Broadly tunable high-power InAs/GaAs quantum-dot external cavity diode lasers

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Abstract: A record broadly tunable high-power external cavity InAs/GaAs quantum-dot diode laser with a tuning range of 202 nm (1122 nm-1324 nm) is demonstrated. A maximum output power of 480 mW and a side-mode suppression ratio greater than 45 dB are achieved in the central part of the tuning range. We exploit a number of strategies for enhancing the tuning range of external cavity quantum-dot lasers. Different waveguide designs, laser configurations and operation conditions (pump current and temperature) are investigated for optimization of output power and tunability.

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

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1. Introduction

The development of high-power, broadly tunable, compact and low-cost external cavity diode lasers (ECDLs) is an important research area for a wide range of applications, such as spectroscopy [1], interferometry [2] and testing of telecommunication and wavelength division multiplexing (WDM) systems [3]. In recent years, there has also been a growing interest in the development of broadly-swept tunable laser sources, which are of interest for optical coherence tomography due to their high spectral bandwidth and output power [4,5]. Furthermore, the spectral region encompassing 1.1 - 1.3 μm is particularly useful for biomedical imaging due to the minimal absorption and scattering in human tissue, which can significantly enhance the penetration depth [6]. Other important applications for this spectral range include the generation of coherent radiation in the visible spectral region via second harmonic generation or sum frequency generation, particularly into the yellow-orange spectral region [7], for which compact and efficient sources are relatively scarce.

However, the spectral range between 1.1 - 1.3 μm has been difficult to access with semiconductor lasers based on quantum-well (QW) technology. In this respect, quantum-dot (QD) materials have shown great promise for a new generation of optoelectronic devices and ultrafast technology [8]. Recently developed growth techniques have been able to control the fabrication of InAs/GaAs QDs with different transition energies, allowing the coverage of a broad spectral range between 1.0 μm and 1.3 μm [9]. For instance, the inhomogeneous broadening associated with the strain and size dispersion of the QDs (inherent to the Stranski-Krastanow growth techniques) results in a distribution of energies which, to some extent, parallels the distribution of QD sizes. This feature, together with the manipulation of the chemistry and strain of the capping layers and barriers, can be flexibly engineered to widen the emission spectral bandwidth. By exploiting such broad gain bandwidths, QD external cavity diode lasers (QD-ECDLs) have demonstrated impressive tuning ranges up to 200 nm, for the spectral range between 1095 and 1245 nm [10] or between 1033 and 1234 nm [11]. However, the power emitted from these previously reported lasers was reasonably low (of the order of a few tens of mW). Nevsky *et al*. have demonstrated output power higher than 200 mW from a QD-ECDL, within a tuning range of 155 nm (between 1125 nm and 1280 nm) [12]. However, this tuning range was not realized at the same injection current. Very recently, a low-threshold tunable QD-ECDL in the spectral range 1141.6 – 1251.7 nm with a maximum output power of 53 mW has been reported [13].

In this paper, we present a high-power (0.48 W) InAs/GaAs QD-ECDL with a continuous tuning range of 202 nm – the highest tuning range with high output power achieved in a QD-based laser. A number of strategies for enhancing the tuning range of QD-ECDLs are also demonstrated through a comparative investigation of the tuning characteristics of InAs/GaAs QD-ECDLs for different waveguide designs, laser configurations, temperature and current conditions.

2. Experimental setup

In an ECDL setup, it is crucial to minimise as much as possible the effective facet reflectivity of the gain element, which can be attained with the fabrication of devices where the waveguide is at a particular angle with the facet. In this work two waveguide structure designs were investigated: a bent ridge waveguide gain chip and a tilted ridge waveguide semiconductor optical amplifier (SOA). Both devices were fabricated from the same QD

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wafer structure, with an active region which contained 10 non-identical InAs QD layers, incorporated into $Al_{0.35}Ga_{0.65}As$ cladding layers and grown on a GaAs substrate by molecular beam epitaxy. A broad spectral emission was achieved by changing the thickness of the $In_{0.15}Ga_{0.85}As$ capping layers for different groups of QD layers. This approach results in increased indium segregation into the quantum dots that have thicker capping layers, and as such, the average size of the quantum dots capped with thicker layers becomes larger. Furthermore, the level of confinement in these quantum dots allows for the existence of not only a ground-state energy level but also of a first excited-state transition, which in combination with the distribution of different QD sizes, results in a QD structure specifically designed for continuous tuning between the ground and excited-state optical transitions of the different QD groups. The broad electroluminescence (EL) spectra obtained from both the SOA and gain chip are represented in Fig. 1.

