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Retrieval of satellite pulses of single isolated attosecond pulses

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When isolated attosecond pulses are reconstructed from an ideal streaked photoelectron spectrogram, the relative amplitude of accompanying satellite pulses can be identified from their interference. However, the interference pattern in the spectrogram can be smeared by variation of the streaking laser intensity in the focal volume and by interpolation when using large delay steps acquiring the spectrogram, making accurate measurement of the relative intensity of the satellite pulses difficult. We investigate these effects on the reconstruction of satellite pulses with full- and half-cycle separations. Our simulations show that satellite pulses with full-cycle separation are largely unaffected by these issues. © *2009 American Institute of Physics*.
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Single isolated extreme ultraviolet (XUV) pulses less than 300 as in duration have to date been generated by amplitude gating,[1] polarization gating,[2] and double optical gating (DOG).[3,4] However, pre- and post-pulses always accompany the main pulse, separated by a half or full cycle of the driving laser field depending on the gating scheme. Amplitude gating and polarization gating use single-color driving laser fields. In these cases, attosecond bursts are produced from photoelectrons ionized at both positive and negative extremes of the driving laser field, leading to a half-cycle separation between the main pulse and adjacent satellite pulses. In DOG, however, a second harmonic field is added to the polarization gating field in order to break the symmetry of the driving laser field. This two-color technique leads to the production of attosecond bursts with full-cycle periodicity.

Accurate characterization of the relative intensity of satellite pulses is crucial for proving the presence of a single isolated attosecond pulse as well as for improving the pulse quality for experimental applications. Typically, isolated attosecond pulses are measured using the streaking method, whereby electrons ionized by the XUV pulse are momentum shifted by a near infrared (NIR) laser field.[5] The resulting photoelectron number S as a function of electron energy W and the time delay τ between the XUV and the NIR pulse can be analyzed using frequency-resolved optical gating (FROG) methods to retrieve the pulse shape and phase, a technique known as CRAB (complete reconstruction of attosecond bursts).[6]

When the central momentum approximation is applied, the streaked spectrogram can be written in the form of a FROG trace and can be used for CRAB.[6,7] It is given in atomic units by

$$S(W,\tau) \approx \left| \int_{-\infty}^{\infty} E_X(t) G(t+\tau) \exp[\mathrm{i}(p^2/2 - \Omega_X + I_p)t] dt \right|^2, \quad (1)$$

$$G(t) = \exp[-i\varphi(\mathbf{p}_0,t)] = \exp\left[-\mathrm{i} \int_t^{\infty} \mathbf{p}_0 \cdot \mathbf{A}_L(t') + \tfrac{1}{2}|\mathbf{A}_L(t')|^2 dt' \right], \quad (2)$$

where $E_X(t)$ is the complex field amplitude of the XUV pulse, Ω_X is the central XUV photon energy, $\mathbf{A}_L(t)$ is the vector potential of the NIR pulse, $\mathbf{p}$ is the final momentum of the electron in the continuum, $\mathbf{p}_0$ is the central momentum, I_p is the ionization potential of the detection atom, and $\varphi(\mathbf{p},t)$ is the phase shift of the ionized electron introduced by the NIR field. Here $G(t)$ is considered as a temporal phase gate. The dipole transition matrix element for a transition from the ground state to a continuum state with momentum $\mathbf{p}$ is assumed to be constant.

Ideally, the presence of satellite pulses can be determined from features in the CRAB trace. The interference between the main and satellite pulses will lead to modulations in the electron spectrum, with a period of one or two photon energy units for full- or half-cycle separations. However, the streaking field may influence the interference and introduce fringes along the energy and delay axes, and fringes in the delay axis can be lost when the delay step is large.[7] Furthermore, experimental CRAB traces are susceptible to distortion from streaking intensity variation, which can mask the presence of interference fringes in the spectrogram and lead to error in the reconstruction. These issues are certainly prevalent in the experiment and in the recent measurement of 80 as pulses,[1] an alternative method was needed to estimate the relative intensity of the satellite pulses. In this paper, we determine the severity of these two issues for satellite pulses with full- and half-cycle separations.

