Ultrasensitive direct-field retrieval of femtosecond pulses by modified interferometric field autocorrelation

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We report on spectral phase retrieval of 50 MHz, 374 fs optical pulses at 1560 nm with 28 aJ coupled pulse energy by measuring two modified interferometric field autocorrelation traces using a 5-cm-long periodically poled lithium niobate waveguide. The corresponding sensitivity is 1.1×10^{-7} mW^2, improving on the previous record by about 20 times. The same data traces can also be used to retrieve the power spectrum, given that the ratio of powers at two specific wavelengths is known. © 2009 Optical Society of America

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Diagnosis and control of the spectral phase of ultrafast optical signals plays a pivotal role in coherently controlled nonlinear spectroscopy [1], pulse formation from externally modulated cw laser combs [2], and signal monitoring in coherent telecommunications. Linear measurement techniques based on electro-optical intensity [3] or phase [4] modulation have been used to characterize picosecond pulses in the telecommunication band with high sensitivity. However, they need additional rf electronics and demanding synchronization between the optical pulse and rf modulation, limiting the applications in measuring femtosecond pulses at other wavelengths. In terms of self-referenced schemes with femtosecond resolution, nonlinear optical effects are widely used to provide ultrafast temporal gating or spectral shearing. For instance, spectral phase interferometry for direct electric field reconstruction (SPIDER) [5], and frequency-resolved optical gating (FROG) [6] have been demonstrated to measure spectral phase or complex field. These existing techniques typically utilize thin nonlinear crystals to phase match the broad nonlinear polarization spectrum in the upconversion processes, which compromise the measurement sensitivity. Thick nonlinear crystals have also been used for ultrashort pulse measurements. In GRENOUILLE [7], different second-harmonic frequency components can be phase matched at different output angles by tightly focusing the beam into a thick crystal. However, the requirements of noncollinear geometry and spatially dispersed output beam prohibit the use of highly efficient waveguide devices in this scheme. The primary advantage of LX-SPIDER [8] lies in the elimination of the highly chirped pulse used in achieving spectral shearing and is applicable only for a particular combination of the crystal's dispersion and length, and the wavelength under investigation. To the best of our knowledge, the existing sensitivity record on self-referenced complete pulse measurement is about 2×10^{-6} mW^2, achieved by using an aperiodically poled lithium niobate (A-PPLN) waveguide with a 59-mm-long quasi-phase-matching (QPM) grating in second-harmonic generation (SHG) FROG [9,10]. The high sensitivity arises from (1) strong optical confinement over a long interaction distance in the waveguide and (2) the fact that the linearly chirped QPM period can broaden the phase-matching (PM) bandwidth without substantially sacrificing the SHG yield.

We have proposed and demonstrated a modified interferometric field autocorrelation (MIFA) method for spectral phase recovery using a thick nonlinear crystal with extremely narrow (δ-like) PM spectrum in a typical intensity autocorrelator [11]. Here we utilize a PPLN waveguide with a 49-mm-long QPM grating in an MIFA measurement and achieve a sensitivity of 1.1×10^{-7} mW^2, about 20 times better than the previous record. The further enhancement of measurement sensitivity over that in [10] is attributed to (1) elimination of loss due to frequency-resolving optics, (2) employment of a sensitive point detector (photomultiplier tube, compared with an intensified CCD camera) and lock-in detection, and (3) maximized SHG yield of short pulse when using a δ-like PM spectrum aligned with the nonlinear polarization spectral peak [12]. Better sensitivity can be anticipated if a longer QPM grating or longer lock-in time constant is used in the MIFA measurement. Moreover, our fiber-based system is alignment free, does not need the custom A-PPLN waveguide, and allows for fast refresh rates owing to the noniterative data-inversion process.

Assume the pulse has a complex temporal envelope $a(t)$ and a carrier frequency f_0. As explained in [11], processing a single MIFA trace measured by using a thick crystal with central PM frequency of $2f_0$ gives a complex even spectral function,

$$A_{e1}(f)=A(f)A(-f)=P_{e1}(f)\exp[j2\psi_{e1}(f)], \qquad (1)$$

where $A(f)=F\{a(t)\}=|A(f)|\exp[j\psi(f)]$ stands for the

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spectral envelope of the pulse and $P_{e1}(f)=|A(f)A(-f)|$, $\psi_{e1}(f)=[\psi(f)+\psi(-f)]/2$ are the even spectral intensity and phase, respectively. A second MIFA trace due to a shifted central PM frequency of $2(f_0-\Delta)$ leads to another spectral function,

$$A_{e2}(f)=A(f)A(-f-2\Delta)=P_{e2}(f)\exp[j2\psi_{e2}(f)], \quad (2)$$

where $P_{e2}(f)=|A_{e2}(f)|$ and $\psi_{e2}(f)=[\psi(f)+\psi(-f-2\Delta)]/2$ contain all spectral components symmetric with respect to the frequency of $f_0-\Delta$. A recursive relation has been derived to combine Eqs. (1) and (2) to reconstruct the complete (second-order and higher) spectral phase $\psi(f)$ of the pulse:

