Generation of the wavelength-tunable XUV pulse using the two-color and three-color infrared pulses*

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We present an efficient method to generate an ultrashort wavelength-tunable XUV pulse by using the harmonic selective enhancement scheme. The results show that by properly controlling the delay times of a two-color field or a three-color field, selective enhancement of the harmonics with photon energies between 80 eV and 315 eV can be obtained. Further, a wavelength-tunable and bandwidth-controllable XUV radiation can be obtained by Fourier transformation of these enhanced harmonics.

Keywords: high-order harmonic generation, XUV pulse, harmonic selective enhancement

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1. Introduction

With the rapid development of laser technology, wavelength-tunable XUV radiation with a narrow spectral bandwidth has received a lot of attention due to its potential application in three-dimensional (3D) biological imaging, nanolithography, and XUV interferometry, exploring atomic and molecular structure, etc. High-order harmonic generation (HHG) as a promising way to produce this light source has been intensively investigated in the last two decades.[1–15] So far, there have been two useful methods that have been used to produce this XUV light source from the HHG spectra, i.e., (i) using the filter or the grating to spectrally select the desirable spectral components,[16,17] which usually causes significant optical loss in the XUV or the soft X-ray regime; and (ii) using the phase-matching technique to coherently build up an intense XUV radiation near a specific frequency,[18,19] which is usually complex and difficult to implement experimentally. Thus, how to produce the XUV pulse by a purely optical approach is important and valuable for experimental realization.

Therefore, in this paper, we present an efficient optical method to generate a wavelength-tunable XUV pulse. It shows that by properly controlling the delay times of the two-color field (800 nm + 2400 nm) or the three-color field (800 nm + 2000 nm + 2400 nm), harmonic selective enhancement in the range from 80 eV to 315 eV can be obtained. Further, by performing the Fourier transformation of these enhanced harmonics, the wavelength-tunable (photon energies between 80 eV and 315 eV) and bandwidth-controllable (sub-500 as) XUV pulses can be directly obtained.

2. Computational aspects

The interaction of an atom with a linearly polarized intense laser field can be investigated by solving the time-dependent Schrödinger equation (TDSE)[20–24] within the single-active electron approximation. In the dipole approximation, the TDSE is given by (atomic units are used throughout this paper unless otherwise stated),

$$\mathrm{i}\frac{\partial\phi(r,t)}{\partial t}=\left[-\frac{1}{2}\nabla^2+V(r)+r\cdot E(t)\right]\phi(r,t), \tag{1}$$

where

$$V(r)=-Z_{\mathrm{eff}}/r$$

is the Coulomb potential with $Z_{\mathrm{eff}}=1.353$ to match the ionization potential of 24.6 eV for the ground state of a He atom. The synthesized laser field can be expressed as

$$\begin{aligned}E(t) &= E_1 f_1(t-\tau_{\mathrm{delay}})\cos(\omega_1(t-\tau_{\mathrm{delay}}))\\ &\quad + E_2 f_2(t)\cos(\omega_2 t)+E_3 f_3(t)\cos(\omega_3 t),\end{aligned} \tag{2}$$

where ω_i and E_i ($i=1$–3) are the frequencies and amplitudes of the 800-nm pulse, the 2400-nm pulse and the 2000-nm pulse, respectively, τ_{delay} is the delay time between the 800-nm pulse and the 2400-nm (2000-nm) pulses, and $f_i(t)$ are the envelope functions and

$$f_i(t)=\exp[-2\ln(2)t^2/\tau_i^2], \tag{3}$$

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with τ_i ($i = 1$–3) being the pulse durations of the three pulses.

