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Variation of the feedback sensitivity in a 1.55 μm InAs/InP quantum-dash Fabry–Perot semiconductor laser

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Dynamic feedback properties of a 1.55 μm InAs/InP quantum dash laser are reported. The ground state linewidth enhancement factor (α_H-factor) is found to be enhanced from ~1 to ~14 as the bias current is increased beyond the threshold value. As a consequence of the variation in the α_H-factor, the feedback sensitivity of the quantum dash semiconductor laser is dramatically affected over the entire range of operational currents. The onset of its critical feedback regime, which is incompatible with data transmission, is shown to exhibit a variation of approximately 20 dB for the quantum dash device. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2998397]

Quantum dot (QD) lasers have attracted a lot of interest in the last decade due to their expected remarkable properties arising from charge carrier confinement in three spatial dimensions.[1] Low threshold current densities and high material gain,[2,3] temperature insensitivity,[4] and ultralow α_H-factor at the lasing wavelength[5,6] have been reported. This latter property combined with a high damping rate[7] is of paramount importance because theory predicts it will increase the tolerance to optical feedback in these devices and may offer potential advantages for direct modulation without transmission dispersion penalty. Among the various properties of QD lasers, the α_H-factor is one of the most important and is used to distinguish the behavior of semiconductor lasers with respect to other types of lasers.[8] The α_H-factor influences several fundamental aspects of semiconductor lasers, such as the linewidth[9] and characteristic behavior under optical feedback.[10]

In QD lasers, the variation in the α_H-factor is usually more pronounced when measured above threshold compared to quantum well (QW) devices. Large variations in the α_H-factor have been reported[11] and attributed to the carrier density not being clearly clamped at threshold in QD lasers. Thus, the lasing wavelength can switch from the ground state (GS) to the excited state (ES) as current injection increases, indicating that a carrier accumulation occurs in the ES even though lasing in the GS is still occurring. The filling of the ES enhances the α_H-factor of the GS above threshold as experimentally and numerically shown.[11,12] The variation in the GS α_H-factor will theoretically produce a significant change in the onset of coherence collapse due to optical feedback.[13] Among the five regimes of optical feedback,[14] the coherence collapse regime is the least preferred as it exhibits a dramatic linewidth broadening of up to several gigahertz. Previous reports have already confirmed moderately high tolerance to optical feedback in 1.3 μm quantum-dot lasers,[10,15] where 14 and 8 dB coherence collapse onsets were achieved. Additionally, in direct modulation at 10 Gb/s of a 1.55 μm quantum dash laser, a coherence collapse at 24 dB feedback was demonstrated with a penalty lower than 1 dB, which is more tolerant than QW distributed feedback (DFB) lasers.[16] The low frequency fluctuation regime close to threshold in which the time-trace exhibits infrequent power dropouts was also observed in quantum dash lasers, similar to bulk or QW devices.[17] More recently, the differential gain was found to be the dominant parameter in describing optical feedback sensitivity in InAs/InP quantum dash lasers.[18]

This paper reports the dynamic properties of a multimode Fabry–Pérot (FP) quantum dash laser emitting on the GS at 1.55 μm. In particular, it is shown that the GS α_H-factor drastically increases from ~1 to ~14 as the bias current goes beyond the threshold value. Consequently, the feedback sensitivity of the laser, which is evaluated through the onset of its coherence collapse, is found to vary by ~20 dB over the range of current investigated.

The device under study was grown on an n^+-InP substrate and its structure is described as a 500 μm long cleaved-cavity ridge waveguide with a 4 μm wide stripe. Details of the structure have already been published elsewhere.[19] The inset of Fig. 1 shows the light-current characteristic measured at room temperature. The threshold current leading to a GS-emission at 1.55 μm is ~45 mA and the external differential efficiency is about 0.2 W/A. Beyond a pump current of ~100 mA, ES lasing emission occurs. As

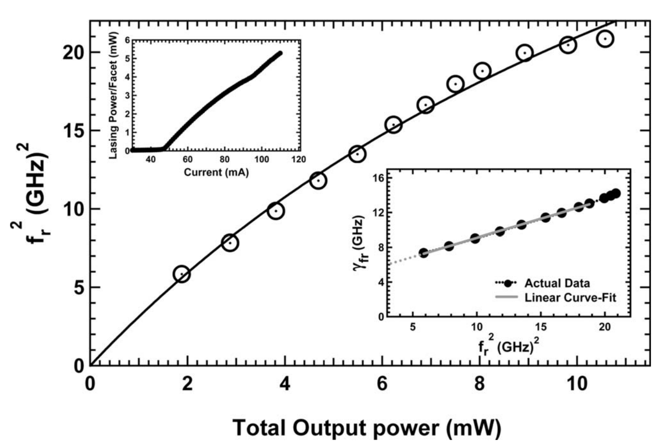

FIG. 1. The square of the resonance frequency vs the output power (open circles). The figures in the inset shows the light-current characteristic of the QD laser under study and the damping factor vs the square of the relaxation frequency.

