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Effect of Gate Width on High Harmonic Generation from Polarization Gating Pulse with Longer Pulse Duration

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Abstract. We simulate the high order harmonic generation (HHG) in the frequency domain and attosecond pulse in the time domain from helium atom subjected to the polarization gating pulse composed of the two counter-rotation circularly polarized pulses with longer pulse duration by using the strong field approximation model. It is found that when the width of the polarization gate is adjusted from traditional half optical cycle to one optical cycle, the peak position of the synthesized pulse moves to inside the gate from outside the polarization gate due to the shortening of time delay between two pulse peaks. As a result, harmonic spectrum with the high efficiency and the regular plateau structure can be obtained, and further a single 127-as pulse can be generated from the polarization gating pulse with 10-fs pulse duration.

Key words. Polarization gating pulse, high-order harmonic generation, attosecond pulse.

1. Introduction

Isolated attosecond pulses make the study and control of ultrafast electron processes in atoms and molecules possible[1-3]. High order harmonic generation (HHG) in atom and molecule is the most promising way to generate such pulses[4-11], benefited from the broad plateau structure of the typical HHG spectrum. So far, the shortest isolated attosecond pulse with 67-as pulse width was realized in the laboratory by using the polarization gating (PG) scheme[9].

The polarization gating scheme relies on the fact that the ellipticity of the driving laser pulse varies with time. If the driving pulse's ellipticity is carefully adjusted to be nearly linear for one-half of a laser cycle (polarization gate width), an isolated attosecond pulse will be obtained. Usually, the driving pulses with the shorter pulse width are adopted in the polarization gating scheme because the polarization gate width is easily adjusted to one-half of a laser cycle. Chang et al. obtained theoretically a 58-as pulse by using two counter-rotating circularly-polarized pulses with 5-fs pulse duration and 5-fs time delay[12]. While, compared with the generation of the 5-fs pulse, the driving pulse with longer pulse duration is easily realized in the laboratory and its intensity is relatively stronger. Based on it, the research on the HHG from the polarization gating pulse the longer duration is necessary. Currently, for the driving pulses with the longer pulse duration, the time delay between the two pulse peaks should be drastically increased to realize the polarization gate with half cycle width. As a result, the field outside the polarization gate is much stronger than the inside one. Therefore, the harmonic conversion efficiency is much lower because most of the laser energy is lost outside the gate. To overcome this disadvantage, the double optical gating method is demonstrated by Kun Zhao in Zenghu Chang's group in 2012. They released the polarization gate width to one cycle by adding a second harmonic pulse to the polarization gating pulse with 10-fs pulse width and obtained a 67-as isolated short pulse[9]. However, the presence of the second harmonic pulse increases the difficulty of the experimental operation.

In this paper, we demonstrate that even without the second harmonic pulse, as the driving pulse with 10-fs pulse duration is adopted in the polarization gating scheme, an effective isolated attosecond pulse can still be realized by directly adjusting the polarization gate width to one optical cycle, rather than half cycle.

It is known that for the usual PG pulse, the width of the polarization gate is nearly one-half of an optical cycle, and the position where the driving field equals zero within the polarization gate is in the center of the whole polarization gate (t=tc). So the first quarter cycle of the electric field (before tc) is used for atomic ionization, and the second quarter cycle (after tc) is used for the recombination between the electrons and nuclei. Therefore, an isolated attosecond pulse comes from the recombination of the electrons ionized by the first quarter cycle of the electric field (before tc). When the polarization gate width is adjusted to one optical cycle, there is linearly polarized half cycle before tc. It is found that an isolated attosecond pulse still comes from the recombination of the electrons ionized by a quarter cycle of the electric field immediately adjacent to tc before tc since electrons ionized by another quarter cycle field before tc only emits harmonics less than 40 order. More importantly, the release of the polarization gate width decreases the time delay between two pulse peaks, so the peak position of the synthesized pulse moves to inside the gate from outside the polarization gate. As a result, harmonic spectrum with high efficiency and regular plateau structure can be obtained due to the sufficient ionization electrons and avoidance of the interference effect.

