Extension of high-order harmonics and generation of an isolated attosecond pulse in the chirped laser field*

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This paper theoretically investigates the high-order harmonic generation cutoff extension using intense few-cycle linearly chirped laser pulses. It shows that the cutoff of the harmonic can be extended remarkably by optimising the chirping parameters. The time-frequency characteristics of high-order harmonics with different chirping parameters are analysed by means of wavelet transform of the dipole acceleration. It also gives out the classical three-step model pictures of electron. By superposing a properly selected range of the harmonic spectrum, it obtains an isolated 65as pulse.

Keywords: high-order harmonic generation, isolated attosecond pulse, chirped laser field

PACC: 3280K, 4265K

High-order harmonic generation (HHG) is a phenomenon which occurs in the multi-photon physics when the atoms or molecules are driven by a short intense laser pulse.[1] Because of its potential application such as obtaining a coherent light in the extreme ultraviolet (XUV), a coherent soft x-rays source[2,3] and the generation of attosecond pulses,[4−6] it has been rapidly developed in the past decade. The HHG spectrum has the general character: a fast decrease for the first few harmonics then exhibits a broad plateau and ends up with a sharp cutoff. The HHG process can be well understood by means of the well-known semi-classical three-step model.[7] A great deal of attention has been devoted to enhance the harmonic efficiency and extend cutoff position of the harmonic plateau.[8−13]

Due to the discrete nature and broad spectrum with equidistant frequency, HHG has been used to generate attosecond pulses. The capability of generating attosecond pulses enables us to trace and probe the ultrafast processes of the electrons in atoms and molecules.[4] To obtain an isolated attosecond pulses with shorter duration has been a common goal of many people in the past decade. Hong *et al.*[14] obtain isolated attosecond pulses with the duration about 100as by adopting a few-cycle driving pulse combined with its second harmonic field. Through the investigation of HHG in helium atoms driven by a multi-cycle two-colour optical field, Zou *et al.*[15] obtain an ultrabroad XUV supercontinuum with a spectral width of 130 eV and an isolated 67as attosecond pulse in the water-window spectral region. Xiang *et al.*[16] study the control of the high-order harmonics cutoff through the combination of a chirped laser and static electric field and obtain an isolated 10as pulse. Carrera and Chu[17] used a hyperbolic tangent chirped laser fields to remarkably extend the cutoff position of the harmonic. Zhao *et al.*[18] use intense few-cycle shaped infrared laser in combination with an ultraviolet attosecond pulse to enhance the harmonic efficiency and obtain an isolated 57as pulse. It is shown that there are two paths, so-called long path and short path, which contribute to every harmonic. Because the two paths have different emission times, the harmonics are not phase-locked.[19] As a result, superposing several harmonics leads to an irregular attosecond pulse with two separate bursts. To resolve this problem, it is essential to control the quantum path so as to pick out one single path,[20] and finally, filter several consecutive harmonics in the cutoff region.[21,22]

In this paper, we choose the linearly chirped laser pulse as the driving laser pulse,[23] and investigate the effect of the chirping parameter on the HHG. When the chirping parameter varies from 0 to 0.55, the cutoff of the harmonic plateau has been remarkably extended from $I_{\rm p} + 3.17U_{\rm P}$ to $I_{\rm P} + 12.12U_{\rm P}$, where $I_{\rm p}$ is ionisation potential and $U_{\rm P}$ is ponderomotive energy. To explore the underlying mechanism responsible for the cutoff extension, we perform a classical simulation by virtue of the three-step model. Our results also show

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that chirping the laser pulse can modify the trajectory of the electron wave packet. Since one of the two paths is suppressed, we obtain an isolated 65as pulse, which can be explained through the time-frequency analysis of the emitted pulses by means of the wavelet transform of the induced dipole acceleration.

We investigated HHG and the generation of attosecond pulse by solving numerically the time-dependent Schrödinger equation for the one-dimensional model hydrogen atom with the help of the splitting-operator fast-Fourier transforms technique. We choose the soft-core Coulomb potential $V(x) = -1.0/\sqrt{x^2+2}$ as the atomic potential.[24] The laser field is linearly polarised and can be expressed in the form $E(t) = E_0 f(t)\cos[\omega t + \delta(t)]$, where E_0 is the peak laser field amplitude, $f(t) = \exp[-2\ln(2)t^2/\tau^2]$ is the laser field envelope, ω and τ are the corresponding frequency and the duration, respectively. And $\delta(t)$ is the carrier-envelope phase,[23] which has the time-varying form $\delta(t) = -\beta\omega t^2/T_0$. The chirp form is controlled by adjusting the two parameters β and T_0. When $\beta = 0$, the pulse is chirp-free.

