Fiber-laser-based frequency comb with a tunable repetition rate

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Abstract: A phase-locked, self-referenced frequency comb generated by a mode-locked fiber soliton laser with a tunable repetition rate is presented. The spacing of the frequency comb is set by the laser's repetition rate, which can be scanned from 49.3 MHz to 50.1 MHz while one tooth of the comb is held phase-locked to a stable RF source. This variable repetition-rate frequency comb should be useful for wavelength and length metrology, synchronization of different fiber laser-based frequency combs, and the generation of precise swept wavelength sources.

OCIS codes: (140.3510) Lasers, Fiber; (190.4370) Nonlinear Optics, Fibers; (120.3930) Metrological Instrumentation;

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1. Introduction

Phase-locked self-referenced fiber-laser-based frequency comb sources have been developed for precision infrared frequency metrology using a figure-eight fiber laser [1], a pulse-compression mode-locked fiber laser [2], and several different designs of fiber ring lasers [3-5]. The basic designs of the fiber-laser frequency combs duplicate that used for Ti:Sapphire laser-based frequency combs [6, 7]; an octave-spanning supercontinuum [8] is generated and used to detect the carrier envelope offset (CEO) frequency [9, 10]. Unlike their Ti:sapphire laser-based counterparts, fiber laser-based frequency combs can be relatively compact and operate in the telecommunications band. As a result, they are of particular importance for telecommunications and optical sensing applications.

Here we describe a frequency comb based on a passively mode-locked soliton laser [11] with a tunable repetition rate. The high gain of the fiber laser allows us to change its repetition rate by 800 kHz, or ~1.6 %, using a fiber-coupled free-space delay line with a ~1 dB insertion loss. By injecting amplified pulses from the soliton laser into highly nonlinear fiber, we can generate the octave of supercontinuum bandwidth needed to self-reference the frequency comb using the standard f-to-2f interferometer [6]. In a closely related work, a passively mode-locked fiber laser with a variable repetition rate was recently demonstrated [12]; here we demonstrate that the repetition rate can be significantly changed while the laser remains mode-locked *and* the comb offset frequency remains phase-locked to a microwave reference.

The optical frequency of the n^{th} tooth of a self-referenced comb is given by the simple expression $f_n = nf_r + f_0$, where f_r is the repetition rate and f_0 is the comb offset frequency, set by the CEO frequency. The CEO frequency is given by $f_0 = (\omega_0/2\pi)(1-v_g/v_p)$, where ω_0 is the carrier frequency of the laser pulse, and v_g (v_p) is the appropriately averaged group (phase) velocity around the fiber laser cavity. For the fiber laser, $f_0 \sim 2.5$ THz. However, in metrology experiments using a self-referenced comb, the offset frequency is typically defined modulo f_r to a range $-f_r/2 < f_0 < +f_r/2$, so that it represents the frequency of the lowest comb line if the optical comb were to be extended to zero frequency. Using this definition, here we phase-locked the up-shifted offset frequency at $2f_r + f_0$. (This frequency was convenient given the available electronics.) With this comb tooth fixed, a change in the repetition rate leads to an elastic-tape or accordion-like expansion of the entire frequency comb about this fixed point [13]. In other words, a change in the laser's repetition rate of 800 kHz corresponds to a 3 THz (25 nm) change of a comb tooth in the 1550 nm region. There are many attractive features of a frequency comb with a tunable repetition rate. First, it can be used for precision metrology without a wavelength meter [14]. Second, it can be used to match the repetition rate of a second frequency comb, which can be useful, for example, for tests of the stability of the frequency comb [15]. Third, a frequency comb with a tunable repetition rate can be used to scan precisely the frequency of a continuous wave laser locked to the comb.

