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TEMPORAL CHARACTERIZATION OF LASER PULSES FROM JIGUANG-I LASER FACILITY WITH A COMPACT DUAL FUNCTION AUTOCORRELATOR*

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An optical pulse autocorrelator for rapid and slow scanning is described in this paper. Using an audio loudspeaker on one arm, an interferometric rapid-scanning signal of the output from a high-repetition laser oscillator is obtained. However, by adjusting the positions of the mirrors and using a step-motor on another arm, the intensity autocorrelation function of the output from a low-repetition laser amplifier can be easily measured. Using all-reflecting optics and an adequate nonlinear crystal, the whole instrument is very compact and has been used to measure sub-20 fs light pulses in both configurations with excellent agreement. In the slow-scanning configuration, a pulse train as long as 500ps has been determined. Using this autocorrelator, the home-made JIGUANG-I CPA laser facility was characterized for its pulse duration evolution.

Keywords: interferometric autocorrelation, intensity autocorrelation, femtosecond laser pulses
PACC: 4280W, 0660, 4260F

I. INTRODUCTION

Autocorrelation measurement is a fundamental way to determine the pulse duration of ultrashort pulses. Because of its simplicity, it remains the most interesting area[1] in ultrashort pulse laser technology, while a more complete characterization[2,3] for ultrashort pulses has been possible. The commonly used strategy is a combination of a Michelson interferometer with a second-order process, which is connected to the autocorrelation function of femtosecond laser pulses. A number of nonlinear interactions have been utilized in autocorrelation measurement, such as the second harmonic generation, two-photon fluorescence, multiple-order fluorescence, the optical Kerr effect, surface harmonic generation, second harmonic generation on reflection, and two-photon absorption in semiconductors etc. These have been extensively applied to the intensity or field multiplication process necessary for obtaining an autocorrelation function. Among these, the second harmonic generation (SHG)[4,5] is the most important and has been most comprehensively applied for its simplicity and convenience. Furthermore, a large variety of nonlinear crystals provide nonlinearities with very fast response and very broad spectral range.

Basically, there are three kinds of SHG autocorrelation scheme. The first two are based on the noncollinear method with intensity autocorrelation: one is the so-called scanning autocorrelation, and the other is single-shot autocorrelation.[6,7] Both of these schemes should be calibrated measurements, for they may result in error and doubt. The third scheme is the collinear rapid-scanning scheme[8] that utilizes interferometric autocorrelation (IAC). Being a self-calibrated measurement,[9] by which the pulse width can be read out directly, IAC is the most widely accepted standard for pulse duration characterization.[10] The shortcoming of the third scheme is that it can only be used for pulses with a repetition no smaller than 1kHz and a duration no longer than a few picoseconds.[11] Here, we introduce a method combining the two scanning autocorrelations (the first and the third schemes) in one compact design of autocorrelator. Using a specifically designed light path, noncollinear and collinear configurations can be easily exchanged. Thus, the advantages of the two schemes can be fully exploited; the noncollinear scanning autocorrelation, which can be utilized for low repetition and long pulse duration, is an internal-calibrated measurement with the collinear IAC measurement on the same instrument. Moreover,

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the use of all-reflecting optics and reasonable choice of BBO (β-BaB_2O_4) crystal enables us to obtain a large bandwidth and tuning range. The whole instrument is very compact and has been used to successfully measure sub-20 fs light pulses in both configurations. In the slow-scanning configuration, up to 500ps pulses at a 10Hz repetition has been observed. The rapid-scanning signal is obtained with an oscilloscope, while the slow-scanning curve can be displayed in a computer.

II. PRINCIPLE AND DESIGN

In the two configurations for the scanning autocorrelation measurement stated above, the laser beam is split into two and then combined in a frequency-doubling crystal. The first scheme uses a retroreflector mounted on a linear motion device, such as an audio loudspeaker or other shaker. As the loudspeaker is driven by a sinusoidal or triangular waveform, a collinear interferometric rapid-scanning autocorrelation signal is produced.

