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ABSTRACT

This paper describes an investigation of the linewidth enhancement factor $\alpha_H$ in a semiconductor quantum-dot laser. Results are presented for active region parameters and laser configurations important for minimizing $\alpha_H$. In particular, the feasibility of lasing at the gain peak with $\alpha_H = 0$ is explored. The study uses a many-body theory with dephasing effects from carrier scattering treated at the level of quantum-kinetic equations. InAs quantum-dot lasers with different p-modulation doping densities are fabricated and measured to verify the calculated criteria on laser cavity design and epitaxial growth conditions.

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Quantum well (QW) gain regions have replaced bulk ones for virtually all commercial applications. Further improvement in laser performance may have to come from an underlying physics level. A strong candidate is the class of lasers with quantum-dot (QD) active regions, where quantum confinement increases from one-dimensional to three-dimensional, or equivalently, electronic density of states reduces from two-dimensional (2-d) to zero-dimensional (0-d).1 The atomic (0-d) nature of optical emission was demonstrated in the 1990s.2,3 Predicted advantages of low lasing threshold,4 high temperature operation,5 tolerance to crystalline defects, and optical feedback6,7 are being realized.

With successes in threshold performance, attention in QD lasers is shifting toward the above-threshold properties. Important for applications, ranging from datacom and telecom to chemical sensing and laser radar, are laser linewidth,8 chirp during high-speed modulation,9,10 and optical feedback sensitivity.11 A critical gain-medium parameter is the linewidth enhancement factor, $\alpha_H = 0$ is explored. The study uses a many-body theory with dephasing effects from carrier scattering treated at the level of quantum-kinetic equations. InAs quantum-dot lasers with different p-modulation doping densities are fabricated and measured to verify the calculated criteria on laser cavity design and epitaxial growth conditions.

We investigated the minimization of $\alpha_H$, in particular, the feasibility of $\alpha_H = 0$ at the gain peak. This paper describes application of a many-body QD gain theory to identify relevant device parameters and desirable laser configurations. The study involves lasers, each consisting of multiple QWs embedding InAs QDs. The QWs are separated by GaAs barriers, and the entire gain region is cladded by graded-index AlGaAs layers.14–18 The calculations are for the gain and carrier-induced refractive index at laser frequency $\nu$ and with various p-modulation doping densities and inhomogeneous broadening. These parameters represent tunable criteria in laser cavity design and epitaxial growth conditions for engineering $\alpha_H = 0$ QD lasers.

From semiclassical laser theory, the intensity gain $G$ and carrier-induced refraction index $\delta n$ at laser frequency $\nu$ are

$$[2K\delta n(\nu) + iG(\nu)]e = \frac{2\nu}{c m n_B c h} \left[ \sum_n \varphi_n \sum_q n_{\alpha q}^{\text{inh}} \varphi_{\alpha q}(\nu) + \frac{1}{A} \sum_k \varphi_k p_k(\nu) \right].$$

where $\delta n$ is the carrier-induced refractive index, $G$ is the intensity gain, $N_e$ is the carrier density, and $K$ is the lasing wavevector.
where \( c \) and \( \varepsilon_0 \) are the vacuum speed of light and permittivity, \( n_b \) is the background refractive index, \( k \) is the QW width, \( \varepsilon \) is a weak laser probe field for extracting the susceptibility, \( A \) is the QW area, and \( p_n \) and \( p_k \) are the QD and QW dipole matrix elements. The subscripts \( n \) and \( k \) label the QD and QW optical transitions, \( p_n, q \) and \( p_k \) are the QD and QW polarizations, and \( n_{\omega_{\text{diss}}} \) is the density of QDs with electronic structure labeled \( q \), contributing to the \( n \)th QD transition. The computed \( G \) and \( \delta n \) are useful in 2 ways. They give the gain parameters at saturated carrier density in the often used class B semiconductor laser model.\(^{21} \) They are also used in predicting general laser performance (such as light–current characteristics) when the saturated gain and carrier density are clamped at the threshold values.\(^{22} \)

The calculations start with solving the equations of motion for electron–hole polarizations. For the \( n \)th QD transition belonging to the \( q \)-th population group,

\[
\frac{dp_{n,q}}{dt} = i\left(v - \omega_{\text{n},q}\right)p_{n,q} - i\frac{2\varepsilon_0\varepsilon k}{\hbar}\left(f_{n,q}^e + f_{n,q}^h - 1\right) + \frac{i}{\hbar} \sum_k V_{n,k}\left(f_{n,q}^e + f_{n,q}^h\right)p_{n,k} + \frac{i}{\hbar} \sum_k V_{n,k}\alpha_k + S_{\text{inh}}^{\text{p},\text{p}} + S_*^{\text{c},\text{c}}.
\]

