Comparison of the noise performance of integrated 10GHz QW and QD Mode-Locked Laser Diodes

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***Abstract*—This paper reports the experimental characterization of the noise performance of monolithically integrated quantum dot and quantum well 10GHz passively mode locked laser diodes.**

Keywords-passive mode locking, quantum dot, quantum well, phase noise.

I. Introduction

Semiconductor mode-locked lasers are key components for optical data transmission and for optical signal processing as a result of their compactness, robustness, performance stability, power consumption and low cost [1]. These integrated devices commonly comprise two sections, a saturable absorber (which represents its main difference with continuous wave lasers) and a gain section. The shape of the generated pulses depends heavily on the pulse interactions in these sections, which produce opposite effects on the pulse, namely shortening in the saturable absorber and broadening in the gain section [2]. The interactions in turn depend on the material structure of the active layer, which is commonly either a quantum-well (QW) or quantum dot (QD) structure. Both are low-dimensional structures but the intrinsic differences between QWs and QDs (such as the density of states) gives rise to very different dynamics which can account for the improvement of the QD performance as well as improving key device parameters such as the threshold current density or mode overlap factor [3]. In addition, a recent review has pointed that the passive mode locking (PML) regime of QD devices has a far superior performance over QW in terms of noise [3, 4]. The RF frequency noise for PML lasers is dominated by the spontaneous emission noise, having a Lorentzian shaped single side band (SSB) PSD, given by [5]:

$$S_{\phi RF}(f)=\Delta\nu_{RF}/\pi f^2 \quad (1)$$

which is completely defined by the full width at half maximum (FWHM) of the first harmonic ($\Delta\nu_{RF}$). In this paper we report an experimental comparison of the passive mode locking regime in a 10GHz QD laser versus a QW device.

II. QW & QD Devices

Both devices have an all-active two-section structure with 4mm total length for a 10GHz repetition rate. Both devices were processed using state-of-the-art gain material structures, having similar threshold current densities, 250 A/cm^2 for the QD and 262 A/cm^2 for the QW lasers, both measured at 20ºC with the absorber in the open circuit condition..

The QD device has a 580µm long absorber section and a 3420µm long gain section, which have an ~1300nm bandgap wavelength. The active region contains a five fold stack of InGaAs QD in well layers [6]. Horizontal confinement of the optical field is achieved by the formation of 6µm wide ridge waveguide structure. The device is packaged in a case that includes a microwave 50Ω microstrip line port to the saturable absorber section and a thermoelectric cooler/thermistor that allows temperature stabilization. Laser facets are as cleaved, and light is coupled via a fiber lens to a single mode fiber pigtail with an angled connector.

The QW device has an 85µm long absorber section and a 3915µm gain section. The active region contains one well InGaAsP/AlGaInAs QW laser emitting at ~1512nm [3]. Horizontal confinement of the optical field is achieved by the formation of a 2µm width ridge waveguide structure. The facet at the absorber end is HR coated, and light is coupled on the gain facet (which is as cleaved) via single mode AR coated lensed fiber.

Both devices have been characterized on the same set-up. The gain current is injected from a 3724B ILX diode controller and the reverse bias to the saturable absorber from a HP E3631A voltage source. Both devices are mounted on a thermoelectric cooler/thermistor stage that allows temperature stabilization, and an optical isolator is used following the output coupling fiber.

The optical spectrum is measured on a HP 86140 analyzer and the electrical RF spectrum on a 22-GHz Lightwave analyzer HP 70000 system.

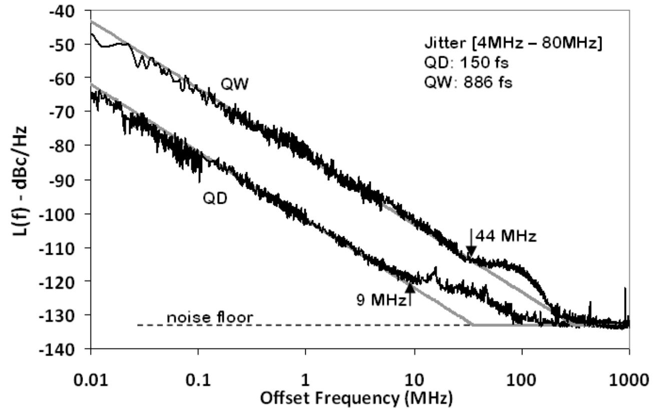

Figure 1. SSB phase noise power spectral density of the mode-locked lasers

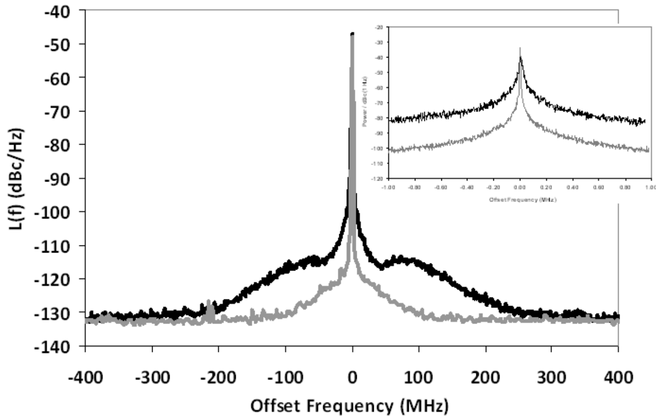

Figure 2. RF electrical spectrum showing the phase noise relative to the 10GHz carrier for the QW (black) and the QD (gray). The inset has a span of 1 MHz, and a RBW of 10 KHz

