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

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Abstract: The frequency comb of a Cr:forsterite femtosecond laser is stabilized using the *f*-to-2*f* self-referencing technique. The frequency noise of the comb components at 1064, 1314, and 1550nm differs significantly from the noise of f_0.

OCIS codes: (120.3940) Metrology; (320.7090) Ultrafast lasers; (320.7140) Ultrafast processes in fibers;

1. Introduction

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 and the measured frequencies were in the range of 400 to 1100 nm because ultrafast Ti:sapphire laser, broadened in a microstructured fiber, have been employed almost exclusively. Recently, there have been efforts to develop 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 maser[4]. A few groups have also demonstrated a phase-locked frequency comb based on Er-doped fiber lasers using the *f*-to-2*f* self-referencing technique[5-7]. Although diode and fiber lasers may be low-cost and the most compact sources, our Cr:forsterite femtosecond laser[8] pumped by an efficient Yb fiber laser offers the desirable features of high repetition rate, short pulse duration, and high average power.

We report the measurement and self-referenced stabilization of the carrier-envelope offset frequency (f_0) of the Cr:forsterite-laser-based near-infrared frequency comb. The repetition rate is simultaneously stabilized to a hydrogen (H) maser that is calibrated by the National Institute of Standards and Technology (NIST) F1 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 a short term instability of $\leq 3\times10^{-13}$ for the Cr:forsterite comb and an upper limit to its frequency uncertainty of 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 nm, 1314 nm, and 1550 nm. Significant excess noise exists in f_0 that is not present in the individual optical beat notes.

2. Stabilization of a Cr:forsterite laser

A 10 mm long Cr:forsterite crystal, inside the six-mirror ring cavity with a 3% output coupler, is pumped by a 10 W Yb:glass fiber laser at 1075 nm. The 433 MHz, 1.2 nJ, 35 fs pulses centered at 1.26 μm are generated with this Cr:forsterite laser. The output pulse is injected into a ~2-m long piece of dispersion-flattened highly nonlinear optical fiber (HNLF) to generate a supercontinuum[9]. An octave-spanning supercontinuum from 1.0 μm to 2.2 μm is generated through this fiber. The f_0 is detected using the conventional *f*-to-2*f* self-referencing technique. To do so, the 2024-nm light is frequency-doubled by a $KNbO_3$ crystal and combined with the fundamental light at 1012 nm. The f_0 beat signal between the 10 μW fundamental light and the 230 nW frequency-doubled light at 1012 nm is detected with an InGaAs photodetector with a 125 MHz bandwidth.

The f_0 beat note is as broad as 6.7 MHz FWHM, and was mixed with a maser-referenced synthesizer output at 840 MHz to generate a 1 GHz signal. After division by a factor of 64 (in order to reduce the phase excursions), the signal 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 fed back to the acousto-optical modulator that controls the pump power of the Cr:forsterite laser to stabilize f_0. In addition, the repetition rate signal was detected and mixed with a synthesizer tuned to the desired repetition rate. The resultant error signal was fed back to a piezoelectric

transducer mounted behind a mirror in the ring cavity in order to control the cavity length of the laser and hence the repetition rate. When we counted the frequency of f_0 with 1 s gate time under these conditions, the standard deviations were typically 1 mHz and 1.2 Hz after and before the divider of 64, respectively. We presume that the standard deviation before the divider is larger than 64 mHz because of errors introduced in frequency counting the broadband f_0.

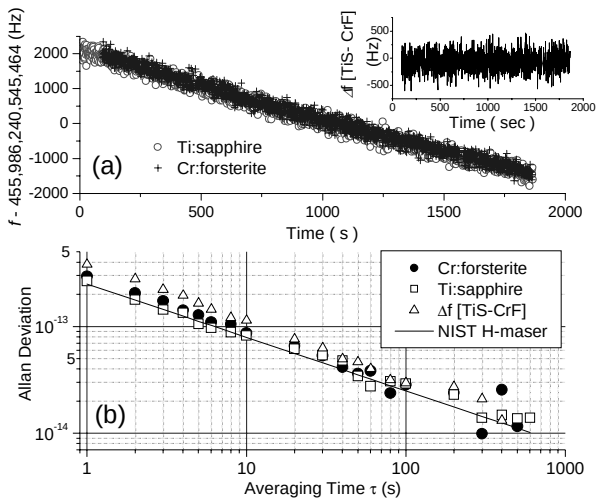

Fig. 1. (a) Simultaneous frequency measurements of a stabilized CW laser at 657 nm (456 THz) using the beats against the comb elements of the stabilized Cr:forsterite (+) and Ti:sapphire (○) laser systems. The standard deviation of each measurement is 133.1 Hz and 120.1 Hz for Cr:forsterite and Ti:sapphire laser systems. The inset graph is the frequency difference between the measurements made with the Ti:sapphire and Cr:forsterite laser systems, $f_{TiS} - f_{CrF}$. (b) Measured frequency instabilities of Cr:forsterite (circles), Ti:sapphire (squares) laser systems, Δf [TiS – CrF] = $f_{TiS} - f_{CrF}$ (triangles), and the H-maser (solid line).

