Control of the polarization of attosecond pulses using a two-color field

Camilo Ruiz\textsuperscript{1}, David J Hoffmann, Ricardo Torres, Luke E Chipperfield and Jonathan P Marangos

Blackett Laboratory, Imperial College London, London SW7 2BW, UK
E-mail: camilo@usal.es

\textit{New Journal of Physics} 11 (2009) 113045 (12pp)
Received 29 July 2009
Published 24 November 2009
Online at \url{http://www.njp.org/}
doi:10.1088/1367-2630/11/11/113045

Abstract. Control over the polarization of an attosecond pulse train (APT) is demonstrated theoretically using orthogonally polarized two-color fields. The carrier envelope phase of the two pulses is used as a control parameter to generate both an APT with linear polarization in two nearly perpendicular planes or a train of elliptically polarized pulses of alternating helicity. By using few-cycle driving laser fields an isolated attosecond pulse with elliptical polarization is shown to be generated after selecting the cut-off region of the harmonic spectrum. The control mechanism is explained in terms of classical trajectories.

Contents

1. Introduction \hspace{2in} 2
2. Theory \hspace{2in} 3
3. APT \hspace{2in} 4
4. Elliptical polarization \hspace{2in} 6
5. Conclusions \hspace{2in} 11
Acknowledgments \hspace{2in} 11
References \hspace{2in} 11

\textsuperscript{1} Author to whom any correspondence should be addressed.
1. Introduction

Attosecond science [1], which studies the behavior of electrons in atoms and molecules with unprecedented temporal and spatial resolution, relies on the efficient production of short (∼100 as; 1 as = 10^{-18} s) pulses of light. These attosecond pulses and attosecond pulse trains (APTs) are synthesized from the high harmonics generated by an atom or molecule driven by an intense laser field [2, 3]. The main mechanism of high harmonic generation (HHG) is well understood as a three-step process [4]: an electron is first tunnel-ionized and then accelerated by the oscillating laser field before recombining with its parent ion to emit a high energy photon. The recombination of successive free electron wavepackets leads to an APT.

Good control over such properties as amplitude, frequency, phase and polarization of the attosecond pulses is essential to explore a wide range of ultra-fast electron dynamics and it is therefore important to determine practical methods of controlling these parameters. We will focus on the control of the polarization of attosecond pulses, which would, for example, lead to better temporal resolution and opportunities to study dichroism. This is analogous to the control of polarization in synchrotron radiation (SR), which has become a major tool for many experimental techniques. In this case, polarization control arises from the insertion of a phase retarder in the beam line or a helical undulator to produce circular polarization [5, 6]. HHG has the significant advantage over this method in being achievable using table-top sources. However, as the mean frequency of attosecond pulses lies in the deep ultraviolet (UV) or extreme ultraviolet (XUV), where optical elements are not readily available for polarization control, such control must be established during generation.

Control over the emitted radiation is achieved by manipulating the free electron trajectories leading to HHG. Using short, few-cycle laser pulses limits the number of recollision events and, by controlling the carrier envelope phase (CEP), a single recollision event can be isolated [7]. Another means of control is through the steering of the electron trajectories with a two-color field. This possibility has been explored further for improving the conversion efficiency [8], extending the harmonic cut-off [9, 10] and exploring the role of the relative phases between different frequency fields in controlling the temporal structure of the attosecond pulse [11]–[13]. Schemes have also been proposed which provide control over the polarization of the generated harmonics. Milosevic and Becker [14, 15] suggested the use of two counter-rotating circularly polarized fields of different colors to generate elliptically polarized harmonics and [16] proposed the use of linear perpendicular (\omega, 2\omega) fields to control the polarization angle of the harmonics. A scheme using (\omega, 3\omega) fields in both linear and circular polarization has also been considered [17].

