Cascaded generation of isolated sub-10 attosecond half-cycle pulses

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Abstract
Sub-10 attosecond pulses (APs) with half-cycle electric fields provide exceptional options to detect and manipulate electrons in the atomic timescale. However, the availability of such pulses is still challenging. Here, we propose a method to generate isolated sub-10 attosecond half-cycle pulses based on a cascade process naturally happening in plasma. A backward AP is first generated by shooting a moderate overdense plasma with a one-cycle femtosecond pulse. After that, an electron sheet with the thickness of several nanometers is formed and accelerated forward by the electrostatic field. Then this electron sheet goes through unipolar perturbations driven by the tail of the first-stage AP instead of the initial laser pulse. As a result, a half-cycle sub-10 AP is cascadedly produced in the transmission direction. Two-dimensional particle-in-cell simulations indicate that an isolated half-cycle pulse with the duration of 7.3 attoseconds can be generated from the cascaded scheme. Apart from a one-cycle driving pulse, such a scheme also can be realized with a commercial 100 TW 25 fs driving laser by shaping the pulse with a relativistic plasma lens in advance.

1. Introduction
Half-cycle pulses, also called unipolar pulses, refer temporally asymmetrical single-cycle pulses whose fields in one polarity are predominantly stronger than that in the opposite polarity [1]. Such pulses normally generate from collective unidirectional motion of electrons. In the near field, half-cycle pulses can offer exceptional possibilities to control and probe electron dynamics by asymmetrically manipulating electron wavepackets in atoms or in solid [2, 3]. In the far field, despite the emergence of a long tail due to diffraction, the pulses are still valuable for many applications not requiring the strict unipolarity [4]. In experiments, half-cycle pulses have been obtained in the terahertz [5], far-infrared [6], mid-infrared [7], and visible ranges [8]. Recently, the generation of attosecond pulses (APs) in extreme-ultra-violet (XUV) range from relativistic laser–plasma interaction [9–11] is attracting much attention. Such attosecond XUV pulses would bring new opportunities to many applications such as nonlinear optics in the XUV region [12], XUV pump–probe spectroscopy of ultrafast dynamics [13], and single-shot diffractive imaging of a single biomolecule [14].
Several schemes for the production of isolated half-cycle APs from solid surfaces or underdense plasmas have been studied. Naumova et al proposed that a single 200 AP could be produced when a tightly focused laser pulse is reflected from a relativistic plasma mirror created by the pulse itself [15]. Wu et al numerically demonstrated that an intense half-cycle pulse with the duration of tens of attoseconds could be produced by irradiating a double-foil target with a few-cycle laser pulse [16]. Continuum XUV spectra that support a 600 AP have been experimentally observed using this scheme, but the temporal profile of the pulse still needs to be measured [17]. Attosecond half-cycle pulses generated from underdense plasmas also have been studied by Li et al [18]. They proposed that an intense, radially polarized, 100 attosecond half-cycle pulse can be generated from ultrathin relativistic electron disks in a quasi-one-dimensional wakefield acceleration regime [18]. Further reduction in durations of the APs can improve the ultimate temporal resolutions in experiments. However, the direct generation of a brilliant half-cycle pulse with sub-10 attosecond duration is still a challenge.

In the present work, we propose a theoretical scheme of generating an isolated sub-10 attosecond half-cycle pulse from the interaction of a relativistic laser pulse with a moderate overdense plasma. We first illustrate the emission mechanism and electron dynamics through one-dimensional (1D) particle-in-cell (PIC) simulations. An isolated, half-cycle, 3 attosecond (defined as the full width at half maximum of the intensity) pulse with a peak electric field of $10^{13}$ V m$^{-1}$ is generated by utilizing a one-cycle driving pulse. Second, the robustness of our scheme is testified by varying the densities of the plasmas and the carrier-envelope phases (CEPs) of the driving pulses. In 2D simulations, the half-cycle feature maintains, and the pulse duration increases to 7.3 attoseconds with the similar parameters. Finally, we demonstrate that our scheme can be realized presently with a 100 TW 25 fs driving pulse by placing a piece of near-critical-density (NCD) plasma slab in front of the overdense plasma to shape the pulse. After the shaping process, the multi-cycle pulse transforms into a pulse with a sharp rising edge, which leads to the generation of a 40 attosecond half-cycle pulse in the same scheme as the one-cycle driving laser.