2. The fiber-laser-based infrared supercontinuum source

The supercontinuum source (Fig. 1) consists of an additive pulse mode-locked (APM) erbium fiber ring laser [11], an erbium-doped fiber amplifier (EDFA), and a length of UV-exposed dispersion-flattened, highly nonlinear, dispersion-shifted fiber (HNLF) [16]. The APM fiber laser has a net negative cavity dispersion and produces solitonic pulses with a spectral bandwidth of 20 nm (Fig. 2(a)) and a chirped output of 210 fs duration. The cavity has 1 m of normal dispersion erbium-doped fiber, 0.3 m of single-mode fiber (SMF) at 1060 nm, and 2.7 m of SMF at 1550 nm. The net cavity dispersion was -0.04 ps^2 neglecting the dispersion of any components. The pulse spectrum exhibits Kelly sidebands that are typically found in the output of a soliton laser [17]. A commercial fiber-coupled free-space, motor driven delay line in the fiber laser cavity allows the repetition rate to be changed from 49.34 MHz to 50.12 MHz (*i.e.*, a total delay of 310 ps). The insertion loss of the delay line ranges from ~0.75 dB to 1 dB. The delay can be scanned quickly (128 ps/s) without any loss of mode-locking. Longer delays may be possible provided that the variation of insertion loss over a scan is minimized.

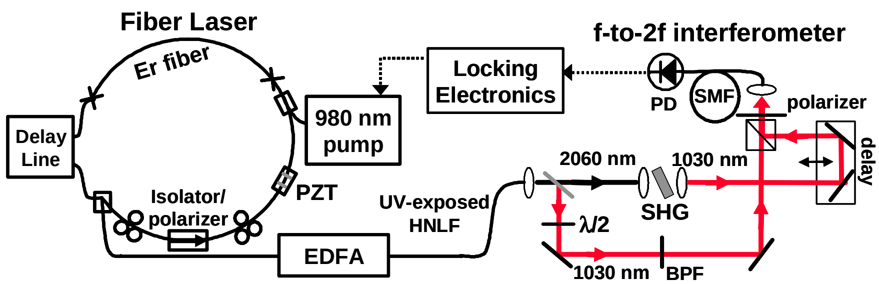

Fig 1. Schematic of the fiber laser frequency comb. The CEO frequency is detected by a photodetector (PD), and is used to control the pump diode current. A piezoelectric transducer (PZT) fiber stretcher in the cavity allowed for adjustment of the repetition rate. The thick solid lines represent free-space paths, the thin solid lines represent fiber paths and the dotted lines represent electrical paths. BPF: Bandpass filter; SHG: second-harmonic generation.

To produce the supercontinuum needed to self-reference the frequency comb output of the laser, pulses from the laser are amplified to an average power of 60 mW, and temporally compressed to less than 90 fs in the EDFA (Fig. 2(b)) before being injected into UV-exposed HNLF. 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/(nm^2 km) at 1550 nm. In order to enhance the supercontinuum generation, this HNLF was exposed to UV radiation [16], which increased the refractive index of the Ge-doped core, enhancing the short wavelength (<1100 nm) portion of the supercontinuum. To generate a supercontinuum, a 40 cm length of HNLF with a 15 cm UV-exposed portion was used. As seen in Fig. 3(a), the generated supercontinuum spanned from 1000 nm to 2100 nm (~157 THz wide).

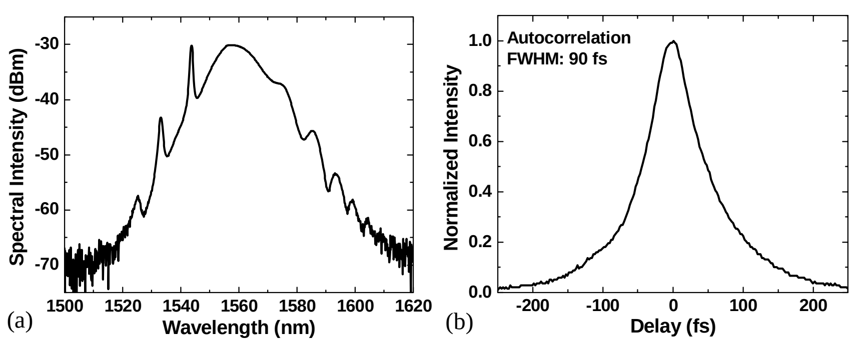

Fig 2. (a) The spectrum from the output of the fiber laser. The spectral full-width at half maximum (FWHM) is 20 nm. (b) The measured intensity autocorrelation of the amplifier output. The FWHM of the autocorrelation trace is ~90 fs, which sets a reasonable upper limit to the pulse width as in Ref. [12]. The original laser output duration is ~210 fs FWHM.