The HHG spectra are obtained by Fourier transforming the time-dependent dipole acceleration $a(t)$ as

$$S(\omega_1) = \left| \frac{1}{\sqrt{2\pi}} \int_0^T a(t)\, \mathrm{e}^{-\mathrm{i}\omega_1 t}\, \mathrm{d}t \right|^2, \tag{4}$$

where $a(t)$ can be given by means of Ehrenfest's theorem as[22,25]

$$a(t) = \left\langle \phi(r,t) \left| -\frac{\partial V(r)}{\partial r} + E(t) \right| \phi(r,t) \right\rangle. \tag{5}$$

Finally, the wavelength-tunable XUV pulses can be generated by the inverse Fourier transformation of the selective harmonics,

$$I(t) = \left| \sum_q \left(\int a(t)\, \mathrm{e}^{-\mathrm{i}q\omega_1 t}\, \mathrm{d}t \right) \mathrm{e}^{\mathrm{i}q\omega_1 t} \right|^2, \tag{6}$$

where q is the enhanced harmonic order.

3. Results and discussion

Figures 1(a)–1(c) show the HHG spectra driven by the two-color field with the delay times being 1.0 fs, 1.25 fs, and 1.75 fs, respectively. The laser parameters are chosen to be 5 fs/800 nm, $I_1 = 3.25 \times 10^{14}$ W/cm^2, and 30 fs/2400 nm, $I_2 = 1.0 \times 10^{14}$ W/cm^2. For comparison, the harmonic spectrum with zero delay is also shown in Fig. 1(a) (dash red line). It shows that with the introduction of the delays ($\tau_{\mathrm{delay}} = 1.0$ fs–1.75 fs), harmonics in the range from 80 eV to 160 eV can be selectively enhanced by one order of magnitude compared with those in the plateau regions.

Figures 2(a)–2(c) show the HHG spectra driven by the three-color time delayed field, consisting of the above two-color field and a 30-fs/2000-nm pulse with the pulse intensity $I_3 = 1.0 \times 10^{14}$ W/cm^2. Clearly, with the introduction of this 2000-nm controlling pulse as well as the proper delays ($\tau_{\mathrm{delay}} = 0.75$ fs–1.3 fs) of the three pulses, the selective enhancements of the harmonics have been remarkably extended from 160 eV to 315 eV.