2. Emission mechanism of the half-cycle AP

The relativistic laser–plasma interactions are extremely nonlinear and complicated due to the strong coupling between the laser field and the self-induced field in plasmas [19]. We first carried out 1D PIC simulations using the EPOCH code [20] to illustrate the emission mechanism of the half-cycle AP in our scheme. For the simplicity of the physics, a one-cycle laser pulse is chosen as the driving pulse with the temporal profile of $E_z = a \times \exp((-t - T_0)^2/\tau^2) \times \sin(\omega t + \phi)$ as displayed in figure S1 of supplementary material (https://stacks.iop.org/NJP/23/053003/mmedia). Here $T_0$ and $\omega$ are the laser period and frequency with $\tau = 0.5T_0$ while $\phi$ is the CEP. The normalized amplitude of the driving pulse is $a = 30$, where $a = eE/m_0\omega c, m_0$ is the rest mass and charge of an electron, $E$ is the peak electric field of the pulse and $c$ is the light speed in vacuum. Fully ionized sharp boundary plasma with a thickness of $0.5\lambda_0$ and electron density of $40n_e$ is initially located between $x = 1.0\lambda_0$ and $x = 1.5\lambda_0$, where $\lambda_0 = 800$ nm is the laser wavelength and $n_e = m_e\epsilon_0\omega^2/e^2$ is the critical density of plasma. Here $\epsilon_0$ is the dielectric constant. The cell size is 40 000 cells/$\lambda_0$ and each cell is filled with 100 macroparticles. The laser is normally incident and the carbon ions are treated mobile for all the simulations. With the developments of laser technologies, similar near-single-cycle laser pulses have been experimentally realized at non-relativistic [21–23] and moderately relativistic intensities [24, 25]. Relativistic one-cycle APs are also promising to be obtained from plasma optic devices [26, 27]. It should be noted that a multi-cycle pulse with a sharp rising edge is also applicable for driving the cascade mechanism.

