Ultrasensitive femtosecond pulse measurement by shaper-assisted modified interferometric field autocorrelation

Chen-Shao Hsu,[1] Hsin-Chien Chiang,[1] Hsiu-Po Chuang,[1] Chen-Bin Huang,[1,2] and Shang-Da Yang[1,2]
[1]Institute of Photonics Technologies National Tsing Hua University Hsinchu 30013, Taiwan
[2]Department of Electrical Engineering National Tsing Hua University Hsinchu 30013, Taiwan
Email: d9566508@oz.nthu.edu.tw

***Abstract*—We report on spectral phase and intensity retrieval of 383 fs pulses using shaper-assisted modified interferometric field autocorrelation (MIFA). The coupled energy is only 20 aJ per pulse, corresponding to an unprecedented sensitivity of 5×10^{-8}mW^2.**

Characterization and manipulation of ultrashort optical pulses have always been important topics in ultrafast optics, especially in coherently controlled nonlinear spectroscopy and pulse formation from externally modulated CW laser comb. For a variety of pulse measurement schemes, a Michelson interferometer (MI) with a variable delay line is essential to perform self-optical gating. Conventionally, MI is implemented by beam splitters (or 3-dB couplers) and mechanical stage, which might be problematic when measuring pulses of extremely broad bandwidth [1]. Meanwhile, a pulse shaper [2] with the capability of programmable amplitude and phase modulation is required to produce the desired waveforms. It has been demonstrated that a pulse shaper can also provide the required delay sweeping pulse pair in MI [3]–[5], which enables the integration of pulse diagnostic systems and pulse-shaping apparatus. The shaper-assisted scheme is immune to fluctuation of delay step size, can handle extremely broad bandwidth and permits a very compact setup only consisting of a pulse shaper and a nonlinear element.

Previously we have proposed and demonstrated the ultrasensitive self-referenced pulse measurement by using modified interferometric field autocorrelation (MIFA) method and a 49-mm-long periodically poled $LiNbO_3$ (PPLN) waveguide, achieving a record sensitivity of 1.1×10^{-7}mW^2 [6]. The experimental setup in [6] uses a mechanical delay-scanning stage (General photonics, MDL-002-35-33-FC/PC-SS), therefore, is subject to a minimum scanning speed (0.3 mm/sec) and the requirements of careful on-line delay calibrations (implemented by the interference of reference CW laser and linear field autocorrelation trace). The two restrictions would limit the maximum time constant of the lock-in amplifier and complicate the setup, respectively. In this work, we demonstrated to generate pulse pair with very stable and highly accurate relative delay and desired phases by a Fourier transform pulse shaper. With a controllable carrier envelope phase (CEP), the required minimum delay increment can be relaxed significantly, allowing for a longer lock-in time constant and thus better signal-to-noise ratio (SNR). The capability to precisely define the absolute delays (τ = 0 and all discrete τ-values) of this shaper-assisted setup also exempt the on-line calibration from being employed.

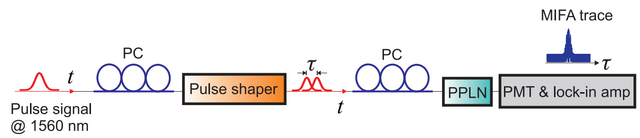

Fig. 1. Experimental setup of shaper-assisted MIFA measurement. PMT: Photomultiplier Tube; PC: Polarization controller.

Fig. 1 shows the shaper-assisted MIFA setup. The signal pulse with 50-MHz repetition rate at 1560 nm wavelength 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, where pulse replicas with variable delay and desired CEP were generated via a spatial light modulator (CRi SLM-640-D-NM). The transfer function of the shaper was set as [4]:

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

where τ is the delay between the two replicas, and γ is the carrier frequency reduction factor. γ was set in 0.038 and 0.018 for this presenting experiment. The signal pulse pair was coupled into a fiber-pigtailed PPLN waveguide with 49-mm-long QPM grating for second-harmonic generation (SHG) . The PM tuning curve of the PPLN waveguide has a sinc^2-shape with an FWHM of ≈ 0.24 nm, and the peak wavelengths are set to 1560.2 nm and 1560.9 nm (PPLN temperature at 45°C and 49.4°C) when acquiring the two MIFA traces, respectively. The average second-harmonic power at each delay is detected by a photomultiplier tube (PMT) and a lock-in amplifier.

Fig. 2 illustrates the spectral phase profiles applied by the shaper (dashed) and retrieved by our setup at an average power (coupled into the waveguide) of 1 nW (dash-dot), respectively. Fitting the phase profile over a frequency range of $\approx$ 1 THz gives rise to quadratic and cubic coefficients of c_2= 1.00 ps^2 (c_2= 1.00 ps^2), c_3= -0.41 ps^3 (c_3= -0.30

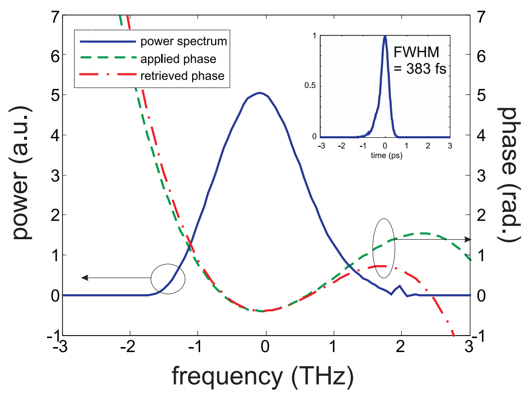

Fig. 2. Power spectrum measured by OSA (solid). The spectral phase profiles applied by the shaper (dashed) and retrieved by our setup at input average power of 1 nW (dash-dot), respectively. The inset shows the retrieved temporal intensity profile.