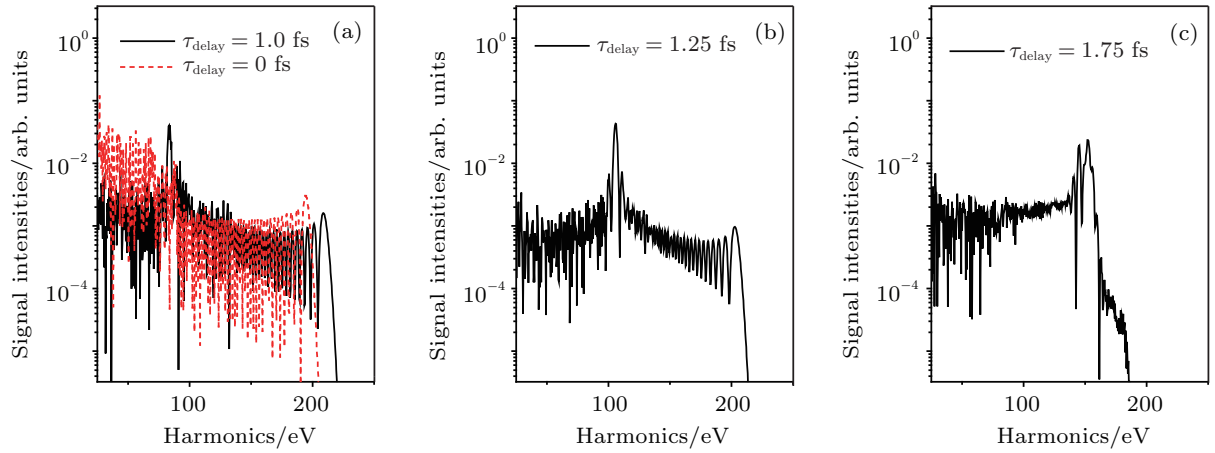


Fig. 1. (color online) HHG spectra driven by the two-color pulse with (a) delay time $\tau_{\mathrm{delay}} = 1.0$ fs (solid black line) and $\tau_{\mathrm{delay}} = 0.0$ fs (dash red line), (b) $\tau_{\mathrm{delay}} = 1.25$ fs, and (c) $\tau_{\mathrm{delay}} = 1.75$ fs. The laser fields are 5 fs/800 nm, $I_1 = 3.25 \times 10^{14}$ W/cm^2 and 30 fs/2400 nm, $I_2 = 1.0 \times 10^{14}$ W/cm^2.

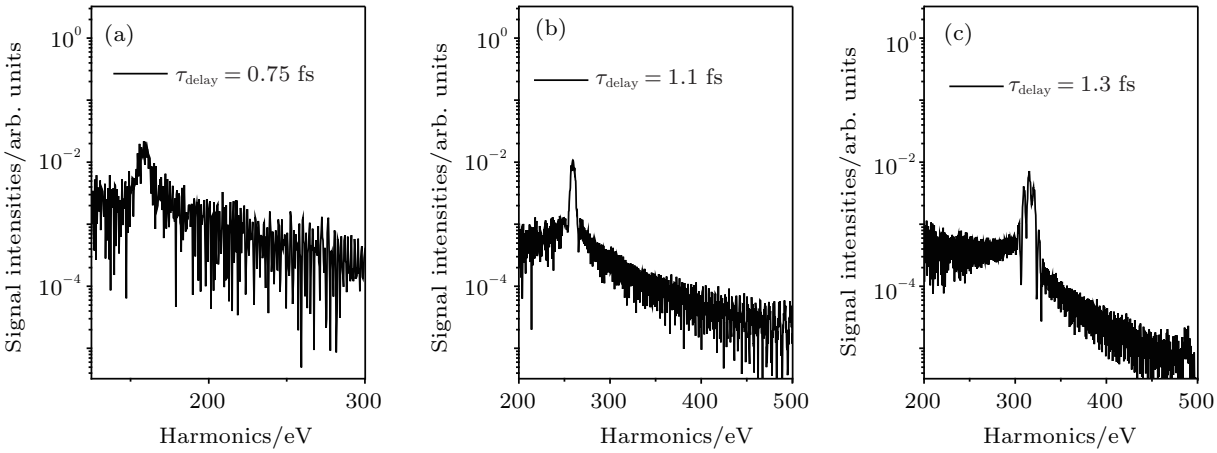


Fig. 2. HHG spectra driven by the three-color pulse with delay time $\tau_{\mathrm{delay}} = 0.75$ fs (a), 1.1 fs (b), and 1.3 fs (c). The laser fields are 5 fs/800 nm, $I_1 = 3.25 \times 10^{14}$ W/cm^2, 30 fs/2400 nm, $I_2 = 1.0 \times 10^{14}$ W/cm^2, and 30 fs/2000 nm, $I_3 = 1.0 \times 10^{14}$ W/cm^2.

To better understand the harmonic selective enhancement process, the time-frequency analysis results of the harmonic spectra above (i.e., two-color with $\tau_{\rm delay} = 0$ fs, 1.25 fs, and three-color with $\tau_{\rm delay} = 1.1$ fs) are shown in Figs. 3(b)–3(d) and the corresponding laser profiles are displayed in Fig. 3(a). The time-frequency analysis results are obtained by the wavelet transformation of the dipole acceleration $a(t)$.[26] Clearly, for the two-color zero delay case (Fig. 3(b)), there are three main energy peaks in the harmonic emission process, which are denoted as P_1, P_2, and P_3, and each of them receives two major electron path contributions for a given frequency of the emitted photon, namely, the long quantum path (with earlier ionization and later recollision) and the short quantum path (with later ionization and earlier recollision).[27,28] However, with the introduction of the delays as shown in Figs. 3(c) and 3(d) for the special cases of the two-color $\tau_{\rm delay} = 1.25$ fs and three-color $\tau_{\rm delay} = 1.1$ fs, the short quantum path of the second peak P_2 has been modified around the emission time of 1 o.c. (o.c. means the optical cycle of the 800-nm pulse) and created an additional quantum path in the folded region. That is to say, the electron following these quantum paths will obtain almost the same kinetic energy and therefore contributes to the same order harmonic emission. Further, due to the constructive interference between these multiple quantum paths, the harmonic selective enhancement can be observed.[29,30]

