Journal of Atomic and Molecular Sciences

ISSN 2075-1303

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

Received: May 8, 2017,
Accepted: June 23, 2017

DOI: 10.4208/jams.050817.062317a

http://www.global-sci.org/jams/

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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

$$\mathbf{S_{st}}(\mathbf{p_{st}},\mathbf{t'},\mathbf{t})=(\mathbf{t}-\mathbf{t'})\mathbf{I_p}-\frac{1}{2}\mathbf{p_{st}}^2(\mathbf{t'},\mathbf{t})(\mathbf{t}-\mathbf{t'}) +\frac{1}{2}\int_{\mathbf{t'}}^{\mathbf{t}}\mathbf{A}^2(\mathbf{t''})\mathbf{dt''}, \tag{2}$$

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 $\widehat{\mathrm{E}}(\mathrm{t})=\mathrm{E_{drive}}(\mathrm{t})\hat{\mathrm{x}}+\mathrm{E_{gate}}(\mathrm{t})\hat{\mathrm{y}}$. 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

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

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 $\mathrm{t}=\mathrm{t_c}$ and the ellipticity $\xi\leq 0.2$. This temporal range is called as the polarization gate width and its expression is

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

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 $\mathrm{E_0}$, 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 $\delta\mathrm{t}_G=T_0/2$. In this case, $\tau_p=\delta\mathrm{t}_G/0.3=T_0/0.6$.

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 $\delta\mathrm{t}_G=T_0/2$, it is expected that only a single attosecond pulse is produced in the plateau region of the XUV spectrum. The required delay time $\mathrm{T_d}$ 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-half of an optical cycle. In this case, $T_d \approx \tau_p$, so the field amplitude inside the gate $\mathrm{E}(0) = \sqrt{2}E_0$, which is higher than the outside, as shown in Fig 2 (a). The shaded area in the figure indicates the position of the polarization gate. While when the incident pulse duration is 10-fs, the time delay between two pulse peaks should be adjusted to 22.5-fs to ensure that the gate width is half cycle according to Fig. 1. In this case, $\mathrm{T_d} \gg \tau_\mathrm{p}$, which means that the field outside the gate is much stronger than the inside one, as shown in Fig 2 (b). It is obvious that the electric field in the shaded area is much lower than the outside one. As a result, the conversion efficiency of the harmonic spectra will be low because most of the laser energy is outside the gate.

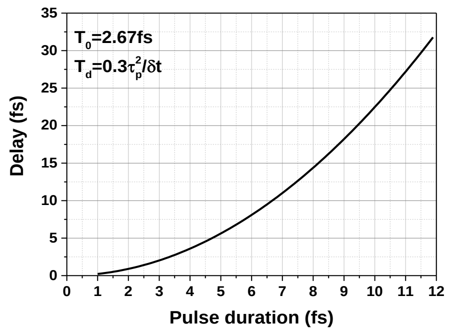

Figure 1: The delay time between two pulse peaks changes with the laser-pulse duration when the polarization gate width is adjusted to one-half of an optical cycle.

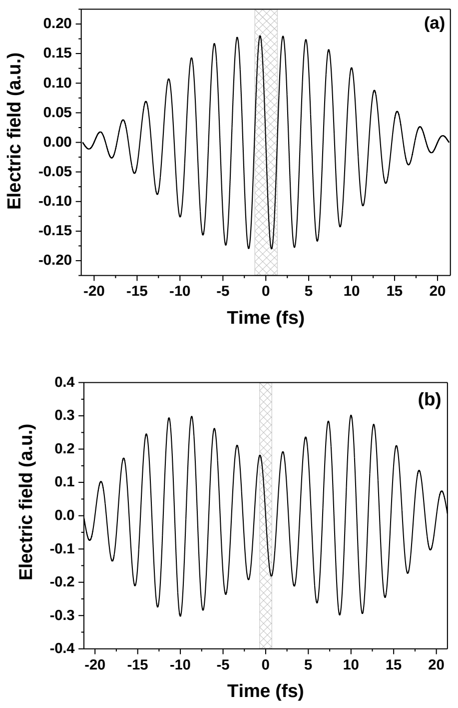

Figure 2: Electric field of the polarization gating pulse from (a) 5fs pulse duration and 5fs time delay. (b) 10fs pulse duration and 22.5fs time delay.

