

# Strong optical injection and the differential gain in a quantum dash laser

Luke F. Lester,<sup>1,\*</sup> Nader A. Naderi,<sup>2</sup> Frederic Grillot,<sup>3</sup> Ravi Raghunathan,<sup>1</sup>  
and Vassilios Kovanis<sup>1</sup>

<sup>1</sup>Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061, USA

<sup>2</sup>U.S. Air Force Research Laboratory, 3550 Aberdeen Ave SE, Kirtland AFB, NM 87117, USA

<sup>3</sup>Telecom Paristech, Ecole Nationale Supérieure des Télécommunications, CNRS LTCI, 75634 Paris Cedex 13, France  
[\\*lflester@vt.edu](mailto:lflester@vt.edu)

**Abstract:** By optically injecting a quantum dash laser and simultaneously producing a significant lowering of the device threshold, a large enhancement in the differential gain is realized. This effect is observed by way of a dramatic reduction in the linewidth enhancement factor and a large increase in the 3-dB modulation bandwidth, especially as the injection wavelength is blue-shifted. Compared to its free-running value, a 50X improvement in the laser's differential gain is found.

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**OCIS codes:** (250.5960) Semiconductor lasers; (250.5590) Quantum-well, -wire and -dot devices; (140.3520) Lasers, injection-locked.

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## 1. Introduction

Quantum dot (QD) and quantum dash (QDash) lasers, so-called nanostructure lasers, have been shown to have superior dynamic properties such as low transparency current density [1] and temperature-insensitivity of the threshold current [2] compared to Quantum-Well (QW) and bulk lasers, which makes them attractive candidates as optical transmitters [3]. In addition nanostructure lasers have been touted to exhibit an increased differential gain [4], and therefore reduced linewidth enhancement factor (LEF) [5] and larger modulation bandwidth, which would make them very suitable for implementation in ultrafast and chirp-free transmitter modules. In reality, it is well known that the latter properties are not necessarily accessible in the same device in nanostructure gain media. In another words, achieving a simultaneous high 3-dB modulation bandwidth ( $f_{3dB}$ ) and small LEF in conventional, directly-modulated nanostructure lasers, if theoretically possible, is still very challenging in practice.

Typically, the differential gain in a semiconductor laser is improved through the use of strain [6], quantum confinement [7], or p-type doping [8] in the active region of the device. These methods have been applied to quantum dot or dash materials to raise the differential gain [9,10], but unfortunately these low-dimensional systems have relatively small maximum gain to start with due primarily to inhomogeneous gain broadening [11] and hot carrier effects [12]. The consequence is that the laser cavity has to be relatively low-loss, which might make the LEF smaller, but comes at the expense of the modulation bandwidth since the photon cavity lifetime is longer. As a result,  $f_{3dB}$  of conventional separate confinement heterostructure (SCH) QD lasers has been limited to only 12 GHz [3]. Moreover, the ultra-low LEF benefit intrinsic to nanostructure gain media is no longer available at the high current densities where large modulation bandwidths are generally accessible. Although below-threshold measurements on QDs [13,14] have reported LEFs that are less than 1 and even negative, the above-threshold values are found to be much larger as a result of the carrier density being unclamped at threshold, which is due to the inhomogeneous gain broadening in dots. In addition, at higher current densities, the LEF becomes more power dependent due to strong gain saturation and carrier filling in both lasing and non-lasing QD states [15,16].

The challenge is to access the large differential gain available in a QD at a low optical gain value without sacrificing the photon lifetime. Strong optical injection is a possible method to accomplish this goal since it is capable of shifting the laser threshold close to

optical transparency [17,18]. Also, larger differential gains are found at wavelengths blue-shifted from the gain peak [19]. Using this latter approach and a strong injection level at zero optical frequency detuning between an external master (control) laser and a QDash Fabry-Perot slave (follower) laser, more than 50X improvement in the differential gain is found compared to the free-running value. Furthermore, the injection-locked QDash laser's simultaneous high bandwidth and low LEF, which are a result of the significant enhancement in differential gain, are described using a set of analytical formulas derived for the zero-detuning, zero-LEF case. From an applications perspective, the combination of an enhanced bandwidth and a very low LEF is promising for transmitter modules in future high-speed optical fiber links and photonic microwave oscillators [20–22].

