A variable repetition rate frequency comb for infrared frequency metrology

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Abstract: A frequency comb generated by a mode-locked fiber laser of variable repetition rate is presented. The spacing of the frequency comb can be scanned while one comb tooth is phase-locked to a stable RF source.

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

1. Introduction

Phase-locked self-referenced fiber-laser-based frequency comb sources have been developed for infrared frequency metrology using many designs including a figure-eight fiber laser [1], a pulse-compression mode-locked fiber laser [2], and several fiber ring lasers [3-5]. Elements of the fiber-laser frequency combs duplicate features of Ti:sapphire laser-based frequency combs [6, 7]. Here we report a frequency comb based on a passively mode-locked soliton laser [8] with a variable repetition rate. The high gain of the fiber laser allows the change of its repetition rate by 800 kHz using a fiber-coupled free-space delay line with a ~1 dB insertion loss. By injecting amplified pulses from the soliton laser into the UV-exposed highly nonlinear fiber [9], the octave of supercontinuum bandwidth needed to self-reference the frequency comb can be generated. Recently, a passively mode-locked fiber laser with a variable repetition rate was demonstrated [10]. Here we demonstrate, for a fiber-laser-based frequency comb spanning from 1000 to 2100 nm, that the repetition rate can be significantly changed while the laser remains mode-locked *and* the comb's carrier-envelope offset (CEO) frequency remains phase-locked to a microwave reference [11].

The optical frequency of the n^{th} tooth of a self-referenced comb is given by $f_n = nf_r + f_0$, where f_r is the repetition rate and f_0 is the comb offset frequency, set by the CEO frequency. In experiments using a self-referenced comb, the offset frequency is typically defined 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, the up-shifted offset frequency at $2f_r + f_0$ is phase-locked. With this comb tooth fixed, a change in the repetition rate leads to an expansion of the entire frequency comb about this fixed point. In other words, a change in the repetition rate of 800 kHz corresponds to a 3 THz (25 nm) change of a comb tooth in the 1550 nm region. A frequency comb with a variable repetition rate has many attractive features. . It can be used for precision metrology without a wavelength meter [12]. Plus, the comb 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 [13]. More significantly, a frequency comb with a tunable repetition rate can be used to precisely scan the frequency of a continuous-wave laser locked to the comb.

2. The fiber-laser-based infrared frequency comb

The supercontinuum source (Fig. 1) consists of an additive pulse mode-locked erbium fiber ring laser [8], an erbium-doped fiber amplifier (EDFA), and a length of UV-exposed dispersion-flattened, highly nonlinear, dispersion-shifted fiber (HNLF) [9]. The fiber laser produces solitonic pulses with a spectral bandwidth of ~15 nm and a chirped output of 205 fs duration. 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 and exhibits an insertion loss of from ~0.75 dB to 1 dB. Pulses from the laser are amplified to an average power output of 60 mW, and temporally compressed to less than 90 fs in the EDFA before being injected into the UV-exposed HNLF in order to produce the supercontinuum needed to self-reference the frequency comb. To enhance the supercontinuum generation, this HNLF was exposed to UV radiation, which increased the refractive index of the Ge-doped core, enhancing the short-wavelength (<1100 nm) portion of the supercontinuum. A 40 cm length of HNLF with a 15 cm UV-exposed portion was used and the generated supercontinuum spanned from 1000 nm to 2100 nm (~157 THz wide). The CEO frequency is detected by mixing 1030 nm light with frequency-doubled 2060 nm light in an f-to-2f interferometer [6]. The 2060 nm light is frequency doubled by second-harmonic generation in a 19 mm long periodically poled lithium niobate crystal and combined on a beamsplitter with the fundamental light at 1030 nm. The interference between the fundamental 1030 nm light and the doubled 2060 nm light is detected with a 125 MHz InGaAs photoreceiver.

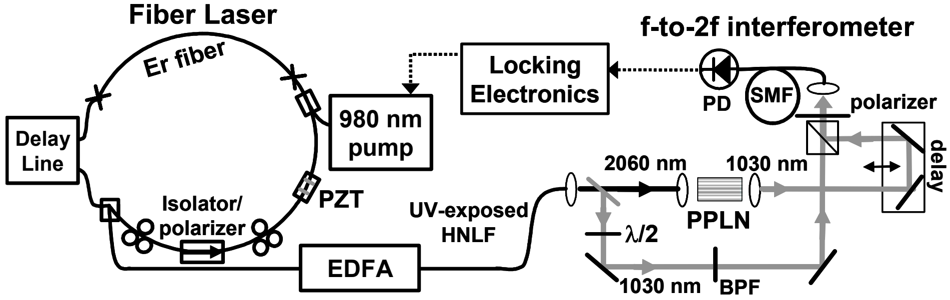

Fig 1. Schematic of the mode-locked fiber laser, erbium-doped fiber amplifier (EDFA), UV-exposed highly nonlinear fiber (HNLF), and f-to-2f interferometer. The CEO beat frequency is detected by a photodetector (PD), and is used to control the 980 nm pump diode current. A piezoelectric transducer (PZT) fiber stretcher in the cavity allowed for a fine adjustment of the repetition rate. The thick solid lines represent free-space optical paths, the thin solid lines represent fiber optic paths and the dotted lines represent electrical paths. BPF: Bandpass filter; PPLN: Periodically-poled lithium niobate.

