AIP Applied Physics Letters

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Citation: Appl. Phys. Lett. **95**, 101111 (2009); doi: 10.1063/1.3227654
View online: http://dx.doi.org/10.1063/1.3227654
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v95/i10
Published by the American Institute of Physics.

Self-pulsing 1050 nm quantum dot edge emitting laser diodes

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(Received 11 July 2009; accepted 21 August 2009; published online 11 September 2009)

We examine self-pulsing, edge emitting, quantum dot laser diodes as continuous broad spectrum light sources emitting at ~1050 nm. Devices are configured with split contacts. When operated without a saturable absorber, the laser emits a number of discrete narrow modes, which merge to form a broad continuous lasing spectrum on application of the saturable absorber. The broadened spectra are consistent with the modulated carrier density expected under *Q*-switched operation. This provides a simple technique for generating emission suitable for biomedical applications. The spectral width achieved is ~10 nm, and the average output power is 7.5 mW. © *2009 American Institute of Physics*. [doi:10.1063/1.3227654]

Broad spectrum light sources centered at 1050 nm are key requirements for state-of-art ophthalmic optical coherence tomography (OCT) application.[1] We investigate a quantum dot (QD) laser as an alternative to bulky and expensive solid state lasers or superluminescent diodes,[2] which although low cost usually have low power and/or efficiency. Self-assembled QD lasers can have low threshold current density and low temperature sensitivity of threshold current as originally suggested in Ref. 3 compared to lasers containing quantum wells and have naturally inhomogeneously broadened gain spectra due to differences in size and shape of the individual dots.[4] The QD laser diode output can therefore be tuned over a wide wavelength range[5] or can simultaneously produce a comb of longitudinal modes.[6]

Due to their small size, laser diodes have relatively large wavelength separation between longitudinal modes compared to other laser types and these longitudinal modes produce secondary subpeaks in the temporal coherence function, which can be detrimental to clear image formation in OCT.[7] Simple simulations show that for 0.5 mm long laser diode output with longitudinal modes with amplitudes described by a 50 nm bandwidth Gaussian envelope centered at 1050 nm, the secondary coherence subpeak limits depth resolution in OCT to less than 1 mm (coherence subpeak separation 1 mm). Broadband QD laser diodes often output groups of longitudinal modes with still larger mode separation[8] and the problem is even more pronounced in this case. In this work, we describe the use of self-pulsation to produce a continuous spectrum from a QD laser diode discrete spectrum.

Self-pulsation or passive *Q* switching is a well known technique to obtain intermediate duration pulses with laser diodes[9] and has previously been used in, for example, CD laser sources to make the laser insensitive to optical feedback.[10] Here we will use self-pulsation, as distinct from mode locking, to produce a broadened emission spectrum with low coherence, while still maintaining reasonable output power. As illustrated in Fig. 1, we will use a split contact configuration making use of self-assembled QDs for both the active gain and saturable absorber material.

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To produce single transverse mode operation, we use a ridge-waveguide geometry with electrically isolated sections using the material of Fig. 2, which was designed to operate in the 1000 nm wavelength band. A ridge of width 2 μm and height 1.54 μm was fabricated by e-beam lithography and dry etching. As indicated in Fig. 1, each section has a length of 100 μm and can be driven individually either by forward or reverse bias. For ease of operation, we would prefer the devices to self-pulsate when the absorber section is simply grounded rather than reverse biased and by varying the number of sections driven into gain we find the balance of gain: absorption to achieve this for 2 mm total length structures is 17:3. The results shown in this paper are for a 2 mm long device with the front three sections (0.3 mm) operated as an absorber.

In Fig. 3, the power output versus current characteristics are shown for a typical device operated with cw current source, mounted *p*-side up and with a peltier controlled heat sink temperature of 15 °C. When all the sections are driven in gain, the laser has a threshold current of 20 mA and an external differential slope efficiency of 0.24 W/A. With three sections earthed, the threshold current increases to 110 mA and the slope of the characteristic has a rapid initial rise, typical of devices with a saturable absorber, followed by an external differential slope efficiency of 0.11 W/A. The decrease of the efficiency results from the decrease in average power during self-pulsation.