The generation process of the half-cycle AP is depicted in figure 1 based on the simulative spatial-temporal evolution of the electron density. When the driving pulse irradiates the plasma, electrons are piled up by the ponderomotive force in the first half cycle of the laser [28], as shown in figure 1(a). Consequently, an electrostatic field as strong as $10^{14}$ V m$^{-1}$ is created due to the charge separation. When the laser field starts to decline after the peak of the first half cycle, the electrons are pulled back by the electrostatic restoring force. Then an ES (ES1) is formed and backward accelerated to the relativistic speed inside the plasma, which simultaneously leads to the generation of a backward AP (AP1) as depicted in figure 1(b) at the simulation time of 6.8 fs. Both ES1 and AP1 contain a strong and short front peak as well as a weak and long tail. After the peak of ES1 reaches the left boundary of the plasma at the simulation time of 7.2 fs, the charge separation field reverses its direction. Driven by this field, part of the electrons in ES1 forms a secondary nanometer-thin ES (ES2) moving in the forward (transmission) direction as displayed in figure 1(c). In the strong charge separation field, ES2 is immediately accelerated to the speed of light, and meanwhile, transversely perturbed by the tail of AP1 in a constant direction. As a result of this transient perturbation, an isolated half-cycle pulse (AP2) propagating in the forward direction is produced as shown in figure 1(d). After that, ES2 is quickly dispersed by the deceleration field at $x > 1.2\lambda_0$, whereas AP2 propagates out of the plasma maintaining the duration around 3 attoseconds as shown in figure 3(a).
The emission process of the half-cycle pulse is determined by the electron dynamics in ES2. Figures 2(a) and (b) display the snapshots of the transverse current and the electromagnetic field at the simulation time of 7.4 fs and 7.7 fs, respectively. $E_z + B_y$ represents the backward field while $E_z - B_y$ represents the forward field. One can see the transverse current in ES2 rises to peak in 0.3 fs due to the perturbation by the tail of AP1. If ES2 is at rest, such a transient current will lead to the emission of an electromagnetic pulse with a duration of about 300 attoseconds. However, the ES is moving forward with a relativistic speed of $v_x$. The Doppler effect compresses the pulse in time domain by a factor of $4\gamma_x^2$, where $\gamma_x = 1/\sqrt{1 - v_x^2/c^2}$ is the Lorentz factor. According to the simulation results, the $\gamma_x$ of ES2 is about 8. As a result, the duration of the generated half-cycle pulse is compressed to few-attosecond timescale in the lab frame. Figures 2(c) and (d) illustrate the trajectories of representative electrons in ES2 from simulation time 7.2 fs to 8.1 fs. The emitted half-cycle pulse also can be viewed as the result of the synchrotron-like motion of the electrons. Noting that there is no conspicuous velocity change of ES2 in $x$ axis between 7.4 fs and 7.7 fs as we utilize a weak transverse force driven by the tail of AP1 to avoid obvious deceleration of ES2.

3. Robustness of the scheme

The plasma density and the CEP of the driving pulse impose significant influences on the electron dynamics. We performed a series of simulations to study the robustness of our scheme by varying the plasma densities and the CEPs. As shown in figures 3(b) and (c), for plasma densities of $35n_c < n_e < 43n_c$ and CEPs of $0.26 < \phi < 0.52$, the durations of AP2 are all below 10 as. The achieved minimum pulse duration is 2.6 as, more than two orders of magnitude shorter than that of the driving pulse. At the meantime, the peak electric fields of the emitted half-cycle pulses keep at the same order of magnitude as the driving pulse.

To include the multi-dimensional effects, 2D PIC simulations were performed with parameters similar to that of 1D cases. The simulation box is $1\lambda_0 \times 8\lambda_0$. The spatial resolution is $\lambda_0/16 000 \times \lambda_0/400$, and the number of particles per cell in the target is 16. The laser linearly polarizes in the simulation plane with a Gaussian transverse profile and a waist radius of $w_0 = 2\lambda_0$. The plasma is located at $0.1\lambda_0 \leq x \leq 0.5\lambda_0$. All other parameters are the same as the 1D simulation above. Move window along $x$ axis with the speed of $c$ is
Figure 2. The electron dynamics which determines the mission process of AP2. (a) Transverse current distribution (blue solid curve), and electromagnetic fields moving forward (red solid curve) as well as backward (red dashed curve) at the simulation time of 7.4 fs. (b) The same as those shown in (a) at the simulation time of 7.7 fs. The forward part of electrons is marked by the blue area. The transverse current is normalized by $j_0 = n_e c$. The magnetic and electric field are normalized by $B_0 = m_e \omega / c$ and $E_0 = m_e \omega c / e$, respectively. (c) and (d) The trajectories of representative electrons in ES2 from simulation time 7.2 fs to 8.1 fs along z and x axis, respectively. The colors of the lines represent the strength of transverse force $e(E_z + v_x \times B_y)$ normalized by $eE_0$. The electrons’ synchrotron motions starting from 7.4 fs leads to the emission of the half-cycle pulse in the forward direction.