III. RESULTS

Figure 1 shows the SSB phase noise spectra for both devices, operating at the conditions which provide the best jitter figure. In agreement with the theory, the lowest noise performance on both corresponds to the highest gain current at which the device remains mode locked [3]. The bias settings are I_{gain} = 70 mA and V_{abs} = -7 V for the QW device, and I_{gain} = 130 mA and V_{abs} = -6 V for the QD laser. The grey straight lines correspond to the Lorentzian lineshape in Eq. 1, fitted down to the noise floor at -133 dBc, with the resulting $\Delta\nu_{RFfitQD}$ = 200 Hz for the QD and $\Delta\nu_{RFfitQW}$ = 15 kHz for the QW lasers. The figure shows that the two SSB phase noise traces follow the ideal -20 dB/dec roll-off up to a given frequency, f_D, namely 9 MHz for the QD and 44 MHz for the QW lasers (see Figure 1), departing at higher frequencies. The most significant difference is that after a plateau, the QD rolls off at -20 dB/dec while the QW decreases with a -40 dB/dec slope. This difference is in agreement with theoretical results which attribute it to amplitude fluctuations [7]. The integrated timing jitter ([4 MHz – 80 MHz]) of the SSB phase noise is shown on the graph, with $\sigma_{T\,QD}$ = 150 fs for the QD and $\sigma_{T\,QW}$ = 886 fs for the QW. When the jitter is calculated by integration of the Lorentzian fit, we obtain σ_{TfitQD} = 91 fs for the QD and σ_{TfitQW} = 760 fs for the QW. The result suggests that the lower jitter in the QD laser is mainly due to the narrower linewidth of this device, which can be attributed to a reduction of the spontaneous emission rate coupled to the lasing mode, due to the interaction with a small fraction of the injected carriers [3].

To confirm this point, the 10GHz RF beat signal for the QD and the QW devices are shown on Figure 2, both exhibiting a carrier-to-noise ratio greater than 42 dB. The beat signal shows a narrow frequency peak with Lorentzian lineshape (see the inset) sitting on a broad noise pedestal. When the frequency peak is fitted to a Lorentzian, the -3 dB linewidth is $\Delta\nu_{RFQD}$ = 500 Hz for the QD [6] and $\Delta\nu_{RFQW}$ = 16 kHz for the QW lasers. The results show a strong agreement between theory ($\Delta\nu_{RFfitQW}$, σ_{TfitQW}) and observed data ($\Delta\nu_{RF\,QW}$, $\sigma_{T\,QW}$) for the QW device, where the difference between σ_{TfitQW} and $\sigma_{T\ QW}$ can be attributed to the difference between the two curves above f_D in Figure 1. Similarly, for the QD, the lower f_D increases the impact of the non-Lorentzian components of the SSB phase noise on the rms timing jitter from the RF linewidth, which explains the observed difference between $\sigma_{T\,QD}$ and σ_{TfitQD}.

IV. CONCLUSSIONS

In conclusion, our results on the passive mode locked SSB phase noise confirm that the extremely good timing jitter performance of the QDs laser is due to the narrower linewidth on the QD device, as these are intrinsically linked. However, the dynamics of the device, which cause a slow roll-off of the pedestals, impact on the resulting jitter from the QD.

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REFERENCES

[1] Kaiser, R. and Hüttl, B. “Monolithic 40-GHz Mode-Locked MQW DBR lasers for high-speed optical communication systems” IEEE J. of Sel. Topics in Quantum Electronics 13(1), 125 – 135 (2007)

[2] Williams, K.A.; Thompson, M.G.; White, I.H. “Long-wavelength monolithic mode-locked diode lasers” New J. Phys. **6** 179 (2004).

[3] Yvind, K.; Larsson, D.; Mørk, J.; Hvam, J.M.; Thompson, M.; Penty, R.; White, I.H. “Low-noise monolithic mode-locked semiconductor lasers through low-dimensional structures” Proc. of the SPIE, Vol. 6909, pp. 69090A-69090A-9 (2008).

[4] Thompson, M.G.; Rae, A.R.; Mo Xia; Penty, R.V.; White, I.H. “InGaAs Quantum-Dot Mode-Locked Laser Diodes” IEEE J. Sel. Topics in Quantum Electronics 15(3), pp. 661 – 672 (2009).

[5] Kéfélian, F.; O’Donoghue, S.; Todaro, M.T.; McInerney, J.G.; Huyet, G. “RF Linewidth in Monolithic Passively Mode-Locked Semiconductor Laser” IEEE Phot. Tech. Lett. 20(16), pp. 1405 – 1407 (2008)

[6] Carpintero, G.; Thompson, M.G.; Penty, R.V.; White, I.H. "Low Noise Performance of Passively Mode-Locked 10-GHz Quantum-Dot Laser Diode" IEEE Phot. Tech. Lett. 21(6), pp. 389-391 (2009)

[7] Mulet, J.; Moerk, J.; Kroh, M. "Identification of amplitude and timing jitter in external-cavity mode-locked semiconductor lasers" in CLEO/IQEC San Francisco, CA, May 16-21 (2004)