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RF linewidth of a monolithic quantum dot mode-locked laser under resonant feedback

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Abstract: The stability of a quantum dot (QD) mode-locked laser is experimentally shown to bifurcate under resonant optical feedback, which leads to either a reduction or an enhancement of the noise within the laser's cavity. These two behaviours, which are theoretically known as the nearly exact resonant and stably resonant feedback conditions, are characterised using the RF linewidth of the QD device. Under the stably resonant case with relatively low feedback strength and constant temperature control, the RF linewidth narrows to a value as low as 170 Hz. Noise enhancement, which is a precursor to coherence collapse, is observed in the device under the nearly exact resonant case. Under proper conditions, the results presented show that the combination of external optical feedback and the relatively low threshold of QD mode-locked lasers make them attractive chip-scale sources for ultra-low noise photonic applications.

1 Introduction

Semiconductor mode-locked lasers (MLLs) have potential use in various fields including optical sampling and clock distribution, photonic analogue-to-digital converters, diverse waveform generation and microwave signal generation [1–4]. To realise the high repetition rates (2–40 GHz) and low timing jitter required by these applications, different semiconductor mode-locking architectures have been proposed [5–8]. Among different MLL configurations, monolithic two-section passive MLLs offer several advantages including compact size, simple fabrication, DC bias only and the ability for hybrid integration to silicon substrates. Compared to active mode locking, however, the timing stability issue is the drawback of passive MLLs because of the lack of an external reference source. Since timing fluctuations in the optical pulse train play an important role in determining the laser performance, reducing the phase noise and stabilising the MLL have attracted numerous theoretical and experimental studies. Several methods have been proposed to reduce the RF phase noise in active and passive MLLs with high repetition rate. Methods such as injection locking, introduction of an intracavity etalon and intracavity active phase modulation have been implemented in harmonically/actively mode-locked semiconductor lasers [9–11]. For passive MLLs, phase noise reduction has been observed through the injection locking method or external optical feedback [12–16]. In this work, the noise performance of a packaged passive quantum dot (QD) MLL subjected to stably resonant and nearly exact resonant external optical feedback and steady temperature control is investigated. In the stably resonant case, an RF linewidth of 170 Hz is achieved at an operation temperature of 17°C. The nearly exact resonant case exhibits significant linewidth rebroadening as the feedback level is increased, which agrees well with previously published theory [17].

This paper is organised as follows. Section 2 is devoted to a brief comparison of jitter and RF linewidth performance in quantum well (QW) and QD MLLs. The external feedback mechanism in the passive QD MLL is also introduced. Device structure and fabrication are presented in Section 3. In Section 4, the experimental setup and results are discussed for the QD MLL. The laser stability is experimentally shown to bifurcate under the resonant feedback situations leading to either a reduction or an enhancement of the noise within the laser's cavity. An RF linewidth as low as 170 Hz is demonstrated in the more favourable resonant configuration whereas an increase to 100 kHz in the nearly exact resonant condition is observed. Finally, key findings and future work are summarised in Section 5.

2 Jitter and RF linewidth performance in QW and QD MLLs

In the characterisation of a passive MLL, the integrated rms timing jitter is generally given in terms of the integrated phase noise power spectral density (PSD) measured from the transient photocurrent through an electrical spectrum analyser (ESA) [18]. Since jitter analysis typically requires a high-performance photodetector and ESA to measure the PSD at a higher-order harmonic of the MLL where the amplitude noise is negligible, the RF linewidth at the first harmonic can provide a simpler, alternative way to characterise the timing stability. Furthermore, the integrated rms timing jitter has been found theoretically and experimentally to vary with the square root of the RF linewidth [15, 19].

In a passive MLL, a pulse circulates in the optical cavity with a dynamic broadening in the gain section and a pulse trimming effect in the saturable absorber (SA). As noted by Yvind *et al.* [20], the minimisation of pulse reshaping is the key to improve the noise behaviour and, consequently, the RF linewidth in these lasers. To date, low noise performance from a monolithic passive QW MLL has been achieved through special design and optimisation of the active structure. In these laser devices, the confinement factor that refers to the overlap of the optical field with the active material is designed to be low, allowing improved timing stability and noise performance. A 3-dB RF linewidth of 30 kHz has been achieved in a 21-GHz passive QW MLL device [21]. Recently, the passive QD MLL device has demonstrated a superior noise performance with an RF linewidth of 500 Hz [22]. From the aspect of material property, the QD structure owns a high-gain saturation energy that indicates a low pulse broadening effect in the gain section. In addition, QD materials also show low internal loss [23], reduced threshold current density, lower associated spontaneous emission [24] and low linewidth enhancement factor (LEF) [25]. All these unique properties in the QD lead to improved noise performance and a demonstrated narrower RF linewidth compared to their QW counterparts.

