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Measuring the temporal evolution characteristics of picosecond pulses based on cross-correlation during nonlinear propagation

Shuguang Deng, Yangbao Deng*, Cuixiu Xiong, Guangfu Zhang, Ye Tian

College of Communication and Electronic Engineering, Hunan City University, Yiyang 413002, People's Republic of China

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ABSTRACT

When the picosecond pulse with a initial temporal modulation propagates and amplifies in the large-scale Nd:glass laser system, the temporal modulation will be accumulated and enhanced, which causes serious temporal distortion in the output picosecond pulse. The output beam quality of the whole Nd:glass laser system will become very poor due to the spatiotemporal coupling effect. So measuring the initial temporal structure and temporal evolutions of the picosecond pulse after nonlinear propagation is necessary. We propose a method of measuring the temporal characteristics of a picosecond pulse by a synchronized femtosecond pulse. This method has advantages of simple operation, convenient and high resolution. The initial temporal fine structure and temporal evolutions of the picosecond pulse passing through different lengths of CS_2 nonlinear medium are measured. The results show that the initial temporal shape of the picosecond pulse is very clean and smooth. When the picosecond pulse propagates in CS_2 nonlinear medium, the pulse width has a trend of slight narrow with increasing the length of CS_2 nonlinear medium due to the spatiotemporal coupling effect.

1. Introduction

With the rapid development of ultrafast laser technology in the past decades, the pulse width of a laser pulse has entered the attosecond field, for example, the 10 as ultrashort pulse has been generated in ultraviolet and X-wave band [1–5], and thus the ultrashort pulses are used for fundamental studies and practical applications rapidly. However generation and manipulation of the attosecond pulse technology is not mature, the femtosecond pulse is used in practical application mainly. Femtosecond laser technology has a broad application prospect in many fields, such as optical communication, optical switch, optical storage, laser–matter interaction, and pump-probe spectroscopy [6–10]. The femtosecond pulse is used as a very short time probe, which provides an important tool for investigation of the microscopic world, such as probing the ultrafast chemical reactions of atoms and molecules, measuring the initial temporal fine structure and temporal evolutions of a picosecond pulse during nonlinear propagation. If the picosecond pulse with a initial temporal modulation propagates and amplifies in the large-scale Nd:glass laser system, the temporal modulation will be accumulated and enhanced, which causes serious temporal distortion in the output picosecond pulse. The output beam quality of the whole Nd:glass laser system will become very poor due to the spatiotemporal coupling effect. Therefore a method for measuring the initial temporal fine structure and temporal evolution characteristics of a picosecond pulse during nonlinear propagation is necessary.

At present, the methods for measuring the temporal characteristics of laser pulses are mainly pure electronic method and all-optical method. The pure electronic method includes photodiodes, high-speed oscilloscope [11] and high-speed streak camera [12], which are only suitable for measuring the pulse width of the picosecond and nanosecond pulse due to the limitation of measurement resolution. In addition, the pure electronic method cannot measure the temporal characteristics of the picosecond pulse, especially the initial temporal fine structure and temporal evolutions during nonlinear propagation. The all-optical method includes autocorrelation [13–15], cross-correlation [16,17], Frequency Resolved Optical Gating (FROG) [18–21], Spectral Interferometry (SI) [22], Spectral Phase Interferometry for Direct Electric-field Reconstruction (SPIDER) [23–26], and Pump-Probe technology [10,27,28]. FROG and SPIDER are very suitable for measuring the temporal and phase characteristics of a given ultrashort pulse accurately when the pulse width is less than 10 fs, but it is need to assume uniform transverse spatial distribution. FROG is needed complex iterative algorithm to retrieve the temporal shape of pre-measured pulse, which only gives approximate information. SPIDER is particularly suitable for measuring the

* Corresponding author. Tel.: +86 07376353136.
E-mail address: dyb5202008@aliyun.com (Y. Deng).

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spectral phase of a pulse, which has an advantageous for tracking the influence of dispersion on an ultrashort pulse. SPIDER neither moves components nor requires iterative algorithm, but it does not give the pulse width information directly. It needs the multiplied result of the measurement spectrum and phase, and then reconstructs the pulse shape by Fourier Transform. Compared with other methods, FROG and SPIDER are more complex in experimental operation. The intensity autocorrelation method is simple operation and no need complex calculation, but it is only suitable for measuring the pulse width information and need to assume the pre-measured pulse shape during the measurement process. While the coherent intensity autocorrelation method can provide some phase information, the accurate phase information is not given directly. The intensity cross-correlation method is also simple operation and no need complex calculation, whose measurement resolution is associated with the pulse width of the probe pulse. When the temporal shape of the probe pulse is very clean and its pulse width is very short, the measurement resolution is higher, and the cross-correlation curve characterizes the temporal characteristics of the pre-measured pulse directly. Pump-probe technology is usually used to measure the ultrafast chemical reactions of atoms-molecules.

Based on the advantages and disadvantages of the above measurement methods, we propose a method for measuring the initial temporal fine structure and temporal evolution characteristics of the picosecond pulse after nonlinear propagation by a synchronized femtosecond pulse based on the intensity cross-correlation. This paper is organized as following. In Section 2 the measurement principle is analyzed detailedly. In Section 3 we mainly introduce the experimental setup. In Section 4 the experimental results are analyzed and discussed in detail. Conclusions are presented in Section 5.

