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Ultra-low-noise carrier-envelope phase stabilization of a Kerr-lens mode-locked Yb:CYA laser frequency comb with a feed-forward method

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We demonstrate ultra-low-noise carrier-envelope phase stabilization of a Kerr-lens mode-locked Yb:CYA laser frequency comb, which is the first time, to the best of our knowledge, that the feed-forward method has been applied to 1 μm all-solid-state lasers. We obtain a signal-to-noise ratio of more than 38 dB at a 100 kHz resolution bandwidth for carrier-envelope phase offset beat signals in two standard in-loop and out-of-loop f-2f interferometers. The residual integrated phase noise amounts to 79.3 mrad from 1 Hz to 1 MHz, corresponding to a timing jitter of 44 as. We also investigate long-term performances of the CEP stabilization in the feed-forward scheme, phase-locked feedback systems and the combining locking techniques in terms of sub-hertz frequency-resolved phase noise and Allan deviation in 1000 s. The results indicate that, although the feed-forward CEP stabilization method dominates in the range of 1 Hz to 1 MHz Fourier frequency, feedback methods with a time integration effect are superior in sub-hertz Fourier frequency phase noise suppression.

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The development of novel femtosecond frequency combs with ultra-low noise has revolutionized frequency metrology with ultra-high accuracy [1–3] and has enabled the generation of isolated attosecond pulses. For example, each reported isolated attosecond pulse record is accompanied by the reduction of carrier-envelope phase noise in driving lasers [4–7]. All-solid-state lasers pumped with laser diodes or fiber lasers are promising candidates for developing novel optical frequency combs with the advantage of high average power, high repetition rate, and low quantum defect, as well as low intrinsic noise [8–11]. Among those prominent gain materials in the regime of 1 μm, the Yb:CYA bulk crystal has attracted interest due to the broadband emission spectrum and high thermal conductivity [12]. Ultra-short pulses with sub-30 fs pulse duration [13,14] and 2 W high output power [15] have been obtained based on a Yb:CYA bulk medium. A carrier-envelope phase offset (CEO) stabilized frequency comb from a Yb:CYA laser was realized by phase-locked loop electronics with an integrated phase noise of 316 mrad (1 Hz to 10 MHz) [16].

With the high time-resolved requirements in atomic and molecular dynamics, it is crucial to suppress the residual carrier-envelope phase noise of femtosecond laser pulse sources to sub-100 mrad. One of the key issues for improving the tight phase locking is the insufficiency of the servo bandwidth. With traditional pump intensity-dependent gain modulation mechanism, the bandwidth of the feedback servo loop is limited by the upper lifetime of the gain medium, which is only dozens of kilohertz for Yb-doped materials [17,18]. A residual phase jitter of 0.3 rad is achieved in a CEO stabilized bulk Yb:KYW femtosecond laser frequency comb [8]. 680 mrad of integrated phase noise remained in a tight-locked Yb:CALGO bulk frequency comb. [11] Several new techniques have been presented in terms of intra-cavity loss modulation. An opto-optical modulator in a semiconductor saturable absorber mirror (SESAM) mode-locking Er:Yb:glass bulk laser exhibits a servo bandwidth of 40 kHz, resulting in a residual integrated phase noise of 63 mrad (1 Hz–100 kHz) [19]. An acousto-optic modulator (AOM) is inserted into a high gain Kerr-lens mode-locked (KLM) Yb:YAG thin disk laser cavity for a fast modulating carrier-envelope phase, and the CEO frequency (f_{ceo}) is stabilized with a residual phase noise of 90 mrad [20,21]. An intra-cavity electro-optic modulator (EOM) is inserted into an erbium-doped fiber laser for CEO stabilization through group velocity modulation, but will introduce high nonlinearity and high-order dispersion [22]. Furthermore, all of these schemes need complicated circuits and elaborate P-I parameter adjustment. The laser cavity can be affected by those actuators to some extent.

