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Sensitivity improvement of spectral phase interferometry for direct electric-field reconstruction for the characterization of low-intensity femtosecond pulses

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ABSTRACT A modified-SPIDER (spectral phase interferometry for direct electric-field reconstruction) technique where external powerful optical pulses are employed as a light source of chirped reference pulses for sum-frequency generation is proposed and is demonstrated experimentally. It provides great improvements in sensitivity and signal-to-noise ratio, and will enable a single-shot measurement for a weak pulse, such as 1 nJ/THz-bandwidth. The technique demonstrates high accuracy for determining the delay-time, t, for weak pulse characterization, which greatly affects the group-delay dispersion of the reconstructed spectral phase.

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1 Introduction

In recent years, significant advances have been made in the measurement [1–5] as well as the generation of ultrashort optical pulses [6–8]. That is, it has been demonstrated that frequency-resolved optical gating (FROG) [1, 2, 7, 8] and spectral phase interferometry for direct electric-field reconstruction (SPIDER) [3–5] techniques are greatly useful for the characterization of the temporal intensity and phase profiles for few-optical-cycle pulses. Particularly, the latter has several advantages over the former as follows: a) the measurement capability of mono-cycle pulses with the ultrabroad bandwidth exceeding one octave, and b) the fast measurement time due to no moving components and non-iterative reconstruction algorithms. This fast measurement is useful for feedback control that is combined with chirp compensation using a spatial light modulator [8, 10, 11]. Furthermore, SPIDER technique, which is based on the spectral interferometry, has the capability of the single-shot measurement. This is unlike the standard FROG measurement as a function of the delay-time which is an average measurement of repetitive pulses, for example. This single-shot measurement is essential for the characterization of few-cycle [9] or mono-cycle pulses because for such pulses the carrier-envelope the phase becomes significant. That is, few-cycle or mono-cycle pulses with the same duration but the different carrier-envelope phase interact differently with matter.

The SPIDER technique so far, however, has the disadvantage of low sensitivity, especially for the characterization of ultrashort, ultra-broadband pulses. This is due to the drastic decrease in peak intensity of the strongly-chirped reference pulse, which wastes most of energy of the pulse to be measured on itself. For a single-shot SPIDER measurement, this insensitivity is a serious problem. The characterization of a weak pulse is also important for external pulse compression of the self-phase modulated and induced-phase modulated output from conventional glass fibers [12] or microstructure fibers [13, 14], the characterization of the optical nonlinear response from absorbing materials, the characterization of higher-order nonlinear optical processes, and the study of ultrafast optical communication.

In order to overcome such a disadvantage, we propose a modified-SPIDER technique in this paper. Instead of a chirped reference pulse split directly from the pulse to be characterized, as a chirped, high intensity pulse, we employ a powerful fundamental seed pulse directly from a regenerative amplifier. According to this idea, we demonstrate the experimental characterization of femtosecond weak pulses propagated through a single-mode, fused-silica fiber and evaluate the sensitivity and the signal-to-noise ratio of the modified-SPIDER apparatus compared with the conventional one.

2 Experimental

Figure 1 illustrates the modified-SPIDER apparatus. It has two optical input parts; the one is for the pulses (test pulse i; $i = 1-3$) to be measured, and the other the intense light source to generate the chirped pulse.

All the employed mirrors, the periscopes PSi, the corner reflectors ORi, and the delay stage (DSi) were aluminum-coated, except for a flip mirror FM1. The beam splitters BSi are broadband dielectric multilayer mirrors. The test pulse i was reflected by the silver-coated flip mirror FM1 and was input into a Michelson interferometer to make two-pulse replicas E_1 and E_2. The mirror FM1 is used as a switch from the conventional-SPIDER mode to the modified-SPIDER one.

