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rf linewidth reduction in a quantum dot passively mode-locked laser subject to external optical feedback

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The effect of external optical feedback on an InAs/GaAs quantum dot passively mode-locked laser is investigated. The rf linewidth narrows from 8 KHz in the free-running situation to a value as low as 350 Hz under relatively low feedback. The rf linewidth characterization under resonant feedback at a multiple of the laser cavity length validates the prediction of a previous numerical simulation. It is also confirmed that the integrated rms timing jitter varies as the square root of the rf linewidth. The results are promising for the development of compact, monolithic semiconductor mode-locked lasers as low noise optoelectronic oscillators. © *2010 American Institute of Physics*. [doi:10.1063/1.3299714]

Monolithic mode-locked lasers (MLLs) are promising candidates for interchip/intrachip clock distribution as well as high bit-rate optical time division multiplexing, arbitrary waveform generation and microwave signal generation due to their compact size, low power consumption, and direct electrical pumping.[1,2] Several unique characteristics of quantum dot (QD) materials, such as ultrabroad bandwidth, ultrafast gain dynamics, and easily saturated gain and absorption, make them an ideal choice for semiconductor monolithic MLLs.[3–5] The rf linewidth, which directly influences the phase noise spectral density, is directly related to the integrated rms timing jitter in a semiconductor passive MLL.[6] Thanks to the lower threshold current density and the lower associated spontaneous emission noise in QD laser devices compared to their quantum well (QW) counterparts, the rf linewidth is generally narrower in a passive QD MLL. In a large number of these applications, performance of the laser in an external optical cavity is an important feature, as the laser is likely to be monolithically integrated on chip with other devices, in which case optical isolation is difficult. In various practical situations, MLLs may be subjected to optical feedback generated by discrete reflections. These perturbations may be induced by discontinuities in the optical waveguide of the monolithic chip or at the device-package interfaces from other optical devices placed along an optical fiber. A number of experimental studies have been performed so as to evaluate the sensitivity of QW based MLLs under optical feedback.[7,8] In our previous letter,[9] the feedback resistance in a passive QD MLL was first analyzed in an arbitrary feedback loop (non-resonant case). Beyond a certain feedback level, the effect of external feedback was found to be detrimental for mode-locking operation enhancing noise in the rf electrical signal. According to the numerical investigation from Avrutin and Russell,[10] however, the timing stability of a two-section passive QD MLL can be improved by introducing a controlled external feedback loop (resonant case) to reduce the phase noise.

In this letter, we experimentally investigate the effect of external optical feedback on a monolithic two-section passive QD MLL operating at a 5.1 GHz repetition rate. When the external cavity length is tuned to the resonant case,[10] at relatively moderate feedback strength, −36 dB, the rf linewidth is reduced from 8 KHz in the free-running condition to a very low value of 350 Hz.[11] The effects of optical feedback vary periodically as the length of feedback loop is changed, with a period equal to the mode-locking frequency of the laser device.

The laser epitaxial structure of the MLL device is a multi-stack "Dots-in-a-WELL" structure that is composed of an optimized six-stack InAs QD active region grown by elemental source molecular beam epitaxy on a n^+-doped, $\langle 100 \rangle$-oriented GaAs substrate.[12] The 3 μm wide optical ridge-waveguide devices are fabricated following standard dry-etch, planarization, and metallization processing. The two-section QD passive MLLs are made with a total cavity length of 7.8 mm and a saturable absorber (SA) length of 1.1 mm. A highly reflective coating ($R \approx 95\%$) is applied to the mirror facet next to the SA and the output facet is cleaved ($R \approx 32\%$).

The QD MLL device was investigated under external optical feedback using the experimental setup shown in Fig. 1. The output optical pulses from the device were coupled to a lensed fiber and then connected to the polarization controller. This unit was used to make the feedback beam's polarization identical to that of the emitted light in order to maximize the feedback effects. The external feedback loop was based on a 50/50 four-port optical fiber coupler. A high-

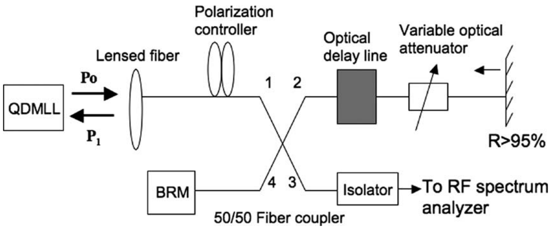

FIG. 1. Schematic drawing of the experimental setup.