After the time-dependent wavefunction is determined, we can then calculate the induced dipole acceleration. The HHG power is proportional to the modulus-squared of the Fourier transform of induced dipole acceleration. Temporal profile of attosecond pulse can be obtained by superposing several orders of the harmonics. The time-frequency characteristics of high-order harmonics with different chirping parameters can be analysed by means of wavelet transform of the dipole acceleration.[25]

We study the HHG when hydrogen is exposed to the 5-fs 1200-nm fundamental laser pulse with the peak intensity $I = 5 \times 10^{14}$ W/cm^2. We present the laser field with different chirping parameters in the Figs. 1(a)–1(c), and the corresponding high-order harmonic power spectra in Figs. 1(d)–1(f). We fix the T_0 as 10 optical cycle (o.c.), the total calculated time, while the parameter β varies. From Fig. 1 we can see that, as the parameter β increases, the oscillatory periodicity of the laser is broken and the cutoff of the harmonic plateau is extended. Figure 1(d) shows that, when $\beta = 0$ (chirp-free) the cutoff of the harmonic spectrum is positioned at the 220th order harmonic, corresponding to the energy $I_\mathrm{p} + 3.17U_\mathrm{P}$ which is consistent with the famous cutoff rule. Figure 1(e) shows that, when $\beta = 0.25$ the harmonic spectrum presents two plateaus, where the first cutoff is positioned at the 265th order harmonic and the corresponding energy is $I_\mathrm{p} + 3.88U_\mathrm{p}$, the second cutoff is positioned at the 355th order harmonic corresponding to the energy $I_\mathrm{p} + 5.27U_\mathrm{p}$. When $\beta = 0.55$, as shown in Fig. 1(f), the cutoff is positioned at 798th order harmonic, corresponding to the energy $I_\mathrm{p} + 12.12U_\mathrm{p}$. From these results we can conclude that the extension of the harmonic plateau can be achieved by adjusting the parameter β of the chirped pulses, which is similar to the numerical results of Ref. [17].

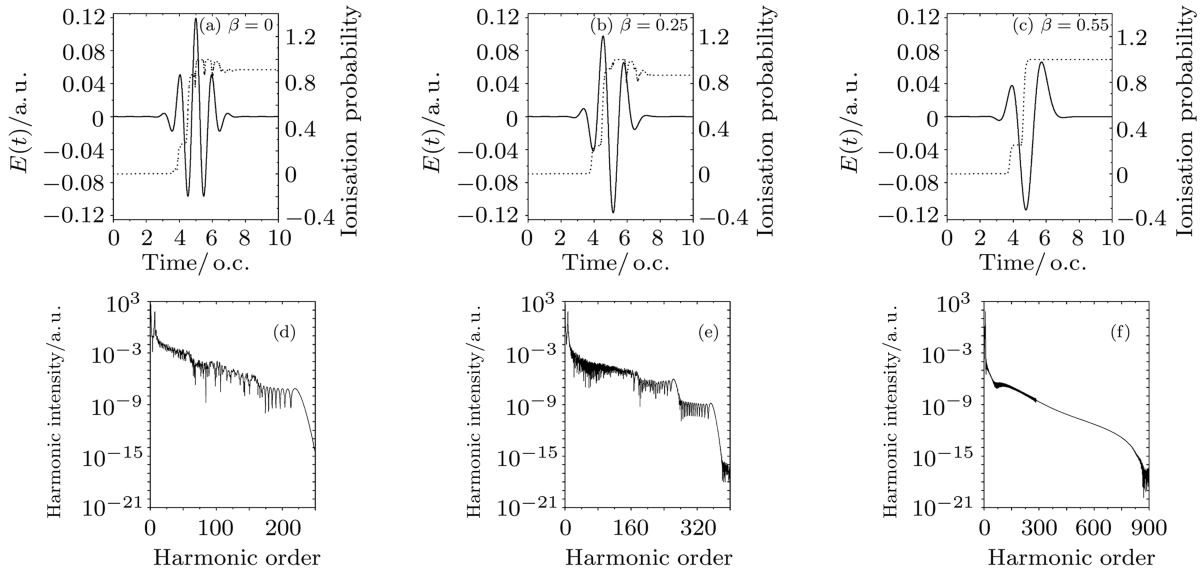


Fig. 1. (a)–(c) are the driving chirped laser fields (the solid curve) and the ionisation probability (the dotted curve) of different chirping parameters, (d)–(f) are the corresponding HHG power spectra, where the parameters (a) $\beta = 0$, (b) $\beta = 0.25$, (c) $\beta = 0.55$, respectively.