Figure 3. 1D and 2D simulation results of the forward AP. (a) The emitted half-cycle AP at 1D simulation time of 9fs. (b) and (c) The durations and normalized intensities $(E/E_0)^2$ of the APs in dependence of the plasma densities and the CEPs $\phi$ of the one-cycle driving laser, respectively. (d) The transverse field distribution of the obtained AP at 2D simulation time of 10 fs. Utilized from the simulation time of 2.2$T_0$. The electron dynamics and the emission process are pretty much the same. Figure 3(d) displays the transverse field of the obtained AP at the simulation time of 10 fs. As one can see, a half-cycle pulse with the duration of 7.3 as is generated. Considering that the numerical dispersion in 2D simulations would widen the pulse durations, maybe the actual durations could be even shorter in experiments. It is interesting to notice that the intensity of the obtained pulse in 2D simulations is higher than that in the 1D case due to the spatially focusing effect.
Figure 4. Cascaded generation of an AP in a double-layer target. (a) The initial multi-cycle driving laser with a duration of 25 fs and the normalized vector potential of $a = 6$. (b) The shaped pulse with a sharp rising edge due to self-modulation and self-focusing effects after the laser propagating in the first-layer NCD plasma. (c) The detailed profile of the one-cycle-like front edge at simulation time $42.5 T_0$ (the same moment of figure 4(b)). Here we display the mean value of electric field in the transverse range $-0.2 \lambda_0 \leq y \leq 0.2 \lambda_0$. (d) The detailed intensity distribution of the emitted AP propagating in the vacuum at simulation time $49 T_0$. The blue dashed curve represents the distribution of intensity along the $x$-axis passing through the peak point of $E_y$. (e) and (f) The dependence of the durations (blue curve) and normalized intensities $(E_y/E_0)^2$ (red curve) of the AP on the densities (e) and locations (f) of the second-layer target, respectively.

4. Realizing the scheme with a commercial 100TW laser system

Our scheme relies heavily on the pileup of the electrons in the plasma at first. The one-cycle pulse provides an ideal driving force for the electrons’ pileup. As a matter of fact, the cascaded scheme also can be realized with multi-cycle pulses as long as they have a sharp rising edge to provide sufficient ponderomotive force. It has been demonstrated in theories and in experiments that a tens-of-femtosecond relativistic laser pulse can be shaped to a sharp-edged pulse by propagating through an NCD plasma [29]. Inspired by the related works, we perform 2D simulations by placing an NCD plasma slab in front of the overdense plasma to generate a half-cycle AP. The simulation box is $12.5 \lambda_0 \times 25 \lambda_0$. The spatial resolution is $\lambda_0/1000 \times \lambda_0/40$, and the number of particles per cell is 16. A 25 fs Gaussian laser is utilized with a normalized amplitude of $a = 6$ and a waist radius of $w_0 = 7.5 \lambda_0$ as displayed in figure 4(a). Such a pulse can be produced with a commercial 100 TW laser system. The first-layer NCD plasma is located at $1.0 \lambda_0 \leq x \leq 26.0 \lambda_0$ with a density of $0.48n_c$ to achieve an optimal laser self-modification according to the plasma lens model [30]. The second-layer overdense plasma is located at $26.0 \lambda_0 \leq x \leq 26.5 \lambda_0$ with a density of $9.5n_c$. Move window is utilized which starts move from the simulation time of $23.0 T_0$ along $x$ axis with light speed in vacuum. As shown in figures 4(b) and (c), after a 25$\lambda_0$-long NCD plasma, the front edge of the pulse is shaped highly similar to a one-cycle pulse. Then the cascaded generation of a half-cycle AP happens in the overdense plasma. The intensity distribution of the emitted AP after it propagating out of the plasma is displayed in figure 4(d). The pulse duration is 46 as, which could be further reduced by utilizing a petawatt femtosecond pulse and higher plasma density. It should be noted that, the sensitivity of the cascaded scheme is utilized to obtain an isolated AP. As shown in figure 4(c), besides the front edge of the shaped pulse which is similar to a one-cycle pulse resulting in the emitting of AP, for the remaining part of the shaped pulse, no strong AP is emitted due to the mismatching of laser intensities and plasma densities.
The robustness of the modified scheme is studied as well by varying the parameters of the targets. The influences of the second-layer plasma’s densities are displayed in figure 4(e) indicating an allowable density fluctuation exceeding 10%. Figure 4(f) illustrates the influences of the first-layer plasma’s densities on the AP durations and amplitudes. Here the thicknesses of the first-layer NCD plasmas are determined by the locations of the second-layer target. The isolated half-cycle AP can be generated in a wide range of thicknesses. By changing the thicknesses of the NCD plasma, the CEPs of the shaped pulses change accordingly (see details in supplementary material), which eventually determine the duration and amplitude of the generated AP.

