Improved stabilization of a 1.3 μm femtosecond optical frequency comb by use of a spectrally tailored continuum from a nonlinear fiber grating

K. Kim and S. A. Diddams

National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305

P. S. Westbrook, J. W. Nicholson, and K. S. Feder

OFS Laboratories, 19 Schoolhouse Road, Somerset, New Jersey 08873

Received August 25, 2005; accepted September 20, 2005

We report significant enhancement (+24 dB) of the optical beat note between a 657 nm cw laser and the second-harmonic generation of the tailored continuum at 1314 nm generated with a femtosecond Cr:forsterite laser and a nonlinear fiber Bragg grating. The same continuum is used to stabilize the carrier-envelope offset frequency of the Cr:forsterite femtosecond laser and permits improved optical stabilization of the frequency comb from 1.0 to 2.2 μm. Using a common optical reference at 657 nm, a relative fractional frequency instability of 2.0×10^{-15} is achieved between the repetition rates of Cr:forsterite and Ti:sapphire laser systems in 10 s averaging time. The fractional frequency offset between the optically stabilized frequency combs of the Cr:forsterite and Ti:sapphire lasers is $\pm(0.024\pm6.1)\times10^{-17}$.

OCIS codes: 120.3940, 320.7090, 320.7140.

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.[1–3] Stabilized optical frequency combs based on femtosecond lasers provide a convenient phase-coherent link between the optical and the microwave domains. One aspect of the frequency stabilization of a frequency comb is self-referencing, which often uses the octave-spanning supercontinuum from a nonlinear fiber to detect and stabilize the carrier-envelope offset frequency (f_0).[1] Another aspect involves heterodyning specific modes of the comb with optical frequency references, hence, higher power at specific wavelengths in the supercontinuum is critical.[3]

While some design elements of nonlinear fibers (i.e., choice of zero dispersion wavelength and fiber core diameter) provide coarse selection of the generated continuum, generally speaking, there is little user control over the output spectrum. To make the matter more difficult, the continuum is rarely uniform but rather contains spectral regions with little light. Thus, several fibers must typically be tested to find one that reliably generates an octave of spectrum plus significant light at the desired wavelengths. Clearly, technologies that permit designed spectral enhancement on top of an octave-spanning supercontinuum would be very beneficial for optical frequency metrology. Spectral enhancement of >10 dB has been observed with ultraviolet- (UV-) inscribed fiber Bragg gratings in highly nonlinear optical fiber (HNLF) at arbitrarily tailored wavelengths such as 990, 1080, and 1480 nm.[4] However, temporal broadening caused by dispersion changes due to the fiber grating made it unclear if an octave-spanning supercontinuum could be obtained along with significant spectral enhancement after frequency doubling from the telecommunication region into the visible.[5]

In this Letter we demonstrate the use of tailored spectra from a nonlinear fiber grating that allows robust generation of a continuum at the specific wavelength important for experiments with the Ca optical frequency standard. We measure a significant increase (+24 dB) in the signal-to-noise (S/N) ratio of optical beat notes between a stable cw laser at 657 nm and the second harmonic of the continuum around 1314 nm that is generated with a Bragg grating. Due to this significant enhancement, we were able to synchronize the Cr:forsterite laser to the stable cw reference laser at ~456 THz. The repetition rate of this optically stabilized Cr:forsterite laser was then compared with that of a similarly stabilized Ti:sapphire laser. The fractional frequency instability of the Cr:forsterite repetition rate relative to the Ti:sapphire laser is measured to be 2.0×10^{-15} in 10 s averaging time. The weighted mean of the optical frequency difference between the Cr:forsterite and the Ti:sapphire laser measurements at 456 THz is (0.11 ± 27.9) mHz, giving a fractional uncertainty of the mean of 6.1×10^{-17} over 5.5 h. To our knowledge, this represents the lowest measured uncertainty and instability for an octave-spanning self-referenced optical frequency comb in the telecommunication wavelength region.[6]

An additional motivation for this work is the generation and distribution of low-noise and ultrastable microwave reference frequencies. For example, this is crucial for the synchronization of remote clocks

0146-9592/06/020277-3/$15.00

over optical fiber networks in NASA's Deep Space Network and Atacama Large Millimeter Array (ALMA).[7] The improved stability of an optical atomic clock can be transferred to the microwave domain by frequency division using femtosecond lasers. Therefore, a stabilized optical frequency comb, as demonstrated here, in the near-infrared region (1.3 to 1.5 μm) could be important for the generation and distribution of microwave and (or) optical frequency standards via fiber-optic networks.[8]

