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Tuning the external optical feedback-sensitivity of a passively mode-locked quantum dot laser

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The external optical feedback-sensitivity of a two-section, passively mode-locked quantum dot laser operating at elevated temperature is experimentally investigated as a function of absorber bias voltage. Results show that the reverse-bias voltage on the absorber has a direct impact on the damping rate of the free-running relaxation oscillations of the optical signal output, thereby enabling interactive external control over the feedback-response of the device, even under the nearly resonant cavity configuration. The combination of high temperature operation and tunable feedback-sensitivity is highly promising from a technological standpoint, in particular, for applications requiring monolithic integration of multi-component architectures on a single chip in order to accomplish, for instance, the dual-objectives of stable pulse quality and isolation from parasitic reflections. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4891576]

In recent years, quantum dot mode-locked lasers (QDMLLs) have shown great promise for monolithic integration into multi-component photonic integrated circuit architectures for applications such as high bit rate optical communications, signaling and clock distribution.[1–3] However, integration into such environments for high performance applications necessitates stable pulse generation with a low noise figure, despite elevated operating temperatures and imperfect isolation from neighboring components. Extensive efforts over the past several years have sought to address these issues. QDMLLs have been shown to be particularly well-suited for high temperature operation in the 60–80 °C range, which allows for superior pulse-shaping and consequently, better pulse quality.[4–6] In Ref. 6, this trend was investigated in detail and attributed to the typically lower values of unsaturated absorption leading to lower values of unsaturated gain in this temperature range, as a result of which pulses are subjected to lower levels of distortion per pass.

Dramatic improvements have also been reported in the noise performance of these devices by means of externally applied optical feedback. Since the early days of their development, semiconductor lasers have been known to be plagued by noise,[7,8] arising primarily from high levels of amplified spontaneous emission (ASE). This becomes particularly problematic in passively mode-locked devices, where the effect of such a buildup of intracavity noise is seen as a manifestation of noticeable levels of pulse-to-pulse timing jitter, owing to the lack of timing stability imposed by an external source. Amplitude-to-timing jitter conversion is thought to be a secondary source of timing instability.[9] And, while the demonstration of the lowest threshold current densities of all semiconductor lasers,[10] and the potential for lower values of internal loss and ASE in QDMLLs makes them highly attractive candidates for low noise applications, extensive recent efforts have sought to exploit external control mechanisms, such as external optical feedback, to further optimize the RF noise performance of these devices. Toward this end, a numerical study by Avrutin and Russell[11] investigated the influence of external optical feedback on the spectral dynamics of monolithic semiconductor MLLs for different ratios of the external cavity length to the laser cavity length. Simulation results of this study predicted that stably mode-locked regimes are possible for integer or fractional resonant configurations, where the ratio of the external cavity to the laser cavity is an integer or rational fraction. Following these predictions, experimental results have shown that the integer resonant configuration can dramatically improve the noise performance of the device.[12–14] Concurrently, the sensitivity of a QDMLL to external optical feedback can be of critical importance, depending on whether the application demands insensitivity or a high degree of sensitivity to external perturbation.[15] In this Letter, we report on the external feedback-sensitivity of a two-section passive QDMLL, highlighting the role of the absorber bias voltage as a control parameter to interactively tune the response of the device to applied optical feedback. Such a tunable response can be immediately seen to be highly pertinent from a technological standpoint, as it enables interactive control over the response of the device to external feedback ranging from highly sensitive to insensitive, using an easily adjustable (external) electrical control.

The 7.8-mm long packaged, two-section passive MLL used in this study is a multi-stack, dots-in-a-well (DWELL) structure with an optimized, six-stack InAs active region and a 1.1-mm saturable absorber. A highly reflective coating ($R \approx 95\%$) was applied to the mirror facet adjacent to the saturable absorber, while the other facet was

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as-cleaved. Figure 1 shows basic free-running device characterization measurements.

