40-photon-per-pulse spectral phase retrieval by shaper-assisted modified interferometric field autocorrelation

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Abstract: We report on spectral phase retrieval of 400 fs pulses using shaper-assisted modified interferometric field autocorrelation. The coupled energy is only 5.2 aJ per pulse, corresponding to an unprecedented sensitivity of $2.7\times10^{-9}\text{mW}^2$.

OCIS codes: (320.7100) Ultrafast measurements; (320.7110) Ultrafast nonlinear optics; (130.3730) Lithium niobate

1. Introduction

Characterization of ultrashort optical pulses is essential in coherent control, generation of attosecond pulses and ultra-broadband RF signals [1], and a variety of techniques have been established for this purpose [2]. Designed for producing arbitrary optical waveforms, pulse shaper [3] has been integrated into the diagnostic setup since very recently. For example, multiphoton intrapulse interference phase scan (MIIPS) uses a shaper to introduce different spectral phases on the input pulse and acquires the resulting second-harmonic (SH) power spectra [4]. The operation is quite straightforward, but it may take an iterative measurement and compensation process to retrieve the higher-order spectral phase terms accurately. Pulse shaper has also been used to replace the conventional Michelson interferometer (MI) to realize four wave mixing autocorrelation [5], FROG [6], and SPIDER [7], respectively. These shaper-assisted schemes permit a compact setup, and are immune to fluctuation of delay step size. The capability of carrier envelope phase (CEP) control of a pulse shaper, however, has not been exploited to improve the performance of pulse measurement. We report on an unprecedented pulse measurement sensitivity of $2.7\times10^{-9}\text{mW}^2$ by shaper-assisted modified interferometric field autocorrelation (MIFA) method [8, 9], where CEP control largely reduces the equivalent carrier frequency and enables a much longer integration time. We also show that the uncertainty of our scheme in quadratic spectral phase measurement is only equivalent to 3.9-cm-long single mode fiber.

2. Experiment

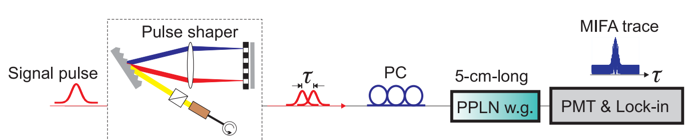

Fig. 1. Experimental setup. PMT: Photomultiplier Tube; PC: Polarization controller.

Fig. 1 shows the setup of shaper-assisted MIFA. The signal pulse train (50 MHz, 400 fs, 1560 nm) coming from a passively mode-locked Er-doped fiber laser was sent into a home-made reflective pulse shaper with 31 GHz spectral resolution and 10 nm spectral window. Detailed shaper setup is described in [10]. The pulse replicas with variable delay τ and desired CEP were generated via a spatial light modulator (CRI, SLM-640-D-NM), delivering a transfer function of [6]:

$$M(f) = [1+e^{-i(f-\gamma\times f_0)\tau}]/2, \tag{1}$$

where γ represents the carrier frequency reduction factor ($\gamma = 0.038$ in our experiments). The signal pulse pair was coupled into a 5-cm-long fiber-pigtailed periodically poled $LiNbO_3$ (PPLN) waveguide for second-harmonic generation (SHG). The PM tuning curve of the PPLN waveguide has a sinc^2-shape with an FWHM of $\approx$ 0.24 nm (50 GHz), and the peak wavelengths were set to 1560.2 nm (45 °C) and 1561.2 nm (51.5 °C) when acquiring the two MIFA traces, respectively. The average SH power at each delay is detected by a photomultiplier tube and a lock-in amplifier.

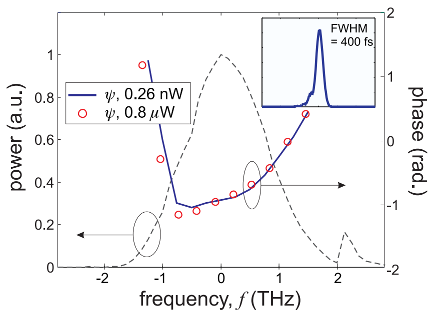

Fig. 2. Power spectrum measured by OSA (dash). The spectral phase profiles retrieved by MIFA at input average power of 0.26 nW (open circles) and 0.8 μW (solid), respectively. The inset shows the retrieved temporal intensity profile.

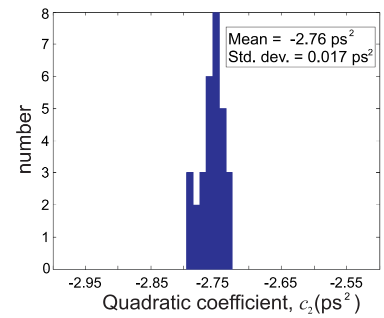

Fig. 3. The histogram shows the retrieved quadratic coefficients of the 30 independent measurements

Fig. 2 illustrates the retrieved spectral phase profiles at coupled average powers of 0.26 nW (open circles) and 0.8 μW (solid), respectively. Fitting the phase profile $\psi(f)$ measured at low (high) input power over a frequency range of $\approx$ 1 THz gives rise to quadratic and cubic coefficients of c_2= 1.12 ps^2 (c_2= 1.12 ps^2), c_3= -0.49 ps^3 (c_3= -0.48 ps^3), where $\psi(f) \equiv c_2 f^2 + c_3 f^3$. The 0.26 nW average power is equivalent to 10 μW peak power, 5.2 aJ pulse energy, and 40 photons per pulse. These numbers correspond to an unprecedented sensitivity (the product of peak power and average power of minimum detectable signal) of 2.7×10^{-9}mW^2, improving on the previous records of FROG [11] and MI-based MIFA [9] by 1,000 and 40 times, respectively. The improvement of sensitivity mainly comes from the longer lock-in time-constant (50 ms, vs. 0.64 ms in [9]), which is made possible by the reduced equivalent carrier frequency ($0.038 f_0$) due to the shaper-assisted CEP control. The high stability of the current experimental configuration was verified by measuring the quadratic spectral phase at 15 nW average power for 30 times (lasting about 150 minutes). As shown in Fig. 3, the standard deviation is only 0.017 ps^2, equals to the dispersion of 3.9-cm-long single mode fiber.

3. Conclusion

We have demonstrated that the shaper-assisted MIFA method using long PPLN waveguides can retrieve the spectral phase of ultraweak ultrashort pulse with extremely high accuracy and stability. The achieved sensitivity is 2.7×10^{-9}mW^2, improving on the previous record by a factor of 41. This work is supported by the National Science Council of Taiwan under grant NSC 97-2221-E-007-028-MY3 and NSC 97-2112-M-007-025-MY3.

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