Improved Quantum Dot Uniformity and Its Impact on Reflection Sensitivity

(Invited paper)

Justin Norman[1], Zeyu Zhang[2], Daehwan Jung[1], Jianan Duan[3], Heming Huang[3], Frédéric Grillot[3], John Bowers[1,2,3]

[1] Institute for Energy Efficiency, University of California, Santa Barbara, USA
[2] Electrical & Computer Engineering Department, University of California, Santa Barbara, USA
[3] LTCI, Télécom ParisTech, Université Paris-Saclay, Paris, France.
e-mail: jnorman@ucsb.edu

ABSTRACT

A semiconductor laser's sensitivity to parasitic reflections is directly tied to its linewidth enhancement factor. Quantum dot lasers have been shown to have significantly lower linewidth enhancement factors than quantum well lasers with values of zero or even negative values having been theorized for sufficiently uniform dot size distributions. Through optimized growth conditions on silicon, we have obtained highly uniform quantum dots with ultralow linewidth enhancement factors of 0.5 for ground state emission at threshold. Between their low linewidth enhancement factor and strongly damped relaxation oscillation, these lasers show an expected ~17 dB increase in the critical feedback level for coherence collapse relative to state-of-the-art commercial quantum wells.

Keywords: quantum dot laser, silicon photonics, epitaxial integration

1. INTRODUCTION

Photonic integrated circuits (PIC) have enabled numerous high performance, energy efficient, and compact technologies for optical communications, sensing, and metrology. Demand for PICs is expected to continue to grow rapidly as performance, cost, and integration density improve to enable such applications as high bandwidth density interconnects for within-the-rack communication for datacenters and high performance computers and for light detection and ranging (LIDAR) systems for self-driving vehicles.

One of the biggest challenges in scaling PICs is dealing with parasitic reflections that feed light back into the laser source increasing noise and, ultimately, causing coherence collapse. To avoid these destabilizing reflections, expensive and bulky optical isolators must be included between the laser and the rest of the PIC leading to large increases in device footprint for on-chip integration schemes and significant increases in packaging complexity for lasers co-packaged with passive PICs.

Fortunately, by transitioning from incumbent quantum well based lasers to lasers with quantum dot active regions, feedback tolerance can be dramatically enhanced, and the need for an isolator can be reduced or even eliminated. In this presentation, we theoretically demonstrate the impact of inhomogeneous broadening on the linewidth enhancement factor, and, thus, the critical feedback level and show experimental results for highly optimized quantum dot lasers grown on silicon with narrow inhomogeneous broadening. The lasers demonstrate record low linewidth enhancement factors and record high stability against optical feedback.

2. METHODS

The quantum dot lasers are grown using molecular beam epitaxy on optimized GaAs/Si buffers with a threading dislocation density of 7×10^6 cm^{-2} [1]. These lasers have demonstrated record performance for any epitaxial laser on silicon with threshold currents < 5 mA, continuous wave operation up to 105°C, and long device lifetimes extrapolated to >10,000,000 hours at 35°C and >60,000 hours at 60°C when defining failure as a doubling of the bias current for 10 mW output power [2]. The quantum dot active region consists of InAs quantum dots in $In_{.15}Ga_{.85}As$ quantum wells which are grown at 495°C with a V/III of 10 in the 2 nm well before the dots, a V/III of 35 during dot deposition (nominally 2.55 ML InAs), and a V/III of 35 during the 5 nm of well capping the dots. Each dot layer is spaced by 37.5 nm of GaAs with a 10 nm *p*-modulation doped layer with 5×10^{17} cm^{-3} doping level. These optimized conditions yield a photoluminescence (PL) full-width-at-half-maximum (FWHM) of < 30 meV and dot density of ~6×10^{10} cm^{-2}.

3. RESULTS AND DISCUSSION

The critical feedback level, f_{crit}, of a semiconductor laser is defined as the fractional proportion of the laser output power that can be externally reflected and fed back into the cavity before coherence collapse. Mathematically, f_{crit} can be defined as

$$f_{crit} = \frac{\tau_L^2\gamma^2}{16C_e^2}\left[\frac{1+\alpha_H^2}{\alpha_H^4}\right] \tag{1}$$

where τ_L is the cavity roundtrip time, $C_e = \frac{1-R}{2\sqrt{R}}$ is the coupling strength of the laser cavity to the external cavity with facet reflectivity R, $\gamma = K f_r^2 + \gamma_0$ is the damping factor defined in terms of the K-factor, relaxation oscillation frequency, f_r, and damping offset, γ_0, and α_H is the linewidth enhancement factor. The linewidth enhancement factor is defined as

$$\alpha_H = -\frac{4\pi}{\lambda}\frac{dn/dN}{dg/dN} \tag{2}$$

where λ is the wavelength, n is the real part of the refractive index, g is the gain, and N is the carrier density. From equation (1), it is clear that low α_H and high γ lead to high feedback stability. Assuming typical damping levels for quantum dots and quantum wells, the critical feedback level as a function of α_H has been calculated as shown in Fig. 1.