The shaded regions enclosed within the contours mapped in Fig. 1(a) correspond to operating conditions under which mode-locked pulses with pulse widths ≤ 20 ps were obtained. In particular, the regions shown were free from instabilities such as pulse breakup/splitting.[16] Clearly, higher temperatures tend to aid stable mode locking, as can be seen from the considerably larger regions bounded by the contours corresponding to 60 °C and 70 °C. The physical explanation for this trend has been recently attributed to the reduced values of unsaturated absorption typically observed in this temperature range,[6] as seen from the inset in Fig. 1(a), wherein, a dip in the absorption curve at each bias voltage was found to occur consistently. As mentioned previously, this typical lowering of unsaturated absorption was thought to instigate a concomitant reduction of unsaturated gain values, which in turn, enabled a more gradual pulse shaping during propagation through the cavity, leading to better pulse quality. In the present work, it was additionally found that the device under study exhibited a superior noise performance at 70 °C. Following these results, an operating temperature of 70 °C was chosen. Fig. 1(b) shows the free-running L-I characteristics of the device at 70 °C. A progressive reduction in output power was observed with increasing absorber bias voltage. Device output was seen to degrade dramatically for bias voltages stronger than -4.5 V.

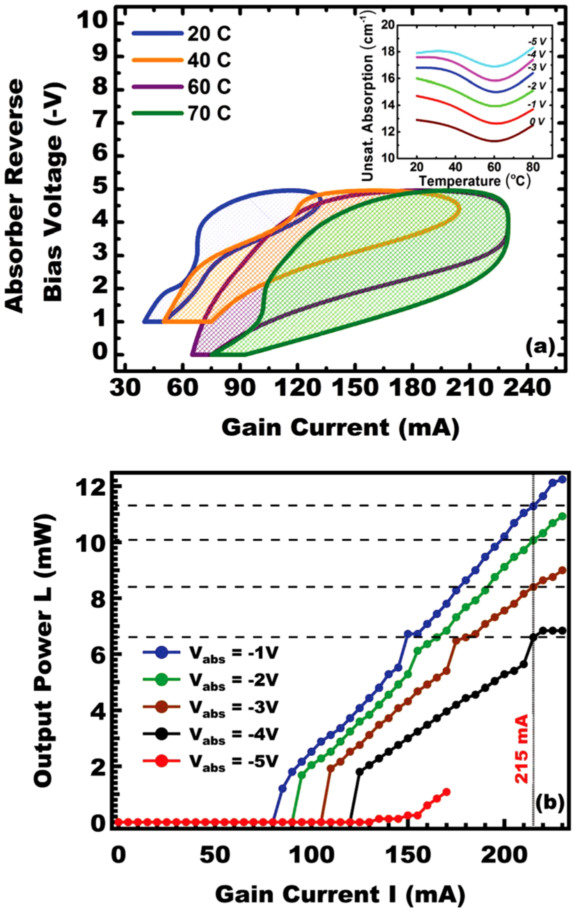

FIG. 1. (a) Mode-locking stability maps (pulse widths $\leq$ 20 ps, obtained with a high speed oscilloscope) as a function of temperature, pump current, and absorber bias voltage. Inset shows unsaturated absorption values measured on unpackaged device over temperature and absorber bias voltage V_{abs}, and (b) Device L-I characteristics at 70 °C (the operating current was 215 mA).

The experimental scheme used for external optical feedback has been described in detail in our previous publications.[12–14] Measurements were performed under the long external cavity length (ECL) regime, so that the product of the relaxation frequency f_r (a few GHz), and the external cavity round-trip time τ ($\sim$120 ns) is much greater than 1. All measurements were performed under the nearly resonant case (where the ECL is about an integer multiple of the laser cavity length), keeping the optical delay condition fixed at 0 ps (setting for maximum stability). In order to study the sensitivity of the device to external optical feedback, the following methodology was used. For each absorber bias voltage, the fundamental RF linewidth was recorded using an Electrical Spectrum Analyzer (Agilent 8565 EC, measurement range 9 kHz–50 GHz) under the free-running configuration. The same measurement was then repeated under a moderately strong feedback condition of ~ -18 dB. This sequence of measurements was repeated for each bias voltage, as shown in Fig. 2.

