Quantum dot laser diode with low threshold and low internal loss

D.G. Deppe, K. Shavritranuruk, G. Ozgur, H. Chen and S. Freisem

Data are presented demonstrating that a low-threshold quantum dot laser diode can achieve very low internal optical loss. The broad-area laser diode operates at the wavelength 1.22 μm and delivers 2 W of power from a 1.6 cm-long cavity with uncoated facets, with a lasing threshold current density of 10.4 A/cm^2. The laser diode's internal waveguide loss is extracted from cavity length measurements to be $\sim$0.25 cm^{-1}. The interdependence of threshold current density and internal optical loss is discussed.

Introduction: Self-organised quantum dot (QD) gain material [1] offers the capability to reach lasing threshold at a very low current density [2–4]. The low-threshold capability is directly related to the very low transparency carrier density. In turn, a low-threshold carrier density can produce very low internal optical loss in a laser diode, since free carrier scattering owing to the electron–hole carrier density of the gain region represents one of the major loss mechanisms of the laser diode. In most waveguide laser diodes that are designed for low internal optical loss, the internal optical waveguide loss is in the range of $\alpha_{WG} \sim 1$ cm^{-1}. This low optical loss is usually achieved through use of a low optical confinement factor [5]. Recently, in specially designed low-loss optical waveguide laser diodes based on planar quantum well active material, a very low internal optical loss has been reported of $\alpha_{WG} \sim 0.35$ cm^{-1}, which was mainly limited by the free-carrier scattering by electrons and holes confined in the active material [6]. The QD gain material, however, offers the possibility of even lower internal optical loss based on its low value of the electron–hole density required for lasing, if the QD laser diode can achieve a low threshold current and carrier density.

Experimental results: In this Letter, we characterise the optical loss of very low threshold continuous-wave (CW) QD laser diodes, and demonstrate that even with high optical gain confinement these devices reach very low internal optical waveguide loss, α_{WG}. The optical loss is $\alpha_{WG} \sim 0.25$ cm^{-1} for QD laser diodes with broad-area cavities between 1 and 2 cm, and that have CW threshold current densities J_{th} that range between 10 and 13 A/cm^2. To our knowledge the threshold current densities are the lowest ever reported for room-temperature CW laser diodes, and the internal optical losses are also the lowest to our knowledge ever reported for room-temperature CW laser diodes.

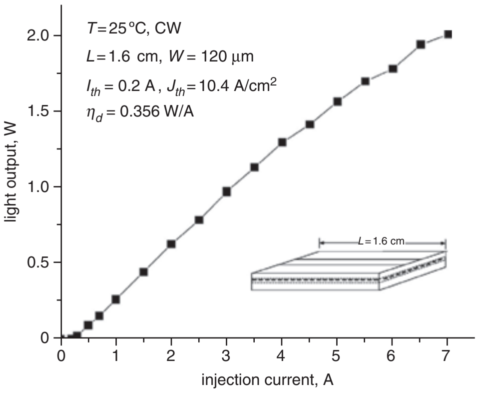

Fig. 1 *Light output against current injection for broad-area QD laser diode with 120 μm-wide stripe and 1.6 cm cavity length*

Inset: Schematic illustration of broad-area QD laser diode with single QD active layer

The inset in Fig. 1 shows a schematic illustration of the broad-area QD laser diode. The GaAs-based heterostructure is grown using molecular beam epitaxy, and the QD density of the single active layer is $\sim 3 \times 10^{10}$ cm^{-2}. Only a single InAs QD active layer with GaAs barriers is used in the broad-area laser diode to produce very low threshold CW current density. The ability to operate CW is important, since pulsed operation produces less junction heating and can introduce errors into the measurements of threshold current density and slope efficiency. The broad-area diodes use a shallow etched mesa for current confinement, and have uncoated facets. The epitaxial material is from the same wafer reported in [4], but *p*-side down mounting has been optimised with a large bonding force for the large cavities for the CW testing. The spectral emission from the QD laser diodes shows laser operation at 1.22 μm.

Fig. 1 shows a light against current curve for a broad-area QD laser diode with a 120 μm wide stripe and 1.6 cm cavity length. Fig. 2 shows the spectral emission demonstrating clear lasing at 1.22 μm at 12.5 A/cm^2, slightly above the threshold. The laser diode operates with a threshold current of 200 mA, which corresponds to a threshold current density of 10.4 A/cm^2. The power reaches 2 W (both facets) at the CW current drive level of 7 A. The slope efficiency of 0.36 W/A is approximately independent of the cavity length for lengths ranging from 1 to 2 cm. The 2 cm-long laser diode has a threshold current density of only 8.8 A/cm^2, but less power than the 1.6 cm device owing to heatsinking problems in the longer cavity. The slope efficiency in the 2 cm-long devices decreases only slightly to 0.33 W/A with the threshold current density decreasing to 8.8 A/cm^2, while for a 1 cm-long cavity the slope efficiency increases to 0.38 W/A with a threshold current density of 13.3 A/cm^2.

