Using Pulse-Front Tilt to Measure Laser Pulses Less Than 100 Picoseconds in Duration

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We demonstrate a frequency-resolved optical grating (FROG) device for measuring the intensity and phase versus time of several-tens-of-picoseconds laser pulses, using a thick nonlinear optical crystal. The huge pulse-front tilt generated by a holographic grating increases the temporal range of the device, which can make a single-shot measurement of laser pulses less than 100 ps in duration. To verify the measurement technique, we generate double pulses using a Michelson interferometer. The measured duration of a single pulse is about 300 fs and the measured maximum delay of two pulses is 60 ps, which implies that the proposed FROG device can measure laser pulses with maximum pulse width of about 120 ps.

Keywords: Pico-Second Laser, Pulse Front Tilt, Single-Shot Measurement, Frequency Resolved Optical Grating
OCIS codes: (320.7100) Ultrafast measurements; (230.0040) Detectors

I. INTRODUCTION

Picosecond (ps) laser systems have been in great demand in many industries. Micromachining routinely uses ps laser pulses for a wide range of applications, such as optical communication and semiconductor processing, including TFT-LCD, PDP, and AMOLED [1-3]. Additionally, supercontinuum sources generated from ps laser systems are widely used for fluorescence imaging, broadband spectroscopy, and optical coherence tomography [4]. Like femtosecond (fs) laser pulses, ps laser pulses generate high peak power, which can minimize microcracks and the heat-affected zone in micromachining. Also, compared to fs laser systems, ps laser systems are much more economical, even though they offer similar industrial performance [5-7].

Generally, ps laser pulses have structures in both time and spectral domains, indicating that the pulses are not close to transform-limited pulses, which could adversely affect applications. Especially when generating supercontinuum radiation with ps pulses, the intensity and phase of the pulses is a critical factor in controlling output bandwidth and spectral shape of the super-continuum. To obtain optimized pulses from a laser system, it is necessary to measure the pulses and control the system's parameters [8]. Until now, however, an exact measurement method for ps laser pulses had not been developed, even though the temporal pulse profile or pulse distortion can affect micromachining

performance. A few research labs have the ability to measure these kinds of pulses using a traditional multishot scheme, which requires highly precise alignment of a long translation stage. One company, femtochrome, sells a device for measuring up to 100-ps pulses using the autocorrelation technique, but it only provides an approximate intensity, without any phase information about the pulses, which is more critical for manipulating the pulses in a ps laser system [9]. In addition, it is well known that the autocorrelation technique can generate many ambiguities if the pulses have structure [10]. As shown in Fig. 1, three different pulse intensities give the same autocorrelation result, which is close to a Gaussian intensity profile. Actually, many different intensities can have the same autocorrelation result, *i.e.* ambiguities exist. One might think that an oscilloscope could measure the intensity of the pulses, but even an oscilloscope of the largest bandwidth cannot reveal any of the details in the pulse. As a result, autocorrelation and other techniques are not suitable to measure ps laser systems.

Single-shot measurements of fs pulses are ordinarily achieved by splitting the beam in two and crossing these beamlets in a nonlinear crystal at an angle, which maps delay onto horizontal position. The frequency-resolved optical grating (FROG) method, however, cannot measure a pulse tens of ps long because the relative delay of the FROG is limited to a few ps. A well-known and simple method for measuring tens-of-ps-long pulses is the
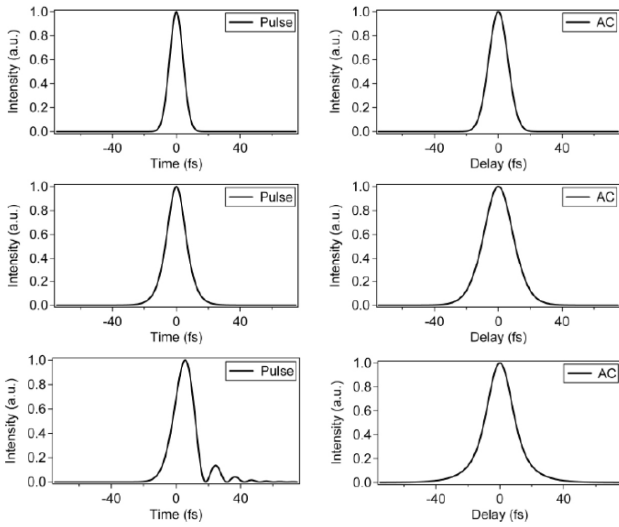
FIG. 1. Examples of theoretical pulse intensities and their intensity autocorrelations. Left: Intensities versus time. Right: The intensity autocorrelation corresponding to the pulse intensity to the left. Top row: A 10-fs Gaussian intensity. Middle row: A 7-fs sech2 intensity. Bottom row: A pulse whose intensity results from third-order spectral phase, a very common occurrence in ultrafast optics labs. Note that the autocorrelation loses the details of the pulse, and as a result all of these pulses have similar autocorrelations. [10]
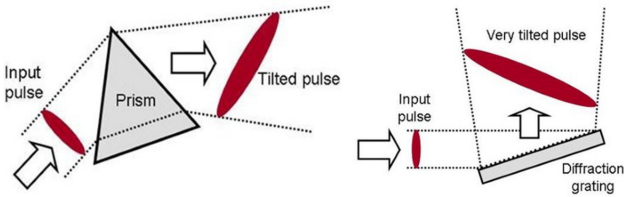

