

Generation of attosecond pulses from relativistic oscillating plasma gratings

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We propose a scheme to generate two isolated attosecond pulses at controllable angles through the interaction between relativistic laser pulses and a solid target. Two *p*-polarized laser pulses with certain frequency chirps are employed to drive oscillating plasma gratings (OPGs) on the target surface, while an *s*-polarized laser serves as the seed to trigger high-order harmonic generation (HHG) from the OPGs. Unlike HHG from the usual oscillating plasma mirrors, the OPGs not only generate harmonics but also diffract them. The evolution of the emission angles of the diffracted harmonics can be controlled through the laser chirp. At three specific angles, selected harmonics can be synthesized to attosecond pulse trains, and at two of these angles to isolated attosecond pulses. Two-dimensional particle-in-cell simulations are used to demonstrate the feasibility and robustness of the scheme, which shows that isolated attosecond pulse with duration around 30 as and intensity close to 10^{17} W/cm² can be stably generated. The scheme enables applications that require two isolated attosecond pulses with independent controllability.

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I. INTRODUCTION

Over the past four decades, the invention of the chirped pulse amplification technique [1] has increased the focused laser intensity by orders of magnitude [2], with intensities now far exceeding the relativistic threshold (i.e., $I \sim 10^{18}$ W/cm² for laser with micrometer wavelength). At such intensities, high-order harmonics can be generated via the interaction of lasers with solid targets. Compared with gas targets [3], constrained by the ionization thresholds of gaseous media [4], solid targets can withstand irradiation by relativistic lasers, thereby generating radiation with significantly higher intensity [5–8]. Thus, solid targets hold potential for synthesizing relativistically intense attosecond pulses.

One well-known mechanism for high-order harmonic generation (HHG) when relativistic-intensity lasers impinge on solid surfaces is the relativistically oscillating mirror [9–14]. In this mechanism, a single intense laser pulse typically serves dual roles: as a driver for surface plasma oscillation and as a source for reflected electromagnetic radiation. The reflected harmonics appear as pulse trains in the temporal domain and align with theoretical predictions, including the polarization selection rule [15] and the spectral scaling law [16].

To generate isolated attosecond pulses from HHG via this mechanism, various schemes have been explored. Heissler

et al. [8] demonstrated that isolated attosecond pulses can be produced by using few-cycle femtosecond lasers. Rykovanov *et al.* proposed a polarization gating technique [17], in which a laser beam with a “circular-linear-circular” polarization profile is employed to achieve isolated harmonic radiation. Vincenti and Quéré proposed an “attosecond lighthouse” scheme, where the spatial chirp of the driving pulse rotates the laser wave front, producing angularly separated attosecond pulses [18]. Naumova *et al.* observed that angular separation of attosecond pulse trains occurs when the laser is tightly focused to form a microdense plasma [19]. Recently, Mondal *et al.* found that the combination of a two-color few-cycle field with appropriate delay and polarization is conducive to generate isolated attosecond pulses [20]. Most existing schemes can only generate single isolated attosecond pulse at a specific angle and impose stringent requirements on the extremely short drive pulse, stable carrier-envelope phase (CEP), or the precise matching of drive pulse and target parameters, making their implementation considerably challenging.

In this paper, we propose a scheme to generate attosecond pulse trains and two isolated attosecond pulses at different angles. Unlike the conventional schemes that mainly rely on the driver lasers’ ultrashort property to control the HHG and the attosecond pulse duration, our approach employs a dynamically oscillating plasma grating (OPG) to control the emission angle and separation of the harmonics through order-dependent diffraction. In the scheme, the phase differences between the harmonic sources arranged at equal intervals in the oscillating plasma grating can be dynamically tuned by the laser, thereby dynamically adjusting the emission angle of the harmonics. This process is analogous to that of a phased array radar [21].

