Electron choreography at the attosecond time scale

B Unzicker, J Vaughan, S Burrows, B Tatum, D Arthur, T Olsson, S Jain, T Hart, P Stringer and G M Laurent

Department of Physics, Auburn University, 380 Duncan Drive, Auburn, AL 36849, United States of America

E-mail: glaurent@auburn.edu

Keywords: attosecond science, photoelectron emission, attosecond pulse shaping, attosecond control

Abstract

In this work, we report on coherent control of electron dynamics in atoms via attosecond pulse-shaping. We show that the photoelectron emission from argon gas produced by absorption of an attosecond pulse train (APT) made of odd and even harmonics can be manipulated along the direction of polarization of the light by tuning the spectral components (amplitude and phase) of the pulse. In addition, we show that APTs produced with a two-color (400- plus 800 nm) femtosecond driving field exhibit high temporal tunability, which is optimized for an intensity ratio between the two colors in the range of 0.1 to 5%.

1. Introduction

Coherent control of quantum phenomena in matter through its interaction with light is a fast-growing field in ultrafast science. It is driven primarily by the ultimate goal of controlling the complex dynamical properties of quantum systems at the heart of many scientific fields. Over the last four decades, femtosecond laser technology has led to remarkable advances in our ability to control the ultrafast femtosecond dynamics in a vast number of systems (from simple to complex molecular systems, clusters, nanostructures, ...) [1–4]. With the recent development of extreme ultraviolet (XUV) light sources with attosecond duration, new capabilities emerge for controlling quantum dynamics in matter with an unprecedented level of precision down to the natural timescale of electron motion [5, 6].

Even though the first attosecond pulses were generated nearly two decades ago, their use for controlling electron dynamics in matter has been elusive so far. Attosecond control has been mostly achieved with pump/probe schemes where an attosecond-pump pulse triggers a given electronic process, and a phase-locked femtosecond-probe field is used to steer its dynamics. The system under scrutiny is thus controlled by varying the time delay between the two pulses. Such an approach has been successfully employed to manipulate benchmark systems such as the electronic charge distribution within a molecular target [7, 8] or the photoelectron emission from atoms [9–11]. Despite these impressive proofs-of-principle, attosecond control of quantum phenomena in matter is still in its infancy, though, mainly because attosecond pulse shaping techniques are still developing. Even though several schemes have already been reported to tailor the spectrum [12–21], the polarization [22–27], or the angular momentum [28] of these pulses, shaping their spectral phases for attosecond control, on the other hand, still remains a challenging endeavor for the attosecond community. Indeed, the low intensity of the attosecond pulses currently produced via high-harmonic generation (HHG) together with the high absorption rate of XUV radiation by most optical materials restrict the use of usual pulse shaping techniques (like chirped mirrors, ...) to manipulate the spectral phase of the pulses after generation.

An alternative approach consists of shaping the spectral phases of attosecond pulses directly during the generation process. Within the widely accepted three-step model describing attosecond pulse generation via HHG (ionization, propagation in the laser electric field, and recombination), the spectral phases of the frequency components making up the pulse are directly related to the recombination times [29], which in
turn are defined by the electron wavepacket trajectories (also referred to as quantum orbits) in the driving laser field. By tailoring the temporal waveform of the femtosecond driving field, the quantum orbits and the recombination times can then be tuned giving some control over the spectral phases of the attosecond pulse train (APT).

Two-color femtosecond waveforms made of a fundamental field and its second harmonic have proved to be very efficient in manipulating quantum orbits in the HHG process. The literature is rich with experimental and theoretical studies reporting the dependence of both the spectrum and the polarization of the resulting APT on the temporal profile of such synthesized waveforms [13–18, 21, 27, 30–32]. On the other hand, the dependence of the APT’s spectral phases on the temporal profile of the two-color field still remains elusive, though. In this work, we show how these phases can be manipulated by varying the intensity ratio and the relative phase between the two components of the driving field. We show that the spectral phases exhibit high tunability for an intensity ratio between the two colors in the range of 0.1 to 5%.

