Phase Correlation Between Lines of Electro-Optical Frequency Combs

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Abstract: Simultaneous measurement of the phase noise of 49 electro-optic comb lines show that the phase-noise has a correlation of over 99.99%. Also the phase noise difference between line pairs is correlated, verifying theoretical predictions.

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1. Introduction

Electro-optical (EO) frequency combs are an attractive light source for spectral superchannels in fiber optical communication systems. Apart from being able to replace a large number of lasers with a single unit, the mutual coherence of comb lines can be utilized by joint processing in the receiver to increase the phase-noise tolerance [1] or decrease the complexity of the digital signal processing [2]. However, these schemes are ultimately limited by the degree of phase coherence between the comb-lines. The phase noise characteristics of electro-optical frequency combs have been predicted theoretically and measured [3], but these measurements were limited to one line at a time, prohibiting studies of the mutual coherence between the lines.

In this work, we measure the phase noise of 49 electro-optic comb lines simultaneously. Simultaneous measurements enables us to study the phase coherence between the lines as well as the properties of the phase noise difference between the lines. We find that the phase noise has a correlation over 99.99%. In addition we find that the phase noise difference between different line pairs is also correlated, with a magnitude linearly dependent on the line index difference. The spectrum of the phase noise difference matches that of the radio frequency (RF) oscillators driving the combs. This verifies the theoretical predictions in [3].

2. Multiheterodyne experiments

The multiheterodyne technique [4], illustrated in Fig. 1(a) is based on mixing two optical frequency comb with slightly different frequency spacings. This results in a down-mixed frequency comb. The center frequency corresponds to the difference of the center lines of the two combs and line spacing of the new comb corresponds to the difference in frequency spacing between the two combs. The phase of the lines of the RF-comb is the combined phase of the corresponding lines of the two optical combs.

The experimental setup is shown in Fig. 1(b). The two EO-combs had the same number of lines with slightly different spacing owing to the use of different RF-oscillators. Since the combs were pumped with nominally identical free-running lasers, the phase noise contributions are assumed to be identical.Figure 1(c) shows a schematic of the combs, consisting of two phase modulators and one intensity modulator resulting in around 50 lines. Two external cavity lasers (ECL) were used as seed lasers.

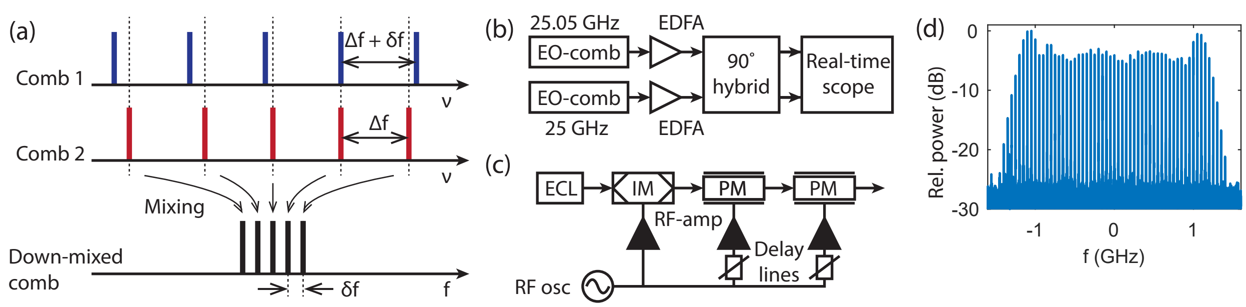

Fig. 1: (a) Principle of multiheterodyne detection. (b) Measurement setup. EDFA: Erbium-doped fiber amplifier (c) EO-comb schematic. IM: Intensity modulator, PM: Phase modulator (d) Measured spectrum of multiheterodyne signal.