$$\psi(f-2\Delta)-\psi(f)=2[\psi_{e2}(f-2\Delta)-\psi_{e1}(f)]. \quad (3)$$

Here we propose another recursive relation to retrieve the power spectrum using the two even spectral intensity functions P_{e1}, P_{e2} [normalized to $P_{e1}(0)=P_{e2}(-\Delta)=1$] and a constant $\alpha=|A(0)/A(-\Delta)|^2$ (i.e., the ratio of powers at frequencies of f_0 and $f_0-\Delta$),

$$|A(f-2\Delta)/A(f)|^2=[\alpha P_{e2}(f-2\Delta)/P_{e1}(f)]^2. \quad (4)$$

Since α is typically measured by an optical spectrum analyzer (OSA), the usefulness of Eq. (4) lies mainly in the inherent consistency check of the experimental data traces. Good agreement between the power spectra measured by the OSA and retrieved by Eq. (4) could confirm the data integrity. Note that the experimentally measured MIFA trace cannot determine the absolute amplitude and phase of $A_{ei}(f)$ $(i=1,2)$, thus leaving the relative amplitude between P_{e1}, P_{e2} and the relative phase between ψ_{e1}, ψ_{e2} ambiguous. As a result, the insertion of constant α in Eq. (4) becomes essential to uniquely determine the power spectral shape. In contrast, the ambiguity of ψ_{ei} causes only the zeroth-order and first-order components of $\psi(f)$ to be undetermined, which is irrelevant to the temporal pulse shape.

Figure 1 shows the fiber-based experimental setup for our ultrasensitive MIFA measurement. The signal pulse at 1560 nm comes from a passively mode-locked Er-doped fiber laser and is combined with the cw reference at 1480 nm using a wavelength division multiplexer (W1). The pulse and the reference are sent into a collinear Michelson interferometer, where an electrically controlled delay line (VariDelay II, General Photonics) is used to scan the optical delay at a speed of 1 ps/s. The interfered cw reference goes to an InGaAs photodetector by way of another wavelength division multiplexer (W2), producing a trace

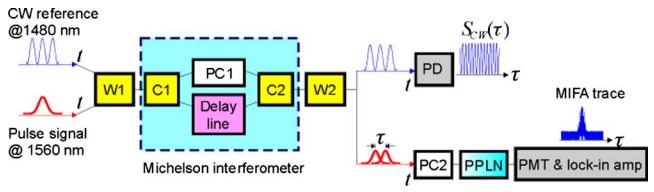

Fig. 1. (Color online) Experimental setup of the MIFA measurement. W#, WDM; C#, 3 dB coupler; PC#, polarization controller; PD, InGaAs photodetector; PMT, photomultiplier tube.

$S_{cw}(\tau)$ used for fringe correction. The signal pulse pair is coupled into a fiber-pigtailed PPLN waveguide [13] with a 49-mm-long QPM grating for SHG. The PM tuning curve of the PPLN waveguide has a sinc^2 shape with an FWHM of 0.24 nm (much smaller than the 10 nm pulse bandwidth), and the peak wavelengths are set at 1559.86 nm and 1560.34 nm (PPLN temperature at 46°C and 50°C) when acquiring the two MIFA traces, respectively. The average second-harmonic power at each delay is detected by a PMT (R636-10, Hamamatsu) and lock-in amplifier. The lock-in time constant is set at 640 μs (limited by the scanning speed of the delay line and the required delay resolution), corresponding to a delay resolution of 0.64 fs (better than the Nyquist criterion of $1/4f_0$ =1.3 fs). It takes only 10 s to acquire one MIFA trace with a 10 ps delay window.

Figure 2(a) illustrates the retrieved spectral phase profiles of a nearly bandwidth-limited pulse at average powers (coupled into the waveguide) of 1.5 nW (dashed–dotted) and 2.6 μW (dotted), respectively. Fitting the phase profile over a frequency range of $\approx$1 THz gives rise to quadratic and cubic coefficients of $c_2=0.065$ ps^2 ($c_2=0.061$ ps^2), $c_3=0.29$ ps^3 ($c_3=0.36$ ps^3) for a coupled power of 1.5 nW (2.6 μW), where the spectral phase is defined as $\psi(f)=c_2f^2+c_3f^3$. Even with a 32 dB input power difference (64 dB difference in SHG power), the retrieved spectral phase profiles agree well with each other. Figure 2(b) shows the evaluated temporal intensity of the pulse based on the retrieved spectral phase and the power spectrum measured by the OSA. The 1.5 nW average power is equivalent to 75 μW peak power, 28 aJ pulse energy, corresponding to an unprecedented sensitivity of 1.1×10^{-7} mW^2.