## 2. Results and discussion

The manipulation of the slave laser's differential gain is observed through measurement of the LEF in an optically-injected QDash Fabry-Perot (FP) laser using two different approaches in this paper. First, using the amplified spontaneous emission (ASE) technique [23], the QDash net modal gain profile is measured as a function of wavelength and current density. Knowing this dependence is crucial to find the optimum free-running operating point at which the LEF can be manipulated to its lowest possible values. Then, using the ratio of the frequency modulation (FM) to the amplitude modulation (AM) indices technique [24], the above-threshold LEF is directly measured under injection at zero-detuning with variable injection power. Second, measured experimental modulation response data is used to extract the relevant operating parameters of the coupled system including the threshold gain shift and LEF. The FM/AM measured LEF values are then compared with those values extracted from the modulation data and correlated to the threshold gain shift, which is the lowering of the electrical threshold in the slave that is induced by optical injection. This threshold gain shift is measured through an increased damping rate in the coupled master-slave system. Emphasis on the zero-detuning case is mainly based on two reasons. First, the zero-detuning case simplifies the theoretical model describing the action of the coupled system under modulation, which makes it easier to fit and properly extract the operating parameters of the injection-locked system from the measured modulation response data. Second, this case demonstrates a relatively flat modulation response compared to other detuning conditions making it most suitable for broadband RF photonic applications. From an applications perspective, the master and slave lasers could be referenced to the same wavelength locker, facilitating implementation in a packaged device suitable for high-frequency optical fiber links.

The QDash material and multi-mode FP lasers similar to the ones used in this work have been described in several prior publications [25–28]. These lasers have a 4- $\mu\text{m}$  ridge waveguide, a 500- $\mu\text{m}$  long cavity length and a nominal emission wavelength around 1565 nm. The threshold current was measured to be 54 mA ( $J_{\text{th}} \sim 2700 \text{ A/cm}^2$ ) with a slope efficiency of 0.2 W/A at room temperature. The data for the net modal gain as a function of wavelength for various injected current densities is shown in Fig. 1, indicating the QDash nominal gain peak at 1565 nm at room temperature. When the slave laser is injection-locked, since the injected light from the master laser is at a fixed wavelength and increasing injection strength shifts the slave's threshold condition to lower pump values, the LEF is expected to progressively decrease with injection since the gain peak is red-shifting. In addition, the LEFs at all wavelengths generally decrease with a lower threshold condition in dashes because of the lower carrier population in the excited states [14]. The QDash LEF is then measured under injection-locking at 1535 nm, 1550 nm and 1580 nm for zero-detuning cases as a function of injected power.

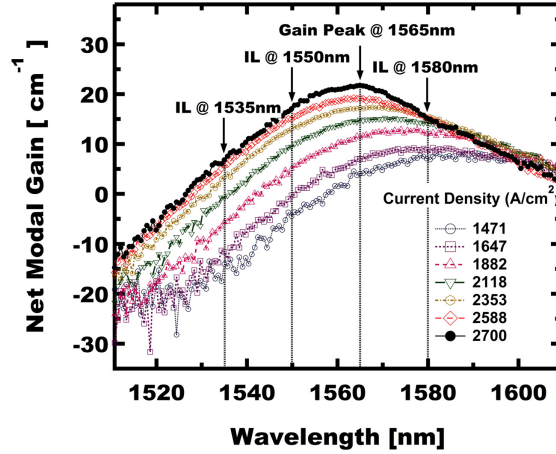


Fig. 1. The measured net modal gain curves versus wavelength for a set of seven current densities at or below the threshold value. Qualitatively, one can see that the differential gain increases for shorter wavelengths. Injection locking (IL) on the nearest Fabry-Perot mode was undertaken at 1535, 1550 and 1580 nm.

The injection-locking experimental setup for measuring the LEF using the FM/AM technique and the modulation response is systematically covered in ref [28]. From the small-signal modulation analysis, the ratio of the FM/AM modulation indices provides a direct measurement of the above-threshold LEF for modulation frequencies well above the slave laser's relaxation frequency [24]. Using this method, the AM index, was modified through the ratio of the ac and dc components of the detected modulated signal using an electrical spectrum analyzer (ESA) and a 50  $\Omega$  terminator connected to a high-speed photo-detector. While the external power ratio was varied, the AM index was kept constant at 6% for all injection-locking cases by adjusting the RF power output from the amplifier. The FM index was obtained by measuring the ratio between amplitudes of the nearest sidebands to the peak frequency using a high resolution spectrometer.