In this paper we build on previous work on using two-colour fields for controlling the polarization of emitted harmonics. We use an (\omega, 1.5\omega) scheme where the two fields are linearly polarized and orthogonal to each other. By controlling the CEP and the intensity of the fields, we demonstrate two distinct polarization regimes: (i) an APT composed of pulses linearly polarized along two alternating axes separated by 76.5° and (ii) either a single attosecond pulse of elliptical polarization or an APT composed of elliptically polarized pulses of alternating helicity and major axis. The advantage of the present scheme is its flexibility and the larger degree of control over the polarization of the harmonics. Control over the degree of ellipticity is possible by adjusting the CEP of the two fields and, in the case of linear polarization, a simple way to change the temporal structure of the APT is obtained. This demands a level of CEP control that is now available in state-of-the-art few-cycle laser systems [18, 19].

New Journal of Physics 11 (2009) 113045 (http://www.njp.org/)
2. Theory

There exist many different strategies for the control of electron trajectories and rather than explore them all we will concentrate on a simple but powerful technique. A low frequency field will ionize and accelerate the electrons while a high frequency field will be used to steer the electrons in the orthogonal direction, modifying their initial and recollision velocities. We employ a non-integer frequency ratio of \((\omega, 1.5\omega)\) between the two fields in order to break the symmetry between consecutive ionization events.

A general expression for the two fields, polarized in the \(x\)- and \(y\)-directions, is the following:

\[
E_x(t) = \begin{cases} 
E_1 \cos^2 \left( \frac{\omega_1 t}{2N_1} \right) \cos(\omega_1 t + \phi_1), & \text{if } |t| < \frac{\pi N_1}{\omega_1}, \\
0, & \text{otherwise}, 
\end{cases}
\]

\[
E_y(t) = \begin{cases} 
E_2 \cos^2 \left( \frac{\omega_2 t}{2N_2} \right) \cos(\omega_2 t + \phi_2), & \text{if } |t| < \frac{\pi N_2}{\omega_2}, \\
0, & \text{otherwise}, 
\end{cases}
\]

where \(E_1, E_2\) are the field amplitudes, \(\phi_1, \phi_2\) are the CEPs and \(N_1, N_2\) are the total number of cycles contained within each pulse, according to this cosine squared envelope. The cycle number as defined by the full-width at half-maximum (FWHM) of the intensity envelope is found by multiplying this number by a factor of 0.36. The choice of the envelope is due only to computational convenience but similar envelopes give similar results.

In order to study the polarization dynamics of the attosecond pulses we solve the time dependent Schrödinger equation (TDSE) for a two-dimensional (2D) model atom of helium \((I_p = 0.9\) a.u.) in the presence of the above fields. The Hamiltonian is:

\[
H = \frac{\hbar}{2m} \left( \frac{\partial}{\partial x} - \frac{A_x(t)}{c} \right)^2 + \frac{\hbar}{2m} \left( \frac{\partial}{\partial y} - \frac{A_y(t)}{c} \right)^2 + V(x, y),
\]

where we model the Coulomb interaction with a soft-core potential

\[
V(x, y) = \frac{-1}{\sqrt{x^2 + y^2 + a^2}}.
\]

The parameter \(a^2 = 0.076\) is used to reproduce the ionization potential of helium in the usual single active electron (SAE) approximation, which is well justified here [20]. As the system evolves mainly in a 2D plane, the 2D model includes all relevant effects. The coupling is calculated using the velocity gauge and the equation is integrated in the \(xy\) plane, perpendicular to the direction of laser propagation, using the split operator method implemented in the qfishbowl software [21]. A spatial grid of \(\Delta x = \Delta y = 0.3\) au extending over 600 au is used, together with a temporal step of \(\Delta t = 0.05\) au.

