Absolute-frequency measurements with a stabilized near-infrared optical frequency comb from a Cr:forsterite laser

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A frequency comb is generated with a chromium-doped forsterite femtosecond laser, spectrally broadened in a dispersion-shifted highly nonlinear fiber, and stabilized. The resultant evenly spaced comb of frequencies ranges from 1.1 to beyond 1.8 μm. The frequency comb was referenced simultaneously to the National Institute of Standards and Technology's optical frequency standard based on neutral calcium and to a hydrogen maser that is calibrated by a cesium atomic fountain clock. With this comb we measured two frequency references in the telecommunications band: one half of the frequency of the d/f crossover transition in ^{87}Rb at 780 nm, and the methane $\nu_2 + 2\nu_3$ $R(8)$ line at 1315 nm.

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Ultrafast lasers broadened in nonlinear optical fibers have revolutionized the field of optical frequency metrology. Over the past three years the stabilization of the comb of optical frequencies emitted from an ultrafast Ti:sapphire laser broadened in microstructured fiber[1] has permitted the determination of optical frequencies with unprecedented precision.[2,3] To date, Ti:sapphire lasers have been employed almost exclusively, and the measured frequencies have been predominantly in the 500–1000-nm range, although this range has been extended with a fiber laser to cover the acetylene (C_2H_2) lines near 1.5 μm.[4] It is advantageous to develop optical frequency combs of similar precision in the near IR by use of alternative nonlinear optical fibers and near-IR ultrafast lasers. Such combs offer more-convenient measurement capabilities in the telecommunications band (1300–1600 nm), thereby facilitating the development of wavelength,[5] length,[6] and frequency standards in this spectral region. Desirable characteristics for the laser source include both a high repetition rate to maximize the power per mode of the resultant comb and a short pulse duration to maximize nonlinear spectral broadening and minimize the amplification of broadband noise.[7] Whereas fiber lasers and diode lasers may ultimately prove to be the most compact, low-cost sources,[8] the Cr:forsterite solid-state laser that we have developed offers the best combination of short pulses and high repetition rates to date.[9]

In this Letter we report the frequency stabilization of a Cr:forsterite laser-based infrared frequency comb and its use for absolute-frequency measurements. The laser output was broadened in a highly nonlinear dispersion-shifted optical fiber (HNLF),[10] and the resultant comb was stabilized by use of two National Institute of Standards and Technology (NIST) frequency standards: the neutral-calcium optical standard[2] and a hydrogen maser that is calibrated by the NIST F1 cesium fountain clock.[11] To demonstrate its utility, we employed the stabilized comb to measure frequency references spanning 1300–1560 nm. This range can be readily extended to 1620 nm, where beats have been observed between the frequency comb and a cavity-stabilized laser.[9]

The laser system and stabilization technique are shown schematically in Fig. 1. A 10-W ytterbium fiber laser at 1075 nm pumps the Cr:forsterite crystal in the six-mirror ring cavity with a 3% output coupler, as shown in Fig. 1 of Ref. 9. The laser has a 433-MHz repetition rate, an average power of ~500 mW, and a center wavelength of ~1275 nm. The spectrum's FWHM is ~50 nm, which corresponds to a pulse duration as short as 35 fs FWHM. The pulse is temporally compressed with a chirped mirror before passing through a 10-m length of HNLF with dispersions of −13 ps/(nm km) at 1280 nm and ~0 ps/(nm km) at 1500 nm. The HNLF is created by standard germanium and fluorine dopants of silica by modified chemical-vapor deposition. While it is propagating in the HNLF the pulse broadens in frequency and forms a supercontinuum spectrum similar to that shown in Fig. 4(i) of Ref. 9 that spans 1080–1920 nm at 20 dB below the peak. Although broader spectra have been obtained by use of hybrid HNLF with

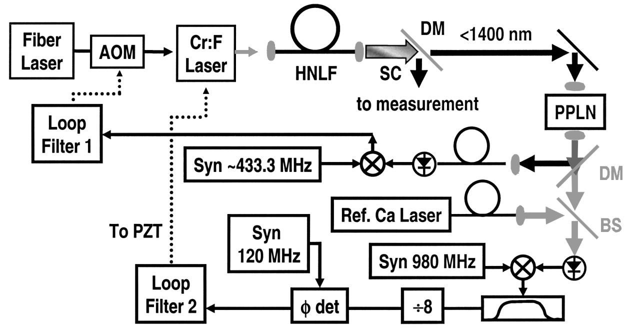

Fig. 1. Schematic of the stabilization scheme for the IR comb: SC, supercontinuum; DMs, dichroic mirrors; Syns, synthesizers; BSs, beam splitters; ϕ det, phase detector; Loop Filters 1, 2, electronic servo filters.

decreasing dispersion, the −13-ps/(nm km) fiber provided the smoothest spectrum, which is desirable for optical frequency metrology.[9,10]