(3)

In the first line are the single-particle contributions from frequency detuning and stimulated emission, where \( \omega_{\text{n},q}^{(0)} \) is the unrenormalized transition frequency and \( f_{n,q}^{\text{p},\text{p}}(\sigma = e \ or \ h) \) is the QD carrier population. The second line contains the many-body corrections due to exchange and excitonic effects, with dependences on the QW carrier population \( f_{n,q}^e \). These effects renormalize the transition frequency and light–matter interaction strength via the Coulomb potential energy matrix element \( V_{n,k} \). In the third line, \( S_{\text{inh}}^{\text{p},\text{p}} \) and \( S_*^{\text{c},\text{c}} \) represent the higher-order many-body effects describing dephasing and screening from carrier–phonon and carrier–carrier scattering. The expression for \( S_*^{\text{c},\text{c}} \) comes from the continuation of the Cluster expansion giving the renormalization contributions to the 2nd level in Coulomb correlations.\(^ {23} \) For \( S_{\text{inh}}^{\text{p},\text{p}} \), we use a non-perturbative, quantum-kinetic approach adapted from treating carriers and phonons as composite polarons.\(^ {24} \) The corresponding equations of motion for the QW transitions are derived similarly, giving

\[
\frac{dp_k}{dt} = i\left(v - \omega_k^{(0)}\right)p_k - \frac{2\varepsilon_0\varepsilon k}{\hbar}\left(f_k^e + f_k^h - 1\right)
+ \frac{i}{\hbar} \sum q V_{n,k} \sum n_{\omega_{\text{diss}}} \left(f_{n,q}^e + f_{n,q}^h\right) S_{\text{inh}}^{\text{p},\text{p}} + S_*^{\text{c},\text{c}},
\]

(4)

where \( V_{n,k} \) is the QW Coulomb potential matrix element.

Many-body Coulomb effects are important for the QD \( \alpha_{\text{diss}} \) because they influence the carrier density dependences of shift and broadening of QD resonances. The shift causes semiconductor QDs to deviate from the ideal \( \Delta_{\text{inh}} = 0 \) of an atom.\(^ {25} \) The broadening modifies the shift effects.\(^ {26} \)

Inhomogeneous broadening from QD dimension and composition variations are treated by grouping the QDs according to the electronic structure. For the QD density in each group, we assume a Gaussian distribution so that

\[
\sum n_{\omega_{\text{diss}}} \to \int d\omega_n \frac{N_{\text{diss}}^{(2d)}}{\sqrt{2\Delta_{\text{inh}}}} \exp\left(-\frac{\left(h(\omega_n - \omega_{\text{n},q})\right)^2}{2\Delta_{\text{inh}}}\right),
\]

(5)

where \( \omega_n \) is the renormalized frequency of the \( n \)th QD transition in the \( q \)-th group and \( \omega_{n,q} \) and \( \Delta_{\text{inh}} \) are the central frequency transition and standard deviation. We assume carrier populations defined by Fermi–Dirac functions, \( f_{n,q}^e = \left\{ \exp\left[(\epsilon_k - \mu_{\epsilon})/k_B T\right] + 1\right\}^{-1} \) and \( f_{n,q}^h = \left\{ \exp\left[(\epsilon_k - \mu_{\epsilon})/k_B T\right] + 1\right\}^{-1} \) where \( \epsilon_k \) and \( \epsilon_k^e \) are the electron and hole \( (\sigma = e \ or \ h) \) energies, \( k_B \) is the Boltzmann constant, and \( T \) is the active region temperature. The chemical potential \( \mu_{\epsilon} \) is determined from the total electron and hole densities, \( N_{\epsilon} = N_{\sigma} + \sum q n_{\omega_{\text{diss}}} f_{n,q}^\sigma \), \( N_{\sigma} \), and \( N_{\epsilon} \) with \( \sigma = e \ or \ h \), respectively, is the doping density.

