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Amplitude and Phase Characterization of 5.0 fs Optical Pulses Using Spectral Phase Interferometry for Direct Electric-Field Reconstruction

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The amplitude and phase of 5.0 fs optical pulses with an ultrabroad bandwidth from 480 to 835 nm were rapidly characterized by the spectral phase interferometry for direct electric-field reconstruction (SPIDER) technique. To our knowledge, this is the shortest pulse ever measured by the SPIDER technique. To solve the problems of dispersion, bandwidth, sensitivity and wavelength resolution, which are essential for few-optical-cycle pulse characterization, we developed a SPIDER apparatus equipped with ultrabroad-band (450–850 nm) beam splitters, a thin (25 μm) β-BaB_2O_4 crystal, a 0.5 m spectrometer capable of the automatic and fast control of two gratings (1200 and 150 lines/mm) and a highly sensitive intensified charge-coupled device.

KEYWORDS: ultrashort optical-pulse characterization, 5.0 fs pulse measurement, temporal intensity and phase profiles, few-optical-cycle pulses

In recent years, significant advances have been made in the development of ultrashort optical pulse generation and measurement.[1–6] For the characterization of few-optical-cycle pulses, the conventional technique of interferometric intensity-autocorrelation (IAC) measurement is not sufficient because of its requirement of the pulse shape and phase assumption, the systematic underestimation of small subpulses owing to the squared signal in the pulse intensity, and the difficulty in estimation of the asymmetric pulse shape caused by the strongly modulated ultrabroad-band spectrum. To overcome these problems, the second-harmonic generation frequency-resolved optical gating (SH-FROG) technique, the spectral phase interferometry for direct electric-field reconstruction (SPIDER) technique[6] and others[7] have been developed, which enable us to determine the temporal profile and phase of pulses. Among these, the SPIDER technique has several advantages as follows: it can eliminate the necessity for moving components, achieve the noniterative reconstruction algorithm and the fast measurement time and use a thicker nonlinear crystal, which gives the high intensity signal as a result of the type-II phase matching for the sum-frequency generation (SFG) between the spectrally ultrabroad-band pulse and the quasi-CW field. More importantly, for the shorter pulse characterization, this technique has the measurement capability of monocycle-like pulses with ultrabroad spectra exceeding the one-octave bandwidth. This is due to the utilization of the sum-frequency light with the quasi-CW field as a signal, the insensitivity of the frequency dependences of the detection system and the phase-mismatching spectral-filter effect of the nonlinear crystal owing to the measurement being based on the spectral interferometry (SI), and the lack of a time-smearing effect as a result of the noncollinear SFG with the quasi-CW field. Nevertheless, the shortest pulse measured to date by the SPIDER technique with a 30 μm β-BaB_2O_4 (BBO) crystal and a less-sensitive spectrometer+charge-coupled device (CCD) has been the 5.9 fs, red to near-infrared, asymmetric pulse with many relatively large subpulses after many accumulations of the direct laser-oscillator output.[6] As the pulse duration becomes shorter and the spectral modulation becomes stronger, the pulse characterization by the SPIDER technique rapidly becomes more difficult because of the dispersion effect and the bandwidth limitation of the optics in the Michelson-interferometric arm, the weak sum-frequency interferometric signal resulting from the marked intensity decrease of the strongly chirped reference beam, and the wavelength-resolution limitation of the broad-band spectrometer.

In this Letter, we report the characterization of 5.0 fs pulses with the ultrabroad-band spectrum from 480 to 835 nm using a SPIDER technique, where specially-designed ultrabroad-band beam splitters from 450 to 850 nm for the s-polarization in the Michelson-interferometric arm, a BBO crystal of 25 μm thickness, and a highly sensitive spectrometer+intensified-CCD with a high resolution wavelength of 0.15 nm and the automatic and fast angle-control function of the two gratings of 1200 and 150 lines/mm are employed.

