A Study of Dynamic Characterizations of GaAs/AlGaAs Self-Assembled Quantum Dot Lasers

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Abstract: In this research, we have solved the rate equations for GaAs/AlGaAs self-assembled quantum dot laser with considering the homogeneous and inhomogeneous broadening of the optical gain using 4th order Runge-Kutta method. With increasing the Full Width at Half Maximum (FWHM) of homogeneous broadening, the threshold current, turn-on delay and steady-state photons increase because of increasing the density of states in the central group. The calculation results show also that the simulated self-assembled dot laser reaches the steady-state faster and the lasing emission is not single mode due to the gain saturation.

Key words: Self-assembled quantum dot laser, Runge-Kutta method, gain saturation, control group, calculation, single mode

INTRODUCTION

Broadband light-emitting devices such as Super Luminescent Diodes (SLDs) and external cavity tunable lasers are ideal optical sources for applications in many areas. For example, SLDs can be used in the fields of Optical Cherenque Tomography (OCT), Fiber-Optic Gyroscope (FOG) and Wavelength-Mode-Multiplexing (WDM) systems while external cavity tunable lasers are used in the fields of optical spectroscopy, biomedical, metrology and Dense Wavelength Division Multiplexing (DWDM).

It was proposed that the characteristic of size inhomogeneity naturally occurred in self-assembled Quantum Dots (QDs) grown by Stranski-Krastanow (SK) mode is beneficial to broadening the material gain spectra (Sun et al., 1999). Broadband emitting QD-SDLs and broadband tuning external cavity tunable lasers with QD gain devices have been studied (Zhang et al., 2004, 2008; Liu et al., 2005; Lv et al., 2008; Sugawara et al., 2000). Here, we present results in broadband emitting QD material laser. These GaAs/AlGaAs QDs exhibit a broad Photoluminescence (PL) Full Width at Half Maximum (FWHM) of 158 nm which is much wider than that grown on GaAs buffer (Lv et al., 2008; Sugawara et al., 2000). The short migration length of gallium atoms on AlGaAs surface increases the size dispersion of GaAs QDs resulting in the broadening of optical spectrum. By optimizing the GaAs spacer thickness of multi-stacked GaAs/AlGaAs QDs, over 150 nm PL FWHM is achieved. In this study, considering the homogeneous and inhomogeneous broadening of the optical gain we have solved the rate equations numerically using 4th order Runge-Kutta method and analyze the dynamics characteristics of GaAs/AlGaAs SAQD-LDs (Tan et al., 2007, 2008).

We have shown that considering the nonlinear gain result in the dynamic characteristic of photons number at the FWHM of homogeneous broadening comparable near or equal to the FWHM of inhomogeneous broadening reaches the steady-state faster. The dynamics characteristics such as maximum of the relaxation oscillation magnitude, turn-on delay, relaxation oscillation frequency and modulation bandwidth are improved as the current is increased.

MATERIALS AND METHODS

Linear and nonlinear optical gain: Based on the density-matrix theory, the linear optical gain of QD active region is given as:

\[ g^{(1)}(E) = \frac{2pe^2\hbar N_p}{cn_em_0^2} \left| \frac{p_{\sigma\sigma}}{E_{\sigma\sigma} - E} \right|^2 B_{\sigma}(E - E_{\sigma}) \]  (1)

Where:
- \( n_e \) = The refractive index
- \( N_p \) = The volume density of QDs
- \( |P_{\sigma\sigma}|^2 \) = The transition matrix element
- \( f_{\sigma} \) = The electron occupation function of the conduction-band discrete state
- \( f_{\sigma^*} \) = That of the valence-band discrete state
- \( E_{\sigma} \) = The interband transition energy

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The linear optical gain shows the homogeneous broadening of a Lorentz shape as:

\[ B_\sigma (E - E_\sigma) = \frac{\hbar G_\sigma / p}{(E - E_\sigma)^2 + (\hbar G_\sigma)^2} \]  \hspace{1cm} (2)

Where, FWHM is given as \(2h\Gamma_\sigma\) with polarization dephasing or scattering rate \(\Gamma_\sigma\). Neglecting the optical-field polarization dependence, the transition matrix element is given as:

\[ |p_{\sigma}|^2 = \left| I_{\sigma} \right|^2 M^2 \]  \hspace{1cm} (3)

where, \(I_{\sigma}\) represents the overlap integral between the envelope functions of an electron and a hole:

\[ M^2 = \frac{m_r^* E_r (E_r + D)}{12m_e^* E_v + 2D / 3} \]  \hspace{1cm} (4)

Where:

\(k_p\) = The interaction between the conduction band and valence band
\(E_r\) = The band gap
\(m_r^*\) = The electron effective mass
\(E_v\) = The spin-orbit interaction energy of the QD material