Figure 1 illustrates the inhomogeneous broadening model with the example of spontaneous emission. A laser sample has QD populations spreading over an energy range according to \( n_{\omega_{\text{diss}}} \) [dashed curve, Fig. 1(a)]. Within the distribution, each group of QDs with similar transition energy emits a homogeneously broadened spectrum (grey curve), which is calculated using Eqs. (1)–(4) and the Kubo–Martin–Schwinger transformation.\(^ {26} \) A luminescence measurement produces the inhomogeneously broadened

**FIG. 1.** (a) Spontaneous emission spectra for carrier density \( N_{\sigma} = 10^{11} \text{ cm}^{-2} \) and inhomogeneous broadening \( \Delta_{\text{inh}} = 0 \) and 8 meV (grey and black solid spectra, respectively). The dashed curve is the Gaussian QD distribution for \( \Delta_{\text{inh}} = 8 \text{ meV} \) centered at the unrenormalized ground-state QD resonance. (b) Spontaneous emission linewidth vs inhomogeneous width. The dotted lines show that \( \Delta_{\text{inh}} = 10 \text{ meV}, 15 \text{ meV}, \) and 20 meV correspond to \( \Delta_{\text{inh}} = 2.4 \text{ meV}, 36 \text{ meV}, \) and 48 meV, At \( \Delta_{\text{inh}} = 0 \), the curve gives 5.4 meV for the room temperature the homogeneous (intrinsic) linewidth of an InAs QD.
spectrum (solid black curve), which is computed by summing the different homogeneously broadened spectra, each weighted by $n_{th,m}^H$. Since its measurement is relatively straightforward, the spontaneous emission linewidth $\Delta_{sp}$ is often used to gauge QD inhomogeneity. A more direct measure of QD uniformity is the inhomogeneous width, $\Delta_{inh}$, which gives the standard deviation in level energies. Figure 1(b) shows the $\Delta_{sp}$ to $\Delta_{inh}$ conversion, using the calculated homogeneously broadened (intrinsic) spectrum. This paper considers active regions ranging from state-of-the-art to typical, with 10 meV $\leq \Delta_{inh} \leq$ 20 meV, corresponding to 24 meV $\leq \Delta_{sp} \leq$ 48 meV.\textsuperscript{27,28}

Figure 2(a) shows the gain spectra for an undoped 7 nm In$_{0.15}$Ga$_{0.85}$As QW with $5 \times 10^{10}$ cm$^{-2}$ InAs QD density and 20 meV inhomogeneous width. The resonances are from one ground-state and two excited-state transitions ($n = 1, 2,$ and 3 with degeneracies 1, 2, and 3, respectively). The absorption edge at 1.2 eV is from theGaAs QW exciton. Figure 2(b) shows the corresponding $\alpha_{H}$ spectra. The points indicate the ground-state peak gain values, which are all positive, with $\alpha_{H}(\nu_{pk}) \approx 2$ prior to the onset of excited-state gain.

Figure 3(a) shows narrower and more distinct QD resonances when inhomogeneous broadening reduces to 14 meV and with carrier densities chosen to produce similar peak gains from the ground-state QD transition. The spectra show that the $4 \times 10^{11}$ cm$^{-2}$ p-doped density leads to similar peak gains with lower carrier densities. Figure 3(b) depicts an interesting feature involving $\alpha_{H}$ at the gain peak. The points indicate $\alpha_{H}(\nu_{pk})$ changing from negative to positive, suggesting that with proper laser design, $\alpha_{H}(\nu_{pk})$ can vanish.

To further explore the vanishing of $\alpha_{H}$, we repeated the calculations for broader ranges of carrier and p-doped densities. Figure 4(a) shows that with sufficient p-doped density, $\alpha_{H}(\nu_{pk}) = 0$ exists at specific carrier densities. Even for curves not crossing $\alpha_{H}(\nu_{pk}) = 0$, a minimum $\alpha_{H}(\nu_{pk})$ exists. Assuming laser operation with the saturated gain clamped at the threshold value, the desired carrier density may be achieved by cavity design via

$$G_{th} = G(\nu_{pk}) = \frac{1}{I}[\alpha_{abs} - \frac{1}{2L}\ln(R_{1}R_{2})].$$

where $I$ is the confinement factor involving the waveguide and the QW embedding the QDs, $L$ is the cavity length, $\alpha_{abs}$ is the intracavity absorption, and $R_{1}$ and $R_{2}$ are the facet reflectivities. Figure 4(b) shows plots of the calculated carrier density dependence of peak gain for the different p-doped densities.