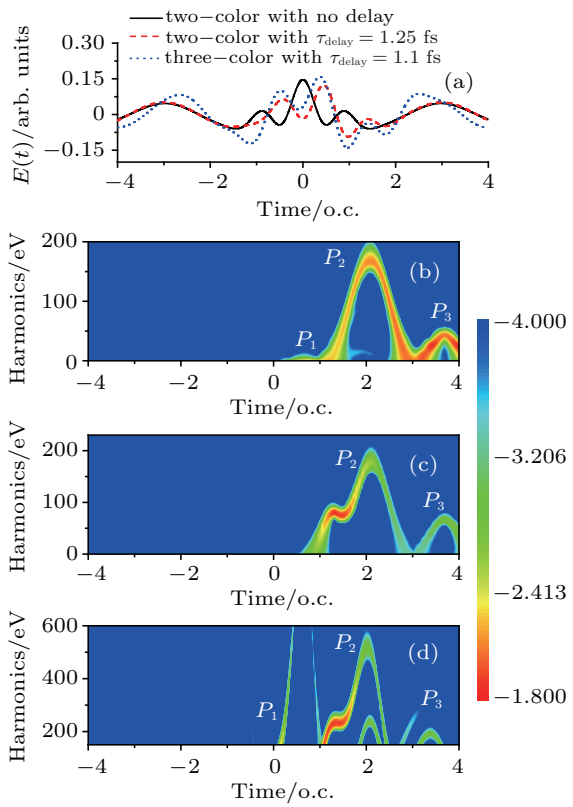


Fig. 3. (color online) (a) The laser profiles of the two-color field with $\tau_{\rm delay} = 0.0$ fs (solid black line), 1.25 fs (dash red line), and the three-color field with $\tau_{\rm delay} = 1.1$ fs (dot blue line). (b)–(d) The corresponding time-frequency distributions for the above three cases. Time is in units of optical cycle (o.c.) of 800-nm pulse in all the following figures unless otherwise stated.

Figure 4 shows the effects of pulse intensities on the harmonic selective enhancement. Here we choose a three-color field with $\tau_{\rm delay} = 1.1$ fs as an example because the others are similar to them. Clearly, with the increase of the pulse intensity I_1, the energy of the enhanced harmonic is extended, but the bandwidth becomes broader and more sub-peaks occur as shown in Fig. 4(a). With pulse intensities I_2 and I_3 increasing as shown in Figs. 4(b) and 4(c), we see that although the harmonic selective enhancement has been extended, the enhanced intensity is reduced. Thus, we see that whether the pulse intensities are too strong or too weak is unbeneficial to the generation of the wavelength-tunable XUV light.