Letting the electric field of the laser pulse be $\varepsilon(\mathrm{t})$, the second-order correlation function reads

$$G^{(2)}(\tau) = \frac{\int_{-\infty}^{+\infty} \varepsilon^2(t)\varepsilon^2(t-\tau)\mathrm{d}t}{\int_{-\infty}^{+\infty} \varepsilon^4(t)\mathrm{d}t} = \frac{\int_{-\infty}^{+\infty} I(t)I(t-\tau)\mathrm{d}t}{\int_{-\infty}^{+\infty} I^2(t)\mathrm{d}t}. \quad (1)$$

In the collinear configuration, the interferometric autocorrelation can be realized. At this time, the fundamental frequency light and the SH light appear at the same time. The generated signal is $S(\tau)$,

$$S(\tau) = A(\tau) + 4B(\tau) + 2C(\tau), \quad (2)$$

where

$$A(\tau) = \int_{-\infty}^{+\infty} [\varepsilon^4(t) + \varepsilon^4(t-\tau) + 4\varepsilon^2(t)\varepsilon^2(t-\tau)]\mathrm{d}t,$$

$$B(\tau) = \int_{-\infty}^{+\infty} [\varepsilon^2(t) + \varepsilon^2(t-\tau)]\varepsilon(t)\varepsilon(t-\tau) \cdot \cos[\omega\tau + \phi(t) - \phi(t-\tau)]\mathrm{d}t,$$

$$C(\tau) = \int_{-\infty}^{+\infty} \varepsilon^2(t)\varepsilon^2(t-\tau)] \cdot \cos 2[\omega\tau + \phi(t) - \phi(t-\tau)]\mathrm{d}t.$$

We have $S(0) = 16\int_{-\infty}^{+\infty} \varepsilon^4(t)\mathrm{d}t$, $S(\infty) = 2\int_{-\infty}^{+\infty} \varepsilon^4(t)\mathrm{d}t$, and the signal-to-noise ratio is 8:1.

The second configuration mounts the retroreflector on a step-motor. As the step-motor is moved slowly and precisely, the noncollinear sum-frequency mixing of two beams generates the optical autocorrelation. At this time, the PMT only detects the pulse envelope, and the detected signal is

$$S(L) \propto G^{(2)}(\tau), \quad (3)$$

where L is the optical path delay, connected to the time domain by light velocity c.

In the former configuration, the visual and clear autocorrelation signal can be displayed on the oscillograph screen, especially for the high-repetition laser pulses with a duration of sub-100 fs. However, when pulses are longer or the repetition is lower, the second configuration is more advantageous. All of these conditions are often met in practical circumstances; for example, in the generation and amplification of ultrashort optical pulses, the technique of chirped pulse amplification (CPA) is a fundamental scheme. Light pulses from the laser oscillator are of a short duration (femtosecond) and high-repetition; the pulses from the stretcher are of a long duration (picosecond) and high-repetition; the pulses from the amplifier are of a long duration (picosecond) and low-repetition; and the pulses from compressor are of a short duration (femtosecond) and low-repetition. Therefore, it is useful to couple these two configurations in a single instrument. By simple adjustment, it can be used to measure all these kinds of light pulses.

In order to combine the desirable characteristics in one compact instrument, we must make a very careful and elaborate design. To realize the non-dispersive optics and to accommodate collinear and noncollinear nonlinear interactions in one focusing system, a reflecting focusing-collimating optics is used to couple the beams from the two arms into the nonlinear crystal. The two off-axis focusing mirrors have the same focal length of 50mm. The BBO crystal is used as the SHG crystal since it has a large effective nonlinear coefficient, broad spectral range and fast response. Two BBO crystals are prepared: one is 100μm thick and used for the measurement of long pulses with low intensity; the other is 20μm thick, which induces negligible pulse stretching and can be used to measure very short pulses. Both of the BBO crystals are type I phase matching, 29.2° cut, which has proved to have a large bandwidth and tuning range for the SHG process of the 800nm laser.[12]

