On the Noise Scaling of Parametric Frequency Combs

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Abstract *We study the impact of RF phase noise and relative intensity noise on optical phase noise of an electro-optic frequency comb pumped fibre parametric comb generator, demonstrating sub-10-kHz linewidth over 110 nm bandwidth with 25-GHz spacing, >0dBm power per tone and more than 30dB OSNR.*

Introduction

Optical frequency combs that generate equally-spaced and phase-coherent optical tones are becoming increasingly exploited in optical communications and optical-assisted signal processing, improving system performance in applications including fibre nonlinearity compensation [1,2], photonic-assisted RF signal processing [3,4], low-noise carrier and clock distribution [5] and high-capacity wavelength division multiplexed (WDM) transmissions [6,7].

Many frequency comb generation techniques have been developed for the applications mentioned above, with an emphasis on the flat spectrum, high power, high optical signal-to-noise ratio (OSNR), low optical phase noise, and polarisation-maintaining (PM), which are desired features for optical transceivers and optical signal processing applications [8-11]. The cavity-less fibre-based parametric frequency comb generator is a promising approach in that it simultaneously delivers all the desired features and provides additional merits of tuneable repetition rate (tone spacing) and strong tolerance to environmental perturbation (e.g., vibration and temperature variation) [12,13].

Previously, we demonstrated a fibre-based parametric frequency comb generator using all-PM components and PM highly nonlinear fibres (HNLF), showing sub-40kHz linewidth over 100 nm bandwidth [13]. The line-by-line phase noise characterisation exhibited a drastic increase of linewidth towards the edge of the comb bandwidth. However, the cause of the linewidth degradation and the origin of the added phase noise was not investigated. Although line-by-line linewidth characterisation has been performed using the self-heterodyne method [14], the scaling of phase noise (PN) and the interaction between amplitude and phase noise in an electro-optical (EO) comb-pumped parametric frequency comb generator has not been investigated. Understanding how noise scales with comb bandwidth is essential to comb-based signal processing and digital signal processing (DSP) design in optical communications such as joint phase estimation and phase-coherent nonlinearity mitigation [1,11,15].

In this paper, we improve the comb design and systematically study the scaling of phase and amplitude noise of EO comb-pumped parametric frequency combs. Compared to the prior art and our previous work [12, 13], the novelties of this paper are threefold. Firstly, we improved our all-PM fibre comb results by improving the nonlinear amplified loop mirror (NALM) design, which resulted in an enhanced OSNR. Secondly, we study the comb's phase noise scaling using two RF signal generators with different phase noise profiles. By characterising the line-by-line optical phase noise of the EO comb and the parametric comb, we show that the RF phase noise plays a critical role in optical tones' phase noise and linewidth. Using an ultra-low noise RF generator, we minimised the RF-induced linewidth degradation and obtained a low noise frequency comb with less than 10 kHz linewidth over 110 nm spectral range. Finally, we characterise the relative intensity noise (RIN) and show the interaction of RIN and phase noise in a parametric frequency comb generator. Importantly, the above results are obtained in a PM-HNLF-based comb generator, desired for comb-based optical transceivers (no PM controller need) and a minimised nonlinear noise [16].

Experiment Setup

Figure.1a shows the experimental setup, comprising an electro-optic frequency comb generator followed by a NALM-based pulse shaper and a highly nonlinear fibre (HNLF) as a nonlinear mixer, all using PM components and fibres. A CW laser seeds the EO comb with a narrow linewidth of 1 kHz, emitting 12 dBm power at 1550.08 nm. The CW laser was amplified to 27 dBm before seeding cascaded intensity and phase modulators driven by 25-GHz RF signals generating a first-stage EO comb with about 75