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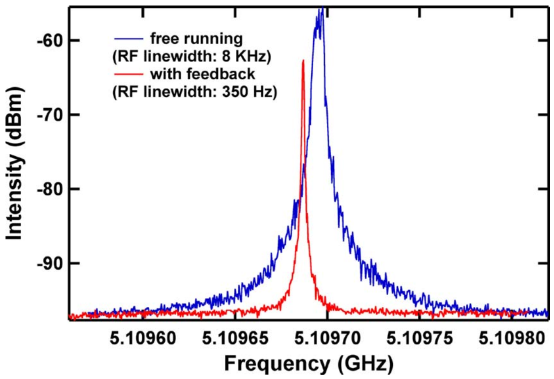

FIG. 2. (Color online) Comparison of rf spectra with and without feedback.

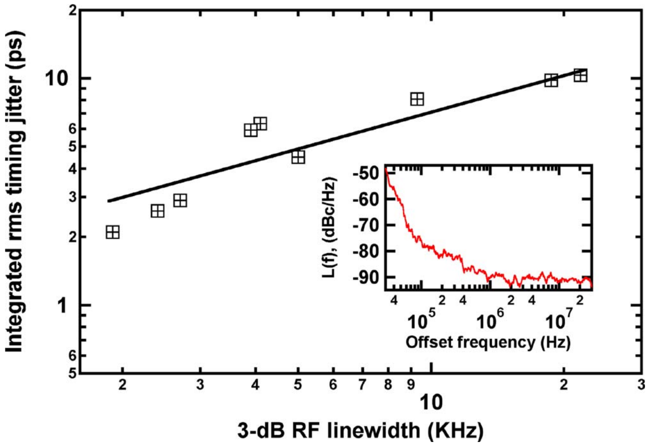

FIG. 4. (Color online) A log-log plot of the integrated rms timing jitter as a function of the rf linewidth under a bias condition of −0.5 V reverse voltage and various gain currents in the free-running case. The slope of the solid line follows a square-root dependence. Inset: SSB-PN spectral density $L(f)$ of the fourth harmonic under 300 mA gain current and −0.5 V reverse voltage.

reflectivity dielectric-coated fiber ($R > 95\%$) located at port 2 was utilized to create the optical feedback. The optical delay line that has a step-controlled fine delay stage was introduced to change the external fiber loop length. The feedback strength was controlled via a variable attenuator and its value was determined by measuring the optical power at port 4, the back reflection monitoring (BRM) port. The effect of the optical feedback was analyzed at port 3 via a 45 GHz bandwidth photodiode coupled to an electrical spectrum analyzer (ESA). An optical isolator was used to prevent any unwanted reflection from the ESA. 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 optical coupling loss of the device to the fiber was estimated to be about −5 dB and kept constant during the whole experiment.

All measurements were operated at a controlled substrate temperature of 20 °C. The laser emits at 1330 nm and the threshold current is approximately 150 mA. Figure 2 shows the rf spectrum results with and without (free-running) external feedback under 280 mA dc bias on the gain section and −1 V applied to the absorber. By optimizing the fiber loop length through the optical delay line to the integer resonant case, the 3 dB rf linewidth was improved from 8 KHz to 350 Hz. This situation is obtained when the optical length of the external cavity L_{ext} is a multiple of that of the solitary laser L such as $L_{\text{ext}}/L \approx n = 1, 2, 3, \ldots$ Under the resonant condition, stabilization of the laser can be obtained.[10] The minimum rf linewidth under external feedback shown in the inset of Fig. 3 was confirmed with a Lorentzian curve-fitting of the ESA data using a frequency span of 250 KHz and a resolution bandwidth of 300 Hz. This measured linewidth reduction should lower the single-sideband phase noise (SSB-PN) spectral density proportionally and enable a decrease in the integrated root-mean-square (rms) timing jitter by a factor of ~4.8.[6] According to the analytical expression from Kefelian *et al.*,[6] the integrated rms timing jitter is proportional to the square root of the rf linewidth. Figure 4 experimentally validates this jitter-linewidth relation in the free-running case under the conditions of a fixed absorber voltage of −0.5 V and the integration of the SSB-PN spectral density, $L(f)$, at the fourth harmonic over the offset frequency range of 30 KHz to 30 MHz.[13]