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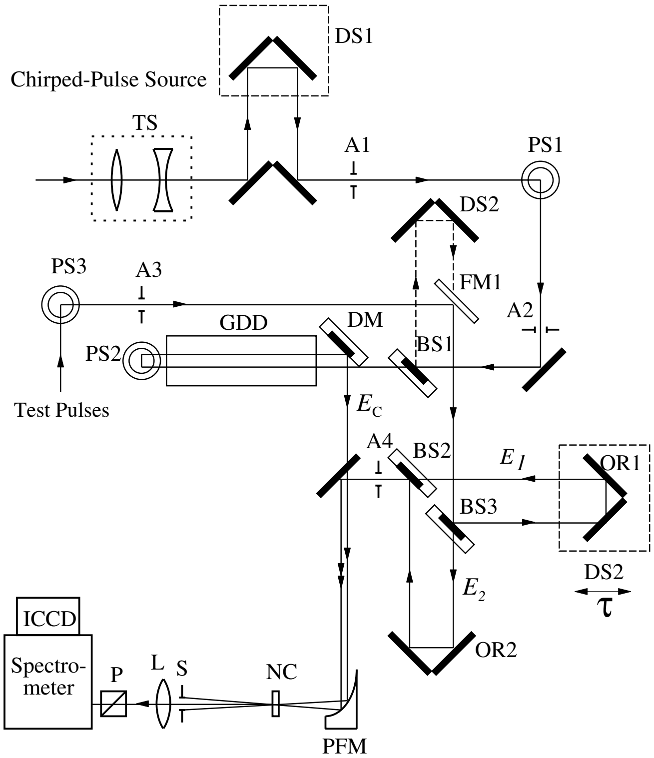

FIGURE 1 Setup of the highly-sensitive modified-SPIDER apparatus. An external intense optical pulse is employed as a light source of a chirped pulse which is used for the sum-frequency generation with the pulse to be measured. TS, telescope; DS*i*, delay stages; A*i*, aperture; PS*i*, periscopes; BS*i*, beam splitters; GDD, TF5 glass, 10-cm long, group-delay dispersion medium; DM, dichroic mirror; FM1, flipper mirror; OR*i*, corner reflectors; PFM, off-axial parabolic mirror; NC, nonlinear crystal; S, slit; L, lens; P, polarizer

When the mirror FM1 is flipped out, this apparatus becomes the conventional-SPIDER mode. The powerful seed pulse (a dashed line) reflected by a fused-silica beam splitter BS1 (96% transmission with an anti-reflection coating) was sent to the Michelson-interferometer to produce two replicas. In addition, this powerful, reflected pulse is conveniently used for an optical guide of the weak test pulse in the modified-SPIDER mode and for the calibration of the delay-time τ between two replicas. After the powerful, transmitted seed pulse passed through a highly dispersive glass TF5 (10-cm in length), its linear polarization was changed to the p-polarization by a periscope PS2 and the pulse passed again through the dispersive glass (round-trip group-delay dispersion of $3.46 \times 10^4\,\text{fs}^2$ at 800 nm). Thus, a strongly chirped pulse with a 3.7-ps duration was generated. The chirped pulse and two replicas were focussed onto a β-barium-borate (BBO) crystal NC (type II phase-matching; 50-μm in thickness) by an off-axial parabolic mirror PFM (5-cm focal length) to produce the SPIDER signal of the interferometric sum-frequency wave. After passing through a slit S, a focusing lens L and a polarizer P, the signal spectra were measured by a 1200-groove/mm spectrometer (SpectraPro-500i) with a 1024-pixel, intensified CCD camera (PI-MAX, Roper Scientific), where the spectral resolution is 0.2 nm. This system enables us to easily compare the sensitivity between the modified-SPIDER technique and the conventional one under the same optical components without realignment.

