High Precision and Large Range Timing Jitter Measurement and Control of Ultrashort Laser Pulses

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***Abstract*—An attosecond precision and femtosecond range timing jitter measurement and control technique is proposed. It is based on the modulation of the combined pulse induced by relative time delay of individual pulses. The core of this timing jitter detection method is the integrated technique of optical cross correlation and electrical energy interferometry. To illustrate this technique, a proof-of-principle experiment is demonstrated based on two 237 fs pulses. The peak-to-valley timing jitter of the two pulses to be combined is less than 700 as in 1 h and the average efficiency of coherent beam combining could reach to 91.6%.**

***Index Terms*—Coherent beam combining, electrical energy interferometry, optical cross correlation, timing jitter.**

I. Introduction

NOWADAYS, a diversity of physical experiments have been performed with ultrashort ultrahigh intensity laser systems, including fast ignition, high-energy-density physics, ultra-intense laser-matter interactions [1]–[3]. Owing to the limited peak power improvement for single-channel laser, coherent beam combining (CBC) is the most promising technique to scale up the available peak-power of lasers without degrading the beam quality of the individual laser system, especially in ultrashort pulse regime. In order to realize efficient CBC for ultrashort pulse, high precision timing synchronization is necessary in femtosecond (fs) and even in attosecond (as) precision [4]–[8]. Moreover, precise timing synchronization and control of ultrashort pulses are essential for many other applications such as ultrafast laser spectroscopy, two-color pump-probe experiments, coherent control of molecules [9], [10].

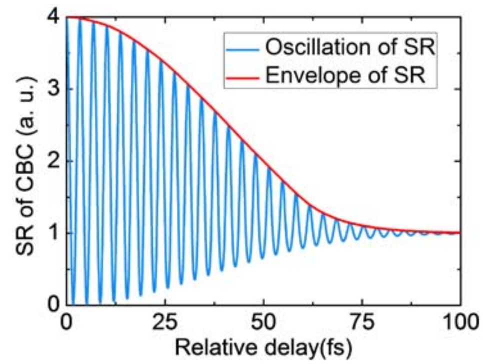

Fig. 1. Temporal SR of combined beam as a function of relative delay.

By now, many techniques have been developed to satisfy the urgent need for femtosecond and sub-femtosecond measurement and control of ultrashort pulse timing, including direct photodetection, optical cross correlation, two dimensions spectral interferometry and frequency resolved optical gating (FROG) [11]–[17]. Although a variety of timing approaches have been proposed and realized in the past, techniques of high precision timing detection and control with wide range are still limited. Especially, few techniques could be implemented conveniently in complex ultrashort ultrahigh intensity laser facility aimed at peak intensity of tens of petawatts (PW) and even exawatt (EW). The timing synchronization including measurement and control is one of the main obstacles before the application of CBC in the above mentioned facilities.

In this letter, a method of timing measurement and control with wide detection range and high precision is proposed. It is based on the temporal modulation of combined pulse caused by the relative time delay between individual pulses. Theoretical and experimental study is systematically presented. The core of this technique is the realization of timing measurement in a few pulse durations range (typically the order of femtosecond) and attosecond precision with optical cross correlation and electrical energy interferometry, respectively.

II. Theory and Experimental Setup

Assuming two ultrashort Gaussian pulses with duration of 50 fs to be combined, the dependence of the temporal

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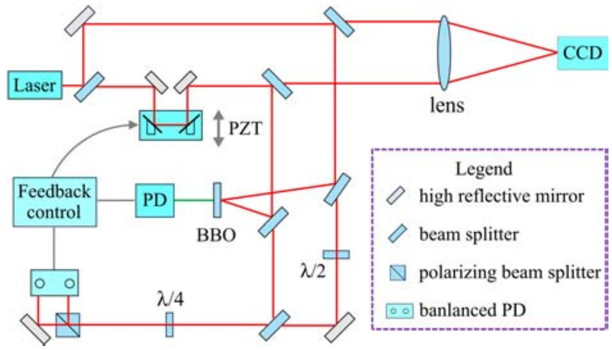

Fig. 2. Experimental setup.

