High-performance, vibration-immune, fiber-laser frequency comb

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We demonstrate an environmentally robust optical frequency comb based on a polarization-maintaining, all-fiber, figure-eight laser. The comb is phase locked to a cavity-stabilized cw laser by use of an intracavity electro-optic phase modulator yielding 1.6 MHz feedback bandwidth. This high bandwidth provides close to shot-noise-limited residual phase noise between the comb and cw reference laser of −94 dBc/Hz from 20 Hz to 200 kHz and an integrated in-loop phase noise of 32 mrad from 1 Hz to 1 MHz. Moreover, the comb remains phase locked under significant mechanical vibrations of over 1 g. This level of environmental robustness is an important step toward a fieldable fiber frequency comb.
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Initially developed for optical frequency metrology and the support of optical clocks [1,2], frequency combs are proving quite versatile and are finding applications in distance metrology, microwave generation, spectroscopy, and optical waveform measurements. These applications make use of the ability to phase lock the teeth of the frequency comb to a reference oscillator. In optical frequency metrology, the primary metric is the relative frequency stability between the relevant comb teeth and reference oscillator over long periods (i.e., seconds and longer). However, in other applications one would like the full coherence of the reference oscillator to be transferred to each comb tooth over shorter periods. State-of-the-art Ti:sapphire, Er-fiber, and Yb-fiber combs can be phase locked to an optical reference with subradian phase noise [3–5], and a corresponding residual frequency stability of 10^{-18} or below, well in excess of that needed for current optical clocks [6,7]. However, there remains excess phase noise at close-in Fourier frequencies; in other words, the comb teeth still do not precisely follow the optical reference frequency. Moreover, in the presence of vibrations this excess phase noise increases, eventually leading the comb to lose phase lock, and possibly even causing the underlying femtosecond laser to stop mode locking. A comb that can achieve a very tight phase lock to the reference oscillator and maintain that tight phase lock even in the presence of vibration is needed to enable the expanding application of combs outside of standard optical frequency metrology and outside of a laboratory setting.

Fiber-laser-based combs have the advantage of environmental robustness compared to solid-state-based combs [8,9]. Here we use a polarization-maintaining (PM)-fiber figure-eight laser to obtain environmental robustness [10]. It includes a commercial intracavity lithium niobate electro-optic phase modulator (EOM) that is driven at the figure-eight's repetition rate of 27.56 MHz to initiate mode locking;

the EOM is switched off afterwards, and the laser operates passively. The EOM can then be used to feedback to the cavity length [11]; it provides a feedback bandwidth in excess of 1.6 MHz, enabling a tight phase lock of one comb tooth to a reference cavity-stabilized cw laser (a so-called optical lock). The fundamental limit to the excess phase noise in this optical lock is the shot noise limit set by the power in the comb tooth. With the high feedback bandwidth we reach this limit, in our case −94 dBc/Hz, at Fourier frequencies from ∼20 Hz to 200 kHz with a peak excess phase noise of −86.7 dBc/Hz at 1.2 MHz.

This high-bandwidth feedback can also be used to suppress the effects of vibration on the comb performance. Vibrations will lead to changes in the resonant frequency of an oscillator, since they lead to changes in the underlying physical cavity length. The vibration sensitivity of oscillators is characterized by Γ, the fractional frequency fluctuation per g of acceleration. For rf oscillators, Γ is a few parts in $10^{-10}\,g^{-1}$ [12]. For cavity-stabilized lasers, Γ has been reduced to similar values [13–16]. To maintain this hard-won level of vibration insensitivity in a stabilized fiber comb, the residual frequency noise in the optical lock between the comb and the cavity-stabilized laser should have an even lower effective value of Γ. Our comb has, without any special packaging, a residual Γ of less than $2.2 \times 10^{-12}\,g^{-1}$ for typical environmental vibration bandwidths below 3 kHz, below that of state-of-the-art cavity-stabilized lasers. Furthermore, the comb remains mode and phase locked even when the figure-eight laser is subject to vibrations of over 1 g.