As an application for such a spectral pulse shaping technique, we also report on a coherent control experiment where the photoelectron emission from atoms generated by tailored attosecond pulses is manipulated along the direction of polarization of the light by tuning the spectral phases of the APT. Manipulation of the angular emission pattern of photoelectrons generated by attosecond pulses has recently received considerable scientific interest owing to the fundamental role played by the photoionization process in nature. A non-exhaustive list of achievements includes the control of the photoelectron motion with a sufficiently strong IR laser field [9], the generation of an asymmetric emission along the laser polarization based on an orbital parity mix interference process [10], or the modification of the symmetric photoelectron angular distributions resulting from the asymmetric contributions of the IR absorption and emission mechanisms in the two-photon (XUV ± IR) ionization process [11]. Our experiment bears a similarity with the recent study reported by Cheng et al, where a sequence of three attosecond pulses combined with a relatively weak IR field is used as an efficient means for controlling the photoemission from atoms [33] through interferences between the temporally-delayed electron wavepackets. Our experiment demonstrates a reverse approach to control the emission by directly tuning the spectral components of the attosecond pulse in the Fourier domain.

2. Principle of the coherent control experiment

The principle of the experiment is presented in figure 1. APTs are generated via high harmonic generation with a two-color femtosecond field (800 + 400 nm). Depending on the intensity ratio \( r \) and the relative phase \( \phi \) between the two components of the field, attosecond pulses with tailored temporal profiles are produced. The pulses are then used to ionize an atomic target in the presence of a relatively weak IR field (\( \sim 10^{11} \text{ W cm}^{-2} \)). Three quantum paths contribute to the generation of an electron waveform at a given energy \( E_\text{q} \) in the continuum: the direct transition by one XUV photon absorption (harmonic \( H_q \)) and two transitions involving absorption of one XUV photon (harmonics \( H_{q-1} \) and \( H_{q+1} \)), and absorption or emission of one IR photon. These three paths interfere, leading to an energy-dependent asymmetric electron emission along the direction of polarization of the light as pictured in the filmstrip sketch shown in figure 1 [10, 34]. Within the framework of second-order perturbation theory, it can be shown that the asymmetric component \( I_q \) of the electron emission is related to the spectral components of the attosecond pulses as [35, 36]:

\[
I_q(q, \tau) \sim I_0(q) \cos \left( \omega \tau + \psi(q) \right),
\]

with

\[
I_0(q) = |M_q| \left[ |M_{q-1}|^2 + |M_{q+1}|^2 + 2|M_{q-1}||M_{q+1}| \cos \left( \phi_q^{q-1} - \phi_q^{q+1} + \varphi_{M q} + \varphi_{M q} \right) \right]^{1/2} \tag{2a}
\]

and

\[
\psi(q) = \text{atan} \left( \frac{|M_{q-1}| \sin(\phi_q^{q-1} + \varphi_{M q}) + |M_{q+1}| \sin(\phi_q^{q+1} - \varphi_{M q})}{|M_{q-1}| \cos(\phi_q^{q-1} + \varphi_{M q}) + |M_{q+1}| \cos(\phi_q^{q+1} - \varphi_{M q})} \right). \tag{2b}
\]

The one- and two-photon matrix elements \( M_{q-1}, M_q \) and \( M_{q+1} \) are proportional to the amplitude of the harmonics \( H_{q-1}, H_q \) and \( H_{q+1} \), respectively, \( \phi_q^{q-1} = \phi_{q-1} - \phi_q \) and \( \phi_q^{q+1} = \phi_q - \phi_{q+1} \) are the relative spectral phases between consecutive harmonics, \( \varphi_{M q} \) and \( \varphi_{M q} \) are small (hundreds of mrad) atomic phases associated to the ionization pathways, \( \omega \) is the angular frequency of the 800 nm field, and \( \tau \) is the relative time delay between the APT and IR field. By tuning the spectral components of the APT, the photoelectron emission pattern can then be controlled, as indicated by equation (1).
Figure 1. Principle of the experiment: APTs with tailored temporal profile are generated with a two-color femtosecond field (800 + 400 nm) by varying both the intensity ratio $r$ and the relative phase $\phi$ between its two components. The pulses are then used to ionize argon gas in the presence of a relatively weak IR field ($\sim 10^{11}$ W cm$^{-2}$). Three quantum paths contribute to the generation of an electron wavepacket at a given energy $E_q$. These interfere, leading to an energy-dependent asymmetric electron emission along the direction of polarization of the light ($\hat{\varepsilon}$) that is controlled by tuning the temporal profile of the APT.