The gain chip ridge waveguide has a width of 5µm and length of 4mm, and is angled of 5° with respect to the normal to the back facet, in order to significantly reduce its reflectivity. Additionally, both facets also had conventional anti-reflective (AR) coatings, resulting in total estimated reflectivities of $2{\cdot}10^{-3}$ for the front facet and less than 10^{-5} for the angled facet. The SOA device has also a width of 5µm and length of 4mm, and is slanted by 5° respectively to the normal to the facets, which were also AR-coated and therefore with resulting reflectivities of 10^{-5} in each facet. The gain chip (or SOA) was mounted on a copper heatsink and its temperature was controlled by a thermo-electric cooler. Both devices were operated under a continuous-wave (CW) forward bias. As the aim of this work is to demonstrate a high-power broadly-tunable quantum-dot external cavity diode laser, a quasi-Littrow configuration was implemented due to its superiority in terms of output power and tuning range, when compared to the alternative Littman-Metcalf configuration. Moreover, the quasi-Littrow configuration is simpler and more compact in comparison with the Littman-Metcalf configuration. Therefore the QD-ECDL was set-up in a quasi-Littrow configuration, whereby the radiation emitted from the back facet was focused with an AR-coated aspheric lens (numerical aperture of 0.55) onto a diffraction grating with 1200 grooves/mm, which reflected the first order diffraction beam back to the gain chip/SOA. Coarse wavelength tuning was made possible by changing the incidence angle of the grating. The output of the front facet was collimated with a similar aspheric lens, as schematically represented in Fig. 2. We investigated the performance of the QD-ECDL with the gain chip for two configurations – with a 20% output coupler (OC) and without an OC. The QD-ECDL with the SOA was also examined for two configurations – with a 20% OC and a 96% OC.

The output of the laser was coupled via an optical fibre into an optical spectrum analyzer (OSA Advantest Q8383) and a broadband thermopile power meter.

3. Results and discussion

The EL spectra of the QD gain chip for various bias and temperature conditions are shown in Fig. 1. Under a fixed temperature, the measured EL spectra broaden with increasing current, and with greater emphasis at the blue side of the spectrum. Such behavior can be attributed to the saturation of the ground states and increasingly high carrier filling of the higher-energy excited states, which also have higher degeneracy, as is widely known in the literature [14]. For a given injected current, the peak of the EL spectrum red-shifts with increasing temperature, as has also been previously observed [15]. The spectra also become broader when the temperature is increased, particularly towards the longer wavelengths – an effect which can be understood by taking into account the thermal excitation of the carriers out of the QDs into the wetting layer. Such escape process will be stronger for the carriers in the higher energy states (in smaller dots) – which then become less populated than the lower energy states (in larger dots) [16].

The light-current characteristics of the external cavity laser - as shown in Fig. 2 - were taken with the QD-ECDL tuned at the wavelengths providing a maximum output power. In the gain chip configuration, this corresponded to 1220 nm without an OC, and to 1150 nm, with the 20% OC. For the different devices and configurations, the threshold current was

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consistently lower than 2 kA/cm^2 in most of the central part of the tuning range (between 130 and 140 nm), with a steep increase close to the extremes of the tuning region. For the gain chip at 10°C, and without an OC, the minimum threshold current density was 0.34 kA/cm^2, while the maximum was 7.85 kA/cm^2. At this point, we would like to stress that, in general, broadly tunable QD-based lasers present a much lower threshold and operation current than their counterpart QW lasers. Indeed, in QW-based lasers, an injection current typically greater than a few tens of kA/cm^2 needs to be injected in order reach broad tuning ranges by accessing not only the first but also the second quantized states (n = 1 and n = 2) that corresponds to shorter wavelengths [17]. On the other hand, it is well known that in QD-based lasers the ground state can saturate at a fairly low current, thus enabling a transition to the ES at much lower values of bias current [10], which is extremely relevant not only to achieve a tunable laser with higher efficiency but also to enable a longer device lifetime. A maximum optical output power of 480 mW for a cw-pump current of 1.7 A, at 10°C was observed for the gain chip.

