

Phase-locked, erbium-fiber-laser-based frequency comb in the near infrared

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A phase-locked frequency comb in the near infrared is demonstrated with a mode-locked, erbium-doped, fiber laser whose output is amplified and spectrally broadened in dispersion-flattened, highly nonlinear optical fiber to span from 1100 to >2200 nm. The supercontinuum output comprises a frequency comb with a spacing set by the laser repetition rate and an offset by the carrier-envelope offset frequency, which is detected with the standard f -to- $2f$ heterodyne technique. The comb spacing and offset frequency are phase locked to a stable rf signal with a fiber stretcher in the laser cavity and by control of the pump laser power, respectively. This infrared comb permits frequency metrology experiments in the near infrared in a compact, fiber-laser-based system.

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In the past several years, stabilized frequency combs have revolutionized frequency metrology and optical clocks.¹⁻³ The output of a mode-locked laser forms a comb of optical frequencies with a spacing set by the laser repetition rate, f_r , and the comb offset from zero, f_0 , set by the carrier-envelope offset (CEO) frequency. Mathematically, the frequency of the n th tooth of the optical frequency comb is simply given by $f_n = nf_r + f_0$. Although it is reasonably straightforward to phase lock the repetition rate to a rf source, it is more difficult to detect and control f_0 . Such detection is accomplished typically by broadening the output of the mode-locked laser to cover a full factor of 2 in frequency (i.e., an octave). The CEO frequency, f_0 , can then be detected through the heterodyne beat frequency between the high-frequency end of the supercontinuum and the doubled low-frequency end of the supercontinuum in an f -to- $2f$ interferometer.² If f_0 is then phase locked to a stable rf oscillator by feedback to the laser, a self-referenced stabilized frequency comb is established. Previously, all phase-locked frequency combs were restricted to wavelengths from 400 to 1100 nm, which is the typical extent of the supercontinuum from a Ti:sapphire-laser-pumped microstructure fiber.

Clearly other regions of the spectrum are of interest for optical frequency metrology; the near-infrared region from 1300 to 1700 nm is of particular interest because of its importance to telecommunications and optical sensing. In a significant step toward a compact phase-locked frequency comb in the infrared, Tauser *et al.*⁴ recently demonstrated self-referenced detection of f_0 with the supercontinuum generated from a fiber-laser-based system. In related work Hong *et al.*⁵ also demonstrated a clever method of detecting f_0 in a doubled fiber-laser-based system. Here we build on the work of Tauser *et al.* by demon-

strating a fully phase-locked comb in the infrared by use of a fiber-laser-based system that exploits a newly developed highly nonlinear fiber.^{6,7} Phase locking both degrees of freedom of the comb to a rf synthesizer directly links the optical frequencies of the comb to a rf oscillator. Stabilization of the comb is required for a wide range of applications, including precision frequency metrology, optical frequency synthesis, high-precision Doppler lidar, precision spectroscopy, stable rf signal generation,⁸ and fiber transmission of optical frequency standards. Furthermore, the fiber-laser-based comb generator has a number of advantages over Ti:sapphire-laser-based systems. It can be much more compact, more robust, lighter, and more power efficient than a bulk optic solid-state laser system and would require less alignment. Finally, it can be easily integrated into a telecommunication system.

Previous to this work, any phase-locked, stabilized comb in the infrared required two references: a rf reference to set the comb spacing and an optical reference to set f_0 . Researchers at NTT have developed an 80-nm-wide supercontinuum source for telecommunications by use of a mode-locked laser diode that was frequency locked to an optical reference.⁹ Researchers at JILA have used a separately stabilized Ti:sapphire-laser-based frequency comb to frequency lock the output of a mode-locked Er-doped fiber laser¹⁰ and, more recently, to phase lock the output of a mode-locked laser diode.¹¹ In another experiment the output of a mode-locked Cr:forsterite laser was broadened to nearly a full octave and stabilized to a hydrogen maser and the Ca optical standard.¹² The difficulty with all these approaches is the requirement of a separate optical reference. Self-referenced detection of f_0 obviates this requirement,^{2,4} and in this work we demonstrate an infrared