5. Discussion

The key to get a sub-10 attosecond half-cycle pulse in the cascaded scheme is to transversely perturb an ultrathin relativistic ES with an AP instead of a femtosecond laser pulse as in other schemes. The resulting pulse duration relies on the perturbation duration as well as the thickness and speed of the ES. We developed a simple analytical model including the above parameters to give an estimation of the pulse duration by taking into account the slowing down of the ES during emission. Considering an ultrashort ES with relativistic factor $γ_0$ $\gg$ 1 is perturbed by a counterpropagating electromagnetic field with constant amplitude of $E$ and $B$. Assuming $v_x(0) = 0$, the transverse dynamics can be expressed as
\[ d(γm_0v_x)/dt = F_z = -Ee/v_0c.\] In the first order approximation, $v_x$ can be written as $v_x ≈ −2Eet/m_0γ_0c$. The derivative of $γ$ can be expressed as $dγ/tdt = −Ee/m_0c^2 = 2E^2c^2t/m_0^2γ_0c^2$. Then the longitudinal dynamics also can be expressed as $d(γm_0v_x)/dt = F_z = 2Ee^2t/m_0γ_0c$. As a result, the central position of the ES is
\[ x_c(t) = v_0t - \frac{2E^2c^2}{3m_0^2γ_0^2}t^3. \]
The forward radiation from the ES is determined by the integral of the retarded transverse current as \[ E(x, Δt) = \frac{1}{2c_0} \int_0^Δt j_x(x - c(Δt - t), t)dt. \]
Assuming the density profile of the ES is unchanged during the emission process, the transverse current can be written as $j_x(x, t) = j(t)f(x - x_c(t))$, where $f(x)$ is the local density function of the ES. One can derive that $j_x = n_ev_x = 2E^2n_0t/m_0γ_0c$ where $n_e$ is the plasma peak density. The field of the AP generated from the corresponding transverse current after perturbation time $Δt$ can be expressed as
\[ E(x, Δt) = \frac{1}{2c_0} \int_0^Δt \frac{2E^2n_0c}{m_0γ_0} f(x - cΔt + (c - v_0)t) + \frac{2E^2c^2}{3m_0^2γ_0^2}t^3)dt. \]
For simplicity, assuming the ES has a δ-like density distribution and will not dilate, then the duration of the AP can be written as
\[ \tau = \left(1 - \frac{\sqrt{2}}{2}\right)\frac{1 - v_0/c}{\sqrt{2}} Δt + \left(1 - \frac{\sqrt{2}}{4}\right)\frac{2E^2c^2}{3m_0^2γ_0^2c^4} Δt^3. \]
The duration of the emitted half-cycle pulse after $Δt$ is determined by the displacement of the ES with respect to $Δt$. If the ES keeps its speed as a constant, the duration of the AP will stretch linearly as $(c - v_0)Δt$. However, the existence of $\vec{v} \times \vec{B}$ force leads to the longitudinal deceleration of the ES by $v_x(t) = v_0 - 2E^2c^2t^2/m_0^2γ_0c$. As a result, the duration of the emitted pulse $τ \propto E^2Δt^3$ as shown in equation (4). In order to generate a sub-10 attosecond pulse, the perturbation time $Δt$ should be short enough, and the perturbation strength $E$ should not be too high. For example, if $γ_0 = 10$, $n_e = 1000n_c$, and $E = 2 \times 10^{13}$ V m$^{-1}$, the perturbation time should be less than 400 as. In our cascaded generation scheme, the ES is perturbed by an AP instead of a femtosecond pulse, which eventually leads to the generation of a sub-10 attosecond pulse.