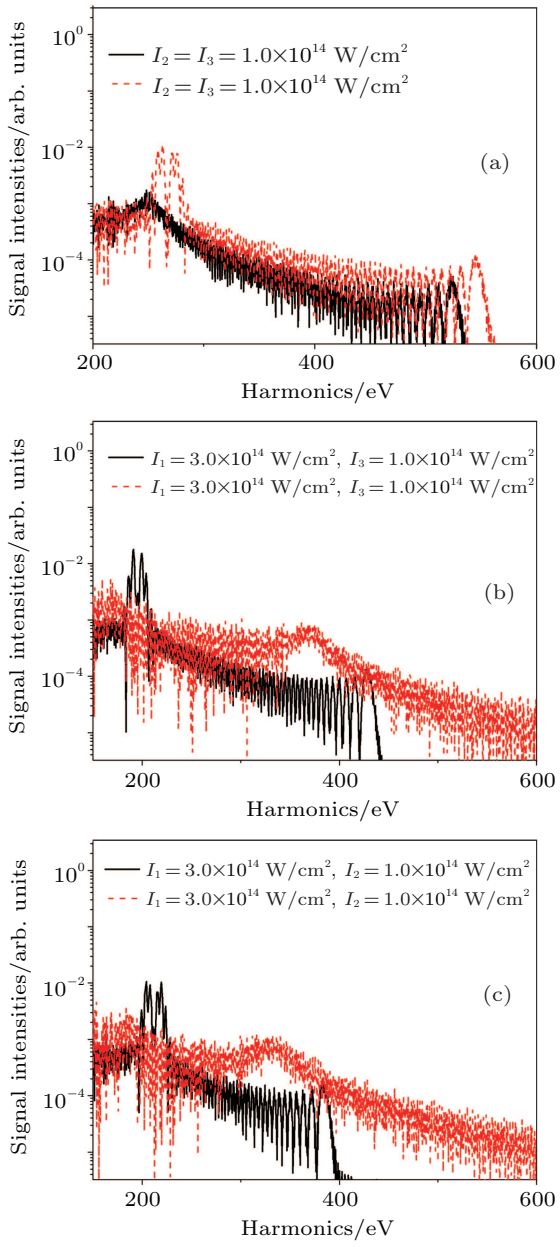


Fig. 4. (color online) HHG spectra driven by the three-color pulse with $\tau_{\rm delay} = 1.1$ fs, but with different values of pulse intensity (a) $I_1 = 2.0\times10^{14}$ W/cm^2 (solid black line), 4.0×10^{14} W/cm^2 (dash red line), (b) $I_2 = 5.0\times10^{13}$ W/cm^2 (solid black line), 2.0×10^{14} W/cm^2 (dash red line), (c) $I_3 = 5.0\times10^{13}$ W/cm^2 (solid black line), 2.0×10^{14} W/cm^2 (dash red line). The other parameters are the same as those in Fig. 2.

From our calculations, the optimal pulse intensities for the harmonic selective enhancement and XUV pulse generation are $I_1 = 3.25 \times 10^{14}$ W/cm^2 and $I_2 = I_3 = 1.0 \times 10^{14}$ W/cm^2, respectively. In addition, the controlling pulse durations (25 fs $< \tau_2$, $\tau_3 <$ 100 fs) and the wavelength (2000 nm $< \lambda_2$, $\lambda_3 <$ 3000 nm) effects on the harmonics enhancements have also been investigated, and the results are shown in Figs. 5(a) and 5(b) for the special cases of $\lambda_2 = 2400$ nm, $\tau_2 = 48$ fs and $\lambda_2 = 2000$ nm, $\tau_2 = 30$ fs. Here we only give two special cases as the examples because the others are similar to them. It is found that the harmonic enhancements are not very sensitive to the controlling pulse duration and they can also be achieved by different controlling wavelengths but with different time delays.