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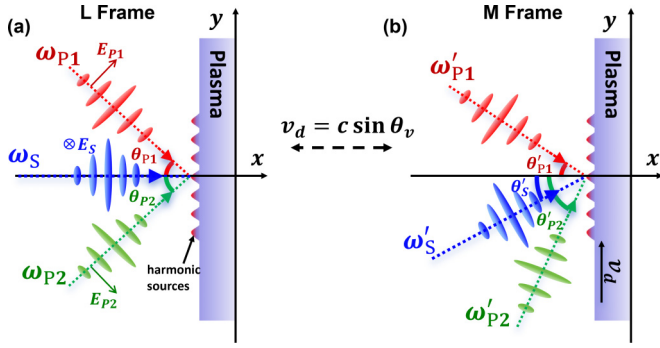


FIG. 1. Schematic of the interaction geometry in the laboratory frame [panel (a)] and moving frame [panel (b)]. Two symmetrically incident p -polarized lasers and one additional s -polarized laser impinge on the solid target. On the plasma surface, equally spaced regions exhibit enhanced electric fields driving plasma oscillations, which serve as the source of harmonic radiation. The two frames are related by a drift velocity v_d .

II. PHYSICAL MODEL

The schematic of the scheme is illustrated in Fig. 1. Three laser pulses impinge on the solid target simultaneously: two symmetrically obliquely incident p -polarized pulses (with electric fields in the x - y plane) and one normally incident s -polarized pulse (with electric field in the x - z plane). The two intense p -polarized lasers form standing/traveling waves on the target surface, which leads to electric field enhancement at specific localized regions and further constructs an oscillating plasma structure with a subwavelength period, functioning as a dynamical plasma metasurface [22,23]. Subsequently, the relatively weak s -polarized laser interacts with this metasurface generating high-order harmonics, which adheres to the high-harmonic generation selection rules [15]: s -polarized harmonics are produced, and their frequency is determined by both the p - and s -polarized lasers. Notably, the harmonics emitted from the periodic regions of the metasurface undergo spatial interference and achieve coherent enhancement in specific directions. This oscillating metasurface thus acts as OPGs, which not only generate high-order harmonics but also diffract them.

As shown in Fig. 1, in the laboratory (L) frame, the parameters of the three lasers are defined as follows: incident frequencies $\omega_{p1}, \omega_{p2}, \omega_s$; incident wave vectors $\mathbf{k}_{p1}, \mathbf{k}_{p2}, \mathbf{k}_s$; and incident angles $\theta_{p1}, \theta_{p2}, \theta_s$, where $\theta_s = 180^\circ$. When the two p -polarized beams have different frequencies, the OPG moves along the surface with a velocity of $\mathbf{v}_d = (\omega_{p1} - \omega_{p2}) / (k_{p1} \sin \theta_{p1} - k_{p2} \sin \theta_{p2}) \hat{\mathbf{y}} \equiv c \sin \theta_v \hat{\mathbf{y}}$, which then introduces Doppler shifts to the generated harmonics. Note that the incident angles (θ_{pi}) on opposite sides of the surface normal are assigned opposite signs. To determine the emission direction and frequency of the harmonics, a Lorentz transformation between laboratory and moving frames is applied, as illustrated in Fig. 1. In the M frame, the wave vectors and frequencies of the lasers are

$$\mathbf{k}'_{pi} = \left(k_{pi} \cos \theta_{pi}, k_{pi} \frac{\sin \theta_{pi} - \sin \theta_v}{\cos \theta_v}, 0 \right), \quad (1)$$

$$\omega'_{pi} = \frac{1 - \sin \theta_v \sin \theta_{pi}}{\cos \theta_v} \omega_{pi}. \quad (2)$$

Here, i indexes the two p -polarized lasers. The harmonic emission positions in this frame are fixed since the p -polarized lasers have the same frequency. So, we note $\omega'_{p1} = \omega'_{p2} \equiv \omega'_p$ for convenience.

The x component of the electric field acting on the surface plasma is

$$E_x \sim \sin \theta'_{p1} \cos(\omega'_p t - k'_p \sin \theta'_{p1} y) + \sin \theta'_{p2} \cos(\omega'_p t - k'_p \sin \theta'_{p2} y) \equiv A \cos(\omega'_p t + \varphi), \quad (3)$$

where the amplitude A is given by

$$A = [\sin^2 \theta'_{p1} + \sin^2 \theta'_{p2} - 2 \sin \theta'_{p1} \sin \theta'_{p2} \cos(k'_p (\sin \theta'_{p1} - \sin \theta'_{p2}) y)]^{1/2}. \quad (4)$$