2. Analysis of the measurement principle

When the field distribution of a probe pulse ($I_1(t)$) is known, the pulse width (full width at half maximum, FWHM) of a pre-measured pulse ($I_2(t)$) can be measured based on the intensity cross-correlation method and a suitable second-order nonlinear effect crystal. The cross-correlation signal generated between the probe pulse and the pre-measured pulse is written as [11]

$$S_{\text{intCC}}(\tau) = \int_{-\infty}^{+\infty} I_1(t) I_2(t+\tau) dt = I_1(\tau) * I_2(\tau) \quad (1)$$

For Gaussian pulse shapes, the corresponding width of the cross-correlation curve ($\Delta t_{\text{int CC}}$), probe pulse (Δt_1) and pre-measured pulse (Δt_2) are related by

$$\Delta t_{\text{int CC}}^2 = \Delta t_1^2 + \Delta t_2^2 \quad (2)$$

For high-power femtosecond laser system, higher-order cross-correlation is very convenient and powerful tool to determine intensity profile by making use of nonlinear optical processes of the order $n+1$ and $m+1$, so the corresponding width of $\Delta t_{\text{int CC}}$, Δt_1 and Δt_2 are related by

$$\Delta t_{\text{higher-order int CC}}^2 = \frac{\Delta t_1^2}{n} + \frac{\Delta t_2^2}{m} \quad (3)$$

When the pulse width (Δt_1) of a probe pulse is known, the pulse width (Δt_2) of a pre-measured pulse is obtained by measuring the width ($\Delta t_{\text{int CC}}$) of the cross-correlation curve from Eq. (2). In the use of second-order intensity cross-correlation, the resolution is higher when the pulse width of the probe pulse is shorter according to Eqs. (1) and (2). For example, if the probe pulse is a $\delta(t)$ signal, the cross-correlation signal is written as $S_{\text{int CC}}(\tau) = \delta(\tau) * I_2(\tau) = I_2(\tau)$, and the width of the cross-correlation curve is the same as that of the pre-measured pulse ($\Delta t_{\text{int CC}} = \Delta t_2$). The temporal shape of the cross-correlation signal and pre-measured pulse are identical. Therefore, as long as pulse width of a femtosecond probe pulse is short and its temporal shape is clean and smooth, measuring the temporal characteristics of a picosecond pulse by use of this femtosecond pulse is completely feasible.

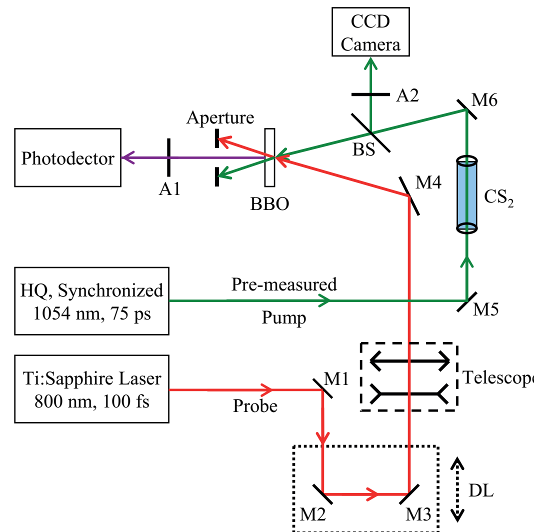

Fig. 1. Schematic diagram of the experimental setup: M1–M6, silver-coated plane mirror; BS, beam splitter; DL, Delay Line; BBO, β-barium borate crystal; A1 and A2, adjustable neutral density attenuator.

3. Experimental setup

The experimental setup is shown in Fig. 1. The probe pulse is generated from the femtosecond Ti:sapphire laser system (Coherent Libra S), whose main parameters are as following: 800 nm central wavelength, pulse width ~100 fs, 1 kHz repetition. The pre-measured pulse is generated from the picosecond laser system (High Q), whose main parameters are as following: 1054 nm central wavelength, pulse width ~75 ps, 1 kHz repetition. The probe pulse passes through the M1 mirror, delay line, telescopes, M4 mirror, and injects the BBO crystal with a thickness of 0.7 mm. The sum-frequency signal with a wavelength of 455 nm is generated in the BBO crystal by a small angle nonlinear sum-frequency interaction between the probe pulse and the pre-measured pulse. The femtosecond pulse scans the picosecond pulse completely by adjusting the delay line, and then the cross-correlation curve is obtained by probing the sum-frequency signal with an oscilloscope and photoelectric detector (PD). Therefore the initial temporal fine structure and pulse width of a picosecond pulse and its temporal evolutions passing through CS_2 nonlinear medium are obtained according to cross-correlation curve and cross-correlation principle [11]. When we measure the temporal evolution characteristics of the picosecond pulse during nonlinear propagation, carbon disulfide (CS_2) is chosen as the nonlinear medium because of its strong Kerr nonlinearity. The charge-coupled device CCD (Coherent Laser Cam-HR, pixel: 1280 × 1024, resolution: 6.7 μm × 6.7 μm) is used to measure the spatial evolutions of the picosecond laser passing through CS_2. Because the picosecond laser beam spot is smaller than the femtosecond laser, in order to make their beam spots matching, the femtosecond laser beam spot should be shrunk by a telescope. In addition, the regenerative amplifier systems of the femtosecond Ti:sapphire laser and the picosecond laser are adjusted to synchronize before doing the experiment.