Timing Jitter from Optical Phase Noise in Quantum Dot Coherent Comb Laser at C-Band

Youxin Mao, Zhenguo Lu, Jiaren Liu, Guocheng Liu, Chunying Song, and Philip J. Poole
Advanced Electronics and Photonics Research Centre, National Research Council, 1200 Montreal Rd., Ottawa, ON, Canada.
Tel: 613-993-7331 Fax: 613-954-3338 youxin.mao@nrc-cnrc.gc.ca

Abstract: Timing jitter obtained from optical phase noise is investigated in InAs/InP quantum dot Fabry-Pérot coherent comb lasers with 11, 25, and 34.5 GHz pulse repetition rates. These lasers exhibit ultra-low timing jitter making them excellent sources for tens terabit optical networks.
OCIS codes: (230.5590) Quantum well, wire and dot devices; (140.4050) Mode-locked lasers

1, Introduction

Semiconductor-based monolithic coherent comb lasers (CCLs) are a promising technology for optical communications with the ability to emit stable optical pulse trains at high repetition rate and narrow pulse width. Other advantages include compact size, low power consumption, simple fabrication, and the ability for hybrid integration with silicon substrates. CCLs utilizing quantum dots or dashes (QD) rather than quantum wells are particularly attractive due to the reduced amount of amplified spontaneous emission, lower intrinsic noise, and narrower linewidth, hence achieving lower timing jitter [1]. They are promising sources for the next generation of high speed optical networks, optical signal processing and millimeter wave generation. For all these applications, low timing jitter is necessary in order to fulfill low bit error rate and high sampling accuracy. For a QD Fabry-Pérot CCL, i.e. QD single-section CCL, due to material nonlinearities, the phase correlation of the optical longitudinal modes can take place through self-phase and cross-phase modulations, four wave mixing process, and results in passive mode locking (PML) [2]. A pulse-to-pulse time jitter estimation method was proposed for a PML CCL by using the Lorentzian linewidth of the first harmonic of the RF power spectral density (PSD) [3]. This method overcomes the limits of measuring the time jitter by optical cross correlation which requires high pulse peak power to generate a sufficiently large second harmonic signal from the nonlinear crystal. However, to measure the RF PSD requires the use of a photodetector that can respond at a frequency corresponding to the repetition rate of the pulse train. Due to the limitation of the bandwidth of available photodiodes, this restricts the application of this technique to repetition frequencies below 100 GHz. Another technique for measuring timing jitter, using the phase noise of the optical modes of the laser, has been studied recently [4]. This technique is not restricted by the repetition rate of laser being measured.

We have previously demonstrated InAs/InP QD CCLs with pulse repetition rates from 10 GHz to 437 GHz and a total output power up to 50 mW per facet at room temperature [5-11]. We have recently demonstrated femtosecond timing jitter in an external cavity self-injection feedback locking InAs/InP QD 25-GHz C-band CCL by analysis of the Lorentzian linewidth of the first harmonic RF PSD [12]. In this presentation, we report timing jitter analysis of InAs/InP QD PML CCLs at 11, 25 and 34.5 GHz pulse repetition frequency. A comparison is made of the timing jitter measured from the fitting of the optical phase noise, and from directly measuring the RF PSD. Very good agreement is achieved.

2. Theory

Following the approach from ref. [4], which considers only the effects of phase fluctuations induced by quantum noise, the timing jitter exhibits a diffusion-like behavior. This leads to the FWHM Lorentzian optical spectral linewidth (i.e. phase noise) $\Delta\upsilon_n$, and RF spectral linewidth $\Delta\upsilon_{RFm}$ for a PML CCL, given by:

$$\Delta\upsilon_n = \Delta\upsilon_{min} + 2\pi\, \upsilon_r^2\, D\, (n-n_{min})^2 \quad (1)$$

$$\Delta\upsilon_{RFm} = \Delta\upsilon_{RF1}\, m^2 = 2\pi\, \upsilon_r^2 D\, m^2 \quad (2)$$