Figure 2. Schematic view of the experimental setup. It combines a femtosecond laser system, an attosecond XUV pump–IR probe Mach–Zehnder interferometer, a velocity-map imaging system (VMI), and an XUV spectrometer. APTs are generated with a linearly-polarized two-color field (800- and 400 nm) formed with a collinear optical system. The attosecond pulses are then used to ionize argon gas in the presence of the IR field. Both the energy and angular distributions of the photoelectron emission are captured by the VMI system. The asymmetric component of the electron emission along the direction of polarization of the light $\hat{\varepsilon}$ is deduced from the electron yields measured on either side (up and down) of the polarization vector. BS: 80/20 beam splitter, MX1,2 and M1-3: mirrors, LX and LI: lenses, RM: recombination mirror, TM: toroidal mirror, FG: flat-field grating.

3. Experimental setup

The experiment was performed at the ASAP (Auburn source of attosecond pulses) laboratory. A schematic view of the experimental setup is shown in figure 2. It combines a Ti:Sapphire laser delivering linearly-polarized 35 fs, 800 nm pulses at a 10 kHz repetition rate, a stabilized XUV-IR Mach–Zehnder interferometer, a VMI system, and an XUV spectrometer [37]. APTs made of both odd and even harmonics were generated with a linearly-polarized two-color (800- and 400 nm) field via high harmonic generation [14, 38] in one arm of the interferometer. The two-color field was created in a collinear geometry using a $\beta$-barium-borate (BBO) crystal, a calcite plate, and a zeroth-order half-wave plate (at 800 nm) [35]. The duration of the 400 nm pulse was not measured directly, but is expected to be somewhat longer than the...
Figure 3. Density plot of the asymmetric component of the photoelectron emission [defined as \((Y_{\text{up}} - Y_{\text{down}})/(Y_{\text{up}} + Y_{\text{down}})\), where \(Y\) is the electron yield] as a function of the time delay between the APT and IR fields and the photoelectron energy, for different intensity ratios \(r\) and relative phases \(\phi\) between the two colors of the HHG driving field. For illustrative purposes, the asymmetric components for electron energies corresponding to HHG orders H14 to H19 at the time delay indicated by the dashed line are shown in the top panels.

800 nm pulse. The relative intensity \((r = I_{400}/I_{800})\) between the two colors was adjusted by tuning the phase matching conditions in the BBO while maintaining the total intensity relatively constant. A few-degree rotation of the BBO crystal along its axis perpendicular to the polarization of the incoming light allowed for adjusting the relative intensity in between 0.5 and 3%. The relative phase \(\phi\) between the two colors, on the other hand, was controlled with a pair of fused-silica wedges. The absolute phase between the 400- and 800 nm fields was also not measured directly but was instead inferred from theoretical calculations as described later. The resulting linearly polarized two-color field was focused onto a 2 mm windowless gas cell filled with 10 Torr of argon. The peak intensity at the interaction region was estimated to be \(\sim 2 \times 10^{14} \text{ W cm}^{-2}\) from the cut-off energy of the high harmonics produced. APTs with an average duration of 10–20 fs were then formed by filtering out the harmonics below the 11th order with an ultra-thin Al foil. A replica of the IR (without the 400 nm) was sent into the other arm of the interferometer, whose total length could be changed to vary the time delay between the APT and the IR pulses. Both beams were focused, co-axially recombined, and finally sent into a vacuum chamber containing an effusive argon gas jet. At the focal point, the IR intensity is estimated to be below \(10^{11} \text{ W cm}^{-2}\). A home-built velocity map imaging system was used to capture the photoelectron emission \[39\]. The three-dimensional photoelectron momentum distributions were then reconstructed using the DAVIS algorithm \[40\].

4. Results

4.1. Attosecond control of the electron emission

Figures 3(a)–(f) show the measured asymmetric component of the photoelectron emission [defined as \((Y_{\text{up}} - Y_{\text{down}})/(Y_{\text{up}} + Y_{\text{down}})\), where \(Y\) is the electron yield] in a density plot as a function of the time delay \(\tau\) between the APT and IR field and the photoelectron energy. These measurements were performed with APTs generated with two-color driving fields having distinct intensity ratios \(r\) and relative phases \(\phi\) between the 400 nm and 800 nm components. At the electron energy associated to a given harmonic order, the asymmetric component oscillates with \(\tau\) at the frequency \(\omega\) of the 800 nm IR field \((T \simeq 2.7 \text{ fs})\), as indicated by equation (1). The phase of the oscillation, on the other hand, varies with the photoelectron energy,
Figure 4. Average spectral components (spectra (blue) and relative phases between consecutive harmonics (red)), and average temporal profile (inset plots) of the attosecond pulses in the train retrieved from figures 3(a)–(f).

