Monolithic CEO-stabilization scheme based frequency comb from an octave-spanning laser*

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(Received 18 November 2015; revised manuscript received 1 December 2015; published online 25 February 2016)

We first demonstrate a carrier-envelope phase-stabilized octave-spanning oscillator based on the monolithic scheme. Wide output spectrum extending from 480 nm to 1050 nm was generated directly from an all-chirped mirror Ti:sapphire laser. After several improvements, the carrier-envelope offset (CEO) beat frequency accessed nearly 60 dB under a resolution of 100 kHz. Using feedback system with 50-kHz bandwidth, we compressed the residual phase noise to 55 mrad (integrated from 1 Hz to 1 MHz) for the stabilized CEO, corresponding to 23-as timing jitter at the central wavelength of 790 nm. This is, to the best of our knowledge, the smallest timing jitter achieved among the existing octave-spanning laser based frequency combs.

Keywords: octave-spanning laser, optical frequency comb, carrier-envelope offset, low phase noise

PACS: 42.55.–f, 42.62.Eh, 42.65.Re, 42.62.Fi **DOI:** 10.1088/1674-1056/25/4/044205

1. Introduction

Octave-spanning laser based frequency combs have increasingly applications in many fields like frequency metrology[1] and optical spectroscopy,[2,3] benefiting from the direct output broad spectra from the oscillators.[4,5] Currently, the most widely used technique to measure and control the CEO frequency ($f_{\rm ceo}$) of an octave-spanning oscillator is the so-called self-referenced scheme,[6–11] in which supercontinuum generation and f–$2f$ interferometer are essential for the $f_{\rm ceo}$ detection. However, the apparatus employed in these two procedures are relatively complex and bulky in size. And the stability of the $f_{\rm ceo}$ signal is sensitive to the fiber coupling and the double-optical-path alignment of the f–$2f$ systems. Moreover, a considerable portion of the laser beam should be split off the main output to the interferometer to generate the $f_{\rm ceo}$ beat note, which inevitably decreases the output power available for the subsequent experiments.

In 2005, a novel CEO measurement technique based on the difference frequency generation (DFG) was proposed by Fuji *et al.*[12,13] This scheme, which is termed monolithic scheme or 0–f scheme, has a simple coaxial light configuration and has been demonstrated to possess relatively lower phase noise in comparison with the traditional self-reference method.[13,14] Besides, beam splitting is not necessary here and there is almost no power loss in the process of $f_{\rm ceo}$ measurement. Nevertheless, the utilization of the monolithic CEO stabilization scheme is still limited to the oscillators with quasi-octave-spanning spectra[15–18] so far, because both high single-pulse energy and broad output spectrum of an oscillator are essential conditions to cause strong nonlinear processes for the $f_{\rm ceo}$ signal generation.[19,20] This, on the other hand, indicates that the octave-spanning lasers, who have broader output spectra and thus potentially shorter pulse durations comparing with quasi-octave-spanning lasers, would be more suitable to adopt the monolithic method for the CEO control.

Up to now, there is no report about CEO stabilized octave-spanning laser by use of monolithic scheme. In this letter, we first experimentally demonstrate the octave-spanning laser based frequency comb by use of monolithic CEO stabilization scheme. Wide spectrum ranging from 480 nm to 1050 nm was directly generated from an all-chirped mirror Ti:sapphire laser. With this monolithic method, the signal-to-noise ratio (SNR) of $f_{\rm ceo}$ of the octave-spanning laser was measured to be as high as 58 dB under a resolution of 100 kHz. This is, to the best of our knowledge, the highest $f_{\rm ceo}$ SNR among the exiting octave-spanning laser based frequency combs. Using phase-locking loop with feedback bandwidth of 50 kHz, we realized an IPN (integrated from 1 Hz to 1 MHz) of 55 mrad for the locked CEO beat signal, equivalent to a timing jitter of 23 as at the central wavelength of 790 nm. The Allan deviation (1-s gate time) of the $f_{\rm ceo}$ is 2×10^{-17} to the optical carrier frequency. These good performances in phase noise and long-term stability derive from the high stability of our oscillator and the monolithic CEO detection method.