The HHG spectrum from helium atom subjected to the PG pulse with 10-fs pulse duration confirmed the above conclusion, as shown by the solid black curve in Fig. 3. Here the time delay between two pulse peaks is 22.5-fs and the peak field of the input pulse is 0.35a.u. ($4.30*10^{15}$W/cm^2). Accordingly, the peak field within the polarization gate is 0.09 a.u.($2.84*10^{14}$W/cm^2). It can be seen from Fig.3 that the cutoff frequency of the harmonic spectrum is the 55th order and the plateau width with the regular structure is 25 orders (from the 30th to 55th order). Especially, the efficiency of the harmonic plateau is below 10^{-14}.

In the following, we analyze the low harmonic efficiency from the angle of the atomic ionization probability. By using the Ammosov-Delone- Krainov (ADK) model, we show the ionization probability within the polarization gate by the solid blue curve in Fig. 4 (a). In this figure, the ellipticity ξ shown by the red curve changes from 0 to 0.2, so the electric field shown by the black curve is within the polarization gate. It can be seen from the blue curve in Fig. 4 that at the begin of the polarization gate, atomic ionization probability is up to 0.193489, while at the end of the gate, atomic ionization probability is 0.193497. It can be seen that atomic ionization mainly occurs before the polarization gate or after the polarization gate. So one in ten thousand ionization difference within the polarization gate makes it difficult to obtain the high order harmonic with high efficiency and optimized attosecond pulse emission.

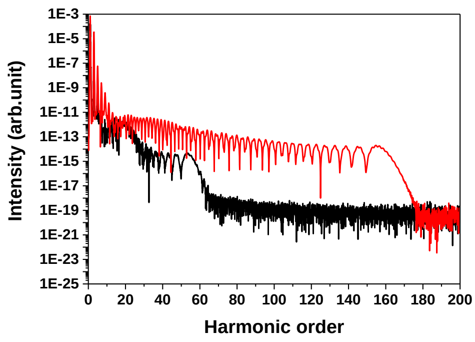

Figure 3: HHG spectra from helium atom exposed to a polarization gating pulse with the gate width $\delta t_G = T_0/2$ (solid black) and $\delta t_G = T_0$ (solid red).

While, for the same 10-fs incident pulse, when the width of the polarization gate is adjusted to one optical cycle, the optimized harmonic spectrum can be realized, as shown by the solid red curve in Fig. 3. Here it is worth pointing out that to compare the effect of the polarization gate width on the harmonic spectra, we keep the ionization probability at the end of the polarization gate close to the same (the ionization probability is between 17% and 20%). In current case, the time delay between two pulse peaks is 12-fs and the peak field of the input pulse is 0.286 a.u. ($2.87*10^{15}$W/cm^2). Accordingly, the peak field within the polarization gate is 0.18 a.u. ($1.13*10^{15}$W/cm^2). Other parameters are the same as those from the solid black curve in Fig. 3. It can be seen from the figure that the cutoff frequency of the harmonic spectrum has been stretched to the 160th order and the plateau width with the regular structure is up to 120 orders (from the 40th to 160th order). And meanwhile, the efficiency of the harmonic plateau is 10^{-12}, higher two orders of magnitude than the black solid line in the figure 3.

To explain the wide and regular harmonic plateau structure, we calculate the recombination instants and the corresponding kinetic energy of electron ionized at different times within the polarization gate in terms of the semiclassical three step model theory[19]. These results are given in Fig. 5. The harmonic evolution with ionization (black solid) time is given by the black solid curve and the harmonic evolution with recombination time is given by the red solid curve. According to the semiclassical theory, attosecond pulse emission usually happens twice during each cycle of the driving laser field. If the polarization gate width is adjusted to one-cycle, we should obtain the irregular high harmonic spectrum due to the interference effect between two emissions. But, in Fig. 5 we find that the electrons ionized by the first quarter cycle before t_c (in region I_1) only emits the harmonic less than the 40th order, and the electrons ionized by the second quarter cycle before t_c (in region I_2) makes the main contribution to the whole harmonic plateau and cutoff position. Therefore, when the polarization gate width is released to one cycle, we still obtain the regular harmonic plateau structure consisted of a long and a short trajectory. Here the long trajectory comes from the electrons which are ionized earlier and back to the nucleus later, and the short one comes from the electrons which are ionized later but back to the nucleus earlier.

