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Nonvanishing turn-on delay in quantum dot lasers

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A turn-on of a quantum dot semiconductor laser is analyzed in detail both theoretically and experimentally. We show that quantum dot lasers have a nonlinear damping rate which strongly affects laser turn-on dynamics due to the non-instantaneous capture of carriers to a dot. It results in nonvanishing turn-on delay even at very high pumping in good agreement with experiment.

Semiconductor quantum dot (QD) based optical materials and devices have been intensively studied in recent years due to their high efficiency and multiple technological applications. Turn-on experiments where the electrical pump is quickly changed from a below to an above threshold value are of great interest. Outside the seminal work Ref. 1, most of the research activities concentrate on the phenomenon of relaxation oscillations and its damping properties.2–4 The nonlinearity and non-instantaneous capturing of the carriers into a dot is known to strongly affect the recovery of QD material,5 but its impact on the laser turn-on time remains partially unresolved except for results recently published in Ref. 6.

In this letter, we explain that due to the nonlinear interaction between the dots and the wetting layers, a QD laser cannot be turned on faster than a fixed value determined by the material gain and losses. This particular dynamical property is not observed for conventional quantum well (QW) semiconductor lasers.

In order to contrast the difference between QD and QW semiconductor lasers, we briefly analyze the turn-on response of a QW laser. The latter is a class B laser that admits the following dimensionless rate equations for the normalized field intensity I and the number of carriers D (Ref. 7):

\[ I' = I(-1 + D), \]
\[ D' = \eta(J_+ - D(1 + I)), \]
\[ D(0^+) = J_-, I(0^+) = I_0 \ll 1. \]

Prime means differentiation with respect to \( t \equiv t'/\tau_{ph} \), where \( \tau_{ph} \) is the photon lifetime. \( \eta \equiv \tau_{ph}^{-1} \ll 1 \), where \( \tau \) denotes the carrier recombination time. \( J(0^-) = J_- < 1 \) and \( J(0^+) = J_+ > 1 \) are below and above threshold values of the pump parameter. During the turn-on experiment, the intensity remains small until it quickly increases exponentially. Solving first Eq. (2) with \( I = 0 \) and then Eq. (1), we obtain the following solution for the intensity:

\[ I = I_0 \exp \left( \frac{1}{\eta} F(s) \right), \]

where \( s = \eta t \) and \( F(s) \) is given by

\[ F(s) = (J_+ - 1)s - (J_- - J_+)(\exp(-s) - 1). \]

The turn-on time \( s_{on} \) is defined by the condition \( I(s_{on}) = I_{ref} \), where \( I_{ref} \) is a fixed reference value. Assuming \( s \ll 1 \) as \( J_+ \rightarrow 1 \), the expression (5) simplifies as

\[ F(s) = -1 - (1 - J_-)s + \frac{J_+}{2} s^2 \]

and leads to \( s_{on} \sim 2(1 - J_-)J_+^{-1} \). In terms of the original time, the turn-on delay is

\[ t_{on}^* \sim 2(1 - J_-)tJ_+^{-1} \]

and is clearly vanishing as \( J_+ \rightarrow \infty \).

We should emphasize the fact that Eq. (7) is asymptotically valid if \( \varepsilon J_+ \ll 1 \) (\( \varepsilon \equiv \eta n_b I_{ref}/I_0 \) fixed). If \( \varepsilon J_+ = O(1) \) or \( \varepsilon J_+ \gg 1 \), different expressions for the turn-on time can be derived. In the case of very large \( J_+ \), we find that \( s_{on} \sim \sqrt{2e/J_+} \) as \( eJ_+ \rightarrow \infty \) which remains vanishing as \( J_+ \rightarrow \infty \).

