Non-iterative Data Inversion of Phase Retrieval by Omega Oscillating Filtering (PROOF)

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Abstract: We proposed a non-iterative data inversion process for the PROOF method that could measure attosecond extreme ultraviolet pulses. Our experiments successfully retrieved the spectral phases of near infrared comb.
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1. Introduction

Pulse trains of 100% duty cycle, i.e. optical arbitrary waveform (OAW) [1], cannot be characterized by standard pulse measurement techniques (e.g. FROG, SPIDER) that need to split the signal pulse into two isolated replicas. Two methods, dual-quadrature spectral shearing interferometry (DQ-SSI) [2], and dual-quadrature spectral interferometry (DQ-SI) [3], succeed in characterizing OAW in the near-infrared (NIR) regime. However, they are subject to lower sensitivity (due to the employment of nonlinear optics) and requirement of well characterized reference pulse, respectively. Phase retrieval by omega oscillation filtering (PROOF) [4] was developed to measure extreme-ultraviolet (EUV) attosecond pulses, and just succeeded in characterizing the record short (67-as) pulses [5]. In practice, PROOF is OAW-compatible, free of nonlinear optics, and only needs a trivial reference (synchronized temporal phase modulation). However, the iterative algorithm used in reconstructing the pulse from the measured PROOF trace increases the complexity and limits the refresh rate. We proposed a non-iterative data inversion process with built-in self-consistency check for the PROOF method, and experimentally measured OAW in the NIR regime. The new approach can be directly applied to measurement of attosecond EUV pulses.

2. Theory

Assume the complex temporal and spectral envelopes of the unknown pulse as $a(t)$ and $A(\omega)\equiv F\{a(t)\}\equiv U(\omega)e^{j\psi(\omega)}$, where $U(\omega)$ (normalized to unit peak) can be obtained by an optical spectrum analyzer (OSA). A synchronized temporal phase modulation $\phi(t)\equiv\Phi_m\cos(\omega_m t)$ is introduced on the OAW pulse train with a variable delay τ, where $\omega_m/(2\pi)=f_m$ equals to the repetition rate of the pulse train. The modulated temporal envelope is approximated by

$$a'(t,\tau)\equiv a(t-\tau)\times e^{j\phi(t)}\approx a(t-\tau)\times[1+j\phi(t)]=a(t-\tau)\times[1+j0.5\Phi_m(e^{j\omega_m t}+e^{-j\omega_m t})]\ (\text{if } \Phi_m<<1).$$

The experimentally measured PROOF trace $I(\omega,\tau)$ (normalized to unit peak) satisfies with $b\times I(\omega,\tau)\equiv|A'(\omega,\tau)|^2$, where $|A'(\omega,\tau)|^2\equiv|F\{a'(t,\tau)\}|^2$ is peaked at constant b. It will be shown that b, Φ_m, and $\psi(\omega)$ can be retrieved from the PROOF trace itself. Fourier transform of the scaled PROOF trace $b\times I(\omega,\tau)$ with respect to τ gives 3 components centered at delay-angular frequencies of 0, $\pm\omega_m$, $\pm2\omega_m$, where the DC component (around ω=0) is

$$b\times I_0(\omega)=U^2(\omega)+0.25\Phi_m\left[U^2(\omega-\omega_m)+U^2(\omega+\omega_m)\right]\ . \quad (1)$$

As a result, $\{b, \Phi_m\}$ can be solved by two algebraic equations obtained by sampling Eq. (1) at $\omega=\omega_v$, ω_u. The data integrity can be verified by comparing the solutions of $\{b, \Phi_m\}$ due to different sampling frequency pairs (ω_v,ω_u). The demodulated first-harmonic component (around $\omega=+\omega_m$) of the scaled PROOF trace is

$$b\times I_{+1}(\omega)=-j0.5\Phi_m\times U(\omega)\{U(\omega+\omega_m)e^{j[\psi(\omega)-\psi(\omega+\omega_m)]}-U(\omega-\omega_m)e^{j[\psi(\omega-\omega_m)-\psi(\omega)]}\}. \quad (2)$$

Starting with $\psi(0)=\psi(\omega_m)=0$, the spectral phase $\psi(\omega)$ can be reconstructed by a recursive relation.

