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Accurate and automatic characterization of femtosecond optical pulses

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Abstract
We introduce a technique for the measurement of femtosecond optical pulses. This technique significantly reduces the uncertainty coming from the filter when used in the traditional technique, and an accurate spectral phase is retrieved. With the retrieved phase, the electric field, phase, waveform, as well as the duration of femtosecond optical pulses can be precisely reconstructed. The simulated autocorrelation traces deduced from the reconstructed pulsed electric field are in good agreement with the measured ones. This technique removes the manual procedure of selection and adjustment of the filter, an automatic measurement being realized.

(Some figures may appear in colour only in the online journal)

1. Introduction

An ultrashort optical pulse has an extremely short duration, an extremely broad spectral bandwidth and an extremely high peak power [1]; it has therefore been widely used in a variety of applications, such as ultrafast pumping and detection, time-resolved spectroscopy, optical telecommunications, ultra-fine microfabrication, non-linear optics and femtosecond chemistry. Femtosecond optical pulses have also brought revolutions in contemporary metrology [2], including time and frequency standards [3], terahertz metrology [4] and ultrafast electric pulse characterization [5]. Shape and width are key parameters of ultrashort optical pulses, because they directly affect experimental results obtained using them. Experimental data cannot be deemed credible unless the waveform and pulse width of the pulses are known. Accurate knowledge of the temporal shape of optical pulses is therefore crucial to scientific research.

In the past three decades, several measurement techniques for ultrashort optical pulses have been developed. Autocorrelation [6], frequency-resolved optical gating (FROG) [7] and spectral phase interferometry for direct electric-field reconstruction (SPIDER) [8] are the most commonly used. Autocorrelation is simple and convenient, but can give only the autocorrelation width, the waveform and phase being difficult to obtain. FROG is a two-dimensional measurement technique; pulse waveform and phase can be retrieved from the FROG trace, but an iterative procedure is needed. SPIDER can directly extract the spectral phase and reconstruct the pulse waveform; it is therefore suitable for accurate and fast measurement of ultrashort optical pulses, especially for femtosecond optical pulses. In this paper, we introduce a new spectral phase retrieval technique for accurate waveform reconstruction of femtosecond optical pulses.

2. Experiments and results

The spectrum of a pulse can easily be measured with a spectrometer. The pulse would be completely known if we could, in addition, determine the phase across the spectrum [9]. SPIDER is a technique for the measurement of spectral phase of femtosecond optical pulses. In the SPIDER setup, two replicas of the input pulse to be characterized are generated

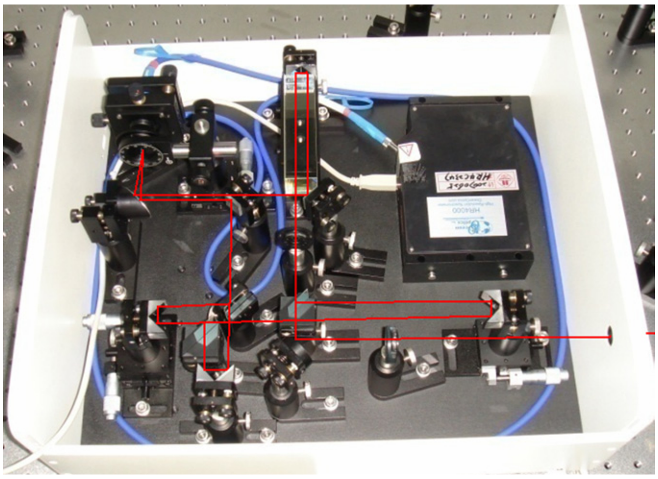

Figure 1. Our home-made SPIDER setup and the optical path.

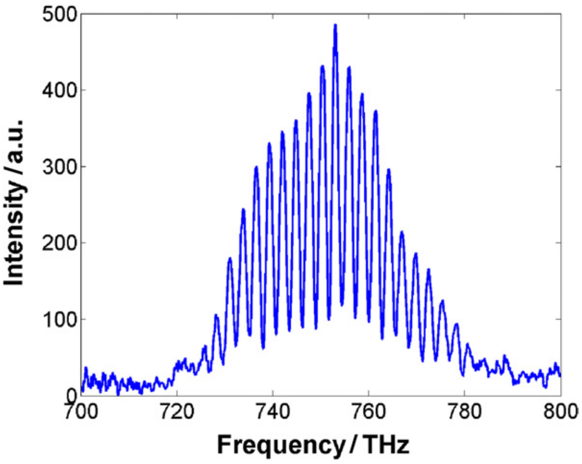

Figure 2. Measured spectral interferogram.

