

Line-by-Line Comb Noise Measurements Using an Electro-Optic Comb Local Oscillator

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Abstract: We present line-by-line phase noise characterisation for a 2.5GHz repetition-rate frequency comb, achieved by heterodyne beating with a 25GHz repetition-rate, low noise optoelectronic comb, furthering the understanding of combs in coherent optical communications.

Keywords: Optical transmitter and receiver subsystems

I. INTRODUCTION

Low-noise optical frequency combs (OFCs) are promising light sources for optical and radio wireless communications. High-repetition rate comb like Kerr Microcomb and optoelectronic comb have been exploited in coherent optical fiber communication by separately modulating individual lines with data [1]. Low-repetition rate combs have been used to synchronize clock and radio frequencies (RF) in passive optical networks (PON) [2] and radio access networks (RAN) [3], enabling low latency and high-capacity access networks. In all these applications, low phase noise tones are the primary requirements, particularly for PON and RAN where 10s of tones with a repetition rate of (2.5 - 10) GHz are expected to be distributed over optical fibers to facilitate synchronization.

Solid-state mode locked lasers have shown ultra-low phase noise, compactness, and high stability [4] that could benefit access network applications. However, the demonstrated repetition rate is mainly limited to 1 GHz and below. Although previous studies have investigated the phase noise of the one comb tone in the center of the spectrum, the evolution of phase noise across a wide spectral range has not been systematically studied. Furthermore, such studies are challenging due to the lack of low bandwidth (<2.5 GHz) and widely tuneable optical filters, which preclude characterization using conventional delay interferometer-based self-homodyne methods.

In this paper, we report the line-by-line phase noise characterization of a 2.5 GHz repetition-rate solid state mode-locked laser (MLL). This is achieved by mixing the tested comb source with an ultra-low noise high repetition rate optoelectronic frequency comb, which is developed in-house using an ultra-low linewidth (1 Hz) continuous wave (CW) laser as a seed, followed by comb expansion using modulators driven by an ultra-low phase noise RF synthesizer. The optoelectronic comb ensures high power per line with 25 GHz spacing, which permits self-heterodyne beating for line-by-line phase noise characterization. To the best of the authors' knowledge, this is the first report of line-by-line measurement of a solid-state comb of its kind.

II. EXPERIMENTAL SETUP

Fig. 1a shows the experimental setup of our noise characterization system. A 1 Hz intrinsic linewidth laser, with a tuning range of (1553.25 - 1553.95) nm, seeded the electro-optic (EO) modulation stage, which was first amplified to 27 dBm prior to modulation. The low-repetition-rate comb under test is a solid-state MENHIR-1550 MLL, manufactured by Menhir Photonics, outputting 12.9 nm optical bandwidth (full-width half-maximum of the spectral envelope), centered at 1551.62 nm, a sech^2 shape pulse width of 755 fs in the time domain, and with a repetition rate of 2.5 GHz. The EO modulation frequency, which determines the repetition rate, was set to 25 GHz, while the repetition rate of the MLL is around 2.5 GHz, permitting a fundamental beat-note between (0.05 - 1.25) GHz when only one of the tone from the EO comb is presented. The EO comb was driven using an ultra-low noise RF synthesizer with an integrated jitter of 15fs to ensure low noise across the whole spectral range.

The EO and Menhir Photonics combs were combined through a polarization-maintaining (PM) 50:50 coupler, before being filtered by using a 30 GHz optical bandpass filter (OPBF); conceptually demonstrated in Fig. 1b. The filter provides a selection of tones (~15) of the Menhir Photonics comb, and a single tone of the EO comb, a local oscillator (LO). The filtered tones and the LO were amplified together using a single PM erbium-doped fiber amplifier (EDFA) to ensure sufficient power of the beat note lay above the thermal noise floor of the photodetector. The post-filtering EDFA has a noise figure of 5.5 dB. Equipment availability limited the experiment to a single low-noise EDFA, hence simultaneous EO and Menhir Photonics OFC filtering and amplification. Implementing separate filtering and amplification stages for both LO and filtered Menhir Photonics combs would offer greater LO and Menhir Photonics comb amplitude control.

The receiver uses a 5 GHz bandwidth photodiode (PD), with a responsivity $\sim 0.9 \text{ AW}^{-1}$ at 1550 nm, followed by an RF amplifier of 4dB noise figure; a (0.05 - 1.05) GHz low-pass filter (LPF) is applied after the RF amplifier to suppress the complementary beat-note ($f_{\text{rep}} - f_{\text{beat}}$); demonstrated in Fig. 1c. Higher-order beat notes generated from the LO and

signal comb; and high-frequency noise originating from the PD and amplifier. The output amplified signal was recorded on a Rohde & Schwarz FSWP50 (an electrical spectrum analyzer), where single-sided noise characteristics were extracted.