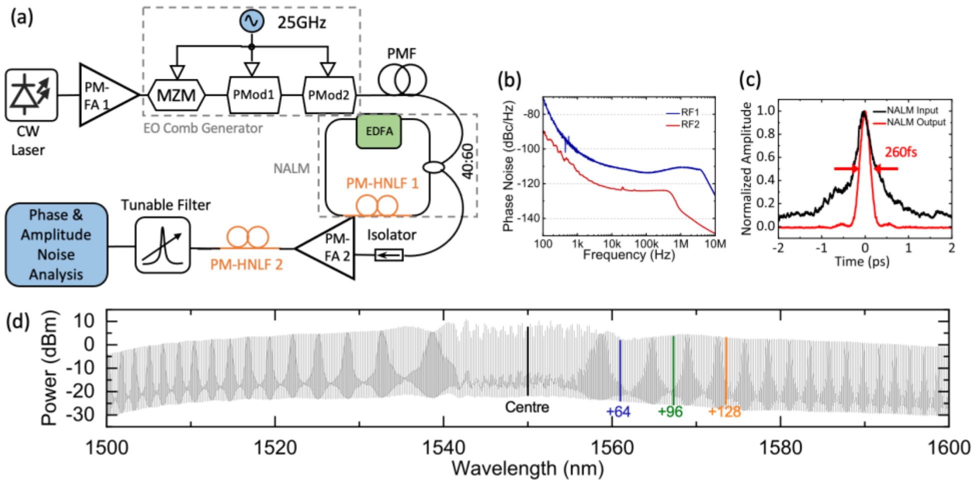

Fig. 1: (a) Experimental Setup. (b) RF phase noise of the 25-GHz signals: RF1 (blue) and RF2 (red). (c) Autocorrelator measurement for the pulses before (black) and after (red) the NALM, (d) Spectrum of the comb output (0.02 nm resolution).

tones spacing at 25-GHz (about 12 nm bandwidth). Two RF generators were employed, and their phase noise is compared in figure 1b (measured using the cross-correlation method, R&S FSWP50). RF1 is an OEM low noise frequency synthesiser (SignalCore SC5521A) whose phase noise is shown in blue in Fig.1b. RF2 (red curve) is generated using a state-of-the-art low noise RF synthesiser (Rohde & Schwarz SMA100B), which has approximately 10 dB lower phase noise than RF1 in the sub-300 kHz region and more than 30 dB better in the >1MHz region. The output of the EO comb generator consists of a 25 GHz repetition rate pulse train in the time domain, with each pulse possessing a quasi-linear frequency chirp. The bandwidth of the EO comb is 14 nm, consisting of 70 tones. Before entering the pulse shaper (NALM), 50-m PM single-mode fibre is used to compress the strongly chirped pulses to the transform limit, yielding 470 fs full-width half-maximum (FWHM) pulse width, as shown in black Fig. 1c). The NALM acts as an intensity-discriminating gate, transmitting the high intensity of each pulse while suppressing the low-power pedestals formed due to nonlinear chirping [17] to provide a high OSNR signal for the following PM-HNLF-based nonlinear mixer. The NALM consists of a 60:40 coupler, a bi-directional erbium-doped fibre amplifier (EDFA), and a 40 m PM-HNLF 1, which has a dispersion of -0.5 ps/(nm·km) at 1550 nm). Compared to our previous design [13], we doubled the pump power to the bi-directional EDFA in the NALM and obtained about 10 dB higher power at the output of the NALM, which subsequently saturated the pulse amplifier for an improved OSNR. The output pulses after the NALM are compressed to 260 fs (red curve in Fig. 1c) with an improved signal-to-pedestal ratio of 15 dB. Following, the optical pulses are amplified to an average power of 32 dBm using a pulse amplifier (PM-FA2) before pumping the 50 m PM-HNLF 2, which has a dispersion of -1.3 ps/(nm·km) at 1550 nm and a zero dispersion wavelength of 1605 nm. The increase of pedestal suppression ratio and output power of NALM has led to a flat parametric comb output with more than 500 tones of >0 dBm per tone and a spectral flatness of <6 dB over 100 nm, as shown in Fig.1c. Considering 0.1 nm noise bandwidth, the OSNR of the broadened comb is 30-35 dB. We used a 120-pm tunable filter to extract the individual tones for the measurement to test and characterise the line-by-line RIN and phase noise. The phase noise of the EO comb and the broadened comb are measured using both RF1 and RF2.

Results and discussions

Figure 2 shows the measured linewidth of the optical tones for the parametric comb using β- seperation method [18]. The linewidth values are calculated from the phase noise measurement for 100 µs observation time. Using RF1, the linewidth scales quadratically from

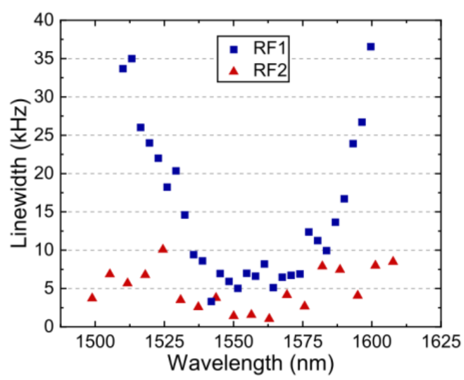

Fig. 2: Measured 100-µs linewidth for tone (with 400 GHz interval) of the parametric comb using two different RF generators: RF1 (blue square), RF2 (red triangle).