In the simulations discussed below, the NIR streaking laser pulse was assumed to be 9 fs in duration with a spectrum centered at 800 nm and with peak intensity of 1×10^{12} W/cm^2. The XUV spectrum was assumed to support transform-limited pulse 90 as in duration, with satellite pulses separated by a half or full cycle of the NIR field. The satellite pulse contrast I_s/I_m was set to be 0.01 or 0.1, as indicated below, where I_m and I_s are the peak intensities of the main and satellite pulses, respectively. To account for the intrinsic chirp of the attosecond burst, a linear chirp of

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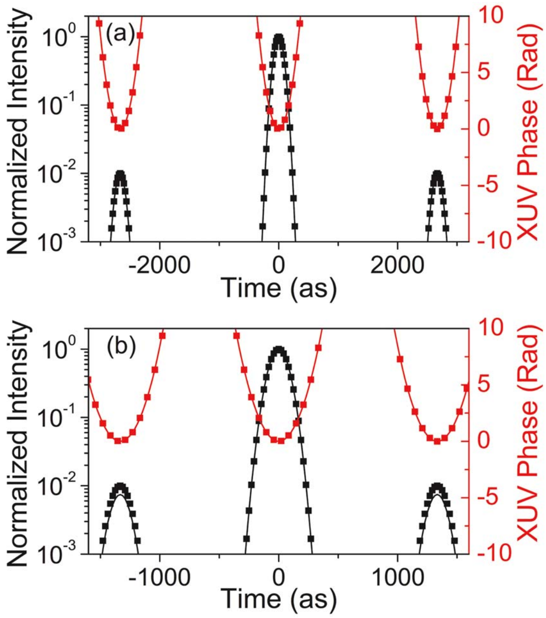

FIG. 1. (Color online) XUV intensity and phase for satellite pulses separated from the main pulse by (a) a full cycle and (b) a half cycle of the streaking laser field. The black and red squares represent the actual XUV pulse intensity and phase, whereas the black line and red line represent the retrieved intensity and phase, respectively.

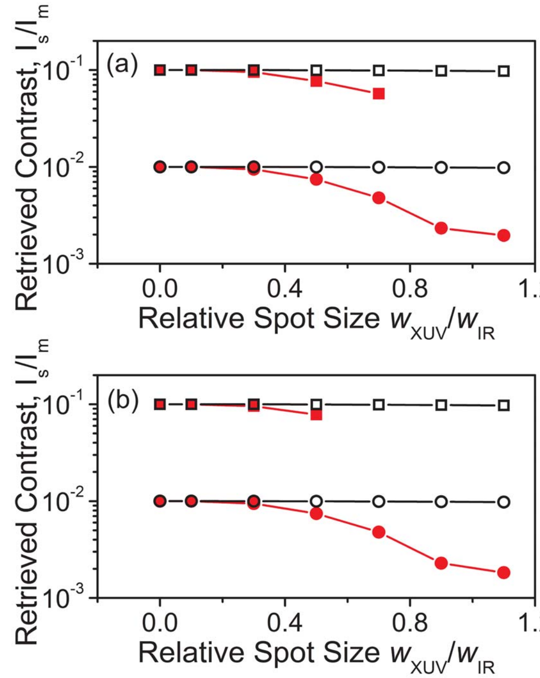

FIG. 2. (Color online) Retrieved satellite pulse contrast for attosecond pulses with full-(black open symbols) and half-cycle separation (red filled symbols) and with (a) 5000 as^2 linear chirp and (b) flat phase. The satellite pulses with full-cycle separation are always retrieved within an accuracy of 2%, whereas those with half-cycle separation are severely underestimated for large intensity variation.

