Direct spectral phase retrieval of ultrashort pulses by double one-dimensional autocorrelation traces

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***Abstract*—We demonstrate an original method to analytically retrieve complete spetral phase of ultrashort pulses by measuring two modified interferometric field autocorrelation traces using thick nonlinear crystals with different central phase-matching wavelengths.**

I. Introduction

The existing techniques for ultrashort pulse measurement are usually restricted by time-consuming iterative algorithm [1], [2], excessive data redundancy [2], [3], and sufficiently broad phase-matching (PM) spectrum (typically broader than the input pulse bandwidth) to avoid undesirable spectral truncation [1], [2], [3], [4]. As a result, thin nonlinear crystals are routinely used in ultrashort pulse measurements, however seriously hindering the measurement sensitivity. Pulse measurement schemes using thick crystals have been reported. For example, tight focusing of an optical beam in a thick nonlinear birefringence crystal, or longitudinally chirping the period of a thick quasi-phase matched grating permits different frequency components of the short pulse being phase matched at different angles [5] or different grating positions [6]. Nevertheless, the effective PM spectrum in these two schemes still has to be broader than the signal bandwidth (as in other methods). We have proposed in theory a new scheme to analytically retrieve spectral phase profile of ultrashort pulses by measuring two modified interferometric field autocorrelation (MIFA) traces using a thick nonlinear crystal in a collinear-type autocorrelator [7]. In this manuscript, we report the first experimental demonstration of MIFA scheme by measuring sub-picosecond pulses with pre-specified spectral phase modulations. This scheme is reference-free, fast (no iterative data inversion), cost-effective (no spectrometer, detector array), and is sensitive due to the long nonlinear interaction length.

II. Theory

Consider a pulse of scalar e-field: $e(t) = \text{Re}[a(t) \cdot \exp(j2\pi f_0 t)]$, where Re[ ] denotes real part, $a(t)$ is the complex temporal envelope, and f_0 represents carrier frequency, respectively. By using a thick nonlinear crystal with narrow PM spectrum $H_1(f)$ centered at $2f_0$ in a collinear Michelson interferometer (MI), the generated second-harmonic average power is proportional to [6], [7]:

$$\begin{aligned} S_1(\tau) \propto \quad & 1 + 2|G_1^{'}(\tau)|^2 + \\ & 4\text{Re}[G_1^{'}(\tau)]\cos(2\pi f_0 \tau) + \cos(4\pi f_0 \tau), \end{aligned} \tag{1}$$

where the modified field autocorrelation function is defined as:

$$G_1^{'}(\tau) \equiv \langle a(t)a(t-\tau)\rangle / \langle a^2(t)\rangle. \tag{2}$$

Fourier analysis of (1) produces the complex function $G_1^{'}(\tau)$, and its Fourier transform becomes:

$$\widetilde{G}_1^{'}(f) \propto A(f) \cdot A(-f), \tag{3}$$

where $A(f) = F\{a(t)\} = |A(f)| \times \exp[j\psi(f)]$ stands for the spectral envelope of the pulse. The phase of (3), $\psi(f)+\psi(-f)$, is an even function of baseband frequency f, providing all spectral phase components symmetric with respect to carrier frequency f_0:

$$\psi_{e1}(f) \equiv [\psi(f) + \psi(-f)]/2 = \angle\widetilde{G}_1^{'}(f)/2. \tag{4}$$

Complete spectral phase retrieval can be accomplished if we measure a second MIFA trace $S_2(\tau)$ by using a narrow PM spectrum $H_2(f)$ centered at $2(f_0 + \Delta)$. The same procedures give rise to an even function of new baseband frequency $f^{'} = f + \Delta$, providing all spectral phase components symmetric with respect to carrier frequency $f_0 + \Delta$:

$$\psi_{e2}(f) \equiv [\psi(f) + \psi(-f + 2\Delta)]/2. \tag{5}$$

Combining (4) and (5), we can derive differential spectral phase (with a resolution of 2Δ) and reconstruct the complete spectral phase $\psi(f)$ of the pulse by concatenation:

$$\psi(f + 2\Delta) - \psi(f) = 2[\psi_{e2}(f + \Delta) - \psi_{e1}(f)]. \tag{6}$$

III. Experiment

The fiber-based experimental setup for MIFA measurement is shown in Fig. 1. Signal from a femtosecond pulse laser at C-band and reference from a CW laser at 1480 nm are combined by a wavelength division multiplexer (W1), then sent into a MI where an electrically controlled delay line (OZ optics, ODL-650) is used for delay scanning. A second wavelength division multiplexer (W2) and another 3-dB coupler (C3)

