Compact in-line autocorrelator using double wedge

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Abstract: A new optical design for an autocorrelator using a double wedge is proposed and experimentally demonstrated. It consists of two wedges placed in a mirror-image configuration. Instead of splitting a beam by 90 degree angle as done in a conventional autocorrelator based on Michelson interferometer, the wedge splits the beam by 180 degrees. The angle of incidence is nearly normal to all the wedge surfaces so that this new design provides the compact in-line layout for an autocorrelator. The time delay can be adjustable by scanning the separation between two wedges. Due to the geometry, the double wedge produces multiple reflections, but they are angularly separated among each other. The laser pulse of 28 fs duration is measured by using the double wedge autocorrelator and compared with Michelson-type autocorrelator. The effect of material dispersion and angular chirp introduced by the wedge pair is discussed for shorter pulse measurement.

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References and links


1. Introduction

Since the optical pulse duration has become shorter than the response time of a photo-electric detector, which is typically tens of picoseconds, one needs to rely on self-referencing...
techniques to retrieve the information of the electric field. The shortest pulse generated directly from the oscillator is now reaching a single-cycle which is about 2.7 fs at 800 nm carrier wavelength [1]. An amplified pulse can also be compressed to a single-cycle by using nonlinear compression scheme [2] or it can be produced directly from OPCPA after linear compression [3]. Such ultrashort pulses can be used as a direct source of attosecond XUV pulses via variable methods [4–6]. To retrieve the information of ultrashort femtosecond laser pulses, there are several methods such as FROG [7], SPIDER [8], MOSAIC [9] and so on. Other recent techniques on ultrashort pulse diagnostics are well summarized in reference [10]. These tools provide the information of both field envelope and phase, which show every detail of an optical pulse including high-order dispersion and wave breaking. Once well-shaped ultrashort pulses are produced, the primary interest afterwards is to estimate the pulse duration and the presence of chirp. For this purpose, an autocorrelator is the simplest form among the self-referencing diagnostic tools and has been widely used for daily analysis. There are two types of autocorrelator: a scanning autocorrelator and a single-shot autocorrelator. The scanning autocorrelator can provide the interferometric autocorrelation trace and have a benefit of high sensitivity, while the single-shot autocorrelator can measure instant information and can be assembled in a compact space when a bi-prism [11] or a Babinet [12] is employed. In a scanning type autocorrelator, Michelson interferometer is typically used for generating two replicas and providing a delay between two pulses. Since a scanning autocorrelator based on Michelson interferometer splits the beam by 90 degrees, it usually requires more space compared to a single-shot autocorrelator, which typically shows in-line layout. Previously, an in-line scanning autocorrelator is reported by swinging birefringent plate rather than translating mirrors [13]. Here, we present a new compact in-line scanning autocorrelator, which uses a pair of wedges. This design greatly reduces not only the size of the autocorrelator but also the number of optical components. Actual volume of wedge interferometer is 50 x 50 x 80 mm$^3$, which corresponds to the volume of two 1-inch mirror mounts.

2. Double wedge interferometer

The primary beam paths at double wedge are depicted in Fig. 1(a). Two wedges are facing parallel to each other. The surface $S_{AR}$, which is between two wedges, is anti-reflection coated, thus there are effectively three optical interfaces in the wedge pair. $S_0$ has 50% reflectance over broad bandwidth where the pulse splits and recombines as well. $S_1$ and $S_2$ are partially reflecting surfaces where any reflectance can be used but the reflectance should be same for both surfaces. $S_1$ and $S_2$ act like two arms in the Michelson interferometer so they reflect the beams back to the beam splitter $S_0$. Tracing the beam paths, an incident beam $0$ enters through $S_1$ and is split into the beam 1 and beam 2 at the surface $S_0$. The beam 1, reflected off $S_0$ and the beam 2, transmitted through $S_0$ bounce back at the wedge surface $S_1$ and $S_2$ respectively. Finally, they meet together at $S_0$ and transmit through the surface $S_2$. The optical delay can be adjusted by translating one of the wedges along the optical axis and the delay is nearly proportional to two times of a distance between the surface $S_{AR}$ and $S_0$. The remaining parts of the autocorrelator are the same as a conventional autocorrelator, consisting of a second harmonic generation (SHG) medium and a detector. The double wedge geometry simply replaces the Michelson interferometer.
Fig. 1. (a) Beam paths in a double wedge. $S_0$, $S_1$, $S_2$ are partial reflection coated, $S_{AR}$ is anti-reflection coated. The beam 0 is main incident beam. The beam 1 and beam 2 are replicas for autocorrelation measurement. $d$ is distance between two wedges and $\theta$ is the angle of a wedge.

(b) Multiple reflections at the double wedge are shown.

Unlike an autocorrelator based on Michelson interferometer, the double wedge autocorrelator produces many stray lights due to the multiple reflections between wedges as shown in the Fig. 1(b). The number of beams in a bunch of stray light is doubled for each transmission. The angle of stray light increases by about $2\theta$, where $\theta$ is the angle of wedge. Thus, the primary beams for autocorrelation can be separately measured.