*Project supported by the National Basic Research Program of China (Grant No. 2012CB821304) and the National Natural Science Foundation of China (Grant Nos. 11078022 and 61378040).

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2. Octave-spanning Ti:sapphire laser

The octave-spanning frequency comb, as revealed in Fig. 1, is based on a home-made all-chirp-mirror Ti:sapphire laser with a repetition rate of 83 MHz. A 1.9-mm-thick Ti:sapphire crystal ($\alpha_{532} = 7\ \text{cm}^{-1}$) is placed in the middle of two folding mirrors with 100-mm radii of curvature. All the intracavity mirrors (M1–M6) are broadband doubled-chirped mirror (DCM) pairs with high reflection from 580 nm to 1000 nm and group delay dispersion (GDD) from 600 nm to 980 nm, totally providing around -200-fs^2 GDD to compensate for the positive dispersion introduced by the gain crystal as well as air path. A pair of wedges (W1) at the Brewster angle is used to finely tune the intracavity dispersion.

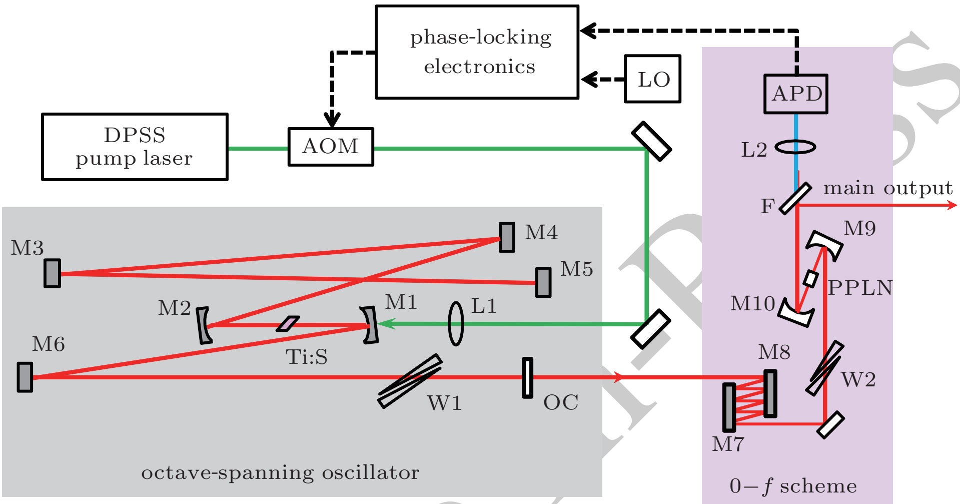

Fig. 1. (color online) Experimental setup of the octave-spanning frequency comb based on monolithic carrier–envelope (0–f) scheme. AOM, acousto–optic modulator; L1, pump lens ($f = 50$ mm); L2, filter lens (silica-doped, $f = 30$ mm, cutoff frequency: 1000 nm); T:S: Ti:sapphire crystal (1.9-mm-thick, $\alpha_{532} = 7\ \text{cm}^{-1}$); M1–M6 and M7–M8, double-chirped mirror pairs (HR: 580 nm–1000 nm, GDD: 600 nm–980 nm)); M9–M10: silver mirrors (ROC = 30 mm); OC, fused-silica output coupler (3-mm-thick); W1–W2, fused-silica wedges; PPLN: periodically poled lithium niobate crystal (3-mm-thick, Poling period: 17.84 μm); F: broadband filter (HR: 600 nm–980 nm); APD: avalanche photodiode; LO: local crystal oscillator.

