Phase Noise Spectral Properties Across Individual Comb Lines in Quantum-Dot Mode-Locked Lasers

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Abstract: We study phase-noise spectral properties of comb lines from a QD-MLL, show that their large linewidth variability attributes to the low-frequency phase variations, and has minimal effect on coherent system performance at practical symbol rates. © 2020 The Authors.

1. Introduction: Optical datacenter interconnects (DCIs) are expected to provide >400 Gb/s data rate capabilities in the foreseeable future, driven by the continuing growth of internet applications and centralized cloud services. At these throughputs coherent solutions can rival and best intensity modulation (IMDD) by measure of density, power per bit and reach [1-3]. Coherent transmission can also improve system reach and spectral efficiency for applications with relatively lower symbol rates, such as passive optical networks (PONs) and mobile network backhaul systems [4,5]. Quantum-dot(dash) mode-locked lasers (QD-MLLs) are attractive multi-wavelength light sources by virtue of their small footprint, energy efficiency, and integrability in photonic integrated circuits (PICs) [6-8]. QD-MLLs can simultaneously generate tens of continuous wave (CW) signals (or *comb lines*) equally spaced by a specified repetition frequency over a wavelength window of typically ~10 nm [6-9]. The demonstration of these devices with desired line spacing on the order of tens of GHz shows that they are suitable for wavelength-division multiplexing (WDM) applications. These devices, however, can suffer from relatively high phase noise exhibited by individual comb lines compared to distributed-feedback (DFB) and external cavity lasers (ECLs) commonly used in communication applications [7,9,10]. It has been shown that the linewidths of comb lines of a QD-MLL vary with the wavelength parabolically [6,7,9]. In this work we study the FM noise spectral profiles of different comb lines across the emission window and show that the variation of linewidths as the function of wavelength is mainly caused by the variation of low-frequency components of the FM noise of these spectral lines. Although the linewidth varies by >500% across the emission band, we show that the system performance using these spectral lines as light sources only change slightly. We show that with proper device biasing, and careful receiver carrier phase recovery (CPR) design, all comb lines of a QD-MLL can be used for coherent transmission, even at relatively low symbol rates. This is due to the relatively low FM noise components at the high frequency for all comb lines. This avoids the need for linewidth reduction techniques such as feed-forward [11] or feedback injection locking [12].

2. Experimental procedure and results: The QD-MLL used in our experiment is a single section InAs/InP operating in the lower half of the C-band from 1531 to 1541 nm with 25 GHz comb line spacing. Figure 1(a) shows the optical spectrum of the device with two different bias current and device temperature combinations chosen to align the same comb lines to the 25-GHz ITU-T Grid. To characterize spectral properties of individual comb lines, we used a 25:50 GHz interleaver followed by a tunable bandpass filter and an EDFA to select and amplify individual comb lines. An integrated phase-diversity coherent receiver with a tunable ECL (linewidth <30 kHz) as the local oscillator (LO) was employed to downshift the selected comb line to the RF domain. The I and Q components of the RF signal were captured at 50 GS/s by a real-time oscilloscope with an electrical bandwidth of 23 GHz and a nominal vertical resolution of 10 bits. The temperature sensitivity of QD-MLL comb line wavelength was found to be ~0.1 nm/ºC. We chose four cases of the set temperature from 16ºC to 22ºC in a step of 2ºC (0.2 nm wavelength change) to align the comb to the 25-GHz grid. At the same time, the bias current was reduced in every step to re-align the same comb line back to the same original wavelength (see the legend of Fig.1(b)). On the other hand, the required current change ranges from 55mA to 85mA (depending on the temperature) to create a 0.2-nm wavelength change. Change of frequency spacing between comb lines due to temperature and current change was not observed for the given range of measurements. We characterize the linewidth of individual lines by two different measures: (1) a *statistical* linewidth calculated from the phase difference variance, $\sigma_\varphi^2(\tau) = var[\varphi(t) - \varphi(t-\tau)]$, at τ =10 ns, where the linewidth is obtained as $\delta v = \sigma_\varphi^2/(2\pi\tau)$ [13]; and (2) a *spectral* linewidth calculated from the normalized field spectrum at -20 dB and converted to the -3dB linewidth, assuming a Lorentzian shape, as $\delta v_{-3dB} = \delta v_{-20dB}/\sqrt{99}$. Figure 1(b) shows the calculated linewidths for 10 comb lines for each of the 4 bias cases covering the 6-dB emission window of Case 4. Each point in the figure shows an average of three different measurements,

