Complete Spectral Phase Retrieval by Modified Interferometric Field Autocorrelation Traces

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Abstract: We propose analytic retrieval of complete spectral phase profile by measuring two modified interferometric field autocorrelation traces using thick nonlinear crystals with slightly different central phase-matching wavelengths.

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1. Introduction

Femtosecond optical pulse measurement normally relies on nonlinear optical effects to achieve ultrafast signal gating or spectral shearing. For example, PICASO [1], FROG [2], MEFISTO [3], and SPIDER [4] have been demonstrated to completely measure complex fields. These existing techniques, however, are usually restricted by requirements of iterative algorithm [1,2], data redundancy [2,3], spectral resolution [2-4], and sufficiently broad phase-matching (PM) spectrum (typically broader than the input pulse bandwidth) to avoid distortion of correlation trace [1] or undesirable spectral truncation [2-4]. As a result, thin nonlinear crystals are routinely used in measuring extremely short pulses, seriously limiting the measurement sensitivity. Pulse measurement schemes using thick crystals have been reported earlier [5,6], greatly simplifying the measurement device and improving the sensitivity. Nevertheless, the effective PM spectra in [5,6] are still made broad compared with the signal bandwidth.

We have shown that measuring modified interferometric field autocorrelation (MIFA) trace by using a standard collinear Michelson interferometer and an extremely narrow (δ-like) PM spectrum allows for analytic determination of all even-order spectral phase components of femtosecond pulses [6,7]. Here we extend the capability of MIFA scheme to complete (even- and odd-order) spectral phase retrieval by slightly changing the crystal configuration. This method is simple (free of reference pulse, spectrometer, detector array, and iterative data inversion), and is inherently sensitive due to the long nonlinear interaction length.

2. Theory

Fig. 1 illustrates the schematic diagram of MIFA measurement. A pulse of complex envelope $a(t)$ and carrier frequency f_0 is sent into a collinear Michelson interferometer to produce a pulse pair with variable delay τ: $a_\omega(t,\tau)=a(t)+a(t-\tau)\cdot\exp[-j2\pi f_0\tau]$. The pulse pair passes through two thick nonlinear crystals for second-harmonic generation (SHG). The two PM spectra should be narrow in width, and centered at $2f_0$ and $2(f_0+\Delta)$, respectively. This requirement can also be met by tuning the angle between the input beam and the optical axis of single birefringence crystal. A slow point detector is used to measure the τ-dependent averaged second-harmonic (SH) powers. As shown in [6,7], the MIFA trace $S_1(\tau)$ due to the first crystal (with central PM frequency of $2f_0$) is:

$$S_1(\tau) \propto 1 + 2\left|G_1'(\tau)\right|^2 + 4\,\mathrm{Re}\left\{G_1'(\tau)\right\}\cos(2\pi f_0\tau) + \cos(4\pi f_0\tau) \tag{1}$$

from which the complex modified field autocorrelation function $G_1'(\tau)$ $\left[\equiv \langle a(t)a(t-\tau)\rangle \big/ \langle a^2(t)\rangle\right]$ can be derived by Fourier analysis. The spectral phase of $G_1'(\tau)$ [$\equiv\angle F\{G'_1(\tau)\}$, where $F\{\ \}$ denotes Fourier transform] equals $2\psi_{e1}(f_c)=\psi(f_c)+\psi(-f_c)$ (except for the time-reversal ambiguity [7]), where $f_c\equiv f-f_0$ represents frequency detuning, $\psi(f_c)\equiv\angle F\{a(t)\}$, and $\psi_{e1}(f_c)$ is the even component of $\psi(f_c)$. Similarly, the trace $S_2(\tau)$ arising from the second crystal [with central PM frequency of $2(f_0+\Delta)$] gives rise to an even function $\psi_{e2}(f_c')$ ($f_c'\equiv f_c-\Delta$), which is symmetric with respect to $f_c=\Delta$. The complete spectral phase $\psi(f_c)$ can be derived by a recursive relation (with a resolution of 2Δ):

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

The validity of MIFA scheme is attributed to: (1) A δ-like PM spectrum "samples" the nonlinear polarization spectrum, where each frequency component is contributed by the entire pulse spectrum through autoconvolution [6]. Therefore, spectral information of the pulse is still preserved, and it is not necessary to use broad PM spectrum in pulse measurement. (2) $\psi_{e2}(f_c')$ due to the second trace is neither even nor odd in terms of variable f_c, which can

provide the odd-order components of $\psi(f_c)$. As a result, MIFA is fundamentally different from GRENOUILLE [5], except that they both utilize thick SHG crystals.