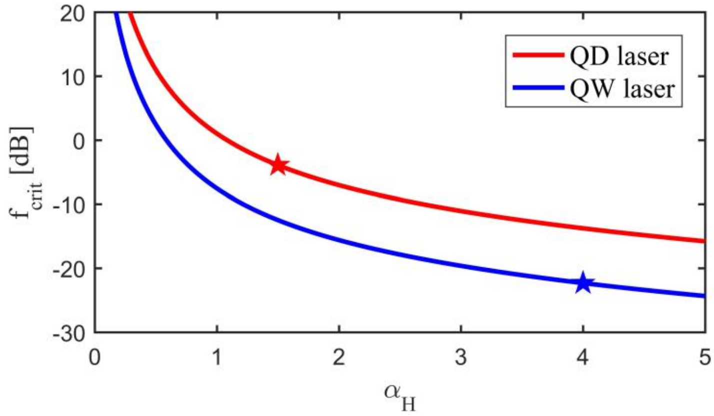

Figure 1. The critical feedback level for coherence collapse as a function of the linewidth enhancement factor, α_H, for typical damping characteristics of quantum dot (QD) and quantum well (QW) lasers. Typical values for the linewidth enhancement factor above threshold are denoted by stars.

In quantum dot materials the inhomogeneous broadening associated with their nonuniform size distribution leads to highly symmetrical, Gaussian gain spectra, which, from the Kramers-Kronig relationship, should yield a linewidth enhancement factor of zero at the gain peak. Unfortunately, many-body effects and inhomogeneous broadening lead to non-zero values at the gain peak that significantly increase with detuning [3]. Initial results for quantum dot lasers on silicon showed relatively broad PL with a FWHM of 54 meV which yielded a linewidth enhancement factor of 0.5 from subthreshold measurements [4]. Through optimized quantum dot growth conditions and development of a smooth III-V/Si buffer, we have developed lasers on silicon with highly uniform dot size distributions with PL FWHM as narrow as 30 meV. Such material yields an ultralow linewidth enhancement factor of 0.16 from subthreshold measurements [5].

Even considering the higher α_H of 0.5, when coupled with the high damping in our material ($K = 0.75$ ns and $\gamma_0 = 6.35$ GHz) and assuming a three-fold increase in α_H above threshold, the critical feedback level can be estimated to increase by ~18 dB over typical values for quantum wells ($\alpha_H = 4$, $K = 0.3$ ns, $\gamma_0 = 0.651$ GHz). When considering a three-fold above threshold increase for our optimized material, the difference between a quantum dot and quantum well laser increases dramatically to values well above 0 dB suggesting isolator free operation is readily achievable.

Recently, experiments were conducted using a fiber coupled back-reflector to probe the stability of our optimized laser material and compare it to a commercial quantum well laser [6]. Even at back-reflection levels of 100%, which corresponds to 18% of the output power returning to the cavity after coupling losses and a 10% tap for measurement, the quantum dot laser shows perfectly stable operation. The results are shown in Fig. 2. In contrast, the quantum well laser undergoes coherence collapse at a feedback level much less than 1%.

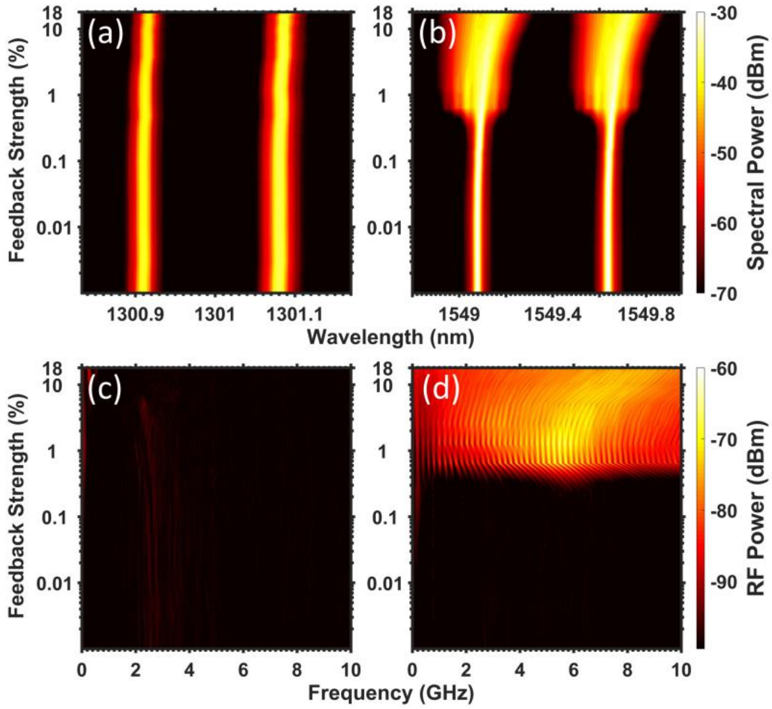

Figure 2.(a)(b) Optical spectra for a (a) quantum dot and (b) quantum well laser as a function of feedback level defined as the percentage of the laser output power re-entering the laser cavity. (c)(d) The corresponding RF spectra for the (c) quantum dot and (d) quantum well laser. Figure adapted from [6].

4. CONCLUSIONS

In summary, quantum dot lasers are capable of achieving much lower values of the linewidth enhancement factor and are much more damped than quantum well lasers. Together these properties lead to a substantial increase in optical feedback tolerance for quantum dot devices relative to quantum wells. The degree of feedback tolerance of the quantum dot gain medium is highly dependent on inhomogeneous broadening due to dot size variations, but through careful optimization, even epitaxial lasers on silicon can achieve performance suggesting their capability for isolator-free photonic integration.

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