Carrier-envelope offset frequency stabilization of a 100 fs-scale Ti:sapphire mode-locked laser for quantum frequency comb generation

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Abstract

The carrier-envelope offset (CEO) frequency stabilization of a Ti:sapphire mode-locked laser with a Fourier-transform-limited pulse width of 100 fs-scale has been successfully realized. With the home-built f-2f interferometer, the CEO beat signal has been measured with a signal-to-noise ratio (SNR) as high as 40 dB under a resolution bandwidth of 100 kHz, which means that the coherence of the octave-spanning supercontinuum (SC) is well retained, although the evaluated pulse soliton order \((N \approx 23)\) completely violate the previous theoretical limitation that \(N\) should be smaller than 16. Furthermore, a stabilized CEO frequency is achieved with residual phase noise suppressed to 660 mrad (integrated from 1 Hz to 100 kHz) and an Allan deviation relative to the optical carrier of \(7.6 \times 10^{-18}\) at 1 s integration time. This realization constructs a solid foundation for further generation of quantum frequency comb needed for ultra-sensitive optical timing measurement applications.

1. Introduction

Frequency combs from femtosecond mode-locked lasers have played increasingly important roles in many areas such as frequency metrology\(^[1-3]\), optical clocks\(^[4]\), optical spectroscopy\(^[5, 6]\), highly nonlinear optics and attosecond physics\(^[7, 8]\), etc. Recent investigations further imply that quantum frequency combs can be applied to optimize the sensitivity of optical timing measurements and yoctosecond range \((10^{-21} - 10^{-24} \text{ s})\) precision of time transfer between remote clocks is expected to be achieved\(^[9]\). In such a specific application, the generation of a quantum frequency comb is normally based on the so-called synchronously pumped optical parametric oscillation (SPOPO)\(^[10, 11]\) process pumped by a Ti:sapphire frequency comb with a low fundamental noise\(^[12]\), of which both the laser repetition rate and the carrier-envelope offset (CEO) frequency are required to be well stabilized\(^[9]\). According to the research, the efficiency of SPOPO is heavily dependent on the phase matching condition; therefore the pump pulse duration should be longer than the temporal walk-off time between the signal and pump beam along their propagation inside the crystal\(^[13]\). To satisfy such requirement, a Ti:sapphire mode-locked pump laser with a Fourier-transform-limited pulse duration of around 100 fs should be used\(^[11, 14]\).

In experiments, the repetition rate of the pump pulse is easy to be detected by a fast photodiode and phase-locked to the microwave reference, whereas the detection of the CEO frequency is a much more challenging task. Currently, the most common way to detect the CEO frequency is using a piece of high-nonlinear photonic crystal fiber (PCF) to extend the comb spectrum to more than one octave, and then obtain the CEO frequency by the f-2f interferometer\(^[2]\). Unfortunately, to the best of our knowledge, previous experiments have shown that
the CEO frequency of a Ti:sapphire mode-locked laser with a pulse duration longer than 50 fs and a repetition rate lower than 80 MHz has not been stabilized with the self-referenceable scheme for the reason that the signal-to-noise ratio (SNR) of the CEO beat note is not sufficient for the phase locking loop (PLL) [6, 15]. According to the previous investigations [16–18], the capability of stabilizing the CEO frequency of a femtosecond laser is dependent on the coherence of the octave-spanning supercontinuum (SC). To estimate the SC coherence, a numerical guideline has been introduced, which is given by the so-called pulse soliton order \(N\) and a value of \(N \leq 16\) (even \(N < 10\)) is required for ensuring the high SC coherence [16].

In this paper, we demonstrate the experimental realization on the CEO frequency stabilization of a 100fs-scale Ti:sapphire mode-locked laser and provide a strong experimental violation of the numerical guideline. Furthermore, we present that the noise performance of the utilized pump laser has a deterministic effect on the quality of the detected CEO beat signal and therefore the stabilization property. In the end, using the home-built f-2f interferometer setup and phase-locking circuit, the cumulative phase-noise of the stabilized CEO frequency integrated from 1 Hz to 100 kHz was suppressed to 660 mrad and the Allan deviation of stabilized CEO frequency relative to the optical carrier was achieved to be 7.6 \(\times 10^{-18}\) at 1 s integration time. This realization constructs a solid foundation for further generation of quantum frequency comb needed for ultra-sensitive optical timing measurement applications.

