Single-Shot Cross-Correlation of Counter-Propagating, Short Optical Pulses Using Random Quasi-Phase Matching

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A single-shot cross-correlator based on the sum–frequency generation (SFG) of counter-propagating beams in SBN61 ($Sr_xBa_{1-x}Nb_2O_6$ with $x = 0.61$) has been demonstrated.[1] Random quasi-phase matching in disordered ferroelectric crystals such as SBN61 allows for nonlinear interactions in nonstandard geometries, e.g., the observation of a transverse second-harmonic–generation signal resulting from two co-propagating or counter-propagating pulses.[2,3] This diagnostic measures the cross-correlation between two laser facilities, leading to the relative delay between the pulses generated by each facility on every shot. It supports their precise co-timing and the study of their relative jitter with high precision over a time range larger than 150 ps.

The cross-correlation of optical pulses with instantaneous power profile $P_A(t)$ and $P_B(t)$ generated by the Multi-Terawatt (MTW) laser (λ_A = 1053 nm) and the idler of the MTW-OPAL laser (λ_B = 1170 nm) [Fig. 1(a)] were measured. The two beams are focused in a counter-propagating configuration in the underdense-plasma target chamber designed for Raman-amplification studies. Transverse SFG in an SBN61 maps out the cross-correlation signal $C_{AB}(\tau) = \int P_A(t) P_B(t-\tau)\mathrm{d}t$, where τ is the relative delay between the two pulses onto the longitudinal spatial coordinate. The generated transverse signal is re-imaged onto a camera, therefore allowing for single-shot cross-correlation acquisition over a range of relative delay set by the crystal length and group velocity of the two pulses, resulting in more than 150 ps for the 10-mm crystal used in these experiments. Both pulses generate a time-integrated transverse second-harmonic–generation signal at 526.5 nm and 585 nm, respectively, adding a background on the cross-correlation signal of interest [Fig. 1(b)]. Background-free acquisition with enhanced signal-to-noise ratio is obtained using a bandpass filter at the SFG wavelength (~550 nm). The cross-correlator has been used to co-time the two laser facilities at the common focal region where Raman-amplification in a gas jet are conducted. It has also provided valuable information on the relative jitter between the two laser facilities and for pulse-shape optimization.

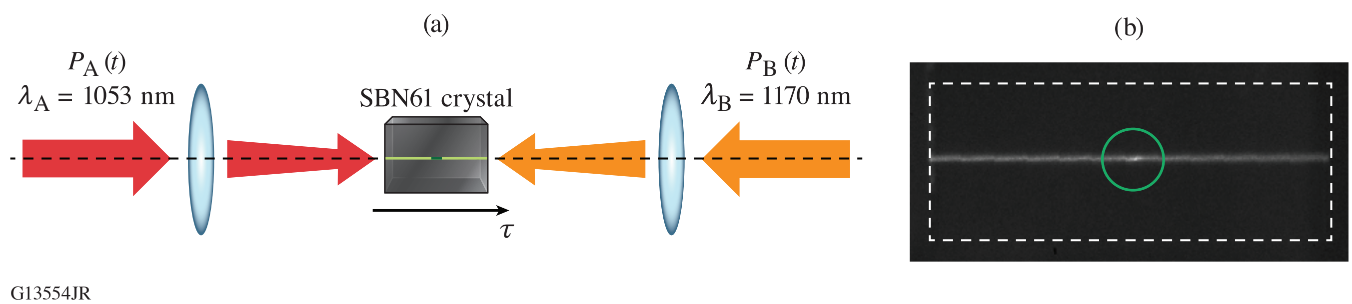

Figure 1
(a) Experimental setup. (b) Example of a signal acquired by the camera, without spectral filtering. The green circle identifies the cross-correlation signal, which is the only signal acquired by the camera when a bandpass filter at the SFG wavelength is used to remove the time-integrated SHG signals.

Fourier processing of the measured cross-correlation trace allows for extraction of its delay relative to reference and retiming for averaging purposes (Fig. 2). The collection of relative delays over a large number of shots represents the statistics of the jitter between the two laser facilities. As an example of application, Fig. 3(a) displays histograms of the relative delay between the two