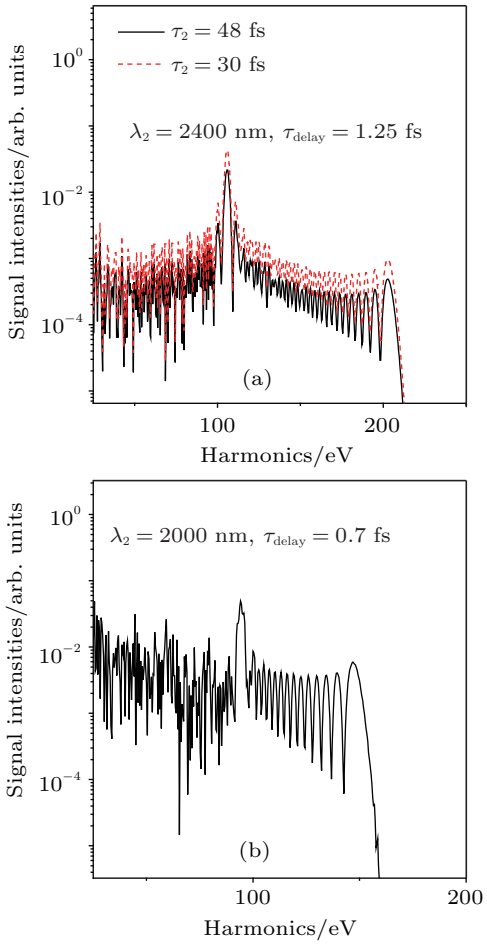


Fig. 5. (color online) HHG spectra driven by the two-color pulse with (a) delay time $\tau_{delay} = 1.25$ fs and controlling pulse durations: $\tau_2 = 48$ fs (solid black line) and $\tau_2 = 30$ fs (dash red line), and controlling wavelength $\lambda_2 = 2400$ nm, and (b) delay time $\tau_{delay} = 0.7$ fs and controlling wavelength $\lambda_2 = 2000$ nm. The other parameters are the same as those in Fig. 1.

Figure 6 shows the XUV pulses by using the selected enhanced harmonics as shown in Figs. 1 and 2. For instance, a 320-as pulse with the photon energy 105 eV and a 450-as pulse with photon energy 260 eV can be obtained, respectively, by performing an inverse Fourier transformation of the enhanced harmonics driven by the two-color $\tau_{delay} = 1.25$ fs case (102 eV–108 eV) and three-color $\tau_{delay} = 1.1$ fs case (254 eV–263 eV). If all the enhanced harmonics shown in Figs. 1 and 2 have been chosen to produce the XUV lights, a series of wavelength-tunable (photon energies between 80 eV and 315 eV) and bandwidth-controllable (sub-500 as) XUV lights can be obtained.

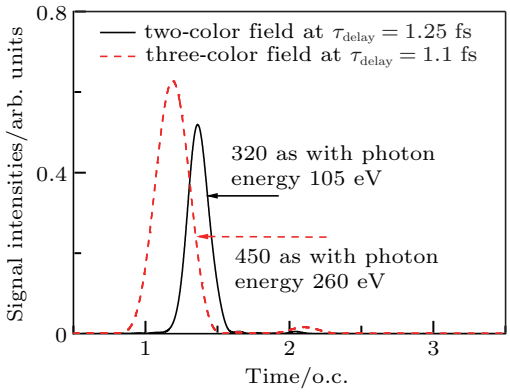


Fig. 6. (color online) Temporal profiles of the XUV pulses by performing an inverse Fourier transformation of the enhancement harmonics in the cases of two-color pulse with $\tau_{delay} = 1.25$ fs (solid black line) and three-color pulse with $\tau_{delay} = 1.1$ fs case (dash red line).

4. Conclusion

In this paper, by using the harmonic selective enhancement scheme, we theoretically present an effective method of generating a wavelength-tunable XUV pulse from the two-color and three-color time delayed infrared pulses. It is found that by properly controlling the delay times of the two-color and the three-color pulses, the harmonics energies between 80 eV and 315 eV will be selectively enhanced. Further, by performing an inverse Fourier transformation of these enhanced harmonics, a sub-500-as XUV light with the wavelength-tunable between 80 eV and 315 eV can be obtained. Moreover, through investigating the effects of other parameters on the harmonic selective enhancement, we see that this scheme is insensitive to the controlling pulse duration and pulse wavelength, which is much more beneficial to experimental realization.