3. Varying the frequency comb spacing

To demonstrate the variable repetition-rate frequency comb, the CEO beat frequency was phase-locked and the repetition rate of the laser was scanned by moving the in-cavity delay line. The phase-locked CEO beat frequency had a standard deviation of ~25 mHz for a fixed repetition rate. Because of the choice of RF bandpass filter the frequency that was actually fixed during a scan was the up-shifted CEO frequency $2f_r + f_0$, rather than simply f_0. Figure 2 shows the divided-down CEO beat frequency for repetition rate scans over 47 kHz (Fig. 2(a)) and the full range of 800 kHz (Figs. 2(b)). The relatively low signal-to-noise ratio (SNR) of the CEO beat note caused cycle slips to occur. Excluding these cycle slips, the CEO frequency in a 1 s gate is phase-locked to better than a few hertz. The corresponding contribution to the instability of the optical comb frequencies is 10^{-14} or less, which is negligible for most applications.

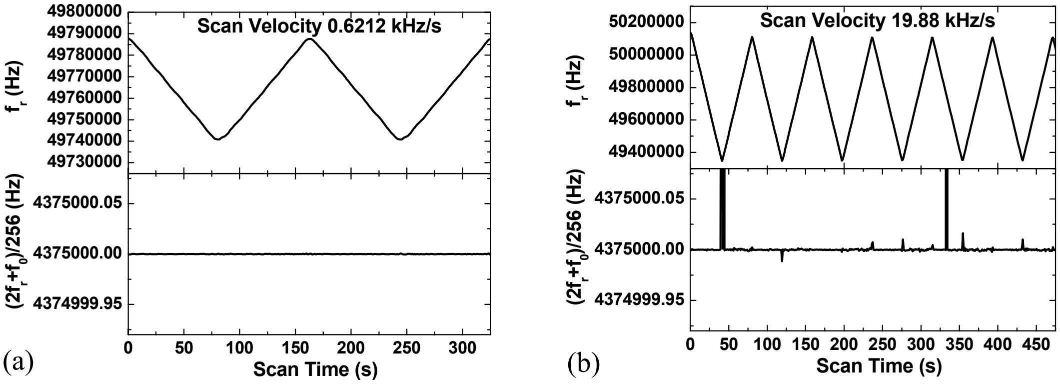

Fig. 2. Scanning the laser's repetition rate (f_r) while the up-shifted CEO beat frequency ($2f_r+f_0$) is phase-locked. The repetition rate and divided-down CEO frequency were counted with a gate time of 1 s. (a) The divided-down CEO frequency experiences no phase slip as the repetition rate is scanned over a 40 kHz span in 200 s. (b) The scan velocity was increased to 19.82 kHz/s.

The insertion loss of the delay line varied periodically as it was scanned over specific delay ranges (Fig. 3(a)). This periodic loss is perhaps due to coupling misalignment as the delay line is moved. According to the analysis presented in Ref. [14], the phase-locked comb should compensate for these variations by varying the pump power current so that the net gain is constant. This current variation was indeed observed as shown in Fig. 3(b)-(c).

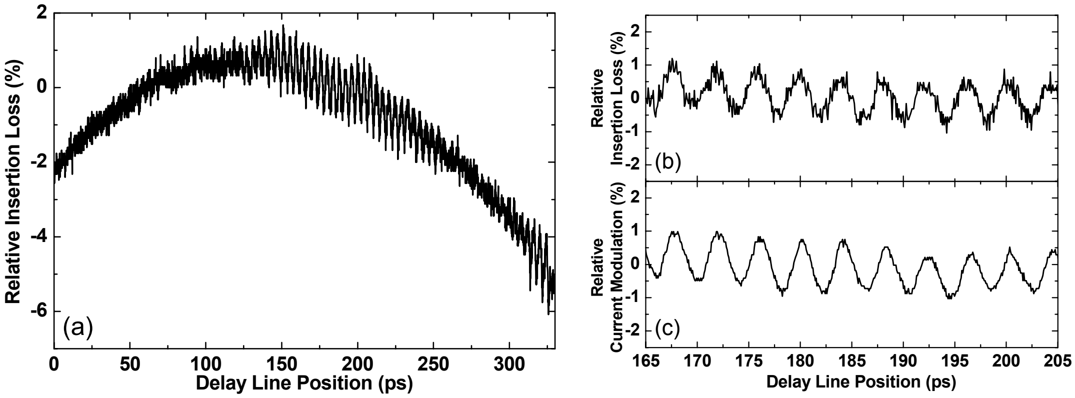

Fig. 3. (a) The relative insertion loss of the delay line with respect to the midpoint loss. (b) An expanded view of the oscillations in the insertion loss. (c) The current modulation measured while the CEO frequency was phase-locked and the delay line was scanned over the same range. Both the loss and current modulation change by 2%. The data of (b) and (c) were taken at different times and may have an error in absolute delay position.

4. Applications for frequency metrology

A phase-locked frequency comb with a variable comb tooth separation has many potential uses for 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 [12]. An 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 supercontinuum. If f_0 is phase-locked while the repetition rate is changed from f_r to $f_\mathrm{r}+\delta f_\mathrm{r}$ then each n^th comb tooth moves in frequency by $n\delta f_\mathrm{r}$. If the CW laser remains locked to the n^th comb tooth, then its frequency will also change by $n\delta f_\mathrm{r}$.

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