Lasers with double asymmetric barrier layers: Direct versus indirect capture of carriers into the lasing ground state in quantum dots

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Static and dynamic characteristics of a quantum dot (QD) laser with double asymmetric barrier layers – an advanced type of semiconductor laser – are studied. Both direct and indirect capture of carriers into the lasing ground state in QDs is considered. The intradot relaxation of carriers, which controls the laser characteristics in the case of only indirect capture, is shown to not be a significant factor in the case of both direct and indirect capture. In the latter case, both the output optical power and modulation bandwidth are considerably increased.

Introduction: Semiconductor heterostructure lasers have been one of the key optoelectronic devices since their inception [1–4]. A number of factors limit the performance of such lasers [5–21]. Among them is recombination of electrons with holes outside of the laser active region. This parasitic recombination has detrimental effects on the laser characteristics [12–15]. In particular, the threshold current is increased [12], the characteristic temperature is decreased [13], the internal quantum efficiency is decreased, and the light-current characteristic (LCC) is sublinear [14]. Incorporating asymmetric barrier layers (ABLs) in the laser structure should prevent this parasitic recombination [16–18]. As seen from Figure 1, electrons and holes can be both present, and hence recombine with each other, only in the quantum-confined active region of such an advanced laser with double (one on each side of the active region) ABLs.

In this work, we report on a theoretical study of static and dynamic characteristics of quantum dot (QD) lasers with double ABLs (DABLs). We consider a situation, where the stimulated emission is generated by recombination of ground-state electrons with such holes in QDs. In addition to the lasing ground state, we also consider a single non-lasing excited state (one for electrons and one for holes) in QDs (Figure 1). We allow both indirect (i.e. occurring through the excited states) and direct capture of carriers from the waveguide region (optical confinement layer [OCL]) into the lasing ground states in QDs. We compare this case to the case of only indirect capture, where carriers are first captured from the OCL into the excited state before relaxing to the lasing ground state in QDs. Other scenarios in the presence of excited states are also possible in QD lasers as discussed, for example, in reference [19].

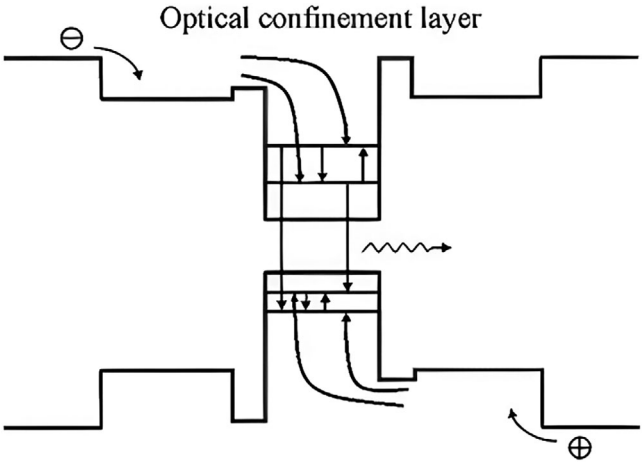

Fig. 1 *Schematic energy band diagram of a double asymmetric barrier layer semiconductor laser. Both indirect (by virtue of excited state) and direct capture of electrons and holes from the waveguide region (optical confinement layer) into the lasing ground state in QDs is considered*

Theoretical model: With the assumption of electron–hole symmetry, we start with a set of four rate equations describing the carrier density $n_{\rm L}$ on one side of the OCL, the ground and excited state occupancies in QDs, f_1 and f_2, respectively, and the photon density $n_{\rm ph\,1}$,

$$b_1\frac{dn_{\rm L}}{dt}=\frac{j}{e}+\sigma_2 v_n n_2 N_{\rm S} f_2-\sigma_2 v_n n_{\rm L} N_{\rm S}(1-f_2)+\sigma_1 v_n n_1 N_{\rm s} f_1-\sigma_1 v_n n_{\rm L} N_{\rm S}(1-f_1)-dBn_{\rm L}^2, \quad (1)$$

