Precise and long-term stabilization of the carrier-envelope phase of femtosecond laser pulses using an enhanced direct locking technique

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Abstract: We demonstrate a long-term operation with reduced phase noise in the carrier-envelope-phase (CEP) stabilization process by employing a double feedback loop and an improved signal detection in the direct locking technique [Opt. Express 13, 2969 (2005)]. A homodyne balanced detection method is employed for efficiently suppressing the dc noise in the *f*-2*f* beat signal, which is converted into the CEP noise in the direct locking loop working at around zero carrier-envelope offset frequency (f_{ceo}). In order to enhance the long-term stability, we have used the double feedback scheme that modulates both the oscillator pump power for a fast control and the intracavity-prism insertion depth for a slow and high-dynamic-range control. As a result, the in-loop phase jitter is reduced from 50 mrad of the previous result to 29 mrad, corresponding to 13 as in time scale, and the long-term stable operation is achieved for more than 12 hours.

OCIS codes: (120.5050) Phase measurement; (320.2250) Femtosecond phenomena; (320.7100) Ultrafast measurements.

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1. Introduction

Since late 1990s, the carrier-envelope phase (CEP) stabilization of femtosecond laser pulses has been intensively studied as a key technique for high-precision frequency metrology [1] and attosecond science [2, 3]. The CEP stabilization technique in mode-locked femtosecond lasers was first proposed by ultrafast laser scientists [4,5] and experimentally realized by frequency metrology researchers [6,7]. Recently, the CEP stabilization was successfully extended to chirped-pulse amplification (CPA) laser systems [8] for the generation of high-energy and high-intensity CEP-stabilized pulses [9-13]. The CEP-stabilized laser has become a revolutionary light source for the frequency metrology as proven by the Nobel physics prize in 2005 [14,15], whereas the CEP-stabilized CPA lasers have become an essential tool for the generation of reproducible attosecond XUV pulses that can probe ultrafast electron dynamics in atoms and molecules [16]. Other CEP-sensitive phenomena, such as above-threshold ionization [17] and Rabbi flopping [18], have been also investigated. For reliable applications of the CEP stabilization technique, low phase noise and excellent long-term stability are crucial, so great efforts have been made for the enhancement of these parameters in the CEP-stabilized femtosecond lasers.

Conventional CEP stabilization technique is based on the phase-locked loop (PLL) [7] that stabilizes the carrier-envelope offset frequency, f_{ceo}, to a reference RF signal. Even though this technique became much more common after being commercialized, recently, Lee *et al.* [19] introduced the direct locking (DL) technique as an alternative method of the CEP stabilization. The DL technique was proven to be reliable from an out-of-loop measurement and successfully worked with a CPA system [20]. It has several distinctive features, compared to the conventional PLL technique operating in the frequency domain. First, no reference RF signal is necessary because a feedback signal is generated directly from an f-to-2f beat signal in the time domain using a simple dc reference. Thus, the electronic circuit is relatively simple. Second, shot-to-shot CEP change is always locked to zero, simplifying the synchronization scheme when used in a CPA system. Third, the CEP value can be easily and intuitively modulated in an electronic manner using a shaped external signal. This property is still preserved when combined with a CPA system [20]. Despite these good features, we found that the DL setup was exposed to the CEP distortion coming from the detection balancing process to remove background dc noise, and that the slow drift of feedback signal prevented the long-term CEP stabilization.

In this paper, we demonstrate an enhanced operation of the simple DL system by introducing a homodyne balanced detection (HBD) setup and a double feedback method. In section 2, we discuss the technical details of the simple DL technique and the enhanced DL technique employing HBD and then show the experimental result. In section 3, the double feedback method for an excellent long-term stability using both an acousto-optics modulator (AOM) and an intracavity prism is described. Conclusions are given in section 4.