The chart shown in Fig. 2 provides a comparison between the evolution of the RF linewidth of the fundamental as a function of the applied bias voltage for the free-running (open red circles) and moderate feedback condition of -18 dB (open green diamonds) at an operating temperature of 70 °C, and a pump current of 215 mA. It may be noted that owing to the long ECL and the resultant losses in the feedback loop, the pump current was chosen to be 215 mA in order to maximize the average pulse power at each absorber bias condition while still maintaining good pulse quality. Four distinct regimes can be clearly identified. In region I, for absorber bias voltages less than -1.5 V, the laser was found to exhibit pulsed operation, but not stable, fundamental mode-locking. Fig. 3(a) depicts a typical RF spectrum captured for device operation in this regime, where the second harmonic peak dominates the fundamental. As the absorber bias was increased past -1.5 V, the device was steered into stably mode-locked operation, as seen from both, the mode-locking map in Fig. 1(a), as well as the RF spectrum in Fig. 3(b) where the fundamental peak is dominant. The device was found to exhibit the best free-running mode-locking performance between -1.5 V and -2.5 V, with an RF linewidth $\sim$4.5 kHz over the entire interval.

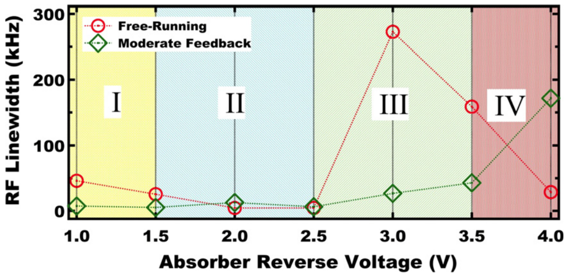

FIG. 2. Evolution of RF linewidth as a function of absorber bias voltage for the free-running (open red circles) and moderately strong resonant feedback condition of -18 dB (open green diamonds). Note the different dynamical regimes: I (unstable/incomplete mode-locking), II (feedback insensitivity), III (linewidth reduction), and IV (linewidth enhancement).