2. Experimental setup

In the experiment, the investigated femtosecond pulse laser is a commercial Kerr-lens mode-locked (KLM) Ti:sapphire oscillator (Femtolasers GmbH, fusion), which is pumped by a diode-pumped solid-state (DPSS, Lighthouse photonics Inc. Sprout-D) green laser with a power of 8 W. A simplified layout of the Ti:sapphire oscillator is shown in the black solid frame of figure 1. The oscillator is a folded cavity with chirped mirrors applied for intra-cavity dispersion management. Such oscillator provides pulses with a repetition rate of 75 MHz and an average output power of 1.5 W. As shown in figure 2(a), the optical spectrum of the output pulse is measured to have a center wavelength of 814 nm and a full width at half maximum (FWHM) spectral bandwidth \(\Delta \lambda\) of 7 nm. The autocorrelation (AC) measurement of the pulse duration is shown in figure 2(b), indicating that the FWHM pulse duration \(\tau_p\) is 103 fs with fits for sech\(^2\) pulses (\(\tau_p \sim 120\) fs with fits for Gaussian pulses). Based on the spectral and time duration measurement results, one can conclude that the output femtosecond pulses are Fourier-transform-limited [19].

Without any additional pulse compressions, approximately 420 mW of the above oscillator output is focused by an aspheric lens (Thorlabs A230TM-B) with a focal length of 4.51 mm and numerical aperture (NA) of 0.55 before coupled directly into an 80 mm-long polarization maintaining highly nonlinear PCF (NKT photonics NL-PM-750, NA@780 nm = 0.38 \pm 0.05) for spectrum broadening. Then the generated SC is

![Figure 1. Simplified layout of the 75 MHz Ti:sapphire oscillator and the f-2f interferometer based CEO frequency detection and stabilization scheme. Pump laser: DPSS 532 nm pump laser; P1, P2: highly reflectivity (HR) mirrors at 532 nm; L: lens; M1, M2: chirped focusing mirrors; M3, M4, M5, M6, M7: chirped HR mirrors at 800 nm; OC: output coupler, a wedge with 10 degree wedge angle; L1, L2: lens; PCE: photonic crystal fiber; DM: dichroic mirror; D: variable delay; SM1, SM2: silver mirrors; BBO: 3 mm-long BBO crystal; HWP1, HWP2, HWP3: half-wave plates; PBS1, PBS2: polarizing beam splitters; G: grating; PH: pin hole; APD: avalanche photodiode; AOM: acousto-optic modulator; PLL: phase locking loop.](image-url)
launched into a standard nonlinear f-2f interferometer for CEO frequency detection. The layout of the f-2f interferometer is also shown in figure 1. A dichroic mirror (DM, cut-off wavelength at ∼700 nm) separates the octave spectrum into two parts. The infrared part of the spectrum which transmits through the DM is frequency doubled in a 3mm-long BBO crystal and subsequently overlapped with the green part of the spectrum by means of a polarizing beam splitter (PBS1) and a variable delay stage. With the help of the combination of a half-wave plate (HWP3) and a polarizing beam splitter (PBS2), the overlapped beams are then mapped onto a common polarization axis. Afterwards, the heterodyne beat signal is spectrally filtered out by a grating (1800 lines/mm) and sent to a fast avalanche photodiode (APD, Hamamatsu C5658). The detected signal from the APD is processed and compared to a reference signal at 20 MHz provided by a RF function generator (Stanford Research Systems, SG382). Then the generated feedback signal is applied to an acousto-optic modulator (AOM, IntraAction Corp. ASM-803B47-1), which modulates the CEO frequency via the pump laser power sent to the Ti:sapphire oscillator. For signal processing and phase locking, a self-developed PLL system is used.

Once the CEO frequency is stabilized, the in-loop measurement can be done. The in-loop phase noise spectrum of the stabilized CEO beat signal is determined by mixing the CEO beat signal with the local reference signal of 20 MHz as described above. The mixing product is then analyzed in a Fourier-transform dynamic signal analyzer (Stanford Research Systems, SR785). The long-term stabilization of the CEO signal is recorded with a dead-time Λ-type frequency counter (Keysight 53230A).