The OPG period is $d = 2\pi/k'_p (\sin \theta'_{p1} - \sin \theta'_{p2})$. In the M frame, the harmonic emission can be considered as the following process: The s -polarized laser (labeled as s laser) couples with one of the two p -polarized lasers (labeled as p_i laser, $i = 1, 2$) to generate the n_i th-order harmonic, which is simultaneously diffracted by the gratings driven by the two p -polarized lasers. The grating equation governing this diffraction process is

$$k'_{i,n_i} \sin \alpha'_{i,n_i,m_i} = m_i \frac{2\pi}{d} + n_i k'_p \sin \theta'_{pi} + k'_s \sin \theta'_s, \quad (5)$$

where $\theta'_{pi,s}$ are the incident angles of the three lasers in the M frame. n_i indexes the harmonic order generated by the combination of the p_i laser and the s laser, and m_i indexes the diffraction order of the n_i th harmonic by the grating. $k'_{i,n_i} = k'_s + n_i k'_p$ and α'_{i,n_i,m_i} are the wave number and the emission angle of the harmonic in the M frame, respectively. In the following, we label such harmonic with (n_i, m_i) . The emitted harmonic frequency (ω_{i,n_i,m_i}) and angle (α_{i,n_i,m_i}) in the L frame can then be calculated by

$$\omega_{i,n_i,m_i} = \omega_s + n_i \omega_{pi} + m_i (\omega_{p1} - \omega_{p2}), \quad (6)$$

$$\sin \alpha_{i,n_i,m_i} = \frac{n_i \omega_{pi} \sin \theta_{pi} + m_i (\omega_{p1} \sin \theta_{p1} - \omega_{p2} \sin \theta_{p2})}{\omega_s + n_i \omega_{pi} + m_i (\omega_{p1} - \omega_{p2})}. \quad (7)$$

It shows that when the incident angles of the lasers are fixed, the emission angle of each harmonic can be controlled by adjusting the frequencies of the p -polarized lasers. To be simple, we first investigate the dependence of emission angles of the harmonics with diffraction order of $m_1 = 1$ on the p_2 laser wavelength. All other laser parameters are fixed when we calculate the emission angle according to Eq. (7). Figure 2(a) shows the dependence of $\alpha_{1,n_1,1}$ on the p_2 laser wavelength (λ_{p2}). One can see that the emission directions of such harmonics are around the reflection direction of the p_1 laser (i.e., 45°), but they only merge at this direction when the p_2 laser has the same wavelength as the p_1 laser (i.e., 800 nm). Attosecond pulses can be generated when phase-locked harmonics arrive at the observer simultaneously. Such dependence of the harmonic emission angle on the driver laser wavelength shows its potential for synthesizing isolated attosecond pulse. For example, if p_2 laser has a frequency chirp and its central wavelength is 800 nm, when λ_{p2} approaches this central wavelength, all harmonics with diffraction order

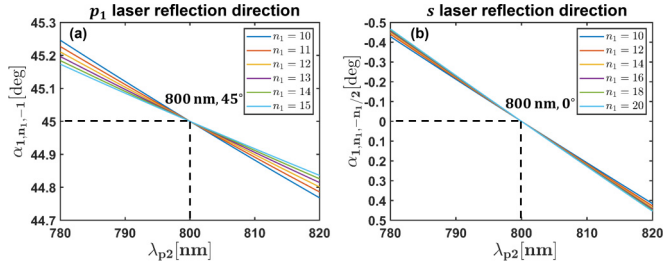


FIG. 2. Dependence of the emission angles (α) of the (n_i, m_i) harmonics with $i = 1, m_1 = 1$ [panel (a)] and $i = 1, m_1 = -n_1/2$ [panel (b)] on the p_2 laser wavelength (λ_{p2}). Here, the p_1 laser wavelength is $\lambda_{p1} = 800$ nm and the s laser wavelength is $\lambda_s = 400$ nm. The incidence angles of the p_1 and p_2 lasers are -45° and 45° , respectively. The incidence angle of the s laser is 180° .

of $m_1 = 1$ will emit at the same angle (45°). At this angle and instant, an isolated attosecond pulse can be generated.

Now we investigated the other set of harmonics satisfying $m_1 = -n_1/2$, with n_1 being an even number. Figure 2(b) shows the dependence of $\alpha_{1,n_1,-n_1/2}$ on λ_{p2} . Similarly, all of these harmonics emit at the same angle (0° , i.e., the reflection direction of the s laser) when λ_{p2} is 800 nm. As we mentioned before, this provides a possible direction to synthesize an isolated attosecond pulse. In the following, we verify these theoretical predictions and investigate the properties of the isolated attosecond pulses through two-dimensional particle-in-cell (2D PIC) simulations with epoch code [24].