In order to measure the fractional frequency instability of the stabilized comb from the Cr:forsterite laser, we frequency-doubled the spectral components of the supercontinuum from the Cr:forsterite laser near 1314 nm in periodically-poled Lithium Niobate (PPLN), and heterodyned them with the CW light from a stabilized laser diode at 657 nm (linewidth ~10 Hz). This beat note was tracked by a phase-locked voltage controlled oscillator (VCO) and the output signal from the VCO 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, yielding a beat note that could be counted simultaneously. Figure 1(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 are referenced to an 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. 1(a) shows the frequency difference of two measurements, Δf [TiS–CrF] = $f_{TiS} - f_{CrF}$, with the mean value of -61 Hz and the standard deviation of 173.5 Hz. Because of the broad bandwidth and limited signal-to-noise ratio of f_0, we observed evidence for "cycle slips" (undetected by the monitoring counters) in the f_0 lock of these Cr:forsterite laser system, which could lead to this 61 Hz offset. Based on this measurement, we assign a fractional uncertainty of 1.3×10^{-13} to the Cr:forsterite frequency comb measurements. After removal of the linear drift, the measured fractional frequency instabilities, given as the Allan deviation in Fig. 1(b), are $2.9\times10^{-13} \cdot \tau^{-1/2}$ (Cr:forsterite, f_{CrF}, circles), $2.4\times10^{-13} \cdot \tau^{-1/2}$ (Ti:sapphire, f_{TiS}, squares), and $3.9\times10^{-13} \cdot \tau^{-1/2}$ (frequency difference, Δf [TiS– CrF]= $f_{TiS} - f_{CrF}$, triangles). The instability of the H-maser is $2.5 \times 10^{-13} \cdot \tau^{-1/2}$ and is also plotted as the solid line. These data suggest that the instability of all measurements is limited by the maser-referenced synthesizers.

3. Noise characterization of the supercontinuum

Direct measurements of optical beat notes are very useful to measure the frequency noise of the frequency comb components because they have ~10^6 times larger frequency changes compared to repetition rate measurements. In an attempt to better understand the noise in the frequency comb and the broad f_0, we have examined the beats between optical comb elements of the Cr:forsterite laser 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 DFB fiber laser with linewidth < 5 kHz), and 1314 nm. With a 100 kHz resolution bandwidth and 4 ms sweep time, as shown in Fig. 2(a) and (b), these jittering narrow beats appears as a single beat with FWHM of 0.85 MHz and 0.81 MHz at 1064 nm and 1550 nm, respectively. On the other hand, the 1314 nm beat is still as narrow as the

10 kHz resolution bandwidth for a single 129 ms sweep, as shown in Fig. 2(c). This implies that the frequency fluctuations of the beats at 1064 nm and 1550 nm are faster and larger than those at 1314 nm. In addition, the f_0 beat is shown in Fig. 2(d). These data show that the f_0 is dramatically broader than the other beats.