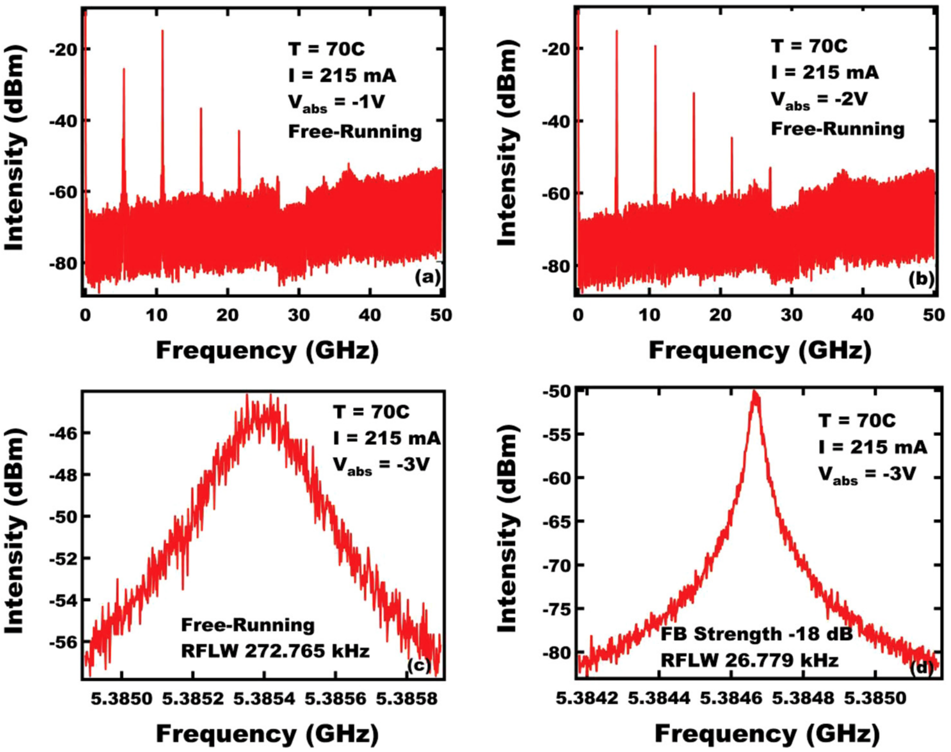

FIG. 3. RF spectra at 70 °C, 215 mA: (a) typical full-span capture of incomplete/unstable mode-locking in region I, (b) typical full-span capture of stable mode-locking in regions II, III, and IV, (c) free-running RF spectral profile of fundamental at a −3 V absorber bias, and (d) RF spectral profile of fundamental at a −3 V absorber bias, external optical feedback strength ∼−18 dB.

A striking feature of the dynamics exhibited in this region of operation was the broad insensitivity of the device to external feedback, as can be easily seen from the near overlap of the trend lines for the solitary and moderate feedback configurations. A closer examination of the L-I characteristics of the device reveals that this region of stable mode locking corresponds to the highest average pulse power levels ($\geq$9.5 mW), so that the RF linewidth of the pulse is robust to even moderately high feedback levels.

However, as the absorber bias was increased further, the dynamics of the output changed dramatically, and the device exhibited a high degree of sensitivity to the applied feedback. Between −2.5 and −3.5 V, a drastic enhancement of the free-running RF linewidth was observed, as seen from region III in Fig. 2. In this region of operation, the effect of the moderately strong feedback was seen to be beneficial toward reducing the RF linewidth, with a maximum reduction by a factor of ten, from ∼273 kHz to ∼27 kHz for an absorber bias of −3 V (Figs. 3(c) and 3(d)). For absorber bias voltages beyond −3.5 V, however, the effect of applied feedback was found to be detrimental to the RF performance of the device, as seen from region IV. Broadly speaking, this performance-degradation can be attributed to two key factors: (i) The higher bias voltage causes an enhanced carrier sweep-out effect, which leads to a lower stimulated photon density, which in turn, results in a significantly reduced average pulse power, as is evident from the L-I characteristics in Fig. 1(b) and (ii) the higher bias voltage also results in higher threshold current densities, which, coupled with the length of the gain section, leads to a significant buildup of amplified spontaneous emission along the length of the device. The combination of these factors leads to a significantly degraded noise figure.

A deeper understanding of the range of dynamical behavior exhibited by the device under the influence of near-resonant external optical feedback as a function of absorber bias voltage can be obtained by examining the nonlinear dynamics of the device output. Detailed theoretical and experimental studies have previously found that the sensitivity of quantum dot semiconductor lasers to external optical feedback is strongly influenced by the extent to which the relaxation oscillations (ROs) of the output are damped.[17–19] In this connection, it may be noted that the influence of Spectral Hole Burning (SHB) on the dynamical response of semiconductor lasers has received considerable attention over the years. Generally speaking, SHB is known to increase the damping rate of ROs, so that a stronger SHB-effect will lead to strongly damped ROs.[20] The QD active region provides a particularly conducive material system for SHB-effects to play a significant role, owing to pronounced gain compression-effects and the considerably longer capture and escape times between the wetting layer and the dot levels.[21–24] Fig. 4 plots the evolution of the optical spectra of the free-running device as the absorber bias