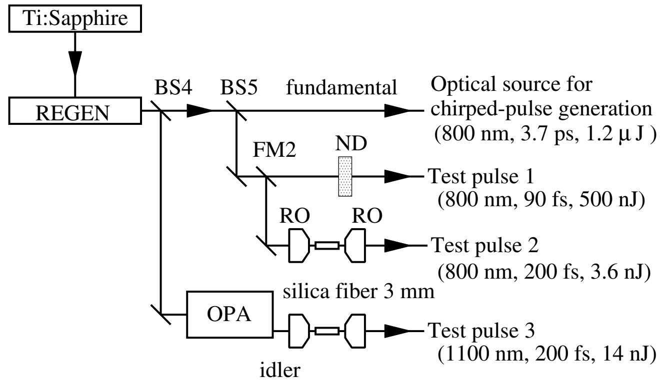

FIGURE 2 Experimental setup of the optical sources both for the chirped pulse and for the test pulses to be evaluated by the modified-SPIDER. The intensity of test pulse 1 was controlled by neutral density filters. The test pulse 2 centered at 800 nm, $\Delta f = 20$ THz (of the test pulse 3 at 1100 nm, $\Delta f = 50$ THz) was output from a 3-mm-long single-mode optical fiber, where the pulse was spectrally broadened by the self-phase modulation

The experimental setup concerning the optical sources is shown in Fig. 2. A few percents of the 80-fs, 800-nm, 600-μJ optical pulses from a Ti:sapphire regenerative amplifier (REGEN) operating at a 1-kHz repetition rate passed through BS4 to be used for the test pulses 1, 2 and for the reference pulse (1.2 μJ before NC in the apparatus). For generating the test pulses, one third of the pulse energy was split at BS5. The pulse which is guided by beam splitters BS4 and BS5 was reduced to appropriate pulse energy by neutral density filters ND and was used as a test pulse (test pulse 1). To demonstrate the characterization of the weak pulse propagating through a glass fiber, we used a single-mode, fused-silica, 3-mm long, 2.7-μm core diameter fiber (Newport, F-SPV). To focus the input pulse into the fiber and to collimate its output, we used a pair of non-dispersive reflective objectives ($\times$ 36) coated with gold (in) and silver (out), respectively. Test pulse 2 was the self-phase modulated output from the fiber (3.6 nJ) when the fundamental pulse was injected. Most of the energy of the amplified pulse from REGEN was also used for excitation of the optical parametric amplifier (OPA) system to shift the center wavelength of the pulses (idler pulse). We abbreviate the self-phase modulated output from the fiber (centered at 1100 nm, 14 nJ) as the test pulse 3 when the idler pulse was injected.

All the pulses were originated from a common light source (REGEN). Therefore, the carrier-phase differences among them were locked [15]

3 Results and Discussion

3.1 *Sensitivity comparison*

Figure 3 shows the SPIDER signal intensity as a function of energy of the input pulse to be characterized for modified (open circles) and conventional (open squares) techniques. The plotted relative intensity of the signal was evaluated from the intensity of the positive AC($+\tau$) component of the inverse Fourier transform of the observed interferometric SPIDER signal, which corresponds to the amplitude of the oscillating interferometric part. In the case of the modified-SPIDER technique, the energy of input test pulse 1 (90 fs, 800 nm) was varied while the energy of the 90-fs, 800-nm

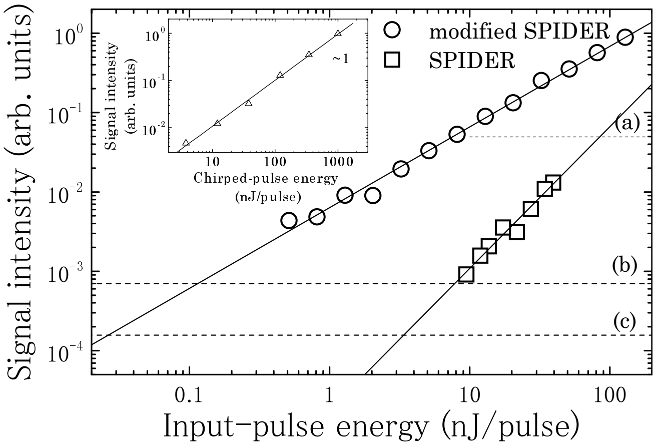

FIGURE 3 SPIDER signal intensities of the conventional SPIDER and the modified SPIDER as a function of the pulse energy to be measured. *Inset* shows the signal intensity as a function of chirped-pulse energy