3. Experimental results

To demonstrate a double wedge autocorrelator as shown in Fig. 2(a), we used the femtosecond laser pulse from FEMTOPOWER which produces 28 fs pulse with pulse energy of 0.9 mJ at 3 kHz repetition rates. The fused silica wedges with a diameter of 20 mm and a thickness of 2 mm were used. The angle of wedge is 2 degrees. The reflectivity of the wedged surface is 33% to maximize the throughput. Since the intensity of the laser pulse is quite strong in our case, a focusing optics for SHG was not needed. The type-I BBO crystal of 200 $\mu$m thickness was used for generating the second harmonic light. The spectrometer was used for detecting the second harmonic signal without color filters. The spectrometer is actually more useful than the photodiode detector in finding time-zero delay because spectral interference helps to find the time-zero, so that the period of ripple on the spectrum is getting larger when the delay is getting close to zero. The autocorrelation trace can be obtained by monitoring the spectral power integrated over the second harmonic bandwidth while one of the wedges is being driven. For comparison, a conventional Michelson autocorrelator has also been setup as shown in Fig. 2(b). The measured autocorrelation traces are shown in Fig. 3. Assuming the Gaussian pulse shape, the full width at half maximum (FWHM) intensity of the pulse duration is measured to be about 29 fs by Michelson autocorrelator with 1 mm thick
beam splitter (Fig. 3(a)). The estimated pulse duration from double wedge autocorrelator is about 40 fs as shown in Fig. 3(b). This difference is due to the material dispersion introduced by the difference in the material thickness. By using the acousto-optic programmable dispersive filter (DAZZLER), the group delay dispersion (GDD) of $-245 \text{ fs}^2$ was introduced. After compensating GDD, the measurement was done again using the double wedge autocorrelator. The result is shown in Fig. 3(c), which is almost identical to Fig. 3(a), the autocorrelation trace using the autocorrelator based on Michelson interferometer.

Fig. 2. Optical layout for (a) double wedge autocorrelator (b) balanced autocorrelator using Michelson interferometer

Fig. 3. Autocorrelation traces by using (a) Michelson autocorrelator (b) double wedge (c) double wedge after GDD compensated ($-245 \text{ fs}^2$) (d) Spectrum of the input pulse
Since a wedge acts like a prism, an angular chirp can be induced while the beams are passing through wedges. In Fig. 4, the angle of the transmitted beam with respect to an incident beam is calculated for a wedge angle of 2 degrees. The slope of the curve indicates the angular chirp $C_\alpha$ due to the optical property of fused silica,

$$C_\alpha = \left[ \frac{\partial \varphi}{\partial \lambda} \right]_{\lambda_0}$$

where $\varphi$ is the propagation angle and $\lambda$ is the wavelength in the vacuum. The angular chirp is 2.4 $\mu$rad/nm at 800 nm. The maximum angular spread for the current bandwidth (100 nm) is about 0.25 mrad, which is smaller than far-field beam divergence. The presence of angular chirp can be interpreted as a pulse front tilt. But a standard autocorrelator cannot measure the pulse front tilt except for the case of the inverted-field autocorrelator [14]. Still the angular chirp can affect the autocorrelation result via a bandwidth narrowing for each propagation direction. In our case, the bandwidth narrowing is only about 0.1%, which is practically negligible. However, the angular chirp significantly extends pulse duration around a focal position when the laser beam is focused for the second harmonic generation [14]. Thus the double wedge autocorrelator may not be appropriate to a weak laser beam which requires focusing to generate the second harmonic beam. The angular dispersion is proportional to the wedge angle and can be minimized by decreasing the wedge angle. However, the angle between multiple reflections also decreases so that it requires a longer propagating distance to distinguish the test beams from the other stray lights.

![Fig. 4. (a) Wavelength dependence of propagation angle and angular chirp for a fused silica wedge pair ($\vartheta = 2^\circ$) (b) Pulse durations after propagating through a fused silica window of various thickness](image)

With respect to the measurement of a few-cycle laser pulse with an autocorrelator, one needs to consider the material dispersion introduced by propagating through an optical medium such as a beam splitter. In the double wedge autocorrelator, each beam passes 4 times through a wedge. To reduce or get rid of dispersion introduced by wedges, one can reduce the thickness of the wedge or place a proper chirped mirror to compensate the positive dispersion. If a thickness of a wedge is 0.5 mm, which is commercially available, the overall propagation length through materials is about 2 mm. According to Fig. 4(b), this double wedge autocorrelator can approximately measure the pulse duration down to 20 fs without significant pulse broadening ($< 10\%$). Thus, the double wedge autocorrelator can be properly used to measure a few-cycle pulse only with an aid of chirped mirrors, which eliminates a dispersion introduced by wedges. One may consider another variation of wedge autocorrelator, keeping the same concept of double wedge. The essence of the double wedge autocorrelator is not the wedge itself but the three interfaces with such an angled configuration. The problem of
material dispersion can be avoided by using three thin pellicles instead of wedges. In this case, the angular dispersion also disappears completely as well.

4. Conclusions

We have presented the scanning autocorrelator using a double wedge, and measured the pulse duration of 28 fs by using the double wedge with a tilt angle of 2 degree. The double wedge replaces the Michelson interferometer in the conventional autocorrelator, so it provides compact and simple configuration for an autocorrelator. The angular chirp introduce by the double wedge is 1.3 µrad/nm and it has practically no influence to the autocorrelation measurement for the non-focusing case. By using 0.5 mm thickness wedges, one can measure the pulse duration down to 20 fs without significant pulse broadening.

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