The configuration of the comb is shown schematically in Fig. 1(a). The intracavity EOM is fiber coupled with an insertion loss of 1.6 dB, a 20 GHz bandwidth, and a V_π of ±4.1 V. The output pulses of the figure-eight laser are amplified by an erbium-doped fiber amplifier (EDFA) from 0.2 to 1.6 nJ, com-
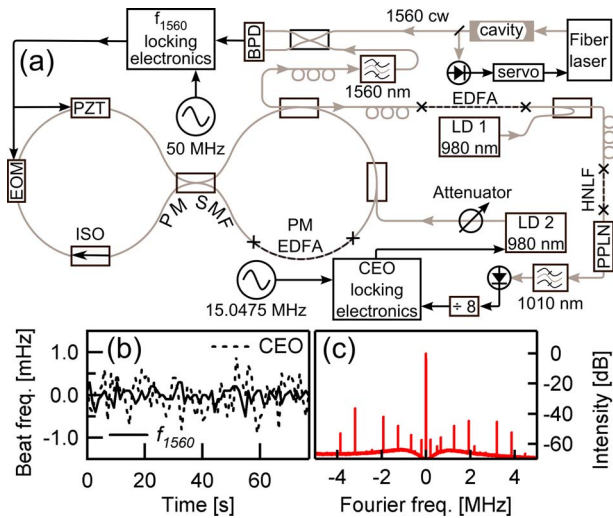
Fig. 1. (Color online) (a) Setup of the optical comb. Black lines represent wire, and gray lines and curves represent fiber. Only the intracavity fiber of the figure-eight laser is PM. BPD, balanced photodetector; ISO, optical isolator; PPLN, periodically poled LiNbO$_3$; LD, laser diode. (b) The counted beat frequencies of the optical and CEO locks with a 1 s gate time are counter limited. These data were taken while the comb laser was being actively vibrated at over 1 g. (c) The rf spectrum of the locked beat note between the figure-eight laser and the 1560 nm cw reference laser with a resolution bandwidth of 300 Hz.

Fig. 2. (Color online) (a) In-loop phase and amplitude noise PSD S_φ and S_A of the optical lock beat f_{1560} at 50 MHz and the corresponding S_φ under white-noise vibration (shaded area). For comparison the optical lock S_φ (ring) of a ring laser is also shown. (b) Schematic setup of the vibration experiment consisting of a 30 cm × 30 cm breadboard on aluminum–rubber posts with a speaker beneath driven by an audio amplifier. The figure-eight laser is simplified; it actually covers the whole breadboard surface. (c) rms acceleration pattern for a swept sine wave measured with an accelerometer placed at different points on two lines from points A to B and C to D [as indicated in (b)] on the vibrating breadboard. At the center of the breadboard, the strongest acceleration is 1.9 g and occurs at 1 kHz.

pressed in ∼47 cm of single mode fiber (SMF) to a 53 fs FWHM, and launched into ∼45 cm of highly nonlinear fiber (HNLF) [17] to generate an octave-spanning continuum. As shown in Fig. 1(a), the carrier-envelope offset (CEO) frequency is phase locked with a feedback bandwidth of 59 kHz using a standard approach [18]. The optical lock is achieved by heterodyning a cavity-stabilized cw fiber laser at ∼1560 nm with optically filtered light from the rejection port of the figure-eight laser. Using light from the rejection port rather than the supercontinuum (as well as using balanced detection) allows us to optimize the signal-to-noise ratio on this heterodyne beat note, f_{1560}, as in two-branch comb systems [19]. The resulting beat note is phase locked to an rf oscillator by feeding back to the cavity length by use of the EOM and an additional piezoelectric transducer (PZT), which increases the dynamic range of the cavity feedback at low frequencies. The optical lock bandwidth, estimated at the feedback oscillation frequency, is limited by the servo loop filter to 1.6 MHz and is 1 order of magnitude wider than in previous combs.

As shown in Fig. 1(c) the rf spectrum of the optical beat, f_{1560}, exhibits a single resolution-limited peak on an almost flat noise background. [The rf spikes at and above 200 kHz are partially a result of uncompensated electromechanical resonances between the PZT and the high voltage amplifier; the low frequency spikes, seen in Fig. 2(a), are harmonics of 60 Hz.] Figure 2(a) shows the corresponding in-loop phase-noise power spectral density (PSD) S_φ. Any excess phase noise of the beat note above the white phase-noise floor at −94 dBc/Hz is completely sup-
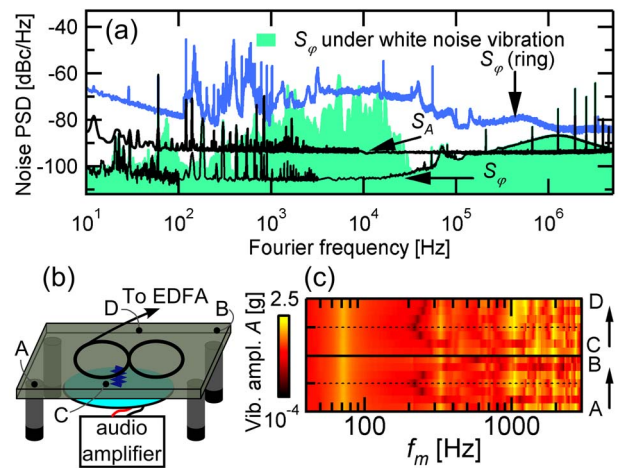
pressed at Fourier frequencies below 200 kHz, and the phase lock can even "dig in" down to −105 dBc/Hz at those low frequencies. (This dig in would not be observed in an out-of-loop measurement, but indicates how tightly the comb and reference can be locked.) For comparison, we also show the phase-noise PSD, S_φ(ring), from a metrology frequency comb based on a fiber ring laser with a fast PZT [4,7]. The extrapolated integrated phase noise of the figure-eight laser up to the Nyquist frequency of 13.78 MHz is 138 mrad and is dominated by the servo bump at 1.2 MHz and the white phase-noise floor that extends to the Nyquist frequency. The contribution of the f_{1560} phase noise to the residual timing jitter is 26 as integrated from 1 Hz to 1 MHz; the residual timing jitter is completely limited by the residual noise on the CEO frequency [18].