5000 as^2 was added in the spectral domain except where otherwise noted, such that the main and satellite pulses had identical temporal phase. The electron collection angle was set to zero. Using these parameters, CRAB traces were created with a time window of 10.67 fs and an energy resolution of ~0.39 eV on a grid of 512 by 512 pixels. The retrieval of the XUV field and the NIR phase gate from the CRAB trace was done using the principle component generalized projections algorithm (PCGPA).[8]

Clearly the phase gate and thus the CRAB trace depend on the streaking laser intensity. However, in experiments, the electrons are produced within a volume of the target gas determined by the XUV spot size and the length of the interaction region. Within this volume, the streaking laser intensity varies both transversely and longitudinally. Specifically, the intensity varies by a factor of two within the Rayleigh range and has a nearly Gaussian profile along the transverse direction. Typical mirrors used to focus the XUV and IR pulses to the target gas have surface accuracy distances many times larger than the XUV wavelength, which can lead to an XUV focal spot similar in size to the NIR focal spot. Photoelectrons born at different locations are thus streaked by different laser intensities, which causes smearing along the energy axis of the CRAB trace.

In order to study this effect, CRAB traces simulated using different NIR streaking intensities were averaged together and sent to the PCGPA for retrieval. We assumed the XUV and NIR focal spots to be Gaussian in shape and weighted the average by the relative XUV photon number corresponding to each intensity. Figures 1(a) and 1(b) show the retrieval results for XUV pulses with satellite pulses of 1% contrast separated by a full and half cycle of the streaking field, respectively. The spot size ratio was set to $w_{XUV}/w_{NIR}=0.5$, where w_{XUV} and w_{NIR} are the $1/e^2$ radii of the XUV and NIR focal spots. We find that for full-cycle separation, the relative intensity and temporal phase of the satellite pulses can be retrieved when the XUV to NIR spot ratio is 0.5. For half-cycle separation, the relative intensity of the satellite pulses is underestimated by nearly 30%.

As the spot size ratio is further increased, thus increasing the intensity variation, the satellite pulses with full-cycle separation can still be retrieved accurately, whereas those with half-cycle separation are underestimated even more. This is shown for chirped attosecond pulses in Fig. 2(a) and for transform-limited pulses in Fig. 2(b). As the intensity variation increases, the satellite pulses with full-cycle separation are always retrieved within 2%, whereas those with half-cycle separation are underestimated by nearly an order of magnitude. For half-cycle separation with contrast of 0.1, the algorithm failed to converge properly for spot size ratios of 0.9 and greater for chirped pulses and for 0.7 and greater for transform-limited pulses.

This effect can in fact be easily understood when the streaking laser field contains several optical cycles. For satellite pulses with full-cycle separation, the main and satellite pulses experience nearly identical phase gates induced by the streaking field. When the temporal phase of the satellite pulse is similar to that of the main pulse, only the full-cycle separation determines the interference. Therefore, the interference from photoelectron spectra produced by different streaking field intensities will remain in phase, as is shown in Figs. 3(a) and 3(b). However, for satellite pulses with half-cycle separation, the main and satellite pulses are streaked by opposite phase gates. The features of this interference pattern differ for different streaking intensities and the interference patterns will move in and out of phase with one another, as is shown in Figs. 3(c) and 3(d). This effect will smear out the spectral fringes when the intensity fluctuates, leading to an underestimation of the satellite pulse intensity.

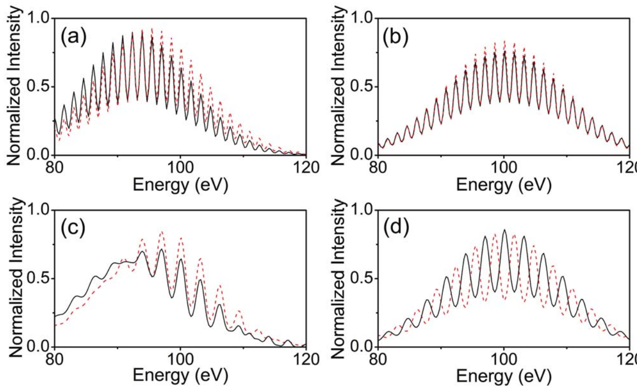

FIG. 3. (Color online) Interference of satellite pulses in the photoelectron energy spectrum for streaking with intensities of 1×10^{12} W/cm^2 (black solid line) and 5×10^{11} W/cm^2 (red dashed line). (a) Full-cycle separation, delay $\tau=2$ fs. (b) Full-cycle separation, delay $\tau=0$ fs. (c) Half-cycle separation, delay $\tau=2$ fs. (d) Half-cycle separation, delay $\tau=0$ fs.

