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Isolated attosecond pulse generation in a 800 nm laser field by adding a terahertz (THz) pulse

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Abstract. We theoretically study the high-order harmonic and the isolated attosecond pulse generation in the near-infrared (IR) (3-fs, 800 nm) laser pulse by adding a terahertz (THz) controlling field with proper phases. It is found that the high-order harmonic spectrum in the IR pulse by adding a terahertz field is broader and smoother than that in the single IR pulse. The underlying physical mechanism is illustrated by means of the time-frequency analysis and the three-step model. We calculate the ionization rate by ADK model to further demonstrate the process of high-order harmonic generation. By superposing a proper range of harmonic spectrum, an isolated attosecond pulse with the duration of 71 as is obtained.

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Key words: High-order harmonic generation, isolated attosecond pulse, terahertz pulse

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1 Introduction

High-order harmonic generation (HHG) has attracted a lot of attention for its excellent characteristics about spectrum for generating attosecond pulses [1-5] and coherent soft x-rays source [6]. The generation of attosecond pulse leads the study of ultrafast nonlinear optics into a new territory for observing the relaxation processes and the motion of electrons inside the atom or molecule [7]. Therefore, a lot of researches have been taken for characteristic of the high-order harmonic emission, and many efficient methods have been suggested [8-12].

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HHG is a nonlinear phenomenon when an atom or molecule are exposed to intense laser fields which can be well explained by the semi-classical three-step model [13]: the electron tunnels through the barrier of the atomic potential which is suppressed by the incident laser pulse, then it moves along with the vibrated electric field without the Coulomb interaction and captures energy, finally it may turn back to the parent ion, emitting high energy photon and the maximum energy of which reaches $I_p+3.17U_p$, where I_p is the atomic and U_p is the ponderomotive energy. Nowadays, a lot of advanced techniques have been proposed to enhance the HHG and generate an isolated attosecond pulse in experiment and theory, such as few-cycle laser driving [14], double optical gating (DOG) [15], the few-cycle pulses [16], polarization gating [17], two-color fields [18-20]. The rapid progress in the terahertz technology makes the extremely strong and long-wavelength THz field become experimentally available [21,22], which leads to a new area to study the effects of THz fields for controlling harmonic emission and generating attosecond pulses [23-25]. Scheme of a terahertz field superposing a mid-infrared driving laser can efficiently extend the cut-off of the spectrum for capturing much more energy during the acceleration and a double-plateau-structured spectrum has been observed [26].

In this paper, we theoretically study the generation of high-order harmonic and isolated attosecond pulses in an 3-fs, 800 nm laser pulse by adding a terahertz (THz) field with proper phases. The spectrum of the second plateau in the IR laser pulse by adding a THz field is broader and smoother than that in the single IR pulse. By superposing a proper range of harmonic spectrum, an isolated attosecond pulse with the duration of 71 as is obtained.

2 Theoretical method

In our calculations, the Lewenstein model [27] is applied to investigate the HHG of He atom in the intense laser field, in which the ground depletion is taken into account. The time-dependent dipole moment of an atom in the intense laser field can be described as

$$\begin{aligned} d(t)=i\int_0^{\infty}d\tau\left(\frac{\pi}{\varepsilon+i\tau/2}\right)^{\frac{3}{2}} & d^*(p_{st}(t,\tau)-A(t))a^*(t)d(p_{st}(t,\tau)-A(t-\tau)) \\ & \times a(t-\tau)E(t-\tau)e^{-iS_{st}(t,\tau)}+c.c., \end{aligned} \tag{1}$$

where ε is a positive regularization constant, τ is the traveling time of free electron between ionization and recombination. $E(t)$ is the electric field of the laser pulse and $A(t)$ is its associated vector potential. $p_{st}(t,\tau)$ is the stationary momentum obtained by the stationary points integral algorithm, which can be defined as

$$p_{st}(t,\tau)=\frac{1}{\tau}\int_{t'}^{t}A(t')dt'', \tag{2}$$

$S_{st}(t,\tau)$ represents the quasi-classical action at the stationary points given by

$$S_{st}(t,\tau)=\tau I_p-\frac{1}{2}p_{st}^2(t,\tau)\tau+\frac{1}{2}\int_{t'}^{t}A^2(t'')dt''. \tag{3}$$

