atom absorption spectrum). At the same time, the vibration of EC system always changes the light path and the angle of grating, resulted simultaneously the decrease of output power and mode hopping. To exclude these

undesirable characteristics, further works of the ECQDL system are integrated into vacuum system on the vibration reduced platform.

In ECQDL system, the mode-hoping-free (MFH) tuning range is an important parameter, which is influenced by the factors of operation temperature, grating angle, injection current, internal cavity length and external cavity length. It may exhibit complicated behavior of wavelength change in response to an external feedback since the existence of many oscillation modes could easily cause the peak mode to hop among some of the modes in addition to the continuous shift. For example, the frequency of the ECQDL at a fixed temperature is determined by the injection current, the grating angle and the length of cavity. This mode hopping of ECQDL system restricts their applications in the high resolution requirements system. To obtain a broad continuous MHF tuning range, the frequency supported by all the above factors must tune synchronously, which means that the shift of frequency caused by the change in injection current and temperature must be equal to the frequency shift caused by change in cavity length and grating angle. Recently, MHF tuning over 135 GHz has been obtained in external cavity diode laser (Dutta et al. 2012). However, there are not any detailed reports about the mode-hoping-free in ECQDL system. Therefore, more works should be carried out on the very important parameter of MFH tunable range.

4.3 Miniaturization and integration of ECQDL system

So far, most of studies were focused on the tunable range of wavelength and the output power of ECQDL system. The EC set-up is usually composed of isolated elements (including a QD gain laser, a lens and a grating) and shows a larger volume. It is obvious, however, that the micro-scale ECQDL systems have been as well attracting the research interests in recent years. Although, a small size of 5×5 mm size of EC tunable laser has been reported by a micro-fabricated technique and obtained about 20-nm range wavelength tuning (Uenishi et al. 1996), the micro-mirror for this laser diode was fabricated using nickel plating and that was incompatible with the integrated circuit. At the same time, the gain element using a normal laser diode limits the wavelength tunable range. Recently, an InGaAsP/InP heterostructure optical amplifier was integrated by an active region, a wave guide and an etched diffraction grating on a monolithically chip and obtained only 8.5-nm range wavelength tuning (Kwon et al. 2008). While, the ECQDL is still in its infancy and has a long way to realize the miniaturization and Integration. The successful fabrication of InAs quantum dot on the silicon/ or germanium substrate (Liu et al. 2011; Lee et al. 2012) opens the road to the Integration of ECQDL system on a monolithically chip. The future ECQDL configuration is considered to show the miniaturization and Integration and have the ability to realize a wide wavelength tunable range.

5 Conclusions

The grating-coupled ECQDL system plays a very important role in the applications of spectroscopy, biomedical, interferometer and wavelength-division-multiplexing (WDM) system because this system can achieve a single narrow-linewidth frequency. Comparison with conventional techniques, i.e., the DFB lasers, the DBR lasers and VCSEL, the superiority of ECQDL system is that it can obtain a narrow linewidth wavelength with a wide tunable range by adjusting the angle of grating. These unique and special performances are due to the QD materials, which have a low density of states and broad gain profile owning to the size non-uniform distribution. By inhibiting the lasing from internal cavity, the tuning range

can cover the ground state and excited states of QD laser. At the same time, the ECQDL has an advantage over the EC quantum well laser system in the threshold current density and quantum efficiency. In this article, we mainly introduce the recent developments of InAs/InP quantum dot laser at wavelength of 1.55 µm, InAs/GaAs quantum dot laser of 1.3 µm and quantum dot mode-locked laser. High output power and wide wavelength tuning range have been obtained in these lasers. However, there are still some challenges in the fields of good stability, larger MHF tuning range, miniaturization and integration of the external cavity quantum dot laser system. Therefore, more studies should be carried out in these fields in future.

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