Toward all-optical sub-cycle visible-to-infrared pulse envelope measurement via cross-correlation sonogram

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Abstract: We numerically characterize visible-to-infrared pulses with durations down to 2.3 fs (0.88 cycle) by cross-correlation sonogram using a 20-μm-thick BBO crystal. This method is simple, sensitive, and potentially applicable to even shorter pulses.
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1. Introduction

Single-cycle pulses in the visible-to-infrared range are a powerful engine for generating isolated attosecond pulses [1], which can be used in observing the fleeting electronic dynamics [2]. Streaking technique is able to characterize the driving pulse with attosecond resolution, however, it requires a sophisticated apparatus and only applies when the laser intensity is sufficient for photo-ionization [3]. All-optical techniques, such as frequency-resolved optical gating (FROG) [4] or spectral shearing interferometry [5], are much more simplified and sensitive. However, they are seriously restricted by the enormous phase-matching (PM) bandwidth in measuring sub-5 fs (~2 cycles at 800 nm) pulses. Sonogram techniques [6-8] can be all-optical, but receive less attention than their FROG siblings partly due to the bigger challenge in temporal intensity measurement. In this work, we propose a cross-correlation scheme to fully access the great potential of sonogram in single-to-sub-cycle pulse measurement. By using a synchronized reference pulse of duration Δt_r to measure the temporal intensity of each filtered signal spectrum via intensity cross-correlation (IXC), the required PM bandwidth in IXC can be greatly relaxed to the order of $1/\Delta t_r$. Our simulations show accurate spectral phase retrieval of a multi-plate continuum (MPC) spectrum [9] with temporal duration down to 2.3 fs (0.88 cycle) by using a 20-μm-thick BBO crystal (too thick for any existing all-optical methods).

2. Theory

As shown in Fig. 1(a), the cross-correlation sonogram (XS) of a signal spectrum $E_s(\omega)$ measured by ideal IXC [i.e. no distortion due to group delay dispersion (GDD) or group velocity mismatch (GVM) walk-off] with a reference intensity $I_r(t)$ is formulated by

$$I_{XS}(\Omega_i,t_j) = \kappa_i\times\int I_f(\Omega_i,t')\times I_r(t'-t_j)dt',\ \ I_f(\Omega_i,t_j) = \left|\int E_{sig}(\omega)\times H_i(\omega)\times\exp(j\omega t_j)d\omega\right|^2, \tag{1}$$

where κ_i and $H_i(\omega)$ represent the relative nonlinear conversion efficiency and spectral filter function at center angular frequency Ω_i, respectively. The ideal sonogram $I_f(\Omega_i,t_j)$ can be obtained by de-convolution of $I_{XS}(\Omega_i,t_j)$ to suppress the distortion due to finite Δt_r [6], from which the phase of $E_s(\omega)$ can be reconstructed by existing algorithms [10-11].

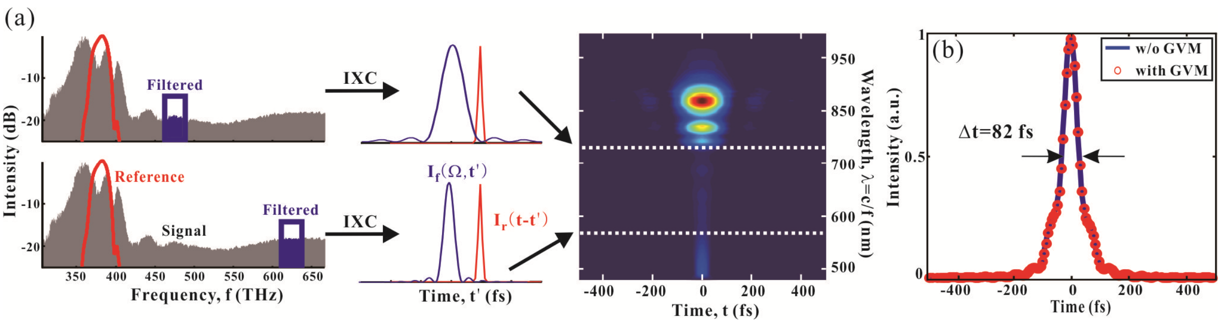

Fig. 1. (a) Schematic of cross-correlation sonogram. (b) IXC traces sampled at λ_i=600 nm without (solid) and with (circles) GVM walk-off due to 20-μm-thick BBO.