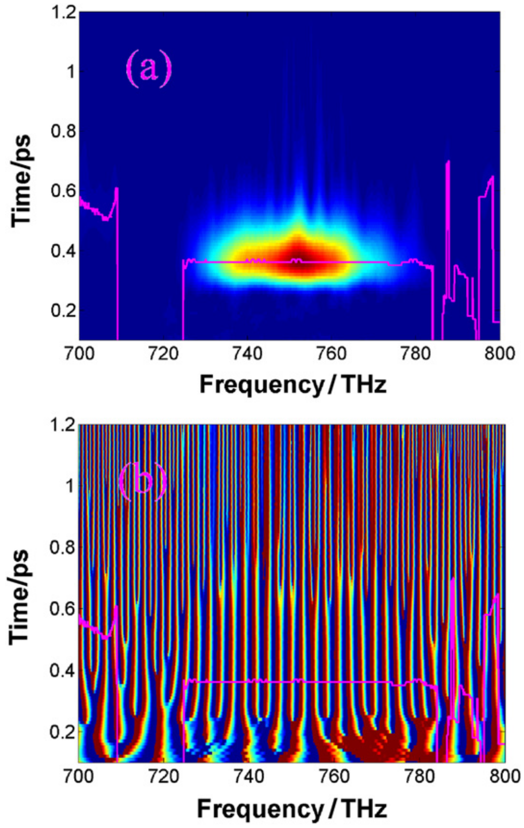

Figure 3. Wavelet transform of the spectral interferogram. (*a*) Intensity topography and (*b*) phase topography. The ridge of the wavelet transform is indicated with a pink coloured line.

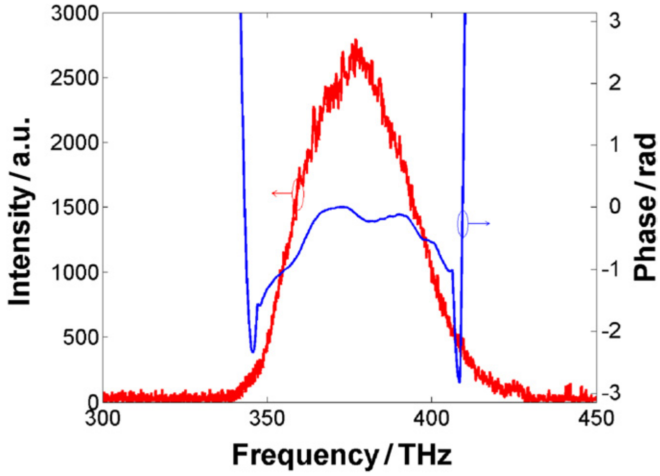

Figure 4. Measured spectrum and the retrieved spectral phase.

with a fixed time delay between them. These two replica pulses are then upconverted by sum-frequency mixing with a strongly chirped pulse derived from the same original input pulse. Because the two replica pulses are separated in the time domain, they interact with different parts of the chirped pulse and are therefore upconverted to different frequencies. From the interferogram of these spectral shearing pulses, it is possible to extract the amplitude and phase of the initial pulse using an algebraic inversion algorithm [2]. Our home-made SPIDER setup is shown in figure 1, with the optical path superposed.

In the traditional phase retrieval algorithm, phase is extracted from the filtered alternating-current component of the Fourier transform [8]. The filter is set by manual selection and adjustment, and different widths or shapes of filter windows produce different phases [10]. The uncertainty of the reconstructed pulses comes from the uncertainty of the spectral phase.

The novelty of our method is the introduction of a wavelet transform for spectral phase retrieval of femtosecond optical pulses [11]. The phase is directly extracted from the ridge of the wavelet transform. There is no filter in this procedure so that the uncertainty from the filter width or filter shape is eliminated. In what follows, a demonstration of the procedure of wavelet transform for spectral phase retrieval is shown.