The CEPs of the two pulses are the most important parameters in determining the ellipticity of the APT. While the importance of the relative phase between fields in two-color HHG has been acknowledged, even for longer pulses [12], our numerical exploration has shown that for the short pulses used here the absolute value of each phase is also very important. We will describe two of the more interesting cases and point out that typical experimental fluctuations in CEP (< 0.5 radians) do not significantly deviate from these observations.
The first example demonstrates control over the polarization plane of an APT. The frequencies of the fields are \( \omega_1 = 0.057 \) au (corresponding to \( \lambda_1 = 800 \) nm) and \( \omega_2 = 1.5 \omega_1 \) (\( \lambda_2 = 533 \) nm), with intensities \( I_1 = 5 \times 10^{14} \) W cm\(^{-2} \) and \( I_2 = 2 \times 10^{14} \) W cm\(^{-2} \) respectively. The pulse durations are identical, with \( N_1 = 12, N_2 = 1.5 N_1 \) cycles (\( \sim 30 \) fs) and both pulses are sine-like (\( \phi_1 = \phi_2 = \pi/2 \)). Note that for such long pulses, it is only the relative phase, defined as \( \Delta \phi = \phi_1 - \kappa \phi_2 \) with \( \kappa = \omega_1/\omega_2 \), which must be controlled, as opposed to both \( \phi_1 \) and \( \phi_2 \)\(^{[22]} \). If the two fields are phase-locked, which will usually be the case, then control over \( \Delta \phi \) can be easily achieved experimentally by controlling the amount of linear dispersion in the beam path.

The HHG spectra obtained from the components of the dipole acceleration projected along the \( x \) and \( y \) polarization directions are shown in figure 1(a). Two distinct plateaus are visible in each spectra due to the two frequency components of the two-color field; the energies of the corresponding cut-offs match well with those given by classical calculations for each of the two colors, indicated by the vertical blue lines.

Filtering out the harmonics below the 23rd in both spectra and transforming back into the temporal domain generates the APT of figure 1(b). The APT is made of pulses linearly polarized along two alternating planes and separated by \( T_1/2 \), where \( T_1 = 2\pi/\omega_1 \). There is a constant CEP value across the train in each polarization plane and a CEP shift of \( \pi \) between the planes, i.e. each pulse in the train has advanced by \( \pi \) over the preceding one. The varying peak intensity from pulse to pulse across the train reflects the envelope of the driving pulses. This alternating linear polarization is a good example of CEP-induced polarization control in an APT by using two orthogonal fields of different frequencies.

The observed structure in the APT is a consequence of the trajectories taken by the recolliding electrons for these particular CEP values. Our numerical study shows that tunnel-ionization occurs in the instantaneous direction of the electric field. For this regime, a classical analysis of these trajectories is useful for explaining the control mechanism. Our assertion that the field \( E_x(t) \) is primarily responsible from ionization and acceleration of the electron, with \( E_y(t) \) serving to steer the free electron wavepacket, is confirmed by a comparison of the full TDSE and classical simulations.

Figure 2(a) shows the classical trajectories obtained from an integration of Newton’s equations, illustrating the two most important classes of electron trajectories leading to HHG. These are mirror images about the polarization axis of the low frequency field and are almost linear, with each leading to a very narrow range of incidence angles and producing linearly polarized harmonics in two different planes. The incidence angle between these two trajectories is close to perpendicular, specifically 76.5° in this case. Other angles are obtained by an alternative choice of fields and phases. Perfect perpendicular fields can be achieved but at the cost of having larger attosecond pulses in the train.

Figure 2(b) shows the path traced by the electric field in the \( xy \) plane and the corresponding position of the ionization (red) and recollision (green) events. Figure 2(c) shows the electric fields plotted against time, with the ionization and recollision times of the relevant trajectories again highlighted. Electrons are ionized close to the maximum of the total electric field and the subsequent recollision coincides almost exactly with the zero of the low-frequency field, as with the corresponding one-color case. The fact that ionization events occur every half-cycle is seen as the cause of the \( \pi \) shift in CEP between successive pulses in the APT.