LEF values can also be extracted from modulation response data for comparison, and zero optical detuning is an especially simplifying case. Next, we describe that process and the necessary equations. The modulation response  $H_R$  of an injection-locked coupled system is described by the following set of equations [25]:

$$|H_R|^2 = 10 \log \left[ \frac{\left(\frac{C}{Z}\right)^2 (\omega^2 + Z^2)}{(C - A\omega^2)^2 + (B\omega - \omega^3)^2 (1 + (\omega/\gamma_c)^2)} \right] \quad (1)$$

$$A = (\gamma_{fr} - \gamma_N) R_{FE}^2 + \gamma_N + \gamma_{th} \quad (2)$$

$$B = (\omega_r^2 + \gamma_N \gamma_{th}) + (\eta_0 / R_{FE})^2 + \gamma_{th} [(\gamma_{fr} - \gamma_N) R_{FE}^2 + \gamma_N] \quad (3)$$

$$C = (\eta_0 / R_{FE})^2 [(\gamma_{fr} - \gamma_N) R_{FE}^2 + \gamma_N] - (\omega_r^2 + \gamma_N \gamma_{th}) Z \quad (4)$$

where  $\omega_r$ ,  $\gamma_{fr}$ ,  $\gamma_N$ , and  $\gamma_c$  are the free-running relaxation frequency, free-running damping rate, inverse differential carrier lifetime and inverse RC parasitic roll-off, respectively, and are known parameters of the QDash slave laser that have been reported previously [25]. The non-linear gain has been implicitly incorporated into the model through the free-running relaxation oscillation and damping rate. The parameter  $\eta_0$ , which is a known quantity, denotes the

maximum injection strength, which depends on the coupling efficiency,  $\eta_c$ , the external power ratio,  $R_{ext}$ , cavity length,  $L$ , and front facet reflectance,  $r$ , of the FP slave laser [25]. The external field ratio,  $R_{FE}$ , is the slave field enhancement factor that takes into account the deviation of the steady-state field magnitude at high injection ratios compared to its free-running value. The frequency detuning is defined as  $\Delta\omega = \omega_{slave} - \omega_{master}$ . The steady-state phase offset between the master and slave under the zero-detuning case is given by  $\phi_0 = -\tan^{-1}(\alpha)$ , which reduces  $Z$  and  $\gamma_{th}$ , the threshold gain shift, to:

$$Z = \frac{-\eta_0}{R_{FE}} \sqrt{1 + \alpha^2} \quad \gamma_{th} = \frac{2\eta_0}{R_{FE} \sqrt{1 + \alpha^2}} \quad (5)$$

where  $\alpha$  is the LEF. When using these equations to curve-fit measured response data, the number of fitting parameters is vastly reduced using the known free-running terms and by recognizing that  $\gamma_{th}$  cannot exceed the inverse cavity photon lifetime,  $\gamma_p$ , of 312 GHz (or a cavity loss of 36 cm<sup>-1</sup>). Furthermore at zero detuning,  $R_{FE}$  follows a quadratic expression:

$$R_{FE}^4 - \left[ (1/\gamma_p) \left( 2\eta_0 / (1 + \alpha^2)^{1/2} \right) + 1 \right] R_{FE}^2 - (\gamma_N / \omega_r^2) \left( 2\eta_0 / (1 + \alpha^2)^{1/2} \right) = 0 \quad (6)$$

Using the measured FM/AM values as a guide, the LEF is allowed to fluctuate between zero and a positive number such that  $\gamma_{th}$  does not exceed  $\gamma_p$ . Thus, the LEF is the only free parameter and can be directly extracted from modulation response data. This is the unique situation zero detuning affords.

Figure 2 shows the zero-detuning, small-signal modulation response at the three different injection wavelengths indicated in Fig. 1. In all cases, the external power ratio was held fixed at  $R_{ext} = 9.3$  dB.

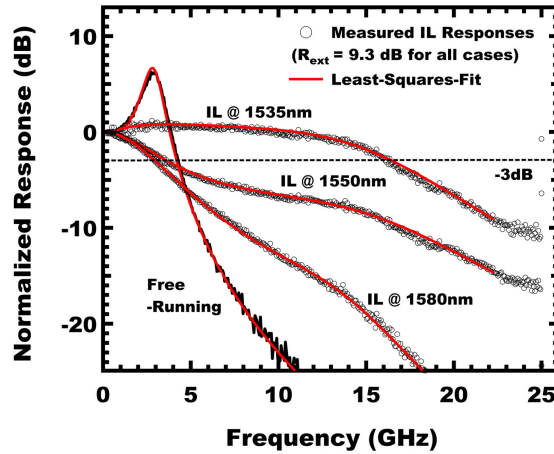


Fig. 2. Small-signal modulation response of the slave diode laser at zero optical detuning for three injection wavelengths. The data for the free-running laser is also included. Notice that at 1535 nm the modulation response is flat, spanning a 16.5 GHz bandwidth.

A comparison of the response curves shows that the  $f_{3dB}$  systematically improves as the injection wavelength is blue-shifted from 1580 to 1535 nm. Whereas the responses at 1550 and 1580 are over-damped, the behavior at 1535 nm is nearly flat over a wide frequency range, and the  $f_{3dB}$  is pushed out to 16.5 GHz. Compared to the free-running case, where no flat response was observed and the  $f_{3dB}$  was found to be 4.5 GHz, injection locking at 1535 nm achieved a 3.7X bandwidth enhancement.