We use the parameters from simulation results as input to verify our model. The average $γ$-factor and maximum density $n_0$ of the ES are 8 and 1050$n_c$, respectively. The electron distribution from simulation as shown in figure 5(a) is applied instead of a δ-like distribution. The average field strength of driving pulse AP1 is estimated as $E = 8 \times 10^{12}$ V m$^{-1}$ according to figure 2(a). Figure 5(a) displays the evolution of transverse current density in the light-speed frame. One can see the deceleration of ES1 due to the driving pulse. Using the above parameters, the calculated duration and strength of field after a perturbation time $Δt$ is displayed in figure 5(b), which are in agree with the PIC simulation results. It can be seen from figure 5(b) that reducing the perturbation time will lead to a shorter AP with the price of reduced intensity. There is a
Figure 5. The illustration of pulse stretching process. (a) The evolution of transverse current density $j_z$ at various perturbation time $\Delta t$ in the light speed frame. The red and blue curves present the locations of light and the ES, respectively. The velocity of the ES will decrease as $\Delta t$ increases. The emitted AP will stretch as a result of the velocity variation between ES and light. (b) The dependence of the pulse duration $\tau$ and normalized field strength $E/E_0$ on the perturbation time $\Delta t$. The dashed line represents the case of a $\delta$-like density distribution as equation (4). The solid line shows the calculated duration (blue line) and strength of field (red line) respectively for the case of a realistic density distribution in simulations (see details in supplementary material). The stars represent the values generated directly from the simulations.

Figure 6. The spectra of the AP in 1D case. The solid line is directly obtained from fast Fourier transform of $E(t)$ as shown in figure 3(a) while the dashed line is derived from equation (5).

trade-off between the duration and intensity of the AP by varying the perturbation time. We found the moderate overdense plasma is optimal in terms of generating a strong sub-10 attosecond pulse. For underdense plasmas, AP1 could not be generated due to the weak reflection of the driving laser pulse. For highly overdense plasma, the perturbation time will be too short to produce an AP strong enough.

The spectrum of AP2 also can be estimated by the simple model. The spectrum of AP2 can be written as

$$I(\omega) = 4\pi^4 \alpha_0^4(\alpha_1 \omega)^{-4} \left( A_{\alpha_1}' \left( \alpha_1^{-\frac{4}{3}} \delta \omega^\frac{2}{3} \right) \right)^2 |f(\omega)|^2,$$

where $\alpha_0 = 2Ee^2n/m_0c$, $\alpha_1 = \alpha_0^2/2vn^2$, $\delta = 1 - \nu$, $A_{\alpha_1}'$ is the derivative of the Airy function of the first kind and $f(\omega)$ is the Fourier transform of the shape function of ES2. Here $\nu = 0.992$ and $n = 1050$ are the normalized speed and peak density of ES2, respectively, while $\alpha_0 = 525$ for $E = 8 \times 10^{12}$ V m$^{-1}$. The electron distribution from simulations is shown in figure 5. Finally, the theoretical spectrum of AP2 can be derived as displayed in figure 6, which is consistent with the spectrum directly obtained from the Fourier transform of AP2 at simulation time $9 \text{ fs}$. For the harmonic range $\omega_0 < \omega < 100\omega_0$, the theoretical intensity scaling law is $I(\omega) \propto \omega^{-4/3}$. One can see the low frequency part is smaller than the predicted one due to the absorption of AP2 propagating in the plasma.