chirped reference pulse (1.2 μJ) was maintained. In the case of the conventional technique, the energy of the 90-fs, 800-nm input pulse had been varied before the energy of the input pulse was split. The energy for the chirped reference pulse is 96 percents of the incident energy at BS4. From Fig. 3 we find that the intensity for the modified-SPIDER mode indicates a linear function of input energy, while the intensity for the conventional mode indicates a quadratic dependence. This result suggests that the modified-SPIDER technique has a great advantage for the characterization of the weak intensity pulse. In Fig. 3 we also plot three broken lines (a), (b), and (c) that represent the experimental noise levels for (a) a single-shot case, (b) a 5000-pulse-accumulation case (corresponding to the five-second measurement time), and (c) a 100 000-pulse-accumulation measurement. The sensitivity of the modified-SPIDER technique is hundred times higher than that of the conventional one. For a single-shot measurement, the modified one is ten times higher and has 1 nJ/THz-bandwidth.

The signal intensity $D(\omega+\omega_c)$ for both conventional- and modified-SPIDER techniques is written as [3]

$$D(\omega+\omega_c) \propto |\chi^{(2)} E_c(\omega_c) E_{unk}(\omega) \times \chi^{(2)} E_c(\omega_c+\Omega) E_{unk}(\omega)| \times \cos[\phi(\omega+\omega_c+\Omega) - \phi(\omega+\omega_c) + \tau \times (\omega+\omega_c)],$$

where $E_{unk}(\omega)$ and $\phi(\omega)$ are the spectral amplitude and phase of the input-pulse electric field to be characterized at an angular frequency of ω, respectively, $E_c(\omega_c)$ is the spectral amplitude of the electric field of the chirped reference pulse at an angular frequency of ω_c, Ω is the spectral shear and $\chi^{(2)}$ is the second-order susceptibility of the BBO crystal. The quadratic dependence of the sensitivity for the conventional-SPIDER technique results from the fourth-order dependence of the $D(\omega+\omega_c)$ on all electric fields E_i ($i = c$ and unk). For the modified-SPIDER technique we employed the external E_c as the chirped pulse independent of the test pulse. Thus, the signal was proportional to the square of the electric field E_{unk} of the test pulse, that is, the linear dependence of the test pulse intensity. The equation also suggests that the linear dependence of the signal to the intensity of the chirped pulse, which is chosen to be much more powerful, compared with that of the conventional-SPIDER technique. The inset of Fig. 3 shows the signal intensity of the modified SPIDER measured as a function of energy of the chirped reference pulse for a fixed test pulse energy of 100 nJ. This linear dependence indicates the good agreement with the prediction mentioned above.

All the analyses of the electric-field reconstruction for test pulse 1 were carried out using the measured $\Omega/2\pi = 3.87$ THz and $\tau = 746$ fs in the same manner as ref. [5]. It was confirmed that the reconstructed temporal-intensity profile with the 90-fs duration agrees with the results of the independent measurement of the autocorrelation trace under the assumption of a sech^2 shape.

3.2 *Weak pulse characterization*

For the demonstration of the high sensitivity of the modified-SPIDER technique, we characterized the weak pulse propagated through a glass fiber for two different-color pulses (test pulse 2 and test pulse 3), as shown in Figs. 4 and 5. Figure 4A is the experimental results of the modified-SPIDER signal (solid curve), and the sum-frequency-wave spectra of the replica 1 and 2 (dotted curves) for the 800-nm, 3.6-nJ, self-phase-modulated pulse, where the signal was accumulated for 100 000 pulses. They were measured with an excellent signal-to-noise ratio. Figure 4B is the corresponding spectral inten-