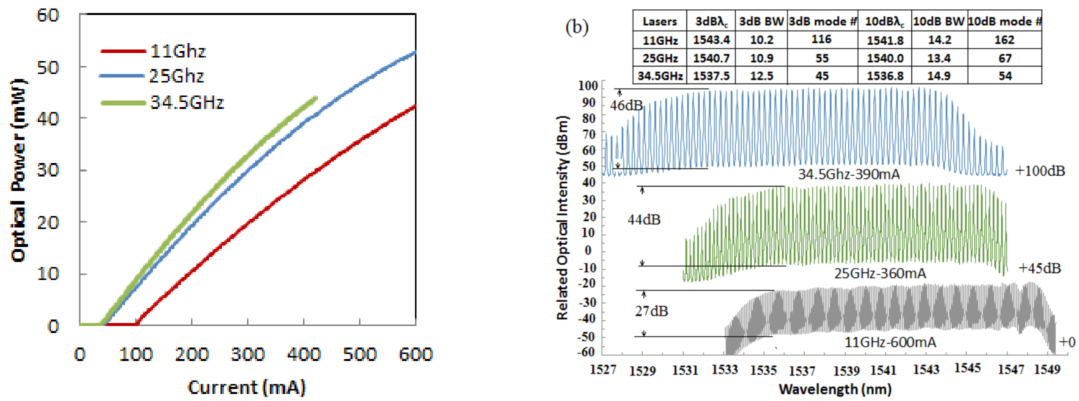
Where D is the timing jitter diffusion constant, n and m are the mode number of optical spectrum and RF spectrum, respectively, and υ_r is laser's repetition frequency. From Eq. (2), the higher order harmonic RF Lorentzian linewidth $\Delta\upsilon_{RFm}$ has a quadratic relationship with m. From the coefficient of Eq. (2), the first harmonic RF spectrum linewidth relating timing jitter diffusion constant D is given by: $\Delta\upsilon_{RF1} = 2\pi\, \upsilon_r^2 D$. Substituting it to Eq. (1), it yields:

$$\Delta\upsilon_n = \Delta\upsilon_{min} + \Delta\upsilon_{RF1}\, (n-n_{min})^2 \quad (3)$$

The pulse-to-pulse timing jitter σ_{ptp} can be expressed by RF spectrum linewidth $\Delta\upsilon_{RF1}$ as [3]: $\sigma_{ptp}=(1/\upsilon_r)*(\Delta\upsilon_{RF1}/2\pi\upsilon_r)^{1/2}$. Therefore, the pulse-to-pulse timing jitter can be given from the first harmonic RF linewidth $\Delta\upsilon_{RF1}$, which is obtained by a parabolic fitting from a measured curve of optical linewidth (phase noise) vs. optical mode number.

3, Experimental results and discussion

The three InAs/InP QD CCLs investigated in this work were grown by chemical beam epitaxy (CBE) on an exactly (100) oriented n-type InP substrate and taken from the same wafer. The structure consists of 5 layers of QDs in a 350 nm thick InGaAsP waveguide core as the gain medium, surrounded by n- and p- type InP cladding layers. More detailed QD growth information is contained in [13]. The wafer was fabricated into single lateral mode ridge waveguide lasers with a ridge width range of 1.8 -2.6 µm, and then cleaved to form Fabry-Perot laser cavities. The cavity lengths were 3848, 1693 and 1225 µm yielding repetition frequencies υ_r of 11, 25 and 34.5 GHz, respectively. No facet coatings were used on those devices. The lasers were driven with an ultra-low-noise battery powered laser diode driver and tested on a temperature controlled heat sink at an operation temperature range of 16 – 20°C.