We choose the He atom as the target atom, the corresponding ionization energy I_p is about 0.824 a.u.. In Eq. (1), $a(t)$ is the ground state amplitude described as

$$a(t)=\exp\left[-i\int_{-\infty}^{t}\omega(t'')dt''\right], \tag{4}$$

where $\omega(t'')$ can be calculated by ADK theory [28]:

$$\omega(t)=\omega_s|c_{n^*l^*}|^2G_{lm}(4\omega_s/\omega_t)^{2n^*-m-1}\exp(4\omega_s/3\omega_t), \tag{5}$$

where $\omega_s=I_p/\hbar.\omega_t=\varepsilon/(2mI_p)^{1/2}$, $n^*=(E_s^n/I_p)^{1/2}$, $G_{lm}=\frac{(2l+1)(1+|m|)!(2^{-|m|})}{|m|!(1-|m|)!}$, $|c_{n^*l^*}|^2=2^{2n^*}[n^*\Gamma(n^*+l^*+1)\Gamma(n^*-l^*)]^{-1}$, E_s^n is the ionization energy of He atom; ε is the amplitude of the laser field; l and m are the orbital quantum number and magnetic quantum number; n^* is the effective principal quantum number .

The harmonic spectrum intensity is proportional to the Fourier transformation of the time-dependent dipole acceleration

$$P_a(\omega)\sim\left|\frac{1}{T-t_0}\int_{t_0}^{T}d(t)e^{-i\omega t}dt^2\right|. \tag{6}$$

By superposing several orders of the harmonic spectrum we can obtain the ultrashort pulse as follows:

$$I(t)=\left|\sum_q a_q e^{iq\omega t}\right|^2, \tag{7}$$

$$a_q=\int d(t)e^{-iq\omega t}dt. \tag{8}$$

3 Results and discussions

The target atom is driven by a 3 fs, 800 nm driving laser (IR) pulse by adding a THz field. The central wavelength of the THz field is 4800 nm (corresponding to 62.5 THz). Both the IR and THz field are linear polarized and the IR pulse by adding a THz field has the form

$$E(t)=E_1e^{-2ln2(\frac{t}{\tau_1})^2}\cos(\omega_1t+\varphi_1)+E_2e^{-2ln2(\frac{t}{\tau_2})^2}\cos(\omega_2t+\varphi_2), \tag{9}$$

where τ_1=3 fs and τ_2=32.044 fs are the pulse durations (full-width at half-maximum (FWHM)) of the laser fields; $I_1=9\times10^{14}$ W/cm^2 and $E_2=1.2\times10^8$ V/cm (equivalent

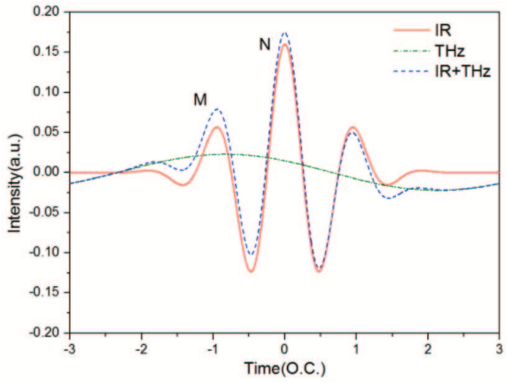

Figure 1: (Color online) Electric field of the 3-fs, 800 nm driving laser (IR) pulse with φ_1=0 and φ_2=0.28π (red solid line), the THz pulse (green dash-dotted line) and the IR laser pulse by adding a THz field (blue dashed line).

to 2×10^{13} W/cm^2) are the peak intensities of IR field and THz field; $\varphi_{1,2}$ is the relative phase, respectively. As shown in Fig. 1, for the IR pulse by adding a THz field, the intensity of the laser field is enhanced around peak M and N, and the corresponding ionization rate around -1 optical cycle of the single IR pulse (O.C.) and 0 O.C. is increased, which can be seen in the Fig. 2(b). The efficiency of harmonic signal is mainly attributed to the ionization rate of the electron which dues to the pulse shaping. Thus the free electrons can capture more kinetic energy while moving back and forth in response to the electric field, which is beneficial for the high-order harmonic emission.