The measured values of the LEF as a function of  $R_{ext}$  using the FM/AM technique and those extracted from modulation responses are shown in Fig. 3(a). The related threshold gain

shifts are plotted in Fig. 3(b). The extracted LEF values for both cases are in good agreement with the FM/AM measured values. The key result is that the LEF plummets to zero at large  $R_{ext}$  at 1535 and 1550 nm with its correspondingly high threshold gain shift (up to 68% of the maximum possible). This is the region where the differential gain enhancement is very high, except for 1580 nm, which is consistent with Fig. 1.

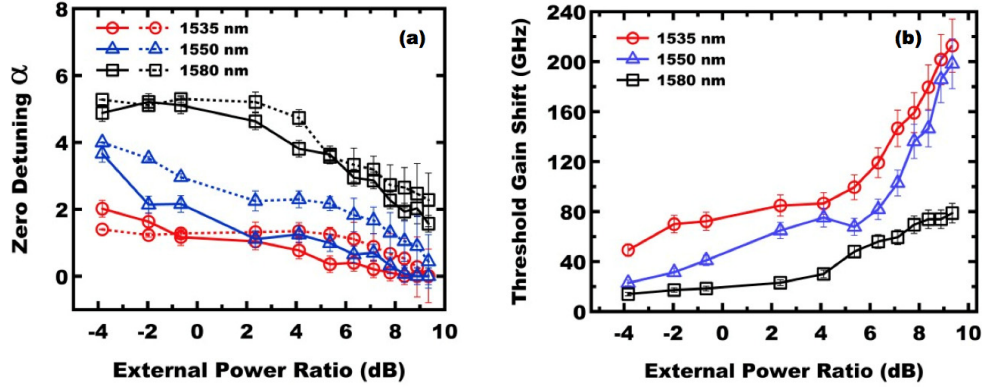


Fig. 3. a) linewidth enhancement factor and b) threshold gain shift as a function of external power injection ratio,  $R_{ext}$  for the QDash slave laser at 1535, 1550 and 1580 nm. The solid lines in (a) correspond to the FM/AM data, and the dotted lines correspond to values extracted from the modulation responses. The error analyses for the extracted values of the LEF and threshold gain shift shown in (b) are calculated based on a one standard deviation confidence interval.

Further evidence of the large increase in the differential gain is seen in the modulation bandwidth results. Note that the  $f_{3dB}$  for the 1535 nm case at  $R_{ext} = 9.3$  dB as shown in Fig. 2 corresponds to a 3.7X improvement compared to the free-running case. Given the damped, nearly flat response of the injected laser under this condition, only a significant increase in differential gain and a resultant increase in the free-running relaxation frequency could account for this improvement. Since the LEF is essentially zero for these strong injection cases, the equations for  $Z$ ,  $\gamma_{th}$  and  $R_{FE}$  further simplify and the free-running relaxation frequency is very easy to extract from the optically-injected response data. In turn, the differential gain, which varies as the square of the relaxation frequency, can be found. The injection-induced increase in differential gain is shown for several cases in Table 1. As shown in the table, as the injection strength is increased and the wavelength is blue-shifted, the increase in the differential gain is more apparent. The maximum observed value of  $5.9 \times 10^{-14}$   $\text{cm}^2$  represents a more than 50 times enhancement compared to the free-running laser value of  $1.1 \times 10^{-15}$   $\text{cm}^2$ .

Table 1. Differential Gains of Quantum Dash Laser Comparing the Free-running Case to Strong Injection Cases at 1550 and 1535 nm for which the LEF is Essentially Zero

Case	Differential Gain ( $\text{cm}^2$ )
Free running laser (1565 nm)	$1.1 \times 10^{-15}$
Injection @ 1550 nm, 9.3 dB	$5.2 \times 10^{-15}$
Injection @ 1535 nm, 9.3 dB	$5.9 \times 10^{-14}$

#### **4. Conclusions**

We have demonstrated that the use of strong optical injection in a QDash laser significantly increases the differential gain of the device. This technique allows for manipulation of the LEF to near-zero values and significant enhancement of the 3-dB modulation bandwidth. We have found greater than 50X improvement in the differential gain in an injection-locked QDash FP laser compared to its free-running value as a result of strong optical injection at wavelengths blue-shifted from the gain peak and operation near optical transparency. A broadband and flat response with a simultaneous, near-zero LEF indicate that this optically-coupled nanostructure laser system has the potential in future long-haul and high performance optical fiber links as an RF photonic transmitter for demanding applications and environments.

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