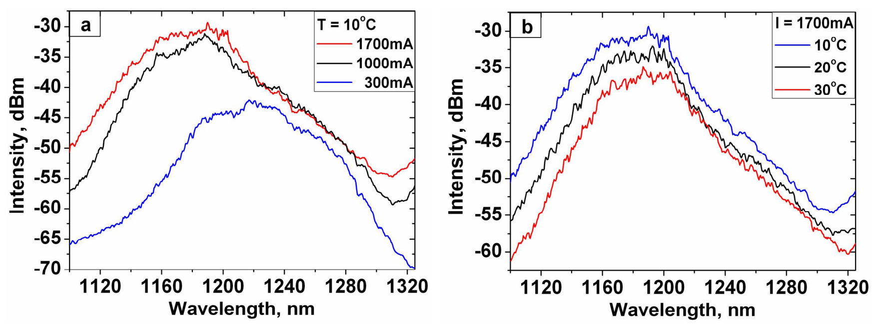

Fig. 1. Electroluminescence spectra of the QD gain chip for different bias and temperature conditions.

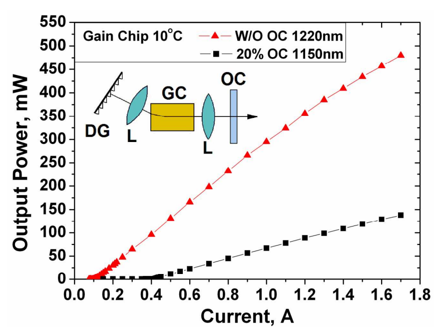

Fig. 2. Light-current characteristics for InAs/GaAs QD-ECDL at 10°C. Inset: Simplified schematics of the QD-ECDL configuration (DG – diffraction grating, L – aspheric lens, OC – output coupler, GC – gain chip).

The dependence of the output power with the different wavelengths for the gain chip QD-ECDL is represented in Fig. 3, for the configurations with 20% OC and without an OC, and for two distinct temperatures: 10°C and 30°C. Notably, for the QD-ECDL configuration without the OC, a maximum optical output power of 480 mW was achieved for a cw-pump current of 1.7 A, at 10°C (when tuned to λ = 1220 nm, and as previously shown in Fig. 2). On the other hand, only 138 mW were achieved (when tuned to λ = 1150 nm), when a 20% OC was included in the cavity (Figs. 2 and 3). The various optical spectra obtained while tuning this laser across the 1122.5 nm – 1324.5 nm wavelength range, are also presented in Fig. 3. The emission spectrum exhibited a side-mode suppression ratio in excess of 45 dB in the central part of the tuning range. The resulting optical spectrum exhibited a full-width half-maximum spectral bandwidth around 0.13 nm, limited only by the instrumental resolution of

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the spectrometer. Using a cw-pump current of 1.7 A, a tuning range exceeding 187 nm has been achieved for InAs/GaAs QD-ECDL in the gain chip configuration without the OC. We would like to stress that an output power in excess of 400 mW was achieved for a tuning range of 110 nm, as depicted in Fig. 3(a). Furthermore, the output power only varies by ~10% in the central part of the tuning range under a constant forward bias of 1.7 A, which is an extremely desirable feature for the development of a fast swept tunable laser source with high output power. Likewise, the threshold current is also relatively constant across this spectral range. The tuning range can be extended by changing a configuration of the cavity by the addition of the OC – in fact, the same laser demonstrated a 202 nm continuous tuning in the configuration with the 20% OC (Fig. 3). Moreover, we would like to emphasize that, to our knowledge, the lasing wavelength of 1324 nm is the longest GaAs-based QD lasing wavelength reported until now from a tunable GaAs-based QD laser.

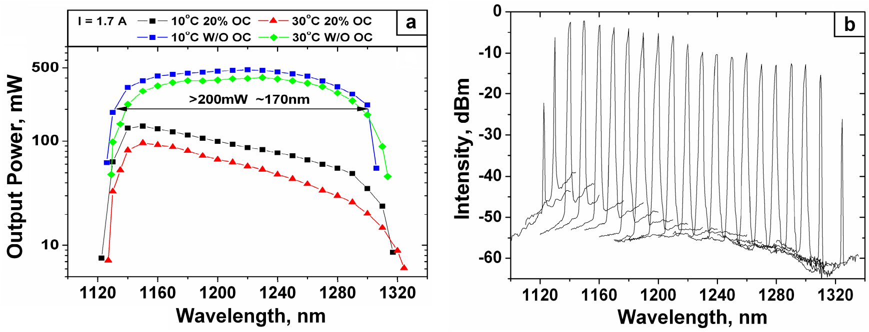

Fig. 3. Dependence of output power on wavelength for different temperatures and configurations (a) and spectra (b) of the QD-ECDL with the gain chip, tuned across the 1122.5 nm – 1324.5 nm wavelength range, under an applied constant current of 1.7 A.

