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Controlling attosecond pulse generation with a double optical gating

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Numerical simulations have revealed that by adding a second harmonic field to a laser field with a time-dependent ellipticity, single isolated attosecond pulses can be generated as a result of the combined power of the two-color gating and the polarization gating. The duration of the pump laser applicable to this double optical gating scheme is a factor of 2 longer than that for the conventional polarization gating. Pulses with 200 attosecond duration can be generated from argon gas even with 10 fs lasers. It was discovered that the number of attosecond pulses and their intensities could be controlled by either the relative phase between the two color fields or the carrier-envelope phase.

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Two types of attosecond light sources based on high order harmonic generation have been developed so far, pulse trains and single isolated pulses [1,2]. The temporal separation between adjacent attosecond pulses in a train is one-half of a laser optical cycle due to the symmetry of the laser field and the source atoms [1]. A weak second harmonic wave can be added to break the symmetry of the driving field [3], increasing pulse spacing to a full optical cycle that sets the width of the time window within which the dynamics in atoms and molecules can be measured. For Ti:sapphire lasers, the optical period, T_0, is ~2.5 fs. Single isolated attosecond sources do not have such a limit.

Two schemes have been experimentally demonstrated for the generation of single isolated attosecond pulses; both used few-cycle pump lasers. When the duration of the laser pulse approaches two cycles, the harmonic peaks in the cutoff region merge into a continuum, which has been filtered out to produce single isolated attosecond pulses [2,4]. The pulse duration is 250 as with the neon target due to the limited spectrum width. Much shorter attosecond pulses, 130 as, have been generated by polarization gating of the high harmonic generation process [5,6]. In this case, both plateau and the cutoff harmonics merged to a supercontinuum.

Several ideas have been proposed to generate single isolated attosecond pulses with long pulse lasers because they are easier to access. For example, it has been proposed to mix a weak second harmonic wave with a linearly polarized fundamental field as in [3], so that a continuum spectrum in the cutoff can be generated with multiple-cycle two-color field [7]. The continuum has been observed experimentally whereas the pulse duration is yet to be measured [8]. It was predicted that a relatively long attosecond pulse (300–500 as duration) would be generated because the discrete harmonic peaks in the plateau region of the spectrum cannot be used. Here we propose to combine this two-color gating with the polarization gating to generate shorter attosecond pulses using long driving lasers. The scheme is named double optical gating.

The conventional polarization gating is based on the strong dependence of the high harmonic generation efficiency on the ellipticity of the pump laser, ξ. The gating can be applied with laser pulses whose ellipticity changes from circular to linear and back to circular. The center portion of the pump pulse where the ellipticity is less than a certain value (e.g., $\xi=0.2$) is defined as the polarization gate [9,10]. The gate width should be narrower than the spacing between adjacent attosecond pulses to generate single isolated attosecond pulses.

The laser pulses for polarization gating could be generated by combining two counter-rotating, circularly polarized laser pulses with a proper delay [11,12]. Experimentally, the pump pulse is formed by splitting a linearly polarized laser pulse into two perpendicularly polarized fields with a birefringence plate [12,13]. A delay between the two pulses is introduced as the difference in the group velocity along and perpendicular to the optic axis of the plate. They are converted to circularly polarized pulses with a quarter-wave plate to create pulses with a time-dependent ellipticity. The polarization gate width can be estimated by the expression $\delta t_{\xi=0.2} \approx 0.3\tau_p^2/T_d$, where τ_p is the full width at half maximum of the circularly polarized pulses and T_d is the delay between them [9]. The calculated required delay time for producing a single isolated pulse as a function of the laser pulse duration is shown by the blue solid line in Fig. 1. It should be kept in mind the predictions with this simple equation should only serve as guidance for experiments. Phase-matching effects must be taken into account to determine the exact laser parameters [9], as they can play a fundamental role in cleaning up the single dipole response in time [14].

The prediction presented in Fig. 1 seems to suggest that polarization gating can be applied with any pump pulse duration as long as the delay is large enough. This is not true because the intensity of the generated attosecond pulses decreases with the pump pulse duration. The dipole moment of the driven atom responsible for the attosecond light emission is proportional to the ground state population. When the intensity at the center of the gate was chosen as 2.8×10^{14} W/cm^2, the depletion of the ground state of an argon atom by the leading edge of the laser pulse with a time-dependent ellipticity as a function of laser pulse duration was calculated by using the Ammosov-Delone-Krainov (ADK) nonadiabatic rate [15]. The upper limit of pump pulses duration for polarization gating was set by the dura-