The stabilization of an optical frequency comb requires the control of two degrees of freedom of the laser: rate f_0 at which the relative phases of the carrier and the envelope of the optical pulse evolve in the cavity, and pulse repetition rate (f_r). The frequency of the nth mode of the comb can then be expressed as $f_n = f_0 + nf_r$, where n is an integer.[1] One elegant technique for stabilizing f_0, namely, self-referencing,[1] is most conveniently implemented when the spectrum covers a full factor of 2 in frequency. An alternative technique, employed here, involves stabilizing one mode of the comb to an optical-frequency reference while simultaneously stabilizing the repetition rate to a microwave-frequency reference.[3]

To stabilize the frequency comb we frequency doubled the spectral components of the supercontinuum near 1314 nm in periodically poled lithium niobate (PPLN), and beat them against as much as 2 mW of light from the calcium optical frequency standard at 657 nm.[2] The beat note near 20 MHz was mixed with a synthesizer output near 980 MHz to generate a signal near 960 MHz. This frequency was divided by a factor of 8 to generate a control signal near 120 MHz with a reduced phase excursion suitable for input into a phase detector. The resultant error signal was filtered and fed back to a piezoelectric transducer (PZT) for predominant control of the comb spacing. With one tooth of the comb phase locked as described, the remaining fluctuations of f_0 were transferred to fluctuations in f_r, which were detected on a fast photodetector. The photodetector's output signal was mixed with a maser-referenced synthesizer set to the desired repetition rate, and the resultant error signal was filtered and fed back to the acousto-optical modulator (AOM) that controls the pump power to the Cr:forsterite crystal. The two error signals are not completely orthogonal, but together they allow for stabilization of both f_0 and f_r of the comb.

The two phase-locked electrical signals are shown in Fig. 2, as measured with a rf spectrum analyzer. Both the locked repetition rate of the laser and the beat of the doubled comb against the calcium reference show a narrow carrier, with a width of <10 Hz, which is the resolution of the spectrum analyzer employed. We made direct phase-noise measurements by mixing in quadrature f_r or $f_{\mathrm{Ca\ Beat}}$ with a synthesizer signal at the same frequency. We low-pass filtered the mixer's output voltage and recorded it with either an oscilloscope or a fast-Fourier-transform spectrum analyzer to measure the phase noise. These investigations revealed that f_r is phase locked to the synthesizer with <0.2 mrad of phase excursion integrated from 1 Hz to 10 MHz, whereas f_0 is phase locked (i.e., less than π rad of phase excursion) from 1 Hz to 1 kHz.

It is interesting to examine the potential stability and accuracy of the comb. The comb is frequency doubled, and one mode, $n_{\mathrm{Ca}/2}$, is offset locked to calcium frequency reference f_{Ca}. That particular mode will have the fractional frequency instability of the calcium reference, shown to be as good as $4 \times 10^{-15}\ \tau^{-1/2}$ (for τ in seconds).[2] The instabilities of other comb modes will degrade with distance from $n_{\mathrm{Ca}/2}$ because of the greater instability of the hydrogen maser ($\sim 2 \times 10^{-13}\ \tau^{-1/2}$). The fractional frequency uncertainty of the comb, however, will be limited to that of $f_{\mathrm{Ca}/2}$, namely, 4.4×10^{-14},[12] because the hydrogen maser can be calibrated by use of the NIST F1,[11] which thereby transfers its superior fractional frequency uncertainty of 1×10^{-15} to the hydrogen maser. The net result is a comb of optical frequencies spanning 1100–1800 nm, spaced by 433 MHz and known to better than 11 Hz with an instability smaller than 10 Hz in 1 s.

Once the comb is stabilized, it can be used for frequency measurements. The frequencies of the comb modes depend on f_r, which is measured directly, and on f_0, which one finds by solving

$$f_{\mathrm{Ca}} \pm f_{\mathrm{Ca\ Beat}} = 2(n_{\mathrm{Ca}/2} f_r + f_0) \tag{1a}$$

or

$$f_{\mathrm{Ca}} \pm f_{\mathrm{Ca\ Beat}} = (2n_{\mathrm{Ca}/2} + 1) f_r + 2f_0 , \tag{1b}$$

where $f_{\mathrm{Ca\ Beat}}$ is the 20-MHz beat signal between the calcium light and the doubled comb line at $n_{\mathrm{Ca}/2}$. These two equations arise because, when the comb passes through the nonlinear crystal (PPLN), two interleaved combs are created: one that represents the doubling of each comb mode (and the sum-frequency generation of modes separated by even integers) and another that represents the sum-frequency generation of comb modes that are separated by odd integers. One finds the sign in front of $f_{\mathrm{Ca\ Beat}}$ by increasing f_r and observing the change in $f_{\mathrm{Ca\ Beat}}$. Once f_0 has been found, the frequency of any unknown laser, f_u, can be found from $f_u = f_0 + n_u f_r \pm f_{u\ \mathrm{Beat}}$, where the beat-note frequency $f_{u\ \mathrm{Beat}}$ is measured with either a frequency counter or a rf spectrum analyzer and mode number n_u is known from a wavelength-meter

