Stabilized frequency comb with a self-referenced femtosecond Cr:forsterite laser

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A frequency comb is generated with a Cr:forsterite femtosecond laser, spectrally broadened through a highly nonlinear optical fiber to span from 1.0 to 2.2 μm, and stabilized using the f-to-2f self-referencing technique. The repetition rate and the carrier-envelope offset frequency are stabilized to a hydrogen maser, calibrated by a cesium atomic fountain clock. Simultaneous frequency measurement of a 657-nm cw laser by use of the stabilized frequency combs from this Cr:forsterite system and a Ti:sapphire laser agree at the 10^{-13} level. The frequency noise of the comb components is observed at 1064, 1314, and 1550 nm by comparing the measured beat frequencies between cw lasers and the supercontinuum frequency combs.

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In the past several years the technological maturity of ultrafast lasers as well as supercontinuum generation in nonlinear optical fibers has revolutionized optical frequency metrology and optical clocks.[1–3] Stabilized frequency combs have enabled us to measure optical frequencies with unprecedented precision. Until now, most of the phase-locked frequency combs were in the range 400–1100 nm and employed Ti:sapphire lasers broadened in microstructured fiber. Recently there have been efforts to develop self-referenced optical frequency combs of similar precision in the near-infrared region from 1300 to 1700 nm because of its importance to telecommunications and optical sensing. Corwin *et al.* stabilized the optical frequency comb from a Cr:forsterite laser by simultaneously referencing the comb to the Ca optical standard and a hydrogen (H) maser.[4] A few groups of researchers have also demonstrated a phase-locked frequency comb based on Er-doped fiber lasers using the f-to-2f self-referencing technique.[5–8] Although diode and fiber lasers may be low cost and the most compact sources, our Cr:forsterite femtosecond laser[9] pumped by an efficient Yb-fiber laser offers the desirable features of high repetition rate, short pulse duration, and high average power.

In this Letter we report the measurement and self-referenced stabilization of the carrier-envelope offset frequency (f_0) of the Cr:forsterite-laser-based frequency comb. The repetition rate is simultaneously stabilized to a H maser that is calibrated by a cesium fountain clock. The frequency of a stable 657-nm cw laser is measured simultaneously with this Cr:forsterite comb and an independent Ti:sapphire frequency comb, which allows us to check the reproducibility and stability of the Cr:forsterite system. The result demonstrates short-term instability of $\leqslant 3 \times 10^{-13}$ for the Cr:forsterite comb and an upper limit to its frequency uncertainty of 1×10^{-13}. We also compare the frequency noise of f_0 with the noise in different spectral regions of the optical comb by heterodyne beats with cw lasers at 1064, 1314, and 1550 nm. Significant excess noise exists in f_0 that is not present in the individual optical beat notes.

Figure 1(a) is a schematic of our experimental setup. The 433-MHz Cr:forsterite laser generates 1.2-nJ, 35-fs pulses centered at 1.26 μm.[9] The output pulse is injected into an ~2-m long piece of dispersion-flattened highly nonlinear optical fiber (HNLF) to generate a supercontinuum. The dispersion slope of this fiber is reduced by a factor of 2.5 compared with the similar design in Ref. 10, and a combination of Ge and F dopants are used to produce

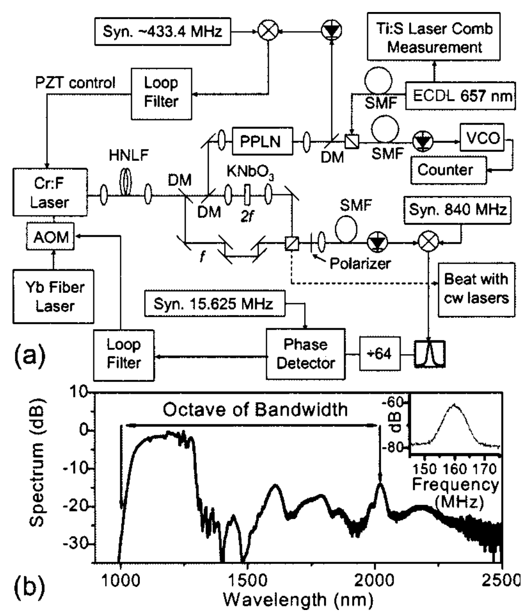

Fig. 1. (a) Schematic of the experimental setup. DMs, dichroic mirrors, Syns; maser-referenced synthesizers; PZT, piezoelectric transducer; Ti:S, Ti:sapphire; SMF, single-mode fiber; ECDL, external cavity laser diode; PPLN, periodically poled lithium niobate; AOM, acousto-optic modulator. (b) Supercontinuum generated through a 2-m-long HNLF. The inset graph is the f_0 beat note measured with a 300-kHz RBW.

a nonlinear coefficient of $\gamma \sim 10.6\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$, a dispersion of 1.74 ps/(nm km), and a dispersion slope of 0.009 ps/(nm^2 km) at 1550 nm. An octave-spanning supercontinuum from 1.0 to 2.2 μm is generated through this fiber as shown in Fig. 1(b).