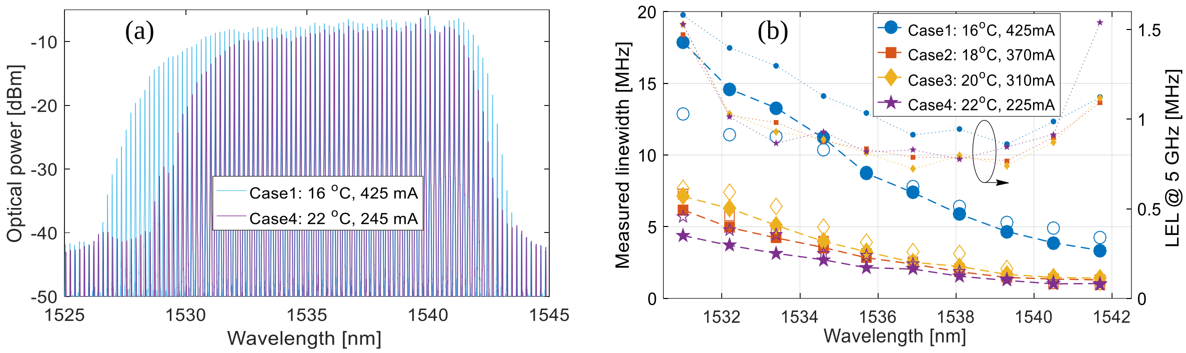

Fig. 1. (a) Optical spectra of the QD-MLL (RBW=0.01nm) for two different bias and temperature cases; and (b) measured linewidths of 10 different comb lines. Filled markers: statistical linewidths; open markers: spectral linewidths; smaller markers: LELs.

each of 1 million samples (20 μs duration). Unlike the case for most single-mode semiconductor lasers, we find that the QD-MLL does not show monotonic decrease of linewidths when increasing the current or decreasing the temperature. Instead, for all cases, the spectral widths of comb lines have similar dependence on the wavelength. Also shown in Fig. 1(b) are the Lorentzian-equivalent linewidths (LEL) [10] for the corresponding measurements, with the small size markers. LELs are equivalent to the statistical linewidths calculated at a specific sampling frequency ($1/\tau$); 5 GHz was used here. For lasers with non-white FM noise, LELs at high frequencies are better indicators of the laser performance in coherent systems than the actual spectral linewidths [10]. The measured statistical and spectral linewidths show comparable values for all measurements except for the short wavelength region of Case 1. Fig. 1(b) also indicates that the measured linewidths can change significantly over the wavelength. For example, Case 2 shows a change of statistic linewidth from 1.5 MHz to 4.8 MHz (220% variation) for the comb lines at 1532.29 and 1539.37 nm. However, the corresponding LELs at 5 GHz show a much smaller variation from 0.75 MHz to 1 MHz (33% variation) across the entire wavelength window of between these comb lines.