To verify the calculations, we fabricated three laser batches with undoped, $5 \times 10^{11}$ cm$^{-2}$ and $10^{12}$ cm$^{-2}$ p-doped active regions. Each laser is epitaxially grown on the Si substrate, with a 1.25 mm long, uncoated-facet, Fabry–Perot cavity, and 3.5 $\mu$m wide ridge. The active region has 5 QD layers, where each layer is as in the...
The experimental results are plotted as diamonds in Fig. 4. Figure 4 also indicates $\alpha|_{\nu_{pk}} < 0$, as observed in QD laser experiments in the form of absence of filamentation. While eliminating filamentation is useful for high-power single-mode performance, we chose instead to concentrate on datacom and telecom applications, where there are more opportunities for QD lasers to contribute. There, the concerns are linewidth, chirp, and feedback sensitivity so that minimizing the absolute value of the gain-peak linewidth enhancement factor, $|\alpha|_{\nu_{pk}}$, is more important.

Further parametric study suggests that lasing at $|\alpha|_{\nu_{pk}} = 0$ is unachievable regardless of p-doped density. The challenge is fabricating a resonator accurately for a prescribed $G_{\text{th}}$, assuming $\Delta_{\text{inh}} = 10$ meV. When $\Delta_{\text{inh}} > 16$ meV, $\alpha|_{\nu_{pk}} = 0$ is achievable regardless of p-doped density. For an active region consisting of 5 QD layers in a 0.3\,μm long waveguide with facet reflectivities $R_1 = 0.32$ and $R_2 = 0.90$, Eq. (6) gives $G_{\text{th}} = 86$ cm$^{-1}$, assuming $\Delta_{\text{inh}} = 7.9$ cm$^{-1}$. For 1.3\,μm lasing wavelength, this translates to a resonator Q factor of 4800. Not shown in the plots but relevant to modulation bandwidth and threshold current are differential gain and threshold carrier density ranges of $2 \times 10^{-16}$ cm$^{-2} < dG/dN_e < 4.3 \times 10^{-16}$ cm$^{-2}$ and 1.5

### Table I. Experimental device parameters

| $N_p$ (10$^{11}$ cm$^{-2}$) | $G_{\text{mode}}$ (cm$^{-1}$) | $\alpha|_{\nu_{pk}}$ | $G_{\text{max}}$ (cm$^{-1}$/QD layer) | $\Delta_{\text{inh}}$ (MeV) | $N_e$ (10$^{11}$ cm$^{-2}$) |
|-----------------------------|----------------|-------------------|-------------------------------|----------------|------------------|
| 0                           | 10             | 1.855             | 16                           | 10             | 1.63             |
| 5                           | 50             | 0.198             | 81                           | 10             | 1.20             |
| 10                          | 57             | 0.097             | 93                           | 10             | 0.88             |

**FIG. 4.** (a) Linewidth enhancement factor at the gain peak and (b) peak gain per QD layer vs carrier density for ground-state transition and 10 meV inhomogeneous broadening. The calculated curves are labeled by p-doped density in units of 10$^{11}$ cm$^{-2}$. The diamonds are from measurements for p-doped densities $N_p = 0, 5 \times 10^{11}$ cm$^{-2}$, and $10^{12}$ cm$^{-2}$ (black, blue–green, and brown, respectively).
$10^{11}$ cm$^{-2}$, $N_e < 2.8 \times 10^{11}$ cm$^{-2}$ for lasing with $\alpha_H(\nu_{pk}) = 0$. At the low $N_e$ limit, the threshold current density is $J_{th} \approx 320$ A/cm$^2$, using $J_{th} = \frac{eN_e\eta^{-1}}{A + C(N_e^{0.7})^2}$, where $J_P = 3.4$ A/cm$^2$ is obtained from the gain calculation. We also use defect (Shockley–Read–Hall) loss to determine the $\alpha_H$ from the gain calculation. We also use defect (Shockley–Read–Hall) loss to determine the $\alpha_H$ from the gain calculation.

In summary, QD lasers may be configured to operate with linewidth enhancement factor $\alpha_H = 0$. The beneficial effects are the reduced linewidth, chirp elimination, and reduced optical feedback sensitivity. That $\alpha_H = 0$ can occur at the gain peak simplifies device design and minimizes power consumption, which are important considerations in datacom and telecom applications. Many-body renormalizations and dephasing significantly contributed to QD linewidth enhancement factor $\alpha_H$. The parametric study, supported with experiment, provides the necessary combinations of the inhomogeneous linewidth, $p$-doped density, and threshold gain that are reachable by the present QD lasers.

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