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Internal optical loss and light-current characteristic in injection lasers

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Abstract. Possibility of tailoring the light-current characteristic (LCC) shape in quantum dot (QD) lasers by varying uniformity of QDs is discussed. Making the QD ensemble less uniform results in roll-over in the LCC. The second branch in the LCC appears with making the QD ensemble even less uniform.

1. Introduction

Internal optical loss that is inherent in semiconductor lasers combines different processes of unwanted photon loss as opposed to mirror loss – on purpose output of photons through the cavity mirrors. While the mirror loss presents the useful optical output from semiconductor lasers, the internal loss is undesired as it consumes the photons emitted during the laser action.

In this paper, the effect of uniformity of quantum dots (QDs) on the light-current characteristic (LCC) in QD lasers is discussed in the presence of internal optical loss. While diode lasers have been extensively studied both experimentally and theoretically before (see, e.g., a review article [1]), a new interesting feature has been however predicted in [2]-[4]: in the presence of internal optical loss that depends on the charge carrier density, roll-over of the LCC can occur. The more so, the second branch can appear in the LCC in addition to the first ‘conventional’ branch. Here we discuss the possibility of tailoring the LCC shape in QD lasers in the presence of internal optical loss by varying uniformity of QDs.

2. Theoretical model

Our theoretical analysis is based on rate equations that describe the dynamics of charge carriers and photons in the laser. In the simplest case, we use a set of three equations – two for carriers [free carriers in the optical confinement layer (OCL) and confined carriers in QDs] and one for photons.

The equations for carriers are

$$b \frac{\partial n_{\text{OCL}}}{\partial t} = \frac{j}{e} + N_S \frac{f_n}{\tau_{\text{esc}}} - v_{\text{capt},0} (1 - f_n) n_{\text{OCL}} - b B_{3D} n_{\text{OCL}}^2, \quad (1)$$

$$N_S \frac{\partial f_n}{\partial t} = v_{\text{capt},0} (1 - f_n) n_{\text{OCL}} - N_S \frac{f_n}{\tau_{\text{esc}}} - N_S \frac{f_n^2}{\tau_{\text{QD}}} - c_g g^{\text{max}} (2f_n - 1) n_{\text{ph}}. \quad (2)$$



Table 1. Physical quantities entering in eqs. (1)-(3).

Notation	Meaning
n_{OCL}	Free carrier density in the OCL
f_n	Occupancy of the energy level in a QD by a charge carrier
n_{ph}	Density of emitted photons (per unit area of the laser heterointerface)
j	Injection current density
e	Electron charge
N_S	Surface density of QDs
τ_{esc}	Thermal escape time of charge carriers from an individual QD to the OCL
$v_{\text{capt},0}$	Velocity of carrier capture into an unoccupied (at $f_n = 0$) QD ensemble (in cm/s)
b	Thickness of the OCL
B_{3D}	Spontaneous radiative recombination constant for the bulk (OCL) region (in cm^3/s)
τ_{QD}	Spontaneous radiative lifetime in a QD
c_g	Group velocity of light
g^{max}	Maximum modal gain (cm^{-1})
β	Mirror loss coefficient (in cm^{-1})
α_{int}	Internal optical loss coefficient (in cm^{-1})

The equation for photons is

$$\frac{\partial n_{\text{ph}}}{\partial t} = c_g g^{\text{max}} (2f_n - 1)n_{\text{ph}} - c_g (\beta + \alpha_{\text{int}})n_{\text{ph}}. \quad (3)$$

The parameters entering in eqs. (1)-(3) are described in table 1.

The internal optical loss coefficient in (3) is presented as

$$\alpha_{\text{int}} = \alpha_0 + \sigma_{\text{int}} n_{\text{OCL}}, \quad (4)$$

where α_0 is its constant component and σ_{int} is its the cross-section.

Solving the set of eqs. (1)-(3) at the steady-state, we then find the emitted optical power as follows:

$$P = \hbar\omega c_g \beta S n_{\text{ph}}, \quad (5)$$

where $\hbar\omega$ is the emitted photon energy and S is the cross-section area of the laser heterointerface.

Calculations show that in the presence of internal optical loss that depends on the charge carrier density in the OCL [eq. (4)], roll-over of the LCC can occur at high pump currents and the second branch can appear in the LCC in addition to the conventional branch.

