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Tunable single and dual mode operation of an external cavity quantum-dot injection laser

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Abstract
We investigate quantum-dot (QD) lasers in an external cavity using Littrow and Littman configurations. Here, we report on a continuously tunable QD laser with a broad tuning range from 1047 to 1130 nm with high stability and efficient side mode suppression. The full-width at half-maximum of the laser line is 0.85 nm determined mainly by the quality of the external grating. This laser can be operated in a dual-mode modus, where the mode-spacing can be tuned continuously between 1.1 and 34 nm. Simultaneous emission of the two laser modes is shown by sum frequency generation experiments.

Currently, the prospects of using semiconductor quantum-dot (QD) lasers in telecommunication applications are extensively discussed in the literature. Various arguments motivate such an innovation step. First, the δ-like density of states in QDs promises improved laser properties such as low threshold currents and temperature insensitivity [1–3]. Also high-speed devices, such as pulsed laser diodes or high bandwidth modulators, would benefit from the enhanced differential gain of QD lasers as compared with quantum-well (QW) lasers [4]. In addition QD lasers with emission wavelengths up to 1.3 μm and beyond [5, 6], provide an inexpensive and interesting method for data communication in optical fibres.

In the past a key focus in the investigations of QDs as the optically active medium was the issue of carrier relaxation from high-energetic barrier states into the QD ground state (see, e.g. [7–13]). A fast carrier capture of only several picoseconds is commonly found showing that QD lasers are well suited for high-speed applications [14]. An important property of self-assembled QDs is the broad gain spectrum, which is due to the almost inevitable dot size fluctuation during the growth process [1]. Whereas this feature is less desirable for high power single mode laser diodes, a broad gain spectrum can be attractive for other applications, such as tunable lasers or mode-locked lasers. Tunable laser diodes are highly desirable for modern wavelength division multiplexing (WDM) telecommunication schemes, where information channels are encoded in different wavelengths. In [15, 16], a laser diode can be tuned over a spectral range of 11 nm limited by the gain spectrum of the semiconductor material. A simultaneous dual-mode operation has also been shown.

In this paper, we demonstrate the advantage of the broad gain spectrum of a QD laser in an external cavity configuration: tunability over 83 nm on the QD ground state is shown. In addition, the simultaneous operation of one QD laser diode on two independently tunable laser modes is demonstrated. All measurements are taken at room temperature.

The QD laser used in this study contains self-assembled InAs/GaAs QDs that are grown by molecular beam epitaxy at a low growth temperature of 480˚C. These growth conditions generate a high dot density of about 10^{11} cm^{-2} and a small QD size of only 4 nm in height [17]. For the active layer of the laser diode seven layers of QDs are stacked with a separation of 10 nm of GaAs as barrier material, and the whole structure

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is embedded in an AlGaAs/GaAs graded-index wave-guide on a GaAs substrate. The laser itself is an edge-emitting metal clad ridge waveguide structure with cleaved facets, a mesa width of 5 μm, and a length of 1.6 mm. The laser diode is connected to a copper heat sink to prevent excessive heating of the device. Typical lasing spectra of the free running diode can be found in [18] showing commonly observed effects of QD lasers like modal gain saturation and spectrally broad laser emission [19, 20].

For the external cavity set-up an antireflection (AR) coating is deposited on one facet. The AR coating increases the threshold current of the laser diode from 100 mA without coating to about 235 mA with coating. The external cavity configuration is a standard Littrow set-up shown in the inset of figure 1. A microscope objective couples the laser light from the AR coated facet to an external grating, which diffracts the -1st order back into the laser diode. By rotating the external grating the emission wavelength of the laser is selected and can be tuned.

The main part of figure 1 shows a superposition of emission spectra of the QD laser in the external cavity set-up taken for different rotation angles of the grating at an injection current of 235 mA, i.e. just below the laser threshold of the internal laser diode. Figure 1 shows that the QD laser is continuously tunable from 1047 to 1130 nm with high stability of the laser mode and excellent side mode suppression. The full-width at half-maximum (FWHM) for all laser spectra is about 0.85 nm and is determined mainly by the quality of the external grating and the resolution of the monochromator. A different QD laser has been investigated in an external cavity [21]. However, clean single mode operation over the entire tuning range as shown in figure 1 could not be demonstrated.

The laser threshold injection current of the external cavity QD laser as a function of the spectral position is shown in figure 2. It can be seen that the tuning range increases continuously with increasing injection current. In contrast to [21] the parabola shape of this plot gives us reason to believe that the QD laser operates only from the electronically ground state. This is in agreement with the suggestion of only one electronic state in the conduction band of these QDs presented in [17].