We have measured ultrashort optical pulse trains emitted from a Ti : sapphire laser (Micra-5, Coherent Inc.). The average output power of the laser is 360 mW after a pulse compressor. The repeat frequency is 82 MHz, and the central wavelength is 800 nm with a spectral bandwidth (FWHM) of 100 nm. We perform a SPIDER measurement of the ultrashort

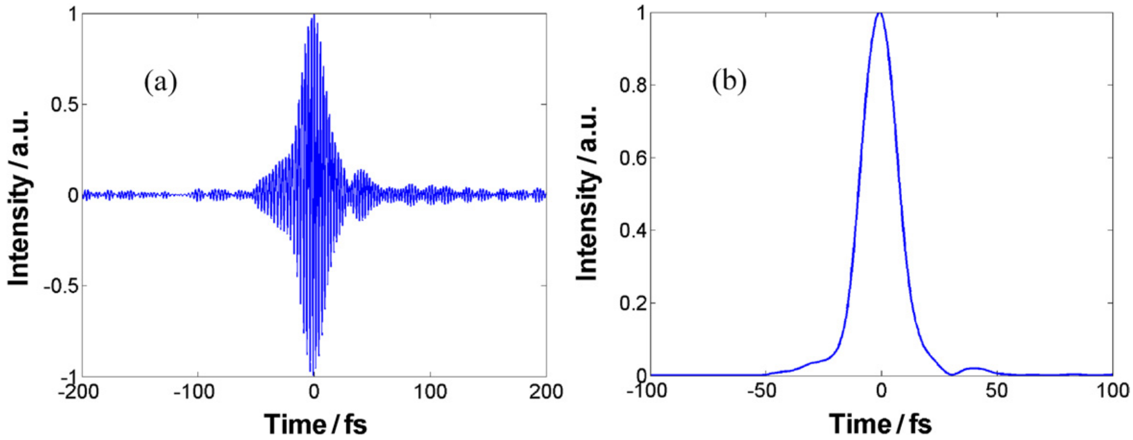

Figure 5. Reconstructed electric field and waveform. (*a*) Electric field and (*b*) waveform.

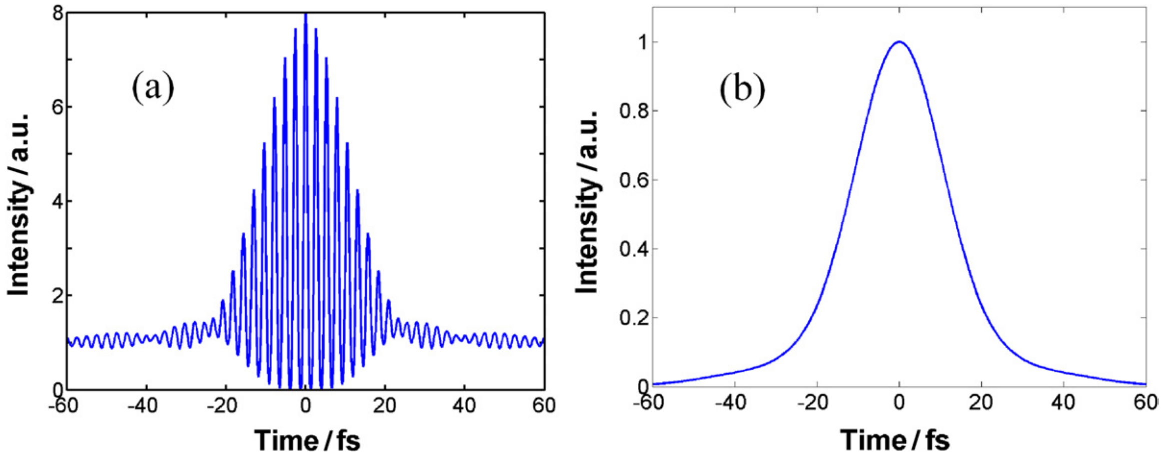

Figure 6. Simulated autocorrelation traces with reconstructed pulsed electric field. (*a*) Interferometric autocorrelation and (*b*) intensity autocorrelation.

optical pulses with our home-made SPIDER setup. The measured spectral interferogram is shown in figure 2.

A wavelet transform was applied on the measured spectral interferogram, and the time and frequency distributions are exhibited on a two-dimensional plane. The intensity map and the phase map are shown in figures 3(*a*) and (*b*), respectively.

We search for the maximum value from the intensity topography (figure 3(*a*)) along each frequency column. Connecting the positions of the maximum value at each frequency point constructs the ridge of the wavelet transform [12], which is superposed on figure 3(*a*) with a pink coloured line. Then we project the position of the ridge from intensity topography (figure 3(*a*)) on the phase topography, as is shown in figure 3(*b*). The phase of the spectral interferogram was directly extracted from the phase topography at the position of the ridge. With the extracted interferometry phase, the spectral phase was obtained with a concatenation algorithm [8], as is shown in figure 4.