New Journal of Physics 11 (2009) 113045 (http://www.njp.org/)
Figure 1. (a) Harmonic spectra obtained from the dipole acceleration projected onto the $x$- and $y$-polarization axes (red and blue, respectively), for the CEPs $\phi_1 = \phi_2 = \pi/2$. The classical cutoffs of the corresponding single-color fields $E_x(t)$ (right) and $E_y(t)$ (left). The shaded area represents the spectral filtering used to synthesize the APT. (b) The resulting APT, plotted in the time domain, showing the alternating polarization planes.

This alternating linear polarization can be exploited to control the temporal structure of the train through the use of a polarizer (e.g. a mirror with a high polarization discrimination ratio). Figure 3 shows different trains obtained by projecting the harmonic field of figure 1(b) over different axes with the polarizer. By aligning the polarizer along either of the two polarization planes of the APT, we can obtain a train separated by $T_1 = 2\pi/\omega_1$ (figures 3(a) and (c)). All the attosecond bursts in these cases have the same CEP as we have eliminated those with the CEP inverted. Aligning the polarizer along the bisector or the two planes will produce a train of less intense pulses separated by $T_1/2$, as in the case of one-color HHG (figure 3(b)). By using shorter driving pulses we can produce trains consisting of fewer attosecond pulses, providing a way to isolate a single attosecond pulse [23].

Similar trains can be obtained in a $(\omega, 2\omega)$ scheme [16], but the angle between polarization planes deviates significantly from $90^\circ$. This will greatly reduce the potential of selecting
Figure 2. The classical trajectories responsible for the APT of figure 1, with CEP values $\phi_1 = \phi_2 = \pi/2$. (a) The two most important families of classical trajectories projected into the $xy$-plane. (b) The path traced by the electric field vector in the $xy$-plane. The corresponding ionization events are represented as red dots, indicating the initial direction of motion of the ionized electron, and the recollision events are shown in green. (c) Electric fields in the $x$- and $y$-directions as a function of time. The ionization and recollision events for the trajectories depicted above are again represented as red and green dots, respectively.

polarization planes through applying a polarizer, as described above. In addition, such trains would be constructed by selecting only the cut-off region of the spectrum, while here we use the harmonics in the plateau thus imparting more energy to the train.

4. Elliptical polarization

We next present a further control scenario, where we use similar parameters as the previous example but change the CEPs of the two fields in order to obtain APTs with elliptical polarization. Furthermore, by using short driving pulses we show how to obtain a single attosecond pulse with elliptical polarization. This case is of particular importance because, as mentioned previously, the elliptical polarization of the harmonics must be established during generation due to the absence of half wave plates for XUV radiation.
Figure 3. APT obtained by applying a linear polarizer to the APT of figure 1(a). Panels (a) and (c) result from aligning the polarizer parallel to each of the polarization planes. The separation of these pulses is $T_1$ and the CEP is constant across the train. (b) Placing the polarizer axis along the bisector of the two polarization directions yields a train with temporal separation of $T_1/2$, with consecutive pulses having a difference of $\pi$ in CEP.

The driving field frequencies are again $\omega_1 = 0.057$ au and $\omega_2 = 1.5\omega_1$. The intensities are in this case $I_1 = 4 \times 10^{14}$ W cm$^{-2}$ and $I_2 = 1 \times 10^{14}$ W cm$^{-2}$, thus preserving the roles we want to assign to each field, namely that the $\omega_1$ field ionizes and accelerates the electron wavepacket along one direction while $\omega_2$ steers the wavepacket to control the recollision and with it the characteristics of the HHG spectrum and the attosecond pulses. The two pulses have the same length, $N_1 = 32$ and $N_2 = 1.5N_1$ cycles ($\sim 80$ fs) and with CEP values $\phi_1 = \phi_2 = 0$.

By solving the TDSE for these conditions we obtain the HHG spectrum which contains a large plateau and a cut-off around the 70th harmonic as shown in figure 4(a). By selecting the cut-off region (starting from harmonic 66th shown in figure 4(a) and reconstructing the APT preserving the phases of the harmonics, we obtain the APT shown in figure 4(d). The APT is made of pulses which are elliptically polarized, the major axes of the ellipses lies in two planes, alternating direction from pulse to pulse. The helicity of the pulses alternates also from pulse to pulse, such that the fields rotates clockwise or anticlockwise in each pulse.

