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Optical frequency comb with an absolute linewidth of 0.6 Hz–1.2 Hz over an octave spectrum

Su Fang, Haiqin Chen, Tianyin Wang, Yanyi Jiang,[a] Zhiyi Bi, and Longsheng Ma[a]
State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, China

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We demonstrate a narrow-linewidth optical frequency comb based on a femtosecond Ti:sapphire laser by precisely phase-locking it to a subhertz-linewidth Nd:YAG laser at 1064 nm. Each comb tooth inherits the phase coherence and frequency stability of the subhertz-linewidth laser. By comparing against other independent narrow-linewidth lasers, we measured the absolute linewidth of the comb teeth to be 0.6 Hz–1.2 Hz over an octave spectrum. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4809736]

Narrow-linewidth lasers with ultra-low phase noise and spectral purity are widely used in optical atomic clock,[1–4] high-resolution laser spectroscopy,[4,5] tests of fundamental physics,[6] and gravitational wave detection.[7] Recently, laser systems with subhertz-linewidth at some specific wavelengths have been constructed around the world for above mentioned applications.[3,4,8–13] To meet their full potential, by using an optical frequency comb (OFC) as a "flywheel," it is convenient to transfer the coherence and frequency stability of the subhertz-linewidth lasers from one frequency to any other optical frequencies[14,15] or even to the microwave domain.[16–18] A relative linewidth added by OFCs was measured to be sub-mHz to tens mHz by comparing two OFCs referenced to a same optical oscillator.[14,19,20] Other than a "flywheel," when tightly phase-locked to a subhertz-linewidth laser, an OFC is equivalent to an enormous number ($>10^5$) of optical oscillators with a linewidth from subhertz to hertz evenly spaced across the spectrum. Such a unique tool will be of great benefit to real-time precision spectroscopy,[21,22] low phase noise frequency synthesis,[16–18] optical atomic clock,[1–4] frequency ratio measurement of quantum transitions,[23,24] and rapid, long-range distance measurement.[25] For those above applications, they all rely on the absolute linewidth of OFCs. A fiber-laser-based OFC with an absolute linewidth of 3 Hz (FWHM: full width half maximum) at 1535 nm (Ref. 15) and Ti:sapphire-laser-based OFCs with an absolute linewidth of 4 Hz at 657 nm (Ref. 19) have been demonstrated. Recently, the linewidth of a beat note between an Yb-doped-fiber-laser-based OFC and a crystalline-coating cavity-stabilized laser at 1064 nm was measured to be 0.7 Hz in JILA. In this letter, we demonstrate a narrow-linewidth OFC based on a Ti:sapphire femtosecond (fs) laser with a repetition rate of 800 MHz, which is phase-locked to a subhertz-linewidth Nd:YAG laser at 1064 nm using the techniques of collinear self-referencing[26] and cross-phase modulation.[27] The most probable linewidth of the comb teeth was measured to be 0.6 Hz–1.2 Hz from 1064 nm to 532 nm.

Fig. 1 shows the experimental setup for our narrow-linewidth OFC. The output light from a Ti:sapphire mode-locked fs laser with nearly 600 mW average power and a repetition rate f_r of 800 MHz is coupled into a piece of polarization-maintaining photonic crystal fiber (PCF) for spectrum broadening to more than one octave from 520 nm to 1200 nm. The PCF is sealed in an aluminum tube with end facet beam expansion, enabling long-time and robust running. A collinear self-referencing technique[26] is employed to detect the carrier-envelop offset frequency f_{ceo}, where both the IR light near 1064 nm and the visible light near 532 nm from the comb are collinearly sent to a periodically poled $KTiOPO_4$ (PPKTP) crystal for 1*f*-2*f* self-referencing interferometer. The PPKTP crystal is utilized for the second harmonic generation (SHG) of the comb teeth at 1064 nm. Then, both the comb light at 532 nm and the frequency-doubled light of the comb teeth at 1064 nm are filtered at 532 nm by a grating and steered on a fast photo-detector to obtain the beat signal of f_{ceo}. The signal to noise ratio (SNR) of f_{ceo} is more than 50 dB at a resolution bandwidth (RBW) of 300 kHz without using any optical delay line and beam splitters in the 1*f*-2*f* interferometer. Then, the signal of f_{ceo} is sent to servo systems to be phase-locked to a radio-frequency (RF) reference by controlling the pumping power of the mode-locked laser via an acoustic-optical modulator (AOM). Benefiting from the collinear self-referencing setup, it is not necessary to realign the 1*f*-2*f* interferometer in the past year, and it enables long-time continuous frequency stabilization of f_{ceo} (more than 10 h without optimizing the coupling of PCF). The collinear self-referencing setup and the Ti:sapphire mode-locked fs laser are enclosed in an aluminum box.

