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PERFORMANCE OF A QUANTUM DOT PASSIVELY MODE-LOCKED LASER UNDER OPTICAL FEEDBACK AND TEMPERATURE CONTROL

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The effect of external optical feedback on a packaged monolithic quantum dot passively mode-locked laser is investigated. The radio-frequency (RF) linewidth narrows from 8 KHz in the free-running situation to a value as low as 170 Hz under relatively low feedback and temperature control. The RF linewidth characterization under resonant feedback at a multiple of the laser cavity length agrees well with the published theory. The narrow RF linewidth with external optical feedback makes the chip-scale quantum dot mode-locked laser an attractive source for ultra low noise applications such as optical clocking and optoelectronic oscillators.

1. Introduction

Compact and high repetition rate optical sources are needed for various applications including optical clock distribution, optical interconnects, and microwave signal generation [1-3]. In all of these applications, pulse durations from 5-20 picoseconds and sub-picosecond integrated root-mean-square (rms) timing jitter are required since the fluctuation of the pulse arrival time degrades the timing resolution of the device. Semiconductor mode-locked lasers (MLLs) are ideal sources to provide stable and ultra-short pulse trains with multi-gigahertz repetition rates. Among different MLL configurations, monolithic two-section passive MLLs offer several advantages: 1) the devices are compact and suitable for hybrid integration with silicon substrates as intra-chip/inter-chip transmitters [1]; 2) they produce much shorter pulsewidths using intracavity saturable absorbers compared to active MLLs; 3) only DC bias is needed without any external electrical oscillator. The timing stability issue, however, is the drawback of passive MLLs due to the lack of an external reference source. Thus, reducing the timing jitter is crucial to improve the noise performance of passive MLLs.

In comparison to their quantum well (QW) counterparts, semiconductor quantum dot (QD) lasers demonstrate a smaller threshold current density and a lower associated spontaneous emission noise [4, 5]. Thus, the RF linewidth is generally narrower in a passive QD MLL, a condition that leads to lower jitter [6]. Under particular conditions, optical feedback also reduces the linewidth and jitter [7-9]. In our recent study [9], optical feedback stabilization of the laser's phase noise using a resonant feedback situation was investigated on a two-section passive QD MLL showing good agreement with the published theory [10].

In this work, the low noise performance is further improved by utilizing temperature control and a packaged QD MLL module that reduces environmental noise and enhances mechanical stability under external optical feedback. A record low RF linewidth of 170 Hz is achieved at an operation temperature of 17^{o}C.

2. 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" (DWELL) layers. In each layer, an equivalent coverage of 2.4 monolayer InAs QDs is confined approximately in the middle of a 10 nm $In_{0.15}Ga_{0.85}As$ quantum well (QW) [11]. The epitaxial structure and waveguide design are displayed in Fig. 1. The 3-μm-wide ridge-waveguide devices were etched by inductively coupled plasma (ICP) etching and planarized using benzocyclobutene (BCB). 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^{o}C for 1 minute to form the n-ohmic contact. The two-section QD passive MLLs were made with a total cavity length of 7.8-mm and a saturable absorber (SA) length of 1.1-mm. The nominal repetition rate of the QD MLL is 5 GHz. A highly reflective coating (R ≈ 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 ≈ 32%).

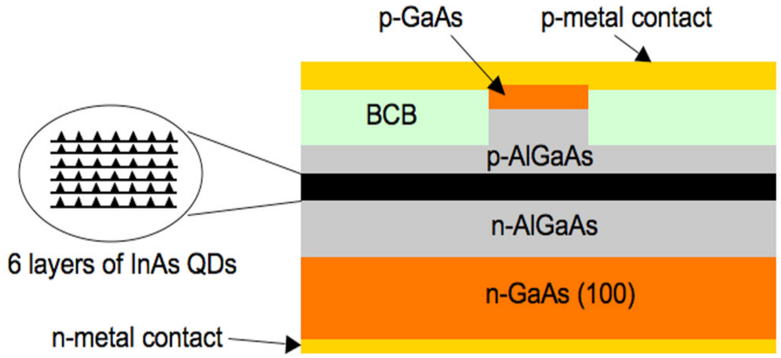

Fig. 1. Schematic of the epitaxial layer structure of the InAs QD laser.

