Maximum operating temperature of quantum dot laser

Li Jiang [a] and Levon V. Asryan [b]

Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA

High temperature stability of threshold current density j_{th} is anticipated from semiconductor quantum dot (QD) lasers [1]. In actual QD lasers, the T-dependence of j_{th} is mainly controlled by recombination processes in the optical confinement layer (OCL) [2]. Thus, when the carrier distribution (below and at the lasing threshold) is described by the equilibrium statistics (typically, at room temperature and higher), the free-electron and -hole densities, n and p, and hence the recombination current density in the OCL, j_{OCL}, depend exponentionally on T.

Different factors can also contribute to the T-dependence of the confined-carrier level occupancies in QDs, $f_{\mathrm{n,p}}$, and hence of the recombination current density in QDs, j_{QD}. In [2, 3], violation of charge neutrality in QDs ($f_{\mathrm{n}} \neq f_{\mathrm{p}}$) was shown to be among such factors.

In this work, we study the effect of carrier-density-dependent internal optical loss, α_{int}, in the OCL on the T-dependence of j_{th} of a QD laser. As in other diode lasers [4]–[7], such a loss can strongly affect the temperature stability of QD lasers [8]. It is shown here that α_{int} sets an upper limit T^{max} for operating temperatures and considerably reduces the characteristic temperature T_0 of a QD laser defined as $T_0 = (\partial \ln j_{\mathrm{th}} / \partial T)^{-1}$. At the maximum operating temperature, T_0 drops to zero.

This work is based on [9], where j_{th} has been calculated in the presence of carrier-density-dependent α_{int}. The lasing threshold condition is written as

$$g^{\mathrm{max}}(2 f_n - 1) = \beta + \alpha_0 + \sigma_{\mathrm{int}} n, \qquad (1)$$

where g^{max} is the maximum (saturation) modal gain of a laser, β is the mirror loss, α_0 is the constant component of the internal loss, and σ_{int} is the effective cross section for the internal absorption loss processes [9].

In the absence of n-dependent internal loss ($\sigma_{\mathrm{int}} = 0$), f_{n} = const (T) [see (1)] and hence j_{QD} = const (T). As seen from (1), the carrier-density-dependent internal loss couples n and f_{n} and, in view of the T-dependence of n, makes f_{n} T-dependent as well. Thus, the n-dependent α_{int} causes the T-dependence of the threshold current density component j_{QD} associated with recombination in QDs.

As seen from Fig. 1, T_0 is considerably reduced due to n-dependent internal loss. At room temperature, T_0 is about twice as low as that neglecting such a loss.

T_0 falls off profoundly with increasing T (Fig. 1). At a certain temperature T^{max}, presenting the maximum operating temperature of the device (T^{max} = 335 K for a specific case considered), T_0 goes to zero. It is the n-dependent α_{int} that sets up an upper limit for operating temperatures of a laser. The point is that the carrier density n and hence the internal loss $\alpha_{\mathrm{int}} = \alpha_0 + \sigma_{\mathrm{int}} n$ increase continuously with T. At the same time, the maximum gain can not exceed g^{max} [see (1)]. For $T > T^{\mathrm{max}}$, the threshold condition (1) can not be satisfied.

The larger the QD size fluctuations, the lower are T_0 and T^{max} (Fig. 2). In the presence of n-dependent α_{int}, T_0 decreases with δ much faster than that neglecting such a loss. While the latter remains nonvanishing (though low) with increasing δ, T_0 in the presence of n-dependent α_{int} turns to zero at the maximum tolerable RMS of QD-size fluctuations $\delta = \delta^{\mathrm{max}}$. For $\delta > \delta^{\mathrm{max}}$, no lasing is attainable in the presence of n-dependent α_{int} [9].

This work was supported by the U.S. Army Research Office under Grant No. W911–NF–05–1–0308.

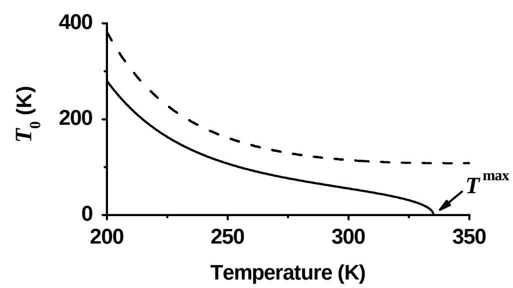

Fig. 1. Characteristic temperature against T calculated including (solid curve) and neglecting (dashed curve) the carrier-density-dependent internal loss. For a GaInAsP/InP heterostructure lasing near 1.55 μm, the parameters are as follows: $\beta = 7$ cm^{-1}, $\alpha_0 = 3$ cm^{-1}, $\sigma_{\mathrm{int}} = 2.67\mathrm{x}10^{-17}$ cm^2.

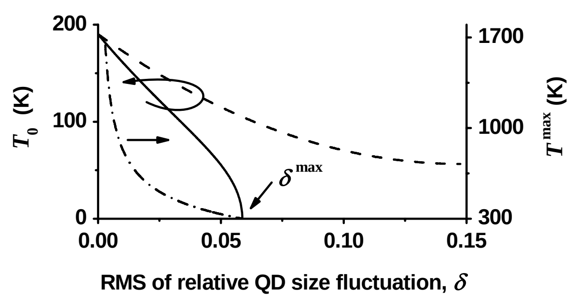

Fig. 2. Characteristic temperature calculated including (solid curve, left axis) and neglecting (dashed curve, left axis) the carrier-density-dependent internal loss in the OCL, and maximum operating temperature (dash-dotted curve, right axis) against RMS of QD size fluctuations.

[1] Y. Arakawa, H. Sakaki, Appl. Phys. Lett. **40**, 939 (1982).
[2] L. V. Asryan, R. A. Suris, IEEE J. QE **34**, 841 (1998).
[3] L. V. Asryan, R. A. Suris, IEEE J. Select. Topics QE **3**, 148 (1997).
[4] P. S. Zory, Ed., *Quantum Well Lasers*. Boston, MA: Academic, 1993.
[5] L. A. Coldren, S. W. Corzine, New York: Wiley, 1995.
[6] C. H. Henry et al., IEEE J. Quantum Electron. **19**, 947 (1983).
[7] D. A. Ackerman, G. E. Shtengel, M. S. Hybertsen, P. A. Morton, R. F. Kazarinov, T. Tanbun-Ek, and R. A. Logan, IEEE J. Select. Topics QE **1**, 250 (1995).
[8] N.-H. Kim et al., IEEE Photon. Technol. Lett. **18**, 989 (2006).
[9] L. V. Asryan, S. Luryi, IEEE J. QE **40**, 833 (2004).

[a] lijiang@vt.edu

[b] asryan@mse.vt.edu