Ultrashort pulses ($\sim$10 μJ/pulse) to be characterized are generated from an optical pulse compressor of amplified Ti:sapphire laser pulses (1 kHz repetition rate) based on capillary-fiber self-phase modulation and spatial-light-modulator (SLM) chirp compensation.[3,8,9] This system can generate 4.1 fs transform-limited pulses under IAC measurement and 5.0 fs pulses under SH-FROG measurement.[9] Our SPIDER apparatus is shown in Fig. 1. After the rotation to the s-polarization by the silver-coated periscope, the input pulse E is divided into two equal-intensity beams by an ultrabroad-band dielectric beam splitter, BS1, ranging from 450 to 850 nm. The beam splitter BS1 has 50 $\pm$ 3% reflectivity for the input pulse spectrum from 480 to 835 nm with the single-stacking coating on a 0.5 mm fused-silica glass. One beam is reflected by a silver-coated retro-mirror for the adjustment of the time delay between the two beams and is sent to the Michelson-interferometric arm to make two-pulse replicas, E_1 and E_2, with the delay of τ. The value

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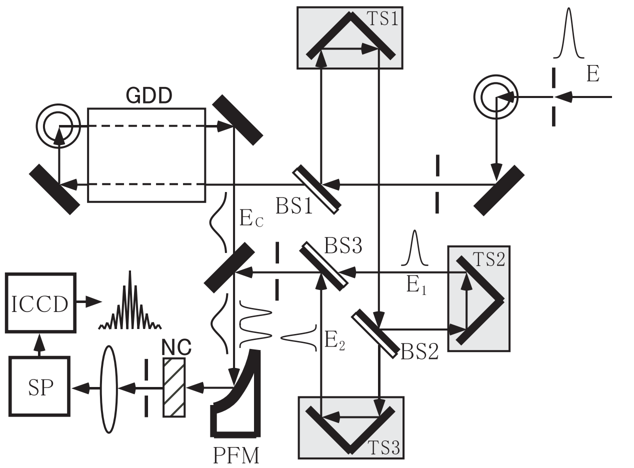

Fig. 1. SPIDER setup: BS1-BS3, beam splitters (450–1300 nm); GDD, TF5 glass block; TS1, translation stage for adjustment of temporal overlap of the short pulse pair with the stretched pulse; TS2, TS3, translation stage for adjustment of delay; PFM, aluminum 50 mm focussing parabolic mirror; NC, nonlinear crystal (25-μm-thick type-II BBO); SP, spectrometer; ICCD, intensified charge-coupled device.

of τ is selected to be 857 fs based on the Nyquist sampling theorem and the numerical simulation result of the optimum $\tau \cong (1/\Delta\omega)(N_s/N_t)$ in ref. 10 (N_s is the pixel number corresponding to the FWHM bandwidth $\Delta\omega \cong 133$ THz of the pulse spectrum and N_t is the pixel number per interference fringe of the SPIDER signal). The interferometer with balanced reflectivity and dispersion uses two 500-μm-thick dielectric beam splitters, BS2 and BS3, possessing the same reflection-transmission property as that of BS1. Another beam is double-transmitted through a 10-cm-thick TF5 dispersive glass, GDD (group delay dispersion: 4.6×10^4 fs^2), being rotated to the p-polarization by a periscope during the pass, to produce the strongly chirped pulse E_c for up conversion with the quasi-CW field. The two replica pulses, E_1 and E_2, are combined and mixed noncollinearly with the chirped pulse E_c by focusing on a 25-μm-thick type-II BBO crystal[6)] using a 50 mm focal-length aluminum parabolic mirror (the calculation showed that the 25 μm BBO generates the sum-frequency wave over the spectral range of 480 to 835 nm of the fundamental pulse E_1 or E_2). As a result, the SPIDER signal of the interferometric sum-frequency beam, $E_1E_c + E_2E_c$, is generated with a spectral shear of $\Omega = 2.81$ THz, satisfying the Whittaker-Shannon sampling theorem.[10)] After the removal of these fundamental spectral pulses E_1, E_2 and E_c by a 0.5 mm slit, the spectral interferogram signal $E_1E_c + E_2E_c$ is focused on a multimode fiber-coupling spectrometer of 0.5 m (Acton Research Co., Spectro Pro-500i) by a 22 cm focallength silica lens, and is detected by a 1024×256-pixel UV-enhanced intensified-CCD array that allows rapid data acquisition. An incident slit of 150 μm and a 1200 lines/mm grating result in the total wavelength resolution of 0.15 nm at 400 nm and the limited bandwidth of 37.5 nm. Therefore, the full bandwidth of the signal is recorded automatically by the synthesis of seven spectral parts of different center wavelengths at updated times of $7 \times 2.5\,\text{s} = 17.5\,\text{s}$ with the calibration in wavelength and sensitivity, as shown in Fig. 2. This measurement time is much shorter than that of the SH-FROG technique, being typically five minutes.[9)]

As additional data, we measure the two sum-frequency spectra of E_1E_c and E_2E_c in the main spectral region (Fig. 3(a)) in order to determine the value of the spectral shear Ω, and the interferometric second-harmonic spectrum of $(E_1 + E_2)^2$ in the main spectral region (Fig. 3(b)) by the 45° rotation of the BBO crystal in order to determine the value of the delay time τ. We confirmed the clear similarity between the former two spectra after smoothing. The modulation depth of the latter spectrum is sufficient to determine the accurate value of τ. Also, the input spectrum of E (Fig. 3(c)) is measured using the 150 lines/mm grating which is rapidly exchanged and controlled automatically in the same detection system.