giving rise to unique emission patterns. It can be observed that the emission pattern strongly depends on both $r$ and $\phi$. At low intensity ratio ($r \sim 0.5\%$) and for a relative phase $\phi$ close to 20° (figure 3(a)), the asymmetric emission exhibits a checkerboard-like pattern, revealing that electrons with energy associated to odd and even HHG orders are emitted in opposite directions, respectively. The asymmetry is stronger for the most energetic electrons, though. At $\phi \sim 40°$, a more consistent checkerboard-like pattern is observed as the asymmetry is nearly constant over the whole photoelectron energy range (figure 3(b)). As the phase between the two components of the driving field is further increased, such a checkerboard-like pattern gradually fades. At $\phi \sim 70°$, electrons with energy associated to HHG orders H14, H15, and H16 are roughly emitted in the same direction (figure 3(c)). The dependence of the emission pattern on $\phi$ is even more pronounced at a higher intensity ratio between the two colors. Comparing figures 3(d)–(f), it can be seen that the emission pattern smoothly evolves from a checkerboard-like to a stripe pattern, which indicates that the photoelectrons are emitted in the same direction for a given APT-IR delay. Considered together, these measurements provide good evidence that the photoelectron emission can be manipulated by shaping the temporal profile of the two-color HHG driving field.

4.2. Spectral components of the attosecond pulses

To reveal the mechanisms responsible for the coherent control observed in figure 3, we have retrieved the average spectral components (amplitudes, phases) of the attosecond pulses used in the experiments. The spectra of the APTs were directly measured with both the VMI and XUV spectrometers in the absence of IR field. The relative spectral phases between consecutive harmonics, on the other hand, were determined by solving the system of coupled equations, equation (2) with the iPROOF procedure described in reference [35]. The spectral components and the reconstructed temporal profiles of the APTs used in the measurements shown in figures 3(a)–(f) are plotted in figures 4(a)–(f), respectively. At low intensity ratio ($r \sim 0.5\%$), it can be seen that neither the shape of the spectrum nor the temporal profile of the APT vary
Figure 5. Calculated relative phase between consecutive odd and even harmonics (a) and (c) and ratio between the HHG rates generated by each half-cycle of the driving field (b) and (d). Calculations were made for $I_{800} = 2 \times 10^{14}$ W cm$^{-2}$ and for various intensity ratios $r$ and relative phases $\phi$ between the 400- and 800 nm components of the two-color driving field.

much with the phase difference $\phi$ between the two colors of the driving field, which indicates that the control of the electron emission is achieved almost uniquely by tuning the spectral phases of the APT. Indeed, as shown in figures 4(a)–(c), the relative phases between consecutive harmonics strongly depends on $\phi$. For $\phi \sim 20^\circ$ and $40^\circ$, large relative phase shifts are observed over the whole harmonic range. At $\phi \sim 70^\circ$, the phase shifts decrease, especially for lower harmonics (13th to 17th) where the relative phases are nearly constant. At higher intensity ratio ($r \sim 3\%$), the situation changes as both the spectrum and the relative phases (and consequently the temporal profile) of the APT strongly depends on $\phi$. In that case, the emission pattern is thus determined by both the relative amplitude and phase of the harmonics as predicted by equation (1).

4.3. Relative phase between odd and even harmonics
To better understand the observed dependence of the relative phases between odd and even harmonics on the temporal shape of the two-color driving field, we performed theoretical calculations of the HHG process within the strong field approximation (SFA) theory [41, 42], which has proved to be successful at qualitatively reproducing the characteristics of the XUV radiation (amplitude, phase, emission time, ...) generated with single- and multi-color fields [14, 20, 21, 29]. Calculations were made for $I_{800} = 2 \times 10^{14}$ W cm$^{-2}$ and for various intensity ratios $r$ and relative phases $\phi$ between the 400- and 800 nm components of the two-color driving field. Both the harmonic emission rate $A_q^n$ and the emission time $t_{ne}^q$ from the short trajectory were calculated for each half-cycle of the driving fields (labeled $n$ with $n = 0, 1$). The temporal profile $E_q(t)$ of the electric field for the harmonic radiation of order $q$ was then reconstructed by adding both contributions coherently:

$$E_q(t) = \sum_{n=0}^{1} (-1)^n A_q^n \cos \left( \omega_q(t - t_{ne}^q - nT/2) \right) = A_q \cos(\omega_q t + \varphi_q)$$

