Amplitude-to-phase conversion in fiber laser frequency combs

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In frequency metrology mode-locked fiber lasers have proven to be a powerful tool to compare arbitrary oscillators with output frequencies ranging from the microwave to optical regime[1,2]. Assuming the validity of $\Delta\phi_m = m \cdot \Delta\phi_{rep} + \Delta\phi_{CE}$ the phase excursions of any individual line (with index m) of the frequency comb can be predicted by measuring the phase excursions of only two comb modes which corresponds to a superposition of fixed correlations between fluctuations of the repetition phase ϕ_{rep} and the carrier-envelope phase ϕ_{CE} for different types of technical perturbations i, i.e. $\Delta\phi_{CE} = \Sigma_i\ \alpha^i \cdot \Delta\phi^i_{rep}$. In turn, any kind of phase noise contribution not obeying the simple linear comb equation above deteriorates the short-term stability during frequency ratio measurements[3]. An intuitive example of such harmful noise is shot noise, which simply adds uncorrelated noise to the measured phase angle of each comb mode.

However, here we want to focus on another quite intuitive example: in Kerr media amplitude fluctuations of the ultrashort input pulse cause fluctuation of the non-linear spectral phase delay. Due to the interaction of different non-linear effects, the correlation coefficient α^{nl} is no longer fixed[4]. In addition, commercially available fiber combs for metrology typically comprise several non-linear media with potentially different values of α^{nl}. They employ a common oscillator that feeds multiple Er^+-doped fiber amplifiers (EDFA) followed by short pieces of highly nonlinear fibers (NLF) to provide high-power output spectra at different wavelengths according to the customers' needs (see Fig. 1).

In order to investigate the effect of amplitude-to-phase conversion in fiber combs we stimulated a sinusoidal amplitude modulation (AM) of the mode-locked oscillator at a certain frequency ($10^2 \ldots 10^5$ Hz) and verified the resulting phase response (PM) at the NLF output at three spectral positions (virtually 0 (*f*-2*f*), 698 and 1550 nm). The AM is realized by modulating the injection current of the pump laser diodes of the common femtosecond oscillator. Finally, the measured AM-to-PM transfer coefficient is used to convert the AM spectrum of the fiber laser into PM noise at the NLF output.

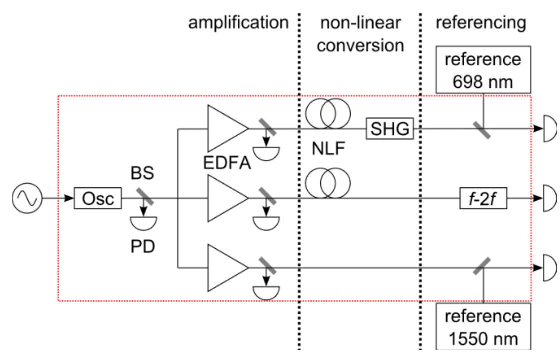

Fig. 1: Measurement set-up. The pump current of a femtosecond oscillator of a commercial multi-branch frequency comb (red box) is modulated. The amplitude and phase response of the system is measured simultaneously with photodiodes (PD). The light is split and combined using fiber splitters (BS).

From first measurements of this kind a relative frequency instability of the system due to AM-to-PM conversion of $\sigma_y = 3\times10^{-16}/\tau$ is revealed. For short averaging times this is on the order of the best oscillators available at present. Thus, if short timescales are of interest, e.g. when transferring the frequency stability to an interrogation laser of an optical clock[2], amplitude stabilization of the femtosecond oscillator may be necessary.

[1] D. Nicolodi et al., Nat. Photon. , online, doi:10.1038/nphoton.2013.361, 2014
[2] C. Hagemann et al., IEEE Trans. Instrum. Meas., vol. 62, p. 1556-1562, 2013
[3] N. R. Newbury et al., J. Opt. Soc. Am. B, vol. 24, p. 1756-1770, 2007
[4] N. Haverkamp et al., Opt. Express, vol. 12, p. 582-587, 2004