To make each comb tooth gain high phase coherence, we phase-locked the OFC to a reference laser with subhertz linewidth. Two 1064 nm monolithic Nd:YAG lasers with a most probable linewidth of 0.6 Hz and frequency instability of $(1\text{–}1.2) \times 10^{-15}$ between 1 s and 40 s (Ref. 28) are employed in the experiment. The lasers are independently frequency-stabilized to two separately located, ultra-stable Fabry-Perot (FP) cavities using the Pound-Drever-Hall (PDH) technique. Each FP cavity is 7.75 cm long and is vertically mounted to suppress the sensitivity to vertical vibration. The cavity finesse is measured to be $\sim 2 \times 10^5$, corresponding to a cavity linewidth of ~10 kHz. Systematic evaluation shows the performance of each laser system is close to the cavity thermal noise limit. More details on those

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[a] Authors to whom correspondence should be addressed. Electronic addresses: yyjiang@phy.ecnu.edu.cn and lsma@phy.ecnu.edu.cn.

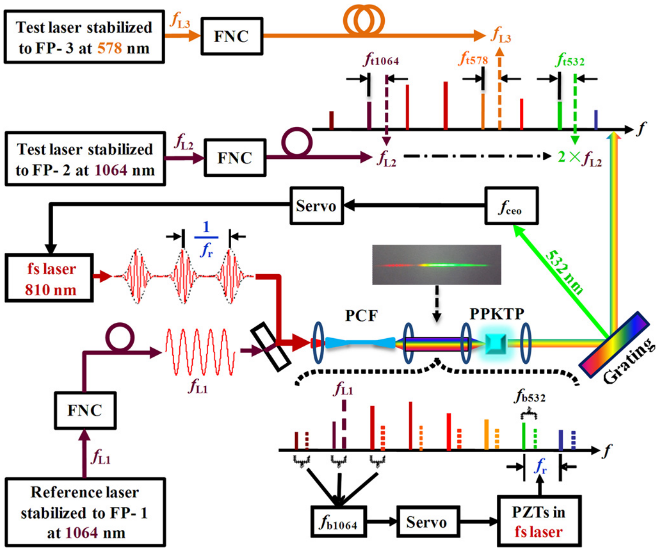

FIG. 1. Schematic of the experimental setup for narrow-linewidth OFC and absolute linewidth measurements. FP-1, FP-2, and FP-3 are three independent Fabry-Perot cavities; f_{L1} is the frequency of the reference laser at 1064 nm; f_{L2} and f_{L3} are the frequencies of the test lasers at 1064 nm and 578 nm, respectively; f_{b1064} and f_{b532} are the beat notes between the Ti:sapphire-laser-based OFC and the XPM-based OFC at 1064 nm and 532 nm, respectively; f_{t1064}, f_{t578}, and f_{t532} are the beat notes between the Ti:sapphire-laser-based OFC and the test lasers; f_{ceo} is the carrier-envelop offset frequency; f_r is the repetition rate of fs-laser; FNC denotes fiber noise cancellation; PCF denotes photonic crystal fiber. The PPKTP crystal is employed for the SHG of the comb teeth at 1064 nm.

subhertz-linewidth lasers can be found in Ref. 28. One of the subhertz-linewidth lasers locked to FP-1 is served as the reference laser, f_{L1}, which the OFC is phase-locked to. The second one (f_{L2}) locked to FP-2 is served as the test laser to measure the linewidth of the comb teeth at 1064 nm and 532 nm.