A commercial audio loudspeaker on one arm, which is mounted on a one-dimensional precise manual movable stage, provides the rapid scanning. By shifting the movable stage, it is easy to transfer from collinear to noncollinear interactions. In noncollinear interaction, the intensity autocorrelation function is generated through slow scanning provided by a step-motor on another arm. The step-motor ensures a relatively large time delay, benefiting the measurement of long pulses. The movement of the step-motor is 0.5mm per 4000 cycles. Since the path length is twice the displacement of the step-motor, the precision corresponds to 0.83fs per turn. The kinetic range of the step-motor is 80mm, and the maximum optical path delay length is 160mm, corresponding to a 530ps foot width. There has not been an available method to measure a pulse with a duration as long as a few hundreds of picosecond. This makes it awkward to design and optimize pulse stretchers in CPA systems. This is one reason that we have used such a long kinetic range step-motor with high precision in our autocorrelator. A computer controls the slow-scanning signal readout, and the corresponding program is edited and compiled using Visual Basic.

The schematic layout of such an autocorrelator is shown in Fig.1. Two configurations are easily transferred to each other by moving the micropositioner, on which the speaker is mounted, as also shown in Fig.1. Such an autocorrelator has been manufactured as a prototype product which is as compact as $350 \times 250 \times 160\text{mm}^3$.

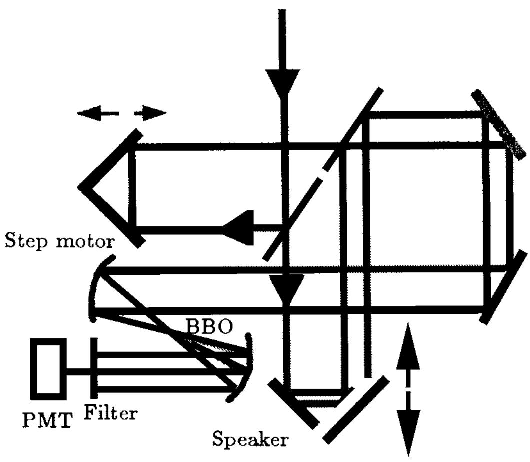

Fig.1. The schematic layout of the autocorrelator, where PMT is a photomultiplier tube.

III. OPTICAL PULSE AUTOCORRLATION MEASUREMENT

The JIGUANG-I laser facility[13] is a recently constructed table-top terawatts Ti:Sapphire laser at the Institute of Physics, Chinese Academy of Sciences. The pulse duration characterization is completed using this autocorrelator.

In the laser facility, the oscillator works at a repetition of 82MHz; the broad bandwidth output from the oscillator can support a pulse duration shorter than 10fs, so that the seeding pulses can be measured in both schemes of collinear and noncollinear. Moving the speaker to the right-hand side where both split pulses from the two arms coincide at the same dot on the focusing mirror, then we have the collinear configuration. Further fine adjustments to the delay to make both pulses overlap in the temporal domain enable us to see an increasing SHG signal. To observe the interferometric autocorrelation trace, we have detected the SHG signal with a photomultiplier tube (PMT) after blocking the fundamental wave by a low-pass filter and then injecting the transferred electrical signal into a fast oscilloscope (Tek Inc, 485). Driving the speaker by a 10Hz triangular wave forming electrical pulses enables us to watch the interferometric autocorrelation trace on the oscilloscope and to deal with this further using a computer. Figure 2 shows a typical interferometric autocorrelation of the Ti:Sapphire laser oscillator, which we have developed, with a duration of 12.8fs. Compared with the bandwidth of 100nm, a small chirp does exist in the laser pulses, which is a key technique in our CPA system.[14]

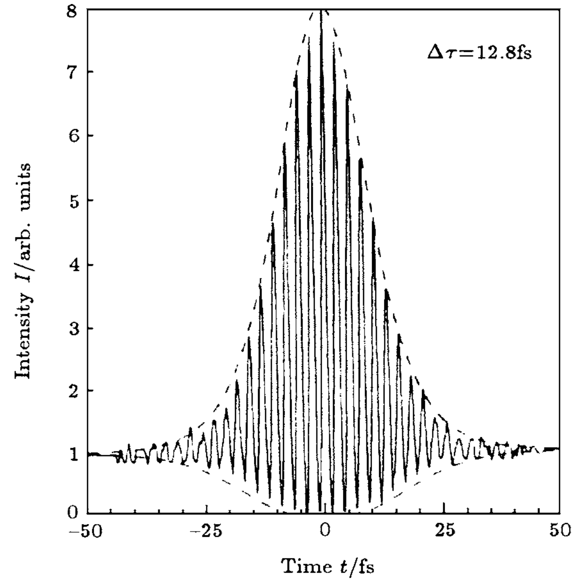

Fig.2. Field autocorrelation measurement of ultrashort pulses.