f_0 is detected using the conventional f-to-2f self-referencing technique.[1] The 2024-nm light is frequency doubled in a type I phase-matched, 1-mm-thick (42.5°-cut $b-c$ axis) potassium niobate crystal with a conversion efficiency of $(P_{2\omega}/P_{\omega}) \sim 10^{-4}$ when $P_{\omega}=2$ mW.[11] This frequency-doubled light is combined with the fundamental light at 1012 nm by use of a beam splitter and injected into a single-mode fiber to ensure spatial overlap between two beams. After this single-mode fiber, the f_0 beat signal between the 10-μW fundamental light and the 230-nW frequency-doubled light (10 nm FWHM centered at 1012 nm) is detected with an indium gallium arsenide photodetector.

The f_0 beat note is as broad as 6.7 MHz FWHM, as shown in the inset of Fig. 1(b), and was mixed with a synthesizer output at 840 MHz to generate a 1-GHz signal within range of the subsequent divider. After division by a factor of 64 (to reduce the phase excursions), this signal [60 dB signal–noise ratio in 100-kHz resolution bandwidth (RBW)] is mixed with the output of another synthesizer set to 15.625 MHz and sent into a digital phase detector. The resultant error signal was filtered and fed back to the acousto-optic modulator that controls the pump power of the Cr:forsterite laser to stabilize f_0 (loop bandwidth <100 kHz). In addition, the repetition-rate signal was mixed with a synthesizer tuned to the desired repetition rate, and the resultant error signal was fed back to a piezoelectric transducer mounted behind a mirror in the ring cavity to control the cavity length of the laser and hence the repetition rate. In light of the broad bandwidth of f_0, it was surprising that when we counted its frequency with a 1-s gate time under these conditions the 1-s standard deviations (σ) were typically 1 mHz and 1.2 Hz after and before the divider of 64, respectively. We presume that the σ before the divider is larger than 64 mHz because of errors introduced in frequency counting the broadband f_0.

To measure the fractional frequency instability of the stabilized comb from the Cr:forsterite laser, we frequency doubled the spectral components of the supercontinuum near 1314 nm in periodically poled lithium niobate and heterodyned them with cw light from a stabilized laser diode at 657 nm (instability $<5\times10^{-15}$ at 1-s averaging, linewidth ~10 Hz). This beat note was tracked by a phase-locked voltage-controlled oscillator, and the output signal from the oscillator was counted by a frequency counter with 1-s gate time. The same 657-nm cw light was also heterodyned with a self-referenced and phase-locked comb from a Ti:sapphire laser,[12] yielding a beat note that could be counted simultaneously. Figure 2(a) shows the frequency measurement results of the 657-nm (456-THz) cw light with the frequency combs from both Cr:forsterite and Ti:sapphire systems that

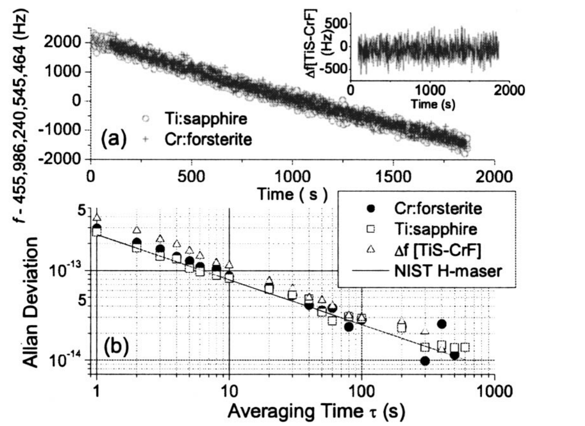

Fig. 2. (a) Simultaneous frequency measurements of a stabilized cw laser at 657 nm using Cr:forsterite (σ=133 Hz) and Ti:sapphire (σ=120 Hz) laser systems. The inset graph is the frequency difference between two measurements, Δf[TiS−CrF]. (b) Allan deviation (instability) determined from the 1-s gate time data of Fig. 2(a). The instability of the H maser is also given.

are referenced to a H maser. These data show good qualitative agreement with both systems measuring the cw laser frequency drift of −2.3 Hz/s. The inset of Fig. 2(a) shows the frequency difference of the two measurements, $\Delta f[\mathrm{TiS-CrF}]=f_{\mathrm{TiS}}-f_{\mathrm{CrF}}$, with a mean value of −61 Hz and σ of 174 Hz. Because of the broad bandwidth and limited signal–noise ratio of f_0, we observed evidence of cycle slips (undetected by the monitoring counters) in the f_0 lock of the Cr:forsterite laser system, which could lead to this 61-Hz offset. For comparison, f_0 of the Ti:sapphire laser has a linewidth <1 Hz. Based on this measurement, we assign a fractional uncertainty of 1.3×10^{-13} to the Cr:forsterite frequency comb measurements. By carefully optimizing the signal–noise ratio of f_0, this offset between the Cr:forsterite and Ti:sapphire systems could be decreased to as small as −2.1 Hz. Recently, Schibli *et al.* measured <20-Hz offset between a turnkey all-fiber system and a Ti:sapphire-laser-based measurement.[6]