FIG. 2. A prism and a grating yield tilted pulses. While the mechanisms for generating tilt appear to be different in both cases, they are both due to dispersion. The maximum delay generated by a grating is approximately proportional to the size of the grating.

use of a pulse front tile (PFT) which is generated by dispersive elements such as prisms and gratings. Figure 2 shows that a prism and a grating yield tilted pulses. Wyatt *et al.* first generated significant PFT by using a diffraction grating and got single-shot autocorrelation results with a temporal range of up to 80 ps [11]. However, they measured just the intensity profiles of laser pulses, without any phase information. Bowlan *et al.* generated significant angular dispersion using etalons and got the results with temporal range from 175 ps to 3 ns [12]. However, a high-energy laser should be required to obtain the autocorrelation results, due to the intrinsic high loss of an etalon(over 10 μJ). Here we report an extension of the FROG technique to measure complete intensity and phase profiles of pulses up to 40 ps long, by using a holographic grating.

II. EXPERIMENTAL RESULTS AND DISCUSSION

Crossing two beams of oppositely tilted pulses, generated using a high-groove-density holographic grating, could yield a pulse in which one side precedes the other by many tens of ps, and overlapping them in a SHG crystal could generate single-shot autocorrelation of pulses tens of ps long. Using this principle, we can generate two diffracted beams with a large PFT using a grating with 1200 grooves/mm.

The maximum delay that can be generated by a grating is proportional to its size. We use a 1" × 1" grating for this experiment, which introduces the maximum delay by one beam of ~50 ps and total delay of ~100 ps. To generate the maximum delay, the angle of the incident beam to the grating should be around 90°. As shown in Fig. 3, the pulse to be measured is split in two by a beam splitter, and the two beams impinge upon a grating with a large angle (~80°). The diffracted beams with high PFT emerge almost normal to the grating's surface. These two beams with large PFT are imaged horizontally and focused vertically onto a 10.5-mm-thick $LiIO_3$ crystal using one cylindrical
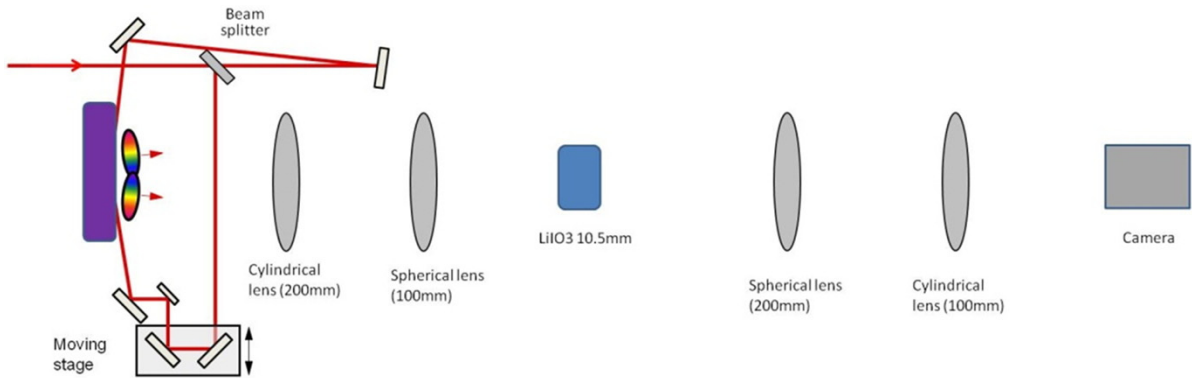