Equation 3 holds as long as we consider QDs with a nearly symmetrical shape (Markus et al., 2003; Grundmann, 2002; Sugawara et al., 1997). In actual SAQD-LDs, we should rewrite the linear optical gain formula of Eq. 1 by taking into account inhomogeneous broadening due to the QD size and composition fluctuation in terms of a convolution integral as:

\[ g_{\sigma}(E) = \frac{2pe^3 \hbar N_0}{cn_e^2} \frac{|p_{\sigma}|^2}{E_{\sigma}} \left( f_c(E) - f_v(E) \right) \]  \hspace{1cm} (5)

Where:

\(B_{\sigma}\) = The center of the energy distribution function of each interband transition
\(f_c(E)\) = The electron occupation function of the conduction-band discrete state of the QDs with the interband transition energy of \(E_c\) and \(E_v\) = That of the valence band discrete state

The energy fluctuation of QDs are represented by \(G(E_{\sigma} - E_{\sigma})\) that takes a Gaussian distribution function as:

\[ G(E_{\sigma} - E_{\sigma}) = \frac{1}{\sqrt{2\pi} \xi} \exp \left( \frac{(E_{\sigma} - E_{\sigma})^2}{2\xi^2} \right) \]  \hspace{1cm} (6)

Whose, FWHM is given by \(\Gamma_\sigma = 2.35\xi\). The width \(\Gamma_\sigma\) usually depends on the band index \(c\) and \(v\) (Lv et al., 2008).

**Rate equations:** The most popular and useful way to deal with carrier and photon dynamics in lasers is to solve rate equations for carrier and photons (Grundmann, 2002; Sugawara et al., 1997; Sugawara, 1995; Coldren, 1995). We consider an electron and a hole as an exciton thus, the relaxation means the process that both an electron and a hole relax into the ground state simultaneously to form an exciton.

We assume that only a single discrete electron and hole ground state is formed inside the QD and the charge neutrality always holds in each QD. In order to describe the interaction between the QDs with different resonant energies through photons, we divide the QD ensemble into \(j = 1, 2, ..., 2M+1\) groups depending on their resonant energy for the interband transition over the longitudinal cavity photon modes. \(J = M\) corresponds to the group and mode at \(E_{\sigma}\).

We take the energy width of each group equal to the mode separation of the longitudinal cavity photon modes which equals to:

\[ \Delta E = \frac{\hbar c}{2n_e L_{\text{c}}^2} \]  \hspace{1cm} (7)

Where, \(L_{\text{c}}\) is the cavity length. The energy of the jth QDs group is represented by:

\[ E_j = E_{\sigma} - (M-j)\Delta E \]  \hspace{1cm} (8)

Where, \(j = 1, 2, ..., 2M+1\). The QD density jth QDs group is given as:

\[ N_{\sigma} G_j = N_{\sigma} G(E_j - E_{\sigma}) \Delta E \]  \hspace{1cm} (9)

Let \(N_j\) be the carrier number in jth QDs group, according to Pauli’s exclusion principle, the occupation probability in the ground state of the jth QDs group is defined as:

\[ P_j = \frac{N_j}{2N_{\sigma} V_0 G_j} \]  \hspace{1cm} (10)

The rate equations are as follows (Liu et al., 2005; Lv et al., 2008; Sugawara et al., 2000; Tan et al., 2008):
\[
\begin{align*}
\frac{dN_x}{dt} &= \frac{1}{\tau_x} N_0 - \frac{N_x}{\tau_x} \sum \frac{N_j}{\tau_j} - \frac{N_x}{\tau_{wn}} N_w \\
\frac{dN_w}{dt} &= \frac{N_x G_j}{\tau_j} - \frac{N_j}{\tau_j} \sum \frac{1}{\tau_j} - \frac{N_x}{\tau_{wn}} N_w \\
\frac{dN_j}{dt} &= \frac{\beta N_j}{\tau_j} + \frac{e \Gamma}{\hbar} g^{(1)}(E) S_n - \frac{S_n}{\tau_j} \\
\frac{dS_m}{dt} &= \frac{2 \hbar \epsilon_0 c N_x}{\tau_j} \left| \frac{P_{\gamma}}{E_{\gamma}} \right|^2 \left( 2 P_{\gamma} - 1 \right).
\end{align*}
\]

Where:
- \( N_p, N_w, \text{and} \, N_j \) = The carrier number in Separate Confinement Heterostructure (SCH) layer, Wetting Layer (WL) and jth QDs group, respectively.
- \( S_n \) = The photon number of mth mode where \( m = 1, 2 \ldots 2M+1 \)
- \( I \) = The injected current
- \( G_j \) = The fraction of the jth QDs group type within an ensemble of different dot size populations
- \( e \) = The electron charge
- \( D_k \) = The degeneracy of the QD ground state without spin
- \( \beta \) = The spontaneous-emission coupling efficiency to the laser mode
- \( g^{(1)} \) = The linear optical gain which the jth QDs group gives to the mth mode photons where is represented by:

\[
g^{(1)}(E) = \frac{2 \hbar \epsilon_0 c N_x}{\tau_j} \left| \frac{P_{\gamma}}{E_{\gamma}} \right|^2 \left( 2 P_{\gamma} - 1 \right).
\]