Lasers	3dBλc	3dB BW	3dB mode #	10dBλc	10dB BW	10dB mode #
11GHz	1543.4	10.2	116	1541.8	14.2	162
25GHz	1540.7	10.9	55	1540.0	13.4	67
34.5GHz	1537.5	12.5	45	1536.8	14.9	54

Fig. 1. (a) Light-current characteristics (b) Optical spectra of 11, 25 and 34.5 GHz QD CCL measured by Anritsu MS9740A optical spectrum analyzer at 0.01 nm resolution. Inset: a table of central wavelength, optical bandwidth, and mode number at 3dB and 10 dB of three QD CCLs.

From the measured LIV curves shown in Fig. 1 (a) lasing threshold currents of 100, 44 and 39 mA were obtained for the lasers with 11, 25 and 34.5 GHz repetition frequency υ_r, respectively. Uniformed single facet slope efficiency of 0.125 to 0.140 W/A and series resistance of 0.90-1.67 Ohm were determined. Fig. 1(b) shows optical spectra of the three QD CCLs at the indicated bias currents and 0.01 nm resolution of optical spectrum analyzer. Central wavelength, spectrum bandwidth and mode number at 3dB and 10dB are shown in the inset. The 3-dB bandwidths of the three lasing spectra are in 10.2 - 12.5 nm range, providing 116, 55, and 45 modes with optical signal-to-noise ratio 27, 44, and 46 dB for 11, 25 and 34.5 GHz CCLs, respectively. The CCL with the higher υ_r (shorter cavity length) has a broader bandwidth.

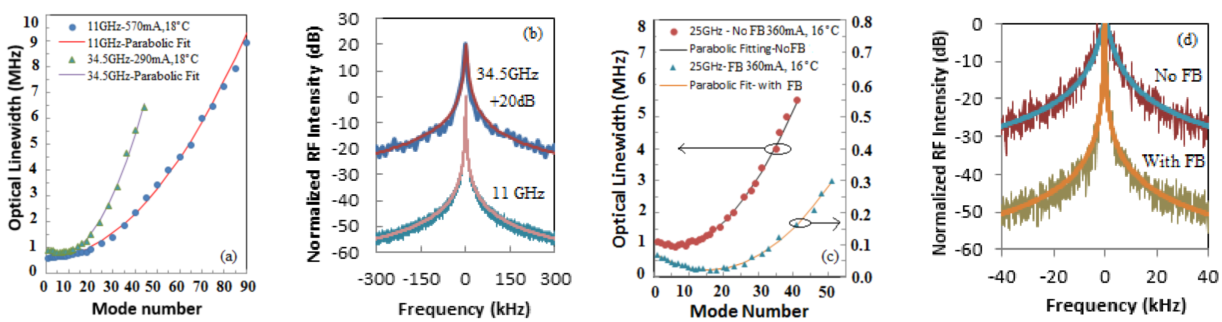


Fig. 2. Measured laser mode optical linewidths vs. mode number and parabolic fits for 11 and 34.5GHz (a) and 25GHz with and without external feedback cavity (FB) (c) QD CCL by using OEWaves OE4000 automated laser linewidth/phase noise measurement system. Normalized first harmonic RF spectra with related Lorentzian fits for 11 and 34.5GHz (b) and 25GHz with and without external feedback cavity (FB) (d) QD CCL measured by using Keysight Technologies N9030A 50 GHz PXA signal analyzer at RBW=100Hz.

Fig. 2 (a) and (c) show the measured optical linewidth (phase noise) for individual longitudinal lasing modes calculated from the frequency noise spectra obtained by the optical auto-correlator (shown as dots) for the 11 GHz and 34.5 GHz (a), and 25 GHz (c) CCLs with related parabolic curve fits from Eq. (3). Fig. 2 (b) and (d) show normalized RF PSD results from the superposition of all the mode beatings for the three QD CCLs at the central frequencies of 11.032, 24.980 and 34.499 GHz. Lorentzian line shapes provide a good fit for the RF PSD.