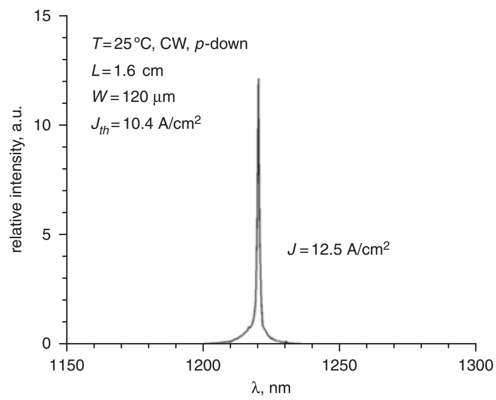

Fig. 2 *Spectral emission of 120 μm-wide and 1.6 cm-long broad-area laser diode demonstrating clear lasing at 1.22 μm at 12.5 A/cm^2, which is slightly above threshold*

Fig. 3 shows the inverse differential slope efficiency against cavity length used to extract the internal waveguide loss and injection efficiency values. From this plot and the formula given in the Figure we find that the QD lasers are characterised by an internal optical waveguide loss value of $\alpha_{WG} \sim 0.25$ cm^{-1} and a lasing injection efficiency of $\eta_i \sim$ 46%. The cause for the low injection efficiency is unclear. We believe that it may be due to a combined effect of the inhomogeneous broadening and temperature sensitivity of the lasing threshold. The inhomogeneous broadening in the QD laser can prevent global pinning of the quasi-Fermi energies, so that any increase in diode junction temperature may increase nonradiative recombination quite strongly, even for drive levels above the lasing threshold. This dependence of the nonradiative recombination rate on the drive level can lead to an increase in the apparent threshold for increasing the drive level even above the actual threshold level. Thus more research is needed to understand the injection efficiency and ways to improve it.

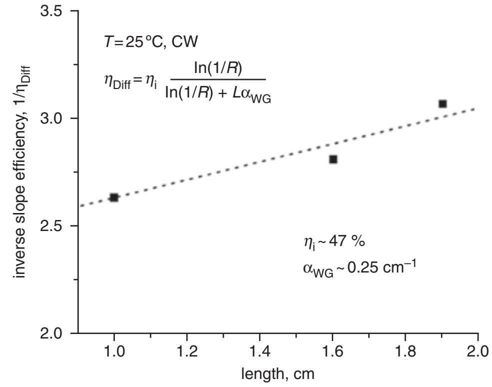

Fig. 3 *Inverse differential slope efficiency against cavity length used to extract the internal waveguide loss and injection efficiency values*

Conclusions: The low internal optical loss due to a low threshold current is expected since both the optical waveguide loss and the threshold current density depend on the value of the threshold carrier density within the QD gain material. The threshold current density can be estimated as

$$J_{th} = \frac{q}{\tau_{sp}} n_{th} \tag{1}$$

while the internal optical loss of the waveguide, assuming $n_{th} = p_{th}$, is given by

$$\begin{aligned}\alpha_{WG} &\simeq \alpha_n + \alpha_p + \alpha_{sc} + \frac{\Gamma}{\Delta z}(n_{th}\sigma_n + p_{th}\sigma_p) = \alpha_n + \alpha_p \\ &+ \alpha_{sc} + \frac{\Gamma}{\Delta z}(\sigma_n + \sigma_p)\frac{J_{th}\tau_{sp}}{q}\end{aligned} \tag{2}$$

In (1) and (2) q is the electron charge, n_{th} is the threshold electron density in the gain region, p_{th} is the threshold hole density in the gain region, α_n is the free carrier electron loss in the n-cladding layer, α_p is the free carrier hole loss in the p-cladding layer, α_{sc} is the refractive index variation scattering of the optical waveguide, σ_n is the electron free carrier absorption cross section, σ_p is the hole free carrier absorption cross section, and $\Gamma/\Delta z$ is the confinement factor normalised by the unit thickness of the gain region. The n- and p-cladding layer losses can be reduced by controlling dopant levels next to the waveguide region, and interface scattering loss can be reduced by optimising the growth conditions to obtain very smooth epitaxy. Reducing the optical confinement factor of the gain region can further minimise the n- and p-cladding layer losses, the interface scattering losses, and the active region losses [5, 6], but generally increases the threshold current density as well. The QD gain region provides the opportunity to reduce the active region loss, and therefore the waveguide loss, because of its low carrier density that can produce a low threshold current density.

We have presented data on laser diodes that, to our knowledge, achieve the lowest threshold current densities and internal losses ever reported for CW room-temperature laser diodes. These low internal losses and low current densities can be important for increasing the laser diode cavity size for applications in high power or high quality factor.

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