(3)

where $A_q$, $\varphi_q$, and $\omega_q$ are the amplitude, spectral phase, and angular frequency of the harmonic of order $q$, respectively, and $T$ is the period of the 800 nm component of the driving field. The calculated relative phase between consecutive odd and even harmonics $\Delta \varphi = \varphi_{q+1} - \varphi_q$ for different ratios $r$ and relative phases $\phi$ between the two components of the HHG driving field are plotted in figures 5(a) and (c) as a function of...
the harmonic order. Our calculations qualitatively reproduce the relatively large phase shifts observed experimentally as well as their dependence with $r$ and $\phi$. At low ratio ($r = 0.5\%$), the phase shifts are maximum for $\phi \sim 40^\circ$, and decrease as $\phi$ tends to 0 or 90°. The same dependence is observed at $r = 3\%$, even though the phase shifts are overall smaller, with a maximum obtained at $\phi \sim 20^\circ$. The origin of the phase shifts lies in the relative strength of the harmonic emission rates produced by each half-cycle of the driving field, quantified by the ratio $A_q^f/A_q^o$ (see figures 5(b) and (d)). The relative phase shifts are maximum for a ratio close to one, which corresponds to the case where both half-cycles contribute equally to the harmonic generation. In that case, two attosecond pulses are emitted per optical cycle. It is worth noting that in the limit of equal emission rates ($A_q^f \simeq A_q^o$), which could be achieved with a very weak perturbative second harmonic field, equation (3) reduces to $E_q(t) \propto \sin(\omega_q t - (t_{q0}^f + t_{q0}^o)/2 - q\pi/2)$, predicting a relative phase shift between odd and even harmonics close to $\pi/2$ as it has been observed in previous studies [10, 36, 43]. On the other hand, when one half-cycle of the driving field contributes predominantly to the HHG emission process, leading to the generation of one main pulse per optical cycle, the relative phase shifts are nearly constant as shown in figure 5(c) for the cases $\phi = 70^\circ$ and 90°. Note that the mean value of the phase shifts indicates which half-cycle contributes the most to the emission: the average phase shift lies in the range $[-\pi, 0] \cup (0, \pi]$ when the first (second) half-cycle contributes predominantly. At even higher ratio ($r > 10\%$), we observe that the HHG emission is predominantly produced by one half-cycle regardless of $\phi$ and that the relative phase between odd and even harmonics remains nearly constant [14]. Based on the results of our SFA calculations, we have found that the tunability of the APT is optimized for an intensity ratio between 0.1 and 5\%.

5. Conclusions

In conclusion, we have shown that the photoelectron emission produced from atoms by absorption of an APT made of odd and even harmonics in the presence of a relatively weak IR field ($\sim 10^{11}$ W cm$^{-2}$) can be coherently controlled by tailoring the temporal profile of the APT. Emission patterns where photoelectrons are emitted in the same direction or, conversely, are emitted in opposite directions depending on their energy can be obtained by tuning one or both spectral components (amplitude, phase) of the pulse. From these patterns, we have also shown that APTs generated with a two-color HHG driving field exhibit a high temporal tunability, which can be reasonably well predicted within the SFA theory. Our work shows that attosecond pulse shaping for coherent control of quantum phenomena is steadily becoming a reality. We expect that this approach can be applied to control more complex quantum systems, thus offering new capabilities for the growing field of attochemistry.

Acknowledgment

This work was supported by the US Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES), under Award # DE-SC0017984. BU acknowledges support from the Undergraduate Research Fellowship (URF) program at Auburn University.

ORCID iDs

T Olsson https://orcid.org/0000-0002-6984-2826
G M Laurent https://orcid.org/0000-0002-3700-7412