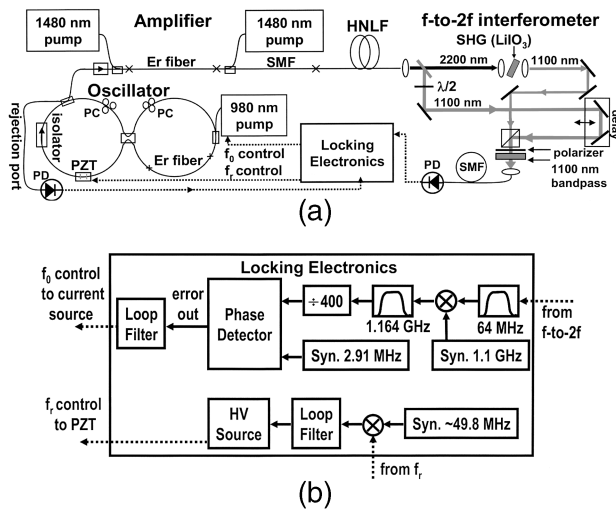


Fig. 1. (a) Schematic of the mode-locked fiber laser, optical amplifier, HNLF, and f -to- $2f$ interferometer used to generate the locked frequency comb. Photodetectors (PD) provide the locking electronics with both the repetition rate (f_r) and CEO beat frequency (f_0). Thick solid lines represent fiber-free-space optical paths, thin solid lines represent fiber-optic paths, and the dotted lines represent electrical paths. SMF, single-mode fiber; SHG, second-harmonic generation; PC, polarization controller. (b) Electronics used to lock f_r and f_0 . The repetition rate is mixed with a 49.8-MHz signal, and the error signal is used to control the PZT fiber stretcher in the laser cavity. The f_0 signal at 64 MHz is filtered, mixed with a 1.1-GHz signal, and divided by 400 in frequency. This signal is compared with a 2.91-MHz signal by a digital phase detector, and the error signal is used to control the 980-nm pump laser current. All synthesizers were referenced to a common time base. HV, high-voltage.

comb for which both the repetition rate and the CEO frequency are phase locked to a stable rf signal.

A schematic of the experimental setup is shown in Fig. 1. A figure-eight laser^{13,14} with ~ 1 m of Er-doped fiber supplies 0.06-nJ pulses at an ~ 50 -MHz repetition rate (3 mW of output power) with a spectral FWHM of 20 nm, corresponding to a bandwidth-limited duration of 130 fs. The output is amplified to 100 mW (2 nJ per pulse) and spectrally broadened in an Er-doped fiber amplifier that also uses ~ 1 m of Er-doped fiber and the appropriate length of single-mode fiber to compensate the dispersion of the Er-doped fiber, thereby minimizing the duration of the amplified pulse. Although the amplified pulses developed observable wings in the interferometric correlations, no sign of pulse breakup was seen. The amplified pulses, which have a pulse duration of < 70 fs and a spectral width of 80 nm, are then injected into a 23-cm-long piece of dispersion-flattened highly nonlinear fiber (HNLF) to produce a supercontinuum [Fig. 2(a)]. The fiber design is closely related to that of Refs. 6 and 7 with modifications made to reduce the dispersion slope by a factor of 2.5. The HNLF uses a combination of Ge and F dopants to produce a nonlinear coefficient of $\gamma \sim 10.6$ W⁻¹ km⁻¹, a dispersion of 1.74 ps/nm/km, and a dispersion slope of 0.009 ps/nm²/km at 1550 nm.

The generation of an octave-spanning supercontinuum does not guarantee the observation of an f_0 heterodyne beat, and there are at least two important similarities between this work and Ref. 4 that did permit observation of the heterodyne beat signal. First, a short ($\ll 1$ -m) length of HNLF is used to generate the octave of the continuum; indeed, we were unable to observe a heterodyne beat signal with the same ~ 1 -m lengths of HNLF in Refs. 6 and 7. Second, the excess noise generated during supercontinuum generation¹⁵ is minimized by use of short, sub-100-fs, amplified laser pulses. Unlike in Ref. 4, we employ a figure-eight fiber laser rather than a stretched pulse laser; currently, it is not clear what effect the oscillator design has on the ability to control the f_0 beat. Also unlike in Ref. 4, the supercontinuum is generated in a completely all-fiber system, since the HNLF is directly spliced to the amplifier output, with an ~ 0.2 -dB splice loss. As a result, we avoid the adjustments of coupling into the nonlinear fiber, which is a serious problem for Ti:sapphire-laser-based systems that use microstructure fiber.

The repetition rate, f_r , was phase locked, as shown in Fig. 1(b) by feedback to a piezoelectric (PZT) fiber stretcher, which had a resonant frequency of 5.5 kHz and a full dynamic range of ~ 7 μ m, corresponding to ± 45 Hz in f_r . The laser remained mode locked over

