Monolithic 0–f Scheme-Based Frequency Comb Directly Driven by a High-Power Ti:Sapphire Oscillator *

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A monolithic 0–f scheme-based femtosecond optical frequency comb directly driven by a high-power Ti:sapphire laser oscillator is demonstrated. The spectrum covering from 650 nm to 950 nm is generated from the Ti:sapphire oscillator with a repetition rate of 170 MHz. The average output power up to 630 mW is delivered under the pump power of 4.5 W. A 44-dB signal-to-noise ratio (SNR) of the carrier-envelope phase offset (CEO) beat note is achieved under the resolution of 100 kHz and is long-term stabilized to a reference source at 20 MHz. The integrated phase noise (IPN) in the range from 1 Hz to 1 MHz is calculated to be 138 mrad, corresponding to the timing jitter of 63 as at the central wavelength of 790 nm.

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Consisting of equally spaced frequency lines, femtosecond optical frequency combs provide an accurate, reliable and practical approach to link optical frequency and microwave reference source[1] and enable compact broadband sources for accurate remote spectroscopic sensing and precision spectroscopy.[2] As early as 1978, Hänsch *et al.* proposed the idea of using femtosecond pulsed laser to measure optical frequency.[3] In 2000, the first practical femtosecond optical frequency comb based on the self-referenced scheme or the f–$2f$ method was reported, which marked the birth of practical optical frequency comb.[4,5] A series of results about frequency measurement with extreme precision have since been reported.[6–9] Over the last few decades, optical frequency combs have been applied to high harmonic generation,[10] attosecond science,[11] frequency metrology,[12] and related frontier scientific research fields.[13–15] Moreover, the advent of infrared frequency combs should enable accurate, precise measurements of small gas enhancements over long ranges to support verification and monitoring of emissions of distributed sources.[16] Specifically, atmospheric sciences and global change requires continuous remotely monitoring transparent thin cirrus clouds, where the 1.38-μm atmospheric-water-vapor band is very effective in detecting thin cirrus clouds for NASA Fire-Breathing Storm Systems.

Up to now, the self-referenced (f–$2f$) scheme is a common approach to measure CEO frequency ($f_{\rm ceo}$),[17] which usually requires one optical octave to be delivered directly by an octave-spanning laser oscillator[18–21] or by external broadening of a photonics crystal fiber (PCF).[22,23] Although the method of using PCF relaxes the requirement for output bandwidth of the laser oscillator, the system has some inherent defects including poor long-term stability, complex optical path alignment and limited output power. Additionally, the nonlinear phase noise induced by PCF raises contamination of electric field in strong extreme nonlinear optics.[24] The approach of directly employing an octave-spanning laser avoids the above problems, but it increases the difficulty including ultra-broadband intracavity dispersion compensation and suitable output coupler (OC) with specially designed transmittance curve as well as running under the extremely operating condition. Generally, an f–$2f$ scheme for achieving $f_{\rm ceo}$ signal is flexible, which can utilize a Mach–Zehnder type interferometer or a prism-based interferometer as well as a collinear setup.[25] Recently, the compact frequency comb generated directly from a monolithic microresonator[26] and a single monolithic integrated chip were reported.[27] However, its frequency comb lines are originated from a series of four-wave mixing (FWM) processes in a material with inversion symmetry such as silica. This is completely different from the traditional femtosecond optical frequency combs. In 2005, Fuji *et al.* proposed a novel $f_{\rm ceo}$ measurement technique called the monolithic 0–f method based on difference frequency generation (DFG) of the nonlinear crystal.[28,29] Compared with f–$2f$ frequency combs, monolithic 0–f scheme-based femtosecond optical frequency combs driven by a KLM Ti:sapphire laser oscillator have been constantly promoted since the 0–f method was proposed.[30] In 2016, we firstly

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employed an octave-spanning Ti:sapphire laser oscillator based on the monolithic 0–f scheme, which obtained the integrated phase noise (IPN) of only 55 mrad corresponding to a 23-as timing jitter.[31] It indicates excellent performance of the monolithic 0–f scheme. However, it is admirable to get a high SNR $f_{\rm ceo}$ signal from the monolithic 0–f schemed frequency comb directly driven by a common bandwidth-limited Ti:sapphire oscillator. Furthermore, the 0–f scheme combined with feed-forward approach to stabilize the $f_{\rm ceo}$ signal is also a significant and promising technology because it requires no complicated locking electronics and does not compromise laser performance.[32,33]