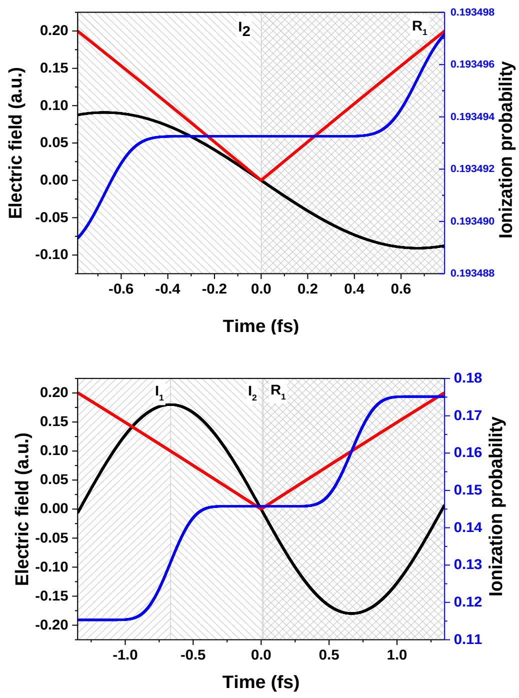

Figure 4: Electric field (solid black), ellipticity (solid red) and the ionization probability (solid blue) within the polarization gate as a function of time.

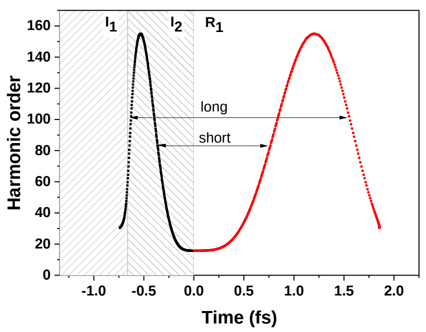

Figure 5: The recombination instants and the corresponding kinetic energy of electron vary with the ionization instant of the electron.

The efficiency of the harmonic plateau can be similarly explained from the angle of atomic ionization probability. The increase of the polarization gate width reduces the time delay between two pulse peaks for 10-fs incident pulse. It will further make the peak position of the synthesized pulse move to within the polarization gate, as shown by the shaded area in Fig 6 (compared to Fig. 2 (b)). It is obvious that when He atom is driven by this electric field, the ionization probability of atoms will also change dramatically.

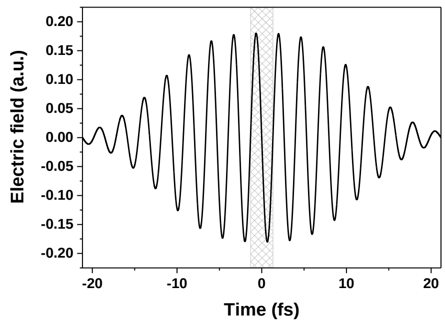

Figure 6: Electric field of the polarization gating pulse with 10fs pulse duration and 12fs time delay as a function of time.

In Fig. 4 (b), we show the ionization probability within the polarization gate by the solid blue curve. It can be seen that at the beginning of the polarization gate, atomic ionization probability is 0.115, while at the end of the gate, atomic ionization probability is up to 0.175. The 6% ionization difference within the polarization gate is much higher than one ten thousand in the case of the half-cycle polarization gate. So we obtain the high harmonic spectrum with efficiency higher two orders of magnitude than the usual polarization gating method consisting of the half-cycle polarization gate. By performing the time-frequency analysis of the harmonic, a 127-as pulse in the time domain is obtained by Fourier transforming the harmonics from 40th to 160th order without compensating the harmonic chirp, as shown in Fig. 7.

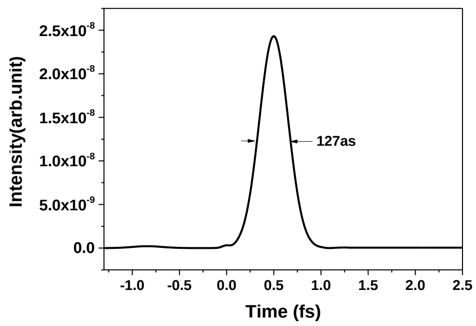

Figure 7: Isolated attosecond pulses obtained by Fourier transforming the harmonics from whole plateau and the cutoff harmonics.

4. Conclusions

We simulate the high order harmonic generation (HHG) from helium atom subjected to the polarization gating pulse with longer pulse duration by using the strong field approximation model. In previous HHG studies by using the polarization gating pulse with longer pulse duration, one needs to dramatically increase the time delay between the two counter-rotating circularly-polarized pulses to generate the nearly-linear half-cycle "polarization gate". It leads to the low harmonic conversion efficiency because the field outside the polarization gate is much stronger than the inside one. In this paper, it is found that even if the polarization gating pulse with the longer duration is adopted, an effective isolated attosecond pulse still can be realized by directly adjusting the polarization gate width to one optical cycle, rather than half cycle. 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. Here it is worth stressing that it is relatively easy for this scheme to operate in the experiment. On one hand, the high intensity pulse with longer pulse duration is relatively easily realized; on the other hand, compared to the double optical gating, we do not need to generate the second harmonic pulse.

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