III. PIC SIMULATIONS AND DISCUSSION

We first show the generation and diffraction of harmonics by the OPGs. The simulation geometry is shown in Fig. 1(a). In the PIC simulations, the parameters are normalized to those of the p_1 laser whose wavelength is $\lambda_{p1} = 800$ nm. The box size is $12\lambda_{p1}(x) \times 50\lambda_{p1}(y)$. The grid size is $\Delta x = \Delta y = \lambda_{p1}/250$ and 32 particles per cell are used for the simulations. Laser pulses are injected from the left boundary ($x = 0$). All other boundaries employ outflow boundary conditions for both particles and electromagnetic fields. The target has a preplasma in front of a plateau with density of $100n_c$, where $n_c = \epsilon_0 m_e \omega_{p1}^2 / e^2 = 1.7 \times 10^{21} \text{ cm}^{-3}$ is the critical density of the p_1 laser, ϵ_0 is the vacuum permittivity, m_e is the electron mass, and e is the elementary charge. The thickness of the plateau region of the target is $2\lambda_{p1}$, and its left boundary is located at $x = 8\lambda_{p1}$. The low-density preplasma in front of the plateau has an exponential profile of $n_e = n_c e^{-x/d}$, where $d = 0.1\lambda_{p1}$ is the scale length, and it is truncated at the density of $n_c \cos^2 \theta_{p1}$. It has been shown that such density truncation can produce high-order harmonics with a higher efficiency [25,26]. The p_1 laser reaches its focus point ($x = 40\lambda_{p1}, y = 0$) with incident angle of $\theta_{p1} = -45^\circ$. The p_2 laser reaches the same focus point with incident angle of $\theta_{p2} = 45^\circ$. The two p -polarized pulses have normalized peak amplitudes of $a_{p1,2} = eE_0/\omega_{p1}m_e c = 3$, where E_0 is the amplitude of the laser electric field. Their focal spot sizes are both $3\lambda_{p1}$. The s laser, with wavelength of $\lambda_s = 400$ nm, has a normalized peak amplitude of $a_s = eE_0/\omega_s m_e c = 0.3$ and focal spot size of $4\lambda_{p1}$. It is normally incident to the same focus point of

the p -polarized lasers. A super-Gaussian temporal profile, $\propto \exp(-t^4/\tau^4)$, is applied for $p_{1,2}$ lasers with duration $\tau_p = 25$ fs and Gaussian temporal profile is applied for s laser with duration $\tau_s = 8$ fs. The peaks of three lasers initiated from the $x = 0$ boundary reach the focus point at the same time ($t = 28.3T_{p1}$) and a phase difference of 180° is applied to the $p_{1,2}$ lasers when they reach their peak. The spatial-temporal evolution of the OPGs generated by lasers is shown in the Supplemental Material [27].

To see the emission angles of harmonic diffracted by the gratings, we present the harmonics distribution in the k space according to the simulated results, via 2D Fourier transformation of $E_z(x, y)$ (see the Supplemental Material [27]), as shown in Fig. 3. We simulated two different cases with $\lambda_{p2} = 800$ and 1000 nm, respectively. Here, the p_2 lasers are not chirped. In the first case, the plasma gratings are formed by the electromagnetic standing wave at the surface and the gratings only oscillate, not move along the surface. However, in the second case, the gratings not only oscillate but also move along the surface since the two driver lasers form a traveling wave along the surface. Different from harmonics generated by oscillating mirrors, harmonics from OPGs are scattered in the k space. The simulated patterns are consistent with the previous theoretical predictions that can be calculated from Eq. (7) and are labeled by the circles. Comparing the two cases, one can see that most of the harmonic positions are shifted, which means that if the p_2 laser is a chirped one, the harmonic emission angle will vary with time. However, it is worth noting that the emission angles of harmonics satisfying ($m_1 = -n_1 - 1$) are always along the reflection direction of the p_2 laser (-45° , as labeled by the green dashed line) in both cases, independent of λ_{p2} . Therefore, along this direction, attosecond pulse trains can be synthesized even the p_2 laser is chirped (see the Supplemental Material [27]).