The variation in the rf linewidth as a function of the optical feedback ratio for the integer resonant case at a gain current of 280 mA and a reverse voltage of −1 V is shown in Fig. 3. The rf linewidth was reduced to less than 800 Hz at a low feedback ratio (~−57 dB) and maintained at or below this level with increasing feedback ratio. It did not display the broadening effect compared to the free-running condition at low feedback ratio that was reported in Ref. 14. The minimum rf linewidth, 350 Hz, was observed at a relatively moderate feedback strength of about −36 dB. In contrast, Merghem *et al.*[11] reported that a significantly stronger feedback level (−22 dB) was needed to reduce the rf linewidth to its lowest value in a pulsed QDash laser at 1550 nm. This difference of roughly 14 dB is attributed to the lower threshold current density generally encountered in 1310 nm QD lasers on a GaAs substrate compared to QDash materials technology, which leads to a smaller free-running rf linewidth in the device.

We have also explored the variation in center frequency and rf linewidth as the feedback loop is changed through the optical delay line (Fig. 5). The experimental results demonstrate a similar trend to those observed in QW MLLs under optical external feedback[7] and confirm the numerical simulation result from Avrutin and Russell[10] in a two-section monolithic MLL under the integer 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. It is noted that when approaching the exact resonant condition ($L_{\text{ext}} = nL$), the noise is enhanced and the laser can become unstable with stronger optical feedback. For instance, an increase in the rf linewidth, which is a

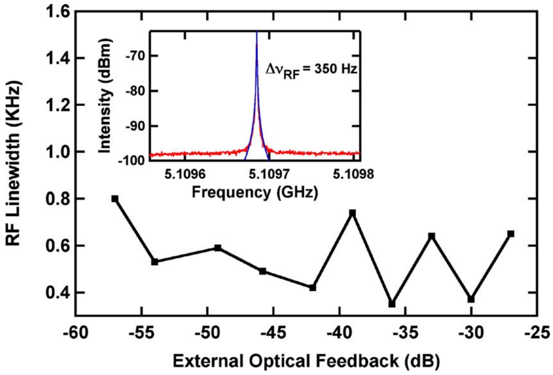

FIG. 3. (Color online) rf linewidth as a function of external feedback ratio at a bias of 280 mA gain current and −1 V on the absorber. Inset: rf linewidth of 350 Hz under a feedback ratio of −36 dB.

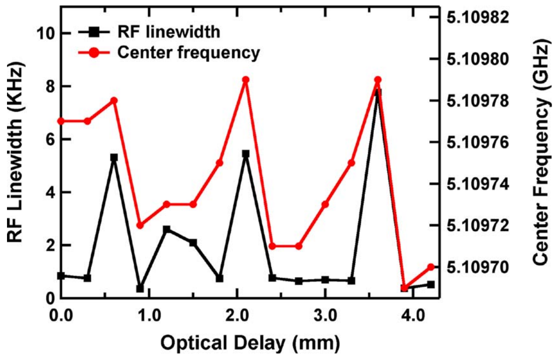

FIG. 5. (Color online) Center frequency shift and rf linewidth variation under feedback ratio of −30 dB as a function of optical delay line change, showing a periodicity of roughly 1.5 mm corresponding to the laser round trip time of 200 ps. Bias condition of MLL: 280 mA gain current and −1 V reverse voltage.

sign of the noise in the laser cavity, is observed in Fig. 5. This experimental result corroborates the numerical simulation result for an integer resonant case in which it was shown that the laser under near-exactly resonant feedback could follow very specific nonlinear dynamics.[10]

In summary, we have investigated experimentally the stabilizing effect of external optical feedback on a two-section passive InAs/GaAs QD MLL and demonstrated that the experimental results agree well with previously published theory. The rf linewidth was reduced to a very small value of 350 Hz considering any semiconductor two-section passive MLL reported up-to-date. The narrow linewidth with external optical feedback offers an attractive method for high-speed and low-jitter chip-to-chip optical interconnects.

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