Figure 2(a) displays the FM-noise PSDs of four equally-spaced wavelengths across the 3-dB optical bandwidth of the comb at Case 2. Although the FM noise spectral contents in the low frequency region around 10 MHz vary by ~7dB, FM noise at high frequencies above 100 MHz show only very small variations. Figure 2(b) shows the corresponding LELs evaluated at different sampling frequencies. In this figure, measured LEL values at 100 MHz and at 5 GHz correspond to the statistical linewidths and the LEL values shown in Fig. 1(b) (Case 2), respectively, for the same set of comb lines. The inset shows the corresponding measured field spectra. It can be noticed that the LELs at 100 MHz (representing the spectral linewidths) have a larger variation (~220%) than that of the LELs at 5 GHz (~33%), analogous to the trend found in Fig. 2(a) for the FM-noise PSDs, as a function of frequency. Since the impact in a coherent system depends mainly on the high-frequency components of the FM noise comparable to the symbol rate [10], all comb lines across the emission band are expected to exhibit comparable performances, with much smaller variation than suggested by their spectral linewidths, as shown below.

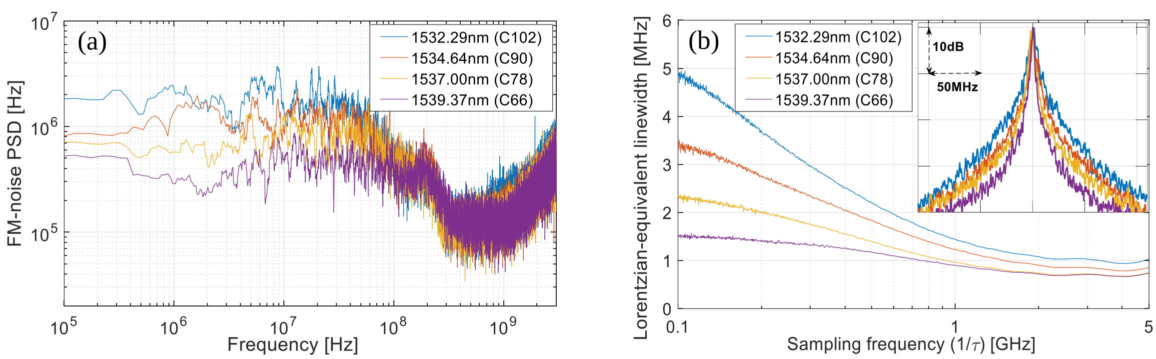

Fig. 2. (a) FM-noise PSD of four different comb lines at Case4 (18ºC, 370mA); and (b) corresponding LELs vs. frequency.

Figure 3(a) shows the measured OSNR performance of a coherent system with single-polarization 16-QAM modulation at 5 GBd. Two different comb lines, at 1532.29 nm and 1540.16 nm, were used as the Tx light sources with statistical linewidths of 4.8 MHz and 1.45 MHz and LELs of 1 MHz and 0.73 MHz, respectively. Comb line selection and coherent receiver used in the system experiments were the same as those described above, except that the signal was I/Q modulated, and extra optical noise was loaded before the coherent receiver to change the OSNR.

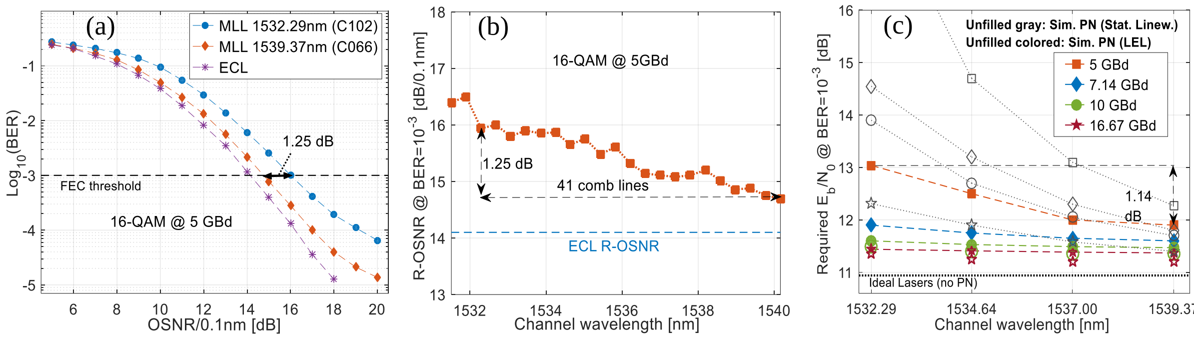

Fig. 3. (a) Experimental BER vs. OSNR; (b) experimental R-OSNR at 0.001 BER; and (c) Simulations of required E_b/N_0 for differential 16-QAM at different system baud. Sim. PN: simulated phase noise (computer-generated as a Weiner process, simulating, e.g., DFB lasers with corresponding linewidths).