The related time constants are as: \( \tau_x \) is diffusion in the SCH region; \( \tau_{wn} \) is carrier recombination in the SCH region; \( \tau_{re} \) is carrier reexcitation from the WL to the SCH region; \( \tau_{rr} \) is carrier recombination in the WL; \( \tau_{qm} \) is carrier relaxation into the jth QDs group; \( \tau_q \) is carrier recombination in the QDs and \( \tau_p \) is photon lifetime in the cavity. The average carrier relaxation lifetime \( \tau_q \) is given as:

\[
\tau_q = \tau_{qm} G_n = \tau_{qm} (1 - P_{\gamma}) G_n
\]

Where, \( \tau_q \) is the initial carrier relaxation lifetime. The photon lifetime in the cavity is:

\[
\tau_p = c / n, + \ln(1 / \rho \rho_x) / 2 L_{wm}
\]
Fig. 2: Simulation results of photon characteristics for different injection currents $I = 2, 2.5, 5$ and 10 mA when the FWHM of homogeneous broadening is 3, 5, 7 and 10 meV.

we call them early photons lead to increasing the stimulated emission rate as a result, the QDs carriers decrease and the lasing photons increase at the new steady-state. With increasing the injection current turn on delay decreases, this occur because the required carriers for start of the relaxation oscillation supply earlier.

Relaxation oscillation frequency and maximum of the relaxation oscillation magnitude also enhance further increment of early photons lead to further increment of maximum of the relaxation oscillation magnitude. On the other side, increasing the stimulated emission rate leads to the rather light amplification and decreasing the cavity photons time as a result the relaxation oscillation frequency increases and the laser reaches the steady state earlier.

As the FWHM of homogeneous broadening increases from c to f, turn on delay increases because density of states of the central group increase as a result the required carriers for start of lasing increase and supply slower. Steady-state photons except to Fig. 2c at the current $I = 2.5$ mA increases due to increasing the QDs within the homogeneous broadening of the central mode. Enhancing of the homogeneous broadening until special value for the specific current (for example, in Fig. 3a, b, until $\hbar\gamma_{cn} = 3$ meV for $I = 2$ mA leads to increasing of maximum of the relaxation oscillation magnitude and the steady-state photons because the central group DOS and thus the central group carriers enhance. Further elevating of the homogeneous
magnitude and the steady-state photons. As shown at injection current $I = 2 \, \text{mA}$ with increasing of the FWHM of homogeneous broadening from $6 \, \text{meV}$, the population inversion is provided at the higher current and the threshold current elevation. As shown in Fig. 4a, the steady-state photons at $I = 2.5 \, \text{mA}$ are $< I = 2 \, \text{mA}$.

Lasing photons at $I = 5$ and $10 \, \text{mA}$ do not reach the steady state after 80 and 40 ns. As it is shown in Fig. 4b, the lasing photons at $I = 5$ and $10 \, \text{mA}$ decreases as the time increases and they become lesser than that of $I = 2 \, \text{mA}$ after 45 ns, they do not reach the steady-state after 80 ns.

Lasing photons at $10 \, \text{mA}$ become lesser than that of $5 \, \text{mA}$ after 30 ns. Lasing photons at $I = 2.5 \, \text{mA}$ increase as the time enhances and they do not reach the steady-state after 100 ns. As it is shown in Fig. 4c, the lasing photons at $I = 2.5 \, \text{mA}$ reach the steady-state after 80 ns but the lasing photons at $I = 5$ and $10 \, \text{mA}$ do not reach the steady-state and they elevate as the time increases. As it is shown in Fig. 4d, the lasing photons at $I = 5$ and $10 \, \text{mA}$ do not reach the steady-state after 300 ns. These non steady-states are due to not considering of gain saturation effect.

**CONCLUSION**

Self-assembled Quantum Dots (QDs) with broadband emitting spectra, QD Super Luminescent Diodes (SLDs) and external cavity tunable QD laser have been studied. Considering the homogeneous and inhomogeneous broadening of the optical gain without and with considering the nonlinear gain and thermal carrier escape from QDs, we have solved the rate equations numerically using fourth order Runge-Kutta method and analyzed the dynamic characteristics of GaAs/AlGaAs SAQD-LDs.

Dynamic characteristics and steady-state photons improve as the current increases.

Considering the nonlinear gain results in improvement of simulation results of the dynamic characteristics of GaAs/AlGaAs SAQD-LD at the FWHM of homogeneous broadening comparable near and equal to the FWHM of inhomogeneous broadening. In this case, the SAQD-LD reaches the steady-state faster and the lasing emission is not single mode due to the gain saturation.

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