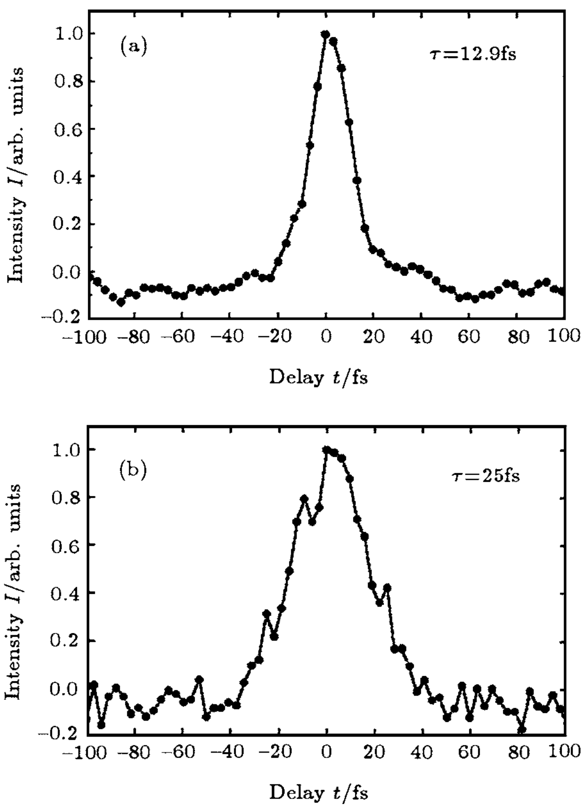

Fig.3. Intensity autocorrelation measurement of ultrashort pulses: (a) pulses from the femtosecond oscillator; (b) pulses after the compressor.

For the stretched laser pulses or the 10Hz amplified laser pulses, it is difficult to carry out the measurement in the rapid-scanning configuration. We have measured them by intensity autocorrelation. But before that, the precision of the step-motor should be determined and the correctness of this configuration should be approved. We made this verification by measuring the pulse length in the slow-scanning configuration. Recovering the position of the speaker to the left-hand side, and letting the beam spots from the two arms apart from the focusing mirror, the noncollinear configuration is then set up. The adjustment of the noncollinear configuration for very short pulses is difficult because the overlaps in both temporal and spatial domains should be fulfilled in an ultra-thin BBO crystal. However, it is much easier to quickly catch the overlap domains by using a thick BBO crystal for pre-adjustment. Once the two replica pulses overlap in the crystal temporally and spatially, the noncollinear frequency-summing light can be seen between two frequency-doubling lights. Maximizing the signals by finely adjusting the overlap, we then replace the thick crystal with the ultra-thin crystal. The signal from the PMT is read out and stored in the computer. To sweep the step-motor enables us to obtain the intensity autocorrelation trace. Figure 3(a) shows the result with this measurement function for the same femtosecond laser oscillator. The pulse duration can be determined precisely to be 12.9fs assuming a sech^2 shape. The result is in excellent agreement with the rapid-scanning measurement as shown in Fig.3(a). This confirms that these two independent measurements are correct.

After passing through the stretcher, the 82MHz laser pulses are divided into 10Hz pulses and sent into a two-stage multipass amplifier. Then the 10Hz amplified pulses are sent into the compressor to cancel the positive chirp. Because of the gain narrowing in the amplification process and spectral cutting in the propagation process, the bandwidth of the compressed pulses is about 50nm. The pulses can only be measured by the intensity autocorrelation. The result is shown in Fig.3(b), showing a pulse duration of 25fs assuming a sech^2 shape, very close to the bandwidth-limited value. In this measurement, the difficulty in originating from the low repetition can be overcome by a high repetition operation.