In this Letter, the monolithic 0–f scheme-based femtosecond optical frequency comb driven by a high-power KLM Ti:sapphire laser oscillator at a repetition rate of 170 MHz is demonstrated. The laser oscillator delivers the bandwidth-limited spectrum spanning from 650 nm to 950 nm, which is less than the reported monolithic 0–f scheme-based frequency combs with the bandwidth of over 400 nm. Around 9-fs pulse duration is measured. By increasing the output power of the laser oscillator to 630 mW, we demonstrate the feasibility of a high SNR monolithic 0–f scheme-based frequency comb without the ultra-broadband Ti:sapphire laser oscillator. To the best of our knowledge, this is the first demonstration of a monolithic 0–f scheme-based frequency comb directly driven by a bandwidth-limited Ti:sapphire oscillator with highest average power. Using a specially designed PP-MgO:LN crystal (HC Photonics) to match up with the spectral distribution of the laser oscillator, the 44-dB free running $f_{\rm ceo}$ beat note is realized to using a feedback system with 50-kHz bandwidth. The IPN in the range from 1 Hz to 1 MHz is calculated to be 138 mrad, corresponding to the timing jitter of 63 as at the central wavelength of 790 nm.

Figure 1 shows the sketch of monolithic 0–f scheme-based femtosecond frequency comb driven by a high-power KLM Ti:sapphire laser oscillator with a repetition rate of 170 MHz. The single-frequency pump laser at 532 nm delivered by a diode-pumped solid-state (DPSS) laser (Verdi V10, Coherent) was tightly focused into the gain crystal via the pump lens (L1) with the focal length of 50 mm. The waist radius of the pump laser in the gain medium was measured to be 7.7 µm by a commercial CCD. A 2-mm-thick Ti:sapphire crystal (GT Advanced Technologies) was chosen as the active medium, which was placed at the Brewster angle in the middle of two pump mirrors (M1 and M2) both with the same radius of curvature (ROC) of 75 mm. The distance between two pump mirrors is around 77.5 mm. The ratio of long arm and short arm is about 2.1 : 1. All the four intracavity mirrors (M1–M4) purchased from Layertec are broadband doubled-chirped mirror pairs (DCMs) coated with high reflection from 600 nm to 980 nm and group delay dispersion (GDD) from 620 nm to 960 nm, which totally provides smooth GDD of around $-145\,{\rm fs}^2$ to compensate for the material dispersion induced by the gain crystal, as well as air path. A 2-mm-thick OC with 3% transmittance from 700 nm to 900 nm was specially designed to maintain intracavity high-power density and suitable spectral output. Moreover, a pair of wedges (W) were inserted in the laser cavity at the Brewster angle to finely tune the intracavity dispersion. The intracavity net average GDD is adjusted to around a few negative fs^2, which is the key for generation of broadband spectrum and high-power output.

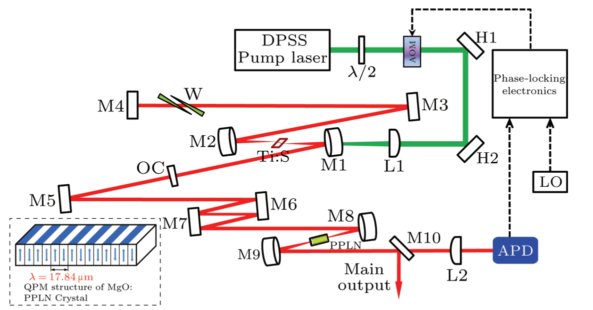

Fig. 1. Experimental setup of the monolithic 0–f scheme-based optical frequency comb driven by a high-power KLM Ti:sapphire laser oscillator: $\lambda/2$, half-wave plate for 532 nm; AOM, acousto-optic modulator; H1–H2, plane high reflectivity mirror (HR: 532 nm); L1, pump lens (f = 50 mm); L2, filter lens (f = 30 mm, cutoff wavelength: 1 µm); M1–M4 and M6–M7, double-chirped mirror pairs; OC, 2-mm-thick output coupler (transmittance of 3%); W, fused-silica wedges; M5, silver mirror; M8–M9, concave silver mirror (ROC = 30 mm); PPLN: 3-mm-thick periodically poled lithium niobate crystal (poling period: 17.84 µm; M10, dichroic mirror (cutoff wavelength 1 µm); APD, avalanche photodiode; LO, local crystal oscillator.