The transverse perturbation from the long tail of AP1 instead of a femtosecond laser pulse is the main characteristic of our cascaded scheme distinct from other published works. The coherent wake emission mechanism has no contributions to the spectra above $7\omega_0$ for a $40n_c$ plasma due to its low cut-off energy as $\sqrt{n_c\omega_0}$ [33]. The relativistically oscillating mirror scheme [34, 35] can be excluded as it emits in the reflection direction. For the coherent synchrotron emission works, with either obliquely [31, 36] or normally [37–41] incident driving laser, the transverse driving force are from the laser itself. The use of a moderate overdense plasma and the CEP control of the driving laser in the cascaded scheme give possibilities for ES2 to be perturbed by the long tail of AP1.
To compare the AP generation efficiency with other published works, we adopt the value $I_a/I_L$ in 1D simulations [32]. Considering the normalized vector potential of the laser $a = 30$ and of AP2 $a = 12$, $I_a/I_L = 0.16$, which is similar to the previous works in transmission direction [40, 41] and a little lower than the APs in the reflection direction [32, 36]. This can be understood as there is no obvious laser absorption effect in the plasmas for the reflection case. Based on the 2D simulations, the energy of AP2 can be estimated as $0.4 \mu J$ if we simply suppose the third dimension $z$ is similar to the $y$ axis, corresponding to an overall efficiency of $4 \times 10^{-6}$.

The experimental realization of the cascaded mechanism for an isolated half-cycle AP requires the fabrication of targets and the characterization method of half-cycle APs. Previous studies show carbon nanotube foams can be utilized as the double-layer targets with the electron densities range from $0.2n_c$ to $20n_c$. Such targets have been successfully applied in enhanced ion acceleration experiments [42]. Planar cryogenic hydrogen targets [43] or focused ion beam processed plastic foil [44] can be used as the $40n_c$ targets. The techniques that directly measure the duration or waveform of the single-shot sub-10 attosecond pulses is highly challenging and may need a long time to be developed after the demonstration experiments. As the first step, a quick and reliable characterization is to measure the spectra of the attosecond pulses. The spectrum of an isolated half-cycle pulse should be quite flat in the low-frequency part with no obvious harmonics. Moreover, the AP also can be confirmed by detecting the secondary effect resulted from the strong half-cycle electric field, for example, by setting a gas cell behind the overdense target and measuring the asymmetric electron spectra at different angles with respect to the laser axis [45].

6. Conclusion

In summary, we propose a novel scheme to generate intense isolated sub-10 attosecond half-cycle pulses in the transmission direction based on a cascade process naturally happening in laser–plasma interaction. Systematic simulations reveal the robustness of this scheme. Presently, our scheme can be realized by shaping a 100 TW 25 fs laser pulse with plasma optics as the driving pulse. Such isolated pulses can be directly utilized as exceptional pump or probe pulses without the need for extra filters, offering new opportunities for high-field physics and ultrashort optics.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