3. Simulation results

In our simulations, $|E_s(\omega)|^2$ comes from an experimentally measured MPC power spectrum [shaded, Fig. 1(a)], $I_r(t)$ is a 25 fs pulse centered at λ_r = 783 nm, and $\{H_i(\omega)\}$ are 15-nm-wide rectangular functions centered at 400-980 nm.

The orientation angle θ of Type I BBO used in IXC is rotated from 44.9° to 26.8° as the filer center wavelength λ_i ($=2\pi c/\Omega_i$) is scanned from 400 nm to 980 nm. Since $I_r(t)$ is always narrower than $I_f(\Omega_i,t)$ ($\Delta t_{TL} = 33$-180 fs), the thickness of BBO (L_{BBO}=20 μm) is limited by the 25 fs reference pulse (instead of the extremely short signal pulse) until λ_i is far from λ_r such that the shape or timing of some IXC trace is seriously distorted by GVM walk-off. We numerically calibrate the κ_i coefficient, and make sure that all the $I_{XS}(\Omega_i,t)$ are close to their GVM-free counterparts with root-mean square (rms) errors below -25 dB [see an example in Fig. 1(b)].

In the first example, the intensity and phase of $E_s(\omega)$ come from the MPC power spectrum spanning over 450-980 nm and the GDD caused by 2-mm thick BK7 glass. Figures 2(a) and 2(b) show that the ideal (GVM-free) and reconstructed sonogram traces $I_{XS}(\Omega_i,t_j)$ are almost identical with each other, corresponding to a low (-30 dB) rms error. The retrieved signal temporal intensity $I_s(t)$ [circles, Fig. 2(c)] agree well with that calculated by $|E_s(\omega)|^2$ and the Sellmeier equation of BK7 [solid, Fig. 2(c)].

Figure 2(d) shows that a 20-μm-thick BBO is able to measure sub-cycle visible-to-infrared pulse, where a broader spectral range (400-980 nm) of the MPC spectrum (inset) and constant spectral phase are taken into account. The retrieved $I_s(t)$ (circles) remains in good agreement with the ideal profile (solid) even the pulse envelope width is as short as 2.3 fs (0.88 cycles at 800 nm).

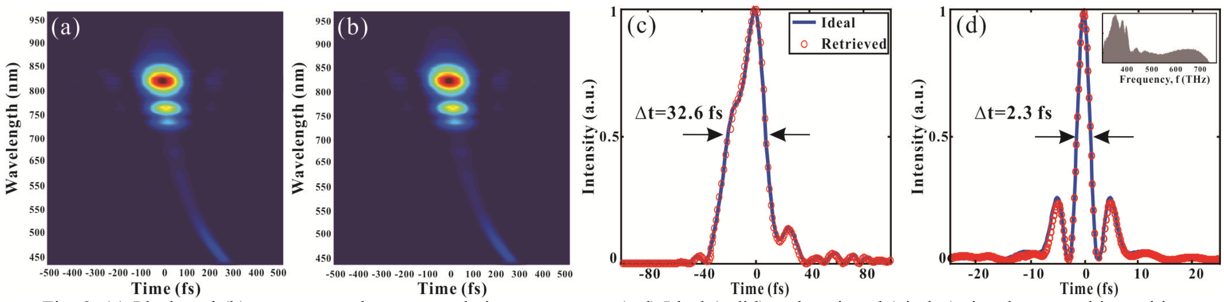

Fig. 2. (a) Ideal, and (b) reconstructed cross-correlation sonograms. (c,d) Ideal (solid) and retrieved (circles) signal temporal intensities with (c) 32.6 fs and (d) 2.3 fs durations, respectively.

4. Conclusion

We numerically demonstrated that the cross-correlation sonogram can measure visible-to-infrared pulse with duration down to 2.3 fs (0.88 cycle) by using a 20-μm-thick BBO crystal, which is made possible by spectrally multiplexed nonlinear conversion (a divide and conquer strategy). The all-optical method is simple, sensitive, and applicable to even shorter pulses if narrower filter function or thinner crystal is used. The measurable pulse width will be limited by available thickness or absorption of the nonlinear crystal. This work is supported by the Ministry of Science and Technology (Taiwan) under grant 104-2112-M-007-012-MY3.

5. References

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