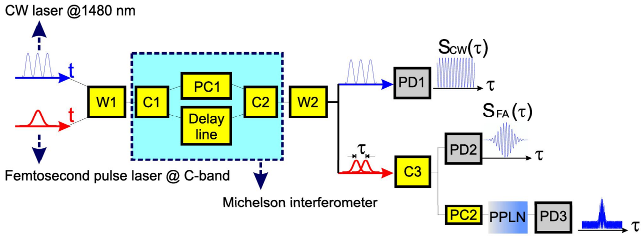

Fig. 1. Schematic diagram of MIFA measurement. W#: WDM, C#: 3-dB coupler, PD1&PD2: InGaAs photodetectors, PD3: Si photodetector.

split the optical wave into three different paths, which are detected by two InGaAs photodetectors (PD1, PD2) and one periodically poled lithium niobate (PPLN) succeeded by a Si photodetector (PD3), respectively. The CW reference goes to PD1, producing a trace of sinusoidal fringes $S_{CW}(\tau)$, which can be used to correct irregularly sampled delays of the MI (arising from instability of scanning speed of the delay line). PD2 measures the average power of the signal pulse pair as a function of delay $S_{FA}(\tau)$. By analyzing $S_{FA}(\tau)$ in software, one can obtain the signal power spectrum $|A(f)|^2$ [8]. By comparing the derived power spectrum and another one directly measured by an optical spectrum analyzer, we are able to verify the fringe correction process. In the third path, a fiber-pigtailed PPLN waveguide (with 59-mm-long quasi-phase matched grating) is employed as the SHG crystal, providing a PM power spectrum of sinc^2-shape and $\approx$ 50-GHz bandwidth (FWHM), which is sufficient to accurately measure pulses with a bandwidth greater than 0.5 THz [7]. Changing the PPLN temperature around 82.5°C enables tuning of the central PM wavelength around 1542 nm at a slope of $\approx 0.1 nm/$ °C. MIFA trace is obtained by measuring the average second-harmonic power as a function of delay by PD3.

We applied spectral phase modulation on the pulse in two different ways to verify the feasibility of MIFA scheme. (1) A section of 5.15-m-long single mode fiber (Corning SMF-28) was inserted into the link to provide (predominantly) quadratic spectral phase modulation. The even-order spectral phase before(after) the insertion of the SMF, shown as dash-dot(dotted) curve in Fig. 2, was obtained by measuring one MIFA trace at fixed PPLN temperature of 107°C (corresponding to 1545-nm central PM wavelength). Fitting the spectral phase difference curve gives rise to a quadratic coefficient of $2.2108 ps^2$, very close to the prediction of the SMF specification ($2.2107 ps^2$ at 1545 nm).(2) A Fourier transform pulse shaper was used to impose cubic spectral phase modulation with a coefficient of $3.7208 ps^3$ (dash-dot curve in Fig. 3). The complete spectral phase before(after) the employment of pulse shaper was obtained by measuring two MIFA traces at PPLN temperatures of 82.5°C and 80.5°C (corresponding to central PM wavelengths of 1541.9-nm and 1541.6-nm), respectively. The resulting spectral phase difference (dotted curve in Fig. 3) is in good agreement with the imposed modulation function, corresponding to a cubic coefficient of $3.7122 ps^3$.

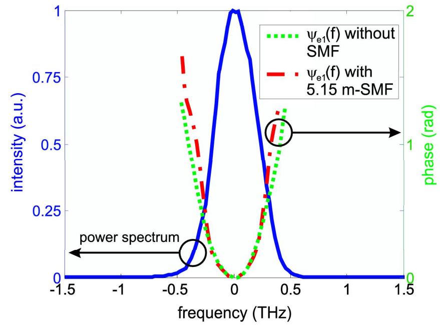

Fig. 2. Even-order spectral phase before (dotted) and after (dash-dot) the insertion of 5.15-m-long SMF.

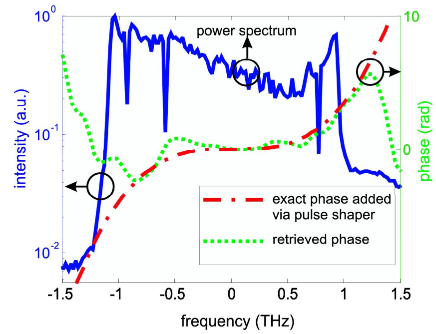

Fig. 3. Complete spectral phase imposed by pulse shaper (dash-dot) and retrieved by MIFA scheme (dotted).

IV. Conclusion

We have experimentally demonstrated that one-dimensional interferometric autocorrelation traces measured by using thick nonlinear crystals are sufficient to directly reconstruct complete spectral phase of untrashort pulses. The setup only requires standard collinear Michelson interferometer and point detector, without using expensive spectrometer, detector array, and time-consuming iterative algorithm.This material is based upon work supported by National Science Council of Taiwan under grant 96-2112-M-007-016.

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