Figure 2(a) shows the temporal profile of the attosecond pulse in the case of $\beta = 0$. We can see that there are two attosecond bursts generated by superposing the harmonics from 175th order to 215th order. The two bursts have the same pulse duration of 95 as. To best understand the mechanism of the generation of the two bursts, we give out the time-frequency analysis through the wavelet transform of the dipole acceleration. As shown in Fig. 2(b), the harmonics from 175th to 215th are located at the main peak B, there are two main electron paths so-called short and long path with different emission times contributing to each harmonic near the main peak B, which are located near the 5.1 o.c. and the 5.3 o.c., respectively.

For the case of $\beta = 0.25$, it is almost the same as the case of $\beta = 0$. We can see from Figs. 2(c) and 2(d) that, there are two attosecond bursts when superposing the harmonics from the 290th order to the 330th order, and the pulse duration of the two attosecond bursts are both about 95 as. But for the case of $\beta = 0.55$, as shown in Fig. 2(e), an isolated 65 as pulse can be generated by superposing the harmonics from the 330th order to the 390th order. From the wavelet transform of the harmonics, we can see only the short trajectory is selected, whose emission time at about the 4.8 o.c., to contribute these harmonics between the 330th order to the 390th order as shown in Fig. 2(f). Once the short path is selected, isolated attosecond pulse can be generated.

