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Generation of high-intensity sub-30 as pulses by inhomogeneous polarization gating technology in bowtie-shaped nanostructure

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ABSTRACT

The generation of high-order harmonics and single attosecond pulses (SAPs) from He atom driven by the inhomogeneous polarization gating technology in a bowtie-shaped nanostructure is theoretically investigated. The results show that by the proper addition of bowtie-shaped nanostructure along the driven laser polarization direction, the harmonic emission becomes sensitive to the position of the laser field, and the harmonics emitted at the maximum orders that generate SAPs occur only at one side of the region inside the nanostructure. As a result, not only the harmonic cutoff can be extended, but also the modulations of the harmonics can be decreased, showing a carrier envelope phase independent harmonic cutoff with a bandwidth of 310 eV. Further, with the proper introduction of an ultraviolet pulse, the harmonic yield can be enhanced by 2 orders of magnitude. Finally, by the Fourier transformation of the selected harmonics, some SAPs with a full width at half maximum of sub-30 as can be obtained.

1. Introduction

The generation of attosecond (1 as = 10^{-18} s) pulses in extreme ultraviolet (XUV) or X-ray spectral regions has become an important and interesting research area in the laser community for its applications in the fields of physics, chemistry, etc. [1–4]. High-order harmonic generation (HHG) as the most important process to produce single attosecond pulses (SAPs) has been widely investigated [5–7]. The HHG process can be explained by the semi-classical three-step model (STM) [8] with the processes of "ionization-acceleration-recombination" or by the quantum mechanism (QM) [9]. Finally, the maximum harmonic cutoff of $I_p + 3.17U_p$ can be found, where I_P is the ionization potential of the system and $U_p = I/4\omega^2 \propto I\lambda^2$ is the ponderomotive energy, with I, ω, and λ being the pulse intensity, frequency, and wavelength of the laser field, respectively.

Both the STM and the QM predicted that the harmonic emission occurs at every half cycle of the laser field, and two quantum paths, the short and the long quantum paths, were observed for a given harmonic order [10], thus leading to larger chirps/modulations in the HHG spectra. As a result, an attosecond pulse train with two main bursts in one optical cycle can be formed. On the basis of the STM, the single harmonic emission process (HEP) with a single quantum path contribution is much better for producing SAPs. Thus, to generate SAPs in an XUV or X-ray region, many methods have been proposed to extend the harmonic cutoff and to select the harmonic emission path. For instance, (i) the few-cycle driven pulse scheme [11], (ii) the two-color or the three-color synthesized field scheme [12–15], (iii) the frequency modulation scheme by using the chirped pulse [16–18], (iv) the lighthouse method using a space–time coupled fundamental beam [19], and (v) the polarization gating (PG) technology [20–24].

Among them, the PG technology is an effective method to generate SAPs and has been widely investigated. It is well known that the physical mechanism of the PG technology is based on the fact that the polarization of a laser field can be changed from circular to linear and then back to the circular. As a result, almost linearly polarized harmonics can be obtained around the laser amplitude region. However, because of the decrease in laser intensity caused by the delay in the two laser fields, the harmonic cutoff and the harmonic efficiency decrease. Thus, to obtain high-intensity SAPs, an improved PG scheme, namely the double optical gating (DOG), was proposed. For instance, Mashiko et al. [25] experimentally obtained an isolated 130 as pulse by using the phase-stabilized DOG scheme. Zhao et al. [26] experimentally obtained a single 67 as pulse, which is the shortest SAP so far. Feng [27] theoretically obtained a series of sub-100 as pulses by using an improved DOG scheme.