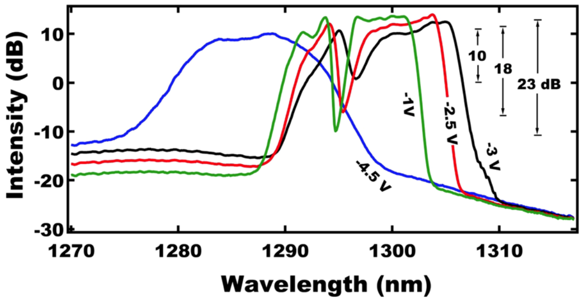

FIG. 4. Evolution of the free-running output optical spectra as a function of absorber bias voltage (OSA Resolution 0.2 nm). Note the “washing-out” of the spectral hole as the absorber voltage is increased, leading to its complete disappearance above −4 V, accompanied by a noticeable blue shift of the entire spectrum.

voltage is increased (captured using an Optical Spectrum Analyzer (OSA), model Yokogawa ANDO AQ6317C).

The key feature in the spectra shown in Fig. 4 is the behavior of the spectral hole, centered at 1296 nm at a −1 V absorber bias voltage. The origin of this hole can be attributed to a wavelength-selective reflection from an element such as a grating.[25] In this case, the wavelength-selectivity, although unintentional, is likely caused by a nonuniformity in the coating on the HR facet. As can be clearly seen from the spectrum at −1 V, the spectral hole is sharply tapered and nearly symmetric about the bottom of the hole, with a depth of 23 dB. Further, the spectrum was seen to become shallower, wider, and increasingly asymmetric with increasing voltage. The depth of the spectral hole was found to be 18 dB for a −2.5 V absorber bias, and significantly reduced to 10 dB for a −3 V bias. It may be recalled from Fig. 2 that it was precisely in this region corresponding to the rapid washout of the hole between −2.5 V and −3 V that the device switched from feedback-insensitivity to a high degree of sensitivity. The considerable weakening of the SHB-effect in this region of operation as the Stark effect begins to dominate, translates to a correspondingly dramatic reduction in the damping rate of the output ROs, so that the device becomes extremely sensitive to all perturbation, including intracavity noise. This would explain not only the high degree of sensitivity to external optical feedback, but also the dramatic linewidth broadening observed at −3 V. Finally, above −4 V, the spectral hole disappeared completely, and the entire spectrum was observed to blue shift by ∼7 nm, and re-centered at 1289 nm. This entire sequence of events has been previously reported by Feng *et al.*[26] in the context of wavelength bistability, and was attributed to the interplay between SHB and the Quantum Confined Stark Effect (QCSE). As part of the findings of that study, it was proposed that at low absorber bias voltages, SHB dominates, as seen in the present case from the depth, sharpness, and symmetry of the spectral hole formed at −1 V. As the bias voltage is increased, the QCSE first competes with SHB at moderate bias voltages, thereby weakening the influence of the latter (seen from the noticeable washing-away of the spectral hole with increasing bias voltage), and eventually dominates, as seen from the complete disappearance of the hole beyond −4 V (−4.5 V spectrum).

It was mentioned previously that the QD material system is known to be particularly conducive to SHB-effects, owing to gain compression-effects, and the longer capture and escape timescales between the wetting layer and dot levels. Furthermore, while the influence of a bias voltage applied to a saturable absorber is known to manifest itself as the QCSE, more recent work has highlighted the dramatic influence of the absorber reverse voltage on recovery timescales.[27,28] As a consequence, the absorber bias voltage can be used as an external control mechanism to tune the relative strengths of the SHB and QCSE effects,[26] and thereby, as a mechanism to tune the feedback-sensitivity of a device by virtue of controlling the damping rate of the output ROs.

In conclusion, in this Letter we report on a systematic study of the influence of the absorber reverse voltage on the sensitivity of a two-section, passive QDMLL to externally applied optical feedback. The experimental data recorded suggest that the absorber bias voltage can be used as a conveniently adjustable and reconfigurable external control parameter to tune the damping rate of the relaxation oscillations of the output, and hence, the feedback-response of the device from insensitive to highly sensitive, even in the resonant cavity configuration. From an applications-standpoint, the combination of stable pulse quality at high temperatures and easily tunable external optical feedback-sensitivity can be seen to be of critical importance to architectures involving multi-component integration on chip.

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