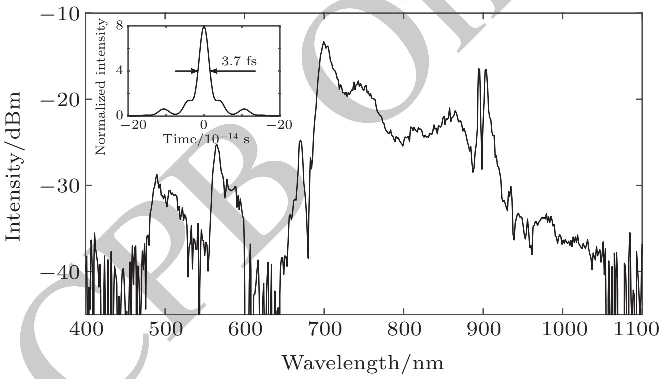

Fig. 2. Typical output spectrum of the octave-spanning oscillator, covering the wavelengths spanning from 480 nm to 1050 nm.

After carefully adjusting the alignment of the oscillator, more than 310-mW stable Kerr-lens mode-locked (KLM) pulses could be obtained under 4.5-W pump power from the diode-pumped solid-state (DPSS) laser. Figure 2 shows the typical output spectrum of more than one octave extending from 480 nm to 1050 nm, corresponding to Fourier transformation limit of 3.7 fs, as shown in the inset of Fig. 2. One can notice that there are two obvious peaks at 490 nm and 564 nm isolated from the continuous spectrum. These spectral modulations, including the peaks and dips, are mainly introduced by the coherent superposition between the intracavity soliton and the dispersive wave,[21] which derives from the strong nonlinearity effect inside the KLM oscillator.

3. Measurement of the CEO signal

After dispersion pre-compensation by a DCM pair (M7, M8) and wedges (W2) outside the cavity, the output pulses were tightly focused into a 3-mm periodically poled Lithium Niobate (PPLN) crystal. The poling period of this crystal (17.84 μm) is specifically designed in terms of the oscillator's spectrum distribution. New spectral components around 1.6 μm were generated by both the self-phase modulation (SPM) and difference-frequency generation (DFG) inside the PPLN crystal at the same time. It is worth noting that the frequency difference between the produced components from the SPM and the ones from the DFG is exactly the f_{ceo} value of the octave-spanning laser.[12] In the experiment, we employed a long-pass filter lens (L2) to filter out the components around 1.6 μm to realize this collinear frequency-beat process. Ultimately, the free running f_{ceo} beat signal was directly detected by an infrared InGaAs avalanche photodiode (APD, New Focus 1181-FS).

We experimentally found the f_{ceo} signal in the monolithic theme was sensitive to the output power of the oscillator and the dispersion compensation outside the laser cavity. In order to obtain a strong beat note, we explored the SNR of the f_{ceo} as functions of average power incident on the PPLN crystal (under -270-fs^2 net GDD provided outside the cavity) and the net GDD provided outside the cavity (under 313-mW power incident on the PPLN crystal), as shown in Fig. 3. We can see that the f_{ceo} almost increases linearly with the incident power above the threshold. This trend, however, could not persist in our experiments since multi-pulse phenomena in our Ti:sapphire oscillator would appear when the oscillator's output power was more than 320 mW. The optimal outside GDD compensation for the f_{ceo} was found to be about -320 fs^2, for providing a pre-compensation to the dispersion caused by the PPLN crystal and ensuring the precision synchronization between two beat beams.

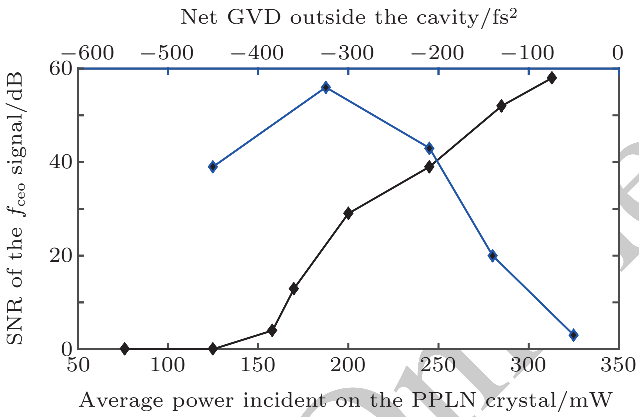

Fig. 3. (color online) The SNR of the f_{ceo} signal as functions of average power incident on the PPLN crystal (black line, under -270-fs^2 net GDD provided outside the cavity) and net GDD provided outside the cavity (blue line, under 313-mW power incident on the PPLN crystal).