Laser υ_r (GHz)	*Ext. Cavity Feedback*	*Fit from Phase noise vs. Mode #*				*RF Measured $\Delta\upsilon_{RF1}$ (kHz)*	*Timing Jitter from Measured $\Delta\upsilon RF1$ σ_{ptp} (fs)*	*Timing Jitter from Phase Noise σ_{ptp} (fs)*
		$\Delta\upsilon_{nim}$ (MHz)	*D (fs)*	*n_{nim}*	*$\Delta\upsilon_{RF1}$ (kHz)*			
11	No	0.591	0.0014	0.018	1.07	1.09	11.42	11.31
25	No	0.968	0.0091	5.568	3.57	3.51	5.98	6.03
34.5	No	0.789	0.00056	6.781	4.17	4.42	4.14	4.02
25	Yes	0.022	0.00005	15.522	0.215	0.24	1.56	1.50

Table 1. Results of Parabolic fit of $\Delta\upsilon_{nim}$, D, n_{nim} and $\Delta\upsilon_{RF1}$ from phase noise vs. optical mode # as shown in Fig. 2(a) and (c) by Eq. (3), measured the 1st harmonic RF linewidth $\Delta\upsilon_{RF1}$, and the pulse-to-pulse timing jitter σ_{ptp} from Phase Noise and RF PSD measurements for three CCLs.

The parabolic fit results of $\Delta\upsilon_{nim}$, D, n_{nim} and $\Delta\upsilon_{RF1}$ from the optical phase noise measurements using Eq. (3) are shown in table 1 and compared to the values from measured $\Delta\upsilon_{RF1}$ using the RF PSD. By comparing the fitted timing jitter diffusion constants D, the CCL with the highest υ_r (short cavity length) has the lowest diffusion constant, i.e. D=0.00056 fs for the 34.5 GHz QD CCL. Very good agreement is obtained when comparing the values of $\Delta\upsilon_{RF1}$ and timing jitter σ_{ptp} obtained by the two different methods. The pulse-to-pulse timing jitter calculated from the phase noise are 11.31, 6.03 and 4.02 fs for the QD CCL without the external cavity feedback locking at 11, 25 and 34.5 GHz repetition frequency, respectively. Again the CCL with higher repetition frequency υ_r (shorter cavity length) has smaller pulse-to-pulse timing jitter. The pulse-to-pulse timing jitter is reduced about 4 fold from 6.03 fs to 1.5 fs for the 25 GHz QD CCL when using external cavity self-injection feedback locking [12]. The 4.02 fs pulse-to-pulse time jitter obtained for the 34.5 GHz CCL in this work is about 3.8 times lower than that reported in [4] with a similar laser at 40 GHz.

In conclusion, we have investigated the pulse-to-pulse time jitter obtained from optical phase noise measurements in 11, 25, and 34.5 GHz C-band InAs/InP QD single-section CCLs. These results are compared to those from a directly measured RF mode beating spectrum. Very good agreement is achieved. The optical phase noise method can be used in higher frequency semiconductor passively mode-locked CCL, which is restricted by the other methods. Pulse-to-pulse time jitter of 4.0 and 1.5 fs are achieved in the 34.5 GHz QD CCL without an external cavity feedback locking and 25 GHz QD CCL with an external cavity feedback locking, respectively. By using our developed QD coherent comb lasers, we have successfully demonstrate > 2 Tbit/s (32x32 GBaud) PAM-4 and > 10 Tbit/s (16QAM 40x32 GBaud PDM) back-to-back (B2B) data bandwidth transmission capacity [14].

4, References

[1] D. Arsenijevi´c, M. Kleinert, and D. Bimberg, "Breakthroughs in photonics 2013: Passive mode-locking of quantum-dot lasers," *IEEE Photon. J.* vol. 6, no. 2, Apr. 2014, Art. No. 0700306.