We also investigated the tuning range for different bias (300 mA - 1700 mA), temperature conditions (10°C - 30°C) and configuration of the QD-ECDL incorporating a gain chip. The obtained results, as depicted in Fig. 4, show that the tuning range is enhanced for higher pump currents. In agreement with the EL spectra depicted in Fig. 1, this enhancement is asymmetric and occurs predominantly on the shorter wavelength side of the tuning range, whereas the longer wavelength side remains practically unaltered, particularly for high current bias. Moreover, a shift of the tuning range to the longer wavelength side of the spectra was observed, when the temperature was increased from 10°C to 30°C (Fig. 4).

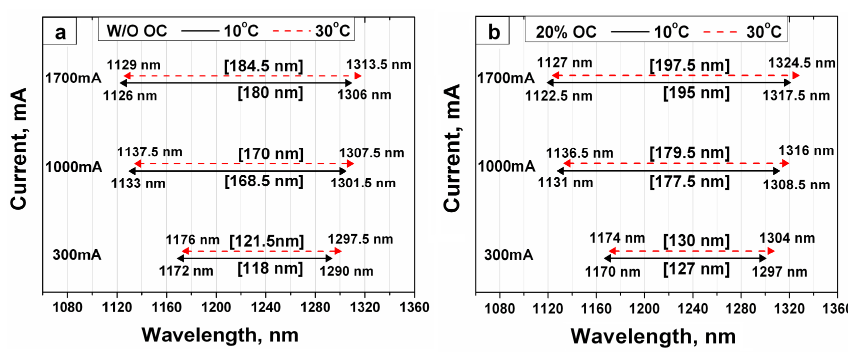

Fig. 4. Tuning range limits for the gain chip for different pump currents and temperatures without an output coupler (a) and with the 20% output coupler (b).

For the 20% OC, an enhancement of the tuning range occurs predominantly on the longer wavelength side, as the lower cavity losses favored laser emission via the ground-state levels of the QD gain material, as had been previously proposed by Li *et al*. [10]. Furthermore, due to the fact that the temperature red-shift was more accentuated on the longer wavelength side

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of the spectra than on the shorter side, the tuning range was actually slightly extended with increasing temperature, which is related to the thermalization effect previously described and also observed in the EL spectra.

Similarly, the QD-ECDL with the SOA was tested in configurations that included a 20% OC or 96% OC, and exhibited the same trend in the dependence of the tuning range on bias and temperature conditions as the gain chip QD-ECDL. A maximum tuning of 194.5 nm and 186.5 nm for 1.7 A has been demonstrated with the 20% OC and 96% OC, respectively (results not shown here). A maximum output power of 377 mW for a cw-pump current of 1.7 A at 10°C was observed for the SOA in the configuration with 96% OC at 1220 nm.

For both gain chip and SOA configurations, an increase of the cavity feedback by the addition of an OC has been shown to extend the tuning range, particularly at the red side of the spectrum. However, a trade-off exists, as the presence of an OC in the cavity reduces its maximum output power.

The primary advantage of the gain chip over the SOA is the fact that there is no need to use an OC in conjunction with the gain chip, because the front facet of the gain chip together with the diffraction grating can create a cavity, whereas the presence of an OC is always necessary for the SOA owing to the lower reflectivities of the facets. Moreover, the waveguide tilt at an angle with respect to the emission facet results not only in a reduction in the effective facet reflectivity but also strongly affects the shape of the emitted beam, which becomes slightly asymmetric [18]. For this reason, the coupling of light feedback from the OC and diffraction grating is more inefficient for the SOA than for the gain chip, where only the back facet is angled. These higher coupling losses are therefore one of the main factors that determine the lower performance of the SOA as opposed to the gain chip, which exhibits higher output power and tuning range.

4. Conclusion

In this paper, we have presented a record broadly tunable high-power InAs/GaAs QD-ECDL with tuning range of 202 nm, between 1122.5 nm and 1324.5 nm. A maximum CW output power of 480 mW and a side-mode suppression ratio greater than 45 dB were achieved in the central part of the tuning range. An average output power in excess of 400 mW was achieved for a tuning range of 110 nm. This represents a promising achievement for the development of a high-power fast swept tunable laser and compact nonlinear frequency generation schemes for the yellow-orange spectral range. Furthermore, the influence of extrinsic conditions on the tuning range of QD-ECDLs was systematically investigated. It is shown that the tuning range can be mostly enhanced on the blue side of the spectrum via bias conditions, whereas reducing the cavity losses assists in the enhancement of the tuning range on the red side of the spectrum. Different waveguide structure designs were investigated, and the improved performance of the QD-ECDL with the gain chip configuration in comparison with the SOA has been demonstrated.

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