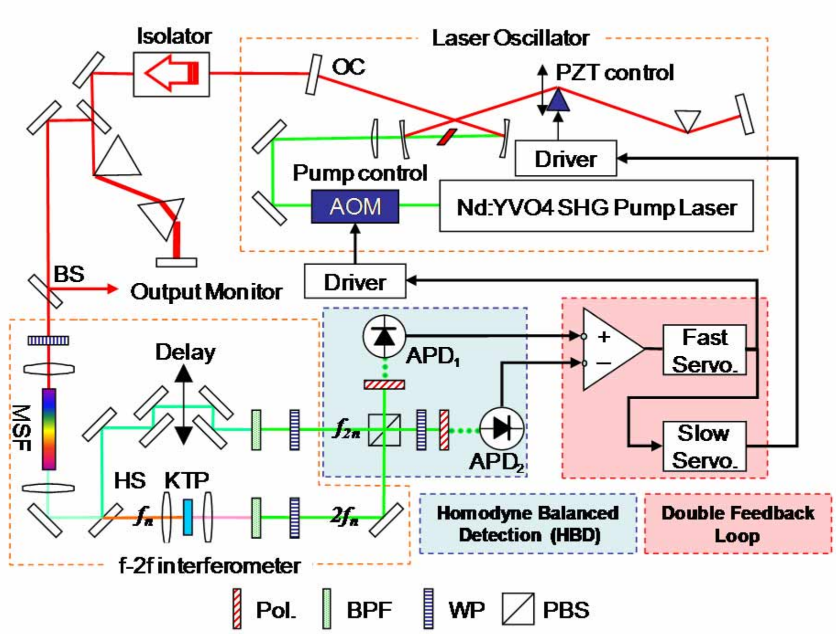

Fig. 1. Layout of the direct locking technique for CEP stabilization. (OC: output coupler, BS: beam splitter, MSF: micro-structured fiber, HS: harmonic separating mirror, KTP: potassium titanium oxide phosphate (KTiOPO4), BPF: 532 nm bandpass filter, HWP: halfwave(1/2) plate, Pol:polarizer, APD1 & APD2: avalanche photodiode, AOM: acousto optic modulator, the blue box(a): homodyne balanced detection, and the red box(b): double feedback loop).

2. Enhanced direct locking setup and homodyne balanced detection

The direct locking setup for the CEP stabilization of a femtosecond laser is composed of an f-to-2f interferometer [21] and a direct locking loop, as described in Ref. [19]. We have improved the previous setup to obtain lower phase noise and better long-term stability. Modification has been made mainly in the following features: 1) the HBD detection setup, and 2) the feedback control of intracavity prism for slow and high-dynamic-range CEP modulation.

The modified experimental setup for the enhanced direct locking technique is illustrated as Fig. 1. A mirror-dispersion-controlled Kerr lens mode-locked Ti:sapphire laser, pumped by a diode-pumped Nd:YVO4 laser (Verdi, Coherent Inc.), produces sub-10 fs pulses at a 75 MHz repetition rate. The femtosecond laser pulses are sent through a Faraday isolator to avoid the back-reflection from the micro-structure fiber (MSF) which has benefits of larger damage threshold, more stable coupling and environmentally sealed device [22] (Femtowhite 800, Crystal-fiber Inc.) in Fig. 1. A prism compressor is installed between the laser cavity and the f-to-2f interferometer for the dispersion compensation of the Faraday isolator and the

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microscope objective. An AOM (10 MHz bandwidth) and a PZT are used to stabilize the CEP of laser pulses by controlling the pump power and the insertion depth of the intracavity prism, which will be utilized for the realization of the double feedback method, as described in Sec. 3.

The CEP variation of the laser pulses is monitored with the f-2f interferometer. An octave-spanning spectrum that simultaneously contains f_n (1064nm) and f_{2n} (532nm) components is generated from MSF, and then f_n and f_{2n} frequency components are separated by a harmonic separation mirror (HS). The f_n frequency component is frequency doubled ($2f_n$) by a 1-mm-thick potassium-titanyl phosphate (KTP) crystal. The $2f_n$ and f_{2n} frequency components from the f-to-2f interferometer are spatially and temporally recombined in a polarizing beam splitter (PBS), and then divided again into two beams for the realization of HBD. Two green beams in the blue box of Fig. 1 go through a polarizer and allow the simultaneous detection of the interference signals at APD1 and APD2, respectively. Three half-wave plates around PBS are used for a precise balancing of two beat signals.