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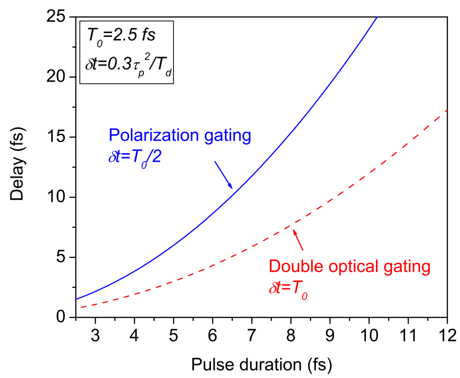

FIG. 1. (Color online) The required delay between two counter-rotating circularly polarized pulses for extracting a single isolated attosecond pulse from a pulse train. Blue solid line: with conventional polarization gating, the gate width equals one-half of an optical cycle. Red dashed line: with double gating, the gate width equals one full optical cycle.

tion at which the ground state is almost completely depleted, which is ~6.5 fs in this case.

The polarization gating pulse can be considered to be a combination of two orthogonally polarized fields, where one serves as a driving field while the other acts as a gating field [16]. When a linearly polarized second harmonic field is added to the driving field, the time interval between adjacent attosecond pulses becomes one full optical cycle of the fundamental wave [3]. To allow one attosecond pulse emission, the width of the polarization gating should be close to one full cycle of the driving field, which is two times what is required by the conventional polarization gating. Consequently, the delay between the two circular pulses can be reduced by a factor of 2, as shown by the red dashed line in Fig. 1. Since the ratio between the field strengths inside and outside of the polarization gate depends strongly on the delay, adding the second harmonic field allows the effective polarization gating to occur with lower field amplitude in the leading edge, which reduces the ground state population depletion. For the chosen target atom (argon) and laser intensity, 2.8×10^{14} W/cm^2, calculation shows that the longest pulse that can be applied to the double optical is more than 10 fs.

Numerical simulations were performed to study the double optical gating. The simulation method is similar to that described in [9,17], which took into account propagating effects in the target such as Gouy phase shift, plasma induced phase mismatch and defocusing, etc. First, the laser field for the double gating was calculated for all spatial grid points by solving a three-dimensional wave equation that includes the plasma defocusing effects. The ionization of the atoms by the laser field was calculated by the ADK model. Then the dipole moment of a single atom at each grid point was calculated by the Lewenstein model [18]. Finally, the dipole moments were inserted as sources to the wave equation in the frequency domain to yield the harmonic field (near field). The spectra in the far field were obtained by performing the Hankel transform. The signals below the 20th harmonic were blocked by a high-pass filter when the high harmonic field was Fourier transformed to the time domain.

It was assumed that the laser beam propagates along the z direction and is focused 3.5 mm before a 1 mm long cell filled with 5 torr of argon gas. The center wavelengths of the fundamental wave and second harmonic wave are 750 and 375 nm, respectively. The radius of the focal spot is 30 μm. The laser field on the target is expressed as $\vec{E}(t)=E_{\text{drive}}(t)\hat{i}+E_{\text{gate}}(t)\hat{j}$, where $\hat{i}$ and $\hat{j}$ are the unit vectors in the x and y directions, respectively. $E_{\text{gate}}(t)$ is the same as that for conventional polarization gating, whereas the driving field is

$$\begin{aligned}E_{\text{drive}}(t) = E_0[&(e^{-2\ln 2[(t+T_d/2)^2/\tau_p^2]}+e^{-2\ln 2[(t-T_d/2)^2/\tau_p^2]})\\ &\times\cos(\omega_0 t+\varphi_{CE})\\ &+a_{\omega,2\omega}(2e^{-2\ln 2[(T_d/2)^2/\tau_p^2]})e^{-2\ln 2(t^2/\tau_{2\omega}^2)}\\ &\times\cos(2\omega_0 t+2\varphi_{CE}+\phi_{\omega,2\omega})],\end{aligned} \tag{1}$$

where E_0 is the amplitude of the circularly polarized fundamental laser field with a carrier frequency ω_0 and a pulse duration τ_p. φ_{CE} is the carrier-envelope phase of the fundamental laser fields; its values at the laser focus are specified for the simulation results. The carrier envelope phase of the second harmonic field is $2\varphi_{CE}$. $a_{\omega,2\omega}$ is the ratio of the amplitudes between the second harmonic field and the driving field at the center of the polarization gate (t=0). The relative phase delay between the two fields is $\phi_{\omega,2\omega}$ when φ_{CE}=0. It was assumed that τ_p=10 fs, T_d=12.5 fs, and the duration of the linearly polarized second harmonic field $\tau_{2\omega}$=25 fs.