Figure 4 shows the lasing spectra corresponding to the conditions of Fig. 3 for an optical output power of

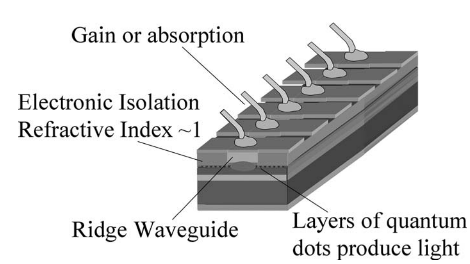

FIG. 1. Schematic of a multisection device, each section has a length of 100 μm and is electrically isolated from other sections, which can therefore be driven individually either by forward or reverse bias.

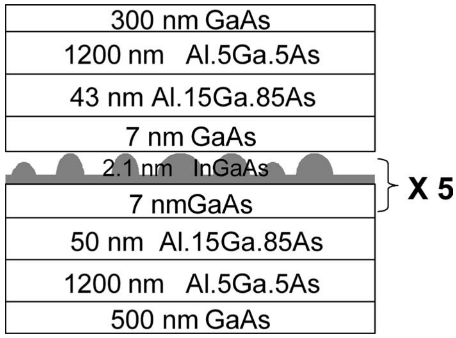

FIG. 2. Schematic of the material. The material contains five repeat layers within the active region. Each layer consists of 7 ML of InGaAs QDs capped with 70 Å GaAs. These are sandwiched by $Al_xGa_{1-x}As$ barrier.

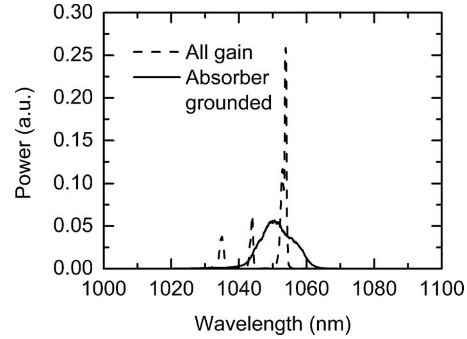

FIG. 4. Lasing spectra when the device with all sections under forward biased current of 50 mA (dashed line) and when the device is operated with absorber grounded and gain section 150 mA (self-pulsing, solid line).

~7.5 mW in each case. The necessary current increases from 50 to 150 mA but the spectrum changes from narrow discrete modes, when all sections are forward biased, to a broad continuous lasing spectrum [~10 nm at full width at half maximum (FWHM)], and centered at around 1050 nm, when three sections are grounded. The grounded sections act as a saturable absorber and we believe that the spectral broadening is due to self-pulsation.

In order to observe the self-pulsation and the spectral broadening at the same time, we examined the devices with a streak camera. To facilitate this, the lasers are driven pulsed with a constant-current source at a frequency of 5 kHz and a pulse length of 1 μs. This provides an injection regime of sufficient duration for the carrier-photon dynamics to evolve beyond the transients induced by the pulse turn-on and to establish repetitive pulsation. The streak camera is operated in conjunction with a 0.3 m spectrometer that provides spectral information with a bandwidth of 27 nm. By using this method, we can observe the pulsation and spectrum at the same time.

The device heatsink is again temperature stabilized to 15 °C although the active layer temperature is different to the previous results due to self-heating under cw operation. The device was driven at 50 mA with all sections under forward bias, and 100 mA under self-pulsed operation. The difference in required operating current from the previous measurements is due to the self-heating. The resulting spectra are, however, similar in form.

In Fig. 5, with the device operated with all sections under forward bias, there are two main discrete modes and one lesser intensity mode whereas with the device operated with three sections earthed a single, broader, and continuous lasing spectrum is observed. On the time axis, we observe continuous emission when the device is operated with all sections under forward bias that becomes self-pulsation with three sections under reverse bias. The pulse duration is measured to be ~270 ps, and the pulse repetition rate is 1.2 GHz. With all sections operated in forward bias, the multiple peaks in the output spectra, which are separated by ~10 nm, are groups of modes originating from the substrate leakage and reflection effect.[8] To confirm that the broadening of the spectrum is obtained due to the buildup and reduction of the carrier density during each Q-switched pulse, the broadening of the spectrum obtained during the relaxation oscillations of a standard QD laser were investigated.