$$2N_{\rm S}\frac{df_2}{dt}=\sigma_2 v_n n_{\rm L} N_{\rm S}(1-f_2)-\sigma_2 v_n n_2 N_{\rm S} f_2+N_{\rm S}\frac{f_1(1-f_2)}{\tau_{12}}-N_{\rm S}\frac{f_2(1-f_1)}{\tau_{21}}-N_{\rm S}\frac{f_2^2}{\tau_{\rm QD2}}, \quad (2)$$

$$2N_{\rm S}\frac{df_1}{dt}=\sigma_1 v_n n_{\rm L} N_{\rm S}(1-f_1)-\sigma_1 v_n n_1 N_{\rm S} f_1+N_{\rm S}\frac{f_2(1-f_1)}{\tau_{21}}-N_{\rm S}\frac{f_1(1-f_2)}{\tau_{12}}-N_{\rm S}\frac{f_1^2}{\tau_{\rm QD1}}-c_{\rm g1}g_1^{\max}(2f_1-1)n_{\rm ph1}, \quad (3)$$

$$\frac{dn_{\rm ph1}}{dt}=c_{\rm g1}g_1^{\max}(2f_1-1)n_{\rm ph1}-c_{\rm g1}\beta_1 n_{\rm ph1}, \quad (4)$$

where b_1 is the thickness of one side of the OCL, j is the injection current density, σ_1 and σ_2 are the cross-sections of carrier capture from the OCL into the ground and excited states in QDs, respectively, v_n is the free carrier thermal velocity in the OCL, $N_{\rm S}$ is the surface density of QDs, B is the spontaneous radiative recombination coefficient in bulk OCL, τ_{21} and τ_{12} are the excited-to-ground state and ground-to-excited state transition times in QDs, respectively, $\tau_{\rm QD1}$ and $\tau_{\rm QD2}$ are the ground- and excited-state spontaneous radiative lifetimes in QDs, respectively, $c_{\rm g1}$ is the group velocity of photons emitted via ground-state transitions in QDs, and β_1 is the mirror loss for ground-state lasing.

In Equations (3) and (4), $g_1^{\max}$ is the maximum modal gain for ground-state lasing, given by (Equation (10) of [15]):

$$g_1^{\max}=\frac{\xi}{4}\left(\frac{\lambda_1}{\sqrt{\epsilon_1}}\right)^2\frac{1}{\tau_{\rm QD1}}\frac{\hbar}{(\Delta\varepsilon)_1^{\rm inhom}}\frac{\Gamma_1}{a}N_{\rm S}, \quad (5)$$

where ξ is a numerical constant (equal to $1/\pi$ and $1/\sqrt{2\pi}$ for Lorentzian and Gaussian QD-size distributions, respectively), ϵ_1 and Γ_1 are the optical dielectric constant and the optical confinement factor in the QD layer (in the transverse direction in the waveguide) at the ground-state lasing wavelength λ_1 in an average-sized QD, a is the average linear size of QDs (in the transverse direction in the waveguide), and $(\Delta\varepsilon)_1^{\rm inhom}$ is the inhomogeneous broadening of the ground-state photon energy caused by the QD-size fluctuation [12].

The quantities n_1 and n_2 in Equations (1)–(3) are given by:

$$n_{1,2}=N_{\rm c}^{\rm OCL}\exp\left(-\frac{\Delta E_{\rm C}-E_{1,2}}{T}\right), \quad (6)$$

where $N_{\rm c}^{\rm OCL}$ is the effective density of states in the conduction band in the OCL, $\Delta E_{\rm C}$ is the difference between the conduction band edge in the OCL and in the QDs, E_1 and E_2 are the ground- and excited state energies in QDs, respectively, and T is the temperature in units of energy.