References

[1] Zewail A H 1994 Femtochemistry - Ultrafast Dynamics of The Chemical Bond (20th Century Chemistry Series vol 1 and 2) (Singapore: World Scientific)
[2] Rabitz H, de Vivie-Riedle R, Motzkus M and Kompa K 2000 Science 288 824
[3] Weiner A M 2011 Opt. Commun. 284 3669
[4] Kitzler M and Gräfe S 2016 Ultrafast Dynamics Driven by Intense Light Pulses: From Atoms to Solids, from Lasers to Intense X-rays (Springer Series on Atomic, Optical, and Plasma Physics) (Berlin: Springer)
[5] Paul P M, Toma E S, Breger P, Mullot G, Augé F, Balco P, Muller H G and Agostini P 2001 Science 292 1689
[6] Hentschel M et al 2001 Nature 414 509
[7] Sansone G et al 2010 Nature 465 763
[8] Ranitovic P et al 2014 Proc. Natl Acad. Sci. USA 111 912
[9] Mauritssson I, Johnsson P, Mansten E, Swoboda M, Rachon T, L’Huillier A and Schaeff K J 2008 Phys. Rev. Lett. 100 073003
[10] Laurent G, Cao W, Li H, Wang Z, Ben-Izhak I and Cocke C L 2012 Phys. Rev. Lett. 109 083001
[11] Buste D et al 2019 Phys. Rev. Lett. 123 133201
[12] López-Martens R et al 2005 Phys. Rev. Lett. 94 033001
[13] Dudovich N, Smirnova O, Levesque J, Mairesse Y, Ivanov M Y, Villeneuve D M and Corkum P B 2006 Nat. Phys. 2 781
[14] Mauritsson J, Johnsson P, Gustafsson E, L’Huillier A, Schafer K J and Gaarde M B 2006 Phys. Rev. Lett. 97 013001
[15] Mansten E, Dahlström J M, Johnsson P, Swoboda M, L’Huillier A and Mauritsson J 2006 New J. Phys. 10 083041
[16] Douny G, Wheeler J, Roedig C, Chirila R, Agostini P and DiMauro L F 2009 Phys. Rev. Lett. 102 093002
[17] Dahlström M, Fordell T, Mansten E, Ruchon T, Swoboda M, Klünder K, Gisselbrecht M, L’Huillier A and Mauritsson J 2009 Phys. Rev. A 80 033836
[18] He X, Dahlström J M, Rakowski R, Heyl C M, Persson A, Mauritsson J and L’Huillier A 2010 Phys. Rev. A 82 033410
[19] Jin C, Wang G, Le A T and Lin C D 2014 Sci. Rep. 4 7067
[20] Chen C et al 2017 Opt. Express 25 28684
[21] Mitra S et al 2020 J. Phys. B: At. Mol. Opt. Phys. 53 134004
[22] Yuan K J and Bandrauk A D 2013 Phys. Rev. Lett. 110 023003
[23] Mediáuskas L, Wragg J, van der Hart H and Ivanov M Y 2015 Phys. Rev. Lett. 115 153001
[24] Ferré A et al 2015 Nat. Photon. 9 93
[25] Kfir O et al 2015 Nat. Photon. 9 99
[26] Dorney K M et al 2017 Phys. Rev. Lett. 119 063201
[27] Jiménez-Galán Á, Zhavoronkov N, Ayuso D, Morales F, Patchkovskii S, Schloz M, Pisanty E, Smirnova O and Ivanov M 2018 Phys. Rev. A 97 023409
[28] Gariepy G, Leach J, Kim K T, Hammond T J, Frumker E, Boyd R W and Corkum P B 2014 Phys. Rev. Lett. 113 153901
[29] Mairesse Y et al 2003 Nature 302 1540
[30] Wei P, Miao J, Zeng Z, Li C, Ge X, Li R and Xu Z 2013 Phys. Rev. Lett. 110 233903
[31] Hamilton K R, van der Hart H W and Brown A C 2017 Phys. Rev. A 95 013408
[32] Birulia V A and Strelkov V V 2019 Phys. Rev. A 99 043413
[33] Cheng Y C et al 2020 Proc. Natl Acad. Sci. USA 117 10727
[34] Yin Y Y, Chen C, Elliott D S and Smith A V 1992 Phys. Rev. Lett. 69 2353
[35] Laurent G, Cao W, Ben-Izhak I and Cocke C L 2013 Opt. Express 21 16914
[36] Laurent G, Cao W, Ben-Izhak I and Cocke C L 2014 J. Phys.: Conf. Ser. 488 012008
[37] Vaughan J et al 2019 Opt. Express 27 30989
[38] Kim I J, Kim C M, Kim H T, Lee G H, Lee Y S, Park J, Cho D J and Nam C H 2005 Phys. Rev. Lett. 94 243901
[39] Klein G et al 2014 J. Instrum. 9 P05005
[40] Harrison G R, Vaughan J C, Hidé B and Laurent G M 2019 J. Chem. Phys. 148 194101
[41] Lewenstein M, Balco P, Ivanov M Y, L’Huillier A and Corkum P B 1994 Phys. Rev. A 49 2117
[42] Lewenstein M, Salières P and L’Huillier A 1995 Phys. Rev. A 50 4747
[43] Keatley P D, Bhardwaj S, Moses J, Laurent G and Kärtner F X 2016 New J. Phys. 18 073009