It is more difficult to measure the stretched pulses, especially for the non-amplified pulses. Normally these pulses have a few nano-joules of energy and hundreds of picoseconds duration, which is over 10^4 times weaker than those pulses from the oscillator. The SHG signal is too weak to be detected by a PMT. In fact, even for the amplified pulses it is still impossible to carry out an exact measurement since the largest measurable foot width is 530ps, which is limited by the total delay of the step-motor. However, the autocorrelator can be used to prove that the stretched pulse duration is longer than 500ps since the SHG signal does exist on the whole delay path. This is one of the reasons that the eight-pass pre-amplifier has obtained a very large amplification and the conversion efficiency is as high as 23%.[13]

IV. CONCLUSION

We have designed and constructed a compact autocorrelator with the dual functions of interferometric and intensity autocorrelation. Measurements have been performed at both high and low repetitions. The autocorrelator is an internal-calibrated instrument, in which a self-calibrated rapid-scanning measurement is utilized to verify the precision and correctness of the intensity autocorrelation measurement, while the latter is more versatile in the characterization for the CPA system. Indeed, the practical operation has proven advantages besides compactness, such as robustness, easy-to-use, etc.

Based on this home-made autocorrelator, the home-made JIGUANG-I TW laser facility was characterized for its pulse duration evolution property. In a rapid-scanning measurement, using an audio loudspeaker on one arm, an interferometric signal of the output from the high-repetition laser oscillator is obtained, and a pulse duration as short as 12fs and a bandwidth as wide as 120nm have been measured. However, by adjusting the positions of the mirrors and using a step-motor on another arm, the intensity autocorrelation trace can be easily measured for the pulses either from a high-repetition laser oscillator or from a low-repetition laser amplifier. For the same pulse train, the two schemes of measurement are in excellent agreement. Besides, in the slow-scanning configuration, chirped pulses as long as 500ps from the pulse stretcher have been determined.

The central wavelength of the measured pulses is 800nm. However, as we have demonstrated in the SHG experiments,[12] the central wavelength is tunable between 710 and 870nm with the same crystal and the same structure. Furthermore, utilizing different SHG crystals or two-photon pin-diodes, this compact and dual function design can be extended to other ultrashort laser systems at different wavelengths.

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References

[1] Dourandin A, Brenner H C and Pope M 2000 *Rev. Sci. Instrum.* **71** 1589

[2] Anderson M E, de Araujo L E E, Kosik E M and Walmsley I A 2000 *Appl. Phys.* B **70S** 85

[3] Iaconis C and Walmsley I A 1998 *Opt. Lett.* **23** 792

[4] Maire M, Kaiser W and Giordmaine J A 1996 *Phys. Rev. Lett.* **17** 1275

[5] Janszky J, Corradi G and Gyuzalian R N 1977 *Opt. Commun.* **23** 293

[6] Collier J, Danson C, Johnson C and Mistry C 1999 *Rev. Sci. Instrum.* **70** 1599

[7] Oba K, Sun P, Mazurenko Y T and Fainman Y 1997 *Appl. Opt.* **38** 3810

[8] Myslinski P 1987 *Rev. Sci. Instrum.* **58** 711

[9] Oksanen J A I, Helenius V M and Korppi-Tommola J E I 1993 *Rev. Sci. Instrum.* **64** 2706

[10] Sutter D H, Gallmann L, Matuschek N, Morier-Genoud F, Scheuer V, Angelow G, Tschudi T, Steinmeyer G and Keller U 2000 *Appl. Phys.* B **70S** 5

[11] Riffe D M and Sabbah A J 1998 *Rev. Sci. Instrum.* **69** 3099

[12] Xia J, Wei Z and Zhang J 2000 *Opt. Laser Technol.* **32** 241

[13] Wei Z, Zhang J, Xia J, Feng B, Zhang X and Qiu Y 2000 *Sci. China* A **43** 1083

[14] Cao D, Wei Z, Teng H, Xia J, Zhang J and Hou X 2000 *Acta Phys. Sin.* **49** 1202 (in Chinese)