Strehl ratio (SR) of combined beam on the relative time delay between two individual beams is shown in Figure 1. The first-order spectral phase reflects the delay between two pulses and the zero-order spectral phase reveals the difference of the carrier envelope phase. The time delay influences the result of CBC in the form of peak power's rapid oscillation and the envelope's decrease. For the CBC of tens of femtoseconds pulses, the effect of zero-order spectral phase is similar to the first-order phase. Therefore, the envelope degradation of SR is caused by the degeneration of the first order phase while the rapid oscillation is caused by the integrated function of the zero and first order.

The rapid oscillation period of the SR equals to λ_0/c, where λ_0 is the central wavelength of the pulses. By detecting the intensity changes of envelope and carrier respectively, and using the results as the sources of feedback control, the timing measurement and control in large range and high precision could be realized simultaneously.

In view of the aforementioned theory, we design a scheme for timing measurement and control of ultrashort pulses in large range and high precision. Figure 2 shows the setup of proof-of-principle experiment. The laser system is an Yb: KGW laser (Pharos SP) which delivers linearly polarized femtosecond pulses with a central wavelength of 1028 nm and the bandwidth is 10 nm. The maximum pulse energy is 1 mJ and the output pulse stability is better than 0.5% root-mean-square (RMS) over 24 h. The repetition rate of the laser is set at 10 Hz in our experiment because the repetition rate of the real Petawatt laser system is less than 10 Hz.

The laser system is split by a half reflecting mirror into two different channels, one of which with a tunable optical time delay line. Before the pulses being combined coherently, a fraction of the pulses are reflected and divided into two sections for timing jitter measurement and control based on optical cross correlation and electrical energy interferometry respectively. In the parts of the optical cross correlation measurement, the pulses are coupled noncollinearly into a 1-mm β-barium borate (BBO) crystal to produce a sum frequency signal. A photodetector (PD) is adopted to detect the sum frequency signal. In the parts of the electrical energy interferometry, a half-wave plate rotates the polarization of the pulse by 90 deg in one path. After going through a quarter-wave plate, the two linear polarized beams which are perpendicular to each other both become circularly polarized with opposite rotation directions. Both beams are separated by a polarized splitter and recorded by a balanced PD.

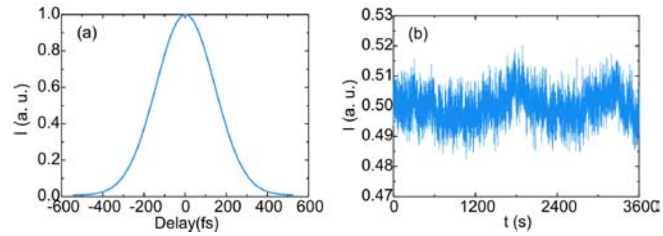

Fig. 3. (a) Normalized cross correlation trace of the two pulses, (b) Intensity fluctuation record of the SFG at half-peak.

III. Results

When the pulses in two channels are overlapped in the BBO crystal noncollinearly, the typical trace of sum frequency generation (SFG) as the delay swept is shown in Figure 3(a). The cross correlation Full Width at Half Maximum (FWHM) is 335 fs and the pulse width is 237 fs with Gaussian assumptions. Near the half value of the SFG intensity, the intensity changes linearly as the fluctuation of the relative time delay. The RMS timing noise is got by recording the intensity fluctuations of SFG signal at its half peak. The control result of the feedback loop in large range and low precision based on the SFG signal is shown in Fig. 3(b). The peak-to-valley (PV) value of timing drift in one hour is 9 fs and RMS timing jitter is 2.2 fs at 2 Hz bandwidth.

The method of optical cross correlation provides a direct detection of envelope timing between the pulses in different channels. The measurement range and precision both depend on the pulse width. The control precision with this method could improve evidently and the PV control of timing jitter can be the order of femtosecond for the pulse duration of dozens of femtoseconds, which is emphasized in the developing ultrashort ultrahigh intensity laser systems of several and even scores of PW. Nevertheless, the approach can not realize the accuracy on the order of attosecond required by efficient CBC.