The CEO frequency is measured by mixing 1030 nm light with frequency-doubled 2060 nm light in an f-to-2f interferometer [6]. A dichroic mirror at the HNLF fiber output

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transmits the supercontinuum above 1800 nm. The 2060 nm light is frequency doubled by second-harmonic generation in a 1 mm thick $KNbO_3$ crystal. This light is then combined on a beamsplitter with the fundamental light at 1030 nm, filtered by a 15 nm bandpass filter (BPF), and launched into a single-mode fiber to ensure spatial overlap. The interference between the fundamental 1030 nm light and the doubled 2060 nm light is detected with a 125 MHz InGaAs photoreceiver, producing the RF spectrum shown in Fig. 3(b). The FWHM of the CEO beat signal is ~1 MHz, which is slightly larger than observed in previous work [1, 2, 9], and may be due to greater amplification of intrinsic laser noise because of the longer initial pulse [18].

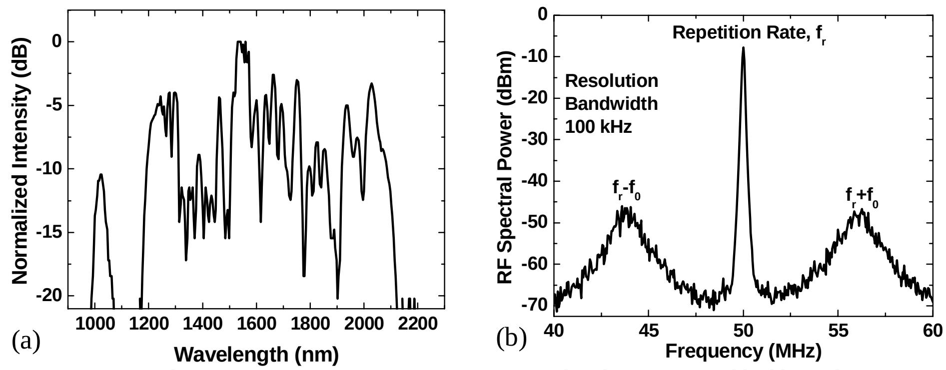

Fig 3. (a) The octave-spanning supercontinuum generated in the UV-exposed highly nonlinear fiber. (b) RF power spectrum from mixing the 1030 nm portion of the supercontinuum with the frequency-doubled 2060 nm portion. The repetition rate signal (f_r) at 49.8 MHz and CEO frequency (f_0) are clearly seen. The CEO beat frequency has a SNR of 20-25 dB.

3. Scanning the repetition rate

To demonstrate the variable repetition-rate frequency comb, the CEO frequency was locked and the repetition rate of the laser was scanned by moving the in-cavity delay line. The repetition rate was free-running for these data, although it could be phase-locked at a given repetition rate by feeding back to the intracavity PZT stretcher [1]. The CEO frequency was locked as shown in Fig. 4. The phase-locked CEO frequency had a standard deviation of ~25 mHz for a fixed (*i.e.* phase-locked) repetition rate. Because of the choice of bandpass filter at 120 MHz the frequency that was actually fixed during a scan (*i.e.* phase-locked to the RF oscillator) was the up-shifted CEO frequency $2f_r + f_0$, rather than simply f_0. As a result, the offset frequency does change during the scan by $-2\delta f_r$ where δf_r is the change in repetition rate. (The sign of f_0 ~+20 MHz was verified by measuring a heterodyne signal with a fixed laser while varying both f_0 and f_r.) During a repetition rate scan, pump power changes of a few mW were required to maintain the CEO frequency phase-lock.

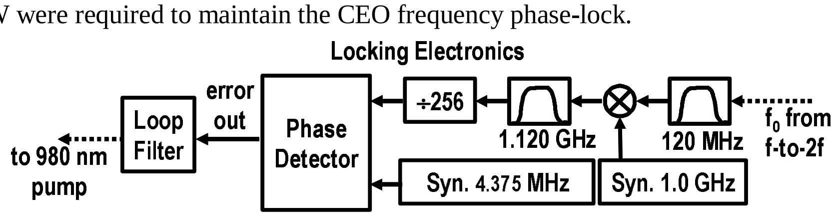

Fig. 4. The electronics used to phase-lock the CEO frequency. The f_0 signal from the f-to-2f interferometer was filtered at 120 MHz (with a 6.7 MHz bandwidth), mixed with a 1 GHz signal, divided, and compared to a 4.375 MHz signal. All synthesizers were referenced to a common time base. The CEO frequency change was ~15 MHz/mW of pump power. The total pump power was ~60 mW.