2. Theoretical methods

The high order harmonic spectrum is determined by two processes: a single-atom response and a three-dimensional nonadiabatic propagation. The single atom response mainly comes from the emission of an atom, while the total emissions from all atoms in the medium can be given by considering the propagation effect. After the harmonic propagation, on one hand, emissions from the long trajectory can be eliminated by appropriate phase matching condition. On the other hand, attosecond/high order harmonic field obtained is stronger due to emission of many atoms. In this paper, we mainly focus on the effect of the polarization gate width on the

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high order harmonic spectra, so only the single atom response is calculated.

In our simulation, the Lewenstein model is applied to calculate the harmonic spectra from a single atom submitted to the PG laser pulse[13-16]. Since the ellipticity of the laser pulse changes over time, the dipole moments in two different directions need to be calculated separately. Previous study works have shown that the intensity of the harmonic spectrum along the y direction is much lower than that along the x direction [17]. Thus, we only give the dipole moment in the x direction. Its specific expression is listed as follows (atomic unit is adopted throughout this paper unless otherwise stated):

$$x(t) \approx i\int_{-\infty}^{t} dt' \left(\frac{\pi}{\varepsilon+i(t-t')/2}\right)^{3/2} d_x{}^*[\boldsymbol{p}_{st}(t',t)-\boldsymbol{A}(t)]\cdot \exp[-i\mathbf{S}_{st}(\mathbf{p}_{st},\mathbf{t}',\mathbf{t})]\times \mathbf{d}[\mathbf{p}_{st}(\mathbf{t}',\mathbf{t})-\mathbf{A}(\mathbf{t}')]\cdot \mathbf{E}(t')g(t)+c.c.\ , \tag{1}$$

In this equation, ε is a positive small number, $\boldsymbol{E}(t)$ is the electric field of the pulse, and $\boldsymbol{A}(t)$ is its associated vector potential. The ground-state amplitude $g(t)=\exp(-\int_{-\infty}^{t}\omega(t'')dt'')$, where $\omega(t'')$ is the ionization rate calculated by the Ammosov-Delone-Krainov (ADK) theory[18].

The quasiclassical action of the electron S_{st} is expressed as

$$\mathbf{S}_{st}(\mathbf{p}_{st},\mathbf{t}',\mathbf{t}) = (\mathbf{t}-\mathbf{t}')\mathbf{I}_p - \frac{1}{2}\mathbf{p}_{st}{}^2(\mathbf{t}',\mathbf{t})(\mathbf{t}-\mathbf{t}') + \frac{1}{2}\int_{t'}^{t}\mathbf{A}^2(\mathbf{t}'')\mathbf{dt}'', \tag{2}$$

Here I_p is the ionization potential of the helium atom chosen as the target gas, and $\boldsymbol{p}_{st}$ is the canonical momentum of the electron corresponding to a stationary phase, which can be expressed as

$$\boldsymbol{p}_{st}(t',t) = \frac{1}{t-t'}\int_{t'}^{t}\boldsymbol{A}(t'')dt''. \tag{3}$$

Finally, we give the field-free dipole transition matrix elements between the ground state and the continuum state in equation (1)

$$d_x[\boldsymbol{p}_{st}(t',t)-\boldsymbol{A}(t)] = i\frac{2^{7/2}}{\pi}(2I_p)^{5/4}\frac{p_{st,x}(t',t)-A_x(t)}{\{[p_{st,x}(t',t)-A_x(t)]^2+[p_{st,y}(t',t)-A_y(t)]^2+2I_p\}^3}, \tag{4}$$

Similarly, we also can give

$$\mathbf{d}[\boldsymbol{p}_{st}(t',t)-\boldsymbol{A}(t')]\mathbf{E}(t') = i\frac{2^{7/2}}{\pi}(2I_p)^{5/4}\cdot\frac{[p_{st,x}(t',t)-A_x(t')]E_x(t')+[p_{st,y}(t',t)-A_y(t')]E_y(t')}{\{[p_{st,x}(t',t)-A_x(t')]^2+[p_{st,y}(t',t)-A_y(t')]^2+2I_p\}^3}, \tag{5}$$

The harmonic spectrum from a single atom then can be obtained by Fourier transforming the dipole moment. It is worth stressing that the harmonic orders higher than the 30th considered in this paper. The photon energy of the 30th harmonic is 46eV, significantly larger than the ionization potential of the helium atom. The Keldysh parameter is $\gamma = 0.54 < 1$ at the center of the PG. The Levenstein model is valid under these given conditions.