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Recently, with developments in laser technology and nanoscale physics, the field of attosecond nanophysics has received much attention in the generation of high-order harmonics and SAPs [28–46]. In this field, the laser and atoms/molecules interact in the metallic nanostructure. Thus, because of the collective oscillation of the free charges around the vicinity of the metallic nanostructure, the laser intensity is enhanced and present inhomogeneous in space. As a result, the harmonic cutoff can be extended without the addition of a second controlling pulse. For instance, using the bowtie-shaped gold nanostructure, Kim et al. [28] was the first to report that harmonics can be obtained below the threshold laser intensity. The physical mechanism of harmonic emission was explained by the quantum and classical methods by Ciappina et al. [29–31] and Husakou et al. [32], respectively. Further, Yavuz et al. [33] obtained a 130 as pulse by using the single-color inhomogeneous field. Cao et al. [34] obtained a 10 as pulse by using the two-color inhomogeneous field. Xue et al. [35] obtained a 35 as pulse by using the three-color inhomogeneous field. Fetić et al. [36] investigated the effects of the carrier envelope phase (CEP) and the pulse duration on the HHG in an inhomogeneous field. Moreover, by using the crossed bowtie structure, Husakou et al. [37] obtained a 59 as pulse and indicated the possibility to produce circularly polarized HHG.

In this paper, we proposed an improved inhomogeneous PG scheme to produce high-intensity SAPs in a bowtie-shaped nanostructure. It is found that with the introduction of the bowtie-shaped nanostructure along the driven laser polarization direction, not only the harmonic cutoff is extended, but also the harmonic modulation is decreased, showing a CEP independent harmonic cutoff with a maximum bandwidth of 310 eV. Further, by the proper addition of a UV pulse, the intensity of the supercontinuum can be enhanced by 2 orders of magnitude. As a result, some sub-30 as SAPs with intensity enhancement of 2 orders of magnitude can be obtained.

2. Method

The HHG from He atom can be investigated by solving the two-dimensional time-dependent Schrödinger equation [47–50]. [Atomic units (a.u.) are used throughout this paper unless otherwise stated.]

$$i\frac{\partial\varphi(x,y,t)}{\partial t} = [-\frac{1}{2}\frac{\partial^2}{\partial x^2} - \frac{1}{2}\frac{\partial^2}{\partial y^2} + V(x,y) + xE_x(x,t) + yE_y(y,t)]\varphi(x,y,t), \quad (1)$$

$$V(x,y) = -1.0/\sqrt{x^2+y^2+0.07}. \quad (2)$$

The synthesized PG laser field consists of co-rotating and counter-rotating circularly polarized laser fields with different delay times.

$$E_x(x,t) = (1+s_x g(z))[E_1 f(t-t_{delay}/2.0)\cos(\omega_1 t+\varphi_1) + E_2 f(t+t_{delay}/2.0)\cos(\omega_2 t+\varphi_2)], \quad (3)$$

$$E_y(y,t) = (1+s_y g(z))[E_1 f(t-t_{delay}/2.0)\sin(\omega_1 t+\varphi_1) - E_2 f(t+t_{delay}/2.0)\sin(\omega_2 t+\varphi_2)], \quad (4)$$

$$f(t) = \exp[-4\ln(2)t^2/\tau_i^2]. \quad (5)$$

$$g(z) = -4.3\times10^{-18}(z+z_0) + 3.2\times10^{-5}(z+z_0)^2 - 5.1\times10^{-22}(z+z_0)^3 - 12\times10^{-10}(z+z_0)^4. \quad (6)$$

Here, E_i, ω_i, τ_i, and φ_i (i = 1, 2) are the amplitudes, frequencies, full width at half maximum (FWHM) and CEPs of the two circularly polarized pulses. t_{delay} is the delay time between the two pulses. $s_{x,y}$ is the switch function with values of 0 and 1. $g(z = x, y)$ is the form of inhomogeneous field, which can be obtained by fitting the real electric field that results from the finite-domain time-difference simulation considering the real geometry of the bowtie-shaped nanostructure with a gap bandwidth of g = 12 nm [35]. z_0 (i.e., x_0 and y_0) is the position of the laser pulse in the nanostructure.

In the present calculations, the electronic coordinates x and y are chosen to be $|x, y| < 150$ a.u. with a grid spacing of 0.1 a.u. The time step is chosen to be 0.1 a.u. Moreover, to guarantee the absorption of wave packets near the surface of the nanostructure, which does not contribute to the HHG, the absorbed function in the form of $\cos^{1/8}$ is used, starting from $x = y = 100$ a.u (with a gap boundary of g = 12 nm).