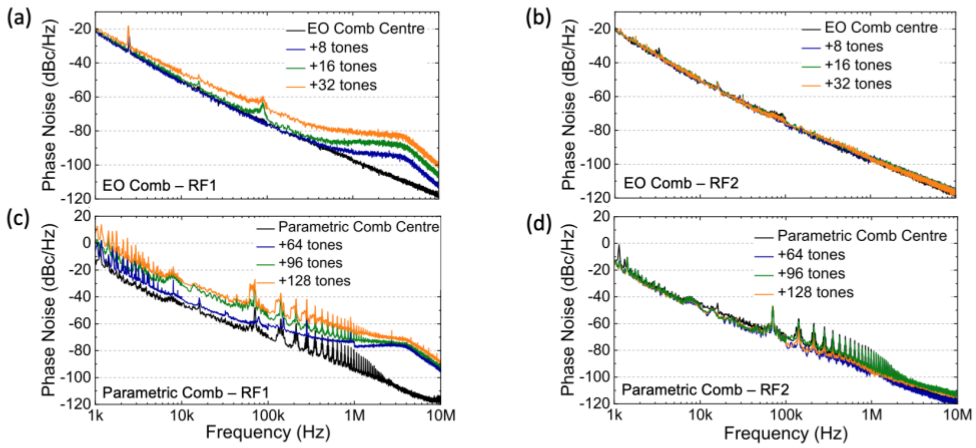

Fig. 3: Phase noise of EO comb using RF1 (a) and RF2 (b), and the broadened comb of +64 (blue), +96 (green) and +128 (orange) tone using RF1 (c) and RF 2(d), respectively.

about 7 kHz in the centre to 40 kHz at the edge. The RF2-based parametric comb generator significantly improves in 100-µs observation time where the linewidth remains sub-10-kHz over 110 nm bandwidth. This improvement is mainly due to the low phase noise of the EO comb, which is a sum of laser phase noise and the multiplied RF noise in the EO comb generation. Figure 3 shows the phase noise for each tone of both EO and parametrically broadened combs driven by RF1 and RF2. Fig.3a shows the phase noise of the EO comb using RF1. As the tone order increases, added RF noise scales with tone number, resulting in degraded optical phase noise, especially in the high-frequency region (100 kHz to 10 MHz). Due to the significantly better RF noise of RF2, the resulting EO comb phase noise does not have discernible degradation. The improved noise performance of the pump resulted in improved phase noise after the nonlinear mixer, as shown in Fig.3c-d. The strong RF phase noise from RF1 is further multiplied through the nonlinear parametric process and dominates the phase noise of the expanded comb tones. Using RF2, however, resulted in an improved phase noise with similar linewidth. Further, we observe harmonic peaks, which are multiples of 70 kHz in the expanded comb tones, as shown in both Fig. 3c and 3d. This was due to the intensity noise of the PM-FA2's pump driver that exhibits a 70 kHz harmonic tone as well as low frequency peaks in the RIN measurement in Fig.4a, which compares the RIN for laser (black curve) and laser pumped by PM-FA2 (blue curve). Interestingly, this single tone was multiplied in the nonlinear process, generating high-order harmonics into the phase noise. Finally, we measure the RIN of the parametric comb using RF2. The integrated RIN (1 kHz-10MHz) scales quadratically but is less than 0.01% over the 100 nm bandwidth, evidencing the high performance of the demonstrated comb generator.

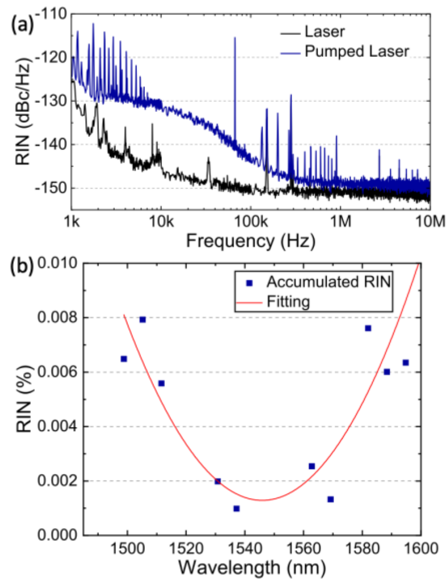

Fig. 4: RIN measurement for (a) laser (black) and pumped laser (blue). (b) Integrated RIN (blue square) and quadratic fitting (red curve) of the parametric comb.

Conclusions

We study the origin of phase noise degradation in EO comb and EO-comb-pumped parametric frequency comb, showing how RF phase noise and amplifier induced RIN affect the phase noise and linewidth of the individual tones. Our results provide insight into the noise performance of parametric frequency comb design and will benefit comb-based communication and signal processing applications.

Acknowledgements

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