For further improvement, external optical feedback can be implemented to lower the phase noise in the laser device. For instance it has been theoretically shown that even small external reflections have to be considered in determining the mode-locking dynamics [17]. On the one hand, under the non-resonant case, which is reached when the optical lengths of the cavities are arbitrary, the operation of the laser gets unstable beyond a certain level of optical feedback with at least two pulses competing with each other [17]. Such 'severe' instabilities lead to a sharp increase of the noise as pointed out in [26]. On the other hand, under the resonant case, which is obtained when the optical length of the external cavity is about a multiple of that of the solitary laser, an RF linewidth reduction can be expected over a wide bias current and external reflectance range as compared to the non-resonant situation [17].

3 Device structure and fabrication

The QD structure investigated in this work was grown by elemental source molecular beam epitaxy on an n^+-doped (100) GaAs substrate. The active region consists of six 'Dots-in-a-Well' layers. In each layer, an equivalent coverage of 2.4 monolayer InAs QDs is confined approximately in the middle of a 10 nm $In_{0.15}Ga_{0.85}As$ QW [23]. The epitaxial structure and waveguide design are described in Fig. 1. The 3-μm-wide ridge-waveguide devices were etched by inductively coupled plasma etching and planarised using benzocyclobutene. Ti/Pt/Au was then deposited to form the p-metal contact. The electrical isolation between the gain and absorber sections was provided by proton implantation with an isolation resistance of >10 MΩ. After the substrate had been thinned and polished, a Ge/Au/Ni/Au n-metal contact was deposited on the backside of the n^+-GaAs substrate and annealed at ~380°C for 1 min to form the n-ohmic contact. The two-section QD passive MLLs were made with a total cavity length of 7.8 mm and an SA length of 1.1 mm. The nominal repetition rate of the QD MLL is 5 GHz. A highly reflective coating ($R \simeq 95\%$) was applied to the mirror facet next to the SA to create self-colliding pulse effects in the SA for pulse narrowing, and the output facet was cleaved ($R \simeq 32\%$). The devices were p-side-up mounted on AlN heatsink carriers. These chip-on-carriers were then packaged with a polarisation-maintaining lensed fibre pigtail as shown in Fig. 2. The function of the packaged module is to reduce environmental noise and enhance mechanical stability. The fibre-coupled light–current (L–I) curve under −1 V reverse voltage bias condition at 20°C is displayed in Fig. 3. The abrupt jump in optical power just above the threshold current is due to the non-linear behaviour of the SA. The inset is the optical spectrum showing the peak lasing wavelength at 1.33 μm under a gain current of 280 mA and an SA reverse voltage of −1 V. The typical average powers emitted by these devices under mode-locking conditions at the end of the fibre pigtail are 1.5–2.5 mW. The pulse durations are on the order of 10 ps.

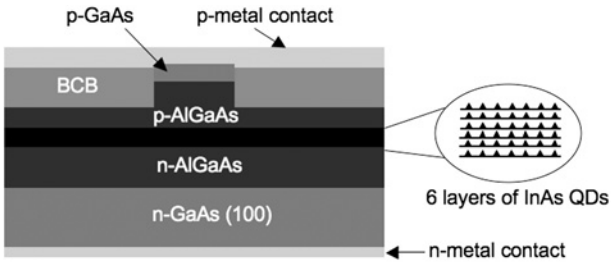

Fig. 1 *Schematic of the epitaxial layer structure of the InAs QD laser*

4 Experimental setup and results

The passive QD MLL module with thermoelectric cooler (TEC) was investigated under external optical feedback using the experimental setup shown in Fig. 4. The emitted light that is coupled from the laser chip through a lensed fibre pigtail is injected into port 1 of a 50/50 optical fibre coupler. The optical feedback is created from a