Instead, the feed-forward method proposed in 2010, using an acousto-optic frequency shifter (AOFS) outside the laser cavity to modulate the CEO frequency shift in real time provides a direct solution without changing laser performances and being insensitive to environmental disturbance [23]. Moreover, the control bandwidth is determined by the acoustic wave transmission time and could exceed 1 MHz. With this feed-forward scheme, the residual phase jitter of a Ti:sapphire frequency comb has been suppressed to 20 mrad [24–26]. The fiber laser frequency comb has also utilized this technique to stabilize f_{ceo} with a residual phase error of 370 mrad [27]. So far, to the best of our knowledge, there is no report about using feed-forward configuration in 1 μm all-solid-state laser frequency combs.

In this Letter, we employ the feed-forward method to stabilize the f_{ceo} of a KLM Yb:CYA solid-state laser frequency comb. The standard in-loop and out-of-loop f-2f interferometers are built to detect and analyze the performances of the stabilized f_{ceo}. The out-of-loop f_{ceo} is tightly phase-locked at 60 MHz by feeding the in-loop CEO beat signal into the AOFS. To fully characterize the phase noise of the stabilized f_{ceo}, we measure the phase noise power spectral density (PSD) from 4 mHz to 1 MHz. The residual integrated phase noise is 79.3 mrad from 1 Hz to 1 MHz (35 mrad from 1 Hz to 100 kHz). We also investigate the long-term performances of the stabilized f_{ceo} by recording time series of the frequency drift. The fractional frequency instability corresponding to the central optical frequency ($\nu_{opt} = 286$ THz) is measured to be 2.87×10^{-17} at 1 s gate time. Through a series of comparisons between feedforward and feedback methods, we conclude that the feed-forward scheme is more powerful in phase noise suppression at high frequencies, while the servo feedback locking is more suitable for long-term CEO stabilization.

Our experimental configuration is depicted in Fig. 1. A home-built KLM Yb:CYA laser serves as a source, which provides pulses with an average power of 200 mW, a repetition rate of 84 MHz and a pulse duration of 57 fs. The laser cavity was described in detail in Ref. [16]. The output pulses centered at 1048 nm were directly injected into a piece of 1.3-m long SC-3.7-975 nonlinear photonic crystal fiber (PCF) with a nonlinear coefficient of 18 $(\text{W} \cdot \text{km})^{-1}$ at 1060 nm to broaden the spectrum. The octave spanning spectrum covering from 700 to 1400 nm was obtained for the CEO detection. The coupling efficiency was approximately 30% and the output power after the PCF was 60 mW.

To control the f_{ceo} with the feed-forward configuration, an AOFS was inserted in the supercontinuum beam after the PCF with 10% insertion loss. In order to obtain the CEO beat signal with high signal-to-noise ratio (SNR) in two standard in-loop and out-of-loop f-2f interferometers, the diffraction efficiency of the AOFS was set to 50% by adjusting the incident angle of supercontinuum beam on the AOFS. The zeroth and the first diffraction beams, with 26 mW power in each branch, were delivered into the standard in-loop and out-of-loop f-2f interferometers, which were built to detect the free-running f_{ceo} and analyze the stabilized CEO beat signal with feed-forward and feedback schemes, respectively. Both in-loop and out-of-loop CEO beat signals were detected by avalanche photodiodes (APDs). The linewidth of the free-running f_{ceo} was estimated to be 9.6 kHz, as shown by red dots in Fig. 2(b) due to the fast phase jitter stemming from the free-running laser [16].

In our experiments, the in-loop f_{ceo} was roughly tuned to 20 MHz through a pair of wedges inside the laser cavity. Then we mixed it with a stable 60 MHz radio frequency generated from a local signal generator (Agilent, E4428C) to obtain the sum frequency of 80 MHz, which was electrically amplified to 2 W to drive the AOFS. Therefore, the out-of-loop f_{ceo} in the first-order diffraction beam is tightly stabilized at 60 MHz with extremely low phase noise.