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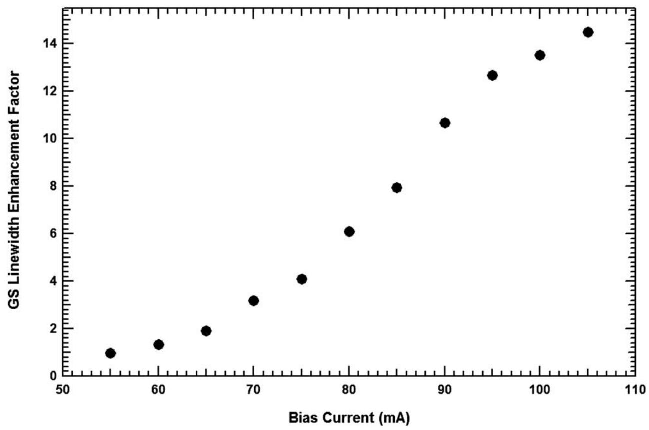

FIG. 2. The GS α_H-factor vs the bias current measured by the injection-locking method.

observed in Fig. 1, the onset of ES lasing leads to a kink in the light-current characteristics as well as a modification of the slope efficiency.

Next, the frequency response of the laser is measured since the damping rate is needed in the calculation of the critical feedback level as shown below. In Fig. 1, the resonance frequency squared f_r^2 is plotted as a function of the output power for the device under study. The experimental dependence of the relaxation oscillation frequency deviates from the expected linear dependence and is modeled via the following relation[20]:

$$f_r^2 = \frac{AP}{1 + \frac{P}{P_{\text{sat}}}} = \frac{AP}{1 + \varepsilon_P P}, \tag{1}$$

where $\varepsilon_P P = P/P_{\text{sat}}$ with ε_P representing the gain compression coefficient related to the output power P. This value means that at this level of output power, nonlinear effects are significant. In the case for the device under test, the curve-fit leads to a $P_{\text{sat}} \sim 17$ mW and a gain compression coefficient of approximately $\varepsilon_P = 1/P_{\text{sat}} \approx 0.06$ mW^{-1}. The maximum of the resonance frequency can be directly deduced from the curve-fitting as $\Omega_r = (AP_{\text{sat}})^{1/2}$ and was expected to be ~ 7.6 GHz. In the inset of Fig. 1, the evolution of the damping rate against the relaxation frequency squared leads to a K-factor of 0.45 ns as well as an effective carrier lifetime of 0.16 ns. The maximum intrinsic modulation bandwidth $f_{\max} = 2\pi\sqrt{2}/K$ is 19.7 GHz.

The above-threshold GS α_H-factor was measured using the injection-locking technique, which is based on the asymmetry of the stable locking region over a range of detuning on both positive and negative side of the locked mode.[21] The ratio of positive to negative detuning should theoretically remain the same for any value of side mode suppression ratio, which was kept at 35 dB for this measurement. The measured GS α_H-factor as a function of bias current is depicted in Fig. 2. It was observed that the GS α_H-factor increased from ~ 1.0 to ~ 14 as the bias current was increased from the threshold value to 105 mA. This enhancement is mostly attributed to the plasma effect as well as to the carrier filling of the nonlasing states,[12] which results in a differential gain reduction above threshold. Consequently, this strong degradation of the GS α_H-factor with the bias current produces a significant variation in the feedback sensitivity of the laser. One method to investigate the tolerance to optical feedback is to evaluate the onset of the coherence collapse regime through the following expression[22]:

$$\Gamma_C = \left(\gamma \frac{\tau}{4C}\right)^2 f(\alpha_H), \tag{2}$$

where $f(\alpha_H) = (1+\alpha_H^2)/\alpha_H^4$ is the function linked to the α_H-factor. In Eq. (2), γ is the damping rate in rad/s, $C = (1-R)/2\sqrt{R} \sim 0.6$ is the coupling coefficient from the facet to the external cavity and $\tau = 2nL/c$ is the internal round trip time in the laser cavity (~ 10 ps) with n being the group effective index, L is the laser cavity length, and c is the speed of light in vacuum. $f(\alpha_H)$ is a function driven by the α_H-factor variation and theoretically varies from ~ 2 down to 4×10^{-3} as given by the α_H data presented in Fig. 2. As a result, the onset of the coherence collapse for this quantum dash laser is expected to shift by as much as 500 (~ 27 dB), except that the variation in the damping rate shown in the inset of Fig. 1 will partially offset this substantial change.