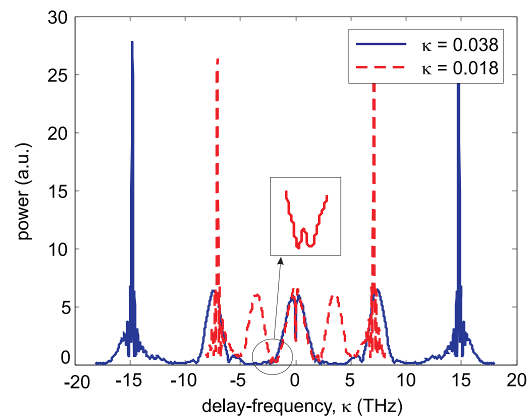

Fig. 4. Fourier transform of MIFA traces with different equivalent carrier frequency. The dips at $\kappa = 0$ result from the artificial subtraction for illustration.

ps^3) for the retrieved (applied) spectral phase curve, which is defined as $\psi(f) = c_2 f^2 + c_3 f^3$. The 1 nW average power is equivalent to 52 μW peak power, 20 aJ pulse energy, corresponding to an unprecedented sensitivity (the product of peak power and average power of minimum detectable signal) of 5×10^{-8}mW^2. The improvement of sensitivity mainly comes from the longer lock-in time-constant (200 ms versus 640 μs), which is made possible by the reduced equivalent carrier frequency ($0.038 f_0$) realized by the shaper-assisted scheme.

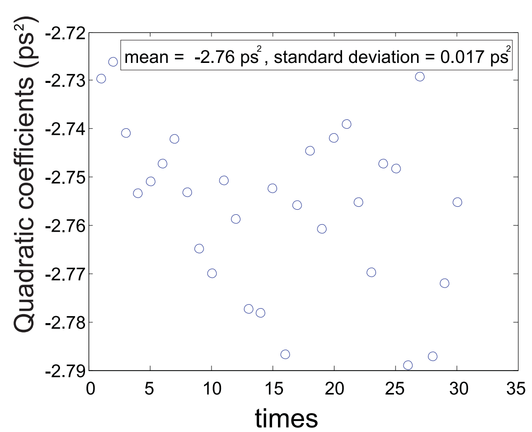

Fig. 3. Quadratic coefficients of the 30 retrieved even spectral phase curves.

To further examine the stability of the current experimental configuration, 30 consecutive measurements (lasting about 150 minutes) for the even spectral phase were performed at 15 nW average input power. As shown in Fig. 3, the average quadratic coefficient is -2.76 ps^2, and the standard deviation is 0.017 ps^2, equivalent to the dispersion of 3.9-cm-long single mode fiber. This nominal standard deviation value confirms the high stability of the shaper-assisted MIFA setup.

In the MIFA method, the complex even spectral function Eqs. (1) and (2) from Reference [6] is the Fourier transform of the modified field autocorrelation function $G_1^{'}(\tau)$, while the magnitude and real part of $G_1^{'}(\tau)$ are determined by $F\{S_1(\tau)\}|_{\kappa\approx 0}$ and $F\{S_1(\tau)\}|_{\kappa\approx f_0}$, respectively (κ means the delay-frequency) [6]. As a result, additional error can arise when the equivalent carrier frequency f_0 in the shaper-assisted scheme is too small such that $F\{S_1(\tau)\}|_{\kappa\approx 0}$ and $F\{S_1(\tau)\}|_{\kappa\approx f_0}$ overlap with each other. Fig. 4 shows the Fourier transform of the two MIFA traces taken at $\gamma = 0.018$ (dashed) and $\gamma = 0.038$ (solid), respectively. In the former case, the two neighboring delay-frequency components appear overlapped (circled), resulting in a non-negligible error of 0.16 ps^2 for the retrieved quadratic coefficient. By choosing a larger γ of 0.038, the delay-frequency components are well separated and the error significantly drops to 0.05 ps^2. The equivalent carrier frequency becomes 7.3 THz, allowing for a delay step size of 33.26 fs. This is much relaxed compared with the conventional conditions (192.3 THz, maximum delay step size 1.3 fs), which permits less data points and longer time constant.

In summary, 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 stability in the absence of on-line calibration of absolute delay values. The achieved sensitivity is 5×10^{-8}mW^2, improving on the previous record by a factor of 2.2. 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.

References

[1] Z.-M. Hsieh, C.-J. Lai, W.-H. Liang, T.-T. Tang, W.-J. Chen, R.-P. Pan, C.-L. Pan, , and A. H. Kung, 2 pages, paper presented at 2009 Conference on Lasers and Electro-Optics, Baltimore, MD, USA: OSA, 2009-05-31.
[2] A. M. Weiner, *Rev. Sci. Instrum.*, vol. **71**, pp. 1929–1960, 2000.
[3] B. von Vacano, T. Buckup, and M. Motzkus, *Journal of the Optical Society of America B-Optical Physics*, vol. **24**, pp. 1091–1100, 2007.
[4] A. Galler and T. Feurer, *JApplied Physics B-Lasers and Optics*, vol. **90**, pp. 427–430, 2008.
[5] Y. Coello, V. V. Lozovoy, T. C. Gunaratne, B. W. Xu, I. Borukhovich, C. H. Tseng, T. Weinacht, and M. Dantus, *Journal of the Optical Society of America B-Optical Physics*, vol. **25**, pp. A140–A150, 2008.
[6] S. D. Yang, C. S. Hsu, S. L. Lin, Y. S. Lin, C. Langrock, and M. M. Fejer, *Optics Letters*, vol. **34**, pp. 3065–3067, 2009.