For better understanding of HBD scheme and clear comparison with the simple DL scheme, we give simple mathematical description. The detected signals of APD1 and APD2 in the simple DL method shown in Ref. [19] can be expressed as follows:

$$V_1(t) = G_1 \times \left(V_{f_{2n}}^S(t) + V_{2f_n}^P(t) + 2\sqrt{V_{f_{2n}}^S(t) \cdot V_{2f_n}^P(t)} \sin\varphi_{cep}(t) \right) \times \cos^2\frac{\pi}{4}, \quad (1)$$

$$V_2(t) = G_2 \times \left(V_{f_{2n}}^P(t) + V_{2f_n}^S(t) \right), \quad (2)$$

where G and V are the gain and signal intensity at APD, respectively. The subscript 1, 2 and superscript S, P correspond to APD1, APD2, and polarization states, respectively. $\varphi_{cep}(t)$ is the time evolution of the detected CEP. Especially, $V_2(t)$ the dc term in the CEP beat signal. The $\cos^2(\pi/4)$ comes from the angle of the polarizer before APD_1. In the conventional PLL-based CEP stabilization method, the time difference values of $\varphi_{cep}(t)$, i.e., carrier-envelope offset frequency (f_{ceo}) is usually fixed to a sub-harmonic RF, f_{rep}/N, of the repetition rate f_{rep}. So an electrical phase detector is necessary to compare f_{ceo} and the sub-harmonic RF. A fixed f_{ceo} in this case means that the pulse-to pulse CEP change ($\Delta\varphi$) given by $\Delta\varphi = 2\pi f_{ceo}/f_{rep}$ is constant. In the time domain, a constant $\Delta\varphi$ does not mean identical pulses, but identical for every *N*-th pulse.

In the DL method, the pure ac term in the beat signal of Eq. (1), i.e., sin $\varphi_{cep}(t)$, can be directly regarded as an optical error signal for the feedback, having an analogy to the electrical error signal from the phase detector in the PLL-based CEP stabilization. Even though sine-function is not linear in the entire range from $-\pi/2$ to $\pi/2$, it can be regarded as linear within a small range around zero, allowing the generation of a linear error signal for the feedback. In other words, the CEP beat signal itself is equivalent to the signal from a phase detector in a PLL circuit, if f_{ceo} is close to zero. To extract the pure ac term from the beat signal, we separately measure the dc term using APD_2. The signal V_2 can eliminate the dc terms from the signal V_1 of APD_1 using a differential amplifier to directly extract the phase error signal, sin $\varphi_{cep}(t)$, without an electrical phase detector.

The perfect balancing between V_2 and the dc term in V_1 is the key process in the CEP locking with a low noise. The gain parameters in two APD's , i.e., G_1 and G_2, should be properly adjusted so as to eliminate the dc fluctuation ($V_{f_{2n}}^S(t) + V_{2f_n}^P(t)$)because the level of V_2 is half the value of the dc level of V_1 due to the polarizer in front of APD_1. In other words, G_1 should be roughly twice larger than G_2 for the signal balancing. This scheme worked quite well for balancing as demonstrated, but it should be noted that the APD's are working in the nonlinear saturation regime to intensify the electric signal. Thus, the value of G_2 is not exactly twice that of G_1 and the response curves are slightly different from each other. This difference can lead small error in the feedback process. Another problem is that the relation between

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$V_{f_{2n}}(t)$ and $V_{2f_n}(t)$ ($\propto |V_{f_n}(t)|^2$) is not linear in the time domain so that a precise balancing in the simple DL method is difficult with only the gain control between two detectors. Because $V_{2f_n}(t)$ is related on the second harmonic process from $V_{f_n}(t)$. The balancing can be done for a

