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Quantum path controlling in the presence of a low frequency field to generate isolated attosecond pulse

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ABSTRACT

In this article, an efficient method is presented to generate an isolated attosecond pulse based on synthesized laser field. The 1D time-dependent Schrödinger equation is numerically solved for a helium atom exposed in a strong laser field. Two color fields containing a chirped laser pulse and its half harmonic as control pulse are modulated by a low frequency field to construct the configuration of strong laser field. The effect of low frequency field dominates the effect of the chirp parameter and extremely affects the acceleration step of high-order harmonic generation process. The low frequency field, in the optimized conditions, eliminates the long quantum path completely and only the short quantum path contributes in the higher harmonics emission mechanism. With such scheme, an extra supercontinuum with 700 eV bandwidth can be generated which supports the creation of a 64 attosecond isolated pulse. Moreover, the classical electron dynamics and the time–frequency analysis for explaining the underlying physics of atom–pulse interaction are also presented.

1. Introduction

The study of attosecond (as) physics in intense ultrashort laser fields is now a forefront subject of much current interest and significance in science, because attosecond pulses opens up a novel avenue to probe ultrafast electronic dynamics deep inside the atoms and molecules and time-resolved studies with unprecedented resolution [1–3]. High-order harmonic generation (HHG) is a powerful and promising approach to creating trains or isolated attosecond pulses (IAP) in the extreme ultraviolet (XUV) [4–6]. The HHG process is caused by the interaction of intense laser field and the atomic or molecular systems. This process is usually described by the well-known classical model, the three-step model (TSM) [7,8]. According to this model, first, the electrons tunnel through the barrier composed of strong electric field and the Coulomb potential; second, freed electrons will be accelerated by the strong electric field and get a large amount of kinetic energy; third, the electrons are pulled back to recombine with their parent ions and emit harmonic photons with frequency equal to $\hbar w_{max} = I_p + 3.17E_k$. HHG from a few-cycle driving pulse [9] and the temporal confinement of HHG using polarization gating [10–12] are the two techniques currently available for creating IAP. Very recently, Zhao et al. [13] have produced a 67 as pulse via latter method, with a 7 fs, 750 nm laser pulse, which is the known world's shortest attosecond pulse at present. A good method was recently proposed which combines the polarization gating and ionization gating by using a driving laser field with two orthogonally components suitably chirped and delayed [14,15]. Also many useful techniques based on field synthesis including the optical gating, polarization gating and ionization gating have been reviewed in recent work [16]. From a theoretical point of view, the application of two-color field scheme provides a new way to study the HHG [17–19]. The underlying physics is that the laser field amplitude varies acutely between the two neighboring half-cycle, and the maximum electron return energy of each individual half-cycle is different. The broad XUV continuum spectrum that supports ultrashort attosecond pulse results from the enlarged difference of the cutoff energies between the highest and the second highest half-cycles.

Control of quantum path of the returning electron is an efficient way to produce supercontinuum HHG spectrum and isolated attosecond pulse. It is well known that there are two dominant quantum paths, which are called short path and long path. These two quantum paths correspond to every different emission time and contribute to each harmonic emission, however, their phases are not locked [20], and the interference between them is detrimental to produce an isolated attosecond pulse, thus, picking out single quantum path is necessary. At present, various ways of controlling quantum paths are proposed in the two-color field scheme. By adding a relatively weak sub-harmonic laser pulse to the fundamental laser pulse, single short trajectory is selected and an isolated 79 as pulse is produced [21]. From spatial filtering, the short trajectory can also be chosen [22]. With an optimal carrier phase, the generated HHG spectrum is

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supercontinuum that corresponds to the selection of the quantum path [23]. Both the long and short quantum paths can be chosen respectively by adjusting the relative phase [24]. The application of the chirp technology provides us a new way to quantum control of HHG process and chooses the single electron trajectory in both theory and experiment [14,15].

In this paper, we report on IAP creation from the HHG process under a synthesized two color laser field with the modulation of a low frequency field. Our idea is triggered by a series of previous works on the influence of a static electric field on HHG, where a weak static electric field plays a role in modulation [25–28]. Based on these works, the presence of the static electric field can not only break the inversion reflection symmetry, but also can effectively extend cutoff of the HHG. Furthermore, an ultrabroad supercontinuum spectrum can be generated. Although the effects of the single and multi-cycle pulses in free and chirped forms combined with the static field have already been investigated [29–32], our aim is to investigate the HHG process in the presence of a low frequency field and two color laser field containing chirped driving and free controlling pulse. Three main reasons support our idea. First, these works have employed a high intensity static electric field to broaden the supercontinuum while we know achieving such field is difficult with current technology, so a low-frequency field can be a good alternative in practice. Second, while the static electric field strengthens the main peak and the neighboring peaks equivalently, the low-frequency field strengthens the main peak more than sub-peaks, so it can affect the ionization and acceleration step in the HHG process. Finally, according to our knowledge, the effect of low frequency field on the quantum path and HHG process in the presence of two color laser field containing chirped driving laser pulse and its half harmonic has not already been investigated. We find that the effect of low frequency field dominates the effects of controlling wave and chirp parameter. In all sections of this paper, the chirped two color field refers to two color field containing a chirped driving field and a free controlling field.