3. Results and analysis

3.1. SC coherence

Through careful adjustment of the PCF coupling (coupling efficiency ∼35%) and appropriately selecting the beat spectrum component at around 515 nm (figure 3(a)), we see that the CEO beat signal is measured to have a SNR as high as 40 dB under a resolution bandwidth (RBW) of 100 kHz (figure 3(b)), which can well meet a rule-of-thumb typical requirement (SNR > 25 dB) for CEO stabilization [20]. It is promising to stabilize the CEO signal to a stable RF reference by active modulating the amplitude of the pump laser with an AOM, which will be discussed in detail later.

The efficient CEO frequency detection is based on the high coherence level of the octave-spanning SC [20]. The input pulse soliton order $N$ [16, 17], which is given by equation (1), is often regarded as a simple and useful numerical guideline for SC coherence estimation:

$$N \approx \frac{L_D}{L_{NL}} \approx \sqrt{\frac{\tau_p \cdot P_0 \cdot \gamma}{|\beta_2|} \cdot 0.283}$$  \hspace{1cm} (1)

$L_D \approx \left( \frac{\tau_p}{1.76} \right)^2 \cdot \frac{1}{|\beta_2|}$ is the dispersive length, $L_{NL} = (P_0 \cdot \gamma)^{-1} \approx \left( 0.88 \cdot \frac{P_0}{P_{0,p} \cdot \gamma} \cdot \gamma \right)^{-1}$ is the nonlinear length, which related to the peak power $P_0$, $\tau_p$, $f_r$ are the pulse duration and repetition rate of the laser source, respectively. $\beta_2$ is the second order dispersion and $\gamma$ is the nonlinear coefficient of the PCF. $P_0$ is the average optical power injected into the PCF. According to reference [18], the degradation of the SC coherence is primarily caused by the sensitivity to noise of the initial soliton fission process that occurs at the onset of the SC.
generation. With the assumption of shot-noise-limited input pulses, numerical studies suggest that the input pulse soliton order $N$ should be less than 16 to ensure a high level of SC coherence [16].

The PCF we used for SC generation has an anomalous dispersion at 814 nm ($\beta^2 \approx -10.5 \text{ ps}^2 \text{ km}^{-1}$) and a nonlinear coefficient $\gamma \sim 91 \text{ W}^{-1} \text{ km}^{-1}$. From equation (1), for our specific laser source with $\tau_p = 103 \text{ fs}$ and $f_r = 75 \text{ MHz}$, the input pulse soliton order $N$ ranges from 17 to 23 when the average optical power injected on the PCF facet changes from 250 mW to 450 mW. Within this whole range, the CEO signal can always be detected. The SNR of the detected CEO signal as a function of the input pulse soliton order $N$ is shown in figure 4. It is worth noting that the CEO beat can be detected with a SNR as high as 40 dB, i.e., the coherence of the octave-spanning SC is well retained, while the pulse soliton order is much higher than the previous theoretical limitation ($N \leq 16$). In addition, when the pulse duration is broadened to about 150 fs due to the high group dispersion delay of the optical isolator (Thorlabs IO-5-850-HP, not used in the current setup) inserted into the beam path, the CEO beat still can be detected with a considerable SNR. This observation opens the door for the CEO frequency stabilization of pulses much larger than 100 fs.