To find the directions for isolated attosecond pulse synthesis, we draw straight lines passing through the origin in k space such that as many scattered points as possible lie on these lines. Two directions are found as shown by the red and blue dashed lines in Fig. 3. As the red dashed line in Fig. 3(a) shows, harmonics with $m_1 = 1$ emit at the reflection direction of the p_1 laser. However, when the p_2 laser's wavelength varies, these harmonic emission directions are shifted as shown in Fig. 3(b). Similar things happen for the harmonics lying on the blue dashed line that represents the s laser reflection direction and the harmonics satisfy $m_1 = -n_1/2$. These two directions and the related harmonics are consistent with those found in Fig. 2.

We then check the feasibility of synthesizing isolated attosecond pulses from selected harmonics by PIC simulations. In these simulations, the p_2 laser is linearly chirped with wavelength changing from 760 to 840 nm ($\pm 5\%$ chirp). To allow sufficient space to resolve harmonics propagating in different directions, we extended the simulation box to $44\lambda_{p1}(x) \times 80\lambda_{p1}(y)$. The grid size is $\Delta x = \Delta y = \lambda_{p1}/500$. The plasma target is now placed at position $x = 40\lambda_{p1}$, and the peaks of the three laser pulses reach the focal spot at $t = 73.5T_{p1}$. All other settings remain unchanged. From previous analysis and simulation, one can see that in this case, the isolated attosecond pulses could be synthesized along both the p_1 and s laser reflection directions. To optimize the

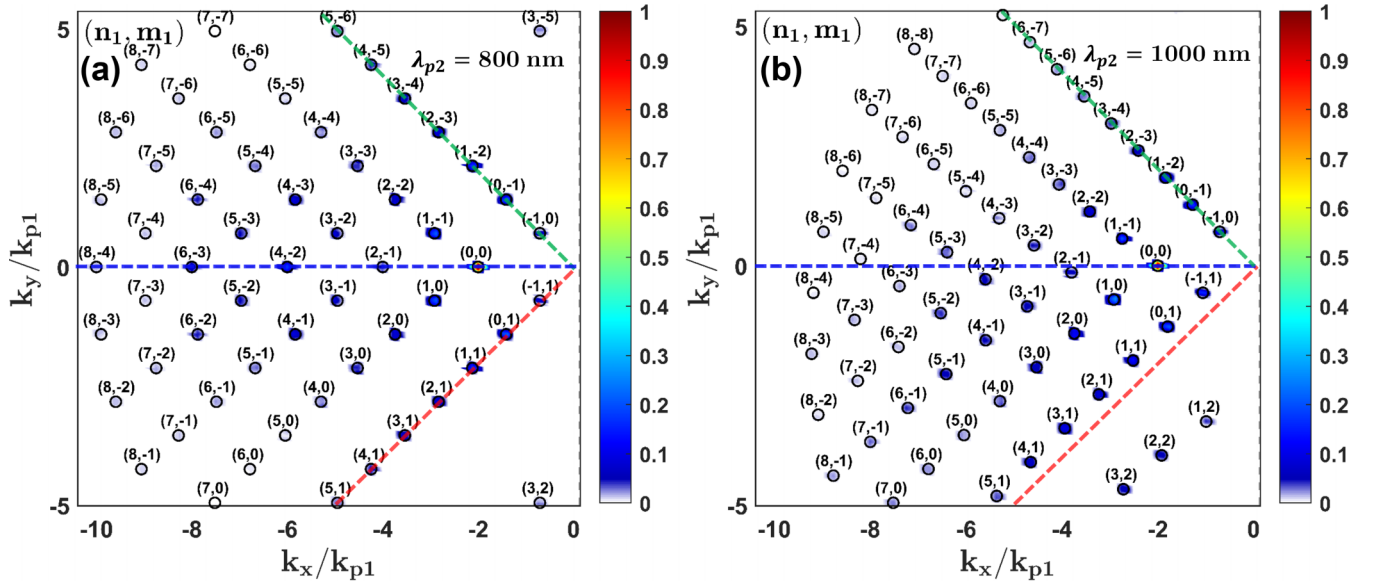


FIG. 3. The background patterns show $|E_z(k_x, k_y)|$ in the k space, with $\lambda_{p2} = 800$ nm for panel (a) and $\lambda_{p2} = 1000$ nm for panel (b). The numbers in the parentheses represent the harmonic order and the diffraction order (n_1, m_1) . The circles show the positions of such harmonics according to Eqs. (6) and (7). Isolated attosecond pulses can be synthesized at 45° (red dashed line, p_1 laser reflection direction) and 0° (blue dashed line, s laser reflection direction), and attosecond pulse trains can be generated at -45° (green dashed line, p_2 laser reflection direction).