Fig. 2(a) shows the harmonic spectra of He atom generated by the single IR pulse and the IR pulse by adding a THz field. It can be seen from Fig. 2(a) that the HHG exhibit a double-plateau structure for both cases. It is shown that the modulations cover the second plateau in the harmonic spectra generated by the single IR pulse and the two cut-offs reach at 76th and 125th order, which corresponds to $I_p+1.78U_p$ and $I_p+3.17U_p$, respectively. However, the harmonic spectra of the second plateau is extended to 165th order and much smoother in the IR pulse by adding a THz field, but the intensity of the harmonic spectra in the second plateau is lower. It has been reported that in the presence of an intense THz pulse, the symmetry of electron trajectories is broken and the cut-off of the harmonic is greatly extended [25], which is in good agreement with our calculations.

We calculate the corresponding ionization rate by ADK model and the dependence of harmonic order on ionization time (red triangles) and recombination time (green circles) by the three-step model as shown in Figs. 2(b), 2(c) and 2(d) to further demonstrate the process of HHG. Figs. 2(b) and 2(c) clearly indicate that in the single IR laser pulse, the electrons are ionized in the region of time -0.65 O.C. to 0.6 O.C., thus only peak A and B make a major contribution to ionization. The maximum kinetic energy of the corresponding recombination peak A′ and B′ reaches at 125th and 76th order, which corresponds to the cut-off of the second plateau and the first plateau. Figs. 2(b) and 2(d) show that the ionization is mainly taken place around peak E, F, G and H in the IR pulse by adding a