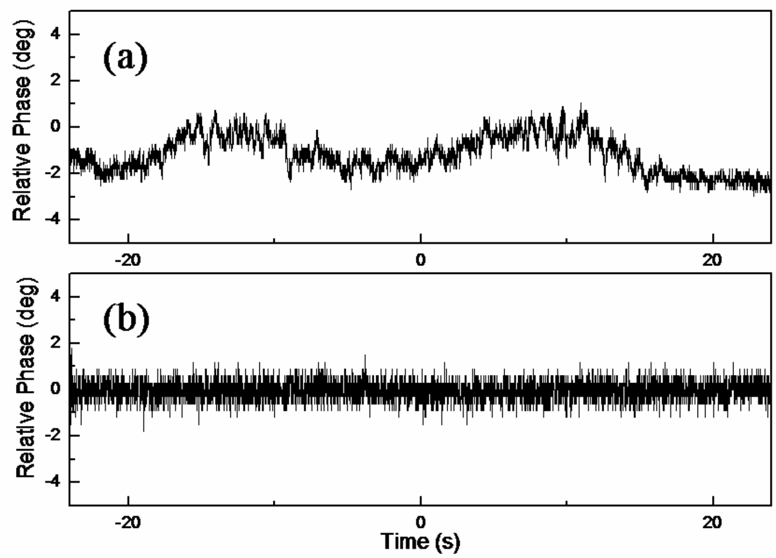

Fig. 2. Comparison of relative phase variation measured with (a) simple Balanced Detection (BD) and (b) Homodyne Balanced Detection (HBD).

moment with the appropriate adjustment of the electrical gain even when the optical balancing is not perfect. We found that this problem was more serious with a long-term stability because the electrically mixed dc offset from the APD gain prohibited the perfect optical balancing. The example of the distorted phase error signal can be shown in Fig. 2(a). It was obtained from the error signal of the subtraction circuit in DL loop when f_{ceo} is much higher than APD bandwidth. The ac term of beat signal is not shown due to the APD bandwidth. Due to the electrical gain effect, the dc was found in the time scale of ~10 seconds.

To solve this distortion problem in this experiment, we incorporate the homodyne balanced detection as shown in the blue box of Fig. 1. An additional polarizer is installed in front of APD_2 to detect the beat signal and make the same level of APD_1, which we refer to as HBD described by following equations,

$$V_1(t) = V^S_{f_{2n}}(t) + V^P_{2f_n}(t) + 2\sqrt{V^S_{f_{2n}}(t)\cdot V^P_{2f_n}(t)}\,\sin\varphi_{cep}(t)\,, \quad (3)$$

$$V_2(t) = V^P_{f_{2n}}(t) + V^S_{2f_n}(t) + 2\sqrt{V^P_{f_{2n}}(t)\cdot V^S_{2f_n}(t)}\,\sin\varphi_{cep}(t)\,, \quad (4)$$

where V_1(t) and V_2(t) are the interference signals with a different DC fluctuation and visibility at APD_1 and APD_2 respectively.

The first two terms show the fluctuating dc offset and the last terms show the pure interference. $V_{f_{2n}}(t)$ and $V_{2f_n}(t)$ are corresponding to the f_{2n}-arm and the $2f_n$-arm respectively. $V_{f_{2n}}(t)$ is divided into $V^S_{f_{2n}}(t)$ and $V^P_{f_{2n}}(t)$, and $V_{2f_n}(t)$ is also divided into $V^S_{2f_n}(t)$ and $V^P_{2f_n}(t)$. We can make the S-pol and P-pol splitting ratio equal using two WPs in both arms, respectively. Two WPs in the interferometer are adjusted so that the APD_1 and APD_2 signal may be equal with the other arm being blocked, and vise versa. Note that the gain and offset of APD_1 and APD_2 are also set to be equal, respectively, so that the detected signal levels

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from APD_1 and APD_2 become equal to each other. After that, by inserting and setting the principle axis of the HWP in front of the APD_2 to the direction of S- or P-polarization, it plays a role of a π-phase retarder without the rotation of polarization. As a result, the difference of the beating signals between APD_1, and APD_2 will be two times as large as in the pure interference with perfectly eliminating low-frequency fluctuation noise as following Eq. (5)

$$V_{err}(t) = V_1(t) - V_2(t) = 4\sqrt{V_{f_{2n}}(t) \cdot V_{2f_n}(t)} \sin\varphi_{cep}(t) \approx 4\sqrt{V_{f_{2n}}(t) \cdot V_{2f_n}(t)} \cdot \varphi_{cep}(t) \qquad (5)$$

The error signal from the optically balanced beat signal is shown at Fig. 2(b). As in the case of Fig. 2(b), the pure beat signal does not appear because it has a very high frequency and filtered due to the bandwidth limit of the APD. It shows a much lower dc noise because the electrical gain of two APD's is set to be the same value. Moreover, the amplitude of the ac term or pure beat signal is two times larger than the simple DL loop as shown from the comparison between Eqs. (1) and (5). This makes the signal to noise ratio larger, allowing a lower CEP noise in the locking condition.