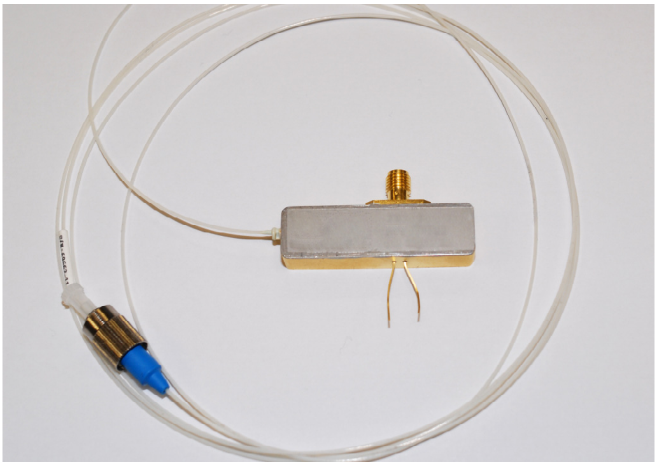

Fig. 2. Picture of the passive QDMLL packaged module. The RF connector shown on the top of the package was not used for this experiment.

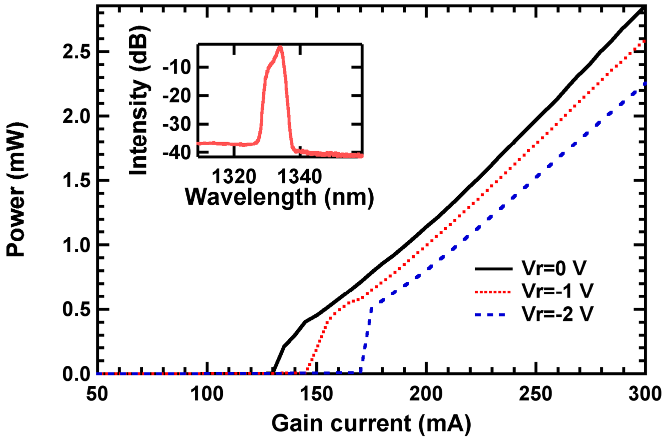

Fig. 3. L-I characteristics measured at 20°C under various absorber biases. Inset: the optical spectrum under 280-mA gain current and -1 V reverse voltage.

The devices were p-side-up mounted on AlN heatsink carriers. These chip-on-carriers were then packaged with a polarization-maintaining lensed fiber pigtail as shown in Fig. 2. The fiber-coupled light-current (L-I) curves under various reverse voltage bias conditions at room temperature are demonstrated in Fig. 3. 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 fiber pigtail are 1-2.5 mW. The pulse durations are on the order of 10 ps. The time-bandwidth product of the MLL typically ranges from 2 to 10.

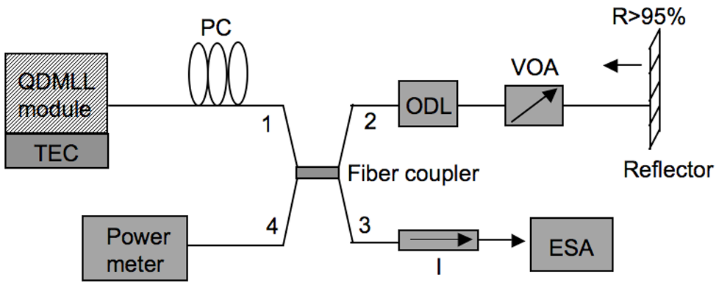

Fig. 4. Schematic drawing of the experimental setup. PC: polarization controller; ODL: optical delay line; VOA: variable otpical attenuator; I: isolator; ESA: electrical spectrum analyzer.

3. Experimental Setup

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 fiber pigtail is injected into port 1 of a 50/50 optical fiber coupler. The optical feedback is created from a high-reflectivity (R> 95%) coating applied to the fiber 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 fiber loop length. In order to maximize the feedback effect, a polarization controller is used to make the feedback beam polarization identical to that of the emitted wave. The effect of the optical feedback is analyzed in port 3 through a 45 GHz bandwidth photodiode coupled to an Agilent 8565EC electrical spectrum analyzer (ESA) that has a 50 GHz frequency range. 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:

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

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

4. Experimental Result and Discussion

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 analyzed over a broad range of optical delays in the feedback loop and a temperature of 20°C. The experimental results demonstrate a similar trend to those observed in QW MLLs under optical external feedback [12]. The periodicity can be viewed approximately as 1.5-mm (delay time: ~200 ps), which corresponds to the mode-locking frequency of ~5 GHz.