attosecond pulse generation, we use spectral synthesis by filtering out the lower-order harmonics ($\omega < 8\omega_{p1}$ for p_1 laser reflection direction and $\omega < 10\omega_{p1}$ for s laser reflection direction) emitted at these two directions. The divergence angle of the harmonics can be estimated by $\pm\lambda/\pi w_0$, where w_0 is the spot size of incident laser. Therefore, such harmonic truncation not only helps increase the central frequency of the pulse but also ensures that the harmonics participating in the synthesis have a sufficiently small divergence angle, facilitating the spatial separation of harmonics along different angles. The proportion of harmonics participating in pulse synthesis to the total harmonic energy radiated along this direction was also calculated: Along the 45° direction, the harmonics participating in the synthesis account for 9.12×10^{-5} of the total harmonic energy; along the 0° direction, this proportion is 4.95×10^{-6} . Notably, since the 45° direction does not contain the directly reflected s -polarized laser, its energy fraction is significantly higher. The spectra and intensity profiles of the synthesized pulses are shown in Fig. 4. The simulation results are consistent with our theoretical predictions. Two high-contrast attosecond pulses are observed along the two directions. The peak intensities are $I_{\max} = 3.2 \times 10^{16}$ W/cm 2 and $I_{\max} = 7.1 \times 10^{16}$ W/cm 2 for the pulses emitted along the two directions at the point of the edge of simulation box ($x = 0$ plane). The noise ratios of the attosecond pulse defined by the intensity ratio between adjacent peaks and the main peak ($I_a/I_{\max}$) are 0.13 and 0.12, and the corresponding pulse durations τ_{FWHM} are 34 and 27 as for the two pulses, respectively. We further examined the isolation degree of the attosecond pulses as a function of emission angle. The results are shown in Fig. 5, which are consistent with theoretical expectations: The high-contrast attosecond pulses only exist within a limited angular range, while most regions exhibit multipulse characters. Isolated attosecond pulses can be observed with an angular width of approximately 1° around

the p_1 laser reflection direction and 1.8° around the s laser reflection direction. Such angular region is large enough for usual applications. The peak intensity as a function of emission angle is also examined, as shown in Fig. 6. The energy conversion efficiency from the input laser to the isolated attosecond pulse was evaluated. For the pulse of 45° , the efficiency relative to the total input energy of the three lasers is 1.07×10^{-8} , and 3.76×10^{-7} relative to the s -polarized laser. For the pulse of 0° , the efficiency is 2.64×10^{-8} relative to the total input energy and 9.27×10^{-7} relative to the s -polarized beam. The far-field pulse waveform and angular

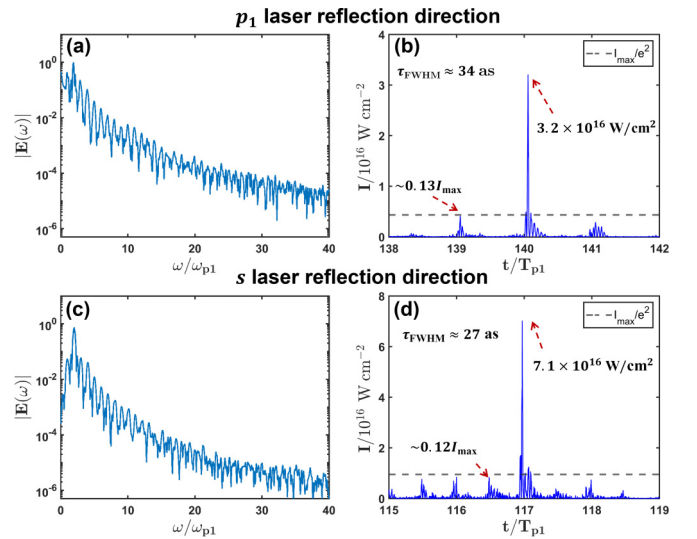


FIG. 4. Harmonic spectra and the pulse intensity profiles after spectral filtering along 45° [panels (a) and (b)] and 0° [panels (c) and (d)]. The dashed horizontal lines represent the $1/e^2$ values of the pulse peak intensity.