After removal of the linear drift, the measured fractional frequency instabilities, given as the Allan deviation in Fig. 2(b), are $2.9\times10^{-13}\ \tau^{-1/2}$ (Cr:forsterite, f_{CrF}), $2.4\times10^{-13}\ \tau^{-1/2}$ (Ti:sapphire, f_{TiS}), and $3.9\times10^{-13}\ \tau^{-1/2}$ (Δf[TiS−CrF]). The instability of the H maser is $\sim2.5\times10^{-13}\ \tau^{-1/2}$ and is plotted as a solid curve. These data suggest that the instability of all measurements is limited by the maser-referenced synthesizers. The fractional instability of Δf[TiS−CrF] was consistently $\sim\sqrt{2}$ times larger than the Ti:sapphire or the Cr:forsterite instability.

In an attempt to better understand the noise in the frequency comb and the broad f_0, we have examined the beats between comb elements of the supercontinuum and stabilized cw lasers at different wavelengths. We measured beat signals at 1064 nm (Nd:YAG laser with frequency linewidth <10 kHz), 1550 nm (Er-doped distributed-feedback fiber laser with linewidth <5 kHz), and 1314 nm. In the case of the 1314-nm beat measurement, we frequency doubled the spectral components of the supercontinuum at 1314 nm in periodically poled lithium niobate and heterodyned them with cw light from the diode laser at 657 nm mentioned above. When we measure these heterodyned beats with a 100-kHz RBW 4-ms sweep time, as shown in Figs. 3(a) and 3(b), they appear as a beat with FWHM of 0.85 and 0.81 MHz at 1064 and 1550 nm, respectively. On the other hand, the 1314-nm beat is as narrow as the 10-kHz RBW for a single 129-ms sweep, as shown in Fig. 3(c). This implies that the frequency fluctuations of the beats at 1064 and 1550 nm are faster and larger than those at 1314 nm. In addition, the f_0 beat, shown in Fig. 3(d), is dramatically broader than the other beats.

The original comb of the Cr:forsterite laser generates the supercontinuum in the HNLF by nonlinear processes such as self-phase modulation, four-wave mixing, and stimulated Raman scattering. In these spectral broadening processes the amplitude noise of the Cr:forsterite laser, generated mainly by the amplitude noise of the Yb:glass fiber pump laser, is transferred to the phase noise of the frequency comb elements.[13–15] Although the time-averaged value of each comb element appears to satisfy the usual comb relationship, $f_n = nf_r + f_0$, our measurements suggest that the comb elements in different spectral regions do not have the same instantaneous phase noise. The dephasing and subsequent broadening appears to be larger for frequency components farther from the original 1.26-μm Cr:forsterite laser comb. One possible explanation for the significant broadening of f_0 is that it is generated from the extremes of the supercontinuum. Considering that the beat with the cw light at 1064 nm is still less than 1 MHz wide, this suggests that most of the noise in f_0 arises from the 2-μm region of the comb. These observations are consistent with similar measurements made with supercontinua from Er-fiber lasers.[6,16]

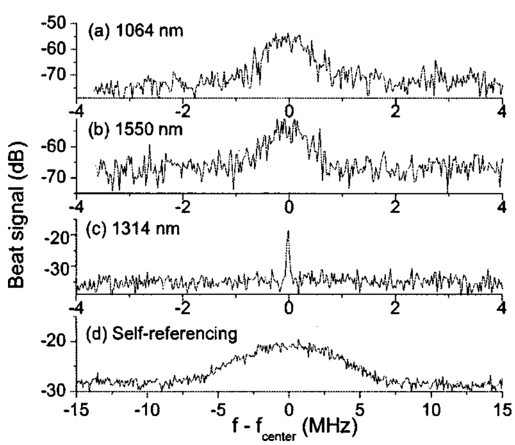

Fig. 3. Beat frequencies observed between the comb elements after the HNLF and cw lasers (a) at 1064 nm and (b) 1550 nm. (c) Beat frequency observed between a cw laser at 657 nm and the frequency-doubled comb after the HNLF from 1314 nm. (d) Self-referenced f_0 beat note. RBW, 10 kHz; sweep time, 386 ms.

In conclusion, we have demonstrated a stabilized frequency comb in the near-infrared based on a Cr:forsterite laser using the f-to-$2f$ self-referencing technique. The stabilized comb has been used to measure the frequency of a 657-nm cw laser. The frequency noise of optical comb elements of the supercontinuum are also characterized by heterodyning them with cw lasers at 1064, 1314, and 1550 nm. The frequency noise is larger at the extreme comb elements far from the center wavelength of the injected Cr:forsterite laser.

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