Figure 5 shows the divided-down CEO frequency for repetition rate scans over 47 kHz (Fig. 5(a)) and the full range of 800 kHz Figs. 5(b)-(c)). Occasional cycle slips occurred due to the relatively low signal-to-noise ratio (SNR) of the CEO beat note. Figures 5(b)-(c)

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demonstrate different scan speeds from 0.62 kHz/s to 19.91 kHz/s; due to mechanical vibrations the phase-locking of the CEO frequency became more difficult as the scan velocity was increased. Higher SNR of this signal should further improve the stability of the phase-lock at high scan speeds. Nevertheless, excluding the cycle slips, the CEO frequency in a 1 s gate is phase-locked to better than a few hertz even for the worst-case example of Fig. 5(c). The corresponding contribution to the instability of the optical comb frequencies is 10^{-14} or less, which is negligible for most applications.

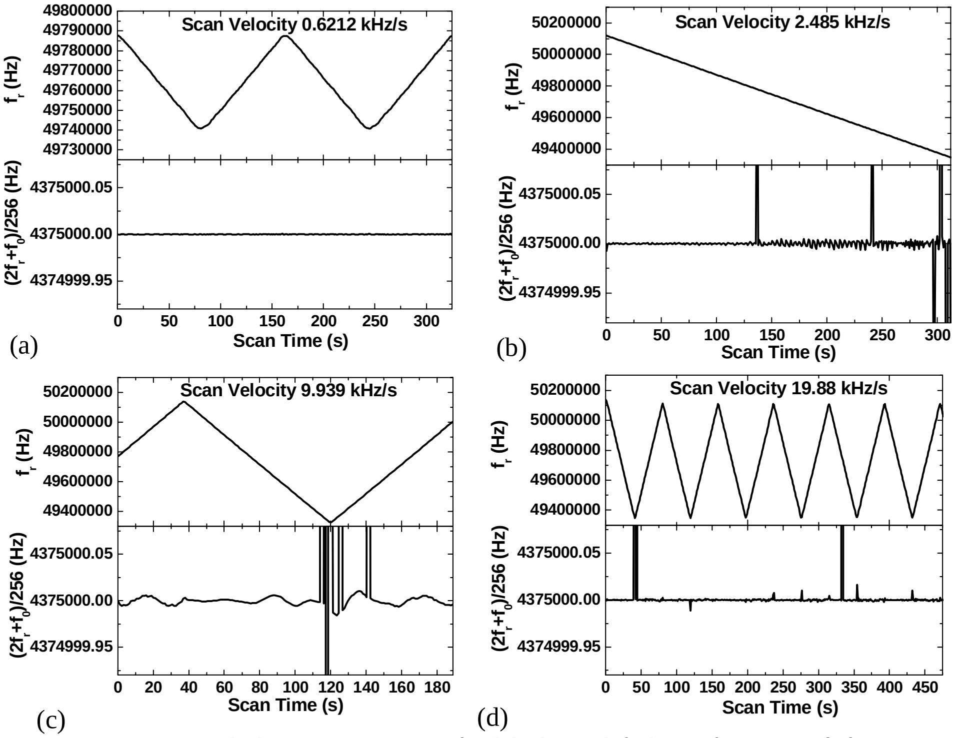

Fig. 5. Scanning the laser's repetition rate (f_r) while the up-shifted CEO frequency ($2f_r$+f_0) is phase-locked. The repetition rate and divided-down CEO frequency were counted with a gate time of 1 s. (a) The divided-down CEO frequency experiences no phase slip as the repetition rate is scanned over a 40 kHz span in 200 s. (b) The divided-down CEO frequency remains locked over an 800 kHz span with a scan velocity of 2.48 kHz/s. Occasional phase slips occur during the scan. (c) The scan velocity is increased to 9.91 kHz/s and small oscillations in the locked f_0 signal occur due to mechanical resonances of the delay line. (d) The scan velocity was increased to 19.8 kHz/s and the phase-lock was improved to prevent oscillations.