The frequency spectrum in the end of the out-of-loop f-2f interferometer is shown in Fig. 2(a). The f_{ceo} is stabilized at 60 MHz with a SNR of 38 dB under a 100 kHz resolution bandwidth (RBW) of a signal and spectrum analyzer (R&S, FSW 26). Apart from the repetition rate frequency and the f_{ceo}, the sum and the difference frequency between them, as well as the spurious signals from electrical noise are also shown in the frequency spectrum. To investigate the details of the controlled out-of-loop f_{ceo}, we measured the linewidth narrowing effect of CEO beat signal before and after phase locking under

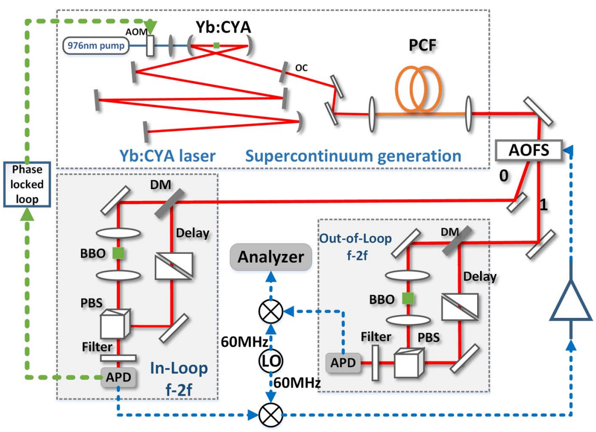

Fig. 1. Schematic of the experimental configuration. OC, output coupler; AOM, acousto-optic modulator; PCF, photonic crystal fiber; AOFS, acousto-optic frequency shifter; DM, dichroic mirror; BBO, barium metaborate; PBS, polarization beam splitter; APD, avalanche photodiode; LO, local oscillator; blue dotted line, feed-forward circuits; green dotted line, feedback circuits.

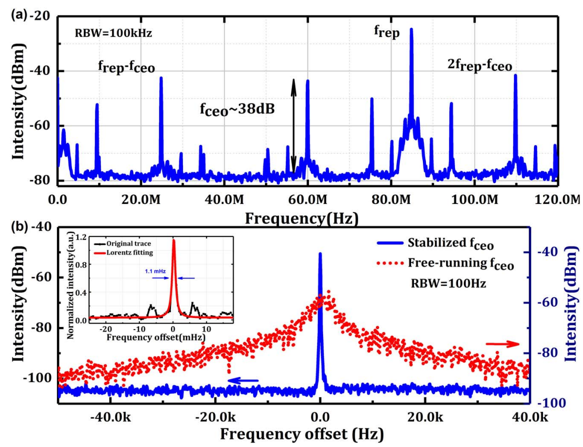

Fig. 2. (a) Frequency spectrum of the first diffraction order with a 38 dB SNR stabilized out-of-loop CEO beat signal (RBW = 100 kHz), f_{rep}: repetition rate frequency; (b) frequency spectrum contrast between stabilized out-of-loop f_{ceo} (blue line) and free-running f_{ceo} (red dots) under 100 Hz RBW in a 100 kHz span. Inset: RBW-limited linewidth of the 60 MHz stabilized out-of-loop CEO beat note.

100 Hz RBW and 477 μHz frequency bin width, as depicted in Fig. 2(b). It is clear that the original free-running f_{ceo} in red dots carries significant amounts of phase noises in Fourier frequency range from 100 Hz to 50 kHz. After stabilized by the AOFS, these phase noises are suppressed effectively, and a distinct CEO frequency spike with a SNR of more than 55 dB appears at exact 60 MHz as shown by the blue trace in Fig. 2(b). Unlike in feedback systems, the noise background in the feed-forward systems is flat within 100 kHz, indicating the servo bandwidth exceeding 100 kHz. We mixed a 60.02 MHz radio frequency generated from another local signal generator, which was synchronously referenced to the E4428C signal generator, with the 60 MHz stabilized CEO beat signal and obtained a 20 kHz sampling signal. The 20 kHz sampling signal was recorded and analyzed by an FFT spectrum analyzer (SRS, SR770) with the minimum linewidth of 0.477 mHz. The results of the measurement show a RBW-limited linewidth for the coherent peak.