The reference laser light, f_{L1}, is transferred to the OFC via a piece of single mode (SM) optical fiber employing fiber noise cancellation (FNC) to cancel the phase noise induced by random fluctuations of the fiber length due to vibration, acoustic noise, and variations of environmental temperature and pressure.[29] In order to effectively phase-lock the OFC to f_{L1}, high SNR of the beat note f_b between f_{L1} and the comb is always pursued since only a single comb tooth with very weak power contributes to the beat note. To increase the SNR of f_b, as shown in Fig. 1, we coupled both the reference laser light and the mode-locked laser light into the PCF. When the OFC and f_{L1} co-propagate simultaneously inside the PCF, they interact with each other through fiber nonlinearity. Due to the nonlinear effect of cross phase modulation[27] (XPM), a set of frequency sidebands beside the reference laser with a frequency spacing of f_r is observed in the experiment, whose frequency is expressed as $f_{L1} \pm mf_r$ (m is an integer), similar to a new-generated optical frequency comb. In the experiment, the spectrum of the XPM-based OFC can be extended from 1064 nm to 532 nm, verified by observing beat notes between two combs at 1064 nm, 800 nm, and 532 nm (f_{b532}, as shown in the right inset of Fig. 2(b)). Since the SNR of f_b is only 10 dB (RBW: 300 kHz) at 800 nm and 532 nm, we use the beat note f_{b1064} between two combs at 1064 nm. By doing this, the SNR of f_b (re-named as f_{b1064}, a beat note between two combs at 1064 nm) can be more than 40 dB (RBW: 300 kHz) since a number of comb teeth contribute to the beat signal instead of a single comb tooth. Moreover, the spatial modes of two comb beams are perfectly matched, which also helps to improve the SNR of f_{b1064}. Then, the signal of f_{b1064} is sent to servo systems to keep f_{b1064} fixed by adjusting the cavity length L of the Ti:sapphire fs laser via two piezoelectric transducers (PZTs) separately attached to two laser cavity mirrors (one PZT is thin for fast control and the other is thick for slow control). Thereby, we make $f_{L1} = nf_r \pm f_{ceo} \pm f_b$, where n is an integer. Since f_{L1}, f_{ceo}, and f_b are all very stable, f_r is indirectly stabilized to the reference laser f_{L1}. In the end, each comb tooth, $f_c = nf_r \pm f_{ceo}$, is phase-locked to the reference laser.

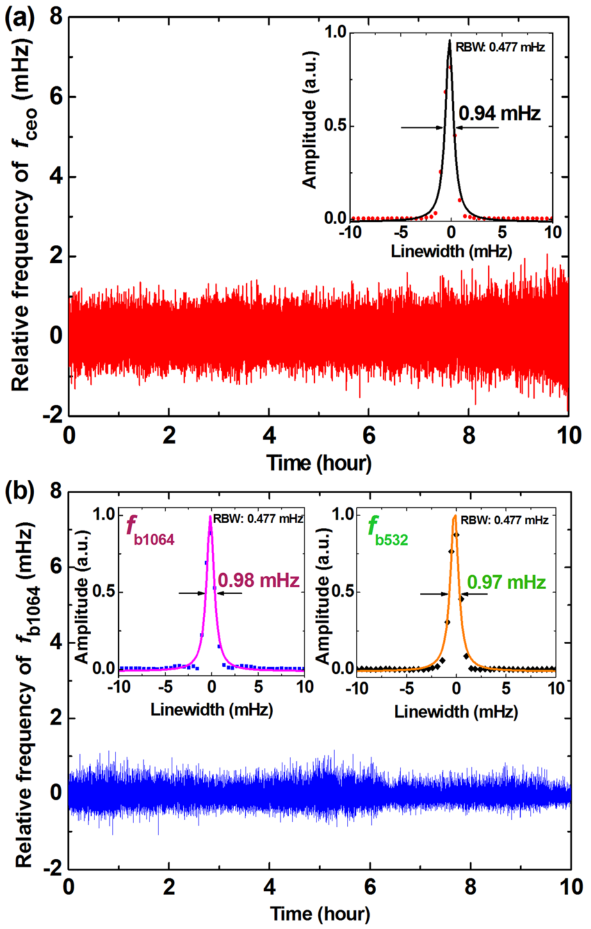

FIG. 2. In-loop measurements of the carrier-envelop offset frequency f_{ceo} and the beat note f_{b1064} (f_{b532}) between the Ti:sapphire-laser-based OFC and the XPM-based OFC at 1064 nm (532 nm). (a) Relative frequency fluctuation of f_{ceo} when stabilized to a RF reference. The inset displays a spectrum of f_{ceo} observed on a FFT spectrum analyzer with the RBW of 0.477 mHz. The linewidth of f_{ceo} is RBW limited. (b) Relative frequency fluctuation of f_{b1064} when stabilized to a RF reference. The left (right) inset displays the spectrum of f_{b1064} (f_{b532}) showing a RBW-limited linewidth.