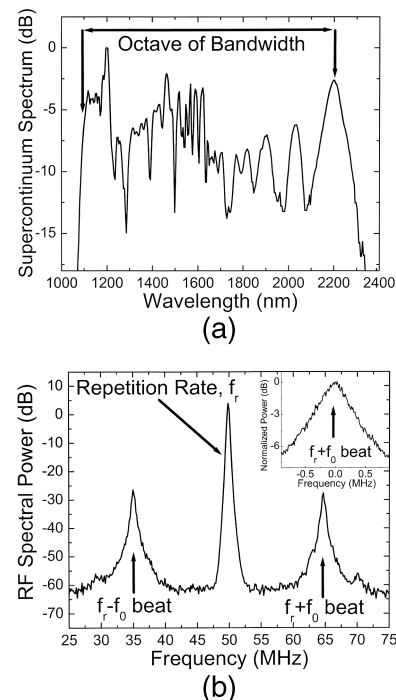


Fig. 2. (a) Supercontinuum generated from the 23 cm of HNLF, showing an octave of bandwidth from 1100 to 2200 nm. The spectrum was acquired with a 1/8m double monochromator and an InAs detector. (b) rf power spectrum from mixing the 1100-nm portion of the supercontinuum with the frequency-doubled 2200-nm portion for an average of ten traces and a bandwidth of 300 kHz. The repetition rate signal at 49.8 MHz and CEO beat frequency (f_0) are clearly seen. The signal-to-noise ratio of the beat in a 300-kHz bandwidth is typically 30 dB. Inset, expanded $f_r + f_0$ beat signal.

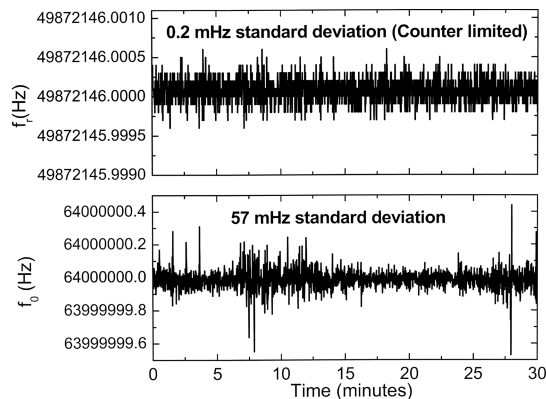


Fig. 3. Frequency counter results for a 1-s gate time for the locked repetition rate (f_r) and CEO beat frequency (f_0).

the full range of the PZT motion. The counted f_r is shown in Fig. 3. Phase-noise measurements show an integrated residual in-loop phase error up to the Nyquist frequency of 25 MHz of <1 mrad, which is the limit of our current phase-noise measurement system.

To detect the CEO beat frequency, f_0 , we employed the conventional f -to- $2f$ self-referencing technique, as shown in Fig. 1. A dichroic mirror at the HNLF output transmits the supercontinuum above 1800 nm. The 2200-nm light is doubled by second-harmonic generation in a type I phase-matched, 1-mm-thick LiIO₃ crystal. This light is then combined with the fundamental light at 1100 nm on a beam splitter, filtered with an 11-nm-wide optical bandpass filter, and launched into a single-mode fiber to ensure spatial overlap. The interference between the ~ 10 μ W of the fundamental 1100-nm light and the 35 nW of the doubled 2200-nm light is detected with a 125-MHz InGaAs photoreceiver, producing the rf spectrum shown in Fig. 2(b). The beat signal, f_0 , is then phase locked, as shown in Fig. 1, by feedback to the 980-nm pump power. (A change in the pump power affects mainly f_0 rather than f_r , yielding a relative frequency shift of $\Delta f_0/\Delta f_r = 5 \times 10^6$.) The counted f_0 is shown in Fig. 3. Phase-noise measurements of the in-loop phase noise for the divided-down signal at 2.91 MHz show an integrated phase error of ~ 50 mrad.

Several significant technical difficulties were solved to phase lock the CEO beat frequency. First, we minimized the length of the HNLF needed to generate an octave of continuum to minimize excess noise generation^{15–17} and temporal spreading of the output. Second, we eliminated environmentally induced drifts in the unlocked f_r and f_0 by mounting the entire laser, amplifier, and HNLF in an enclosed box with a baseplate that was temperature controlled to 0.1°C. Finally, although the full width of the f_0 beat signal was ~ 600 kHz, the feedback control was limited to an ~ 4.5 -kHz bandwidth by the response of f_0 to changes in the pump power; hence the large frequency division in the locking electronics shown in Fig. 1(b).

In this Letter we have demonstrated for the first time a fully phase-locked fiber-laser-based frequency comb in the near infrared. Like Ti:sapphire-

laser-based combs, this comb can remain stably locked for hours at a time. Moreover, the counted phase-locked frequencies exhibit a stability comparable with the initial Ti:sapphire-laser-based systems.³ Finally, a fiber-optic system has a number of potential advantages over a bulk optic system, since it can be much more compact and lighter, require fewer adjustments, consume much less power, and exploit the large range of available telecommunication technologies.

Note added in proof: We have since reduced the uncertainty of f_0 from 57 to 10 mHz.

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