Microwave Characterization and Stabilization of Timing Jitter in a Quantum-Dot Passively Mode-Locked Laser via External Optical Feedback

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***Abstract*—The pulse-to-pulse rms timing jitter of a 5.25-GHz quantum-dot (QD) two-section passively mode-locked laser is characterized through an all-microwave technique. The experimental phase noise spectra at different harmonics are in good agreement with previous diffusion-based theory. This theory is validated for a QD mode-locked laser device for the first time. This measurement technique provides a simple way to characterize the noise performance of a passively mode-locked laser. Furthermore, the average pulse-to-pulse rms timing jitter reduces from 295 to 32 fs/cycle via external optical feedback.**

***Index Terms*—Mode-locked lasers, optical feedback, semiconductor quantum-dot (QD) lasers, timing jitter.**

I. Introduction

THE NEED for cost-effective, power-efficient, and low phase noise optical pulse sources has motivated recent research into semiconductor passively mode-locked laser (MLL) solutions for optical time division multiplexing (OTDM) applications applied to intrachip and on-chip communications [1]–[3]. In these signal processing applications, optical pulses with short picosecond pulse durations and multigigahertz repetition rates are needed. Furthermore, a low pulse-to-pulse timing jitter is also required to prevent errors arising from the ambiguity between successive neighboring pulses. In order to meet these requirements, MLLs are promising candidates for generating stable short optical pulses that have a corresponding broad spectral bandwidth consisting of phase-correlated modes. Of all the 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. In addition, various unique characteristics of quantum-dot (QD) materials, such as high gain saturation energy, reduced threshold current density, and low spontaneous emission noise, make them an ideal choice for semiconductor monolithic MLLs, especially for improved noise performance [4]. However, in contrast to active mode locking, the timing stability issue is still a drawback of passive MLLs due to the lack of an external reference source.

The timing-jitter performance of a passive MLL can be further improved through the optical injection-locking technique or external optical feedback [5]–[12]. In this study, we focus on the optical feedback method since it provides a compact and cost-effective fiber-based feedback arm compared to the optical injection-locking technique that requires an additional continuous wave (CW) tunable laser source. In various potential applications, such as OTDM, performance of the MLL in an external optical cavity is an important feature, as the laser diode is likely to be monolithically integrated on chip with other devices, in which case optical isolation is difficult. Thus, 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. The sensitivity of quantum-well (QW) MLLs under optical feedback has been evaluated experimentally by several groups [5], [6]. On the one hand, resonant reduction of noise for external cavity lengths that are a multiple of the laser's optical length was observed [5]. On the other hand, by using monolithic colliding-pulse passive QW MLLs, Passerini *et al*. have shown that optical feedback negatively affects the phase-locking relation between the longitudinal modes [6]. Recently, the sensitivity and noise performance of QD MLLs under optical feedback have also attracted numerous theoretical and experimental studies [8]–[13]. The reduced RF linewidth and timing jitters have been obtained under the resonant feedback case. Meanwhile, a numerical investigation also demonstrated the influence of optical feedback on the dynamics and spectra of monolithic MLLs [13]. A wide variety of dynamic regimes were numerically simulated taking into account the length of the external cavity in the MLL dynamics.

After introducing the methods to improve the noise performance, it is crucial that the jitter characterization in a passive MLL be studied more thoroughly. Since the timing-jitter fluctuations in a passive MLL constitute a nonstationary process, the phase noise does not scale with harmonic number [14]. Thus, the commonly used model for calculating the integrated

Manuscript received December 6, 2010; revised January 23, 2011 and February 13, 2011; accepted February 14, 2011. Date of publication April 5, 2011; date of current version October 5, 2011. This work was supported in part by the Air Force Office of Scientific Research under Grants FA9550-10-1-0276 and FA9550-09-1-0490.

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Digital Object Identifier 10.1109/JSTQE.2011.2118745

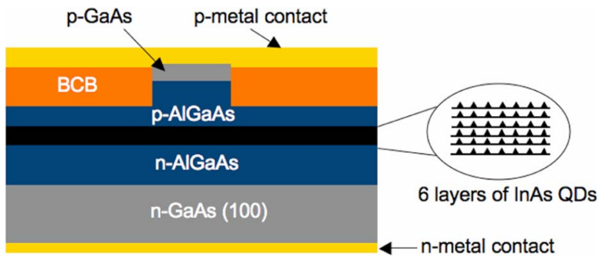

Fig. 1. Schematic of the epitaxial layer structure of the InAs QD laser.

rms jitter proposed by von der Linde [15], which assumes a stationary process only, is not suitable for a passive MLL unless the offset frequency is above the corner frequency. For the pulse-to-pulse timing-jitter calculation, we present an alternative all-microwave technique based on previously published theory [14] and compare this different RF measurement approach to the work reported by Kefelian *et al*. [16].