To demonstrate the insensitivity of the fiber frequency comb to vibrations, we placed the figure-eight laser on a breadboard connected to a speaker as illustrated in Fig. 2(b). We did not directly vibrate the other parts of the comb including the EDFA, HNLF, or CEO detection. In a first experiment, the speaker was driven by a white-noise signal, resulting in an integrated acceleration of 1.6 g at the breadboard's center. The comb remained phase locked throughout this experiment; the shaded area in Fig. 2(a) represents the in-loop phase-noise PSD of f_{1560} (S_φ) measured under white-noise vibration. At frequencies around 5 kHz, S_φ is lifted to about −75 dBc/Hz, compared to −105 dBc/Hz in the absence of vibrations; at frequencies above 25 kHz and below 30 Hz, S_φ is not affected
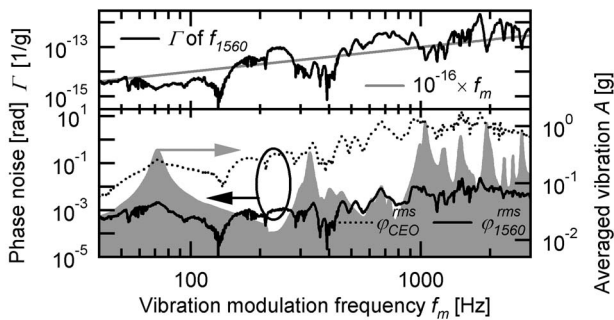
Fig. 3. Top, vibration sensitivity Γ of f_{1560}; the gray line visualizes the increase of Γ with roughly $10^{-16}\,\mathrm{Hz}^{-1}\,g^{-1} \times f_m$. Bottom, rms phase noise of the CEO beat and the optical f_{1560} beat along with the spatially averaged breadboard acceleration spectrum.

by the white noise, owing to the frequency response of the amplifier and speaker. To further quantify the response of the laser to vibration, we drove the speaker with a swept sine wave input ranging from 40 Hz to 3 kHz. The lower part of Fig. 3 compares the rms phase noise of the optical f_{1560}, ($\varphi_{1560}^{\mathrm{rms}}$) and of the CEO ($\varphi_{\mathrm{CEO}}^{\mathrm{rms}}$) beat to the rms vibration amplitude, A, taken as the spatial average of the breadboard acceleration shown in Fig. 2(c), versus the vibration modulation frequency f_m. From these data, the vibration sensitivity Γ of f_{1560} can be extracted by use of $\Gamma = \varphi_{1560}^{\mathrm{rms}}/A \times f_m/v_0$, where $v_0 = 192$ THz is the frequency of the cavity-stabilized cw reference laser. The general trend of the computed Γ, shown in the upper part of Fig 3, is proportional to f_m, because the feedback converts vibration-driven frequency fluctuations into phase fluctuations; deviations are caused by the complex vibration pattern, which affects different parts of the laser in different ways. Conservatively, Γ stays below $10^{-13}\,g^{-1}$ up to $f_m = 500$ Hz, which is better than that of current high-performance optical cavities.

In conclusion, we have presented a fiber comb based on an all-fiber, PM figure-eight laser. The fast in-line PM EOM in series with a slow PZT resulted in 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, close to the shot-noise limit. Even at high vibration levels of well over $1\,g$, 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. While a full characterization with a completely packaged compact comb on a standard vibration table is needed, this work is a first step toward a fieldable frequency comb, which could be useful for applications ranging from portable optical clocks to lidar to spectroscopy. With this approach, the comb would not require an active vibration isolation table or special vibration-isolation packaging to compensate for vi-

brations encountered in buildings ($\approx 0.02\,g$), spacecraft ($\approx 0.2\,g$), or even vibrations on aircraft or other moving platforms ($\approx$ several g) [12]. Finally, the low close-in phase-noise is promising for the generation of low-noise microwave signals, provided that the design can be migrated to significantly higher repetition rates.

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