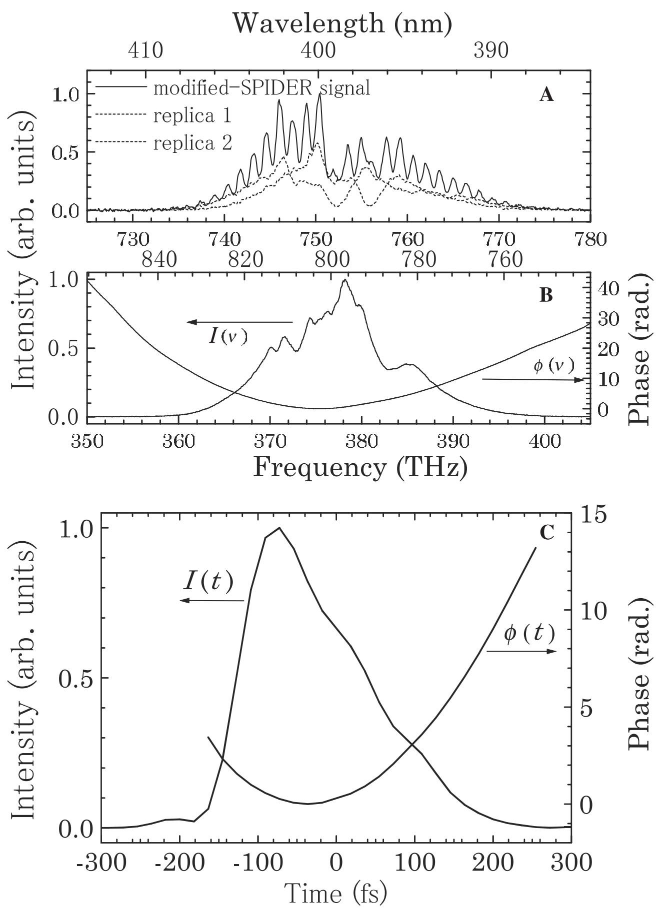

FIGURE 4 **A** Measured SPIDER signal and replica spectra of the test pulse 2, where $\Omega/2\pi = 3.62$ THz, $\tau = 746$ fs), and **B** spectral phase and intensity. (center wavelength 800 nm, pulse energy 3.6 nJ). **C** Reconstructed temporal intensity profile and phase

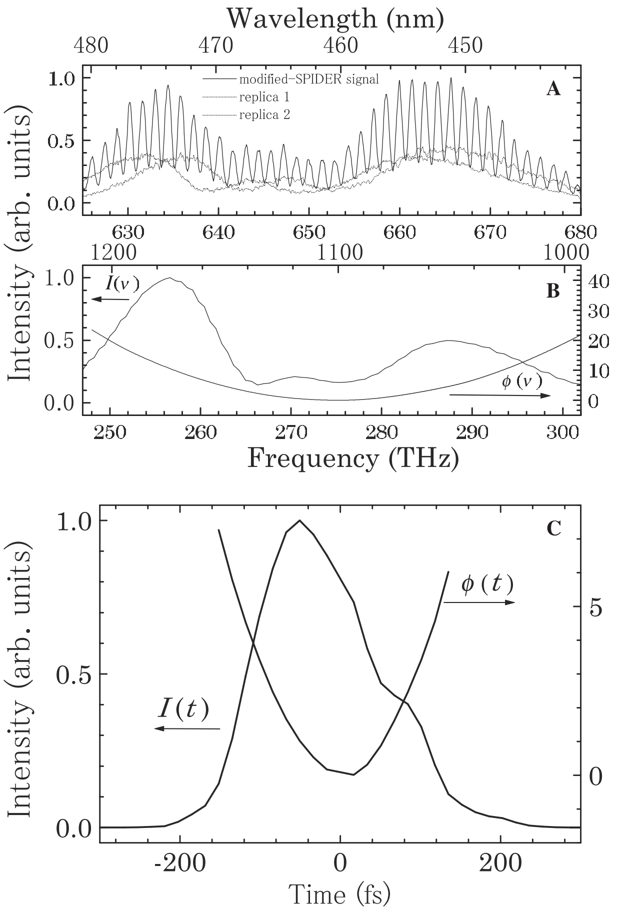

FIGURE 5 **A** Measured SPIDER signal and replica spectra of the test pulse 3, where $\Omega/2\pi = 4.14$ THz, $\tau = 746$ fs), and **B** spectral phase and intensity. (center wavelength 1100 nm, pulse energy 14 nJ). **C** Reconstructed temporal intensity profile and phase