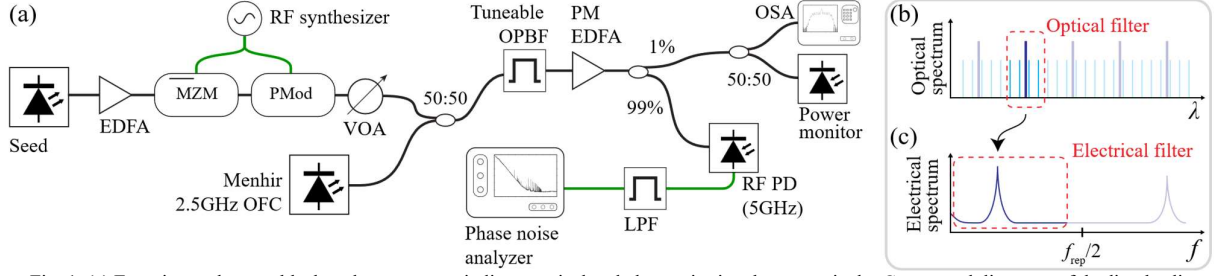


Fig. 1. (a) Experimental setup: black and green traces indicate optical and electronic signals, respectively. Conceptual diagrams of the line-by-line measurement procedure, demonstrating optical (b) and electrical (c) filtering; light and dark blue peaks represent tones of the Menhir Photonics and EO OFC tones, respectively.

The EO OFC seed wavelength (1553.45 nm) was set such that the lowest-order beat note extended beyond the low-frequency technical noise of the system, while providing sufficient spectral range to deduce noise characteristics: approximately 400 MHz. The seed wavelength remained constant during the experiment. By setting the repetition rate of the EO comb to 10 times that of the Menhir Photonics MLL, we were able to achieve a beat-note frequency within 50 MHz across the sample range.

Owing to the semi-automated data acquisition, a relatively high bandwidth was utilised to ensure the LO coincided within the flat-region of the OBPF; all datasets maintained <0.01 dB Menhir Photonics tone peak power variance within 5 tones of the LO. The data were acquired over 6 nm, in steps of equal to that of the RF synthesizer frequency, 25 GHz, thereby sampling each tone of the EO comb. It is well understood that EO combs have flat spectral profiles surrounding the seed wavelength; however, high-power features (“bat ears”) lie at the very edge of this flat region [6]. As the seed tuning range

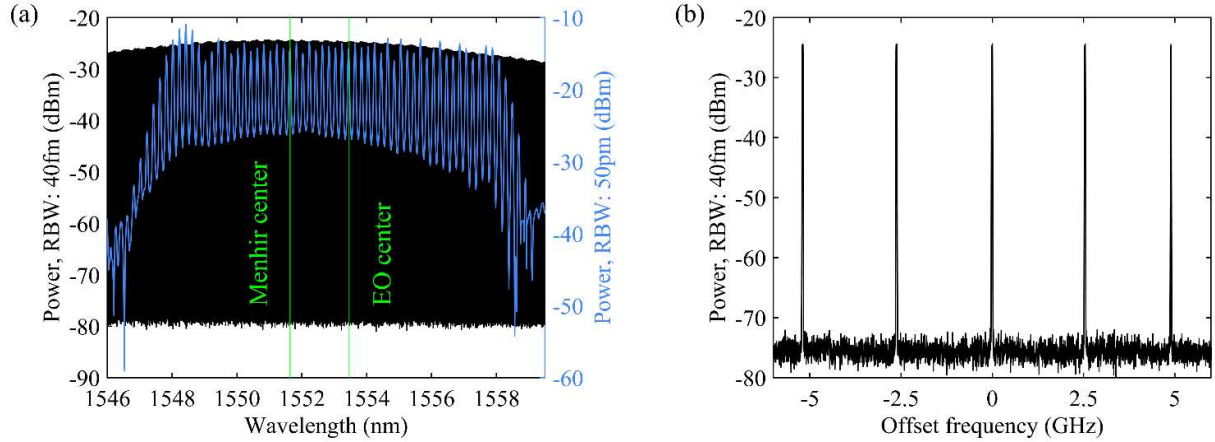


Fig. 2. Optical spectra demonstrating a portion of the Menhir Photonics comb (black) overlaid with the EO comb (blue); axes (a) are separated (left and right) due to different measurement RBWs for the Menhir Photonics and EO OFCs; green vertical lines (a) denote the OFC centers. A magnified portion of the Menhir Photonics comb spectrum is also shown (b), centered about the Menhir Photonics comb central frequency (1551.62 nm).

does not coincide with the Menhir Photonics comb center wavelength (green lines in Fig. 2a), aforementioned high-power EO comb features lay within the measurement range. To prevent LO power variance influencing the shot noise limit of the system, the peak power of the utilised EO OFC tone (serving as the LO) was power matched to that of the lowest power tone utilised within the sweep range; EDFA pump current was not varied in the experiment (350 mA). The LO power was controlled by a VOA and monitored using the peak power on the OSA, as opposed to the power meter; the latter demonstrated low sensitivity given the large attenuation. Despite this, the total optical power into the RF PD increased by ~ 0.4 dBm over the sweep range (inset of Fig. 3b).