4. Applications for frequency metrology: the "accordion" frequency comb

A phase-locked frequency comb with a variable comb tooth separation has many potential uses for infrared frequency metrology. For example, the ability to sweep the comb tooth separation over a large range allows one to unambiguously identify an unknown laser frequency in a heterodyne measurement without using a wavelength meter to distinguish the mode number of the nearest comb tooth [14] (even for a relatively noisy unknown laser frequency). The ability is particularly attractive for the fiber-laser frequency comb since otherwise the ambiguity of 50 MHz in the mode number must be removed by using the highest-accuracy wavelength meter commercially available. Also, as noted in Ref. [12], the tunable repetition rate will allow synchronization between two optical frequency combs for tests of comb stability [15]. Note that the alternative approach of building two fiber lasers with the identical repetition rates by cutting the fiber to the appropriate length is virtually impossible to achieve. A final important application of the variable repetition rate laser is to scan a CW laser precisely in frequency by locking it to a single comb tooth of the

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supercontinuum. Figure 6 depicts a CW laser locked to the n~4 millionth tooth of a frequency comb with a fixed CEO frequency. If f_0 is phase-locked while the repetition rate is changed from f_r to $f_r+\delta f_r$ then each n^{th} comb tooth moves in frequency by $n\delta f_r$. The frequency comb expands likes the bellows of an accordion, with the higher-frequency components experiencing a larger absolute frequency change. If the CW laser remains locked to the n^{th} comb tooth, then the CW laser frequency will also change by $n\delta f_r$. For our soliton laser, a change in its repetition rate by 800 kHz would correspond to a 3 THz change in the optical frequency of a comb tooth around 1550 nm. A CW laser locked to this comb tooth would then experience continuous tuning over 3 THz (25 nm) or over much of the C-band. A CW laser can also be scanned using a fixed frequency comb [19], but this is technically challenging because of the multiple RF beat signals present in the full heterodyne signal and the difficult hand-over of the phase-lock from one tooth of the comb to the next. The method proposed here of locking the CW laser to the same swept comb tooth has the significant advantage that no hand-over is required and that the heterodyne signal between the CW laser and the n^{th} tooth is at a fixed RF frequency.

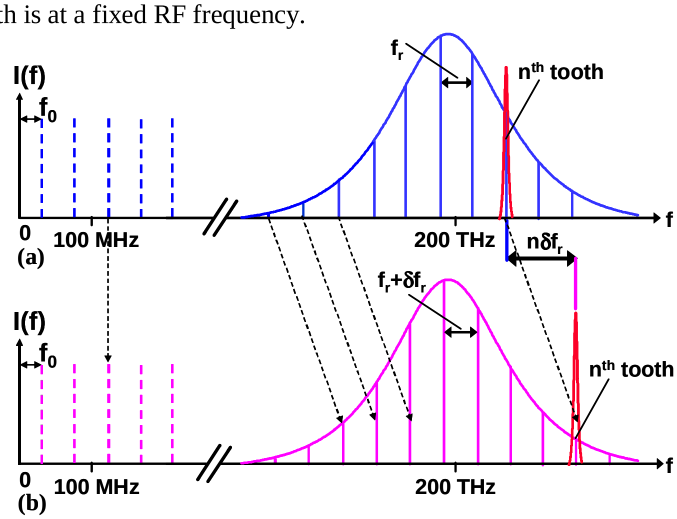

Fig. 6. Scanning a CW laser locked to the variable repetition rate frequency comb. (a) The initial frequency comb (blue) with an offset frequency f_0 and an initial repetition rate f_r where a CW laser (red) is locked to the n^{th} tooth of the comb. (The dotted lines indicate the extension of the frequency comb to zero frequency). (b) The final frequency comb (purple) with the same offset frequency f_0 and a repetition rate f_r that has been increased from f_r to $f_r+\delta f_r$. At low frequencies (100 MHz) the shift of the comb lines is imperceptible on this scale. The CW laser (red) is assumed to be still locked to the n^{th} tooth of the comb. As a result, its frequency has been increased by $n\delta f_r$.

5. Summary

We have demonstrated the ability to phase-lock the CEO frequency of an all-fiber frequency comb while scanning its repetition rate, thus altering the comb spacing while one tooth of the comb is phase-locked to a stable RF source. A phase-locked frequency comb with a variable comb tooth separation has many potential benefits for near-infrared frequency metrology.

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