This paper is organized as follows. Device structure and fabrication process are introduced in Section II. The basic optical characterization in the free-running case is also presented. Section III is devoted to the introduction of noise performance characterization in a passive MLL, including the integrated rms timing jitter and the pulse-to-pulse rms timing jitter $\sigma_{\rm pp}$. Following that, we experimentally characterize $\sigma_{\rm pp}$ using the analytical model by Eliyahu *et al.* [14] and make comparisons with prior research. Timing-jitter reduction is achieved by using a controlled external feedback arm to stabilize the QD MLL. The jitter value reduces from 295 to 32 fs/cycle under external optical feedback. Finally, the key findings of this paper are summarized in Section V.

II. Device Structure and Fabrication

The laser epitaxial structure of the MLL device is a multistack "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 an n+-doped, $\langle 1\,0\,0\rangle$-oriented GaAs substrate [17]. The epitaxial structure and waveguide design are described in Fig. 1. The 3-μm-wide ridge-waveguide devices were formed by inductively coupled plasma etching and planarized using benzocyclobutene. Ti/Pt/Au was then deposited to form the p-type metal contact. The electrical isolation between the gain and absorber sections was achieved by ion 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 ohmic contact. The two-section passive QD MLLs were cleaved with a total cavity length of 7.8 mm and a saturable absorber (SA) length of 1.1 mm, corresponding to a pulse repetition rate of 5.25 GHz. A highly reflective coating ($R \approx 95\%$) 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 as-cleaved ($R \approx 32\%$). The devices were p-side-up mounted on AlN heatsink carriers. These chip-on-carriers were then packaged into an industry-standard 14-pin butterfly package with

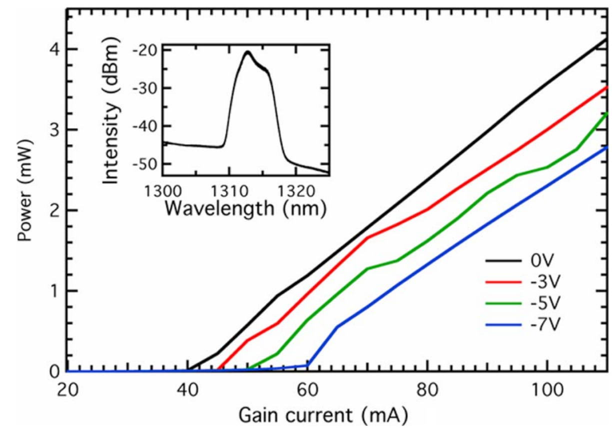

Fig. 2. Light current characteristics measured at 20 °C under various absorber bias voltages. The figure in the inset shows the optical spectrum under 280-mA gain current and −1 V reverse voltage.

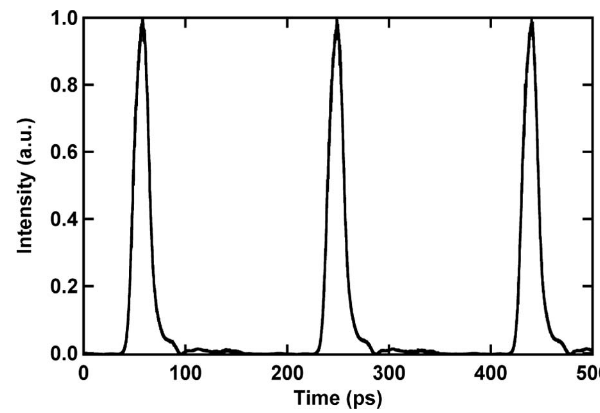

Fig. 3. Pulse width of 10.9 ps under 75-mA gain current and −7-V reverse voltage through high-speed sampling oscilloscope measurement.

a thermoelectric cooler (TEC) and a polarization-maintaining lensed fiber pigtail. The function of the packaged module is to reduce environmental noise and enhance mechanical stability.