Recorded noise spectra demonstrated amplifier saturation artefacts, manifesting as harmonics of ~ 700 kHz on the phase noise analyzer; such features are of experimental error, and have been removed in post-processing. Phase noise spectra are largely dominated by random frequency noise ($S \propto f^{-4}$: $10^2 < f < 10^5$), and white phase noise ($S \propto f^0$: $f > 10^6$). Sharp features, such as the ~ 500 kHz peak in Figs. 3a and 3b, are attributed to the relaxation oscillations within the gain medium of the Menhir Photonics MLL. While phase noise variation within the lower-frequency regime ($f < 10^4$) is present, $\sim 1 \text{ rad}^2 \text{ Hz}^{-1}$ (as shown in the inset of Fig. 3a), there is no significant correlation between noise variation and the tone number of either the EO or Menhir Photonics OFCs (relative to their respective center frequencies).

The seed laser noise spectra (red-dashed curves in Fig. 3) were characterized on a commercial self-homodyne phase noise analyzer. Some high frequency ($f > 5$ MHz) noise harmonics, present in the seed laser (dashed red lines Fig. 3), are also evident when used with, and without, EO modulation. Comparing the white-phase contribution of the non-modulated heterodyne noise (solid black lines in Fig. 3) to that of the seed laser, we observe a ~ 20 dB increase, inferring its origin within the Menhir Photonics MLL. The noise floor increase arising from the EO comb setup, relative to the pure seed, is dominated by the white amplified spontaneous emission of the EDFA. The EO comb also contributes noise in the (0.05 - 12) MHz region, the colored curves in Fig. 3, stemming from the RF synthesizer [5]; the synthesizer noise scales with each tone extending from the seed. Comparison of noise measurements without EO modulation (black curves in Fig. 3) indicate a random frequency to white phase crossover at approximately 500 kHz. This crossover coincides with the white phase plateau of the RF synthesizer, artificially increasing the observed intrinsic linewidth of the Menhir Photonics laser.

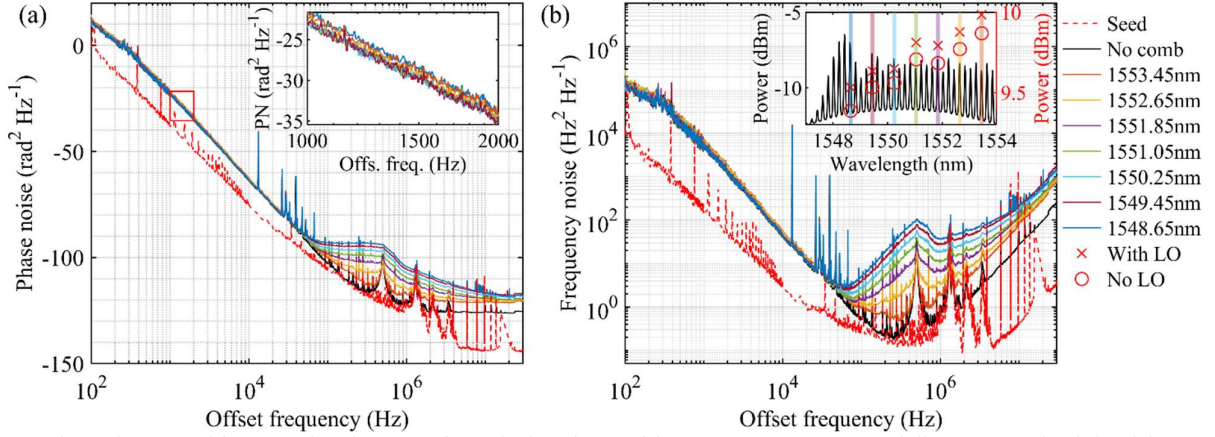


Fig. 3. Phase (a) and frequency (b) noise spectra for a selection of tones of the 6 nm sweep range. RBW of all spectra vary (banded); minimum RBW for any band is 3 kHz. The inset (a) demonstrates a zoomed in portion of the phase noise spectra about 1 kHz (red box on the main plot). The left (black) axis of the second inset (b) demonstrates the combined optical spectra (OSA in Fig. 1a) of both Menhir Photonics and EO OFCs, overlaid with coloured LO wavelengths (colors correspond to those in the main figures); the right (red) axis indicates the average optical power incident on the RF photodiode, with the LO (crosses), and the LO fully attenuated (circles).

III. CONCLUSIONS

We design a high-repetition-rate, low-noise, high-power-per-tone EO comb to measure the line-by-line phase noise of a low-repetition-rate comb across a 6nm spectral range. Our method enables single-tone phase noise measurement in the low-offset frequency range (< 50 kHz), where our seed laser exhibits lower noise than the source under test. However, our approach is limited in measuring high-frequency noise due to the scaling of RF phase noise, even though we are already using a state-of-the-art electronic synthesizer. Our method demonstrated here is still valid if the comb source under test has higher per-tone noise than the reference EO comb. It is evident from the low phase noise characteristics of the 2.5 GHz solid state MLL comb, that it could potentially be used in PON and RAN for data transmission and clock synchronization.

ACKNOWLEDGMENT

The author acknowledges the Innovate UK grant USYNC in addition to EPSRC grants ORBITS (EP/V051377/1) and 6G-MUSICAL (10093329).

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