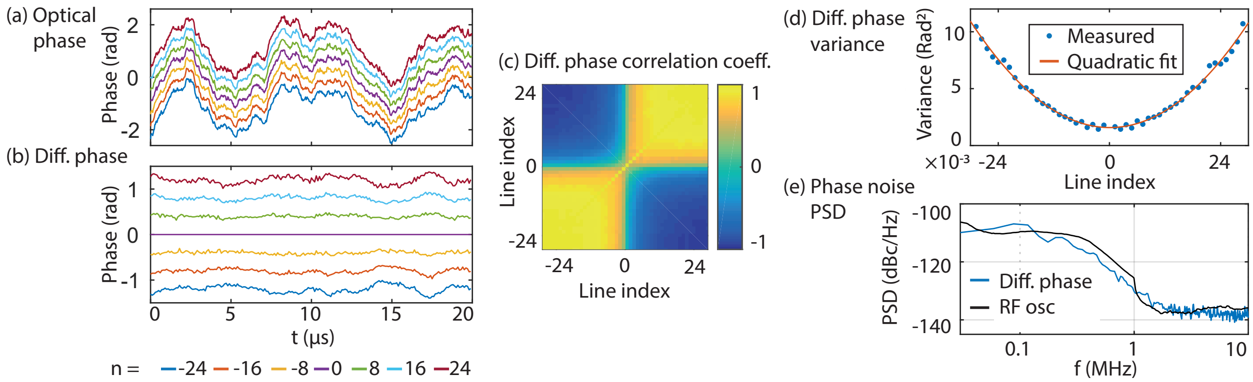

Fig. 2: (a) Optical phase of lines 0, ±8, ±16 and ±24. (b) Differential phase with respect to line 0 of lines ±8, ±16 and ±24. (c) Differential phases in (b) scaled with line index. (d) Correlation coefficient of differential phases (e) Time variance of the differential phase as a function of line index. (e) PSD of the differential phase noise measured between lines 24 and −24 together with phase noise of one of the RF oscillators.

The combs were mixed in a 90° hybrid coupler and sampled with a real time oscilloscope with a 16 GHz bandwidth. A total of 12.5 million samples at 50 GS/s was measured, corresponding to $250\,\mu s$. The spectrum of the downmixed comb can be seen in Fig. 1(d). The sampled signal was processed offline by filtering and recovering the phase evolution of the 49 detected comb lines.

3. Results

Our measurements confirm the theoretical predictions that the phase noise of the nth line of an EO-comb can be expressed $\varphi_n(t) = \varphi_0(t) + n\psi(t)$ [3]. Here $\varphi_0(t)$ is the common mode phase noise originating from the seed laser and $\psi(t)$ is the differential phase noise originating from the RF oscillator.

Figure 2(a) shows the time evolution of the measured phase $\tilde{\varphi}_n(t)$ of line 0, ±8, ±16 and ±24, with an added constant phase offset for clarity. The phases are visibly similar, and we calculated the correlation coefficient to be above 99.99% for all line combinations. By choosing the phase from the center line as a reference and subtracting it form the other lines, the differential phase $\Delta\tilde{\varphi}_n(t) = \tilde{\varphi}_n(t) - \tilde{\varphi}_0(t)$ can be found. The differential phase is plotted in Fig. 2(b), with an added constant phase offset for clarity,which shows that the differential phases are scaled versions of the same phase noise. The similarity is confirmed by the correlation coefficient, plotted in Fig. 2(d). It shows that the differential phase of lines on the same side of the center is highly correlated and that the differential phase of lines on opposite sides is anti-correlated. Furthermore, as seen in Fig. 2(e) the variance of the differential phase varies quadratically with line index, which corresponds to a linear amplitude scaling.

From our measured phase we can calculate an estimated phase noise of the RF oscillator $\tilde{\psi}(t) = (\tilde{\varphi}_n(t) - \tilde{\varphi}_m(t))/(n-m)$. Figure 2(f) shows the power spectral density (PSD) of our estimated RF phase noise, calculated with Welch's method, together with the phase noise spectrum of the RF oscillator driving the 25-GHz frequency comb, obtained with an electrical spectrum analyzer. The estimated RF phase noise has been rescaled with a factor of $1/2$ to account for the fact that two RF oscillators contribute in our measurements. The similarities in both shape and level is a strong indication that the differential phase noise originates from the RF oscillator.

4. Conclusions

We have characterized the correlation of the phase noise of electro-optical frequency combs. We find that both the common-mode and phase noise difference between different line pairs is correlated to a high degree. The phase noise difference scales linearly with line index difference, and its spectrum matches that of the RF oscillator driving the comb, indicating that it originates from the RF oscillator in accordance with previous theoretical descriptions.

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