Again using the streak camera, a 1 mm long single section ridge waveguide laser, driven using a pulsed source (pulse length 1 μs and repetition rate 5 kHz) at 80 mA was examined. As shown in Fig. 6(a), the streak camera was triggered to look at the first few nanoseconds of the light pulse. 1 ns sections of streak camera trace are analyzed at 1 ns after light pulse switch on and at 10 ns after light pulse switch on. After 10 ns the carrier density has stabilized and discrete modes are visible whereas in the first few nanoseconds the spectrum is broad and continuous with a FWHM of 12 nm, as shown in Fig. 6(b).

To summarize, we realized self-pulsation of 1050 nm semiconductor lasers and observed spectral broadening due to the self-pulsation. With the devices operated without a saturable absorber section, the laser emits a number of discrete narrow modes, which merge to form a broad continu-

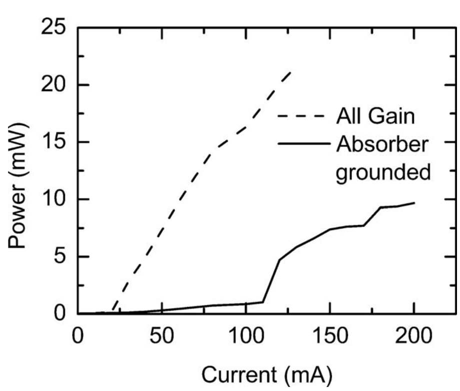

FIG. 3. Single facet power output vs current data when the device with all sections under forward bias (dashed line) and when the device is operated with absorber grounded (solid line).

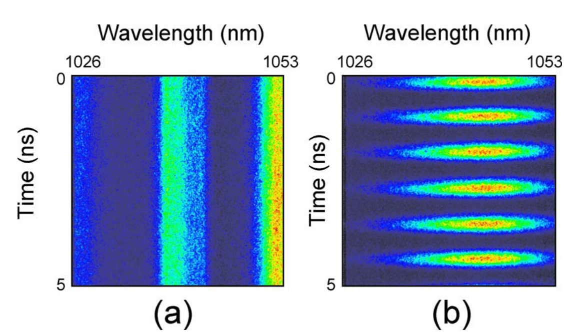

FIG. 5. (Color online) Streak camera image. Light observed in a 5 ns window (0 corresponds to 500 ns into pulse) when (a) the device is operated with all sections under forward bias. (b) The device is operated with absorber grounded (self-pulsing).

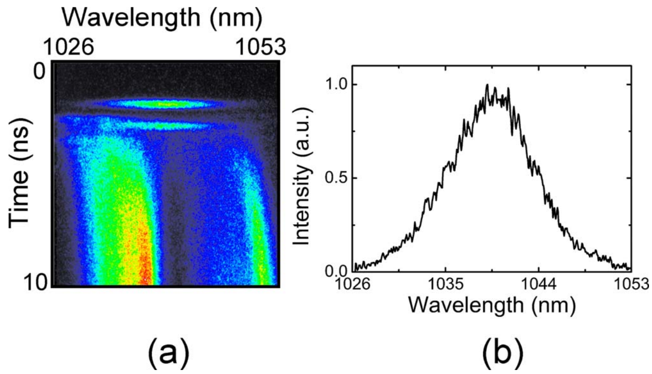

FIG. 6. (Color online) (a) Streak camera image of light observed in a 10 ns window (first 10 ns of the light pulse). (b) The normalized spectra of the first pulse.

ous lasing spectrum. The spectral width achieved is ~10 nm (at FWHM), the power is 7.5 mW. Similar results are obtained, during the first few nanoseconds, when studying the carrier relaxation oscillations of standard QD devices indicating that the broadening is due to carrier density changes during self-pulsation. The technique can be used to generate continuous broadband laser light sources.

The authors acknowledge the support of Cardiff University, the European Commission's Sixth and Seventh Framework Programme Project No. FP6-IST-NMP-2 STREP (Grant No. NANOUB-017128) and Action Medical Research (Contract No. AP1110).

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