While the ABLs should ideally block the parasitic electron–hole recombination in both the left- and right-hand sides of the OCL, such recombination of electrons with holes will still take place in those parts of the layer with QDs that are not occupied by QDs. This parasitic recombination is taken into account by the last term on the right-hand side of Equation (1), where d is the effective thickness of the parts of the layer with QDs not occupied by QDs,

$$d=\left(1-N_{\rm S}a^2\right)a. \quad (7)$$

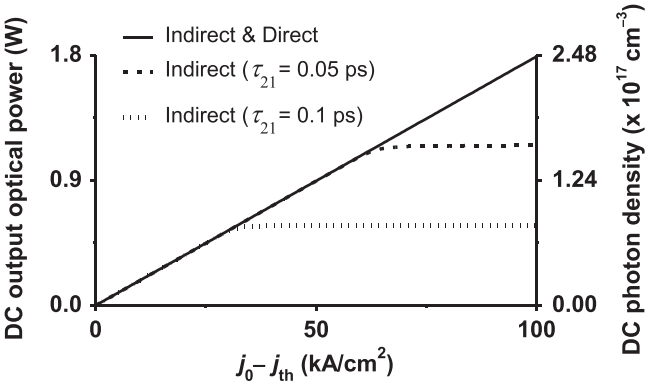

Fig. 2 *DC output optical power (left vertical axis) and DC volumetric photon density (right vertical axis) of a double asymmetric barrier layer quantum dot (QD) laser versus DC component of the injection current density. Solid line: both indirect and direct capture of carriers into the lasing ground state in QDs. Dashed and dotted curves: only indirect capture of carriers into the lasing ground state in QDs at the excited-to-ground state relaxation time values $\tau_{21} = 0.05$ and 0.1 ps, respectively*

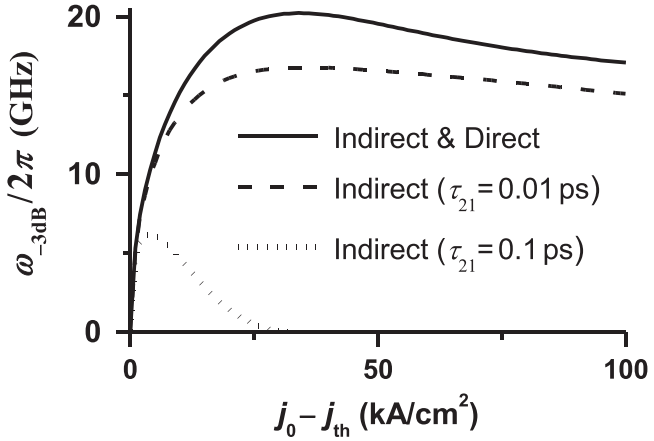

Fig. 3 *Modulation bandwidth of a double asymmetric barrier layer quantum dot (QD) laser versus DC component of the injection current density. Solid curve: both indirect and direct capture of carriers into the lasing ground state in QDs. Dashed and dotted curves: only indirect capture of carriers into the lasing ground state in QDs at the excited-to-ground state relaxation time values $\tau_{21} = 0.01$ and 0.1 ps, respectively*

Since the average size a of QDs is small, so is the effect of the electron–hole recombination in the parts of the layer with QDs that are not occupied by QDs.

In our model, to mainly focus on the impact of intradot relaxation, we assume instantaneous capture of carriers from the OCL into both the ground and excited states in QDs. By using this assumption, which is equivalent to setting $\sigma_1 = \sigma_2 = \infty$ in Equations (1)–(3) (see also reference [20]), we find that the carrier density on one side of the OCL, the excited-state occupancy, and the ground state occupancy in QDs are not independent of one another, which allows us to reduce the number of equations from four down to two. As part of the reduction from four to two equations, the intradot transition times τ_{21} and τ_{12} fall out of the equations, meaning they do not impact the operating characteristics in this case of instantaneous capture of carriers from the OCL into both the ground and excited states in QDs.

We first solve this set of two rate equations at the steady state and find the DC component $\bar{n}_{\mathrm{ph1}-0}$ C component of the injection current density (right vertical axis in Figure 2). We then calculate the LCC of the laser – the DC output optical power P_1 (left vertical axis in Figure 2) as a function of the DC component of the injection current density: C component of the injection current density (right vertical axis in Figure 2). We then calculate the LCC of the laser – the DC output optical power P_1 (left vertical axis in Figure 2) as a function of the DC component of the injection current density:

$$P_1 = \hbar\omega 1 \frac{\bar{n}_{\mathrm{ph1}-0}}{\tau_{\mathrm{ph1}}} bLW = \hbar\omega 1 c_{\mathrm{g1}} \beta_1 \bar{n}_{\mathrm{ph1}-0} bLW, \tag{8}$$

where $\hbar\omega 1$ is the ground-state photon energy emitted in an average-sized QD, b is the thickness of the entire OCL, L is the optical cavity length, W is the lateral size of the device (the stripe width), and $\tau_{\mathrm{ph1}} = 1/(c_{\mathrm{g1}}\beta_1)$ is the photon lifetime in the cavity.

