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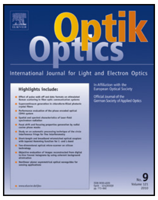

Ultra-broadband supercontinuum generation with a nonlinear chirped pulse for controlling quantum path

Jianghua Luo*, Dahai Xu

College of Physical Science and Technology, Yangtze University, Jingzhou 434023, China

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ABSTRACT

We theoretically investigate the high-order harmonic generation in helium atom driven by a nonlinear chirped laser pulse with few-cycle duration. By employing appropriate chirp to the driving pulse, an efficient electric field waveform of controlling quantum path for ultra-broadband supercontinuous harmonics is realized, and then an isolated sub-50 as pulse with bandwidth of 739 eV can be significantly obtained.

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1. Introduction

The development of high-order harmonic generation (HHG) for isolated attosecond pulses, based on the principle of mode-locked laser, enables ultra-fast studies on inner-shell electronic dynamics in atoms and molecules with unprecedented resolution [1–3]. Nowadays, experimental advances in HHG technique have successfully realized an isolated attosecond pulse with duration of 80 as by synthesizing the generated 40 eV supercontinuum [4]. Since the bandwidth of supercontinuous harmonics plays a crucial role in performing ultra-fast measurements of attosecond-resolution [5], much efforts have been paid to generate more broad supercontinuum [6–8]. To obtain broadband supercontinuum, the well known challenge is the effective control of the HHG process which has been best described by the three-step model [9]: ionization, oscillation and recombination. During this process, the electron is first ionized near the peak of strong laser field, and then it oscillates with the laser field and acquires kinetic energy; after the laser field reverses its direction, the electron is driven back; finally, it recombines with the core and simultaneously releases its energy emitting coherent high harmonic photon with energy equal to the ionization potential plus the kinetic energy.

In the earlier stage, the few-cycle-pulse driving scheme [10] and the polarization gating technique [11] have been introduced to generate isolated attosecond pulses. However, the bandwidths of the generated UV supercontinuum are limited to tens of eV. Recently, waveform-controlled two-color fields have been proposed and demonstrated to be efficient for broadband supercontinuum [12–14]. The key idea of two-color scheme is attributed to shaping the driving field waveform by a relatively weak modulation. Due to the presence of a second field of different frequency and intensity, this scheme is relatively flexible for the well control of electronic dynamics of the corresponding harmonic process, and thereby has the potential not only to energize the possible recombination electron in the oscillation step (extend the cutoff) but also to facilitate specific electron path for coherent radiation (produce supercontinuum) [8,15]. However, for the bandwidth of generated supercontinuum the breakthrough of 200 eV barrier is still a challenge. In this paper, we present another method to achieve ultra-broad supercontinuum by a few-cycle reshaped pulse. Unlike the conventional two-color field scheme, this waveform-controlled approach is to employ a nonlinear chirp to laser phase, rather than weak modulation to laser intensity. The results show that, based on optimizing the chirped parameters of the driving pulse for ideal waveform, an ultra-broad 724 eV supercontinuum covered by spectral range from UV to X-ray is successfully obtained, which potentially enables us probing an extremely wide range of ultra-fast processes with sub-50 as time-resolution.

The rest of this paper is organized as follows: The theoretical model is first given in Section 2, then the numerical results and discussion are presented in Section 3, finally we summarize our conclusions in Section 4.

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* Corresponding author.
E-mail address: jhluo@yangtzeu.edu.cn (J. Luo).

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2. Theoretical model

Our theory is based on solving the one-dimensional time-dependent Schrödinger equation for helium atom in the linearly polarized laser [atomic units (a.u.) are used throughout]:

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

where $E(t)$ is electric field of the laser pulse and $V(x)=Z/\sqrt{\alpha+x^2}$ describes the soft coulomb potential with $Z=-1$ and $\alpha=0.484$ to match the ground ionization potential I_P=0.9035 a.u. of the real helium atom. Eq. (1) is accurately solved by means of split-operator method [16]. After solving the time evolution of the wave function $\psi(x,\,t)$, the time-dependent induced dipole acceleration can be given by Ehrenfest theorem:

$$a(t)=-\langle\psi(x,t)|\frac{\partial}{\partial x}V(x)-E(t)|\psi(x,t)\rangle, \qquad (2)$$

the HHG spectrum can be determined by Fourier transform of $a(t)$:

$$P_q(\omega)=|a_q(\omega)|^2, \qquad (3)$$

where $a_q(\omega)=\int_0^t a(t)\exp(-iq\omega t)dt$, q denotes the harmonic order. A pulse temporal profile can be obtained by superposing several orders of harmonics.

$$I(t)=|\sum_q a_q e^{iq\omega t}|^2, \qquad (4)$$

3. Results and discussion

A linearly polarized chirped laser pulse is introduced in our simulation, the expression can be written as:

$$E(t)=E_0 f(t)\cos\left[\omega\left(t-\frac{T}{2}\right)+\delta(t)+\varphi\right], \qquad (5)$$

here, $f(t)=\sin^2(\pi t/T)$ is the pulse envelope, $T=5T_0$ the pulse duration at full width at half maximum (FWHM) of 5 fs, T_0 the pulse optical cycle, and ω the laser frequency at 800 nm. E_0 denotes the amplitude corresponding to the laser pulse intensity of 3×10^{14} W/cm^2. Then the ponderomotive energy $U_P=E_0^2/\omega^2$ is calculated to be 18 eV. The inherent carrier-envelope phase (CEP) of the laser pulse φ is set as 0.3π and $\delta(t)$ represents the time-varying CEP, which characters the chirp of laser pulse and has a widely used form of [17]:

$$\delta(t)=-\beta\tan h\left[\frac{t-t_0}{\sigma}\right],\ 0\le t\le T. \qquad (6)$$