The supercontinuum is generated with 1.3 nJ, 35 fs pulses centered at 1.26 μm from a 433 MHz Cr:forsterite laser[9] that are injected into as $\sim$2 m long piece of dispersion-flattened HNLF containing a fiber Bragg grating (i.e., a resonant structure with periodic modulations of the core refractive index). The grating was inscribed in the HNLF using a uniform scan of a Gaussian UV beam (248 nm pulsed) through a phase mask.[4] The grating had a length of $\sim$3 cm, Bragg resonance at 1310 nm, and a bandwidth of $\sim$3 nm. The grating was roughly centered in the 2 m length of HNLF.

A portion of the octave-spanning continuum from 1.0 to 2.2 μm previously generated from a HNLF that did not contain a grating is shown in Fig. 1(a).[10,11] A significant spectral enhancement (+20 dB) at 1314 nm is observed with the same HNLF that contains a fiber grating, as also shown in Fig. 1(a). We frequency doubled the spectral components of the supercontinua near 1314 nm from the HNLFs with and without a grating in periodically poled lithium niobate, and heterodyned them with the cw light from a stabilized extended-cavity diode laser at 657 nm (f_{LD}, instability of $<5\times10^{-15}$ at 1 s averaging, linewidth $\sim$10 Hz). Figure 1(b) indicates that the second-harmonic generation spectrum with a grating generates +24 dB enhancement from 150 nW/nm to 41 μW/nm at 657.4 nm. Accordingly,

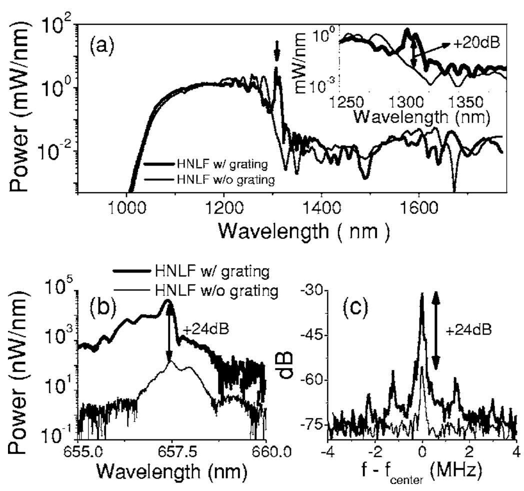

Fig. 1. (a) Supercontina generated using HNLFs with and without a grating. Inset, magnified spectra around the 1314 nm region. (b) Second-harmonic generation powers after frequency doubling of spectral components at 1314 nm using periodically poled $\mathrm{LiNbO_3}$. (c) Heterodyned optical beat notes obeserved between a stabilized 657 nm cw laser and the frequency-doubled comb element after HNLFs with and without a grating (RBW=30 kHz).

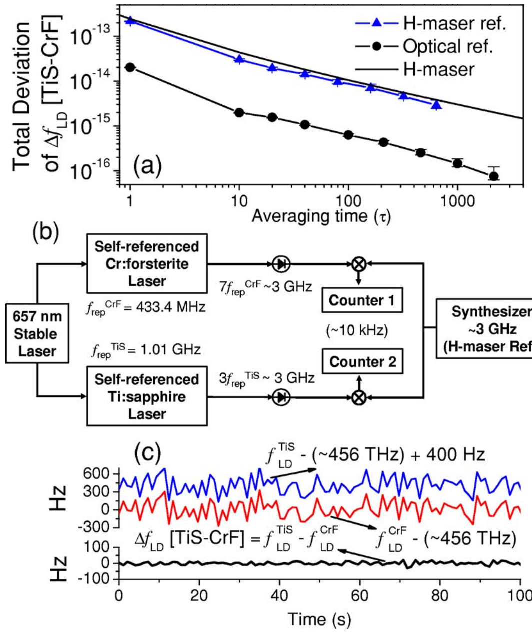

Fig. 2. (Color online) (a) Relative fractional frequency instabilities of $\Delta f_{\mathrm{LD}}[\mathrm{TiS-CrF}]$ with H-maser and optical references. The instability of the H-maser is also given. (b) Schematic of the experimental setup to measure relative instability between the Cr:forsterite and the Ti:sapphire lasers using an optical reference. (c) A magnified graph of the 1 s gate time data shows the strong correlation between $f_{\mathrm{LD}}^{\mathrm{CrF}}$ and $f_{\mathrm{LD}}^{\mathrm{TiS}}$. For visual clarity, we introduced an additional 400 Hz offset into $f_{\mathrm{LD}}^{\mathrm{TiS}}$.