A projection over the two axes is shown in figure 4(b), the APT is produced only in the center of the pulse and contains only few pulses as only the most energetic events contribute to the train. The pulses are separated by $T_1/2$ in time and the temporal width of the pulses is around 10 au (FWHM $\sim 240$ as). Such very short attosecond pulses have a larger component in the $x$ direction which is the polarization direction of the $\omega_1$ field but the small component in the $y$ direction and the relative phase between the fields is responsible for the elliptical polarization. A projection of the APT in the direction of the fields is shown in figure 4(c); from this figure we can see the rotation of the major axes from pulse to pulse and the degree of ellipticity (please note that the scale on each axis is different). The ellipticity varies a little if we use some other intensity ratio, but it is always around the value of $\epsilon = 0.22$. 

New Journal of Physics 11 (2009) 113045 (http://www.njp.org/)
Figure 4. APT with elliptical polarization. (a) The harmonic spectra from the $x$- and $y$-components of the dipole acceleration, the vertical lines show the classical cut-off for each of the two colors. Harmonics above the 66th harmonic (the grey shaded region) are preserved to obtain the train of pulses. (b) Envelope of the pulse in the $x$ (red) and $y$ (blue) directions. (c) Attosecond pulse projected over the plane of the electric field showing the degree of ellipticity obtained. (d) Three-dimensional reconstruction of the attosecond pulse to show the different directions of the major axis of the ellipses formed by the pulses.

As a second example of elliptical polarization, through the use of shorter driving fields and slightly different intensities, we demonstrate the potential to produce a single elliptically polarized attosecond pulse. The driving field frequencies are again $\omega_1 = 0.057$ au and $\omega_2 = 1.5\omega_1$, and the intensities are in this case $I_1 = I_2 = 6 \times 10^{14}$ W cm$^{-2}$. Although the two fields have equal intensity, the ponderomotive energy of the low frequency field is higher and the aforementioned distinct roles of the two fields are thus preserved. The pulses have a cosine squared envelope containing $N_1 = 4$, $N_2 = 1.5N_1$ cycles ($\sim 10$ fs) and with CEP values $\phi_1 = \phi_2 = 0$. This change to CEP leads to a dramatically different class of recolliding electron trajectories, whose properties are passed on to the emitted attosecond pulses. A handle over the CEP of the two fields is thus seen as a powerful way to control the polarization of attosecond pulses.

Figure 5(a) shows the harmonic spectra obtained from the components of the dipole acceleration projected along the $x$ and $y$ polarization directions. By filtering out the spectra below the 67th harmonic and preserving the cut-off region, a single attosecond pulse with ellipticity $\epsilon = 0.22$ is obtained, as shown in figure 5(d). Such filtering can be achieved by a thin Zn film or by spatially dispersing the harmonics and using a spatial filter before recombination. The temporal envelope of the attosecond pulse is presented in figures 5(b) and 5(c) shows
a projection of the harmonic field onto the xy plane. The obtained pulse has a width of approximately 100 as and elliptical polarization over its entire duration, in contrast to previous results [14, 15] where a mixture of linear and circular polarization was obtained.

The ellipticity of the attosecond pulses is product of the coherence between the harmonics in the cut-off and their phase relation. Although the effect can only be fully explained with quantum models, classical models can provide simple pictures to understand the mechanism behind the effect and guide further optimizations.

In the case of a single elliptical attosecond pulse presented above, the classical calculations show that for harmonics in the cut-off region, there are at least two trajectories leading to the same energy, but arriving at different angles and delayed in time. These two trajectories will contribute towards the production of the same harmonic, linearly polarized in two different directions and these two components will be phase shifted as the electrons which produced them are delayed and accumulate different quantum phases in their paths.