In Eq. (6), $t_0=2.5T_0$ corresponds to the middle of the scanning time (pulse duration $5T_0$), and the parameters β and σ can be adjusted to control the chirp form by means of comb laser technology [18]. Under this condition, the field-form may be well controlled by changing the chirped parameters. Figs. 1 and 2 illustrate the schematic description of time-varying field-form versus different chirped parameters. Fig. 1(a)–(d) shows the case when β is fixed at 10 and σ is varied, in contrast, the other case that fixing σ at 200 and varying β is shown in Fig. 2(a)–(d). As shown in Figs. 1 and 2, once β increases or σ decreases, the time interval of electric field peak, i.e., the so-called electron oscillation period will elongate and vice versa. According to the classical three-step model, in the few-cycle driving regime the electron is mainly ionized near the peak of the electric field and form several dominant oscillators. Consequently, this field-form-controlled method induced by chirp seems to be promising to rein quantum path.

To clearly give a physical picture of above forecast, we investigate the HHG process in terms of the three-step model. First, the classical map of harmonic process in chirp-free (β=0) pulse

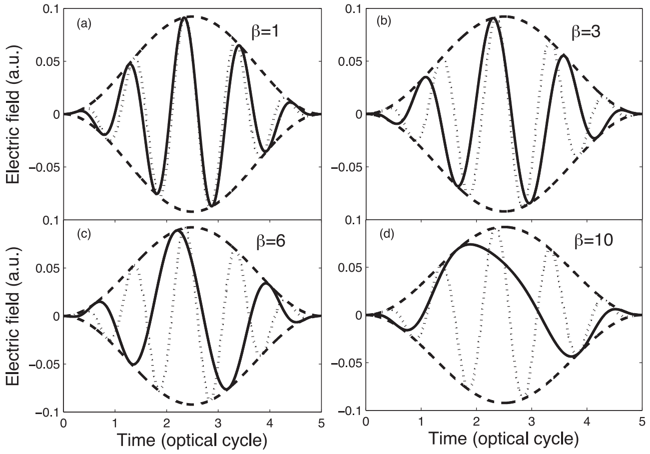

Fig. 1. The time evolution of the chirped laser field (solid line) and its envelope (dash line) for different chirped parameters: (a) β = 1 and σ = 200, (b) β = 3 and σ = 200, (c) β = 6 and σ = 200, (d) β = 10 and σ = 200. The dotted line corresponds to chirp-free laser field.

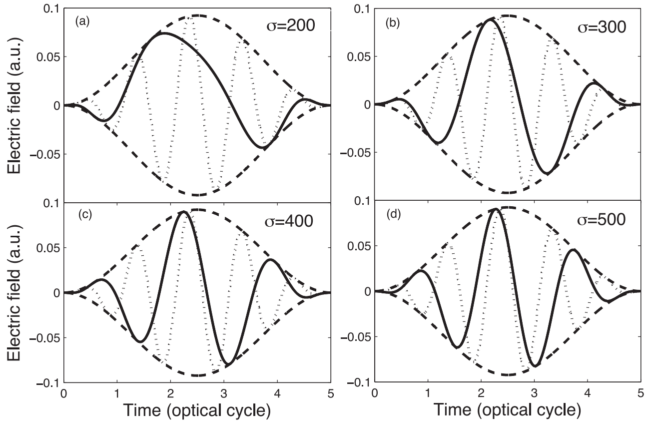

Fig. 2. The time evolution of chirped laser field (solid line) and its envelope (dash line) for different chirped parameters: (a) β = 10 and σ = 200, (b) β = 10 and σ = 300, (c) β = 10 and σ = 400, (d) β = 10 and σ = 500. The dotted line corresponds to chirp-free laser field.

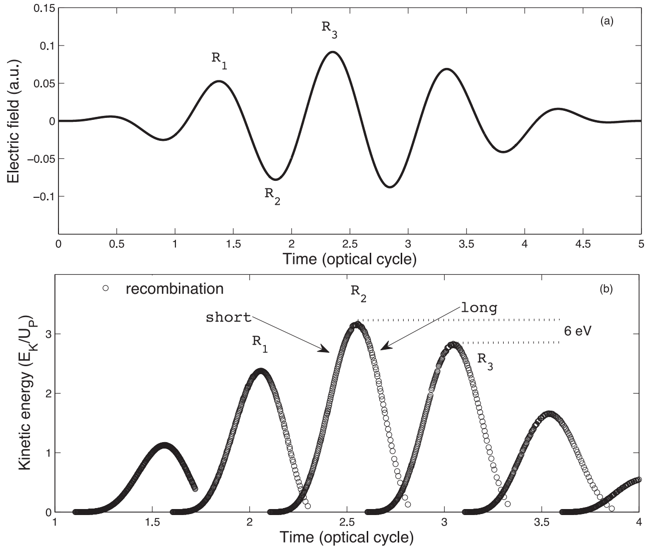

Fig. 3. (a) The time evolution field-form and (b) classical recombination path of electron in a 5 fs (FWHM) 800 nm chirp-free (β = 0) driving pulse. The intensity of the driving pulse is 3×10^{14} W/cm^2.

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