A new method and instrument for accurately measuring interval between ultrashort pulses

Zhonggang Ji (季忠刚), Yuxin Leng (冷雨欣), Yunpei Deng (邓蕴沛), Bin Tang (唐 斌),
Haihe Lu (陆海鹤), Ruxin Li (李儒新), and Zhizhan Xu (徐至展)

Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800

Received October 11, 2004

Using second-order autocorrelation conception, a novel method and instrument for accurately measuring interval between two linearly polarized ultrashort pulses with real time were presented. The experiment demonstrated that the measuring method and instrument were simple and accurate (the measurement error < 5 fs). During measuring, there was no moving element resulting in dynamic measurement error.

OCIS codes: 230.0230, 120.4570, 320.7100.

In most application area of ultrashort laser pulses such as the femtosecond pulses laser micromachining, one needs to exactly measure the interval between different pulses. The current method widely used is to use the optical path length measurement. At first, by adjusting one of the pulses' optical paths, we can control the two pulses to reach one nonlinear crystal at the same time and get the second-harmonic generation (SHG) or the interference patterns, then get the zero delay point. For the changed path length, one can get different time delay. The minimal measurement error of mechanic shift is about 10 μm in general, so the minimal measurement error of the interval is about 33 fs. For pulses short than 50 fs, this error is very large. And using this method, it is difficult to measure the time delay with real time.

In this paper we introduced a new method and instrument based on second-order autocorrelation conception for accurately measuring interval between two linearly polarized ultrashort pulses with real time. First using a half-reflecting mirror, we gathered the two measured pulses into one two-pulse beam. And then it was split into two beams. The two beams with the same intensity and orthogonal polarization irradiated into a nonlinear crystal and got SHG signals. Through the measurement of the SHG signals' spatial position, we could calculate the temporal delay of the two pulses. The measurement error is less than 5 fs, and during the measurement we need not move the optical element so we can actualize a real time measurement.

The incident ultrashort pulses would produce SHG signals when they matched together in temporal and spatial in the nonlinear crystal. By measuring the signals' spatial distribution using a linear array charge-coupled device (CCD) camera, we can get the temporal information of the pulses through simple calculation as

$$\Delta t = 2nx_0 \sin(\theta/2)/c, \qquad (1)$$

where Δt is the pulse duration, x_0 is the SHG signals' separation, and θ is the included angle of two beams. If θ is very small, Eq. (1) can be simplified as

$$\Delta t = nx_0\theta/c. \qquad (2)$$

If an ultrashort pulse was split into two pulses and irradiated into the nonlinear crystal at different angles, we can get the spatial distribution of the harmonic signals. Using Eq. (1) we can calculate the temporal distribution of the incident pulse. This is the principle of the single-shot second-order autocorrelation. If two collinear pulses were split into two beams and irradiated into the same crystal, we would get three separated harmonic signals. Using Eq. (2), we can get the temporal duration and separation of the two pulses (see Fig. 1).

According to the above theoretical analysis, we built an instrument which can measure the 800-nm ultrashort pulses' temporal separation in real time. Figure 2 shows the main structure of the design. As seeing from Fig. 2, using a thin reflection-transmission mirror we can collect two ultrashort pulses into one beam at the point O. And then the beam was transformed into circularly polarized light by a quarter wave plate. The circularly polarized light was split into two beams by a polarizer with the same intensity and orthogonal polarization and then irradiated into a KDP plate. A linear array CCD camera was used to detect the SHG signals and then the signals were shown on an oscillograph. A right-angled reflector consisting of two 45° total reflecting mirrors was used to adjust the optical path length of one of the two beams.

This instrument should be calibrated before use. At point O we used only one ultrashort pulse beam. It was split into two beams at polarizer and then irradiated into

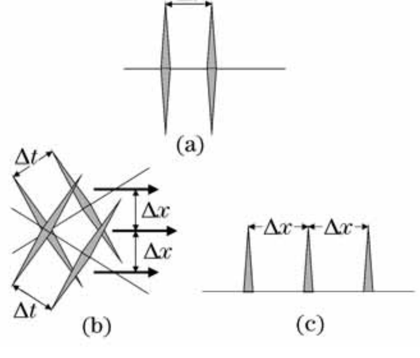

Fig. 1. (a): Two collinear short pulses with Δt; (b): In nonlinear crystal, the SHG signals are generated at three different positions, where the pulses interact each other; (c): Responding to (b), three symmetrical SHG signals in space are generated with Δx.

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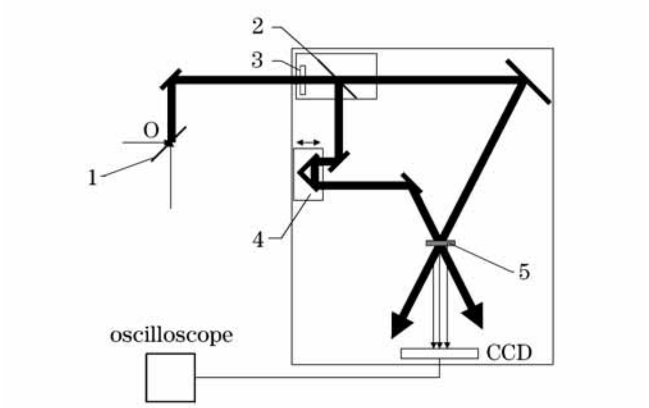