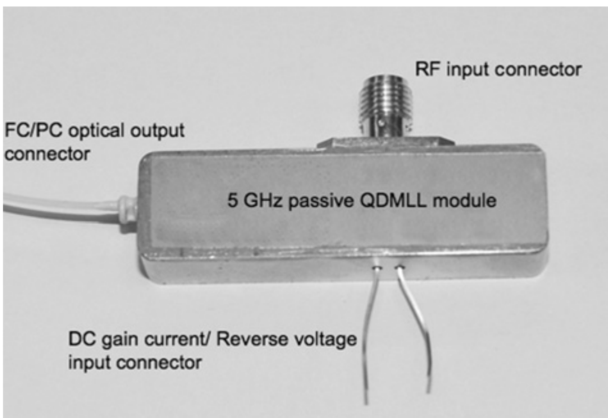

Fig. 2 *Picture of the passive QD MLL packaged module*

RF connector shown on the top of the package was not used for this experiment

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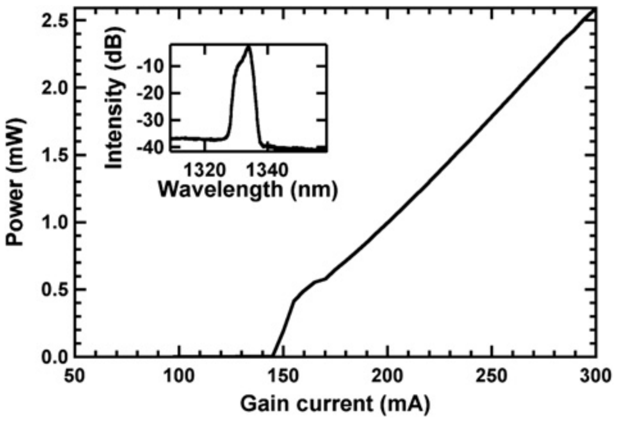

Fig. 3 *L–I characteristic measured at 20°C for an absorber bias of −1 V*

Inset shows the optical spectrum under 280-mA gain current and −1 V reverse voltage

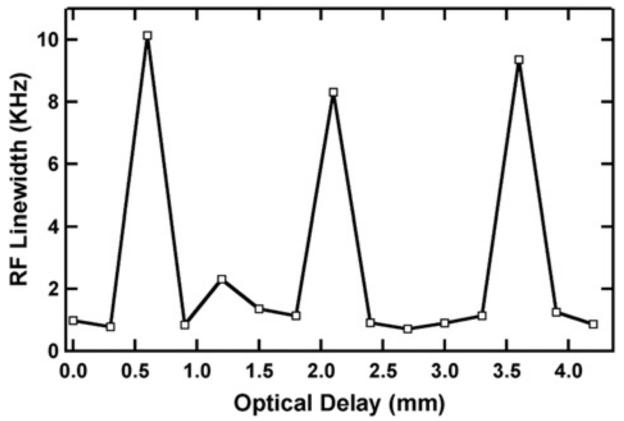

Fig. 5 *RF linewidth variation under feedback ratio of −44 dB as a function of optical delay line change at 20°C, showing a periodicity of roughly 1.5 mm corresponding to the laser round trip time of 200 ps*

Bias condition of QD MLL: 280 mA gain current and −1 V reverse voltage

high-reflectivity ($R > 95\%$) coating applied to the fibre at the end of port 2. The feedback power level is controlled via a variable attenuator and its value is measured by the power meter in port 4. The optical delay line (General Photonics VDL-001) that has a step-controlled fine delay stage (resolution: 0.1 mm) is introduced to change the external fibre loop length. In order to maximise the feedback effect, a polarisation controller is used to make the feedback beam polarisation identical to that of the emitted wave. The effect of the optical feedback is analysed in port 3 through a 45 GHz bandwidth photodiode coupled to an ESA. An optical isolator is used to prevent any unwanted reflection from the ESA. The quantity of injected feedback into the laser is defined as the ratio $\Gamma = P_1/P_0$ where P_1 is the power returned to the facet and P_0 the emitted one. The amount of reflected light that effectively returns into the laser can then be expressed as follows

$$\Gamma\ (\mathrm{dB}) = P_r\ (\mathrm{dBm}) - P_0\ (\mathrm{dBm}) + C_{\mathrm{dB}} \quad (1)$$

where P_r is the optical power measured at port 4, C_{dB} is the optical coupling loss of the device to the fibre which was estimated to be about −5 dB and kept constant during the whole experiment. The feedback experiment is studied under the long external cavity condition that assumes that $f_r\tau \gg 1$, where f_r is the relaxation frequency (a few GHz) and τ is the external round trip time of several hundred nanoseconds.