sity and phase, and C the temporal intensity and phase, which were retrieved using the measured $\Omega/2\pi = 3.62$ THz and $\tau = 746$ fs. Similarly, Fig. 5 A shows the experimental results, B the retrieved spectral intensity and phase, and C the temporal intensity and phase for the 1100-nm, 14-nJ, self-phase-modulated pulse ($\Omega/2\pi = 4.14$ THz and $\tau = 746$ fs), respectively. Available maximum energy (1.2 μJ) of the chirped pulse was only limited by a technical problem at present, that is, under the present experimental setup we wasted most of energy to excite the OPA system mentioned above. As a result, when we use a more powerful chirped pulse, a weaker pulse can be characterized.

In addition to the high sensitivity, the modified-SPIDER technique has another advantage in signal-to-noise ratio, that is, the great reduction of the background light. In both conventional- and modified-SPIDER techniques, the main origin of the background light is due to the second harmonic generation at the nonlinear crystal and its scattering at surface. For the modified-SPIDER technique unlike the conventional one, we can shift the frequency region of the SPIDER signal to the arbitrary frequency region to avoid the background by the independent choice of an appropriate chirped-pulse frequency ω_c.

The further merits of the modified-SPIDER are the possibility of expansion of target pulses, especially for strongly- and complicatedly-chirped pulses. The conventional-SPIDER technique is poor in retrieving such pulses because the spectral shear Ω is not well-defined for those pulses. The strongly-chirped pulse has a wide temporal width, which dims the corresponding temporal frequency of the chirped reference pulse. To circumvent this situation, the spectrally-resolved, modified-SPIDER technique is promising. A chirped pulse selected independently of the test pulse greatly simplifies the characterization of the pulse in the entire spectral region.

Finally, we would like to point out a practical merit of the modified-SPIDER technique concerning the accurate and easy determination of the delay-time τ between two replicas, as we mentioned in the experimental section. In the SPIDER algorithm, the accuracy of the group-delay dispersion of the retrieved pulse depends on that of the delay-time. For a weak pulse, however, the accuracy of the delay-time can hardly be guaranteed in the conventional SPIDER technique. In the modified-SPIDER technique, a high intensity, well-behaved pulse is available for the determination of the delay-time instead of the fragile, weak one.

All the advantages of the modified-SPIDER technique, highly sensitive, high-signal-to-noise ratio, etc. will enable us the single-shot characterization of a weak pulse with an ultra-broad band.

4 Conclusion

A new modified-SPIDER technique, where the external powerful optical pulse was used for the sum-frequency generation, was proposed and demonstrated experimentally. It was shown that it provides great improvements in sensitivity, on the basis that the developed apparatus has a hundred-times greater sensitivity for a 100 000-pulse-accumulation measurement in comparison with the conventional-SPIDER apparatus. It will enable us a single-shot measurement for a weak pulse, such as 1 nJ/THz-bandwidth. Our apparatus also demonstrated that the phase of the 3.6-nJ, 200-fs self-phase-modulated pulse from a single-mode, fused-silica fiber is easily reconstructed. In addition, the novel technique has the other advantage in the signal-to-noise ratio because the modified-SPIDER signal can be shifted to the arbitrary frequency region to avoid the strong background second-harmonic wave. The technique also measured the delay-time τ highly accurately. This delay-time greatly affects the group-delay dispersion of the reconstructed spectral phase. The developed technique is very useful for the characterization of weak pulses such as the externally compressed pulse using a glass fiber, the pulse characterizing the optical nonlinear response from absorbing materials, and the pulse based on high-order nonlinear optical processes.

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