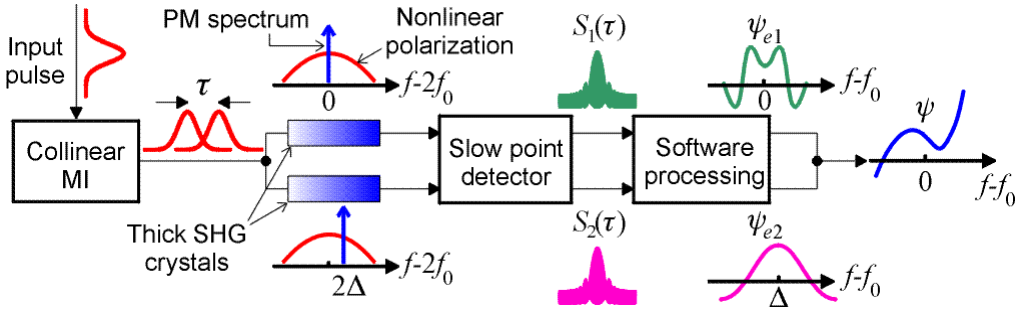

Fig. 1. Schematic diagram of MIFA measurement. MI: Michelson interferometer. PM: phase-matching.

3. Simulation results and discussions

We assume an asymmetric power spectrum $|A(f_c)|^2$ with full width at half maximum (FWHM) Δ_w=5 THz, and a spectral phase $\psi(f_c)=a(f_c/\Delta_w)^2+b(f_c/\Delta_w)^3$ with quadratic and cubic coefficients of a=14, b=39, respectively. The performance of spectral phase retrieval is quantitatively measured by the weighted root-mean-square (rms) error ε used in [2,7]. To verify the feasibility of MIFA scheme, we assume the two PM spectra as ideal δ-functions separated by Δ=0.25 THz. As shown in Fig. 2, the retrieved phase (open circles with 0.5-THz spacing) is in good agreement with the assumed one (solid line), corresponding to a small error of ε=0.20 rad (compared with the 120-rad phase variation within the spectral range of interest). Fig. 3 demonstrates the influence of nonzero PM bandwidth on MIFA scheme, where we assume a pulse spectrum identical to that of Fig. 2, and a series of sinc^2-shaped PM power spectra (typically arising from uniform nonlinear crystals) with different bandwidths Δ_{PM} (FWHM). It shows that a PM bandwidth in the order of one-tenth of the pulse bandwidth is sufficient to perform accurate measurement, which is a relatively large tolerance. Pushing the PM bandwidth to the narrow extreme does not reduce the measurement error significantly. Our simulation also shows that MIFA scheme is immune to unbalanced power splitting ratio [if the condition $G'_1(0)$=1 is used in signal processing], and quite robust against random fringe jitter due to imperfect Michelson interferometer [7].

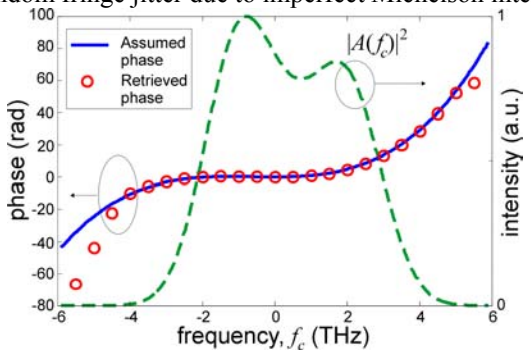

Fig. 2. Assumed (solid) and retrieved (circles) spectral phase profiles. The rms error ε is 0.20 rad.

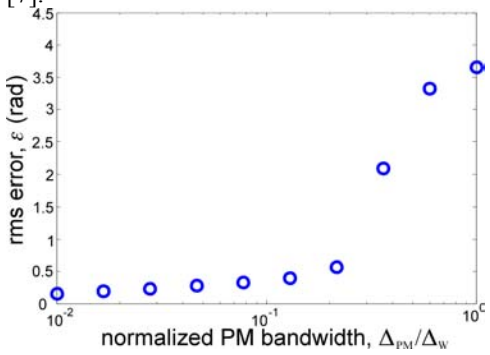

Fig. 3. rms error versus normalized PM bandwidth.

4. Conclusion

We have proposed and numerically demonstrated that one-dimensional autocorrelation trace by using thick nonlinear crystals is sufficient to directly retrieve complete spectral phase profile. In addition to theoretical innovation, this simple method is self-referenced, sensitive, and requires no iteration, spectrometer, and detector array. The authors thank A. M. Weiner for his valuable discussion.

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