All measurements are operated with a controlled TEC to adjust and maintain the substrate temperature. As shown in Fig. 5, the variation in the RF linewidth is first analysed over a broad range of optical delays in the feedback loop

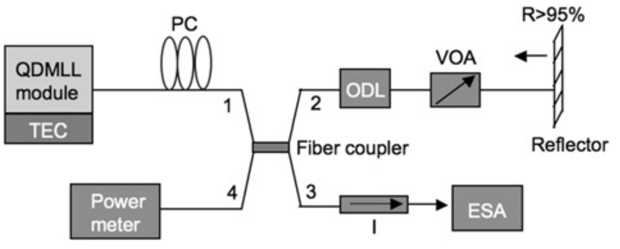

Fig. 4 *Schematic drawing of the experimental setup*

PC: polarisation controller; ODL: optical delay line; VOA: variable otpical attenuator; I: isolator; ESA: electrical spectrum analyser

and a temperature of 20°C. The experimental results demonstrate a similar trend to those observed in QW MLLs under optical external feedback [27]. The noise enhancement as seen in the RF linewidth has been predicted by Avrutin in a two-section monolithic MLL (Fig. 9 of [17]) and is indentified as the nearly exact resonant feedback case. The periodicity can be viewed approximately as 1.5 mm (delay time: ∼200 ps), which corresponds to the mode-locking frequency of ∼5 GHz.

In terms of the optical delay, the stably resonant and nearly exact resonant cases are both in the same general vicinity where the ratio of the optical length of the external cavity to the optical length of the solitary laser, L_{ext}/L, is about an integer. The technologically important regime where the RF linewidth is substantially reduced is called the stably resonant condition. For this case, we have extended our previous study [15] by including a controlled, adjustable temperature and a packaged module that lessens environmental noise and increases mechanical stability. Fig. 6 shows the evolution of the RF spectrum over temperature for the stably resonant feedback case (optical delay set at 2.7 mm) under 280-mA DC bias on the gain section and −1 V applied to the absorber. The RF linewidth of this laser module is 8 kHz in the free-running case at 20°C. By fixing the fibre loop length through the optical delay line to the resonant case and tuning the TEC to lower temperature, the 3-dB RF linewidth is improved from 3.5 kHz at 35°C down to 170 Hz at 17°C under feedback. The measurement is limited to 17°C because of the temperature-induced misalignment between the device and lensed fibre inside the sealed package. The small RF linewidth can be explained by the relatively low threshold of a QD laser and the correspondingly lower amount of spontaneous emission noise coupled into the laser's optical modes. This noise also decreases with temperature and thereby lowers the phase noise and so the RF linewidth. The data for the minimum RF linewidth of 170 Hz, which is realised at a feedback level as low as −42 dB, are shown in Fig. 6. Lorentzian curve fitting of the ESA data using a frequency span of 100 kHz and a resolution bandwidth of 100 Hz is used to calculate the value.

For the nearly exact resonant feedback condition, for which the optical delay is 0.6, 2.1 or 3.6 mm, an increase in RF linewidth is observed as shown in Fig. 5. It is stressed that

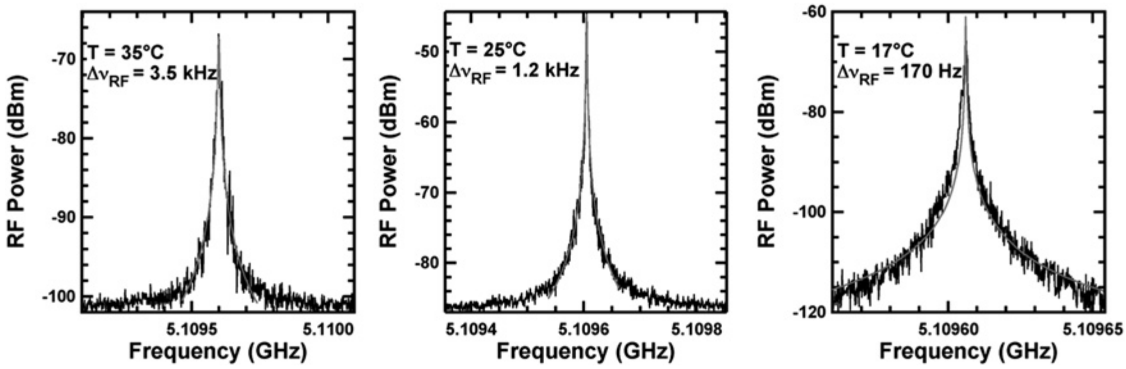

Fig. 6 *Evolution of the RF linewidth for three different temperatures under the stably resonant feedback condition*
Bias condition: 280 mA gain current and −1 V reverse voltage