Fig. 2 shows the fiber-coupled light–current (*L–I*) curve under various reverse voltage bias conditions at 20 °C. The inset is the optical spectrum showing the peak lasing wavelength at 1313 nm under a gain current of 100 mA and an SA reverse voltage of −7 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 shown in Fig. 3 are typically about 10 ps and were measured by a Tektronix DSA 8200 oscilloscope with a 140-GHz optical sampling head. The resolution of the oscilloscope is limited by the bandwidth of the optical sampling head. In our experimental setup, the minimum measurable pulse duration is around 8 ps. Fig. 4(a) demonstrates the full-span RF spectrum with nine detected harmonics under a 90-mA dc bias on the gain section and −7 V applied to the absorber. The optimum 3-dB RF linewidth of the free-running laser at the fundamental harmonic shown in Fig. 4(b) is 46.2 kHz under the same bias condition. The RF linewidth is confirmed with a Lorentzian curve fit on the RF spectrum analyzer (RFSA) output with a resolution bandwidth of 1 kHz.

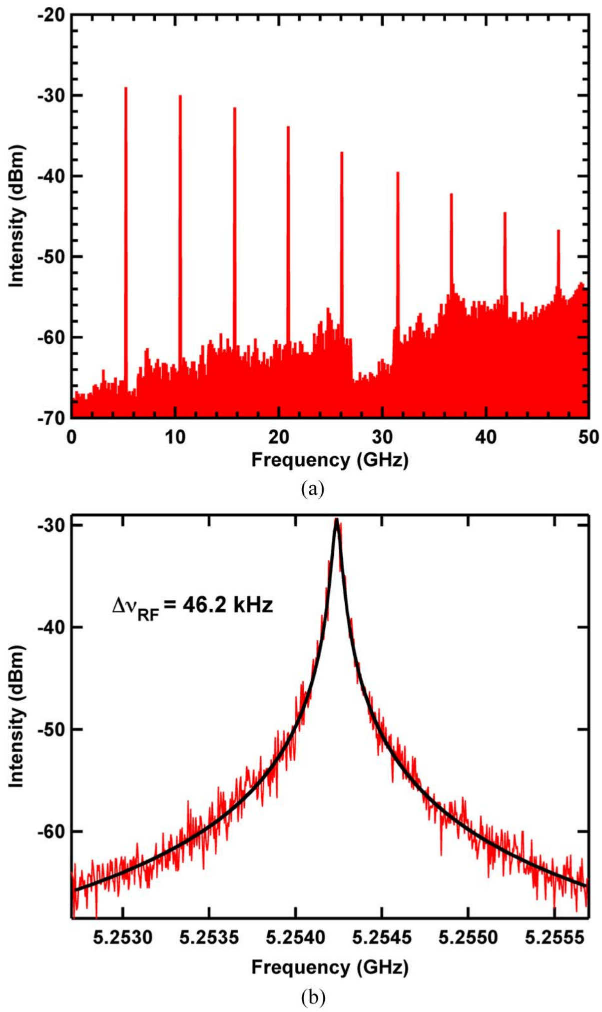

Fig. 4. RF spectrum under 100-mA gain current and −7-V reverse voltage. (a) Full-span condition. (b) 3-dB RF linewidth of 46.2 kHz.

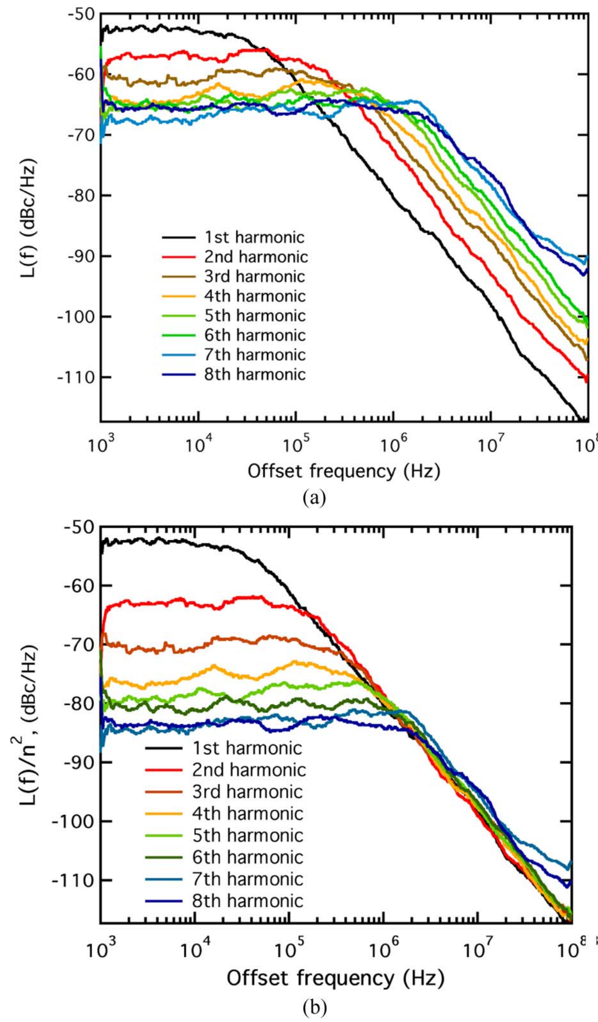

Fig. 5. (a) SSB-PN spectral density for different harmonics under 100-mA gain current and −7 V reverse voltage in the free-running case. (b) SSB-PN spectra density normalized to $1/n^2$.