Figure 4 also shows the spectrum measured with a spectrometer (HR4000 CG-UV-NIR, Ocean Optics Inc.). The electric field and waveform of the femtosecond optical pulse were reconstructed from the spectrum and the spectral phase with an inverse Fourier transform technique, which are shown in figures 5(*a*) and (*b*), respectively. The pulse width (FWHM) is about 18.2 fs.

3. Results verification

To test the reliability of the reconstructed waveform of the femtosecond optical pulses, we simulated the autocorrelation traces with the reconstructed pulses and compared them with the measured ones. The simulated interferometric autocorrelation and intensity autocorrelation with the reconstructed electric field in figure 5(*a*) are shown in figures 6(*a*) and (*b*), respectively.

We have made an autocorrelator for experimental autocorrelation measurement based on a Michelson interferometer. A precise translation stage (M405-DG, Physik Instrument GmbH) is used as the optical delay line and the detected autocorrelation signal is fed into a lock-in amplifier (M405-DG, Physik Instrument GmbH) to improve the signal-to-noise ratio (SNR). By tuning the scanning speed of the translation stage and the time constant of the lock-in amplifier, both interferometric autocorrelations and intensity autocorrelations are obtained. The measured interferometric autocorrelation and intensity autocorrelation traces are shown in figures 7(*a*) and (*b*), respectively.

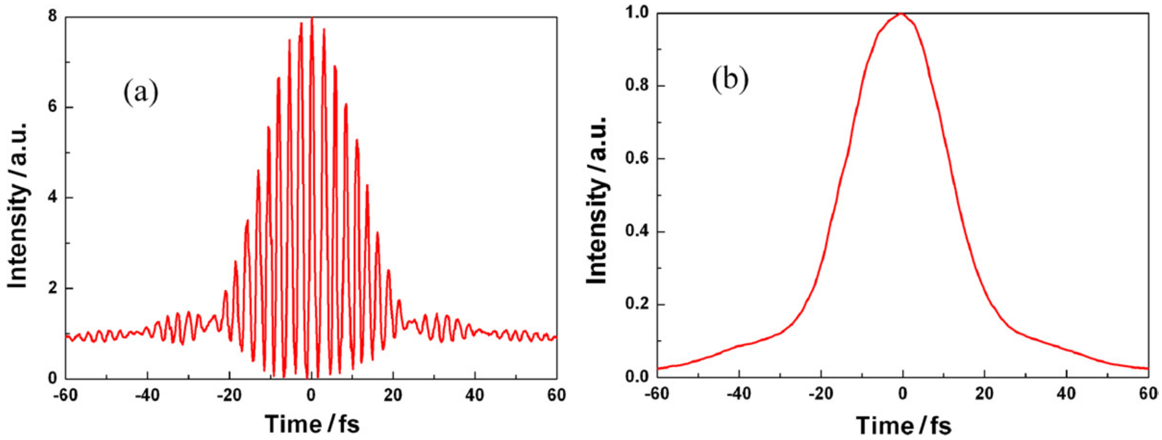

Figure 7. Measured autocorrelation traces. (*a*) Interferomatric autocorrelation and (*b*) intensity autocorrelation.

By comparison with figure 7, the simulated autocorrelation in figure 6 is in excellent agreement with the measured ones. This demonstrates the accuracy of the retrieved phase and the reconstructed pulse.

4. Conclusions

We have introduced a technique, wavelet transforms, for spectral phase retrieval of femtosecond optical pulses. This technique needs no filter; therefore, automatic phase retrieval and pulse reconstruction are realized because no manual operation of selection and adjustment filter is required. The wavelet transform directly extracted the spectral phase of the spectral interferogram from the ridge; the uncertainty coming from the filter with traditional Fourier transform is therefore removed. A demonstration of an 18 fs optical pulse phase retrieval and pulse reconstruction shows that the simulated autocorrelation traces generated from the reconstructed pulse agree excellently with the measured ones. This technique is useful for the accurate measurement of the waveform, pulse width, electric field, peak power and instantaneous power of femtosecond optical pulses. It can play an important role in the measurement and control of ultrashort optical pulses, and reduce the uncertainty budget in terahertz frequency metrology, ultrafast electric pulse metrology, non-linear optics metrology and femtosecond chemistry metrology.

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