The experimental setup to measure the coherence collapse threshold is based on a 50/50 four-port optical fiber coupler. Emitted light was injected into port 1 using a single-mode lensed fiber. The optical feedback was created with a high-reflectivity dielectric-coated fiber ($>95\%$) located at port 2. The feedback level was controlled via a variable attenuator and its value was determined by measuring the optical power at port 4 (back reflection monitoring). The effect of the optical feedback was analyzed at port 3 via a 10 pm resolution optical spectrum analyzer. A polarization controller was used to make the feedback beam's polarization identical to that of the emitted wave in order to maximize the feedback effects. The distance between the laser and the external reflector (L_e) is estimated to be a few meters, which corresponds to a roundtrip time of about $\tau_e = 2n_e L_e/c \sim 10-30$ ns ($n_e \sim 1.4$ being the refractive index of the silica in the optical fiber). As a consequence, the condition $f_r \tau_e \gg 1$ is fulfilled (long external cavity) and means that the coherence collapse regime does not depend on the feedback phase nor the external cavity length. Thus, in order to improve the accuracy of the measurements at low output powers, an erbium-doped-fiber-amplifier (EDFA) was used with a narrow band filter to eliminate noise. The amount of injected feedback into the laser is defined as the ratio $\Gamma = P_1/P_0$ with P_1 being the power retuned to the facet and P_0 being the emitted one. The amount of light that effectively returns into the laser depends on the optical coupling loss of the device to the fiber, which was estimated to be about 4 dB.

In Fig. 3 the onset of the coherence collapse is shown as a function of the bias current at room temperature. In order to take into account the limits of the experimental resolution arising from measurements, error bars of +/−3 dB have been included. Note that solid lines in Fig. 3 are added for visual help only. The plot with black circles corresponds to the coherence collapse thresholds directly calculated by inserting all data from Figs. 1 and 2 into Eq. (2). This calculation predicts a variation in the coherence collapse onset level as high as 20 dB over the examined current range within the same device.

In order to check the accuracy of this method, experiments were repeated using a direct technique based on spec-

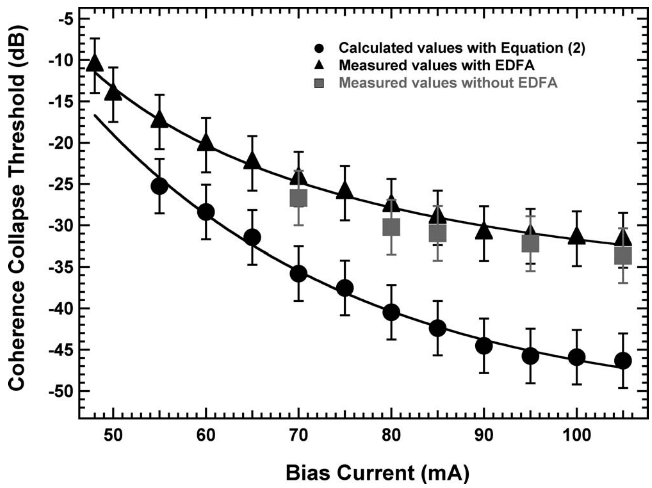

FIG. 3. Coherence collapse thresholds as a function of the bias current for the quantum dash laser under study. Solid lines were added for visual help. (a) Calculated values using Eq. (2) (black circles), (b) measured values with EDFA (black triangles), and (c) measured values without EDFA (gray squares).

tral observation. Assuming that the onset of the coherence collapse is reached at $\Gamma = \Gamma_c$ when the laser linewidth begins to significantly broaden, the black triangles in Fig. 3 measured with the direct method do not agree well with those extracted from the indirect one. Since Eq. (2) was derived empirically under the assumption of weak optical feedback, similar to the more complete analysis based on the Lang and Kobayashi phase equations,[23,24] a discrepancy is found between calculations and measurements except in the low current region of the laser in which the α_H-factor is smaller. When extrapolating the solid line close to the laser threshold, the calculated values will be very close to the experimental data. Finally it is worth noting that when coherence collapse thresholds are measured through the direct method but without the EDFA (gray squares in Fig. 3), results remain in good agreement with bias currents above 70 mA. Below this bias point it becomes extremely difficult to measure the critical feedback regime accurately due to the reduction in output power of the device under test.

The quantum dash FP laser is shown to exhibit a GS α_H-factor enhancement from $\sim$1 to $\sim$14 as current is increased above threshold. Due to this characteristic property, a 20 dB change in the feedback sensitivity has been reported in a quantum dash laser. Results depicted in Fig. 3 constitute an important feature as the onset of the coherence collapse usually increases with the output power following the increased damping rate, which arises from gain saturation. This paper experimentally demonstrates that the route to the coherence collapse is dramatically accelerated due to the strong enhancement in the GS α_H-factor. Consequently, the control of the α_H-parameter remains one of the most important issues for designing feedback-resistant lasers. This result points out the major role of the α_H-factor in the feedback degradation and also the fact that the analysis of the coherence collapse regime remains an extremely important feature for all applications requiring either a low noise level or a proper control of the laser coherence.

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