By properly superposing several harmonics on the harmonic spectrum, an ultrashort attosecond pulse can be generated with the temporal profile

$$\mathrm{I}(t) = \left|\sum_q a_q e^{iq\omega t}\right|^2, \tag{6}$$

where $a_q = \int a(t)e^{-iq\omega t}\,dt$.

3. Results and discussion

In our simulation, the PG pulse with time-dependent ellipticity is formed by the superposition of a left- and a right-circularly polarized Gaussian pulse. The electric field of the combined pulse is $\widehat{\mathrm{E}}(t) = \mathrm{E}_{drive}(t)\hat{x} + \mathrm{E}_{gate}(t)\hat{y}$. The drive pulse and gate pulse are in turn:

$$E_{drive} = \frac{E_0}{2}\{\exp[-2ln2((t+T_d/2)/\tau_p)^2] + \exp[-2ln2((t-T_d/2)/\tau_p)^2]\}\cos(\omega t+\varphi), \tag{7}$$

$$E_{gate} = \frac{E_0}{2}\{\exp[-2ln2((t+T_d/2)/\tau_p)^2] - \exp[-2ln2((t-T_d/2)/\tau_p)^2]\}\sin(\omega t+\varphi). \tag{8}$$

Here E_0 and ω are the amplitude and the carrier frequency for the incident pulse laser, respectively. T_d is the time delay between two pulse peaks, τ_p is the pulse duration, and $\varphi = \pi/2$ is the carrier-envelope phase.

The time-dependent ellipticity of the combined pulse is

$$\xi(t) = \frac{|\exp[-2ln2((t+T_d/2)/\tau_p)^2] - \exp[-2ln2((t-T_d/2)/\tau_p)^2]|}{\exp[-2ln2((t+T_d/2)/\tau_p)^2] + \exp[-2ln2((t-T_d/2)/\tau_p)^2]}, \tag{9}$$

For harmonic orders higher than the 21st, the harmonic intensity drops by more than an order of magnitude when the ellipticity ξ increases from 0 to 0.2. Therefore, the attosecond pulse is only generated in the temporal range around $t = t_c$ and the ellipticity $\xi \le 0.2$. This temporal range is called as the polarization gate width and its expression is

$$\delta t_G = \frac{\xi_{th}}{ln2}\frac{\tau_p^2}{T_d}. \tag{10}$$

Here the threshold value ellipticity ξ_{th} is less than 0.2. In general, in order to obtain an isolated attosecond pulse, the polarization gate width should be shortened to $\frac{T_0}{2}$ (T_0 is one optical cycle). From above formula, it suggests that there are two ways to reduce the polarization gate width. The first one is to increase the delay between the pulses; the second one is to use shorter pulses.

The first approach is at the cost of losing laser amplitude of the linear field for a given delay and pulse duration can be calculated at t=0,

$$\mathrm{E}(0) = \mathrm{E}_0 e^{-\frac{ln2}{2}(\frac{T_d}{\tau_p})^2}. \tag{11}$$

The field is significantly lower than the peak field of each pulse E_0, for $T_d \gg \tau_p$, which means that the field outside the gate is much stronger than the inside one. In such case, the conversion efficiency is low because most of the laser energy is outside the gate.

In experiments, one should choose $T_d \approx \tau_p$ and $\delta t_G = T_0/2$. In this case, $\tau_p = \delta t_G/0.3 = T_0/0.6$.

For Ti: Sapphire laser, τ_p =2.67fs/0.6=4.45fs. The field amplitude inside the gate $\mathrm{E}(0) = \sqrt{2}E_0$, which is higher than the outside. It is obvious that reducing pulse width is more effective because of the quadratic dependence.

Above formula indicates that applying polarization gating scheme to high harmonic generation is equivalent to the reduction of the duration of a linearly polarized pulse by a factor of three. When $\delta t_G = T_0/2$, it is expected that only a single attosecond pulse is produced in the plateau region of the XUV spectrum. The required delay time T_d for producing a single isolated pulse as a function of the laser-pulse duration is shown in Figure 1.

It can be seen from figure 1 that when the incident pulse duration is 5-fs, the time delay between two pulse peaks should be adjusted to 5.5-fs to ensure that the polarization gate width is one-