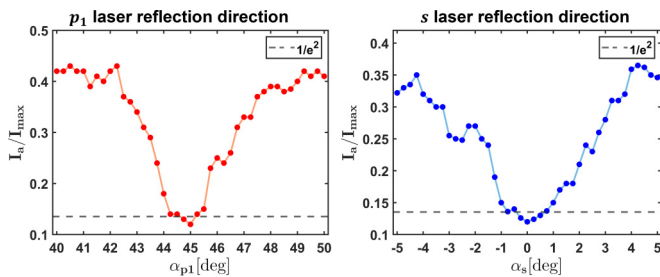


FIG. 5. Noise ratio of attosecond pulses near the p_1 laser reflection direction (45°) and the s laser reflection direction (0°). The dashed horizontal lines represent the $1/e^2$ value.

distribution of the attosecond pulses are also obtained by using the Rayleigh-Sommerfeld diffraction theory. Besides a little increase in $I_a/I_{\max}$ and pulse broadening, the results exhibit no significant changes compared with the near-field results (see the Supplemental Material [27]), which confirms the feasibility of the present scheme for practical applications.

We also investigate the robustness of the attosecond pulse generation. As we know, the attosecond pulse isolation relies on two factors. One is the angular separation of the harmonics resulted from the p_2 laser wavelength variation. The other is the relatively short interaction between the seed pulse and the OPGs. The OPGs are determined by the two p -polarized driver pulses. The generation stability of the attosecond pulse is then sensitive to the CEP of these three pulses. The noise ratio can be used as a criterion to evaluate the generation stability of the attosecond pulse. We first check the CEP effects of the s laser. The results are shown in Fig. 7(a). One can see that compared with the pulse emitted along the s laser reflection direction, the pulse from the p_1 laser reflection direction is relatively more sensitive to the s laser CEP. In these cases, when one varies the CEP, the OPGs are the same. The only difference is the relative interaction time of the seed pulse with the OPGs. From Fig. 3, one can see that for the pulse synthesized along the s laser reflection direction, all orders of harmonics are more sensitive to λ_{p2} . The higher the harmonic order, the larger the angular shifting along with λ_{p2} . As a result, the harmonics are relatively easier to be separated in space when p_2 laser is chirped and the synthesized pulse noise ratio is mainly dependent on the chirp rate of p_2 laser, not the s laser CEP. It exhibits weak modulation in Fig. 7(a). On the contrary, the harmonics along the p_1 laser reflection have relatively weaker dependence on λ_{p2} , and the higher the

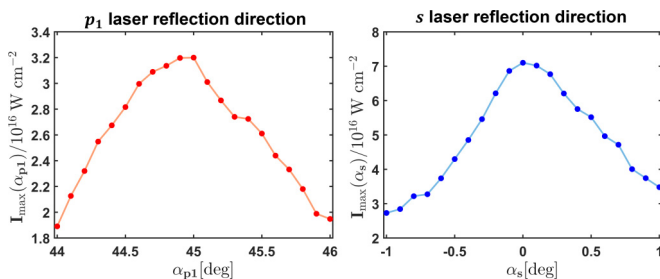


FIG. 6. Peak intensity of attosecond pulses near the laser reflection direction (45°) and the laser reflection direction (0°).

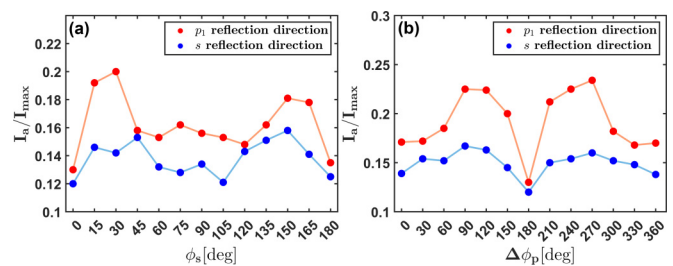


FIG. 7. Dependence of $I_a/I_{\max}$ of the emitted pulse on s laser CEP [panel (a)] and phase difference of the $p_{1,2}$ lasers [panel (b)]. The red and blue points represent the attosecond pulses along the p_1 laser reflection direction and s laser reflection direction, respectively.

harmonic order, the smaller the angular shifting along with λ_{p2} . In this case, the harmonics are difficult to be separated in space by only introducing the p_2 laser chirp. The isolation degree relies more on the s laser CEP as shown in Fig. 7(a).