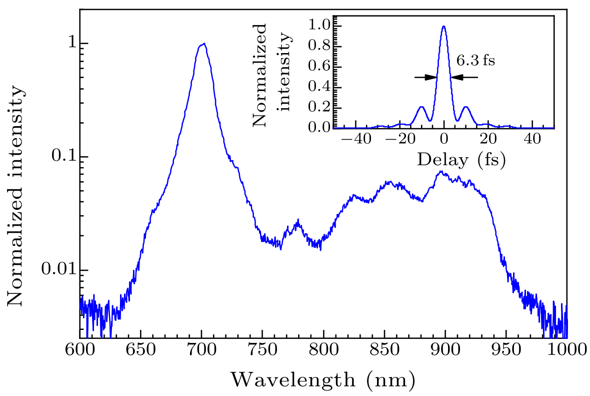

Fig. 2. Typical output spectrum of the frequency comb based on the monolithic 0–f scheme. The inset is the Fourier transformation limited pulse duration.

The laser oscillator was carefully aligned to realize the stable KLM operation at the edge of the upper stability region. Around 660-mW average output power was obtained under the pump power of 4.5 W. The typical output spectrum of laser oscillator spanning from 650 nm to 950 nm is shown in Fig. 2, corresponding to the Fourier transformation limit of 6.3 fs, as inserted in Fig. 2. Then, 9-fs actual pulse duration was directly measured by a commercial interferometric autocorrelation (FEMTOLASER PC-DAQ), as given in

Fig. 3. The slight deviations of measured and theoretical value of pulse duration originated from the need for getting highest SNR f_{ceo} signal. Considering limited space, a pair of wedges were omitted outside the cavity. The intensity of f_{ceo} signal was adjusted by the status of laser oscillator, which must affect output power of the oscillator.

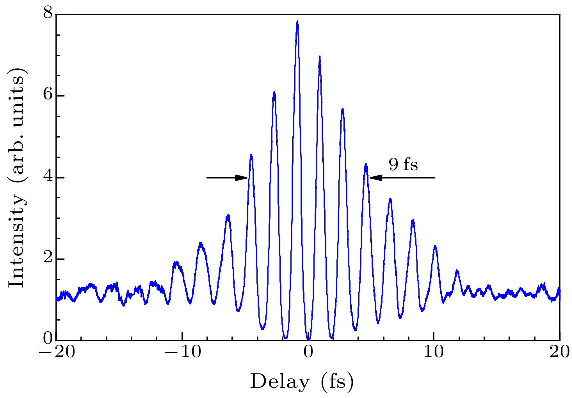

Fig. 3. Interferometric autocorrelation trace of the Ti:sapphire laser oscillator for 9 fs.

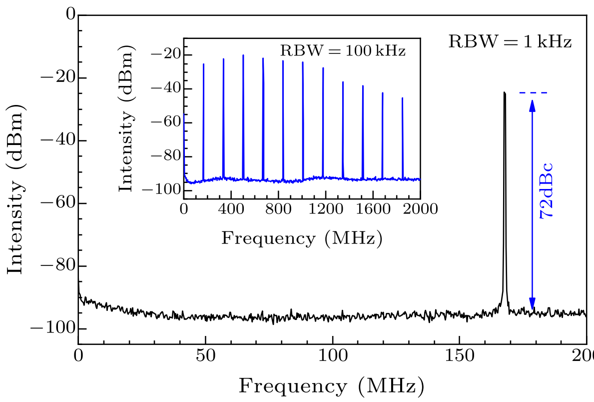

Fig. 4. The RF power spectrum of pulse train detected with a 1 GHz photodetector: with a resolution bandwidth of 1 kHz at the fundamental repetition of 170 MHz and full spectrum up to 1 GHz with 100 kHz resolution.