In order to verify that our OFC has sufficient capability to track the reference laser, we measured the linewidths of both f_{ceo} and f_{b1064} (in-loop) on a fast Fourier transform (FFT) spectrum analyzer, as shown in the inset of Fig. 2(a) and the left inset of Fig. 2(b) accordingly. These measurements were limited by the RBW of the acquisition instrument. The right inset of Fig. 2(b) shows the spectrum of f_{b532} with a RBW-limited linewidth, which indicates the uniformity of the mode spacing of the XPM-based OFC. The frequency of f_{ceo} and f_{b1064} was continuously counted by two RF counters, as shown in Figs. 2(a) and 2(b), respectively. The frequency instabilities of f_{ceo} and f_{b1064} relative to optical frequencies at 1 s are 7.8×10^{-18} and 7.2×10^{-18}, respectively. Less than 15 phase flips were removed from the data recorded over 10 h.

We made out-of-loop measurements to characterize the absolute linewidth of the phase-locked OFC by comparing against test lasers, f_{L2} both at 1064 nm and at 532 nm, and a third cavity-stabilized laser (f_{L3}) at 578 nm. f_{L3} is based on the sum of a 1030 nm fiber laser and a 1319 nm diode pumped Nd:YAG laser. This laser is frequency-stabilized to a third independent FP cavity (FP-3) by feedback control of both a PZT of the 1319 laser and an extra AOM at the output of the summing waveguide. The reference cavity (FP-3) has the same configuration as the above two cavities and its finesse is measured to be $\sim 6.7 \times 10^5$. The experimental setup for linewidth measurement is enclosed in a plexiglass box beside the aluminum box.

The beat signal f_{t1064} between f_{L2} and one of the comb teeth at 1064 nm was mixed down to nearly 5 kHz to be analyzed on a FFT spectrum analyzer with the RBW of 0.25 Hz. 1000 groups of spectra were recorded automatically by a computer without any compensation of laser frequency drift. The inset of Fig. 3(a) shows an example of the spectra (black square markers) and its Lorentzian fit (blue solid curve) with a linewidth of 0.8 Hz (FWHM). Fig. 3(a) shows the linewidth distribution (red triangle markers) and its Lorentzian fit (black solid line). The most probable linewidth of f_{t1064} is near 0.81 Hz, contributed from both the test laser at 1064 nm and the comb tooth at 1064 nm. Since the linewidth of the test laser at 1064 nm is measured to be 0.6 Hz, the linewidth of the comb tooth at 1064 nm is calculated to be 0.6 Hz. The frequency of f_{t1064} was measured by a RF counter. The fractional frequency instability of the comb tooth is $(1.1\text{–}1.3) \times 10^{-15}$ between 1 s and 40 s when a linear frequency drift of 0.08 Hz/s is removed by fitting the data. The frequency instability of the comb tooth near 1064 nm is very close to that of the reference laser. Similarly, we measured the linewidth of the comb teeth near 578 nm by beating against f_{L3} and that near 532 nm by beating against $2 \times f_{\mathrm{L2}}$. The beat notes are named as f_{t578} and f_{t532} accordingly. The insets of Figs. 3(b) and 3(c) show examples of the spectra of f_{t578} and f_{t532} with the RBW of 0.5 Hz and their Lorentzian fit. Figs. 3(b) and 3(c) show their linewidth distributions. The Lorentzian fit of Fig. 3(b) indicates the most probable linewidth of f_{t578} is 1.6 Hz. Thereby, the linewidth of the comb tooth at 578 nm reaches 1.13 Hz under the assumption that f_{L3} and the comb tooth contribute equally. The fractional frequency instability of the comb tooth at 578 nm is measured to be $(1.1\text{–}1.3) \times 10^{-15}$ (1–40 s, 0.08 Hz/s removed). The Lorentzian fit of Fig. 3(c) shows f_{t532} has the most probable linewidth of 1.65 Hz, which is contributed from both that of f_{L2} and the comb tooth. Therefore, the linewidth of the comb tooth at 532 nm is close to 1.2 Hz. Since the frequency of each comb tooth is expressed as $f_{\mathrm{c}} = nf_{\mathrm{r}} \pm f_{\mathrm{ceo}}$ and the mode number of the comb tooth at 532 nm is twice of that at 1064 nm, the linewidth of the comb tooth measured at 532 nm is approximately twice of that at 1064 nm. The above results show that the OFC faithfully transfers the coherence and frequency stability from the reference laser to all the comb teeth from the IR to the visible region over an octave spectrum. The mHz-level linewidths of f_{ceo} and f_{b1064}, as shown in the inset of Fig. 2, indicate that the comb teeth is tightly phase-locked to the reference laser and they are far less than the linewidth of the reference laser (0.6 Hz). At the moment, the linewidths