those beat signals with a stabilized cw light at 657 nm also show +24 dB enhancement with a grating, as shown in Fig. 1(c). The S/N ratio increases from 21 to 45 dB in 30 kHz resolution bandwidth (RBW). This beat note (f_b^{CrF}) with a 45 dB S/N ratio can be directly counted or used for phase locking and leads to improved stabilization of the Cr:forsterite laser relative to the 657 nm Ca standard as described below. The same supercontinuum from the HNLF with a grating is used to detect and stabilize f_0 (S/N ratio $>$30 dB at 100 kHz RBW) to an H-maser referenced synthesizer using an f-to-$2f$ self-referencing technique.[1,11] To stabilize f_0, the pump power of the Cr:forsterite laser is controlled by an acousto-optical modulator.

For the stabilization of f_{rep} of the optical frequency comb, two different reference methods are used in this Letter: an H-maser and an optical reference. For the H-maser referenced stabilization scheme, the repetition rate is stabilized to an H-maser referenced synthesizer by controlling the cavity length of the laser using a piezoelectric transducer mounted behind a mirror in the ring cavity. In this case the fractional frequency instability of the stabilized comb was measured by recording f_b^{CrF} with a frequency counter. The same 657 nm cw light was also heterodyned with a self-referenced and phase-locked comb from a Ti:sapphire laser (1 GHz),[12] yielding a beat note that could be counted (f_b^{TiS}) simultaneously. The solid triangles in Fig. 2(a) show the measured fractional frequency instability (given as total deviation)[13] of the frequency difference of the two measurements, $\Delta f_{\mathrm{LD}}[\mathrm{TiS-CrF}]=f_{\mathrm{LD}}^{\mathrm{TiS}}-f_{\mathrm{LD}}^{\mathrm{CrF}}$, which is limited by the instability of the H-maser and the synthesizers mixed with the repetition rates of the Cr:forsterite ($f_{rep}^{\mathrm{CrF}} \sim 433.4$ MHz) and Ti:sapphire ($f_{rep}^{\mathrm{TiS}} \sim 1.01$ GHz) lasers.

To improve the instability beyond that of the H-maser, we used a stabilization scheme employing an optical reference at 657 nm as shown in Fig. 2(b). f_0 is stabilized to an H-maser referenced synthesizer, and each optical frequency comb element of both the Cr:forsterite and Ti:sapphire lasers is stabilized (phase locking f_b^{CrF} and f_b^{TiS}) to the same optical reference ($f_{\mathrm{LD}} \sim 456$ THz). Using individual InGaAs p-i-n photodiodes, the seventh harmonic ($7f_{\mathrm{rep}}^{\mathrm{CrF}}$) of the Cr:forsterite laser's repetition rate and the third harmonic ($3f_{\mathrm{rep}}^{\mathrm{TiS}}$) of the Ti:sapphire laser's repetition rate are mixed down by the output of an H-maser referenced synthesizer ($f_{\mathrm{syn}} \sim 3.03$ GHz) to be in the range of ~ 10 kHz. Both the mixed-down signals ($f_{\mathrm{mix}}^{\mathrm{CrF}} = |7f_{\mathrm{rep}}^{\mathrm{CrF}} - f_{\mathrm{syn}}|$, $f_{\mathrm{mix}}^{\mathrm{TiS}} = |3f_{\mathrm{rep}}^{\mathrm{TiS}} - f_{\mathrm{syn}}| \approx 10$ kHz) are filtered and directly counted with individual frequency counters. While we effectively measure the repetition rates (microwave frequency) of the two optically stabilized lasers, this also can be cast as measurements of the optical frequency of the cw laser (f_{LD}). Although each optical frequency measurement ($f_{\mathrm{LD}}^{\mathrm{TiS}}, f_{\mathrm{LD}}^{\mathrm{CrF}}$) fluctuates up to the H-maser instability, as shown in Fig. 2(c), the maser noise is strongly correlated between $f_{\mathrm{LD}}^{\mathrm{TiS}}$ and $f_{\mathrm{LD}}^{\mathrm{CrF}}$. Subtracting these two data sets yields the residual fractional frequency instability of Δf_{LD}[TiS−CrF], given by the solid circles in Fig. 2(a). The instability of repetition rates is the same as this instability of optical frequency. The instabilities are 2.0×10^{-14} in 1 s and 2.0×10^{-15} in 10 s averaging time. As for the 10 s gate time data, the fractional offset of Δf_{LD}[TiS−CrF] from zero is $(1.7 \pm 7.1) \times 10^{-17}$ over ~ 140 min.