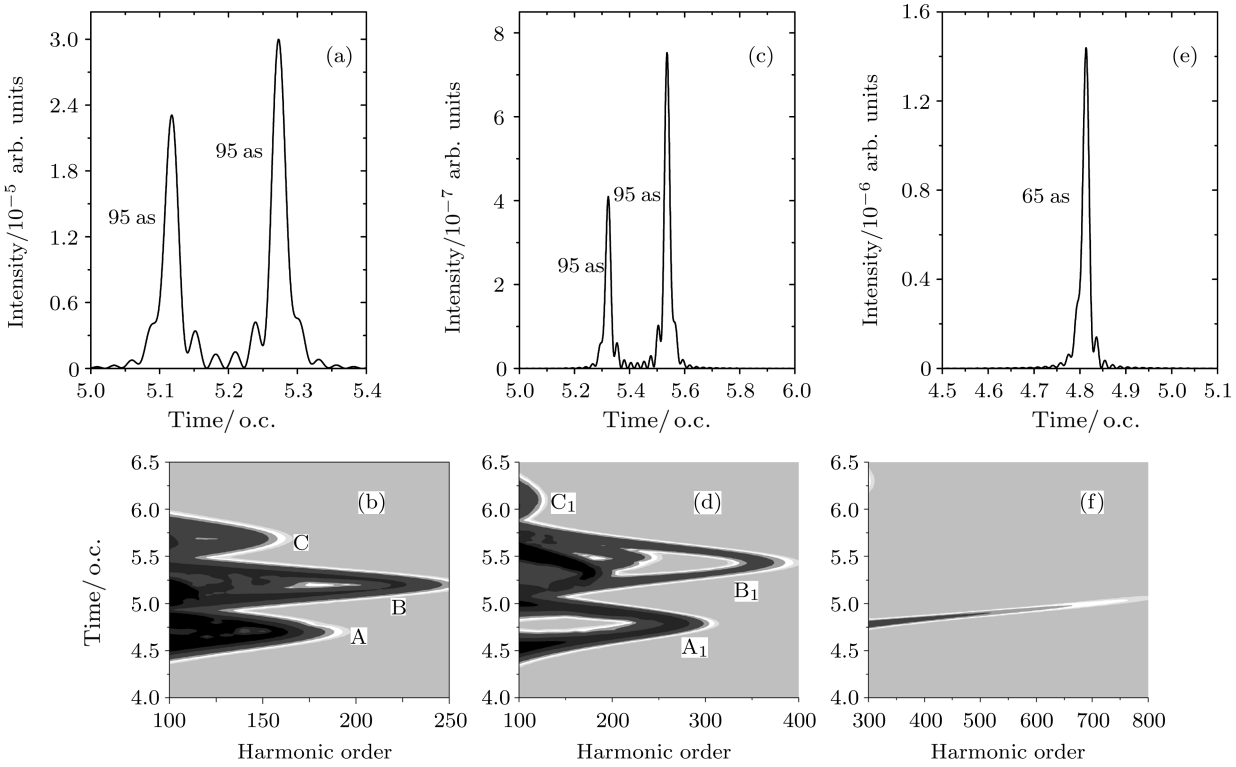


Fig. 2. The temporal profiles of the attosecond pulses: (a) generated by superposing the harmonics from 175th to 215th order for the case of $\beta = 0$; (c) generated by superposing the harmonics from 290th to 330th order for the case of $\beta = 0.25$; (e) generated by superposing the harmonics from 330th to 390th order for the case of $\beta = 0.55$. Figures (b), (d), (f) show the corresponding time-frequency distribution of the HHG for $\beta = 0$, $\beta = 0.25$ and $\beta = 0.55$, respectively.

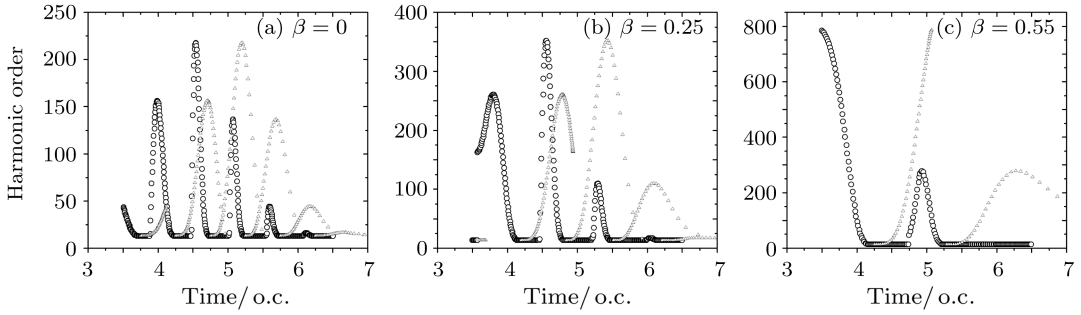


Fig. 3. The dependence of the harmonic order on the ionisation time (the circle curve) and the emission time (the triangle curve): (a) $\beta = 0$; (b) $\beta = 0.25$; (c) $\beta = 0.55$.

To understand the underlying mechanism of the extension of the harmonic plateau and the generation of an isolated attosecond pulse, we give a clear physical picture in terms of the semiclassic three-step model (see Figs. 3(a)–3(c)). We also present the ionisation probability of the electron for different chirping parameters in Figs. 1(a)–1(c) (the dotted curve). We can see from Fig. 1 that, for the case of the $\beta = 0.55$, the ionisation probability is unchanged after about 5.0 o.c. But for the cases of $\beta = 0$ and $\beta = 0.25$, the ionisation probability is unchanged after about 6.5 o.c. Hence, the first 5.0 o.c. laser affects the ionisation of the electron for the case of the $\beta = 0.55$. And the first 6.5 o.c. laser affects the ionisation of the electron for the cases of $\beta = 0$ and $\beta = 0.25$. These are consistent with the classical three-step model because from Figs. 3(a) and 3(b) we can see that, after the 6.5 o.c. the ionisation energy of the electron is almost equal to zero. From the Fig. 3(c) we can see that the ionisation energy of the electron is almost equal to zero after the 5 cycle. Figures 3(a)–3(c) also show that most electrons are emitted nearby the local peaks of the laser before the steady ionisation time with maximum kinetic energies. Hence, if an ionised electron wants to obtain higher emission energy it must have long accelerated time and at the same time it must have enough returning time to combine with the parent ion. If we want to get an isolated attosecond pulse, one of the trajectories of the electron may be supressed and only one trajectory contributes to the harmonics. Just as Fig. 3(c) shows, when $\beta = 0.55$ electrons are mainly ionized nearby the 3.5 and the 5 o.c., but only the electrons ionised nearby the 3.5 o.c. have long accelerated and enough returning time, so these electrons have much higher emission energy. At the same time, there is only one short trajectory near the peak of the 3.5 cycle, the long trajectory is suppressed, and we can obtain an isolated attosecond pulse just as Fig. 2(e) shows.

In conclusion, we have investigated the HHG and generation of the isolated attosecond pulse in the chirped laser field. We found that a remarkable enhancement of the harmonic emission can be achieved by adjusting the chirping parameter, which changes the form of the laser field and the trajectory of the electron. When we choose a proper chirping parameter we obtain an isolated 65 as pulse.

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