III. Noise Performance Characterization

A. Integrated RMS Timing-Jitter Characterization

Conventionally, the noise characterization of an MLL by von der Linde's method uses timing jitter as the figure-of-merit [15]. In particular, the rms timing jitter is calculated by integrating the single-sideband phase noise (SSB-PN) spectral density *L*(*f*) from an RFSA using the following expression:

$$\sigma = \frac{1}{2\pi n f_R}\sqrt{2\int_{f_{\min}}^{f_{\max}} L(f)df} \tag{1}$$

where n is the number of the harmonic at which the phase noise is measured, f_R is the repetition frequency, and $f_{\min}$ and $f_{\max}$ determine the offset frequency range over which the *L*(*f*) is integrated. Fig. 5(a) displays the SSB-PN spectral density for different harmonics of the 5.25-GHz passive QD MLL device in the free-running case. The relatively low repetition rate of this monolithic passive MLL makes the characterization of a relatively large number of harmonics possible in a standard 50-GHz RFSA.

However, although this technique is suitable for noise characterization in an active MLL that naturally has an external reference source, it should be applied carefully to a passive MLL. Since the timing-jitter fluctuation in a passively MLL is a *nonstationary* process, the phase noise does not scale with harmonic number until beyond the corner frequency as clearly seen in Fig. 5(b) [14]. Consequently, it is only appropriate to use the von der Linde's method for offset frequencies above the corner frequency where the phase noise trace shows the typical roll-off with a slope of −20 dBc/Hz per decade. From the phase noise data in Fig. 5(b), we see that a meaningful lower bound to the integration range would be about 1–2 MHz for this particular device.

B. Pulse-to-Pulse RMS Timing-Jitter Characterization

Past research has quoted the integrated rms timing jitter over a variety of different frequency ranges, which can be confusing for comparing devices. Because of the intrinsic phase noise properties of a passive MLL [14], [18], it is more straightforward to investigate the noise performance based on the pulse-to-pulse

TABLE I
TIMING-JITTER CHARACTERIZATION IN THE FREE-RUNNING CASE

Harmonic #	D (sec)	σ_{pp} (fs/cycle)
1	4.01 10^{-16}	276
2	4.01 10^{-16}	276
3	4.50 10^{-16}	292
4	4.98 10^{-16}	307
5	5.14 10^{-16}	312
6	4.87 10^{-16}	304
7	4.56 10^{-16}	294
8	4.67 10^{-16}	298

timing fluctuations since the integration range does not have to be specified. The relevant theory for determining the pulse-to-pulse jitter is described next.

Due to the absence of a restoring external force, the timing of each pulse in a passive MLL depends on that of the previous one, and its fluctuation results from the sum of many assumed independent processes. Thus, the timing-jitter noise can be described by diffusion theory for Gaussian processes whenever fluctuations of timing jitter between successive neighboring pulses are uncorrelated. An analytical model has been derived by Eliyahu *et al*. [14], and the power spectrum in a passive MLL is expressed as the following equation:

$$P_I(\omega) = |F(\omega)|^2 \frac{\sinh(\omega^2 DT/2)}{\cosh(\omega^2 DT/2) - \cos(\omega T)} \tag{2}$$

where $F(\omega)$ is the amplitude term of the pulse, ω is the frequency, T is the pulse repetition period, and D is the diffusion constant that can be described as

$$D = \frac{\left\langle (\delta T_n - \delta T_{n\pm 1})^2 \right\rangle}{T}. \tag{3}$$

Equation (3) represents the timing-jitter fluctuations between successive neighboring pulses and can be rearranged to find the pulse-to-pulse rms timing jitter $\sigma_{\rm pp}$:

$$\sigma_{\rm pp} = \sqrt{DT}. \tag{4}$$

The aforementioned analytical model provides an appropriate method to characterize the noise performance in a passive MLL that obeys a nonstationary process. Thanks to the relatively low repetition rate of our QD MLL device, there are more harmonics available experimentally to examine this analytical model and to extract the average D and $\sigma_{\rm pp}$ values through curve fitting [19]. Table I lists the fitting results that were extracted from the experimental data shown in Fig. 5(a). The experimental results are in good agreement with the analytical model. In the free-running case, an average D of 4.59×10^{-16} s and an average $\sigma_{\rm pp}$ of 295 fs/cycle were obtained with the pulse period T equal to 190 ps.