By rotating the grating it is possible to reflect only one wavelength back to the diode. The very broad gain spectrum motivates the study of dual-mode operation. We thus change set-up to a Littman configuration. As shown in the inset of figure 3 the -1st order of diffraction of the grating is collected with an achromatic lens and reflected back into the laser diode by an end-mirror. An aperture put in front of the mirror is used to select a wavelength [16]. Using a Y-shaped aperture (see inset of figure 3) it is possible to achieve tunable dual-mode operation of the QD laser diode. By moving the Y-aperture up or down, the spacing of the two modes can be continuously

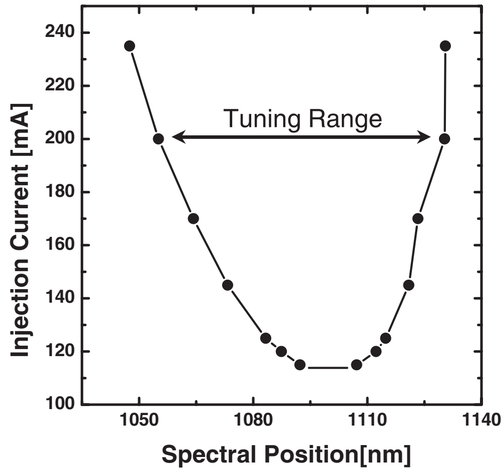

Figure 2. Laser threshold injection current as a function of the spectral position.

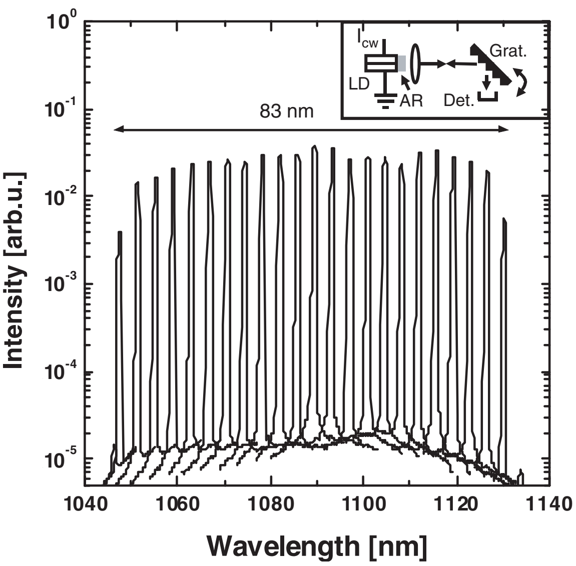

Figure 1. Tuning range of the QD laser in an external cavity at a bias current of 235 mA. The inset shows the experimental set-up (Littrow configuration): the laser emission of an AR coated laser diode (LD) is coupled back by the -1st order of diffraction of a grating (Grat). The 0th order of diffraction is detected (Det).

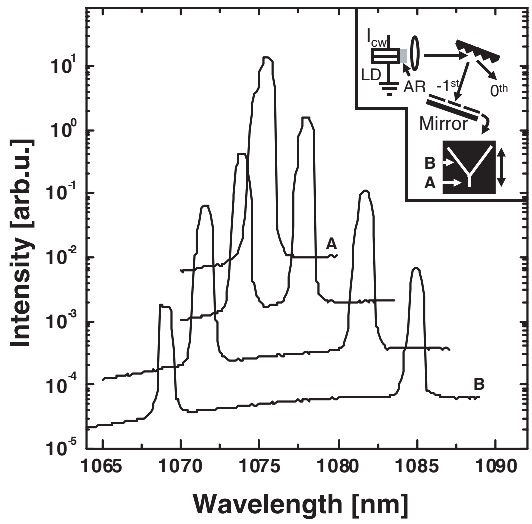

Figure 3. Single- and dual-mode operation using an aperture. The inset shows the experimental set-up (Littman configuration): in contrast to figure 1, the -1st order of diffraction is coupled back to the laser diode by an end-mirror. In front of the mirror an aperture can be inserted to select a desired wavelength. The character next to the aperture represents the vertical position. At position A the laser emits one laser mode. By moving the aperture to position B dual-mode operation is achieved and the spectral distance between these modes is increased.

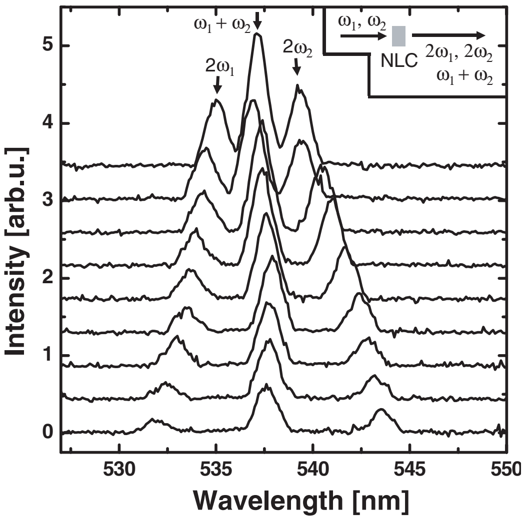

Figure 4. Proof of simultaneous dual-mode operation: the spectra show second harmonic signals ($2\omega_1$, $2\omega_2$) and a sum frequency signal ($\omega_1 + \omega_2$) when the laser emission has passed a nonlinear crystal (NLC). The inset shows the scheme of second harmonic and sum frequency generation in a nonlinear crystal.

tuned from 1.1 to 34 nm. Figure 3 shows spectra for four different positions of the aperture. The curve on the top shows single-mode operation at position A of the aperture (see inset). The aperture is moved down to achieve dual-mode operation, as shown by the lower curves. The line width is limited by the width of the slits in the aperture and is about 1.0 nm in FWHM. The closest distance demonstrated between two modes is 0.9 nm with a FWHM of 0.7 nm using a double-slit aperture.