All the data recorded are analyzed by SPIDER software in which, for the extraction of the essential +ac part[11)] after the inverse-Fourier-transformation of the SPIDER signal, the dc and −ac parts in the quasi-time τ' region shorter than $\tau' = 190$ fs ($\approx\Omega^{-1}$) are eliminated.

The reconstructed temporal intensity $I(t)$ and phase profiles $\phi(t)$ and the corresponding spectral intensity $\tilde{I}(\lambda)$ and phase $\tilde{\phi}(\lambda)$ are plotted in Figs. 4(a) and 4(b), respectively. This result indicates that a 5.0 fs pulse with the constant phase in the main pulse part is measured. The corresponding 4.4 fs

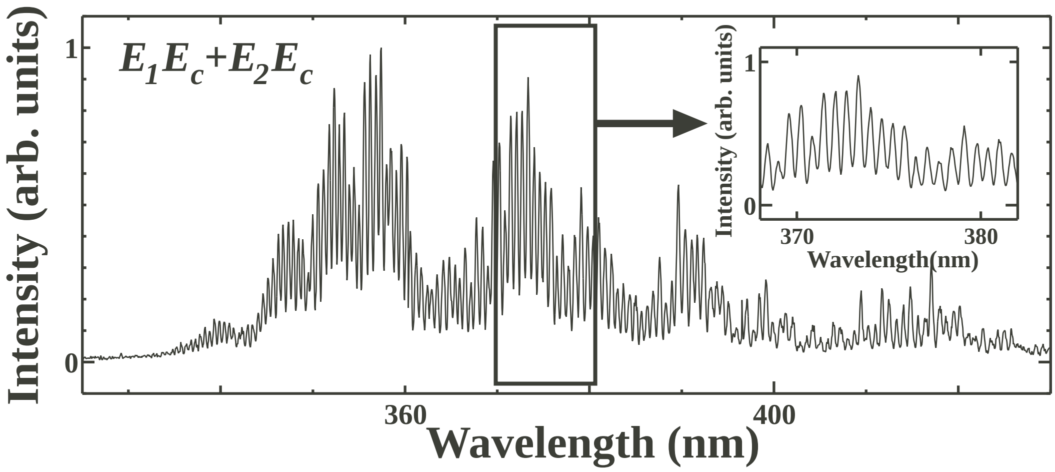

Fig. 2. Measured SPIDER interferogram signal.