Following the same assumption of the noise properties in a semiconductor passive MLL [18], another analytical derivation presented by Kefelian *et al.* [16] explores the RF linewidth of the first harmonic of the photocurrent to characterize the timing stability of a passive MLL. In this approach, the pulse-to-pulse rms timing jitter can be described as follows:

$$\sigma_{{\rm pp}\_K} = T\sqrt{\frac{\Delta\nu_{\rm RF} NT}{2\pi}} \tag{5}$$

where $\Delta\nu_{\rm RF}$ is the 3-dB RF linewidth and N is the number of periods between the two compared pulses. According to (5), using the optimum 3-dB RF linewidth of the free-running QD MLL at the fundamental harmonic, 46.2 kHz, corresponds to a pulse-to-pulse rms timing jitter of 225 fs/cycle. This model provides a way to characterize the noise performance in a passive MLL, especially for those devices with a high repetition rate, where it is difficult to measure the SSB-PN spectral density at higher order harmonics. From our experimental pulse-to-pulse timing-jitter calculations, the analytical models of Eliyahu and Kefelian agree with each other reasonably well. Both methods are based on the assumption that the passive MLL operates under nonstationary processes. In Kefelian's method, the RF linewidth is a figure-of-merit to characterize the pulse-to-pulse timing-jitter performance while Eliyahu's model can obtain a measured pulse-to-pulse rms timing-jitter value from the SSB-PN spectral density.

IV. Optical Feedback Stabilization

For further noise performance improvement, external optical feedback can be implemented to lower the phase noise in a passive MLL. This method provides a simple, compact, and cost-effective fiber-based loop compared to the injection-locking technique, which needs an external CW tunable laser. Under the resonant case (i.e., stably-resonant feedback condition) [13], which is obtained when the optical length of the external cavity is about a multiple of that of the solitary laser, an RF linewidth and timing-jitter reduction can be expected while the nonresonant case (i.e., nearly exact resonant case) usually leads to a degradation of the mode-locking conditions. Consequently, in the following only the resonant case is considered for the jitter optimization.

A. *External Optical Feedback Experimental Setup*

The passive QD MLL butterfly package with TEC was investigated under external optical feedback using the experimental setup shown in Fig. 6(a). All measurements were operated with the TEC at 20 °C. The emitted light 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 tip at the end of port 2. The feedback power level is controlled via a variable optical attenuator (VOA), and its value is measured by the power meter in port 4. An optical delay line (ODL) 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 (PC) 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 the RFSA. An optical isolator is used to prevent any unwanted reflection from the RFSA. Fig. 6(b) shows a photograph of the

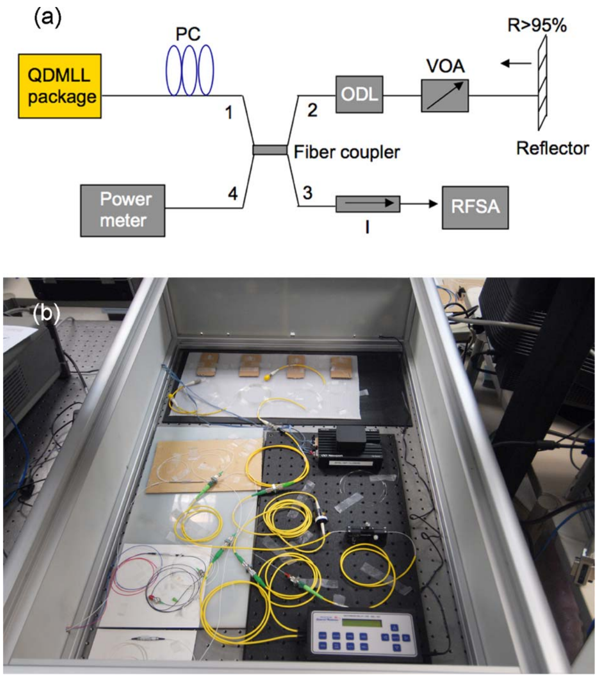

Fig. 6. (a) Schematic drawing of the feedback experimental setup. PC: polarization controller; ODL: optical delay line; VOA: variable optical attenuator; I: isolator; RFSA: RF spectrum analyzer. (b) Photograph of feedback experiment setup within a vibration- and RF-isolated enclosure.