The time-integrated measurements cannot distinguish between simultaneous dual-mode operation and fast switching between two single laser modes. To take advantage of dual-mode laser diodes in telecommunication applications, the emission should occur simultaneously. Using the effect of sum frequency generation we demonstrate simultaneous dual-mode laser emission. In a nonlinear crystal the sum frequency can only be created by the simultaneous presence of two photons with different frequencies. Figure 4 shows spectra of a dual-mode laser beam after passing through a nonlinear crystal. The second harmonic signals of both laser modes are seen ($2\omega_1$, $2\omega_2$). In between, the sum frequency signal ($\omega_1 + \omega_2$) is easily detected. To verify that the sum frequency signal always stays accurately in between the second harmonic signals, the spectral spacing of the two laser modes is changed. The different spectra show different spectral distances of these modes, similar to the spectra shown in figure 3. In addition, this shows the possibility of tuning of a frequency doubled QD laser diode.

In conclusion, we have demonstrated a QD laser, which is continuously tunable over a range of 83 nm in the infrared wavelength region. Also, tunable dual-mode operation of a QD laser is presented. It is demonstrated that these modes are emitted simultaneously. Such systems could simplify future WDM applications using multiple simultaneously emitted modes of one QD laser diode.

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References

[1] Grundmann M 2000 *Physica* E **5** 167–84
[2] Klopf F, Reithmaier J P and Forchel A 2000 *Appl. Phys. Lett.* **77** 1419–21
[3] Sellin R L, Ribbat C, Grundmann M, Ledentsov N N and Bimberg D 2001 *Appl. Phys. Lett.* **78** 1207
[4] Kamath K, Phillips J, Jiang H, Singh J and Bhattacharya P 1997 *Appl. Phys. Lett.* **70** 2952–4
[5] Klopf F, Krebs R, Reithmaier J P and Forchel A 2001 *IEEE Photon. Technol. Lett.* **13** 764–6
[6] Klopf F, Krebs R, Wolf A, Emmerling M, Reithmaier J P and Forchel A 2001 *Electron. Lett.* **37** 634–6
[7] Grosse S, Sandmann J, Plessen G v, Feldmann J, Lipsanen H, Sopanen M, Tulkki J and Ahapelto J 1997 *Phys. Rev.* B **55** 4473
[8] Morris D, Perret N and Fafard S 1999 *Appl. Phys. Lett.* **75** 3593–5
[9] Zhang L, Boggess F, Deppe D G, Huffaker D L, Shchekin O B and Cao C 2000 *Appl. Phys. Lett.* **76** 1222–4
[10] Boggess T F, Zhang L, Deppe D G, Huffaker D L and Cao C 2001 *Appl. Phys. Lett.* **78** 276–8
[11] Feldmann J, Cundiff S T, Arzberger M, Bohm G and Abstreiter G 2001 *J. Appl. Phys.* **89** 1180–3
[12] De Giorgi M, Lingk C, von Plessen G, Feldmann J, De Rinaldis S, Passaseo A, De Vittorio M, Cingolani R and Lomascolo M 2001 *Appl. Phys. Lett.* **79** 3968–70
[13] Zhang L, Boggess T F, Gundogdu K, Flatte M E, Deppe D G, Cao C and Shchekin O B 2001 *Appl. Phys. Lett.* **79** 3320–2
[14] Klotzkin D and Bhattacharya P 2000 *IEEE Circuits Dev.* **16** 17
[15] Breede M *et al* 2002 *Opt. Commun.* **207**
[16] Struckmeier T, Euteneuer A, Smarsly B, Breede M, Born M, Hofmann M, Hilderbrand L and Sacher J 1999 *Opt. Lett.* **24** 1573–4
[17] Chu L, Arzberger M, Böhm G and Abstreiter G 1999 *J. Appl. Phys.* **85** 2355–62
[18] Platonov A V, Lingk C, Feldmann J, Arzberger M, Amann M-C and Abstreiter G 2002 *Appl. Phys. Lett.* **81** 1177–9
[19] Bhattacharya D *et al* 1999 *IEEE J. Sel. Top. Quantum Electron.* **5** 648–57
[20] Patanè A *et al* 2000 *J. Appl. Phys.* **87** 1943–6
[21] Varangis P M, Li H, Liu G T, Newell T C, Stintz A, Fuchs B, Malloy K J and Lester L F 2000 *Electron. Lett.* **36** 1544