Outlines of this paper are as follows. In Section 2, we briefly describe the background physics of the HHG process and the employed numerical method to simulate pulse–atom interaction. In Section 3, we discuss how the HHG process in the presence of a low frequency field and a synthesized two color laser field containing chirped driving laser pulse and its half harmonic as controlling component is affected by laser parameters. Finally, we summarize our important results in the conclusion section.

2. Physical model

This section provides the theoretical background and an overview of the numerical methods used to simulate the physics of pulse–atom interaction. The dynamics of an atomic electron in a strong laser field is mainly along the direction of the field. Hence, it is reasonable to model the HHG in 1D by solving the time dependent Schrödinger equation (TDSE) in the single active electron and dipole approximation.

$$i\frac{\partial\psi(x,t)}{\partial t}=H(t)\,\psi(x,t)=\left[-\frac{1}{2}\frac{\partial^2}{\partial x^2}+V_{atom}(x)+V_{laser}(x,t)\right]\psi(x,t) \qquad (1)$$

The atom units are used in all equations in this paper, unless otherwise mentioned. To model an atom in 1D, we use the soft-core potential which can be expressed as $V_{atom}(x)=-1/\sqrt{(b+x^2)}$. Here, b is the softening parameter. We choose $b=0.484$ which corresponds to the ionization potential (I_p) of 24.6 eV for the ground state of the helium atom. The potential due to the combined laser electric field linearly polarized along the x-axis is

$$\begin{aligned}V_{laser}(x,t) &= -\vec{E}\cdot\vec{r}\\ &= -[E_1 f_1(t)\cos(\omega_1 t+\delta(t))+E_2 f_2(t)\cos(\omega_2 t+\varphi)\\ &\quad +E_3\cos(\omega_3 t)]x\end{aligned} \qquad (2)$$

E_i and ω_i $(i=1\rightarrow 3)$ represents amplitudes and frequencies of the main pulse, the control pulse and the low frequency field, respectively. $\delta(t)$ and φ represents the carrier-envelope phases (CEPs) for the main and control pulses, respectively. For a linearly polarized chirped laser field, its time-varying CEP can be expressed as $\delta(t)=\beta\times \tanh((t-t_0)/\tau)$. The chirp is governed by three parameters β, t_0 and τ, where β controls the frequency sweeping range, τ controls the steepness of $\omega(t)$, and t_0 controls the center of frequency sweeping. To model a short-pulsed laser, we shall use a Gaussian envelope $f(t)$ given by $f_i(t)=\exp(-4ln(2)\ t^2/\tau_i^2)$ where τ_i $(i=1\rightarrow 2)$ are the corresponding pulse durations (full-width at half-maximum) of the two synthesized laser fields. The initial state in TDSE is the ground state of the system before we turn on the laser ($t=-\infty$). It is the solution of the eigenvalue problem

$$\varepsilon\psi(x,0)=H_0\psi(x,0)=\left[-\frac{1}{2}\frac{\partial^2}{\partial x^2}+V_{atom}(x)\right]\psi(x,0) \qquad (3)$$

where $H_0=H(-\infty)$, and ε is the energy of an electron. By using the finite difference approximation, we can express (3) as a linear matrix equation. The algorithm to find a set of eigenstates which diagonalize H_0 is well known, and we can use LAPACK subroutines DSTEBZ (eigenvalue solver) and DSTEIN (eigenstates solver) to do the task. Eq. (1) can be solved numerically by using the Crank–Nicholson scheme and the LAPACK subroutine ZGTSV (complex tridiagonal matrix solver). Once having found the state $\psi(t)$ of the system from 1D-TDSE (1), we can calculate the harmonic spectrum as follows. The photo-emission probability $D(\omega)$ of an atom is proportional to the Fourier transform of the acceleration $a(t)$ of its active electron. That is,

$$D(\omega)=|[1/\tau_1\omega^2]\int_{-\infty}^{\infty}dte^{-i\omega t}a(t)|^2 \qquad (4)$$

where $a(t)$ can be obtained by using the commutator relation, i.e. $a(t)=d^2\langle x\rangle/dt^2=-<\psi(t)\big|[H,[H,x]]\big|\psi(t)>$ where H is the Hamiltonian defined in Eq. (1). The function $D(\omega)$ is called the dipole spectrum. In the classical picture, to find the recollision time we should solve the Newton's equation knowing such time stratifies $x_e(t_r)=0$ equation i.e. the electron comebacks to the initial position. It is found that two couple times (t_r, t_i) satisfies the following equation.

$$\int_{t_i}^{t_r} A(t)\,dt=(t_r-t_i)A(t_i) \qquad (5)$$

With obtained two couple times, the harmonic energy w_h can be obtained through $w_h=0.5\times[A(t_r)\ -A(t_i)]^2+I_p$; here $A(t)$ is called the electric potential and, t_i and t_r are the ionization and recombination times, respectively.

3. Simulation results and discussion

In our wave packet simulation, a 5-fs/800 nm as main field, a 10-fs/1600 nm as control field, and a low frequency field 16,000 nm are synthesized and imposed a helium atom to release high energy photons. In our scheme, t_0 and τ are set as 0.0 and 400 au. The pulse intensity of the fundamental field, the control pulse and the low frequency pulse are chosen to be 5×10^{14}, 1×10^{14} and 1×10^{13} W/cm^2, respectively. The carrier-envelope phase for the control pulse is -0.2π. In order to find how the synthesized field impacts the HHG process, we consider the HHG spectrum of helium atom in three cases. We distinctly study triplet cases. The last discussion in the former published works has been ended to the study of the effect of static electric field combined