Fig. 2. Scheme of the instrument for accurately measuring the interval between ultrashort pulses. 1: thin reflection-transmission mirror; 2: polarizer; 3: quarter wave plate; 4: right-angle reflector consisting of two 45° reflecting mirrors; 5: KDP plate.

the KDP plate. By adjusting the right-angle reflector, we made the two beams get the KDP plate at the same time so we can get the emergent SHG signals at the bisector which can be displayed on the oscillograph. Then we change optical path length of one of the beams by gently moving the right-angle reflector. The SHG signals position on the oscillograph would changed correspondingly. According to Eq. (2) the two beams' temporal separation Δt has an approximate linear relationship with the SHG signals' spatial separation x_0 when θ is not too big. So we can get the relationship of the two beams' real temporal separation Δt and the separation ΔT showed on the oscillograph

$$\Delta t = \frac{2L}{c}\frac{\Delta T}{T_0}, \tag{3}$$

where L is the reflector moving length, T_0 is the corresponding shift position showed by the oscillograph and C is light velocity. Using this method we can also measure the pulse duration.

In our experiment we used a Ti:sapphire laser system running at a 1-kHz repetition rate, producing 50-fs pulse with a central wavelength of 800 nm. Finally we got a correspondence of $\Delta T = 4$ ms showed on the oscillograph with $\Delta t = 1140$ fs of the real temporal separation of the pulses.

In our experiment of femtosecond pulses laser micromachining, two 50-fs pulses with the same line polarization (came from the same laser system described before) converged to one spatial point with an angle of 30° which were used as the pump pulse and probe pulse, respectively. We used the instrument showed as Fig. 2 to measure the time delay of the probe pulse and the pump pulse. Figure 3 shows the measured result of the oscillograph. From it, we can see that the separation between every two neighbor pulses was 1.432 ms, the time delay of the two pulses was about 403 fs, and the pulse duration were about 50 fs.

Because of the limit of the KDP matching angle, θ is usually less than 20°. So Eq. (2) can be used. From it the measuring accuracy has a linear dependence of the two beams separation angle θ when the linear array CCD resolution is fixed. In our experiment θ was about 10°. According to the resolution of the CCD we used, the measuring accuracy is better than 5 fs.

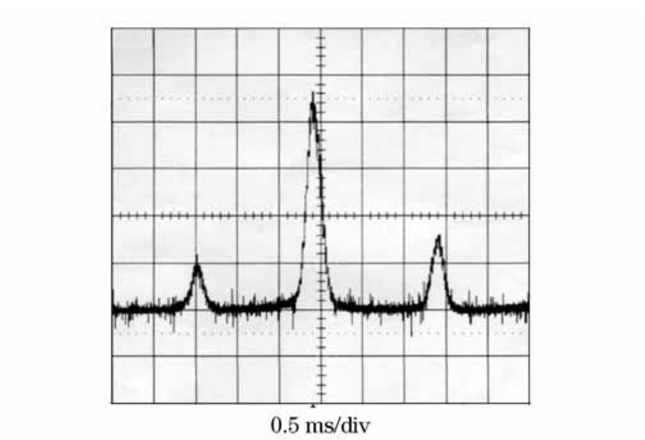

Fig. 3. Measured result in oscilloscope.

In this device the measurement error mainly comes from the time delay of two pulses brought by the thin reflection-transmission mirror. This is a static error which is determinate when the included angle of the two incident beams and the thickness of the thin reflection-transmission mirror are determined. We can calculate this error by

$$\delta t = \frac{d(n-1)}{c(\cos\gamma)}, \tag{4}$$

where $\gamma = a\sin\left[\left(\cos\frac{\phi}{2}\right)/n\right]$, n is the refractive factor of the mirror, and ϕ is the included angle of the two ultrashort pulses beams to be measured. In our experiment $n = 1.55$, $\phi = 30°$, and $d = 2$ μm, so this static error is about 4.7 fs. For pulses longer than 100 fs this error can be neglected but for pulses shorter than 100 fs, the measured results need to be corrected.

The shortest time delay that this device can be measured also depends on the resolution of the SHG signals wave crests. When the pulses' separation is wider than the pulse duration, the SHG peaks may be regarded as resolvable. So for 50-fs pulse, the shortest time delay which can be measured is 50 fs. When two pulses with the same polarization are closed to this separation value, obvious interference patterns would be observed.

Y. Leng is the author to whom the correspondence should be adddressed, her e-mail address is lengyuxin@mail.siom.ac.cn.

References

1. M. Li, S. Menon, J. P. Nibarger, and G. N. Gibson, Phys. Rev. Lett. **82,** 2394 (1999).
2. C. Guo, G. Rodriguez, A. Lobad, and A. J. Taylar, Phys. Rev. Lett. **84,** 4493 (2000).
3. C. Y. Chien, B. La Fontaine, A. Desparois, Z. Jiang, J. W. Johnston, J. C. Kieffer, H. Kieffer, H. Pépin, F. Vidal, and H. P. Mercure, Opt. Lett. **25,** 578 (2000).
4. Q. R. Xing, Tao Sun, M. W. Wang, Lu Chai, W. L. Zhang, and Q. Y. Wang, Chin. J. Lasers (in Chinese) **27,** 131 (2000).
5. F. Salin, P. Georges, G. Roger, and A. Brun, Appl. Opt. **26,** 4528 (1987).