3. Experiment

Figure 1(a) shows our experimental setup. The RF signal (f_m=18 GHz) drives two phase modulators PM1, PM2 coherently. The CW laser (1-kHz linewidth, centered at λ_0 =1545 nm, i.e. f_0=194.2 THz) is modulated by PM1, generating a phase-modulated continuous-wave (PMCW) frequency comb [Fig. 1(b)] with 18-GHz spacing. The nonlinear spectral phase of the PMCW comb is compensated by a line-by-line (LBL) pulse shaper [6] to get transform-limited (TL) pulses [Fig. 1(c), inset]. This is achieved by maximizing the second-harmonic yield through an automated shaper LCM phase control process [6], and confirmed by the good agreement between the simulated and experimentally measured intensity autocorrelation (IA) functions [Fig. 1(c)]. The delay τ of the signal pulse is scanned for 55.6 ps (with 1.36-ps step size) by the same LBL pulse shaper. The output pulse is weakly modulated by PM2, then measured by an OSA to get the PROOF trace $I(\omega,\tau)$. Different extra spectral phases $\psi(\omega)$ were added to the TL pulse train via the same LBL pulse shaper, and retrieved by the non-iterative PROOF method.

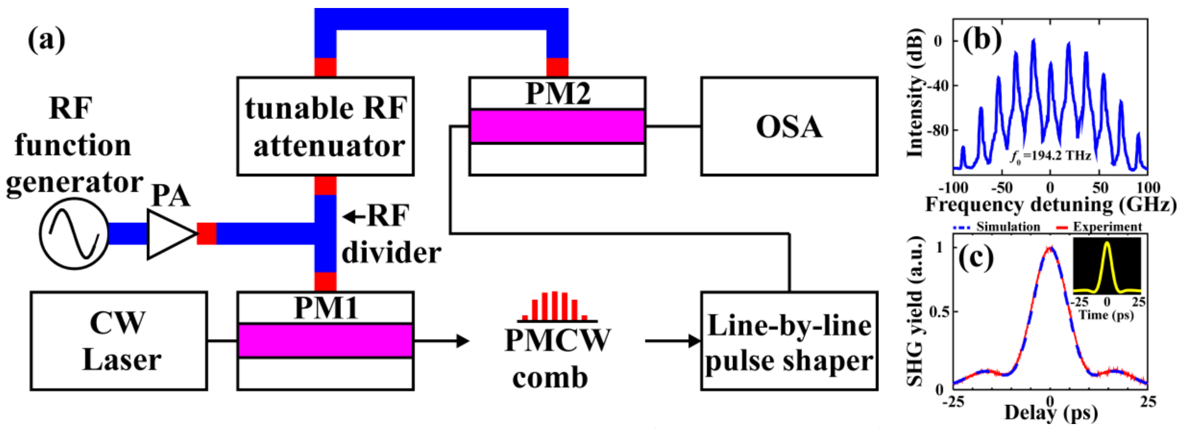

Fig. 1. (a) Experimental setup. PM: phase modulator. PA: power amplifier. (b) Power spectrum of the PMCW comb. (c) The IA functions obtained by simulation (dashed) and experiment (solid) for the corresponding TL pulse (inset).

A third-order polynomial phase $\psi_1(\omega)$=-(6 ps^2)ω^2+(25 ps^3)ω^3 (Fig. 2) and a funnel-shaped phase $\psi_2(\omega)$ (Fig. 3) were experimentally tested. In either case, the retrieved phase [Figures 2(b), 3(b), open circles] agrees well with the applied one (solid). The reliability of phase retrieval was further confirmed by good agreement between the experimentally measured and simulated IA functions [Figures 2(c) and 3(c)]. In the measurement of $\psi_1(\omega)$, sampling $I_0(\omega)$ at two different frequency pairs gave {Φ_m=0.48 rad, b=4.19} and {Φ_m=0.51 rad, b=3.92}, respectively. The good consistency between the two solution sets implies the integrity of the measured PROOF trace.