We integrate Newton’s equations for the same parameters as in figure 5. For each ionization time around $t = -110$ au, we launch a set of trajectories starting at the origin but with some initial velocity (100 trajectories sampling velocities $|\mathbf{v}_x|, |\mathbf{v}_y| < 0.25$ au) to simulate spreading of the wavepacket. By labeling the trajectories that return to a region around the origin (those with $r = \sqrt{x^2 + y^2} < 6$ au), we can obtain the direction and energy of the recolliding trajectories.

Figure 5. Single attosecond pulse with elliptical polarization. (a) The harmonic spectra from the $x$- and $y$-components of the dipole acceleration, the vertical lines show the classical cut-off for each of the two colors. Harmonics above the 67th harmonic (the grey shaded region) are preserved to obtain the single pulse. (b) Envelope of the pulse in the $x$-(red) and $y$-(blue) directions. (c) Attosecond pulse projected over the plane of the electric field showing the degree of ellipticity obtained. (d) Three-dimensional reconstruction of the attosecond pulse.
Figure 6. Classical trajectories for the single elliptical attosecond pulse. (a) Trajectories contributing to the cut-off region in the xy plane. The harmonics are emitted in a direction given by the instantaneous direction of the field around \( t = -110 \text{ au} \), they are emitted in a narrow direction, but small delays in emission time are mapped onto a large range of recollision angles. (b) Vector velocities for the recolliding trajectories, a large range of recollision angles is produced due to the presence of the \( \omega_2 \) steering field. (c) Emission times (red dots) and recollision times for the energies in the cut-off, electrons are emitted around the maximum of the two fields and collision occurs around the zero of the two fields. (d) Emission direction is very sharp as it occurs while both fields are maximum.

The accumulated quantum phases are calculated using the action of the electron trajectories leading to the cut-off harmonics \([24, 25]\). In this case, the action is given by \( S(p, t_{\text{ion}}, t_{\text{rec}}) = \int_{t_{\text{ion}}}^{t_{\text{rec}}} \left( p - A(t') \right)^2/2 + I_p \). The last term represents the phase acquired by the electron in the bound state but that term does not affect considerable to the computation of the acquired phase.

Figure 6(a) shows the recolliding trajectories that contribute to the cut-off region. These trajectories are created around \( t = -110 \text{ au} \) (red dots) and recollide around \( t = -27 \text{ au} \) (green dots in figure 6(c)). They are emitted at the peak of the field as shown in figure 6(d) and recollide close to the zero of the \( \omega_1 \) field. From figure 6(a), it can be seen that the field steers the electrons as they return, expanding the incident angle of these returning electrons.

Figure 7 shows the ellipticity degree for three harmonics in the cut-off, namely H68, H69 and H70. By taking two trajectories leading to the same harmonic, we obtain the recollision angles and the acquired phases of the harmonics. For example for H69, the first trajectory has an incidence angle of \( 0.3635 \text{ rad} \) and the second recollides at \( 0.5129 \text{ rad} \). The accumulated phases are \( \phi_{\text{first}} = 323.6 \text{ rad} \) and \( \phi_{\text{second}} = 325.7 \text{ rad} \). giving \( \Delta \phi = 0.66 \pi \). The ellipses are plotted with the same scale as in figure 5(c) for better comparison.
Figure 7. Reconstruction of the harmonic fields in two directions using the estimations of the classical simulations. The electric field in two directions is plotted for three harmonics in the cut-off. H68 (red), H69 (blue) and H70 (green), all three fields have the axis of the ellipse tilted to one side given by the recollision angles of the electron trajectories leading to these harmonics.

The classical model is thus seen to provide a neat picture to understand the mechanism behind the ellipticity, but the calculated degree of polarization is smaller than calculated in the full quantum simulations. This is likely due to the simplicity of the model, which does not include Coulombic and polarization effects, or the full spreading of the wave packet which is included only partially in the classical model.