[1] Arkhipov M V, Arkhipov R M, Pakhomov A V, Babushkin I V, Demircan A, Morgner U and Rosanov N N 2017 Opt. Lett. 42 2189–92
[2] Monkałenko A S, Zhu Z-G and Berakdar J 2017 Phys. Rep. 672 1–82
[3] Thiele I, Siminos E and Fülöp T 2019 Phys. Rev. Lett. 122 104803
[4] Pakhomov A V, Arkhipov R M, Babushkin I V, Arkhipov M V, Tolmachev Y A and Rosanov N N 2017 Phys. Rev. A 95 013804
[5] Gao Y, Drake T, Chen Z and DeCamp M F 2008 Opt. Lett. 33 2776–8
[6] Greene B I, Federici I F, Dykaar D R, Jones R R and Bucksbaum P H 1991 Appl. Phys. Lett. 59 893–5
[7] Liang H et al 2017 Nat. Commun. 8 141
[8] Hassan M T et al 2016 Nature 530 66
[9] Mourou G 2019 Rev. Mod. Phys. 91 030501
[10] Wang J, Zepf M and Rykovanov S 2019 Nat. Commun. 10 5554
[11] Xu X et al 2020 Optica 7 355–8
[12] Heissler P et al 2012 New J. Phys. 14 043025
[13] Krausz F and Ivanov M 2009 Rev. Mod. Phys. 81 163
[14] Miao J, Ishikawa T, Robinson I K and Murnane M M 2015 Science 348 530–5
[15] Naumova N, Nees J, Sokolov I, Hou B and Mourou G 2004 Phys. Rev. Lett. 92 063902
[16] Wu H-C and Meyer-ter-Vehn J 2012 Nat. Photon. 6 304–7
[17] Ma W et al 2014 Phys. Rev. Lett. 113 235002
[18] Li F, Sheng Z, Chen M, Yu L, Meyer-ter-Vehn J, Mori W and Zhang J 2014 Phys. Rev. E 90 043104
[19] Mourou G A, Tajima T and Bulanov S V 2006 Rev. Mod. Phys. 78 309
[20] Arber T D et al 2015 Plasma Phys. Control. Fusion 57 113001
[21] Nosov N, Nees J, Sokolov I, Hou B and Mourou G 2004 Phys. Rev. Lett. 92 063902
[22] Rivas D et al 2017 Sci. Rep. 7 5224
[23] Lu C-H, Wu W-H, Kuo S-H, Guo J-Y, Chen M-C, Yang S-D and Kung A H 2019 Opt. Express 27 15638–48
[24] Nie Z, Pai C H, Zhang J, Ning X and Joshi C 2020 Nat. Commun. 11 2787
[25] Oullé M et al 2020 Light: Sci. Appl. 9 47
[26] Ji L et al 2009 Phys. Rev. Lett. 103 215005
[27] Zhu X L, Weng S M, Chen M, Sheng Z M and Zhang J 2020 Light: Sci. Appl. 9 46
[28] Zhang Y X, Qiao B, Xu X R, Chang H X, Yu M Y, Zhong C L, Zhou C T, Zhu S P and He X T 2018 Phys. Plasmas 25 023302
[29] Bin J, Ma w, Wang H, Streeter M J V and Schreiber J 2015 Phys. Rev. Lett. 115 064801
[30] Shou Y, Lu H, Hu R, Lin C, Wang H, Zhou M, He X, Chen J e. and Yan X 2016 Opt. Lett. 41 139–42
[31] Cherednychek M and Pukhov A 2016 Phys. Plasmas 23 103301
[32] Edwards M R and Mikhailova J M 2020 Sci. Rep. 10 5154
[33] Nomura Y et al 2009 Nat. Phys. 5 124–8
[34] Tsakiris G D, Eidmann K, Meyer-ter-Vehn J and Krausz F 2006 New J. Phys. 8 19
[35] Thaury C and Quéré F 2010 J. Phys. B: At. Mol. Opt. Phys. 43 215001
[36] An der Brügge D and Pukhov A 2010 Phys. Plasmas 17 033110
[37] Dromey B et al 2012 Nat. Phys. 8 804
[38] Dromey B et al 2013 New J. Phys. 15 013025
[39] Yeung M et al 2014 Phys. Rev. Lett. 112 123902
[40] Couzens S, Reville B, Dromey B and Zepf M 2016 Phys. Rev. Lett. 116 083901
[41] Edwards M R, Fasano N M and Mikhailova J M 2020 Phys. Rev. Lett. 124 185004
[42] Ma W et al 2019 Phys. Rev. Lett. 122 014803
[43] Obst L et al 2017 Sci. Rep. 7 10248
[44] Prencipe I et al 2017 High Power Laser Sci. Eng. 5 1–31
[45] Xu J et al 2018 Sci. Rep. 8 2669