[2]. Lu, Z.G., Liu, J.R., Raymond, S., Poole, P.J., Barrios, P.J. and Poitras, D., "312-fs pulse generation from a passive C-band InAs/InP quantum dot mode-locked laser," *Opt. Express*, 16, 10835-10840 (2008)

[3] 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.

[4] R. Rosales, K. Merghem, A. Martinez, F. Lelarge, A.Accard, and A. Ramdane, "Timing jitter from the optical spectrum in semiconductor passively mode locked lasers", Optics Express, Vol.20, No.8, 9151-9160 (2012).

[5] Lu, Z.G., Liu, J.R., Song, C.Y., Weber, J., Mao, Y., Chang, S.D., Ding, H.P., Poole, P.J., Barrios, P.J., Poitras, D., Janz, S., and O'Sullivan, M., "High performance InAs/InP quantum dot 34.462-GHz C-band coherent comb laser module," *Optics Express*, 26, 2160-2167 (2018).

[6] Lu, Z.G., Liu, J.R., Poole, P.J., Raymond, S., Barrios, P.J., Poitras, D., Pakulski, G., Grant, P. and Roy-Guay, D., "An L-band monolithic InAs/InP quantum dot mode-locked laser with femtosecond pulses," *Opt. Express*, 17, 13609–13614 (2009).

[7] Liu, J.R., Lu, Z.G., Raymond, S., Poole, P.J., Barrios, P.J. and Poitras, D., "Dual-wavelength 92.5 GHz self-mode-locked InP-based quantum dot laser," *Optics Letters*, Vol. 33, No. 15, pp. 1702-1704 (August 2008).

[8] Lu, Z.G., Liu, J.R., Poole, P.J., Jiao, Z.J., Barrios, P.J., Poitras, D., Caballero, J. and Zhang, X.P., "Ultra-high repetition rate InAs/InP quantum dot mode-locked lasers," *Optics Communications*, Vol. 284, No. 9, pp. 2323-2326 (May 2011).

[9] Jiao, Z.J., Liu, J.R., Lu, Z.G., Zhang, X.P., Poole, P.J., Barrios, P.J. and Poitras, D., "A C-Band InAs/InP Quantum Dot Semiconductor Mode-Locked Laser Emitting 403-GHz Repetition Rate Pulses," *IEEE Photonics Technol. Lett.*, vol. 23, pp. 543-545 (2011)..

[10] Lu, Z.G., Liu, J.R., Song, C.Y., Weber, J., Mao, Y., Chang, S.D., Ding, H.P., Poole, P.J., Barrios, P.J., Poitras, D., Janz, S., and O'Sullivan, M., "An InAs/InP quantum dot C-band coherent comb laser," *The Proceeding of Optical Fiber Communications (OFC) 2018*, San Diego, CA, USA, Th1I.4, (11-15 March 2018).

[11] Lu, Z.G., Liu, J.R., Poole, P.J., Song, C.Y. and Chang, S.D., "Ultra-narrow linewidth quantum dot coherent comb lasers with self-injection feedback locking," *Optics Express*, 26 (9), 11909-11914 (April 2018).

[12] Y. Mao, J. Liu, Z. Lu, C. Song, and P.J. Poole, "Ultra-low Timing Jitter of Quantum Dash Semiconductor Comb Lasers with Self-injection Feedback Locking", IEEE J. of Select. Topics in QE, Vol. 25, No. 6, 1900607 (Nov. 2019).

[13] P. J. Poole, K. Kaminska, P. Barrios, Z. G. Lu, and J. R. Liu, "Growth of InAs/InP-based quantum dots for 1.55 μm laser applications," J. Cryst. Growth 311(6), 1482–1486 (2009).

[14] Z.G. Lu, "Quantum dot coherent comb lasers for Terabit optical networking systems," (Invited paper) SPIE Photonics West 2019, San Francisco, CA, USA, 2-8 February, 2019.