We next consider the turn-on response of a QD laser using a three-variable rate equation model that allows analytical investigations. It consists of the following three equations for the electric field intensity I, the occupational probability of the ground state (GS) in a dot \( \rho \), and the carrier density \( n \) in the wetting layers (WL), scaled to the 2D QD density per layer:

\[ I' = [-1 + g(2\rho - 1)]I, \]
\[ \rho' = \eta[Bn(1 - \rho) - \rho - (2\rho - 1)]I, \]
\[ n' = \eta[I - n - 2Bn(1 - \rho)]. \]

The factor 2 in Eq. (10) accounts for the spin degeneracy in the quantum dot energy levels. \( J \) is the pump current per dot, and

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This is a scientific paper discussing the nonvanishing turn-on delay in quantum dot lasers. The authors use a three-variable rate equation model to analyze the turn-on response of QD lasers, contrasting it with QW lasers. They demonstrate that QD lasers have a nonlinear damping rate due to the non-instantaneous capture of carriers to a dot, leading to a fixed turn-on delay even at very high pumping. The theoretical predictions are in good agreement with experimental results.
$J = 2$ is the threshold value due to the spin degeneracy. The gain $g(2p - 1)$ is defined by the dot population and a $g$-factor. $B \equiv \tau_{cap}^{-1}$, where $\tau_{cap}$ denotes the capture time. Typical values are $\tau = 1$ ns and $\tau_{cap} = 10$ ps implying $B = 10^2$. The nonlinear interaction between the WL and the dots is provided by the Pauli blocking factor $(1 - \rho)$ which constitutes the most important difference between QD and QW rate equations.

If $J_+ < 2$, the laser operates at the stable OFF steady state $I = 0$, $\rho = \rho_0 = \frac{J_+}{J_+ + O(B^{-1})}$, and $n = n_0 = B^{-1} \frac{J_+}{J_+ + O(B^{-1})}$. We consider the following initial conditions: $\rho(0^+) = \rho_0$, $n(0^+) = n_0$, and $I(0^+) = I_0 \ll 1$. At time $t = 0^-$, the pump parameter is rapidly changed to $J = J_+ > 2$, and we integrate Eqs. (8)–(10) until the ON steady state is reached. The turn-on time $t = t_{on}$ is defined as the time at which $I$ equals a fixed value $I_{ref}$. We numerically observe that it becomes smaller as $J_+$ increases and that it approaches a constant value independent of $J_+$ (see Fig. 1).

Since $I$ remains small until the intensity quickly increases exponentially, we solve Eqs. (9) and (10) with $J = J_+$ and $I \approx 0$. Eliminating $n$, we find that $\rho$ satisfies the following nonlinear first-order equation:

$$\frac{d\rho}{ds} = B[(z_0 - J_+)\exp(-s) + J_+ - 2\rho](1 - \rho) = \rho,$$  

(11)

where $s = \eta t$ and $z_0 = 2\rho_0 + n_0 = J_+ + O(B^{-1})$. The solution of Eq. (8) is

$$I = I_0\exp\left(\frac{1}{\eta} G(s)\right),$$  

(12)

where $G(s)$ is defined by

$$G(s) = -(1 + g)s + 2g \int_0^s \rho(u) du.$$  

(13)

After solving Eq. (11) for $\rho$, we determine the intensity from Eq. (12). The solution for $J_+ = 10$ is shown in Fig. 1 by an arrow.

We investigate analytically Eqs. (11) and (12) by first examining the limit $B$ large and then the limit $J_+$ large. If $B \to \infty$ and $1 - \rho \gg B^{-1}$, Eq. (11) simplifies as

$$\frac{d\rho}{ds} \approx B[(J_+ - J_+)\exp(-s) + J_+ - 2\rho](1 - \rho),$$  

(14)

which is a Bernoulli equation for $1 - \rho$, which can be solved analytically. The solution for $\rho$ then is

$$\rho = 1 - \frac{\exp(-BF(s))}{(1-\rho_0)^{-1} + 2B \int_0^s \exp(-BF(u)) du},$$  

(15)

where $F(s)$ is defined by

$$F(s) \equiv (J_+ - J_+)(\exp(-s) - 1) + (J_+ - 2)s.$$  

(16)

We next determine the intensity from Eq. (12). The approximation (15) will be useful when we examine the limit $J_+ \to \infty$. The normalized turn-on time $s = s_{on}$ is obtained from the condition $I(s_{on}) = I_{ref}$ and is shown in Fig. 2. In this figure, $s_{on}$ is calculated for $I_{ref} = 10$ using Eqs. (11) and (12). It shows a good agreement with the value determined numerically using Eqs. (12) and (15) valid for large $B$ (arrow in Fig. 2).