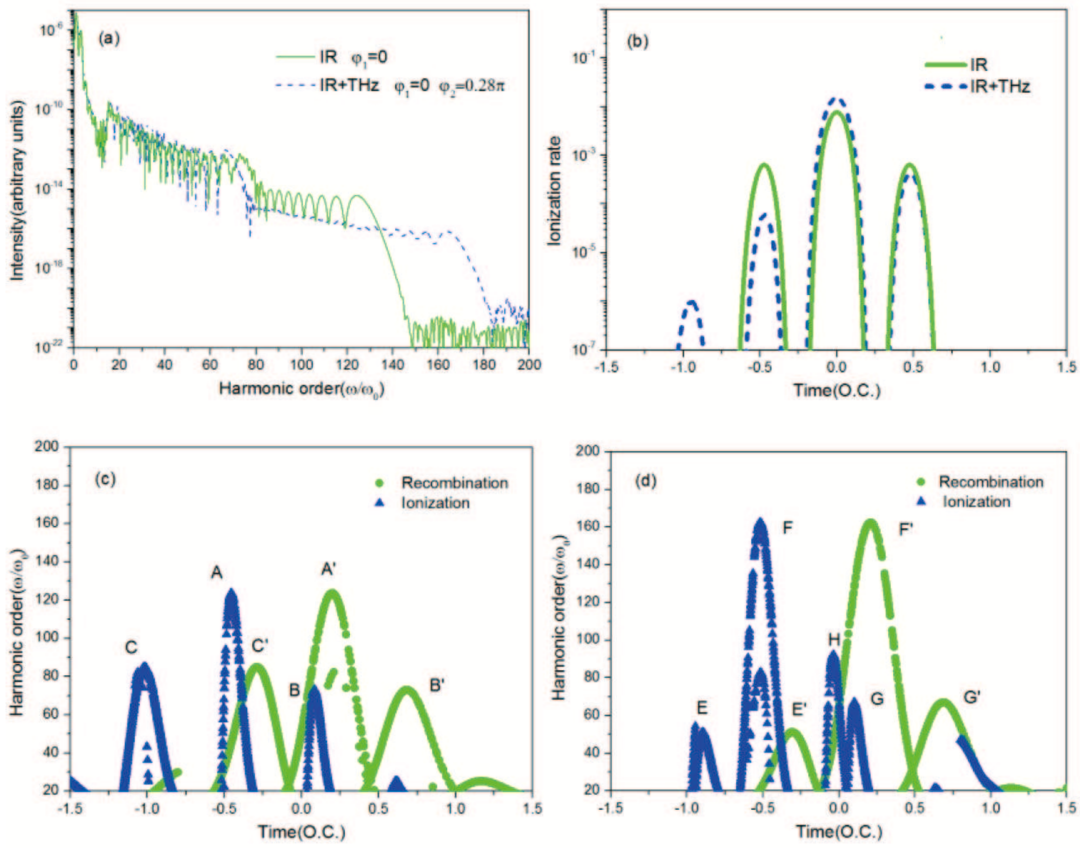

Figure 2: (Color online) (a) Harmonic spectra of He atom generated by the single IR laser pulse (green solid line) and the IR pulse by adding a THz field (blue dashed line). The peak intensity of IR and THz field is 9×10^{14} W/cm^2 and 1.2×10^8 V/cm, respectively. The phases of the two pulses are φ_1=0 and φ_2=0.28π; (b) The time dependence of the ionization rate calculated by ADK theory; (c), (d) show the dependence of harmonic order on ionization time (blue triangles) and recombination time (green circles) in the single IR pulse and the IR pulse by adding a THz field, respectively.

THz field. By calculating the dependence of harmonic order on ionization time and recombination time, we find electrons ionized around peak H experience about 3 O.C. from ionization to recombination, but the pulse duration of the driving laser is only about 1 O.C.. The contribution to HHG from peak H can be ignored since the electrons ionized around peak H can hardly return. Electrons ionized around peak E, F and G return around peak E′, F′ and G′. The recombination peaks E′ and G′ correspond to the first plateau and the harmonics in the second plateau receive the contribution from peak F′, which is extended to 165th order in the IR pulse by adding a THz field. Figs. 2(c) and 2(d) show that the recombination peak A′ and F′ correspond to the second plateau of two cases, which receive the ionization taken place around -0.5 O.C.. The corresponding ionization rate in Fig. 2(b) indicates that around -0.5 O.C., the ionization rate in the single IR pulse is higher than that in the IR pulse by adding a THz field, which makes the har-

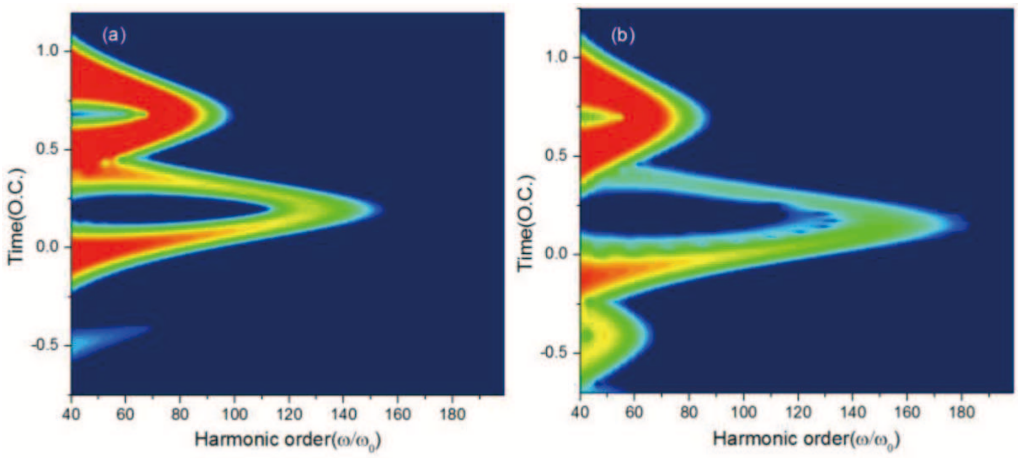

Figure 3: (Color online) The time-frequency analysis of the HHG spectrum generated in (a) the single IR pulse and (b) the IR pulse by adding a THz field, respectively. The parameters are the same as in Fig. 1.

monics signal in the second plateau generated by the single IR pulse about one order of magnitude stronger.