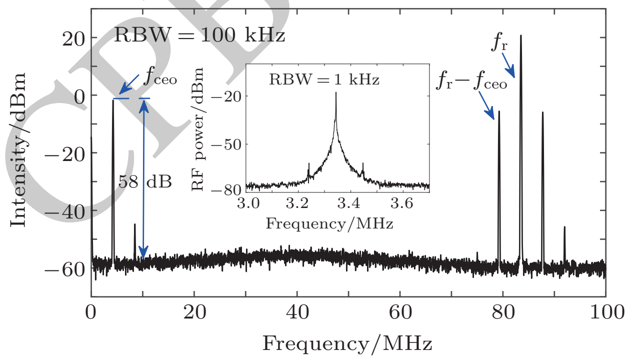

Fig. 4. (color online) Radio-frequency (RF) spectrum of the free running f_{ceo} (RBW = 100 kHz and span = 100 MHz) directly measured by the APD. f_r denotes repetition rate and f_{ceo} denotes the CEO frequency. The inset: the magnified frequency peak of f_{ceo} (RBW = 1 kHz and span = 700 kHz).

Figure 4 shows the f_{ceo}-optimized radio-frequency (RF) spectrum measured with an RF analyzer (FSW 26, Rohde & Schwarz Inc.). A strong f_{ceo} SNR of 58 dB is obtained under a resolution of 100 kHz. Its detail is revealed in the inset of Fig. 4. Such a high f_{ceo} intensity is of great significance in the suppression of the circuit introduced noise and in the demand reduction of the circuit's signal-capture ability. The repetition rate (f_r), the corresponding double sidebands (f_r–f_{ceo} and $f_r + f_{ceo}$) and even the second harmonic of the f_{ceo} can be seen clearly with a wide-span measurement of 100 MHz.

4. Stabilization of the CEO signal

The phase error signal detected by the APD was then feedback to change the power of the pump light via an acoustic optical modulator (AOM). A local quartz crystal oscillator (OL) was employed as an external crystal oscillator. The in-loop noise performance of the stabilized f_{ceo} beat signal is directly measured and revealed in Fig. 5. We can see that the linewidth of the f_{ceo} signal is dramatically narrowed comparing to the previous free-running case (see the inset in Fig. 4), which illustrates a tight phase-lock has been achieved. Although the AOM is experimentally confirmed to possess a broad modulation bandwidth of more than 1 MHz, the whole feedback bandwidth of the phase-locking systems is less than 100 kHz, which is mainly limited by the bandwidth of the phase locked loop and the upper-level life of the Ti:sapphire crystal.[22] This conclusion is also confirmed by the two bumps on the noise pedestal in Fig. 5(a), which are ~ 50 kHz beside the coherent peak.

For a quantitative analysis of the noise property, the power spectral density (PSD) was measured and displayed in Fig. 5(b). The corresponding integrated phase noise (IPN) from 1 Hz to 1 MHz is calculated to be 55 mrad, equivalent to a timing jitter of 23 as at the carrier wavelength of 790 nm. Note that the high-frequency phase noise, especially frequencies higher than the feedback bandwidth of the servo system, has a considerable contribution to the residual phase noise. Even so, our residual phase noise with the same integrated range is still three-fold improvement comparing with the result in Ref. [8], in which f–$2f$ scheme was chosen as the f_{ceo} measurement method for the octave-spanning oscillator.