The calculated attosecond pulses and the corresponding high harmonic spectra with different gating schemes are shown in Fig. 2 for comparison. When argon gas was pumped by a 10 fs linearly polarized fundamental wave (one color), a train of eight attosecond pulses is generated, as shown in the bottom panel of Fig. 2(a). The spacing between the adjacent pulses is one-half of an optical cycle. The pulses are from the short quantum trajectories, while the long trajectory contributions are suppressed by the phase mismatch during the propagation. In the spectral domain, odd order high harmonic peaks are observed, as shown in the bottom panel of Fig. 2(b). The number of pulses is reduced to three with the conventional polarization gating. The separation between the pulses is the same as with linear polarized pump pulses, i.e., 1.25 fs, which is one-half of the calculated polarization gate width, 2.4 fs. The CE phase chosen here favors the pulse in the middle.

When a second harmonic (SH) field is added to the linearly polarized fundamental wave (two-color), the spacing between attosecond pulses in the train is a full fundamental wave cycle. The amplitude ratio, $a_{\omega,2\omega}$, of the added field is 15% of the fundamental wave. Finally, when the SH field is added to the driving field of the polarization gating pulse, it turns off the two satellite pulses left by the polarization gating. Only a single attosecond pulse survives the power of double optical gating, as shown in the top panel, which corresponds to a supercontinuum in the spectrum domain. The duration of the single isolated pulse is ~200 as.

The mixing of the second harmonic field with the polarization gating field introduces many “knobs” that can control the electron trajectories. Three parameters that may affect the

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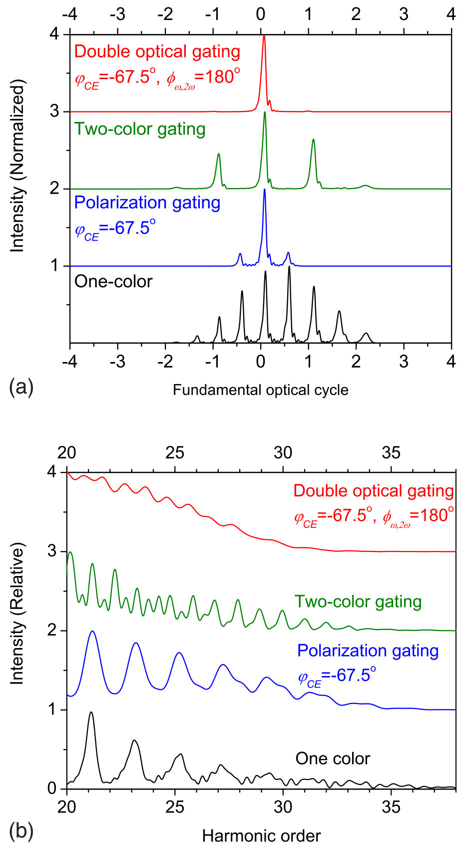

FIG. 2. (Color online) Attosecond pulses (a) and their spectra (b) generated by four different types of laser fields. From bottom panel to the top: with a linearly polarized one color field, with conventional polarization gating, a second harmonic field is added to the linearly polarized fundamental field, and a SH field is added to the polarization gating field.

double optical gating were investigated. The dependence of the attosecond pulses on the ratio of second harmonic field strength to that of the fundamental wave, $a_{\omega,2\omega}$, is shown in Fig. 3. Here the carrier-envelope phase was set at $\varphi_{CE}=-67.5°$ and the relative phase $\phi_{\omega,2\omega}=180°$. $a_{\omega,2\omega}=0$ is the case of conventional polarization gating for which one strong pulse and two satellite pulses are produced. The in-

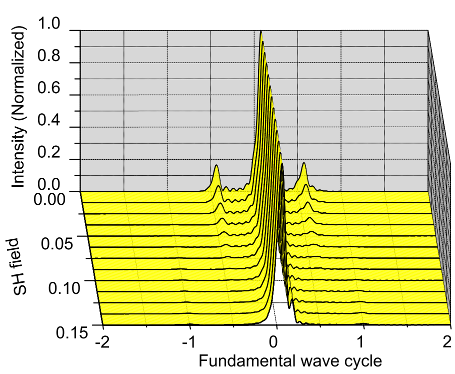

FIG. 3. (Color online) The suppression of the satellite pulses by the second harmonic wave. The main pulse is normalized to show the variation of its intensity ratio to the pre- and post-pulses.