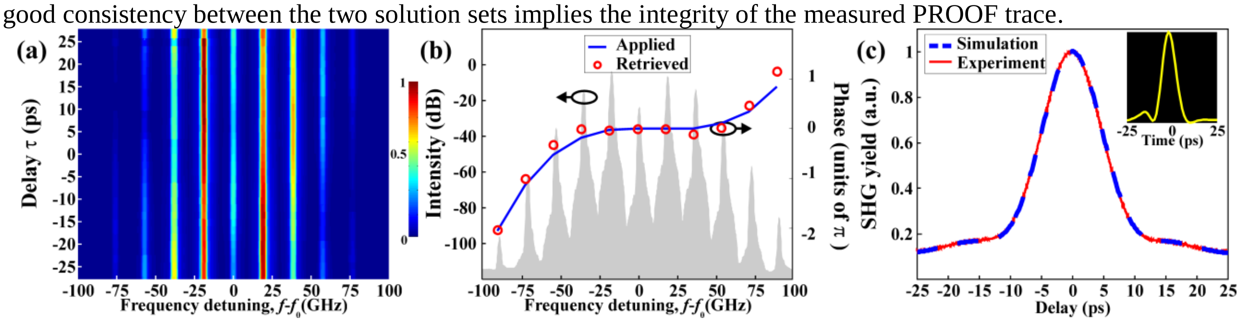

Fig. 2. Measurement of $\psi_1(\omega)$. (a) PROOF trace. (b) Power spectrum (shaded), applied (solid), and retrieved (circles) spectral phases, (c) Simulated (dashed) and experimentally measured (solid) IA functions. The inset shows the temporal intensity of the test pulse.

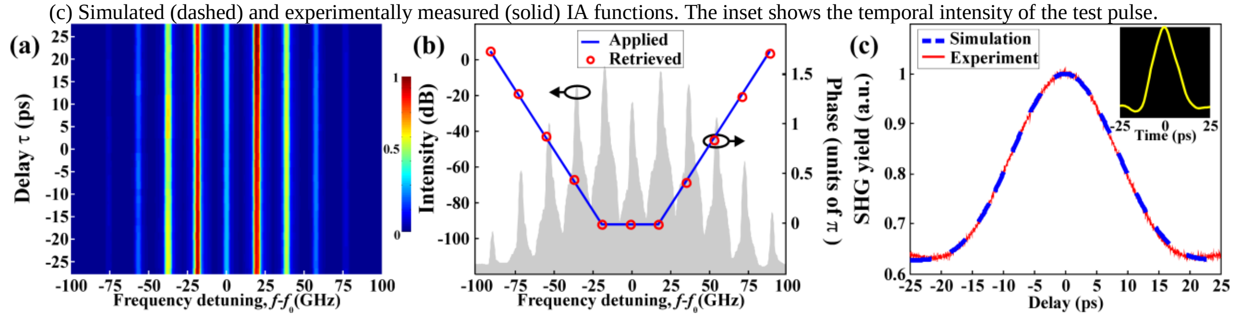

Fig. 3. Measurement of $\psi_2(\omega)$. (a) PROOF trace. (b) Power spectrum (shaded), applied (solid), and retrieved (circles) spectral phases, (c) Simulated (dashed) and experimentally measured (solid) IA functions. The inset shows the temporal intensity of the test pulse.

4. Conclusion

We proposed a non-iterative data inversion process for the PROOF method. The process was experimentally verified in measuring two NIR pulses, and can be directly applied to attosecond EUV pulses. This work was supported by the National Science Council of Taiwan under grants NSC 100-2221-E-007-093-MY3, 100-2112-M-007-007-MY3, 99-2120-M-007-010, and by the National Tsing Hua University under grant 101N2081E1.

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