We have confirmed the above prediction in the experiments based on HBD. We observed the CEP beat signals from both APD_1 and APD_2 and then tuned the beat frequency, f_{ceo}, close to zero by manually adjusting the intracavity prism. The direct locking loop could be turned on immediately after f_{ceo} becomes less than the operation range (~100 kHz). The short-term evolution of the beat signals, obtained before and after activating the looking loop, is shown in Fig. 3. The oscillating structure of the unlocked case is quenched to a dc signal of the locked case. Only the AOM, driven by the fast servo, is associated with the CEP locking in the time range shorter than 1 second. Direct locking method, in contrast to the conventional PLL method, directly provides the information on CEP with a digital oscilloscope. By measuring the rms voltage in the case of stabilized CEP and the peak-to-peak voltage in the case of pure CEP time evolution, we can simply estimate the CEP fluctuation. The histogram of CEP shown in the right side clearly demonstrates a feature of stabilized CEP. The rms phase jitter calculated from this graph is 29 mrad, corresponding to 13 attoseconds in time. The power spectral density (PSD) curve, obtained from the measured beat signal with CEP locked, and the accumulated phase jitter are shown in Fig. 4. The phase noise in the range from milliseconds to ~1 second is also found to be about 30 mrad, which is well matched to the value in Fig. 3. In the previous experiment on the simple direct locking technique, the in-loop phase noise was reported to be 50 mrad [19]. The comparison shows almost twice reduction in the phase noise, as expected from Eq. (5). An out-of-loop measurement for the proof the CEP locking was not attempted because it was already confirmed in the previous reports [19, 20]. The reduced phase noise consequently demonstrates the enhanced operation of the direct locking technique by employing the HBD method.

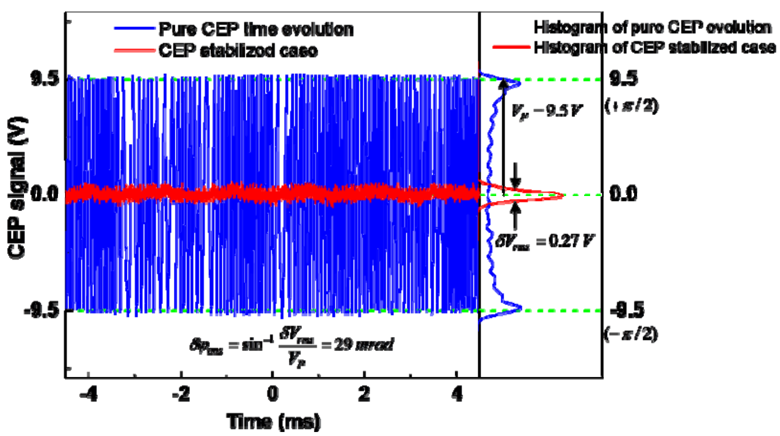

Fig. 3. CEP stabilization using the direct locking method (blue line) Pure beat signal extracted from the Homodyne Balanced Detection and (red line) the stabilized CEP signal. Histograms of the phase noise signal before(blue) and after(red) stabilization