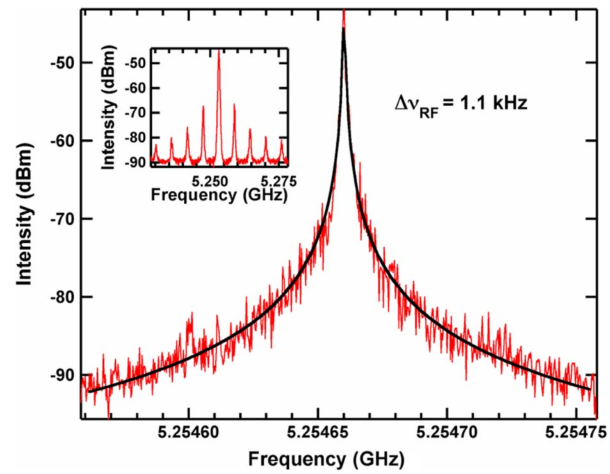

Fig. 7. RF linewidth of 1.1 kHz under optimum feedback condition ($\Gamma = -33$ dB). Inset: RF spectrum with mode-comb separated by 5.7 MHz.

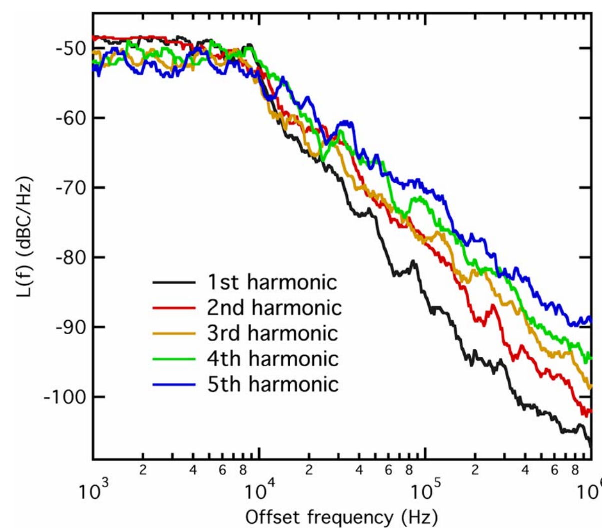

Fig. 8. SSB-PN spectra density from different harmonics under 100-mA gain current and −7-V reverse voltage at the optimum feedback case.

experimental setup including an external enclosure that helps to reduce the environmental noise during the measurement.

The value of the feedback strength 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 value. The amount of the reflected light that effectively returns into the laser can then be expressed as follows:

$$\Gamma(\text{dB}) = P_r(\text{dB} \cdot \text{m}) - P_0 + C_{\text{dB}} \tag{6}$$

where P_r is the optical power measured from the power meter at port 4, C_{dB} is the optical coupling loss of the device to the fiber which was estimated to be about −5 dB and kept constant during the whole measurement. In this study, 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 gigahertz) and τ is the external round trip time of several hundred nanoseconds. The total fiber length of the feedback arm is approximately 18 m.

B. Experimental Results and Discussion

Under the optimum feedback condition ($\Gamma = -33$ dB), the RF linewidth was reduced from 46 to 1.1 kHz as shown in Fig. 7, while simultaneously introducing a comb of adjacent modes separated by 5.7 MHz as shown in the inset. Most importantly, as seen from (6), the reduction of RF linewidth decreases the pulse-to-pulse rms timing jitter. Thus, the 42-fold RF linewidth reduction under optical feedback should decrease σ_{pp} by a factor of ∼6.5. Using (6), the RF linewidth under the optimum feedback case, 1.1 kHz, corresponds to a pulse-to-pulse timing jitter of 35 fs/cyle. This result can be compared to the Eliyahu model calculations using the same approach as for the free-running analysis.

After the RF linewidth characterization, the SSB-PN spectral density at different harmonics was measured under external feedback effect as shown in Fig. 8. Due to the limited dynamic range of the phase noise measurement under feedback, the SSB-PN spectrum at the fifth harmonic is the maximum number that can be evaluated in this measurement. Compared to Fig. 5(a), optical feedback impacts the SSB-PN spectra by decreasing the corner frequency from 2 MHz to about 10 kHz while enhancing plateau levels. The explanation of the influence of optical feedback both on the plateau and on the corner frequency is still under investigation and will be discussed in another paper. With the same approach mentioned in Section III-B, we can extract the values of the diffusion constant D and the pulse-to-pulse timing jitter σ_{pp} at different harmonics under optical feedback. Table II shows the fitting results that were extracted from the experimental data shown in Fig. 8. In the external optical

TABLE II
TIMING-JITTER CHARACTERIZATION IN THE OPTICAL FEEDBACK CASE

Harmonic #	D (sec)	σ_{pp} (fs/cycle)
1	4.97 10^{-18}	30.8
2	6.83 10^{-18}	36.1
3	6.52 10^{-18}	35.2
4	4.35 10^{-18}	28.8
5	4.97 10^{-18}	30.8

feedback case, an average D of 5.53×10^{-18} s and an average $\sigma_{\rm pp}$ of 32 fs/cycle are obtained. Again, this jitter value agrees well with the one derived from (6).