References

[1] Brabec T and Krausz F 2000 *Rev. Mod. Phys.* **72** 545
[2] Osborne I and Yeston J 2007 *Science* **317** 765
[3] Krausz F and Ivanov M 2009 *Rev. Mod. Phys.* **81** 163
[4] Agostini P and DiMauro L 2004 *Rep. Prog. Phys.* **67** 813
[5] Zhou Z Y and Yan J M 2008 *Chin. Phys. B* **17** 4523
[6] Yun C X, Teng H, Zhang W, Zhan M J, Han H N, Zhong X, Wei Z Y, Wang B B and Hou X 2010 *Chin. Phys. B* **19** 124210
[7] Goulielmakis E, Schultze M, Hofstetter M, Yakovlev V S, Gagnon J, Uiberacker M, Aquila A L, Gullikson E M, Attwood D T, Kienberger R, Krausz F and Kleineberg U 2008 *Science* **320** 1614
[8] Feng L Q and Chu T S 2012 *Chin. Phys. B* **21** 124204
[9] Zeng Z, Cheng Y, Song X, Li R and Xu Z 2007 *Phys. Rev. Lett.* **98** 203901
[10] Zhang G T, Wu J, Xia C L and Liu X S 2009 *Phys. Rev. A* **80** 055404
[11] Feng L Q and Chu T S 2012 *J. Chem. Phys.* **136** 054102
[12] Ishikawa K 2003 *Phys. Rev. Lett.* **91** 043002

[13] Lan P F, Lu P X, Li Q G, Li F, Hong W Y and Zhang Q B 2009 *Phys. Rev. A* **79** 043413
[14] Zhai Z and Liu X S 2008 *J. Phys. B: At. Mol. Opt. Phys.* **41** 125602
[15] Zhang C J, Yao J P, Ni J L, Li G H, Cheng Y and Xu Z Z 2012 *Opt. Express* **20** 16544
[16] Dasilva L B, Baraee T W, Cauble R, Celliers P, Ciarlo D, Libby S, London R A, Matthews D, Mrowka S, Moreno J C, Ress D, Trebes J E, Wan A S and Weber F 1995 *Phys. Rev. Lett.* **74** 3991
[17] Warntjes J B M, Gurtler A, Osterwalder A, Rosca-Pruna F, Vrakking M J J and Noordam L D 2001 *Opt. Lett.* **16** 1463
[18] Tosa V, Takahashi E, Nabekawa Y and Midorikawa K 2003 *Phys. Rev. A* **67** 063817
[19] Zhang X S, Lytle A L, Popmintchev T, Zhou X B, Kapteyn H C, Murnane M M and Cohen O 2007 *Nat. Phys.* **3** 270
[20] Rae S C, Chen X and Burnett K 1994 *Phys. Rev. A* **50** 1946
[21] Miao X Y and Du H N 2013 *Phys. Rev. A* **87** 053403
[22] Hu J, Han K L and He G Z 2005 *Phys. Rev. Lett.* **95** 123001
[23] Chu T S, Zhang Y and Han K L 2006 *Int. Rev. Phys. Chem.* **25** 201
[24] Zhang P Y, Lu R F, Chu T S and Han K L 2010 *J. Chem. Phys.* **133** 174316
[25] Burnett K, Reed V C, Cooper J and Knight P L 1992 *Phys. Rev. A* **45** 3347
[26] Feng L Q and Chu T S 2011 *Phys. Rev. A* **84** 053853
[27] Corkum P B 1993 *Phys. Rev. Lett.* **71** 1994
[28] Mairesse Y, Bohan A D, Frasinski L J, Merdji H, Dinu L C, Monchicourt P, Breger P, Kovačev M, Taïeb R, Carré B, Muller H G, Agostini P and Salières P 2003 *Science* **302** 1540
[29] Zeng Z N, Cheng Y, Fu Y X, Song X H, Li R X and Xu Z Z 2008 *Phys. Rev. A* **77** 023416
[30] Yao J P, Cheng Y, Chen J, Zhang H S, Xu H, Xiong H, Zeng B, Chu W, Ni J L, Liu X and Xu Z Z 2011 *Phys. Rev. A* **83** 033835