Fig. 6 shows the evolution of the RF spectrum over temperature for the integer resonant case of external optical feedback (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 under the same bias conditions at room temperature. By fixing the fiber loop length through the optical delay line to the integer resonant case and tuning the TEC to lower temperature, the 3-dB RF linewidth was improved from 3.5 KHz at 35^{o}C down to 170 Hz at 17^{o}C under feedback. The measurement was limited to 17^{o}C because of the temperature-induced misalignment between the device and lensed fiber inside the sealed package. The small RF linewidth can be explained by the relatively low threshold of a quantum dot 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 was realized at a feedback level as low as -42 dB, is shown in the inset of Fig. 4. Lorentzian curve-fitting of the ESA data using a frequency span of 100 KHz and a resolution bandwidth of 100 Hz was used to calculate the value. The 48-fold linewidth reduction using feedback (8 kHz to 170 Hz) should enable a decrease of the integrated rms timing jitter by a factor of ~ 6.9 [6]. According to ref. [6], the RF linewidth of 170 Hz corresponds to an integrated rms timing jitter of 740 fs over the offset frequency range of 100 KHz to 1 GHz. Wider temperature characterization will be investigated in the future by enhancing the coupling efficiency between the laser device and the lensed fiber pigtail when changing temperature.

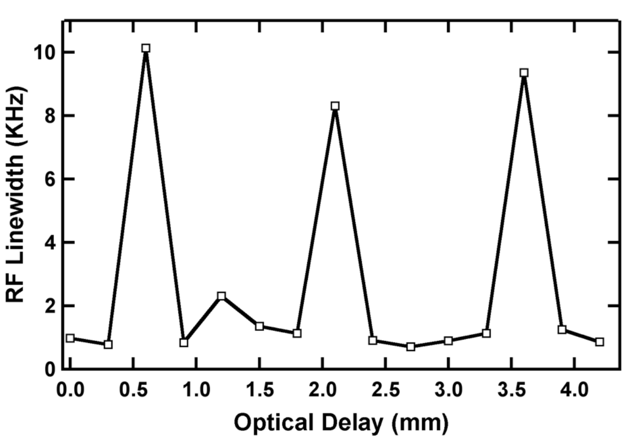

Fig. 5. RF linewidth variation under feedback ratio of -44 dB as a function of optical delay line change at 20^{o}C, showing a periodicity of roughly 1.5 mm corresponding to the laser round trip time of 200 ps. Bias condition of QD MLL: 280 mA gain current and -1 V reverse voltage.

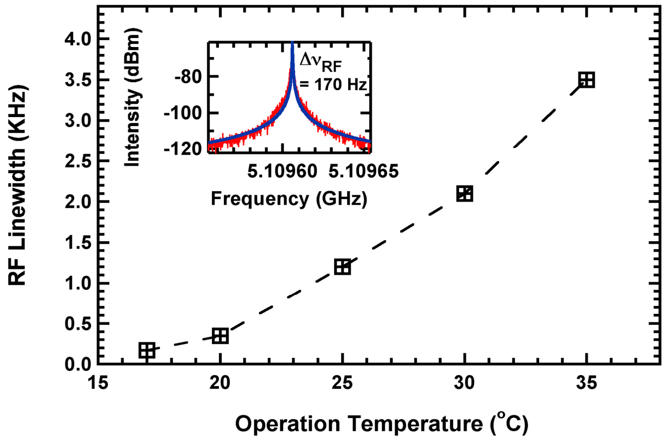

Fig. 6. Evolution of RF linewidth versus operation temperature under optimized external optical feedback. Inset: RF linewidth of 170 Hz at 17°C under a feedback ratio as low as -42 dB.

5. Conclusion

The temperature dependence and stabilizing effect of external optical feedback on a packaged passive QDMLL module has been investigated and the experimental results agree well with previously published theory. To the best of our knowledge, the RF linewidth was reduced to a record low value of 170 Hz due to the environment-isolated package design and steady temperature control. The low threshold and low spontaneous emission noise of a quantum dot active region are also contributing factors to the reported performance.

Acknowledgments

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