Conventionally, the rms pulse-to-pulse timing jitter can be measured directly by optical cross correlation using the second harmonic generation in a nonlinear crystal. However, this measurement needs a particular nonlinear crystal, precise mountings, stable optical alignment, accurate temperature control, and long mechanical scanning. Furthermore, when the timing fluctuation is much smaller than the autocorrelation width, the measurement error becomes very large [20]–[23]. Compared to the optical cross-correlation method, the all-microwave technique based on Eliyahu's theory provides a simpler way to characterize the average pulse-to-pulse timing jitter, thanks to the family of phase noise spectra at different harmonics.

V. CONCLUSION

The timing-jitter performance of a 5.25-GHz passive QD MLL was investigated at different harmonics in the RF spectrum. The relatively low repetition rate of the laser device enables SSB-PN spectra to be measured up to the 8th harmonic in the free-running configuration, and up to the 5th harmonic under feedback. An all-microwave technique has been used to determine the pulse-to-pulse rms timing jitter. Compared to the conventional optical cross-correlation technique, it provides an alternative and simple method to characterize the timing stability in a passive MLL. To the best of our knowledge, the previously published, diffusion-based model by Eliyahu *et al.* has been validated in the passive QD MLL device for the first time. The experimental findings also demonstrated good agreement for both analytical approaches from Eliyahu *et al.* [14] and Kefelian *et al.* [16]. As measured by the Eliyahu model, the pulse-to-pulse timing jitter was reduced by nearly an order of magnitude through the external optical feedback effect. Thus, the QD MLL packaged module with a simple implementation of an optical feedback arm offers an attractive method for OTDM intrachip/on-chip communications.

ACKNOWLEDGMENT

The authors would like to thank J. Gabaldon for designing the vibration- and RF-isolated enclosure in the feedback experiment.

REFERENCES

[1] A. A. Aboketaf, A. W. Elshaari, and S. F. Preble, "Optical time division multiplexer on silicon chip," *Opt. Exp.*, vol. 18, pp. 13529–13535, Jun. 2010.

[2] B. R. Koch, A. W. Fang, O. Cohen, and J. E. Bowers, "Mode-locked silicon evanescent lasers," *Opt. Exp.*, vol. 15, pp. 11225–11233, Aug. 2007.

[3] F. Quinlan, S. Ozharar, S. Gee, and P. J. Delfyett, "Harmonically mode-locked semiconductor-based lasers as high repetition rate ultralow noise pulse train and optical frequency comb sources," *J. Opt. A: Pure Appl. Opt.*, vol. 11, no. 10, pp. 103001-1–103001-23, Apr. 2009.

[4] M. G. Thompson, A. R. Rae, M. Xia, R. V. Penty, and I. H. White, "InGaAs quantum-dot mode-locked laser diodes," *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 3, pp. 661–672, May 2009.

[5] O. Solgaard and K. Y. Lau, "Optical feedback stabilization of the intensity oscillations in ultrahigh-frequency passively modelocked monolithic quantum-well lasers," *IEEE Photon. Technol. Lett.*, vol. 5, no. 11, pp. 1264–1267, Nov. 1993.

[6] M. Passerini, G. Giuliani, and M. Sorel, "Effect of optical feedback on 60-GHz colliding-pulse semiconductor mode-locked lasers," *IEEE Photon. Technol. Lett.*, vol. 17, no. 5, pp. 965–967, May 2005.

[7] T. Habruseva, S. O'Donoghue, N. Rebrova, D. A. Reid, L. P. Barry, D. Rachinskii, G. Huyet, and S. P. Hegarty, "Quantum-dot mode-locked lasers with dual-mode optical injection," *IEEE Photon. Technol. Lett.*, vol. 22, no. 6, pp. 359–361, Mar. 2010.

[8] F. Grillot, C.-Y. Lin, N. A. Naderi, M. Pochet, and L. F. Lester, "Optical feedback instabilities in a monolithic InAs/GaAs quantum dot passively mode-locked laser," *Appl. Phys. Lett.*, vol. 94, p. 153503, Apr. 2009.

[9] C.-Y. Lin, F. Grillot, N. A. Naderi, Y. Li, and L. F. Lester, "Rf linewidth reduction in a quantum dot passively mode-locked laser subject to external optical feedback," *Appl. Phys. Lett.*, vol. 96, p. 051118, Feb. 2010.