In order to investigate the emission time of the harmonic spectrum, the time-frequency distributions of the HHG spectrums generated in the single IR pulse and the IR pulse by adding a THz field are shown in Fig. 3. For the case of the single IR pulse, Fig. 3(a) shows that there are two photon energy peaks located at 0.15 O.C. and 0.7 O.C. contributing to HHG, which corresponds to the second and first plateau. The quantum path of negative-slope branch with earlier ionization time but later emission time is the long path, and the other path with later ionization time but earlier emission time is the short path. It's obvious that for the harmonic spectrum in the second plateau, interference between the short and long paths is strong, which leads to the modulations of the spectrum. However Fig. 3(b) shows that the harmonics of the second plateau in the IR pulse by adding a THz field receive the contribution from the photon energy peak located at 0.17 O.C.. The long path is suppressed and the interference between long and short paths is weak, which results in a smoother spectrum.

We also illustrate the relative phase effect. Fig. 4 shows that in the single IR pulse by adding a THz field for the case of φ_1=0.18π and φ_2=0.28π, a smooth spectrum in the second plateau is obtained. We investigate the HHG process by the semiclassical three-step model in Fig. 5(a). The contributions from electrons ionized around peak L and S can be ignored because of the long time traveling. The recombination peak T′ corresponding to the second plateau is generated at about 0.15 O.C. with the energy of 172 eV. There is only a short path in peak T′, which contributes to the smooth spectrum of the second plateau and is beneficial to generate an isolated attosecond pulse. We also investigate the time-frequency distribution in Fig. 5(b). One can see that there is one photon energy peak around 0.15 O.C. reaches at 172 eV, which contributes to the harmonics of the second

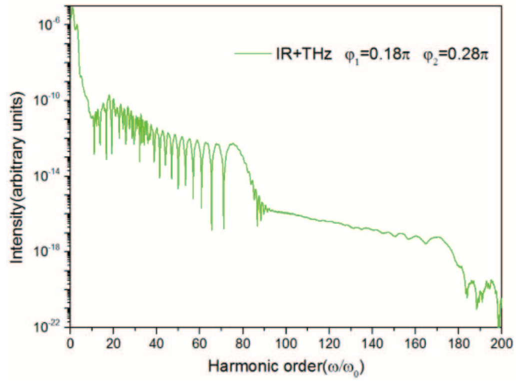

Figure 4: (Color online) Harmonic spectra generated by the single IR pulse by adding a THz field for the case of φ_1=0.18π and φ_2=0.28π.

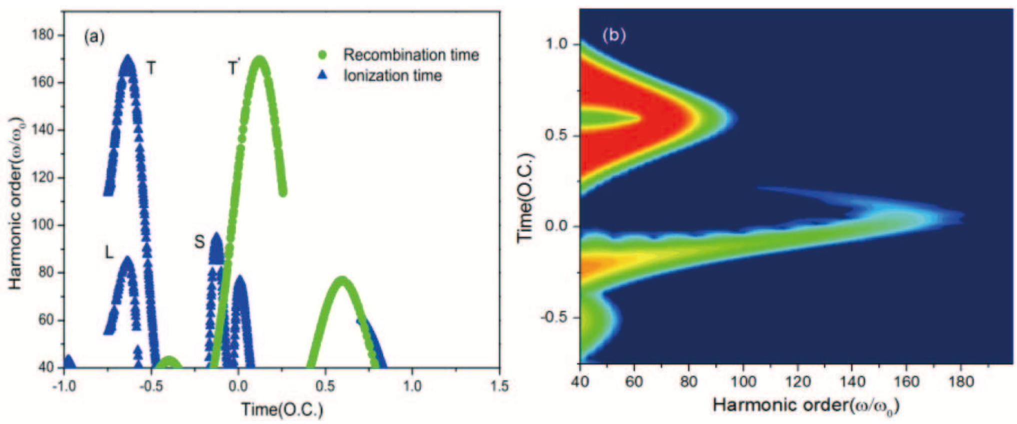

Figure 5: (Color online) (a) The dependence of harmonic order on ionization time (blue triangles) and recombination time (green circles); (b) the corresponding time-frequency analysis of the HHG spectrum in the single IR pulse by adding a THz field for φ_1=0.18π and φ_2=0.28π. Other parameters are the same as those in Fig. 1.

plateau. The long path of the photon energy peak around 0.15 O.C. is too weak to be considered. The little interference between quantum paths leads to a spectrum with little modulation. All those results are corresponding with the discussion of Fig. 5(a).