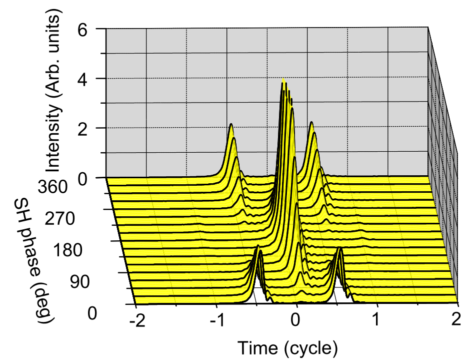

FIG. 4. (Color online) The dependence of the attosecond pulse number and intensity on the relative phase between the second harmonic field to the fundamental field for a given carrier-envelope phase.

tensities of the pre- and post-pulses are about 16% of the main pulse. The two small pulses diminish as the field strength of the second harmonic field increase. The field ratio required to reduce the satellite pulse down to 0.7% of the strong pulse is 10%, which corresponds to a 1% intensity ratio. Such a weak second harmonic field can be generated by converting a portion of the fundamental pulse with nonlinear crystals.

For a given field strength ratio $a_{\omega,2\omega}=0.15$ and a fixed carrier-envelope phase value $\varphi_{CE}=-67.5°$, the relationship between the attosecond pulse and the relative phase is shown in Fig. 4. A single attosecond pulse is generated only when the relative phase is close to 180°. In this case, the second harmonic gating is in favor of the pulse at the center of the polarization gate, which is the main pulse. For other phases, the two satellite pulses are allowed by the second harmonic gating, whereas the pulse at center is suppressed. The spacing between these pulses is one full fundamental wave cycle. Being on the edge of the polarization gate, they are less intense than the single pulse. For a narrow range of relative phase, three pulses are produced. The dependence of the attosecond pulses on the relative phase clearly demonstrates the interplay between the two gating mechanisms.

Since the second harmonic field is generated by converting a portion of the fundamental field, varying the CE phase of the latter by $\Delta\varphi_{CE}$ introduces a CE phase shift, $2\Delta\varphi_{CE}$, to the second harmonic field. Consequently, the total phase difference between the two fields is changed by $\Delta\varphi_{CE}$, which moves the combined field with respect to the polarization gate. Figure 5 shows the attosecond pulses when the CE phase changes from 0° to 360°. Here the relative phase is set at $\phi_{\omega,2\omega}=180°$. The CE phase shift moves the main pulse inside the polarization gate because the electron recollision time is determined by the CE phase. When the pulse is generated at the center of the gate, the intensity is the highest and the two satellite pulses are suppressed by the gating actions. Otherwise two weaker pulses separated by one fundamental cycle are produced. The time-integrated signals repeat every full fundamental wave cycle. As a comparison, the periodicity is one-half of an optical cycle for conventional polarization gating [9]. Thus the two gating schemes can be distinguished experimentally by examining the periodicity.

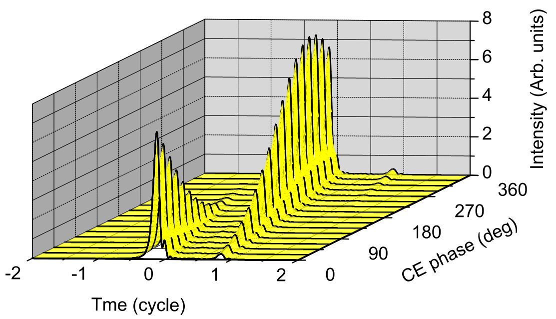

FIG. 5. (Color online) The dependence of the attosecond pulse number and intensity on the carrier-envelope phase on the fundamental wave pulse.

For other relative phase $\phi_{\omega,2\omega}$ values, the number of attosecond pulses generated at a given CE phase is different from that in Fig. 5. It is therefore necessary to stabilize and control the value of both the relative phase and the CE phase in order to generate single isolated attosecond pulses with the double optical gating. When the double gating laser pulses are synthesized by generating and recombining the second harmonic field and the polarization gating field using a Mach-Zehnder interferometer, a piezodriven mirror can be added to one of the arms to change the relative phase by feedback controlling the optical path length difference between the two interferometer arms.

In conclusion, our numerical simulations show that the combination of the conventional polarization gating with the two-color gating leads to a gating scheme for generating single isolated attosecond pulses. The double optical gating produces much shorter isolated attosecond pulses than those with second harmonic gating. The added second harmonic field allows the usage of much longer laser pulses than applicable to the conventional polatization gating. In this work, 10 fs was used for demonstration. Techniquelly, although 10 fs pulses are still much shorter than those directly from chirped pulse amplifiers commercially available, they are much easier to generate, propagate, and manipulate than the 5 fs pulses used in the past for polarization gating.

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