To confirm mode-locked status of laser oscillator, we also measured the radio-frequency (RF) spectrum by a photodetector (PD) and a commercial RF spectrum analyzer (Agilent E4407B), as shown in Fig. 4. The fundamental beat note of 72 dBc at 170 MHz was recorded in a frequency span of 200 MHz under a resolution bandwidth (RBW) of 1 kHz as shown in Fig. 4. Several harmonic frequency signals were also given in the inset with a window of 2 GHz under the RBW of 100 kHz. The clean RF spectrum in a wide-span range indicates the stable KLM operation as seen from the inset. It should be noted that the fluctuation of the harmonics may be derived from the limited sampling rate of the RF spectrum analyzer or response bandwidth of PD rather than unstable KLM operation of the laser oscillator.

The pre-compensated dispersion was realized by four bounces on ultra-broadband DCMs (M6–M7), which accumulate a total GDD of about $-240\,fs^2$ to pre-compensate for the dispersion of OC, PP-MgO:LN crystal, as well as air path. Subsequently, the output pulse trains with appropriate negative GDD were tightly focused into a 3-mm-thick PP-MgO:LN bulk chip by concave silver mirror M8 with ROC of 30 mm. It is worth noting that the polling period (17.84 μm) of PP-MgO:LN crystal is specially designed to match up with the spectral peak distribution of our laser oscillator. Due to large nonlinear coefficient of PP-MgO:LN crystal, SHG, SPM and DFG occurred inside the PP-MgO:LN crystal to obtain new spectral components of around 1.38 μm at the same time. The f_{ceo} value of laser oscillator is actually equivalent to the frequency difference between the produced components from the SPM and the ones from the DFG. A long-pass dichroic mirror (M10) was utilized to reflect the high-power spectrum components less than 1 μm. A long-pass filter lens (L2) with the focal length of 30 mm can further strained out f_{ceo} signal. An infrared InGaAs avalanche photodiode (APD, New Focus 1181-FS) was employed to directly detect f_{ceo} signal. The free running f_{ceo} signal under a resolution of 100 kHz is shown in Fig. 5. The highest SNR of 44 dB could be obtained when the average output power of sub-10–fs laser oscillator is 630 mW under 4.5 W pump power. Except for the fundamental frequency (f_r) and f_{ceo} signal, the frequency signals including the second harmonic of the f_{ceo} ($2f_{ceo}$), the corresponding sidebands (f_r–f_{ceo}, f_r–$2f_{ceo}$ and $f_r + f_{ceo}$) could also be obviously observed. The absence of other messy signals also indicates that the mode locking of the laser oscillator is stable.

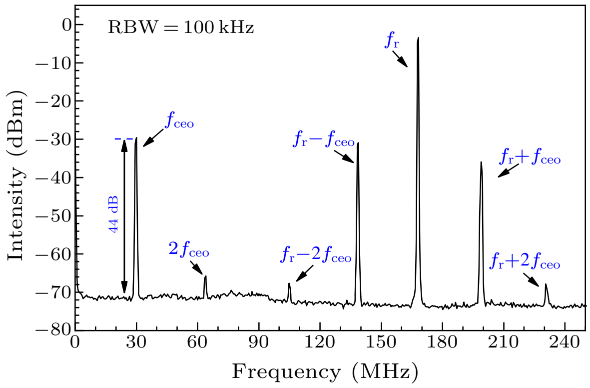

Fig. 5. Free running RF spectrum of f_{ceo} signal directly measured by APD.

