Ultrastable Femtosecond Frequency Combs for Quantum Measurements

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Optical frequency combs (OFCs) are among the most precise measurement tools in existence. They emit a spectrum of equidistant lines separated by the repetition rate f_r of a modelocked laser cavity. The entire comb is shifted from the origin by the carrier-envelope offset frequency f_{CEO}. Noise affecting the width of the individual comb teeth limits the performance of these instruments in fundamental science and high-tech industry. Here, we exploit the interplay between cavity dispersion and pump power to minimize the phase noise in fiber-based OFCs tailor-designed for applications in time-domain quantum physics.

Our femtosecond Er:fiber oscillator is presented in Fig. 1(a). Two erbium-doped fibers (EDF1, EDF2) with different dispersions β_2 form the gain medium. By adjusting the ratio between the two EDFs without changing their combined length, we vary the intracavity dispersion $\beta_{2,cav}$ while keeping all other laser parameters identical. We first analyze the performance of a 200-MHz comb. The CEO linewidth δ_{CEO} of four different oscillators is shown in Fig. 1(b). Surprisingly, the normally dispersive oscillators (green dots: $\beta_{2,cav}$ = +1100 fs^2; red diamonds: $\beta_{2,cav}$ = +1300 fs^2) exhibit distinct minima while the linewidth of those with anomalous cavity dispersion changes monotonously (black squares: $\beta_{2,cav}$ = -830 fs^2; blue triangles: $\beta_{2,cav}$ = -130 fs^2). The most extreme case occurs at +1100 fs^2 (green) where δ_{CEO} drops to 700 Hz (FWHM) at P = 505 mW (see inset in Fig. 1(b)). According to our knowledge, this is the smallest free-running CEO linewidth ever recorded for a fiber laser. Fig. 1(c) presents a broadband analysis of the frequency noise $\Delta\nu(f)$ of the oscillator with $\beta_{2,cav}$ = +1100 fs^2 at P = 505 mW. The frequency noise of f_{CEO} (green) is white, pointing at a quantum origin. The noise spectra of the optical lines between 141 THz and 282 THz show additional contributions: A low-pass characteristics is found at kHz frequencies originating from intensity fluctuations of the optical pump power. For frequencies below 1 kHz, a component decreasing with 1/f emerges. This feature is due to environmental noise affecting the cavity length. A full understanding of the phenomena leads us to the design of OFCs with quantum-limited optical linewidths below 1 kHz over ultrabroadband spectral ranges [1].

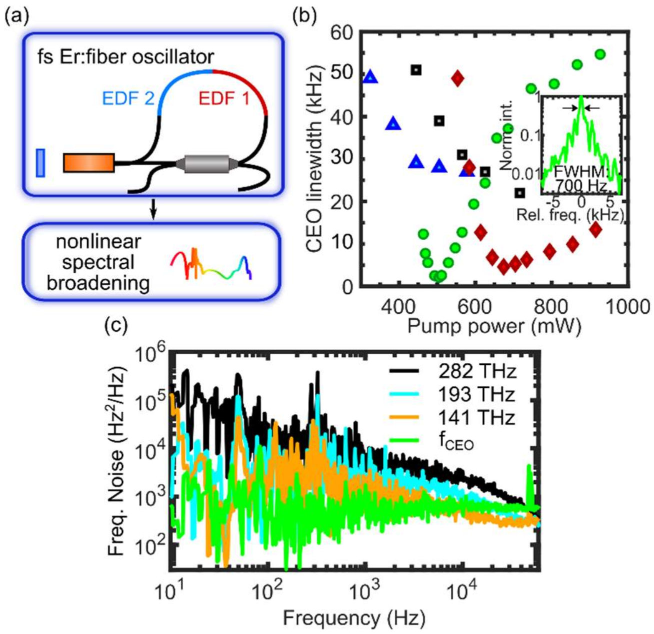

Fig. 1: *(a) Sketch of mode-locked Er:fiber oscillator. (b) CEO linewidth versus pump power of four oscillators differing in cavity dispersion only. Inset: RF spectrum of sharpest CEO beat at P = 505 mW. (c) Broadband frequency noise analysis of oscillator with* $\beta_{2,cav}$ *= + 1100 fs*^{2} *at P = 505 mW. Noise spectra of* f_{CEO} *(green) and of three optical teeth.*

References:

[1] S. R. Hutter, A. Seer, T. König, R. Herda, D. Hertzsch, H. Kempf, R. Wilk, and A. Leitenstorfer, *submitted for publication*.