The effects of the phase difference between the two p -polarized laser pulses ($\Delta\phi_p = \phi_{p2} - \phi_{p1}$, where ϕ_{pi} is the phase of p_i laser when it reaches its peak) are also investigated. Such phase difference determines the shape and oscillation of the OPGs. So, it naturally affects the harmonic generation and attosecond pulse synthesis. The results are shown in Fig. 7(b). One can see that the attosecond pulse emitted along the s laser reflection direction is more stable compared with the one emitted along the p_1 laser reflection direction. The reason is similar as before. The angular separation of the harmonics along the p_1 laser reflection direction is relatively difficult. So, the attosecond synthesis along this direction depends more on the interaction time between the seed pulse and the OPGs. However, in this case, the OPGs are directly related to $\Delta\phi_p$. So, the noise ratio of the pulse along this direction is more unstable.

We also investigated the dependence of the pulse intensity on the incident laser phases, as shown in Fig. 8. When considering the dependence on the CEP of the s laser, the pulse intensities in both directions exhibit good stability. In contrast, when investigating the dependence on the phase difference between the two p -polarized lasers, the pulse along the reflection direction of p_1 laser shows significantly better stability than that along the reflection direction of the s laser. Although the pulse intensity along the p_1 reflection direction exhibits some fluctuations, it remains relatively stable overall.

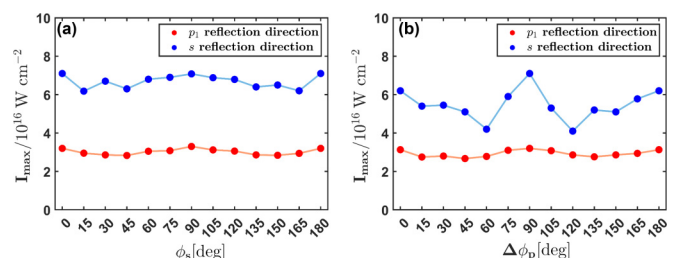


FIG. 8. Dependence of $I_{\max}$ of the emitted pulse on s laser CEP [panel (a)] and phase difference of the $p_{1,2}$ lasers [panel (b)]. The red and blue points represent the attosecond pulses along the p_1 laser reflection direction and s laser reflection direction, respectively.

Previous studies have pointed out that CEP plays a crucial role in the generation of isolated attosecond pulses using few-cycle lasers. When the CEP is random, the probability of generating isolated attosecond pulses is only 17% for incident light with a three-cycle duration [8]. Thus, many existing schemes for generating isolated attosecond pulses rely on stable CEP [18,28]. In contrast, in the current scheme, with longer pulse durations, the pulses show weaker dependence on the CEP of the s -polarized laser and the phase difference of the p -polarized lasers, while both of these cases show that the isolated attosecond pulse along the seed pulse reflection direction is more robust, which benefits the future applications.

IV. CONCLUSION

In summary, a scheme for generating two isolated attosecond pulses by using oscillating plasma gratings is theoretically analyzed and demonstrated by 2D PIC simulations. Dual attosecond pulses with duration around 30 as and low noise ratio can be generated simultaneously within a range of one degree in two different directions. The generation of attosecond pulses in two directions means that the two pulses can be independently manipulated, thus making the scheme adaptable to diverse detection and manipulation requirements, such as three-dimensional resolution of particle motion information [29,30], complex manipulation of materials [31], etc. The isolation of the attosecond pulse is weakly dependent on the initial phase difference of the driver pulses, which shows

the superiority of the scheme. The current study also shows that separating the HHG seed pulse from the OPG driver pulse provides more flexibility in controlling harmonic generation and synthesis. In the future, more functional metasurfaces with specific structures could be constructed by using higher-order driver pulses (e.g., Laguerre-Gaussian pulses), which may offer the potential to simultaneously tune the temporal and spatial structures of high-order harmonics, for instance, generating attosecond vortex pulses [32,33].

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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