[10] S. Breuer, W. Elsaer, J. G. McInerney, K. Yvind, J. Pozo, E. A. J. M. Bente, M. Yousefi, A. Villafranca, N. Vogiatzis, and J. Rorison, "Investigations of repetition rate stability of a mode-locked quantum dot semiconductor laser in an auxiliary optical fiber cavity," *IEEE J. Quantum Electron.*, vol. 46, no. 2, pp. 150–157, Feb. 2010.

[11] K. Merghem, R. Rosales, S. Azouigui, A. Akrout, A. Martinez, F. Lelarge, G.-H. Duan, G. Aubin, and A. Ramdane, "Low noise performance of passively mode locked quantum-dash-based lasers under external optical feedback," *Appl. Phys. Lett.*, vol. 95, p. 131111, Sep. 2009.

[12] C. Mesaritakis, C. Simos, H. Simos, S. Mikroulis, I. Krestnikov, E. Roditi, and D. Syvridis, "Effect of optical feedback to the ground and excited state emission of a passively mode locked quantum dot laser," *Appl. Phys. Lett.*, vol. 97, p. 061114, Aug. 2010.

[13] E. A. Avrutin and B. M. Russell, "Dynamics and spectra of monolithic mode-locked laser diodes under external optical feedback," *IEEE J. Quantum Electron.*, vol. 45, no. 11, pp. 1456–1464, Nov. 2009.

[14] D. Eliyahu, R. A. Salvatore, and A. Yariv, "Noise characterization of pulse train generated by actively mode-locked lasers," *J. Opt. Soc. Am. B*, vol. 13, no. 7, pp. 1619–1626, Jul. 1996.

[15] D. von der Linde, "Characterization of the noise in continuously operating mode-locked lasers," *Appl. Phys. B*, vol. 39, pp. 201–217, 1986.

[16] F. Kefelian, S. O'Donoghue, M. T. Todaro, J. G. McInerney, and G. Huyet, "RF linewidth in monolithic passively mode-locked semiconductor laser," *IEEE Photon. Technol. Lett.*, vol. 20, no. 16, pp. 1405–1407, Aug. 2008.

[17] Y.-C. Xin, Y. Li, A. Martinez, T. J. Rotter, H. Su, L. Zhang, A. L. Gray, S. Luong, K. Sun, Z. Zou, J. Zilko, P. M. Varangis, and L. F. Lester, "Optical gain and absorption of quantum dots measured using an alternative segmented contact method," *IEEE J. Quantum Electron.*, vol. 42, no. 7, pp. 725–732, Jul. 2006.

[18] H. A. Haus and A. Mecozzi, "Noise of mode-locked lasers," *IEEE J. Quantum Electron.*, vol. 29, no. 3, pp. 983–996, Mar. 1993.

[19] C.-Y. Lin, F. Grillot, Y. Li, R. Raghunathan, and L. F. Lester, "Characterization of timing jitter in a 5 GHz quantum dot passively mode-locked laser," *Opt. Exp.*, vol. 18, pp. 21932–21937, Sep. 2010.

[20] L. A. Jiang, M. E. Grein, H. A. Haus, and E. P. Ippen, "Noise of mode-locked semiconductor lasers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 7, no. 2, pp. 159–167, Mar. 2001.

[21] M. T. Todaro, J. P. Tourrenc, S. P. Hegarty, C. Kelleher, B. Corbett, G. Huyet, and J. G. McInerney, "Simultaneous achievement of narrow pulse width and low pulse-to-pulse timing jitter in 1.3 μm passively mode-locked quantum-dot lasers," *Opt. Lett.*, vol. 31, no. 21, pp. 3107–3109, Nov. 2006.

[22] J. P. Tourrenc, S. O'Donoghue, M. T. Todaro, S. P. Hegarty, M. B. Flynn, G. Huyet, J. G. McInerney, L. O'Faolain, and T. F. Krauss,

"Cross-correlation timing jitter measurement of high power passively mode-locked two-section quantum-dot lasers," *IEEE Photon. Technol. Lett.*, vol. 18, no. 21, pp. 2317–2319, Nov. 2006.

[23] J. P. Tourrenc, A. Akrout, K. Merghem, A. Martinez, F. Lelarge, A. Shen, G. H. Duan, and A. Ramdane, "Experimental investigation of the timing jitter in self-pulsating quantum-dash lasers operating at 1.55 μm," *Opt. Exp.*, vol. 16, no. 22, pp. 17706–17713, Oct. 2008.

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