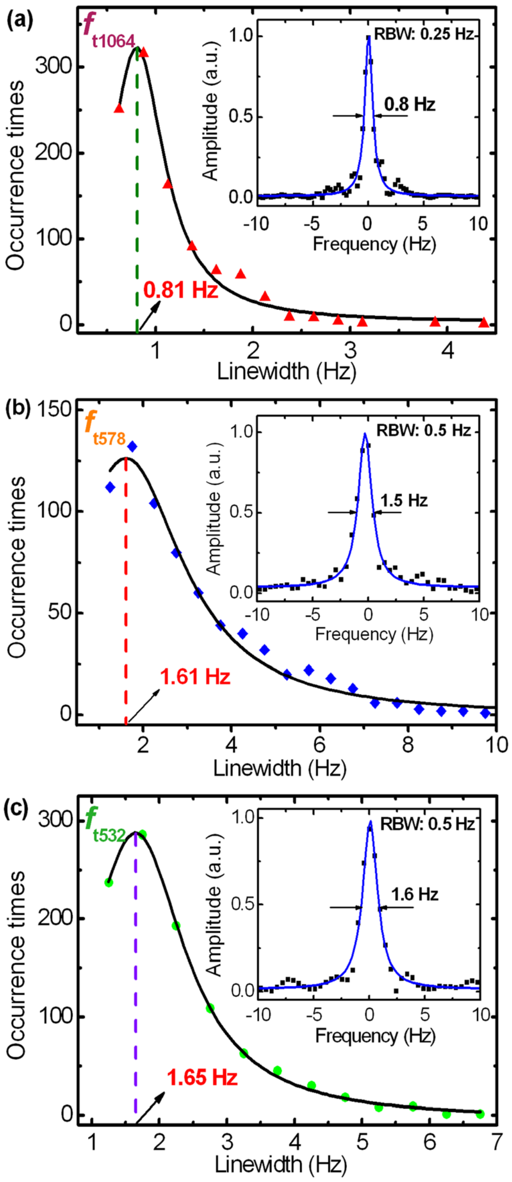

FIG. 3. Out-of-loop linewidth measurements of the beat notes f_{t1064}, f_{t578}, and f_{t532} between optical frequency comb teeth and the test lasers at 1064 nm, 578 nm, and 532 nm. (a) The linewidth distribution of the beat note f_{t1064} between a comb tooth at 1064 nm and f_{L2} (red triangle markers). The black solid line is its Lorentzian fit. The inset shows a spectrum of f_{t1064} observed on a FFT spectrum analyzer with the RBW of 0.25 Hz (black square markers) and its Lorentzian fit (blue solid line). (b) The linewidth distribution of the beat note f_{t578} between a comb tooth at 578 nm and f_{L3} (blue diamond markers) and its Lorentzian fit (black solid line). The inset shows a spectrum of f_{t578} observed on a FFT spectrum analyzer with the RBW of 0.5 Hz (black squares) and its Lorentzian fit (blue solid line). (c) The linewidth distribution of the beat note f_{t532} between a comb tooth at 532 nm and the frequency-doubled laser light of f_{L2} (green dots) and its Lorentzian fit (black solid line). The inset shows a spectrum of f_{t532} observed on a FFT spectrum analyzer with the RBW of 0.5 Hz (black dots) and its Lorentzian fit (blue solid line).

of the comb teeth are limited by the reference laser. Therefore, future improvements on the reference laser will help to further reduce the linewidths of the comb teeth.

In summary, we report a narrow-linewidth OFC which is phase-locked to a subhertz-linewidth laser at 1064 nm. By comparing against other cavity-stabilized lasers, we measured the absolute linewidth of the comb teeth to be 0.6 Hz–1.2 Hz from 1064 nm to 532 nm. Based on this narrow-linewidth OFC, an optical frequency synthesizer will be developed and high resolution comb spectroscopy will be performed.

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