The second branch appears in the LCC if the following condition satisfies:

$$\frac{\sigma_{\text{int}} v_{\text{capt},0}}{2b B_{3D} g^{\text{max}}} > 1. \quad (6)$$

Varying each of the parameters entering in (6) can result in single-to-double branch transformation of the LCC. In [4], the cross-section of internal optical loss σ_{int} was varied in QD lasers; in [5], the thickness of the OCL b was varied in quantum well (QW) lasers; in [6], the capture velocity $v_{\text{capt},0}$ was varied in QW lasers; and in [7], the temperature was varied in QW lasers (the spontaneous radiative

recombination constant B_{3D} entering in (6) is a function of temperature – see [8, 9]). In all these cases, the transformation of the LCC shape from single-to-double branch was shown to occur.

Here, we discuss the transformation of the LCC shape in QD lasers as the QD uniformity is changed.

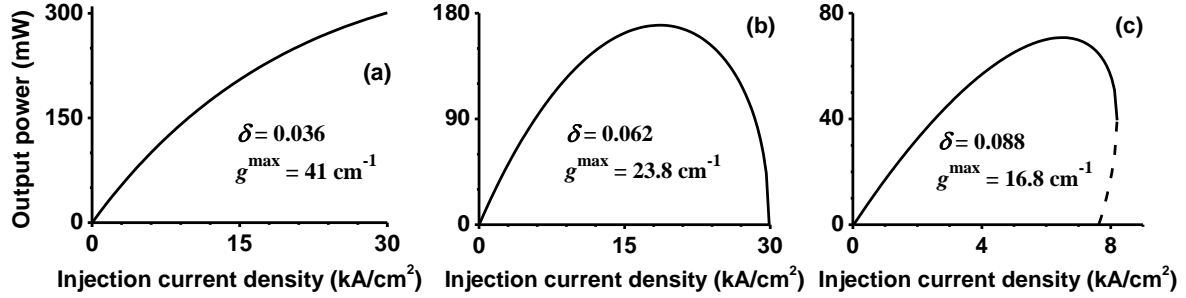


Figure 1. LCC of the QD laser for different values of the RMS of relative QD-size fluctuations δ . The corresponding values of the modal gain g^{\max} are also presented. InGaAsP-based structure emitting near $1.55 \mu\text{m}$ is considered [11, 13]. The internal loss cross-section $\sigma_{\text{int}} = 2 \times 10^{-18} \text{ cm}^2$, and the constant component of the internal loss $\alpha_0 = 2 \text{ cm}^{-1}$.

3. Effect of uniformity of QDs on the LCC shape

Self-assembled QDs are never identical in laser structures – they are primarily different in their sizes. The QD-size dispersion causes fluctuations in the quantized energy levels and leads to broadening in the optical transition energy (inhomogeneous line broadening [8]). Due to nonuniformity of QDs the maximum gain of the laser decreases [8], threshold current increases [8] and becomes more sensitive to temperature (the characteristic temperature decreases) [10], multimode generation threshold decreases [11], internal differential efficiency and output power both decrease [12].

Denoting δ the root mean square (RMS) of relative QD-size fluctuations, the maximum modal gain of a QD laser can be presented as follows [8]:

$$g^{\max} \propto \frac{1}{\delta}. \quad (7)$$

As seen from (7), g^{\max} decreases with increasing δ . Hence it follows from (6) and (7) that the condition for appearing the second branch in the LCC should become satisfied with increasing RMS of QD-size fluctuations, i.e., making the QD ensemble less uniform.

As shown in figure 1(a), at small fluctuations in QD sizes [the case of high modal gain – see (7)], the output power increases with the pump current over the entire range of interest.

At larger fluctuations in QD sizes, the slope efficiency changes from positive to negative with increasing pump current [figure 1(b)]; the output power goes continuously to zero, which marks the stop of lasing. In what follows, such a shape of the LCC is referred to as a ‘conventional’ roll-over to distinguish from the case of strongly nonuniform QDs.

With further increasing RMS of relative QD-size fluctuations up to a certain value, the LCC retains a conventional roll-over shape. Above that value of the RMS, the LCC transforms qualitatively [figure 1(c)]. The stop of lasing with increasing injection current occurs now at a nonvanishing output power: at the maximum operating current, the conventional branch of the LCC (solid portion of the curve) is detached from the X-axis. This upper branch of the LCC is now continued by the second, lower, branch (dashed portion of the curve); in general, with reducing the pump current the output power can follow either the upper (conventional) or lower branch. Experimental observation of the

quenching of lasing at a nonvanishing output power in diode lasers can suggest the presence of carrier-density-dependent internal loss and, in the case of QD lasers, large QD-size dispersion.

4. Conclusions

Possibility of tailoring the LCC shape in QD lasers by varying uniformity of QDs has been discussed. Making the QD ensemble less uniform has been shown to result in roll-over in the LCC. The second branch in the LCC has been shown to appear with making the QD ensemble even less uniform.

Acknowledgments

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