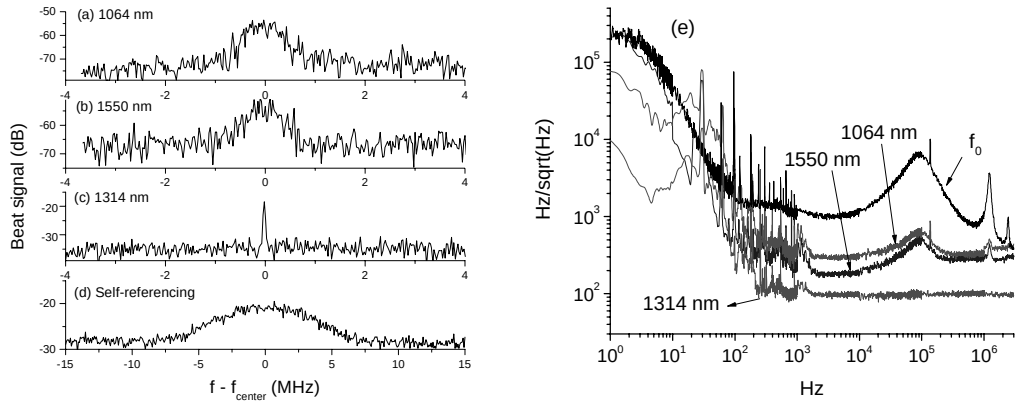

Fig. 2. Beat notes observed between the comb elements after the HNLF and CW lasers (a) at 1064 nm and (b) 1550 nm. (c) A beat note between a CW laser at 657 nm and the frequency-doubled comb after the HNLF from 1314 nm and (d) a self-referenced f_0 beat note. (e) Phase noise measurements at 1064 nm, 1314 nm, 1550 nm, and self-referencing f_0.

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 Cr:forsterite laser, mainly generated by the amplitude noise of Yb:glass fiber pump laser, is transferred to the phase noise of each frequency comb elements[10,11]. Although the time averaged value of each comb element appears to satisfy the usual comb relationship, $f_n = n f_r + f_0$, our measurements suggest that the instantaneous comb elements in different spectral regions do not have the same phase noise as shown in Fig. 2(e). The noise peaks at 100 kHz and 1 MHz are transferred from the amplitude noise of the Yb:glass fiber pump laser. 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]. Furthermore, we observed anti-correlated frequency fluctuations between comb elements at 1064 nm and 1550 nm (opposite sides with respect to the injected laser spectrum), and correlated frequency fluctuations between those at 1064 nm and 1112 nm. This also significantly enhances the broadening of f_0 between two extremes of the supercontinuum.

4. References

1. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stenz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis" Science **288,** 635 (2000).
2. T. Udem, R. Holzwarth, and T. W. Hänsch ,"Optical frequency metrology" Nature **416,** 233 (2002).
3. S. A. Diddams, T. Udem, J. C. Bergquist, E. A. Curtis, R. E. Drullinger, L. Hollberg, W. M. Itano, W. D. Lee, C. W. Oates, K. R. Vogel, and D. J. Wineland, "An optical clock based on a single trapped $^{199}Hg^+$ ion" Science **293,** 825 (2001).
4. K. L. Corwin, I. Thomann, T. Dennis, R. W. Fox, W. Swann, E. A. Curtis, C. W. Oates, G. Wilpers, A. Bartels, S. L. Gilbert, L. Hollberg, N. R. Newbury, and S. A. Diddams, "Absolute-frequency measurements with a stabilized near-infrared optical frequency comb from a Cr:forsterite laser" Opt. Lett. **29,** 397 (2004).
5. B. R. Washburn, S. A. Diddams, N. R. Newbury, J. W. Nicholson, M. F. Yan, and C. G. Jørgensen, "Phase-locked, erbium-fiber-laser-based frequency comb in the near infrared" Opt. Lett. **29,** 250 (2004).
6. T. R. Schibili, K. Minoshima, F.-L. Hong, H. Inaba, A. Onae, H. Matsumoto, I. Hartl, and M. E. Fermann, "Frequency metrology with a turnkey all-fiber system," Opt. Lett. **29,** 2467 (2004).
7. H. Hundertmark, D. Wandt, C. Fallnich, N. Haverkamp, and H. R. Telle, "Phase-locked carrier-envelope-offset frequency at 1560 nm" Opt. Express **12,** 770 (2004).
8. I. Thomann, A. Bartels, K. L. Corwin, N. R. Newbury, L. Hollberg, S. A. Diddams, J. W. Nicholson, and M. F. Yan, "420-MHz Cr:forsterite femtosecond ring laser and continuum generation in the 1-2-μm range" Opt. Lett. **28,** 1368 (2003).
9. J. W. Nicholson, M. F. Yan, P. Wisk, J. Fleming, F. DiMarcello, E. Monberg, A. Yablon, C. Jørgensen, and T. Veng, "All-fiber, octave-spanning supercontinuum" Opt. Lett. **28,** 643 (2003).
10. F.-L. Hong, K. Minoshima, A. Onae, H. Inaba, H. Takada, A. Hirai, and H. Matsumoto, "Broad-spectrum frequency comb generation and carrier-envelope offset frequency measurement by second-harmonic generation of a mode-locked fiber laser" Opt. Lett. **28,** 1516 (2003).
11. N. R. Newbury, B. R. Washburn, K. L. Corwin, and R. S. Windeler, "Noise amplification during supercontinuum generation in microstructure fiber" Opt. Lett. **28,** 944 (2003).