Figure 3 is a summary of the mean values and the uncertainties of Δf_{LD}[TiS−CrF] depending on the reference methods (H-maser or optical reference) and gate times. The mean of these data, weighted by the

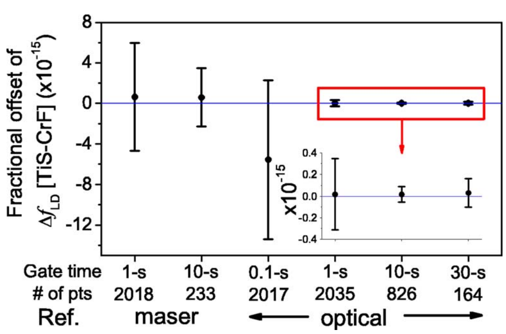

Fig. 3. Fractional offsets and uncertainties of Δf_{LD}[TiS−CrF] depending on reference methods and gate times. Inset, magnified data. The number of data points in each measurement is also given.

inverse of the displayed error bars, is (0.11 ± 27.9) mHz, or fractionally, $(0.024 \pm 6.1) \times 10^{-17}$.

In conclusion, we have demonstrated an improved stabilized frequency comb at 1.3 μm based on a Cr:forsterite laser using a spectrally tailored continuum from a nonlinear fiber grating. With an optical reference at 657 nm, the residual fractional frequency instability as low as 2.0×10^{-15} is achieved between the repetition rates of Cr:forsterite and Ti:sapphire laser systems in 10 s averaging time. The offset between the stabilized combs of Cr:forsterite and Ti:sapphire lasers is 2.4×10^{-19} with an uncertainty of 6.1×10^{-17}.

We thank N. R. Newbury, C. W. Oates, and Y. LeCoq for the loan of equipment. K. Kim's e-mail address is kskim@boulder.nist.gov.

Note added in proof: A recent paper[14] indicates that Er:fiber frequency combs can support an instability of $\sim 1.4 \times 10^{-4}$ at 1 s averaging time.

References

1. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stenz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, Science **288**, 635 (2000).
2. T. Udem, R. Holzwarth, and T. W. Hänsch, 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, Science **293**, 825 (2001).
4. P. S. Westbrook, J. W. Nicholson, K. S. Feder, Y. Li, and T. Brown, Appl. Phys. Lett. **85**, 4600 (2004).
5. B. J. Eggleton, T. Stephens, P. A. Krug, G. Dhosi, Z. Brodzeli, and F. Ouellette, Electron. Lett. **32**, 1610 (1996).
6. P. Kubina, P. Adel, F. Adler, G. Grosche, T. W. Hänsch, R. Holzwarth, A. Leitenstorfer, B. Lipphardt, and H. Schnatz, Opt. Express **13**, 904 (2005).
7. M. Calhoun, R. Sydnor, and W. Diener, in Interplanetary Network Progress Rep. 42-148, Oct.–Dec. 2001 (Jet Propulsion Laboratory, 2002), pp. 1–11.
8. K. W. Holman, D. J. Jones, D. D. Hudson, and J. Ye, Opt. Lett. **29**, 1554 (2004).
9. I. Thomann, A. Bartels, K. L. Corwin, N. R. Newbury, L. Hollberg, S. A. Diddams, J. W. Nicholson, and M. F. Yan, Opt. Lett. **28**, 1368 (2003).
10. J. W. Nicholson, M. F. Yan, P. Wisk, J. Fleming, F. DiMarcello, E. Monberg, A. Yablon, C. Jørgensen, and T. Veng, Opt. Lett. **28**, 643 (2003).
11. K. Kim, B. R. Washburn, G. Wilpers, C. W. Oates, L. Hollberg, N. R. Newbury, S. A. Diddams, J. W. Nicholson, and M. F. Yan, Opt. Lett. **30**, 932 (2005).
12. T. M. Ramond, S. A. Diddams, L. Hollberg, and A. Bartels, Opt. Lett. **27**, 1842 (2002).
13. D. A. Howe, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **47**, 1102 (2000).
14. E. Benkler, H. R. Telle, A. Zach, and F. Tauser, Opt. Express **13**, 5662 (2005).