We then follow the same method of reference [21] to analyse the dynamic response of a DABL QD laser and calculate its modulation bandwidth – a figure of merit describing how fast its optical output can be directly modulated by alternating electrical input (injection current). We find the -3 dB modulation bandwidth $\omega_{-3\mathrm{dB}}$ in the following form:

$$\omega_{-3\mathrm{dB}} = \sqrt{\left(\omega_0^2 - 2\Gamma_{\mathrm{dec}}^2\right) + \sqrt{\left(\omega_0^2 - 2\Gamma_{\mathrm{dec}}^2\right)^2 + (r-1)\,\omega_0^4}}, \tag{9}$$

where

$$\omega_0 = \sqrt{c_{\mathrm{g1}} G^{\mathrm{dif}} \bar{n}_{\mathrm{ph1}-0} \frac{1}{\tau_{\mathrm{ph1}}}}, \tag{10}$$

and Γ_{dec} is the decay rate of relaxation oscillations, G^{dif} is the effective differential gain, and $r = 10^{0.3}$. In (9) and (10), Γ_{dec} and $\bar{n}_{\mathrm{ph1}-0}$ are functions of the DC component j_0 of the injection current density.

Discussion: We consider an InP/GaInAsP based DABL QD laser emitting near 1.55 μm [18]. As discussed in reference [19] (Table III therein), the values for the intradot relaxation time τ_{21} vary in a considerable range in the literature. The τ_{21} values used in our Figures 2 and 3 belong to that range.

Figure 2 shows the DC output optical power (left vertical axis) versus the DC injection current density (the LCC of the laser) for the case of both direct and indirect capture, as well as the case of only indirect capture. The DC volumetric photon density is also shown in the figure (right vertical axis). As seen from the figure, in the case of both direct and indirect capture, the LCC in DABL QD laser is a straight line (the solid line), and, hence, the output power does not saturate. This is due to the fact that pumping the lasing ground state in QDs is not controlled by excited-to-ground state relaxation of carriers in QDs. In the case of only indirect capture, the LCC first follows the straight line, and then it bends down (the dashed and dotted curves in Figure 2) reflecting the fact that the output optical power saturates – it approaches asymptotically a maximum value with increasing pump current. The maximum optical power in this case is controlled by the intradot relaxation time, with shorter time allowing higher power (Figure 2).

Figure 3 shows the modulation bandwidth versus the DC component of the injection current density for the case of both direct and indirect capture, as well as the case of only indirect capture. We see that the case of both direct and indirect capture shows a considerably higher maximum modulation bandwidth, and that only when the intradot relaxation time will approach zero, the case of only indirect capture will approach the same maximum value. In both cases, we see that there exists an optimum DC component of the current density in terms of maximizing the modulation bandwidth.

Conclusion: The static and dynamic characteristics of DABL QD lasers were studied considering the presence of excited states in QDs. We found that compared to the case of only indirect (by virtue of excited state) capture of carriers from the OCL into the lasing ground state in QDs, the case of both direct and indirect capture has a significantly improved (linear, not saturating) LCC and, hence, higher output optical power, and higher modulation bandwidth. These improvements are due to the fact that in the latter case, as opposed to the former case, the intradot relaxation of carriers does not present a factor that limits pumping the lasing ground state in QDs.

Author contributions: **Cody Hammack**: Investigation; software; writing—original draft. **Levon V. Asryan**: Conceptualization; funding acquisition; investigation; methodology; software; supervision; writing—review and editing.

Acknowledgements: This work was partially supported by the U.S. Army Research Office (Grant No. W911NF-17-1-0432).

Conflict of interest statement: The authors declare no conflicts of interest.

Data availability statement: As this research is theoretical, the entire data have already been made available in the article.

Received: *7 October 2024* Accepted: *14 November 2024*
doi: 10.1049/ell2.70117

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