Vibration immune fiber-laser frequency comb based on a polarization-maintaining figure-eight laser

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Abstract: A frequency comb is phase-locked to a cw laser with an electro-optic-modulator providing 1.6 MHz feedback bandwidth. Residual phase noise is as low as -94 dBc/Hz, and the comb remained locked under mechanical vibration of up to 1.9 g.

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Frequency combs are versatile tools and find applications in different fields such as distance metrology, microwave generation, spectroscopy, and optical waveform measurements. State-of-the-art Ti:Sapphire, Er-fiber, and most recently, Yb-fiber combs can all be phase-locked to an optical reference with sub-radian phase noise [1-3], and a corresponding residual frequency stability of 10^{-18} or below, well in excess of that needed for current optical clocks [4-6]. However, the combs still suffer from excess residual phase excursions that lead to a pedestal on any RF heterodyne beat signal and limit the fraction of the carrier power residing in the coherent peak. Moreover, in the presence of vibrations this excess noise will only increase, eventually leading the system to lose phase lock, and even causing the laser to stop mode-locking. With the expanding application of combs outside of standard optical frequency metrology, and eventually outside of a laboratory setting, we require a comb that can maintain a very tight phase lock to a reference oscillator even in the presence of vibration. Here we present an optical frequency comb based on a polarization-maintaining (PM) all-fiber figure-eight laser with a high-bandwidth intracavity electro-optical modulator (EOM) feedback; both the PM fiber and the high-bandwidth feedback ensure environmental robustness.

Fig. 1 shows a schematic of the comb. The comb was referenced against a cavity-stabilized cw fiber laser at ~1560 nm with a ~1 Hz linewidth. The resulting RF beat f_{1560} was phase-locked to a 50 MHz oscillator with a high-bandwidth servo that feeds back to the cavity length by use of the EOM and an additional piezoelectric transducer (PZT) that increases the dynamic range of the cavity feedback at low frequencies. The resulting in-loop phase noise power spectral density (PSD) is shown on the right panel of Fig. 1. The bandwidth of this optical lock is limited to 1.6 MHz by the servo loop filter. As a result of this tight phase lock, any excess phase noise of f_{1560} above the white phase noise floor at -94 dBc/Hz is completely suppressed at Fourier frequencies below 200 kHz, and the in-loop phase lock can even "dig in" down to -105 dBc/Hz at those low frequencies. On a separate branch, the output pulses of the figure-eight laser were amplified, compressed, and launched into a highly nonlinear fiber to generate an octave-spanning continuum; the carrier-envelope offset (CEO) frequency beat was then detected with the standard f-to-2f technique [7] and locked by feedback to the figure-eight's pump laser.

To demonstrate the insensitivity of the PM fiber frequency comb to vibrations, we placed the figure-eight laser on a vibration stage consisting of a 12" × 12" Al breadboard with an audio speaker attached to the board's bottom side, as shown in the left panel of Fig. 2. The speaker was driven by a power amplifier with a swept sine wave input ranging from 40 Hz to 3 kHz. At the center of the breadboard, the strongest acceleration amounts to 1.9 g and occurs at 1 kHz. To quantify the response of the laser to vibration, the right part of Fig. 2 compares the rms phase noise of f_{1560} (φ_{1560}) and of the CEO beat (φ_{CEO}) to the rms vibration amplitude (A, obtained by averaging accelerometer measurements at different locations on the breadboard) for different vibration modulation frequencies f_m. From these data, the vibration sensitivity Γ per g of acceleration was extracted for f_{1560} by use of $\Gamma = \varphi_{1560} / A \times f_m / f_0$, where f_0 = 192 THz is the frequency of the cavity-stabilized cw reference laser. Γ, shown on the top right panel of Fig. 2, is proportional to f_m, because the feedback converts vibration-driven frequency fluctuations into phase fluctuations and stays below 10^{-13} g^{-1} up to f_m = 500 Hz; it is well below that of state-of-the-art cavity-stabilized lasers within typical environmental vibration bandwidths of less than 3 kHz [8-11].

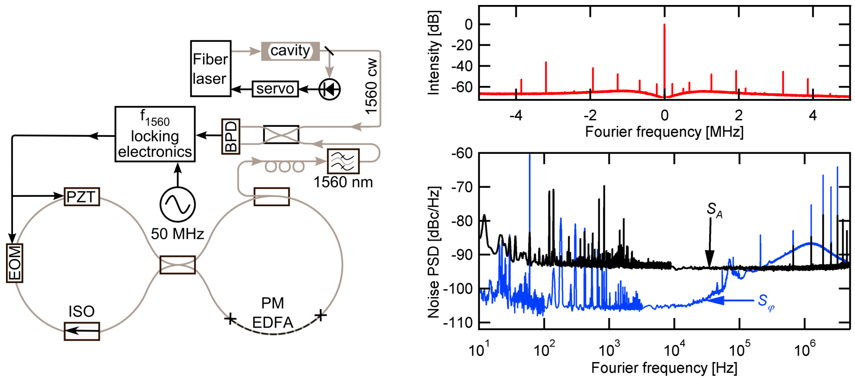

Fig. 1: Left: schematic of the comb (the CEO locking branch is not shown); BPD: balanced photodetector, ISO: isolator. Right: normalized spectrum (shifted by -50 MHz, top) as well as phase (S_φ) and amplitude (S_A) noise power spectral density (PSD) (bottom) of the optical lock beat f_{1560}.

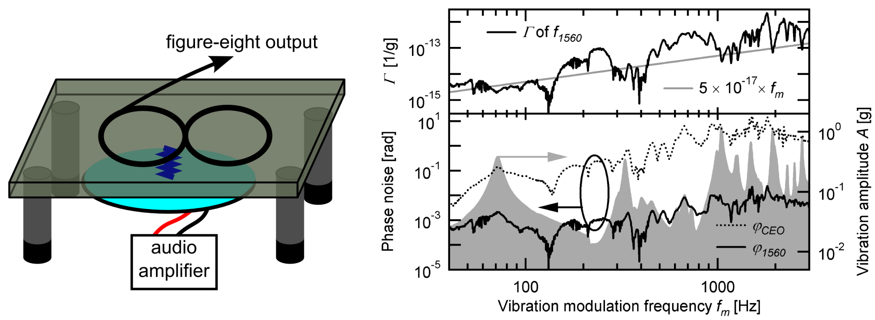

Fig. 2: Left: schematic of the shaking experiment. The laser actually covers the complete breadboard surface. Right: phase noise of the optical and CEO locks under vibration and average vibration amplitude on the breadboard (bottom); vibration sensitivity Γ of the optical lock (top).

In conclusion, we have presented a fiber comb based on an all-fiber PM figure-eight laser with a tight optical phase lock with a 1.6 MHz bandwidth limited by our loop filter, and a residual phase noise floor as low as -94 dBc/Hz. Even at vibration levels of 1.9 g, the comb remains phase-locked, with a frequency stability suitable for the next generation of optical clocks and a residual optical linewidth below that of the next generation of cavity-stabilized lasers; at a vibration modulation frequency of f_m=100 Hz, a vibration sensitivity of $\Gamma = 4.5\times10^{-15}$ g^{-1} was measured.

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