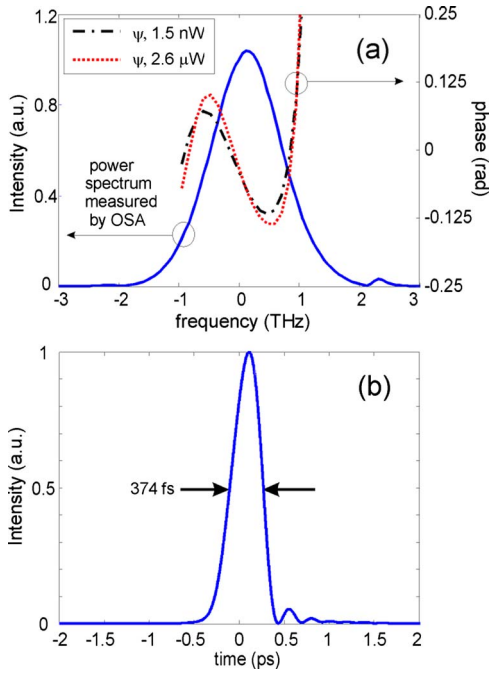

Fig. 2. (Color online) (a) Retrieved spectral phase profiles for input average powers of 1.5 nW (dashed–dotted) and of 2.6 μW (dashed). (b) Retrieved temporal intensity profile.

To further verify the measurement capability, we inserted a 5.15-m-long single-mode fiber (SMF) into the link to increase the quadratic spectral phase and performed the MIFA measurement at two different average input powers (12 nW and 2.88 μW) to retrieve the spectral phase as well as the power spectrum. For simplicity, Fig. 3 shows only the phase difference ($\Delta\psi$) due to the dispersion of the SMF. At an input power of 2.88 μW (dotted), the retrieved quadratic and cubic spectral phase coefficients of the pulses before and after the passage of the SMF are $c_2=0.47$ ps^2, $c_3=0.35$ ps^3, and $c_2=2.79$ ps^2, $c_3=0.36$ ps^3, respectively. The quadratic phase coefficients differ by 2.32 ps^2, close to the prediction of the SMF specifications ($c_2=2.36$ ps^2 at 1560 nm). The cubic phase coefficients are almost identical, since SMF is known to predominantly add quadratic phase. At an input power of 12 nW (dashed–dotted), we measured $c_2=0.18$ ps^2, $c_3=0.23$ ps^3, and $c_2=2.59$ ps^2, $c_3=0.22$ ps^3 for the pulses before and after passing through the SMF, respectively. The difference in quadratic phase coefficient, 2.41 ps^2, is again close to the expected value. By measuring the relative spectral intensity of the pulse at wavelengths of 1559.86 nm and 1560.34 nm ($\alpha=1.023$) and using the same MIFA traces, we can retrieve the power spectrum through Eq. (4). As shown in Fig. 3, the retrieved power spectrum (dashed) is in good agreement with that measured by the OSA (solid). The bump around $f=-2.5$ THz and the missing fine structure around $f=+2.2$ THz are primarily due to the recursive reconstruction error when the value of $P_{ei}(f)$ is low and dominated by the measurement noise.

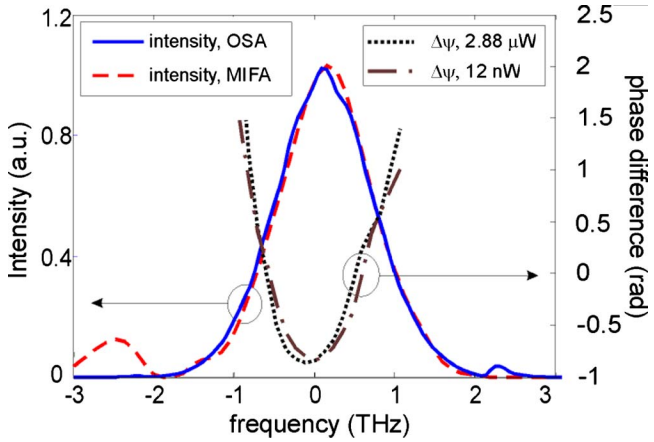

Fig. 3. (Color online) Spectral phase difference due to 5.15-m-long SMF retrieved at average input powers of 2.88 μW (dotted) and 12 nW (dashed–dotted). Spectral intensity measured by OSA (solid) and MIFA method (dashed).

In conclusion, we have demonstrated that the MIFA method in combination with a long PPLN waveguide can retrieve the spectral phase of ultraweak ultrashort pulses noniteratively. The achieved sensitivity is 1.1×10^{-7} mW^2, improving on the previous record by about 20 times. Such a high sensitivity can be realized without the need for the custom aperiodically poled waveguide devices used in the high-sensitivity FROG experiments of [9,10]. Even higher sensitivities can be achieved if longer PPLN waveguides (>5 cm) or longer lock-in time constants (>640 μs) are used. Our measurement setup requires only a standard collinear Michelson interferometer and point detectors, thus sparing the expense of a spectrometer and detector array.

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