We investigate the attosecond pulse generation in the single IR pulse and the IR pulse by adding a THz field for different relative phases. By superposing 40 harmonics from 80th to 120th in the single IR pulse, we can obtain two attosecond bursts (P and Q, which are 105 as and 73 as, respectively), but the intensity of the pulse P is two times stronger than that of pulse Q as shown in Fig. 6(a). The pulses P and Q are generated by the long and short path respectively, which corresponds to the time frequency analysis in Fig. 3(a). Fig. 6(b) shows that an isolated 87 as pulse with several small sub peaks by superposing 84 harmonics from 87th to 160th in the IR pulse by adding a THz field for φ_1=0, φ_2=0.28π. Compared with the satellite pulse Q, the small sub peaks are generated

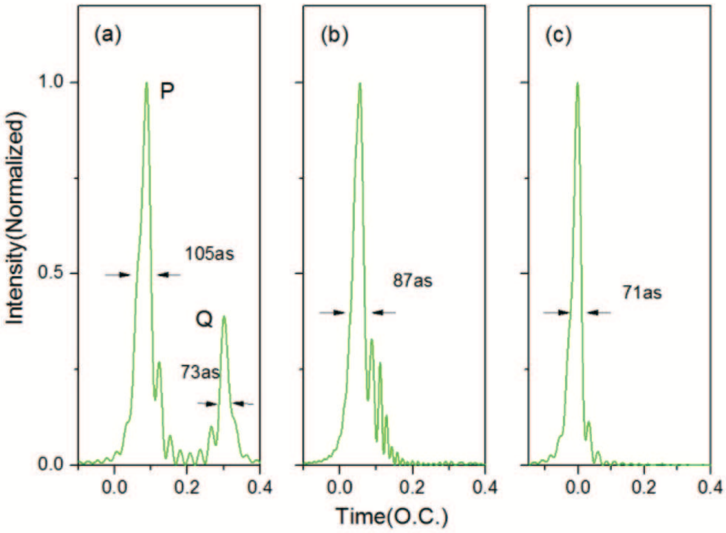

Figure 6: (Color online) The temporal profiles of the attosecond pulses generated by superposing several harmonic orders (a) in the single IR pulse, and in the IR pulse by adding a THz field for relative phase (b) φ_1=0, and (c) φ_1=0.18π.

by the weaker interference between the long and short paths. When the phase of the IR pulse is changed to φ_1=0.18π, only the short path is selected and by superposing 40 harmonics from 110th to 150th, an isolated attosecond pulse with the duration of 71 as can be generated as shown in Fig. 6(c).

4 Conclusions

In summary, we theoretically demonstrate the generation of high-order harmonic and attosecond pulse in the near-infrared (IR) laser field by adding a terahertz (THz) controlling pulse. The Lewenstein model is applied to investigate the high-order harmonic generation of He atom with the ground depletion taken into account. The time-frequency analysis, the three-step model and the ionization rate calculated by ADK model is applied to illustrate the physical mechanism of HHG, which shows that in the IR pulse by adding a THz field, the cut-off of the second plateau is extended to 165th order. But the short and long paths are comparable, which leads to some modulations of the spectrum. For the case of IR pulse by adding a THz field for φ_1=0.18π and φ_2=0.28π, the long path is almost completely suppressed, which result in a smooth spectrum in the second plateau. By superposing 40 harmonics from the 110th to the 150th order of the second plateau, an isolated attosecond pulse with duration 71 as is obtained.

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