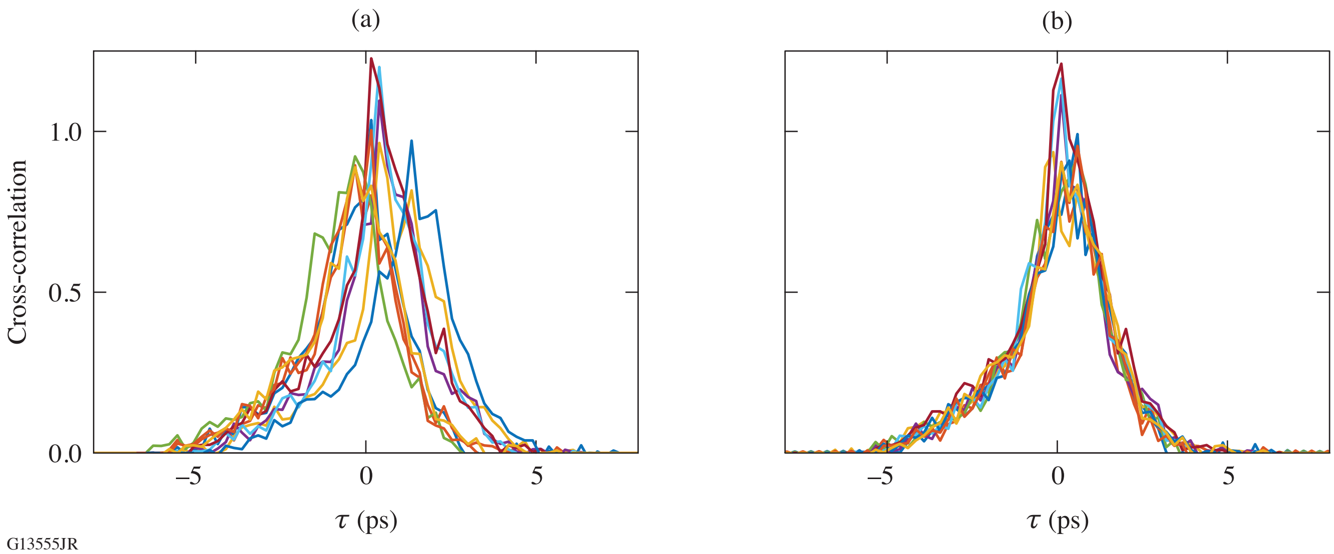

Figure 2
A set of ten measured single-shot cross-correlations (a) before and (b) after retiming.

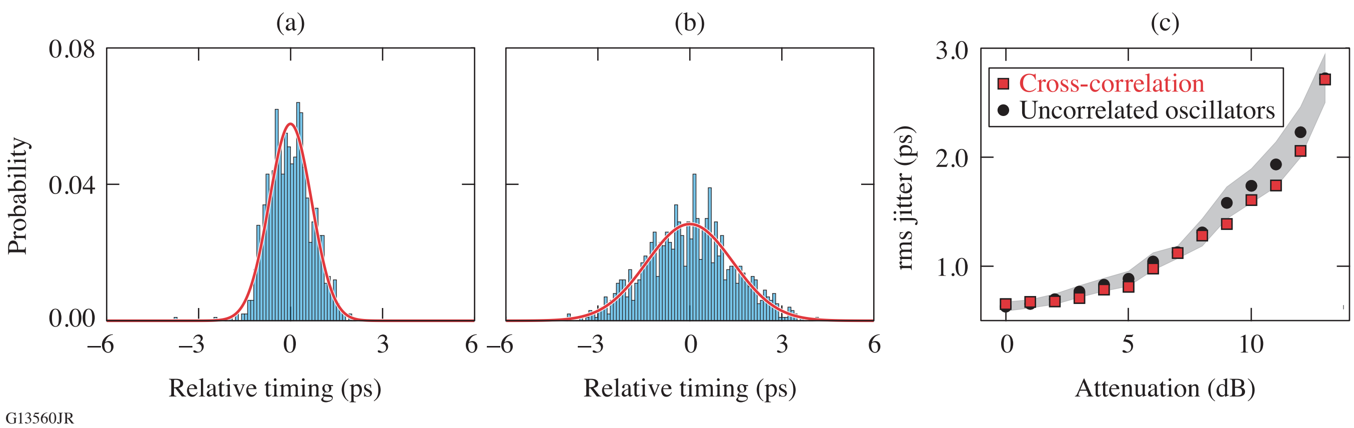

Figure 3
Probability histograms of the delay between the two laser sources measured (a) with a nominal synchronization-photodiode signal and (b) with a 9-dB attenuation. The bin size is 0.1 ps in all cases. A normal distribution with identical standard deviation has been added to (a) and (b) (red lines). On (c), the rms jitter determined from the measured cross-correlations (red squares) is compared to the rms jitter calculated from the jitter reported by the synchronization unit of the two mode-locked lasers (black circles, with confidence interval indicated by the shaded area).

facilities measured for three different synchronization configurations of the mode-locked laser seeding the MTW laser. Attenuation of its reference signal leads to poorer synchronization of that laser to the LLE reference frequency, thereby inducing a higher jitter for that particular laser and for the relative delay between the two facilities. The rms jitter calculated from the measured cross-correlations is in good agreement with the jitter calculated from the jitter of each mode-locked oscillator [Fig. 3(b)].

This simple approach supports the determination of the relative timing between two laser sources on a single shot, which is particularly important for low-repetition-rate sources. It also offers a direct approach to single-shot determination of the time-varying instantaneous power of an optical pulse by cross-correlation with a shorter ancillary pulse. Such determination is important for the development and optimization of chirped-pulse–amplification systems delivering pulses close to their Fourier transform–limited duration, but also for systems delivering pulses with a coherence time much shorter than their duration, e.g., incoherent pulses. Accurate single-shot temporal characterization with high resolution and long record length is paramount for safe operation and optimal interaction with the targets. SBN crystals as long as 20 mm are commercially available, leading to a 300-ps temporal window. Longer acquisition windows can be obtained by combining multiple crystals or implementing multiple passes in a single crystal with different relative delays between the two sources. Cross-correlations in disordered nonlinear crystals can also support the optimization of spatial overlap and timing in complex experiments involving multiple laser beams, such as the counter-propagating geometry used for Raman amplification and the crossing of beams at large angles used for Compton scattering.

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1. C. Dorrer and J. L. Shaw, Opt. Express **30**, 16,677 (2022).
2. J. Trull *et al*., Opt. Express **15**, 15,868 (2007).
3. R. Fischer *et al*., Appl. Phys. Lett. **91**, 031104 (2007).