The HHG spectra are given as follows:

$$S(\omega) = \left|\frac{1}{\sqrt{2\pi}}\int_0^{T_{total}} d_A(t)e^{-i\omega t}dt\right|^2, \quad (7)$$

where $d_A(t) = -\left\langle\psi(x,y,t)\left|\frac{\partial V(x,y)}{\partial x} + \frac{\partial(xE_x(x,t))}{\partial x} + \frac{\partial V(x,y)}{\partial y} + \frac{\partial(yE_y(y,t))}{\partial y}\right|\psi(x,y,t)\right\rangle$ [51].

The time-frequency analyses of the HHG are used to get insights into the recollision process in the quantum approach. It is obtained from the following Gabor time window [52]:

$$A(t,\omega) = \int d_A(t')\sqrt{\omega}W(\omega(t'-t))dt', \quad (8)$$

where, $W(x) = (\frac{1}{\sqrt{\xi}})e^{ix}e^{-x^2/2\xi^2}$ is the Morlet mother wavelet with the wavelet window function fixed at ξ = 18 a.u.

The intensities of SAPs are given as follows:

$$I_{SAPs}(t) = \left|\sum_q(\int d_A(t)e^{-iq\omega t}dt)e^{iq\omega t}\right|^2. \quad (9)$$

3. Results and discussion

Fig. 1 shows the schematic experimental setups for the bowtie-shaped nanostructure and the laser enhancements. The laser fields are depicted relative to E_x or E_y, which is the laser amplitudes in the x or y direction, respectively, in a homogeneous field. The detailed parameters of the nanostructure can be found in Ref. [35]. As shown in the figure, three positions of the nanostructure can be used in the PG scheme: (i) setting the nanostructure in the x direction (driven laser polarization direction), only the intensity of $E_x(x,t)$ can be enhanced [Fig. 1(a) and 1(b)]; (ii) setting the nanostructure in the y direction (gating laser polarization direction), only the intensity of $E_y(y,t)$ can be enhanced [Fig. 1(c) and 1(d)]; (iii) setting the nanostructure in both x and y directions, the intensities of both $E_x(x,t)$ and $E_y(y,t)$ can be enhanced [Fig. 1(e) and 1(f)]. The nanostructure setup for cases (i) and (ii) can be found in Refs. [28,35], while that for case (iii) can be found in Refs. [37,53].

Fig. 2 shows the HHG spectra driven by the PG scheme with t_{delay} = 0.0, 1.0, and 2.0 fs. The laser parameters of the co-rotating and the counter-rotating circularly polarized laser fields are chosen as follows: $I_{1,2} = 3.0\times10^{14}$ W/cm^2, $\lambda_{1,2}$ = 800 nm, $\tau_{1,2}$ = 5.8 fs (corresponding to the pulse duration of 6 optical cycles), and $\varphi_{1,2} = 0.0\pi$. By analyzing Eqs. (3) and (4), the driven and gating fields of the PG scheme are in x and y directions, respectively [i.e., $E_{driven}(x,t) = E_x(x,t)$ and $E_{gating}(y,t) = E_y(y,t)$]. In detail, Fig. 2(a) shows the HHG spectra driven by the homogeneous field with $s_x = s_y = 0$. Clearly, the cutoff and the intensity of the harmonic spectrum both decrease as t_{delay} increases, but the modulations of the harmonics reduce slightly. Fig. 2(b) shows the HHG spectra driven by the inhomogeneous field with $s_x = 1$, $s_y = 0$, $x_0 = 0.0$ a.u. (the nanostructure is located in the x direction). As shown in the figure, by introducing an inhomogeneous effect in the driven laser polarization direction, the harmonic cutoff can be extended and a shorter harmonic plateau from $230\omega_1$ to $270\omega_1$ can be found when t_{delay} = 0.0 fs. As t_{delay} increases, the modulations of the harmonics decrease; however, the intensity and the bandwidth of the harmonic plateau decrease. Fig. 2(c) and 2(d) show the HHG spectra driven by the inhomogeneous fields with $s_x = 0$, $s_y = 1$, $y_0 = 0.0$ a.u. (the nanostructure is located in the y direction) and with $s_x = s_y = 1$, $x_0 = y_0 = 0.0$ a.u. (the nanostructure is located in both x and y directions), respectively. As can be seen, the HHG spectra shown in Fig. 2(c) and 2(d) present almost no change compared with those