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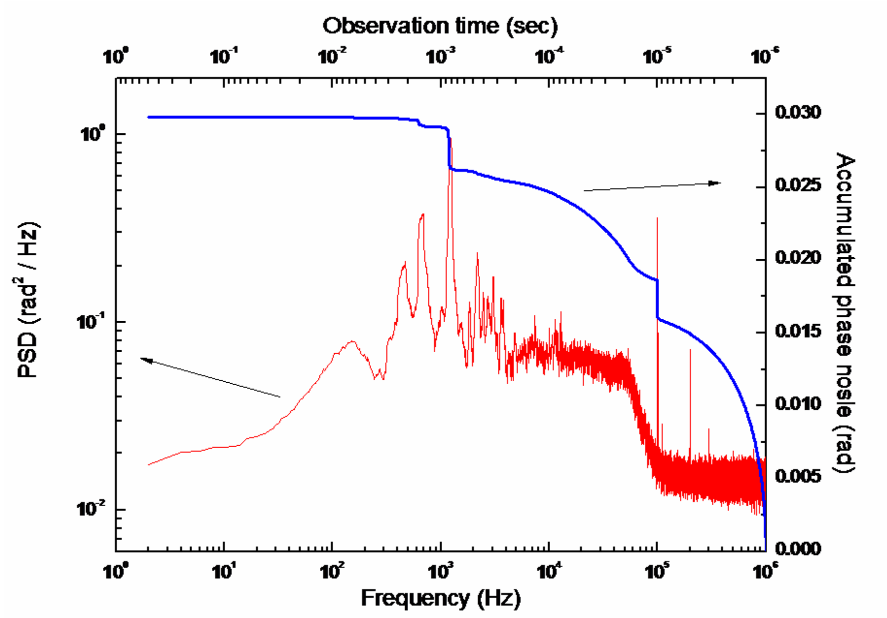

Fig. 4. Phase spectral density (red) and accumulated phase jitter (blue) under CEP stabilization. The scale of observation time (upper) is related to the inverse scale of frequency (bottom)

3. Double feedback method for the long-term CEP stabilization

We introduce here a double feedback method for a long-term CEP stabilization. The pump-power modulation scheme using an AOM has a disadvantage in a long-term stability. A significant f_{ceo} drift, occurring during a long-term operation, can modulate the pump power so strongly to turn off the mode-locking of the laser oscillator. This problem happens both in the direct locking technique and the conventional PLL-based technique, because f_{ceo} should be fixed to a certain value (the former one is operated at f_{ceo}=0 and the latter at f_{ceo}=f_{rep}/N). If the accumulated pulse-to-pulse CEP change ($\Delta\varphi = 2\pi\ f_{ceo} / f_{rep}$) without locking is about a few radians, the feedback process for CEP locking can stop the mode-locking due to the deep modulation of pump power. To solve this problem, we installed a slow servo that drives a piezo-translator for the modulation of the intracavity-prism insertion depth as shown in the red box in Fig. 1. The prism can modulate $\Delta\varphi$ without changing the pump power or influencing the mode-locking condition as long as the dispersion change is small enough. Thus, the prism translation as a slow feedback method allows a high-dynamic-range operation of CEP drift and is suitable for a long-term operation.

By combining fast and slow servos, we have greatly improved the long term operation of CEP stabilization. For the realization of the double feedback method, we simply use two integration circuits with different cutoff frequencies after the subtraction circuit. The cutoff frequency of the slow servo is about 0.3 Hz whereas that of the fast servo is about 30 kHz. Thus, the slow feedback loop only works in the time scale larger than 1 second. The experimental results without and with the slow feedback loop are shown in Figs. 5(a) and (b), respectively. In Fig. 5(a), the CEP locking is preserved only by AOM, but the slow drift of the AOM signal eventually goes beyond the control range to break the CEP locking after 4 minutes. When the average rf power into the AOM was slowly increased as shown in Fig. 5(a)-AOM, It was observed that the pump-beam-pointing was slightly shifted owing to the temperature change of AOM and the pointing shift caused the instability of fs laser oscillator. As a result, the CEP locking could not be preserved any more. It was difficult to maintain the CEP locking over 4 minutes in this situation.

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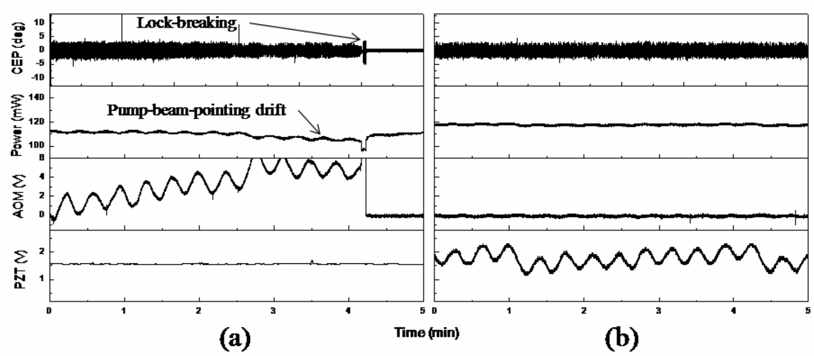