FIG. 3. Experimental setup of a FROG device for measuring the intensity and phase versus time, and spatiotemporal distortions of a several-tens-of-ps laser pulse.
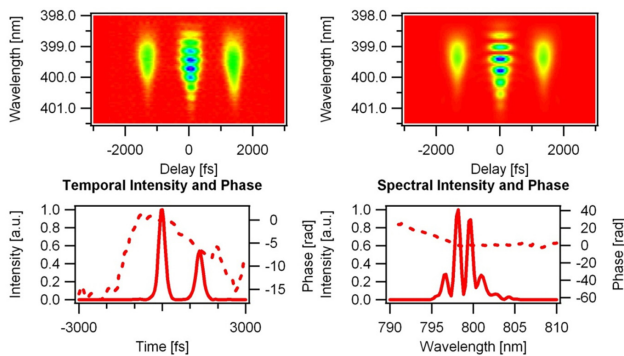
FIG. 4. Measured and retrieved traces of two pulses with delay of 1.5 ps. The thick crystal could resolve the fringes in the center of the trace. The FROG error is about 1.5% when we use a 256 × 256 matrix.

FIG. 5. Measured and retrieved traces of two pulses with delay of 60 ps. The FROG error is about 2.5%. The FROG results are not very good, but they show that the device has a temporal range of 120 ps.

lens of focal length 200 mm and one spherical lens of focal length 100 mm. This two-lens system images the beams onto the crystal horizontally, which is 2 to 1 imaging. In addition, the second lens can focus the beam in the crystal vertically as well. Once they overlap temporally and spatially in the crystal, the SHG signal is generated between the two beams. This SHG signal is sent to a two-lens system to obtain a spectrally resolved trace vertically and image it horizontally. As a result, we can get a spectrally resolved trace, what we call a FROG trace [10], on the camera.

To demonstrate device performance within a temporl range of several tens of ps, we used an 800-nm laser source with a pulse duration of 300 fs and pulse energy of 150 nJ. We built a Michelson interferometer and generated double pulses, because the laser's pulse was not long enough to test the capability of our device. Depending on the relative distance between the two arms of the interferometer, we can easily control the delay between the pulses.

Figure 4 shows the measured and retrieved traces of double pulses with pulse delay of 1.5 ps. Due to the interference of two pulses, the center part of the trace shows some fringes, which the spectral resolution was sufficient to resolve. The spectral resolution of the thick (10.5 mm) crystal could be about 0.2 nm, and the fringes in the center part of the measured trace disappear for pulses more than 4 ps long. However, the FROG algorithm nicely reproduced the fringes in the retrieved trace, and showed the fast fringes in the spectral domain. As a result, the device can measure a long pulse with some structure. This schematic is especially suitable for measuring stretched pulses of relatively large bandwidth.

Figure 5 shows the capability of our device. The delay between two pulses is about 60 ps, and the total delay the device can generate is about 120 ps. If we consider the tails and heads of the pulses, the device can measure pulses 40 ps long. The delay
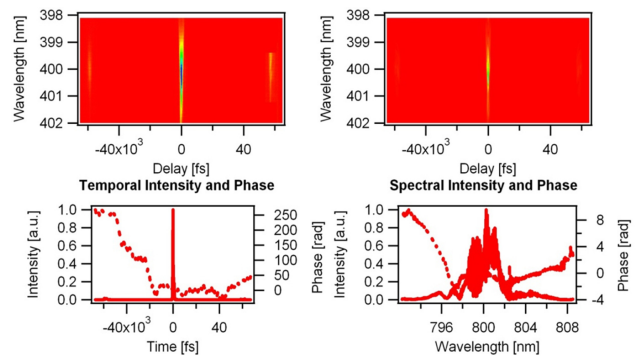
range is large, so we should use a 1024 × 1024 matrix to detect all of the trace. As mentioned, the spectral resolution can be improved by using a grating with a high groove density. Due to the satellite pulses generated by the Michelson interferometer, the trace suffers from a lot of noise, but if the pulses are from a laser systemthen this sort of noise should be absent from the trace. The intensity of the trace for the second pulse diminishes as the delay between pulses increases.

III. CONCLUSION

We demonstrate a single-shot measurement method for measuring laser pulses several tens of ps long, using a grating as the dispersive element. As when using other dispersive elements, we could generate PFT and a large delay, about 120 ps. Using this PFT we could measure double pulses from a Michelson interferometer. By controlling the distance between the two arms, we could generate various double pulses and measure them with our device. The device successfully measured them, and the FROG algorithm retrieved the measured traces. Because a grating is a dispersive element, like a prism or etalon, it is natural to think that the pulses might suffer some distortion; when measuring pulses with a large bandwidth, this could be the case.

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