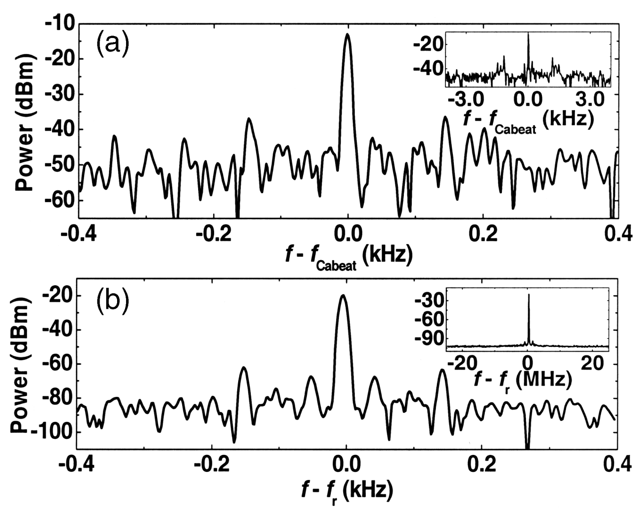

Fig. 2. Electrical signals used for locking, shown while the comb is phase locked, taken with a rf spectrum analyzer with a resolution bandwidth of 10 Hz. (a) Calcium beat with a doubled comb, centered on $f_{\mathrm{Ca\ Beat}} = 20.6$ kHz, with a S/N of the peak of ~35 dB. (b) Repetition rate, centered on $f_r = 433.4352$ MHz, with a S/N of ~50 dB. Insets, the same spectra with expanded frequency scales.

measurement with an uncertainty of less than $f_r/2$. One can find the sign in front of $f_{u\,\mathrm{Beat}}$ by adding a known offset to the frequency of the laser that provides f_{Ca} and then observing the deviation of $f_{u\,\mathrm{Beat}}$.

An attractive frequency standard in the IR is based on a laser near 1560 nm that is frequency doubled and locked to a transition in Rb.[13,14] Whereas some explore the narrow two-photon transition at 778 nm,[13] we report measurements for which the convenient d/f crossover of the $5s\,^2S_{1/2}$–$5p\,^2P_{3/2}$ transition is used.[14] Our Rb spectrometer consists of an extended-cavity diode laser (ECDL) at 1560 nm, amplified in an Er-doped fiber amplifier to 50 mW. This power is frequency doubled to 780 nm in a PPLN crystal and directed to a Rb vapor cell. Frequency tuning the ECDL then locks this 780-nm light to the peak of a sub-Doppler transition, which is observed by use of FM saturated absorption spectroscopy. The pump beam counterpropagates relative to one probe beam at an angle of $\sim$10 mrad, intersecting at the center of the room-temperature Rb vapor cell. A second probe beam passes through the cell, and the difference in power between these two probe beams is detected. On demodulation, the difference signal between the two probe beams yields an error signal that can be used to frequency lock the ECDL to a spectroscopic line. We chose to stabilize the laser frequency to the d/f crossover of the $5s\,^2S_{1/2}$–$5p\,^2P_{3/2}$ transition, which had been used previously as a frequency reference.[14] Once the 1560-nm laser light is stabilized, some fraction of it beats against the comb, and the resultant heterodyne signal is measured with a rf spectrum analyzer because it has an insufficient signal-to-noise ratio (S/N) to be counted with a frequency counter. Using the technique described above, from the measured rf beat frequency we determined the optical frequency to be 192 113 990.7 MHz, with an expanded uncertainty (2σ) of $\pm$0.7 MHz. This corresponds to a 780-nm frequency of 384 227 981.3 MHz with an expanded uncertainty of $\pm$1.4 MHz, which is consistent with a more-accurate determination of the d/f transition.[14] Our uncertainty is dominated by frequency shifts that result from the small angle between the pump and the probe beams in the Rb saturated-absorption spectrometer[15] and a small power dependence. Pressure shifts that are due to contaminants in the Rb cell were not evaluated. The statistical uncertainty (1σ) on this single measurement is only 40 kHz, calculated from the standard deviation of 12 measurements taken over a 1-h period. Whereas this result is almost certainly dominated by the instability of the laser locked to the Rb spectrometer, it indicates a generous upper limit for the instability of the comb.

We also remeasured the NIST methane wavelength standard near 1300 nm.[5] This spectrometer is described in detail in Ref. 5 and consists of an ECDL locked to a Doppler-broadened transition in methane at 8.21 $\pm$ 0.76 kPa. The new measurement of the $R(8)$ transition feature gives 228 050 482.8 MHz $\pm$ 2.3 MHz, which agrees with the previous measurement within its quoted uncertainty. No attempt was made to reassess the systematic errors in the spectrometer, and therefore the uncertainty of our new measurement is not reduced. For this transition the S/N of $f_{u\,\mathrm{Beat}}$ is sufficient to permit the frequency to be counted with an electronic frequency counter. This same general technique should permit higher-accuracy measurements of other methane transitions.

In conclusion, we have stabilized the optical frequency comb from a Cr:forsterite laser to known frequency references. The stabilized comb has been used to measure representative optical frequencies in the telecommunications band. This system should facilitate high-accuracy optical frequency metrology from 1100 to 1800 nm.

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