3.2. Pump noise

The intensity fluctuation of the pump laser is the main amplitude noise source of the Ti:sapphire oscillator, which in turn causes the carrier-envelope phase variations due to the amplitude-to-phase coupling via the nonlinear Kerr effect in KLM [21, 22]. Based on this mechanism, active modulation of the amplitude of the pump laser is treated as an effective means to apply feedback to the oscillator in the CEO frequency control loop, while the intrinsic intensity noise of the pump laser will limit the stabilization due to the same mechanism.
To this end, the influences of two different pump lasers with different noise performances on the CEO frequency stabilization are compared and analyzed in this paper. The two pump lasers are Sprout-D series DPSS laser supplied by Lighthouse photonics Inc., the one used above is a low noise version (Sprout-D10 NET) which has a nominal root mean square (RMS) relative intensity noise (RIN) about 0.03% integrated from 10 Hz to 10 MHz and the other is a standard noise one (Sprout-D8 non-NET) with a RIN about 0.2% in the same integration frequency range. The typical noise spectra of the NET and non-NET lasers are shown in figure 5(a). It is clear that the NET laser has lower noise than the non-NET one, especially in the frequency range from 10 kHz to 1 MHz. As expected, when the Ti:sapphire oscillator pumped by the non-NET laser, the detected free-running CEO beat signal is easily seen in figure 5(b) much more fluctuating and have a broader linewidth than using the NET laser.

3.3. CEO frequency stabilization
Regardless of which laser is used for the pump source of the Ti:sapphire oscillator, we can both stabilize the CEO frequency. However, a significantly narrowed linewidth of the CEO beat can not be observed with the non-NET laser, which mainly resulted from its higher noise in the frequency range of 10 kHz to 1 MHz. According to the concept of the $\beta$-separation line $[23]$, this higher noise occurring at high frequency implies a larger loop bandwidth requirement to achieve a tight phase lock.

When the Ti:sapphire oscillator is pumped by the NET laser, a tight phase-locking can be achieved successfully. Figure 6(a) shows the RF spectra of the CEO frequency with a RBW of 300 Hz. It becomes clear that the linewidth of the stabilized CEO signal is dramatically narrowed compared to the free-running case. The two bumps around the coherent peak on the noise pedestal in figure 6(a) indicate that the bandwidth of the control loop is about 50 kHz, which is mainly limited by the bandwidth of the PLL. The detected in-loop phase spectrum density (PSD) and the cumulated phase noise (CPN) is shown in figure 6(b). The CPN from 1 Hz to 100 kHz was
calculated to be 660 mrad. It is worth noting that the phase noise out of the control loop bandwidth accounts for the majority of the total phase noise.

The long-term stability of the stabilized CEO signal was recorded with a frequency counter as described above. The result of the residual frequency fluctuation of the stabilized CEO signal around 5500 seconds is shown in figure 7(a), which gives a standard deviation of 3 mHz at 1s gate time. The corresponding Allan deviation relative to the optical carrier frequency (∼369 THz) is shown in figure 7(b), it gives a value of $7.6 \times 10^{-18}$ at 1 s integration time. It is reasonable to believe that long-term stability of the stabilized CEO frequency would be further improved, provided some proper steps are taken to shield noise from the surroundings, especially the effects of the long optical path and air flow on beam pointing stability when SC generated with a very small core-diameter PCF.

4. Conclusion

In summary, we have reported the CEO frequency detection and stabilization of a 100 fs-scale Fourier-transform–limited Ti:sapphire mode-locked laser. In our experiment, we find that the CEO beat can be detected with a high enough SNR, i.e. the SC coherence is well retained even in the condition that the pulse has a much higher soliton order of $N \approx 23$. Interestingly, this observation completely violate the previous theoretical limitation that $N$ should be smaller than 16. Furthermore, we have compared and analyzed the influences of the pump noise on the CEO frequency stabilization in this paper. Our experimental implementation demonstrates that the CEO beat signal stabilization is mainly determined by the noise performance of the pump [21]. As a result, by applying the home-built stabilization circuit on the CEO beat signal and optimizing the noise performance of the pump laser, the cumulative phase-noise of the stabilized CEO frequency integrated from 1Hz to 100 kHz can be suppressed to 660 mrad. The standard deviation of the stabilized CEO frequency is 3 mHz, corresponding to an Allan deviation of $7.6 \times 10^{-18}$ at 1 s integration time relative to the optical carrier frequency. This realization has extended the CEO frequency stabilization capability of Ti:sapphire mode-locked lasers to pulses with duration of 100 fs-scale, thus facilitates the generation of quantum frequency comb, which has great potential in quantum information and precision measurement.

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![Figure 7](image_url)
Optical Frequency Combs) and Chinese Academy of Sciences Frontier Science Key Research Project (Grant No. QYZDB-SSW-SLH007).

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