since the step size of the optical delay line is 0.1 mm, an experimental resolution on the peak location has to be considered. Although this means the delay step is in increments of 13 ps, the nearly exact resonant condition has been identified clearly by the abrupt step in the centre frequency shift as described in [15, 27]. In order to verify previously published simulations [17], the variation in the RF linewidth against the optical feedback ratio is found for the optical delay fixed to 3.6 mm. The same bias conditions as described above are used, and the results are depicted in Fig. 7 at a temperature of 20°C. At a small to moderate feedback strength ($\Gamma < -38$ dB), the MLL behaves stably and shows a relative low RF linewidth compared to the free-running case. As the feedback ratio is increased beyond −38 dB, the RF linewidth becomes much broader than the free-running case. This behaviour matches the simulation result (Fig. 10 of [17]) that demonstrates an increase in phase noise with a small external reflectance on the order of 10^{-4} ($\Gamma = -40$ dB). We also observe the same trend at different QD MLL bias conditions for the nearly exact resonant case. The maximum feedback ratio strength was limited to −30 dB in this experiment. This rebroadening phenomenon could be a precursor to the coherence collapse regime [28]. The coherence collapse regime remains independent of the external cavity length and the feedback phase provided that the long external cavity situation is valid ($f_r\tau \gg 1$). Numerous papers describe the coherence

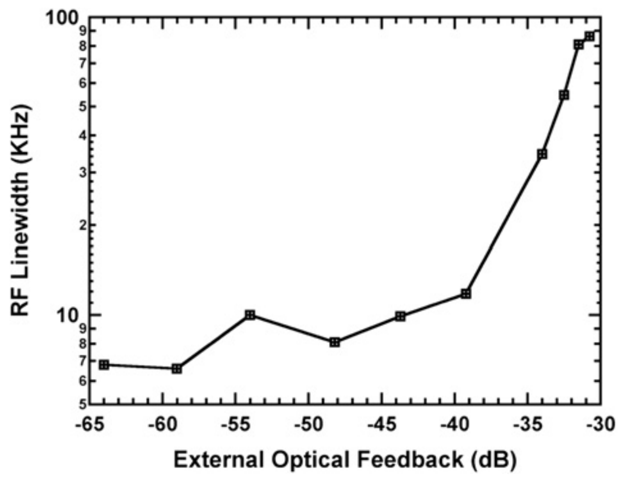

Fig. 7 *RF linewidth as a function of the external feedback ratio at a bias of 280 mA gain current and −1 V on the absorber at 20°C under nearly exact resonant case*

collapse regime as coexisting chaotic attractors [29] whereas others explain it as an important source of noise [30, 31]. Also let us stress that the onset of the coherence collapse is strongly linked to the LEF [32, 33], and the influence of such a parameter on the QD MLL laser dynamics is under investigation. For instance, it has been numerically shown that the LEF is a decisive parameter under the resonant case [17]. Thus, a low LEF should produce a broader stably resonant operation and should also increase the critical external reflectance related to the occurrence of the coherence collapse regime. The low LEF encountered in long-cavity QD lasers could explain the relative wide region of stable resonant operation that is observed in the QD MLL presented here.

5 Conclusion

The effect of external optical feedback for the stably resonant and nearly exact resonant (rebroadening) cases on a passive QD MLL module has been investigated. The experimental results agree well with previously published theory. Under stably resonant feedback, the RF linewidth is reduced to 170 Hz because of the environmentally isolated package design and steady temperature control. The unique properties of QDs including a low threshold, a small LEF and low spontaneous emission noise are also contributing factors to the reported performance. Wider temperature characterisation will be investigated in the future by enhancing the coupling efficiency between the laser device and the lensed fibre pigtail when changing temperature. The RF linewidth rebroadening phenomenon in the nearly exact resonant feedback case represents a precursor to the coherence collapse regime. A stronger feedback ratio is needed for examining the complete evolution of coherence collapse in the future. The QD MLL packaged module with a simple implementation of an optical feedback arm offers an attractive method for ultra-low noise photonics applications.

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