Fig. 5. Comparison of operating characteristics between (a) the fast feedback loop only and (b) the double feedback loop (CEP: stabilized carrier-envelope phase, Power: laser output power, AOM: the feedback signal to AOM (fast feedback), and PZT: the feedback signal to PZT (slow feedback)). With only the fast feedback loop of AOM, mode-locking is broken after 4.2 min. but with the double feedback with PZT, the CEP stabilization is maintained without changing the average power and drifting the signal of AOM.

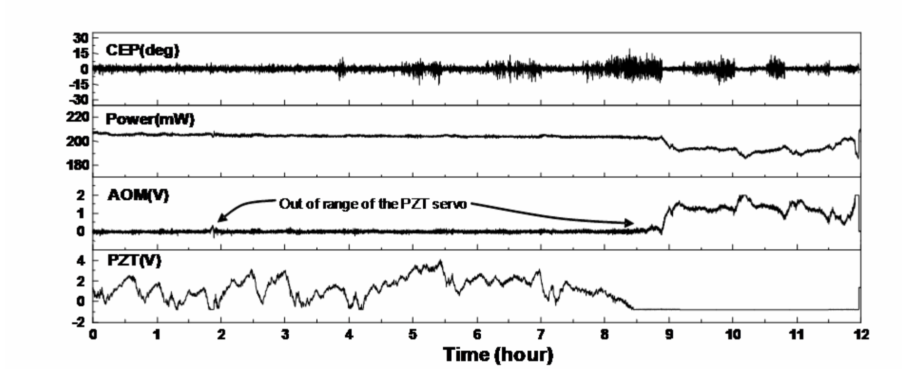

Fig. 6. Long term operation of the carrier-envelope phase stabilized femtosecond oscillator by using the double feedback loop.

In contrast, the long-term operation is much more successful when the slow drift is controlled by PZT, as shown in Fig. 5(b). It is observed that the average rf power drift into the AOM is much smaller in this case of Fig. 5(b) than Fig. 5(a), which makes the laser oscillator work in a more stable manner without serious pump-beam-pointing drift owing to the temperature change of AOM. The regular slow modulation of the slow feedback signal with a period of ~30 seconds was observed. After carefully checking this low-frequency noise source, it was found that the pump power had a very small oscillation with this period, caused by the temperature fluctuation of the chiller cooling the pump laser. Nevertheless, the presence of this oscillation which conversely worked for the CEP locking enforced the effectiveness of our double feedback technique for the long-term stable operation.

We have observed that the CEP-locking operation was improved to several hours from a few minutes due to the double feedback loop even under such poor conditions. After replacing the chiller with smaller temperature oscillation and the mount of AOM with improved thermal conductivity for better CEP stabilization, we have achieved a long-term CEP-locking operation over 12 hours, as shown in Fig. 6. The CEP stabilization time with the double feedback technique was 9 hours due to the lack of the dynamic range of PZT servo. It causes rf power drift on AOM, which leads to the change of average laser power as shown in Fig. 6. As a result, the CEP-locking was stopped due to the presence of the AOM heating problem. However, the CEP-locking still was maintained during 3 hours owing to improving the mount of AOM. We believe that the CEP-locking can be maintained as long as the slow feedback loop gets in the range of PZT servo.

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4. Conclusion

We have demonstrated the improved direct locking technique for precise and long-term CEP stabilization by using the HBD method and the double feedback scheme. The HBD method reduced the CEP noise by a factor of about 2, as expected from the theoretical comparison, achieving the in-loop CEP noise of 29 mrad. The double feedback scheme has enabled the long-term operation more than 12 hours. The CEP-stabilized oscillator using the improved direct locking technique will be a powerful light source not only for the study of CEP-sensitive phenomena [18,23] but also for a stable seed beam to a CEP-stabilized few-cycle high-power femtosecond laser.

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