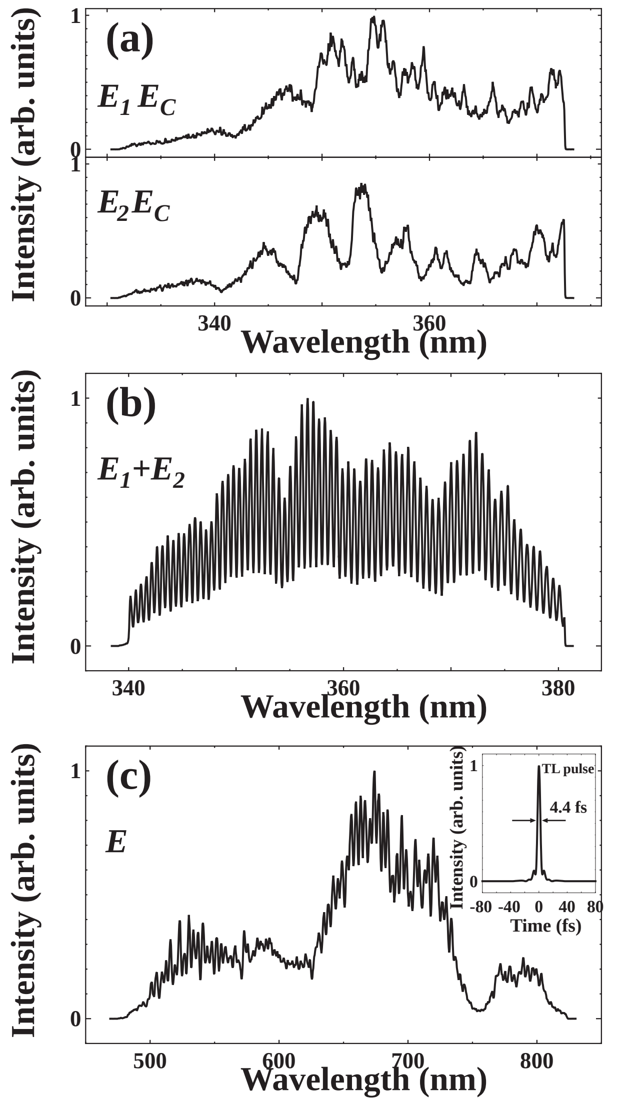

Fig. 3. (a) Two measured sum-frequency spectra, E_1E_c and E_2E_c. (b) Measured interferometric second-harmonic spectrum $(E_1+E_2)^2$. (c) Measured spectrum of the input pulse E, and the 4.4 fs transform-limited pulse (inset).

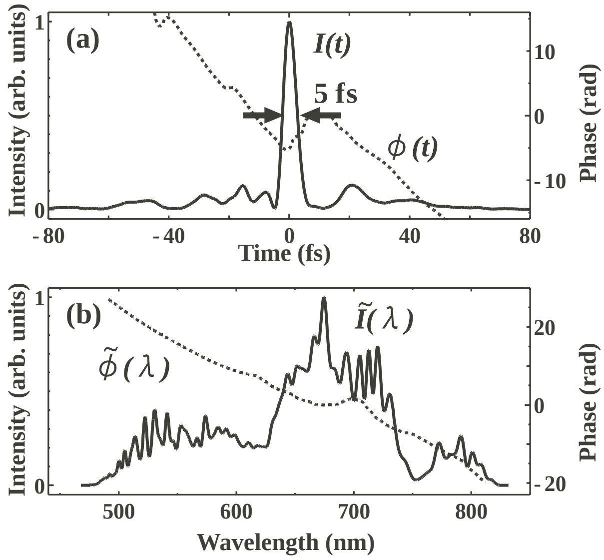

Fig. 4. (a) Retrieved pulse intensity (solid curve) and phase (dashed curve) in the time domain. (b) Retrieved spectrum (solid curve) and spectral phase (dashed curve).

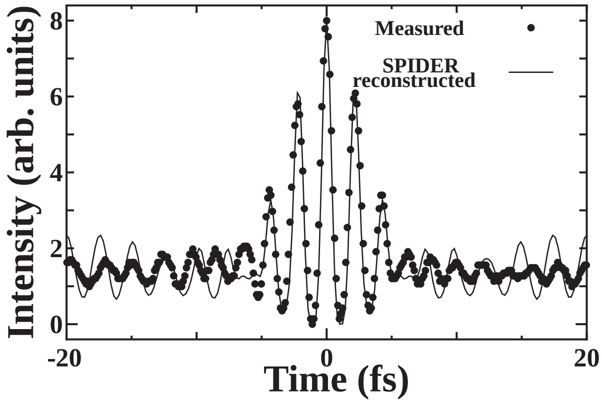

Fig. 5. Comparison of the measured interferometric autocorrelation (IAC) trace (dots) with the SPIDER-reconstructed IAC trace (solid curve).

transform-limited pulse obtained from the fundamental spectrum of E is also shown, in the inset of Fig. 3(c). The spectrum $\tilde{I}(\lambda)$ of Fig. 4(b) obtained from the 256-point analysis for the horizontal axis agrees well with the measured spectrum of Fig. 3(c) after being smoothed to reduce the number of points from 1024 to 256. As an independent check of the accuracy of this result, we simultaneously measure the IAC trace of the pulse and compare it with that calculated from the SPIDER reconstructed pulse, as shown in Fig. 5. The agreement is good, indicating an FWHM of 5.0 fs. However, the pedestal parts are slightly different. This may be explained by the slight difference in dispersion optics between the IAC and SPIDER apparatuses and the insensitivity to the low intensity of subpulses in the case of the IAC measurement.

In conclusion, we have demonstrated experimentally that the SPIDER technique enables us to rapidly characterize the 5.0 fs temporal intensity and phase profiles with the ultrabroad-band spectrum from 480 to 835 nm, in comparison with the SH-FROG technique.[9] To our knowledge, this is the shortest pulse ever measured using the SPIDER technique. We are currently applying this newly developed SPIDER apparatus for the characterization of shorter pulses generated from pulse compression based on SLM chirp compensation of the induced-phase modulation spectrum[12–14] and of microstructure fiber outputs.[15,16]

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