5. Conclusions

We have demonstrated theoretically control over the polarization of attosecond pulses by changing the CEP of two perpendicular fields with frequencies \((\omega, 1.5\omega)\). The scheme is useful in generating both linearly polarized pulses in two planes, which can be used as a way to control the temporal spacing between pulses, and single elliptically polarized attosecond pulses. The control mechanism is well understood in terms of classical electron trajectories which, for short pulses, are highly dependent on the CEP of both driving fields. In the case of longer pulses, the dominant parameter becomes \(\Delta\phi = \phi_1 - \kappa\phi_2\), where \(\kappa = \omega_1/\omega_2\).

Acknowledgments

CR is funded by the Secretaría de Estado de Universidades e Investigación del Ministerio de Educación y Ciencia de España. This work has been supported by EPSRC (UK).

References

[1] Corkum P B and Krausz F 2007 Nat. Phys. 3 381
[2] Antoine P, L’Huillier A and Lewenstein M 1996 Phys. Rev. Lett. 77 1234

New Journal of Physics 11 (2009) 113045 (http://www.njp.org/)
[3] Paul P M, Toma E S, Breger P, Mullot G, Aug F, Balcou Ph, Muller H G and Agostini P 2001 Science 292 1689
[4] Lewenstein M, Balcou Ph, Ivanov M Yu, L’Huillier A and Corkum P B 1994 Phys. Rev. A 49 2117
[5] Tanaka T, Shirasawa K and Kitamura H 2002 Rev. Sci. Instrum. 73 1724
[6] Oura M et al 2007 J. Synchrotron Radiat. 14 483
[7] Kienberger R et al 2004 Nature 427 817
[8] Kim I J, Kim C M, Kim H T, Lee G H, Lee Y S, Park J Y, Cho D J and Nam C H 2005 Phys. Rev. Lett. 94 243901
[9] Chipperfield L E et al 2009 Phys. Rev. Lett. 102 063003
[10] Perez-Hernandez J A, Hoffmann D J, Zair A, Chipperfield L E, Plaja L, Ruiz C, Marangos J P and Roso L 2009 J. Phys. B: At. Mol. Opt. Phys. 42 134004
[11] Mauritsson J, Johnsson P, Gustafsson E, L’Huillier A, Schaefer K J and Gaarde M B 2006 Phys. Rev. Lett. 97 013001
[12] Pfeifer T, Gallmann L, Abel M J, Nagel P M, Neumark D M and Leone S R 2006 Phys. Rev. Lett. 97 163901
[13] Zeng Z, Cheng Y, Song X, Li R and Xu Z 2007 Phys. Rev. Lett. 98 203901
[14] Milosevic D B and Becker W 2000 Phys. Rev. A 62 011403
[15] Milosevic D B, Becker W and Kopold R 2000 Phys. Rev. A 61 063403
[16] Kitzler M, Xie X, Roither S, Scrini A and Baltuska A 2008 New J. Phys. 10 025029
[17] Watanabe S, Kondo K, Nabekawa Y, Sagisaka A and Kobayashi Y 1994 Phys. Rev. Lett. 73 2692
[18] Goulielmakis E et al 2008 Science 320 1614
[19] Cirmi G, Manzoni C, Brida D, De Silvestri S and Cerullo G 2008 J. Opt. Soc. Am. B 25 B62
[20] Vázquez de Aldana J R and Roso L 2001 J. Opt. Soc. Am. B 18 325–30
[21] Qfishbowl http://code.google.com/p/qfishbowl/
[22] Eichmann H et al 1995 Phys. Rev. A 51 R3414
[23] Yu Y, Song X, Fu Y, Li R, Cheng Y and Xu Z 2008 Opt. Express 16 686
[24] Antoine P, L’Huillier A and Lewenstein M 1996 Phys. Rev. Lett. 77 1234
[25] Gaarde M B, Salin F, Constant E, Balcou Ph, Schaefer K J, Kulander K C and L’Huillier A 1999 Phys. Rev. A 59 1367