Error in the reconstruction of satellite pulses can also stem from poor resolution along the energy and delay axes in experimental CRAB traces. Clearly, sufficient resolution is needed along the energy axis to resolve the interference fringes separated by one or two driving laser photon energy units. Furthermore, because experimental CRAB traces are obtained over finite delay step sizes, fast modulation of the interference along the delay axis may be lost if the delay step is too large. To study this effect on the reconstruction of the satellite pulses, simulated traces with no streaking intensity fluctuation were first resampled to a smaller number of delay steps, and then interpolated back to a 512 by 512 square array. The results are shown in Figs. 4(a) and 4(b) for chirped and transform-limited attosecond pulses, respectively. We find that the satellite pulse contrast is accurately retrieved for delay steps below ~100 as when the pulses are separated by a half cycle of the streaking field, whereas the contrast is always retrieved accurately for full-cycle separation.

In conclusion, we find that the streaking laser intensity variation within the focal volume of the XUV pulse is especially important in the characterization of satellite pulses separated by a half cycle of the streaking field, as is the case in amplitude gating and polarization gating. For half-cycle separation, the satellite pulses reconstructed from CRAB traces with similar XUV and NIR focal spot sizes or with large delay steps could be underestimated by an order of magnitude or more. These two issues were not found to significantly affect the reconstruction of satellite pulses separated by a full cycle of the streaking field, as is the case in DOG. This ability to characterize the presence and contrast of satellite pulses directly from the streaked spectrogram gives DOG an important advantage over other gating schemes that require other methods to measure the contrast of satellite pulses.

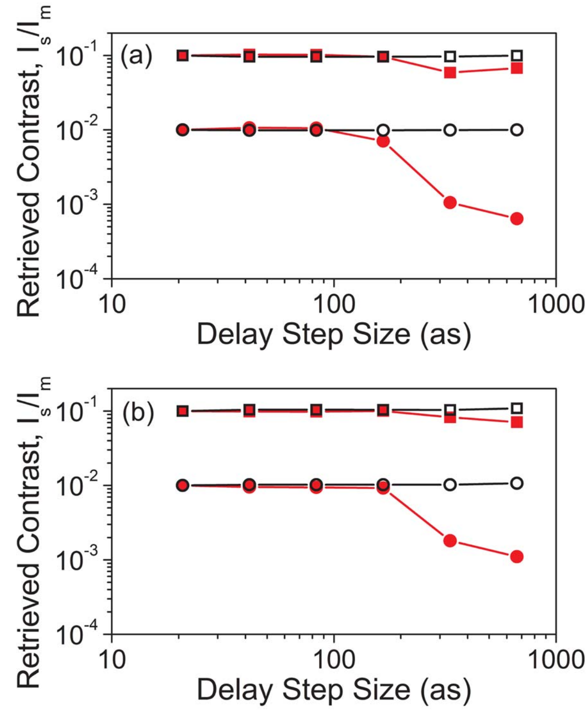

FIG. 4. (Color online) Retrieved satellite pulse contrast for attosecond pulses with full-(black open symbols) and half-cycle (red filled symbols) separation and with (a) 5000 as^2 linear chirp and (b) flat phase. The satellite pulse contrast is always retrieved within 4% for full-cycle separation. For half-cycle separation, the contrast can be underestimated by more than an order of magnitude. The effect is more severe for contrast of 0.01 than a contrast of 0.1.

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