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-2$f$ 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 $f_n = n f_r + f_0$. 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-2$f$ 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 demonstrating 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...
produce a nonlinear coefficient of $g$. HNLF uses a combination of Ge and F dopants to reduce the dispersion slope by a factor of 2.5. The fiber design is closely related to that of Refs. 6 and 7 with modifications made to the continuum [Fig. 2(a)]. The fiber 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 $\sim$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 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 ($\sim1$-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 $\sim1$-m lengths of HNLF in Refs. 6 and 7. Second, the excess noise generated during supercontinuum generation 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 $\sim$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.

A schematic of the experimental setup is shown in Fig. 1. A figure-eight 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 ($f_{0\text{-beat}}$). Thick solid lines represent 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.

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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 $\mu$m, corresponding to ±45 Hz in $f_r$. The laser remained mode locked over...
shown in Fig. 2(b). The beat signal, InGaAs photoreceiver, producing the rf spectrum doubled 2200-nm light is detected with a 125-MHz the fundamental 1100-nm light and the 35 nW of the

 generation in a type I phase-matched, 1-mm-thick output transmits the supercontinuum above 1800 nm.


 The 2200-nm light is doubled by second-harmonic

of continuum to minimize excess noise

as shown in Fig. 1. A dichroic mirror at the HNLF

overlap. The interference between the

fundamental light at 1100 nm on a beam splitter,

limited to an

beat signal was

Nyquist frequency of 25 MHz of

an integrated residual in-loop phase error up to the

locked repetition rate

in Fig. 3. Phase-noise measurements show

frequency comb in the near infrared. Like Ti:sapphire-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. 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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