The turn-on delay is vanishing for a QW laser as $J_+ \to \infty$ (see Eq. (7)). The same limit for QD lasers is, however, different. Indeed, the solution (15) exhibits an initial layer before it saturates at $\rho = \rho_0 \equiv 1 + O(B^{-1})$. This can be seen by analyzing the function (16) for $J_+ \to \infty$. We note that $F(s) \approx J_+[(\exp(-s) - 1) + s]$ in this limit, meaning, the initial layer is $(BJ_+)^{-1}$ small. Consequently, $\rho$ quickly saturates at $\rho = \rho_0 \approx 1$. With $\rho = 1$, the function (13) simplifies as $G = (g - 1)s$ and Eq. (12) gives

$$I = I_0\exp\left(\frac{1}{\eta} \frac{1}{g - 1} \frac{s}{B J_+}\right),$$  

(17)

(see Fig. 2). The normalized turn-on time $s_{on}$ computed using Eqs. (12) and (14) valid for large $B$ is indicated by an arrow. It is compared to the turn-on time determined using the original Eqs. (11) and (12). With $I(0) = I_0 = 10^{-4}$, $\eta = 2 \times 10^{-2}$, $g = 1.25$, and $I_{ref} = 10$, we find analytically that the turn-on time is bounded by $S_{on} = \frac{1}{B J_+} \ln(I_{ref}/I_0) = 0.92$ which clearly appears as a horizontal asymptote for all our numerical data (dashed line).
\[ I \simeq I_0 \exp \left( \frac{1}{\eta} (g - 1) s \right) \]  \hspace{1cm} (17)

In terms of the original time, the turn-on delay is then given by
\[ t'_{\text{on}} = \frac{\tau_{\text{ph}}}{g - 1} \ln\left( I_{\text{ref}} / I_0 \right) \]  \hspace{1cm} (18)

and is independent of \( J_+ \). This contrasts to our conclusion for the QW laser where \( t'_{\text{on}} \) remains a decaying function of \( J_+ \).

Experimentally, the QD laser structures studied were grown on n-GaAs (001) substrates by molecular-beam epitaxy. Their active regions included 1, 5, or 10 layers of self-assembled InAs QDs placed in InGaAs quantum wells (dots-in-well design). Growth and basic properties of similar QD lasers have been described elsewhere.8 The QD sheets were separated with the 38 nm-thick GaAs spacers. The wafers were processed into 4 m-wide ridge waveguide devices. The 4.5 mm long lasers with as-cleaved facets studied in this article lase only via the GS at 1290 nm.

Operation in the pulse-pumped regime is necessary to measure the turn-on delays. Pulses of \( \sim 1 \) ns rise-time (measured at 10%-90% level) obtained from a high power (up to 1.5 A current) DC source were used to turn the lasers on. The laser output was detected using a high-speed pin detector with a cut-off frequency of 30 GHz and a 50 GHz digital oscilloscope. The turn-on delay was derived as the time difference between the rise-up of the pump current pulse measured at the laser diode and that of the signal from the photodetector. The optical and electrical path lengths were carefully estimated, and the difference between the two lengths was taken into account. Further details of the experimental technique can be found in Ref. 9.

Results of the turn-on delay measurements for a range of currents are shown in Fig. 3. We first examine a QW laser and find that the turn-on time is inversely proportional to the above threshold current with an estimated recombination time \( \tau_{\text{ph}} \). The experimental data for the QD laser are more scattered but clearly indicate a quasi-stable value for significant range of the higher currents.

In summary, we found a different turn-on behavior for QD and QW lasers which results from the nonlinear interaction between the dots and the WL. The turn-on delay for QW lasers hyperbolically decays to zero with the pump current. This is the consequence of the slow growth of the number of carriers. By contrast, in QD lasers, the occupational probability \( \rho \) quickly saturates to \( \rho = 1 \) as the pump current increases, and the turn-on process cannot be faster than the fixed value (18). Under the condition of fast capturing time \( \tau_{\text{cap}}^{-1} \gg 1 \) which is always observed for QD lasers, the non-vanishing turn-on delay is fully determined by the gain factor \( g \) and the photon lifetime \( \tau_{\text{ph}} \). It is worth mentioning that while a value of \( g \) close to 1 may lead to a significant turn-on delay, a large \( g \) contributes to its reduction. It applies for the high Q-factor nanocavity lasers with low energy losses.10

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