The 16-QAM signal was differentially pre-coded and Nyquist pulse-shaped with a roll-off factor of 0.1. The *I* and *Q* components from the coherent receiver were captured at 25 GS/s and processed offline with the basic coherent receiver DSP stages comprising resampling, frequency compensation, matched filtering, symbol timing, equalization, CPR, and hard-decision symbol-to-bit de-mapping. A single-stage blind phase search was used for CPR with 64 test phase points, and the optimum half-window length of 6 was used [10,14]. The required OSNRs (R-OSNR) to achieve the conventional FEC BER threshold of 10^{-3} were 15.95 dB and 14.7 dB for the 1532.29 nm and 1540.16 nm comb lines, respectively, with a difference of only 1.25 dB. An ECL was also used as the Tx light source for comparison, which shows a R-OSNR of 14.1 dB at the same BER threshold. We then measured the R-OSNR of every other comb line across the 8.2nm emission band. The I/Q modulator control and the optical input power to the coherent receiver were monitored throughout the experiment to avoid any wavelength-dependent performance dissimilarities in the setup. The results in Fig. 3(b) show that the R-OSNR varies only by 1.25dB across the wavelength window, which is much smaller than one would expect from the large linewidth variation of these comb lines.

With increasing the symbol rate, the sensitivity of performance to low-frequency FM noise is expected to drop. To observe this, we used measured waveforms of the complex envelopes of unmodulated comb lines, to simulate the system performance at different symbol rates [13] for the captured comb lines shown as in Fig. 2. In the simulation, the 16-QAM data symbols were carried by the complex waveforms of the comb lines, and white Gaussian noise was added to change the per-bit signal to noise ratio (E_b/N_0) before CPR and demodulation. Optimum averaging window length was used for each case. Fig. 3(c) shows the required E_b/N_0 to achieve a threshold BER of 10^{-3}. At 5 GBd, the penalty difference between the comb lines of shortest and longest wavelengths is 1.14 dB of ROSNR, which agrees reasonably well with the experimental results (the 1.25 dB for the R-OSNR difference between these lines). The required E_b/N_0 difference reduces drastically with increasing the symbol rate. Negligible performance difference is observed when using all these comb lines at 10 GBd symbol rate and above. For comparison, the unfilled markers represent the case where computer-generated white phase noise is used for each comb line, in which the white FM noise was generated as a Weiner process with Lorentzian linewidths equal to the measured statistical linewidth and LEL (gray and colored unfilled markers, respectively) for each comb line of the QD-MLL. The results of the statistical linewidths show a much bigger variation of SNR performance compared to the phase noise from the QD-MLL, at all symbol rates; whereas the results of the LELs show reasonably accurate predictions at both 10 and 16.67 GBd rates. This indicates that measured statistical and spectral linewidths of the comb lines from a QD-MLL, with their high variability, are not reliable indicators in assessing the impact of phase noise of these light sources in coherent transmission. Instead, LELs show very accurate predictions and could be used to predict the phase noise impact of these lasers at practical symbol rates when compared to lasers with white FM noise profiles such as DFB lasers.

3. Conclusion: We have characterized phase noise spectral properties of individual comb lines from a QD-MLL. It was shown that although the spectral linewidths of comb lines may vary significantly across the emission window, their performance as the light source in a coherent system is quite similar at practical symbol rates. This is attributed to the non-white phase noise characteristics of QD-MLLs.

4. References

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