In order to characterize the phase noise distribution and reveal the short-term frequency stability in the feed-forward locking Yb:CYA laser frequency comb, we measured phase noise PSD of the stabilized out-of-loop f_{ceo} in two Fourier frequency ranges, from 1 Hz to 1 MHz and from 4 mHz to 1 Hz, as shown by the red lines in Figs. 3(a) and 3(b). For further discussion, we also compared the feed-forward methods with the feedback techniques, where an AOM was inserted into the pump beam to realize the feedback stabilization of f_{ceo} in the Yb:CYA laser, as depicted by green dotted line in Fig. 1. The phase noise PSD and residual integrated phase noise for servo feedback locking is shown by the gray lines in Figs. 3(a) and 3(b).

The residual integrated phase noise of the out-of-loop f_{ceo} from 1 Hz to 1 MHz with feedback locking methods is 588 mrad, with an increase suffering from the out-of-loop self-referenced f_{ceo} detection and the SNR reduction of the CEO beat signal. Although the phase noise below 10 Hz is clearly higher in the feed-forward locking in Fig. 3(a), the phase noise in the range of several kilohertz to hundreds of kilohertz is reduced close to the noise floor, more than two orders lower than that of feedback systems. Phase noise PSD tends to rise in the range of tens of hertz to 1 kHz, which is attributed to amplifying electronics and the unsealed experimental configuration. From our previous analysis [16], 70% of the residual integrated phase noise is contributed from dozens of kilohertz to hundreds of kilohertz frequency range, which could not be suppressed due to the bandwidth limitation. As a result, the residual integrated phase noise from 1 Hz to 1 MHz in the feed-forward system amounts to be 79.3 mrad, 160 mrad lower than that of previous report [16] and almost 70% of reduction, which demonstrates the substantial expansion of a servo loop bandwidth.

To detect the phase PSD of CEO beat signal below 1 Hz, we tuned the previously mentioned 60.02 MHz to 60 MHz and the frequency of sampling signal became zero. Analyzing the zero frequency with the FFT spectrum analyzer, as shown in Fig. 3(b), we notice that flicker noise is dominant below 10 Hz in both stabilization schemes, owing to mechanical noise and thermal noise introduced by two-path interferometers, as well as intra-cavity amplified spontaneous emission [28]. The integrated phase noise from 4 mHz to 1 Hz is calculated to be 703 mrad in feed-forward systems, and 272.5 mrad in feedback systems. It was revealed that phase-locked loop feedback method is more reliable in controlling low-frequency noise, such as sub-10 Hz range. The reason is that the PID controller in feedback schemes has superior capacity of controlling slow relative drift of f_{ceo} through the integral term, which integrates the past values of error input to the present point and makes a reaction.

For further insight into the long-term performances in the time domain, we recorded 2 h series of the stabilized out-of-loop f_{ceo} at 1 s gate time using a Λ-type frequency counter (Agilent, 53132A) at timed arming mode. The stabilized f_{ceo} was filtered and amplified to approximately 0 dBm for frequency counting. The standard deviation is measured to be 12.95 mHz, as shown in Fig. 4(a) with blue color, and the calculated Allan deviation exhibits a fractional frequency

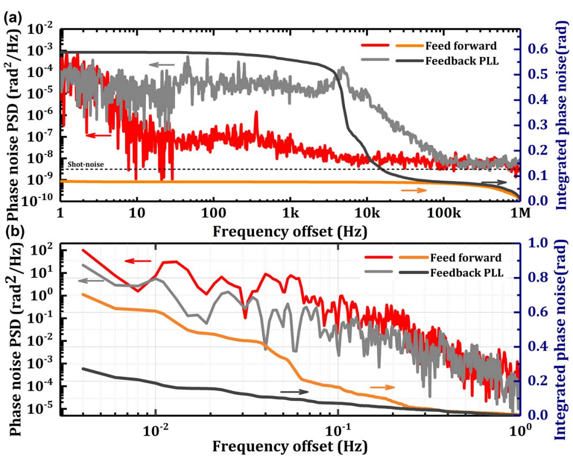

Fig. 3. (a) Phase noise PSD of stabilized out-of-loop f_{ceo} in the feed-forward scheme (red line) and phase-locked loop (PLL) feedback systems (gray line) ranging from 1 Hz to 1 MHz; Integrated phase noise from 1 MHz to 1 Hz of CEO in the feed-forward scheme (orange) and feedback systems (dark gray). (b) Phase noise PSD and integrated phase noise ranging from 4 mHz to 1 Hz.