Then, the free funning f_{ceo} signal was injected into a PID controller, and the phase error signal was feedback to an acoustic optical modulator (AOM) for changing the power of the pump laser. The noise performance of the stabilized f_{ceo} signal was directly measured and revealed in Fig. 6. The distinct coherent peak with 55-dB SNR under RBW of 1 kHz appears exactly at the 20 MHz (corresponding to 0 MHz in Fig. 6), which indicates an effective phase locking status. The details of f_{ceo} signal noise distribution after locking is revealed by phase noise power spectral density (PSD), as shown in Fig. 7 (the black curve). It can be noticed that phase noise between 50 Hz to 100 kHz is well suppressed to a relative low-level phase noise PSD. We could see that servo bump at 100 kHz indicates the phase locking bandwidth of the whole system, which is limited by the upper lifetime of titanium ion. The IPN in the range from 1 Hz to 1 MHz was calculated to be 138 mrad, which was equivalent to the timing jitter of 63 as corresponding to the central wavelength of 790 nm. We could find that nearly 50% of the residual phase jitter is concentrated by the high frequency phase noise outside the servo bandwidth. With an increasing phase locking bandwidth, we believe that the residual timing jitter would be further reduced. Owing to the simple and robust alignment of the 0–f scheme, we observe more stable long-term $f_{\rm ceo}$ locking performances. Frequency drift around 20 MHz was measured by a frequency counter at 1-s gate time within 90 min, as shown in Fig. 8. The standard deviation was calculated to be 1.5 mHz.

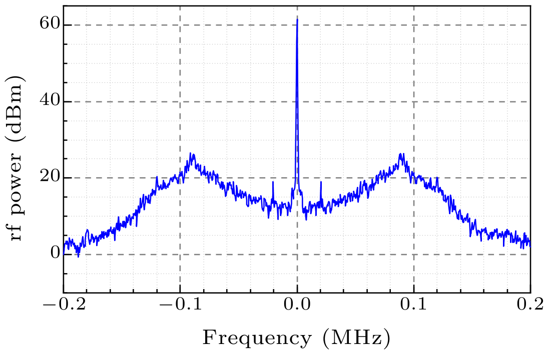

Fig. 6. Noise property of the locked $f_{\rm ceo}$ frequency signal directly measured by APD.

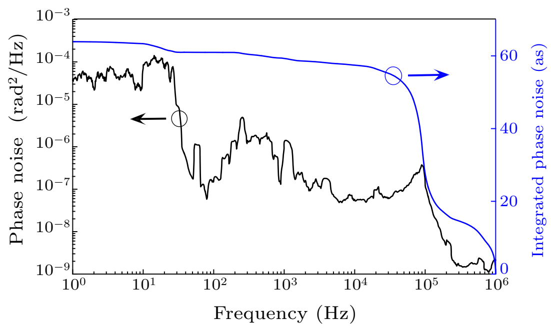

Fig. 7. The phase noise and integral phase of the locked $f_{\rm ceo}$ signal. Black curve: the phase noise. Blue curve: the integrated phase noise.

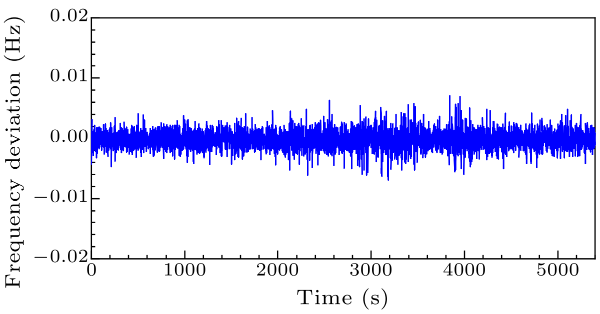

Fig. 8. The locked deviation of the $f_{\rm ceo}$ frequency related to the reference frequency (20 MHz). Gate time: 1 s.

In conclusion, we have demonstrated a monolithic 0–f scheme-based frequency comb directly driven by a high-power bandwidth-limited KLM Ti:sapphire laser oscillator at a repetition rate of 170 MHz. The spectrum covering from 650 nm to 950 nm is generated from a laser oscillator. More than 630-mW average output power is delivered under the pump power of 4.5 W. To the best of our knowledge, this is the highest average power of femtosecond laser oscillator applied to a monolithic 0–f scheme-based optical frequency comb. Free running 44-dB SNR of $f_{\rm ceo}$ is obtained under the resolution of 100 kHz and is stabilized to a reference source at 20 MHz around 90 min. The IPN in the range from 1 Hz to 1 MHz is calculated to be 138 mrad, corresponding to timing jitter of 63 as at the central wavelength of 790 nm.

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