In order to further achieve attosecond precision of timing detection, the technique of electrical energy interferometry is added. It is a fascinating method for timing jitter detection which is insensitive to the energy noise of the pulse itself. This approach is similar to the Hansch-Couillaud detector which is first applied for laser frequency stabilization [18]. As the optical time delay is adjusted within a carrier period, the output of balanced PD changes as a function of sinusoid ($\Delta E = (E_1 E_2)^{1/2} \sin(\omega_0\ \Delta t)$, where E_1, E_2 are the energy of the pulses, ΔE is the output signal of balanced PD, and Δt is the time delay between the pulses), which is used for error signal control by a highly precise closed-loop relative timing jitter stabilization system. However, even number times of the carrier period correspond to the same output signal, so the method is only fit for timing measurement in high precision not large range. As mentioned in Fig. 1, once the intensity of the optical cross correlation gets its maximum value, we lock the output signal of electrical energy interferometry to nearly zero.

Figure 4 shows the experimental results. In an open loop mode, the relative time delay changes slowly to less than twice

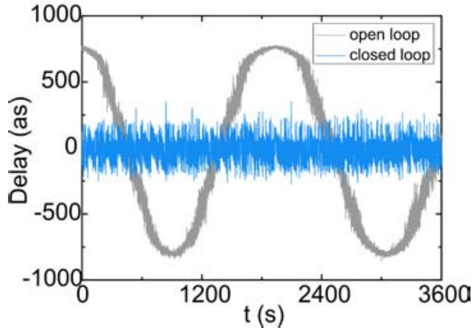

Fig. 4. Error signal recorded in an open and closed loop in 1 hour.

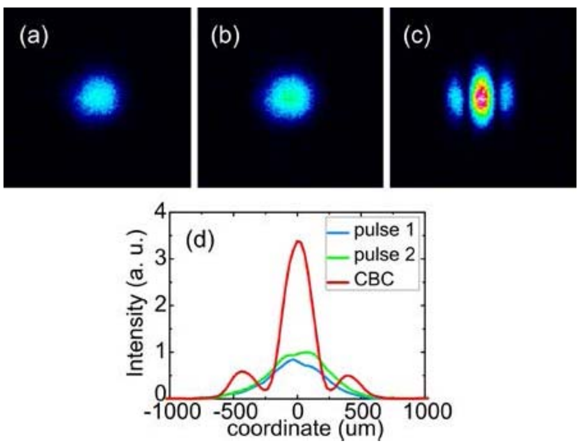

Fig. 5. The beam profile in the focal plane for pulse 1 (a), pulse 2 (b), combined beam (c), and 1D data (d).

of carrier period in one hour, corresponding to a slow drift of 6.85 fs and RMS timing jitter of 493 as. When the high precision closed loop with 2 Hz bandwidth is implemented, the PV of the timing change is less than 700 as in 1 hour, and the RMS timing jitter is 140 as, so the delay is always locked within the same carrier period.

After high precision and large range timing jitter measurement and control are realized, a good long-term stability is acquired. The pulses in two channels are combined coherently in the focal plane of a lens. Figure 5 demonstrates the beam profiles in the focal plane of individual beams and combined beam recorded by beam profiling cameras. The average efficiency of CBC equals to 91.6 %.

However, real ultrashort ultrahigh intensity laser systems are influenced by many factors such as air flow, temperature drift and pump source perturbation. The jitter of some frequency component in the zero-order and first-order spectral phase may be higher than hundreds of Hertz and even on the order of kilohertz [19]. The current active control system with feedback is not able to stabilize the above mentioned disturbances effectively due to the insufficient frequency range, but it is just limited by the current electronic control system not by the time jitter measurement and control technique itself. In the future, we will develop a more robust closed loop electronic control system with sufficient bandwidth and the control accuracy will be further improved.

IV. Conclusion

In conclusion, we have investigated timing jitter measurement and control theoretically and characterized the timing jitter of two pulses. We realized the timing synchronization within ± 350 as during 1 hour by the combination of optical cross correlation and electrical energy interferometry. The average efficiency of CBC equals to 91.6%. In this work, the timing of the two pulses at femtosecond level is adjusted based on the results of optical cross correlation. Meanwhile, the electrical energy interferometry permits the measurement and control of the timing jitter at attosecond precision by a closed loop. This technique of timing jitter measurement and control is beneficial to efficient CBC of short pulse system especially petawatt laser system in the future.

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