Long-term locking of the f_{ceo} signal could be achieved due to the high stability of the monolithic CEO stabilization scheme. The locking result around 90 minutes is shown in Fig. 6. The corresponding Allan deviation is calculated to be 4×10^{-10} (1-s gate time) for the 20 MHz, which only contributes about 2×10^{-17} to the optical carrier frequency instability ($f_c \approx 380$ THz). We believe the IPN and the long-term stability would be both further improved if the locking circuits and the measuring apparatus are all referenced to a stable atomic clock.[23]

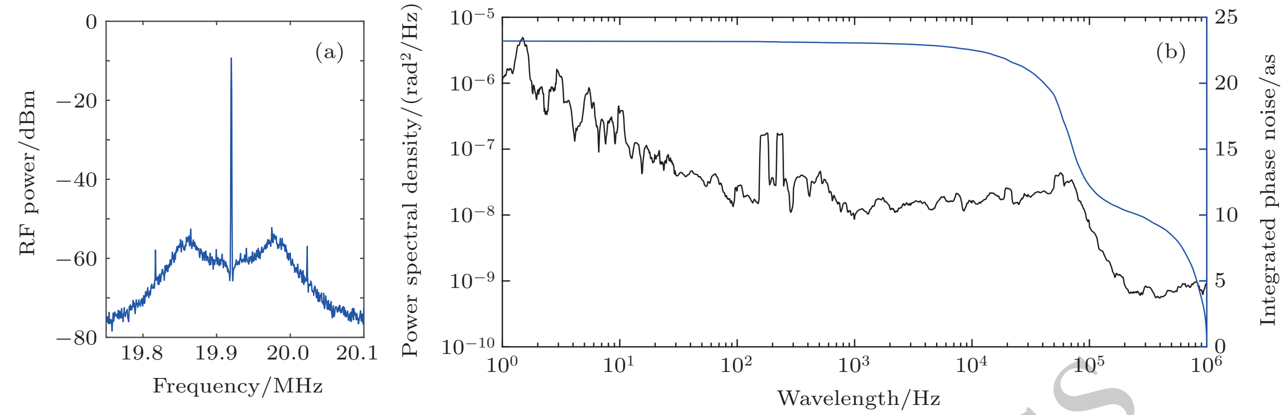

Fig. 5. (color online) Noise properties of the locked f_{ceo} beat signal measured from the in-loop APD. (a) The detail of the f_{ceo} signal (RBW = 1 kHz) observed by an RF analyzers. (b) Power spectral density (PSD) and integrated phase noise (IPN) of the f_{ceo} frequency ranging from 1 Hz to 1 MHz.

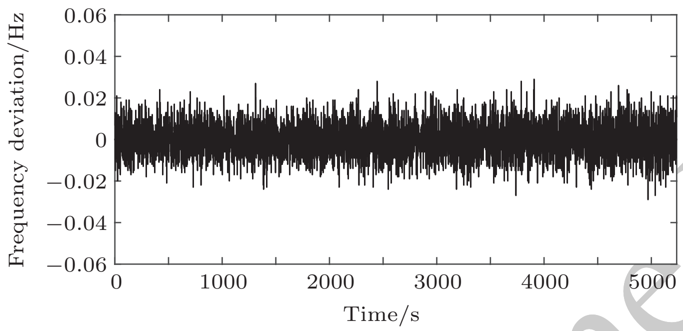

Fig. 6. The frequency deviation of f_{ceo} recorded around 90 minutes. Corresponding Allan deviation for 1-s gate time is 4×10^{-10}.

5. Conclusion

We first utilized the monolithic CEO stabilization scheme to measure and control the f_{ceo} beat note of an octave-spanning oscillator. After a series of improvements, the CEO beat note with a 58-dB SNR (RBW = 100 kHz) was achieved, which is the highest f_{ceo} SNR among the octave-spanning laser based frequency combs to date. When locked to an extra crystal oscillator, the phase error signal of f_{ceo} was obviously suppressed within the feedback bandwidth of the phase-locking loop. We realized the residual phase noise was only 55 mrad (integrated from 1 Hz to 1 MHz), equivalent to a timing jitter of 23 as at the center wavelength of 790 nm. This little jitter between the carrier and envelope phase will have a directly positive impact on the consequent applications, such as the multispectral coherent synthesis and the intense field control of the attosecond pulse generation.

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