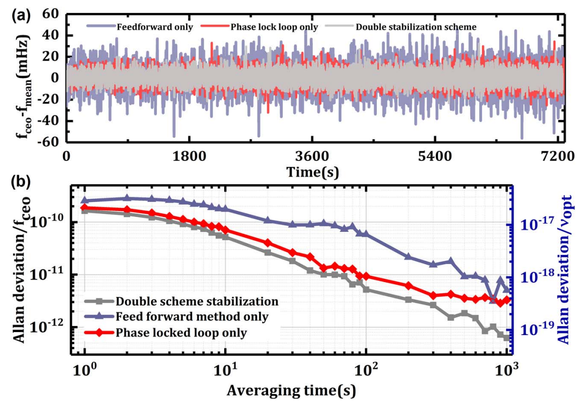

Fig. 4. (a) 2 h time series of stabilized out-of-loop f_{ceo} at 1 s gate time in the feed-forward scheme (blue) and in the feedback phase-locked loop scheme (red), as well as under double scheme stabilization (gray), f_{mean}: the mean value of the stabilized f_{ceo}. (b) Fractional frequency instability with respect to f_{ceo} (left scale) and the optical frequency (right scale) is shown by Allan deviation in feed-forward methods (blue), phase-locked loop feedback systems (red), and double stabilization schemes (gray).

instability of 2.53×10^{-10}/s relative to f_{ceo} and 2.87×10^{-17}/s relative to the optical frequency ($\nu_{opt} = 286$ THz). The measurement was performed without any slow-loop feedback electronics assistant, indicating the great potential in long-term stability of the feed-forward methods.

By contrast, we also recorded time series of the feedback phase-locked loop stabilized out-of-loop f_{ceo} for 2 h at 1 s gate time. The standard deviation is 6.95 mHz and the Allan deviation is shown in Fig. 4(b) with red color. It illustrates that the feedback method is superior to the feed-forward scheme in long-term performance, with a good agreement with the frequency-resolved phase noise below 1 Hz shown in Fig. 3(b).

In addition, double stabilization with both feed-forward and feedback approaches was implemented for comparison, as shown by the gray trace in Fig. 4. The standard deviation is 5.8 mHz, and the Allan deviation shows a fractional frequency instability of 1.1×10^{-10}/s relative to f_{ceo} and 1.13×10^{-17}/s relative to the optical frequency, respectively. To the best of our knowledge, this is the most stable long-term performance by use of double methods. It still needs to carefully optimize the loop filter parameters to reduce the interaction between feed-forward and feedback operation.

We have demonstrated a CEO stabilized KLM Yb:CYA laser with a feed-forward method. The residual integrated phase noise of the out-of-loop f_{ceo} from 1 Hz to 1 MHz is measured to be 79.3 mrad, corresponding to a timing jitter of 44 as. This confirms that the feed-forward scheme is an effective method to fast-locking f_{ceo} with a broad bandwidth. We also investigate the long-term stability for the feed-forward in terms of Allan deviation for the first time. By comparing the phase noise PSD and the long-term frequency series with feedback techniques, we conclude that the feed-forward method has superior capacity of noise control above 10 Hz because of its transient frequency shift without complicated feedback electronics; meanwhile, feedback schemes have more stable long-term performances. From this point, we suggest that the feed-forward schemes are suitable for applications occurring in the fast transient, for example, attosecond science, and the feedback schemes are suitable for applications requiring long-term stability, for example, optical clocks. In a word, we believe that the Yb:CYA laser frequency comb with ultra-low noise f_{ceo} is an ideal source for many applications in a 1 μm regime both in short-term and long-term operation.

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