Propagation effects for attosecond ionization control of efficient broadband supercontinuum generation

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Isolated attosecond uv pulse provides a robust tool to control the high-order harmonic generation and efficient broadband supercontinua have been generated in this attosecond ionization control scheme at microscopic level. Here, we investigate the influences of propagation effects on the supercontinua. We find that efficient broadband supercontinua, which are enhanced by two or three orders of magnitude, can also be obtained at macroscopic level when the harmonics emitted from the short quantum path are phase matching. Moreover, the modulations in the supercontinua are eliminated and the bandwidths of the supercontinua are broadened after propagation.

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I. INTRODUCTION

The appearance and development of attosecond pulse, especially isolated attosecond pulse, enable scientists to control and study the ultrafast dynamics processes with unprecedented resolution [1–5]. Currently, the production of attosecond pulse is mainly based on high-order harmonic generation (HHG) in gases [5–9]. The process of HHG can be easily understood in the framework of the three-step model [10]: first, the electron tunnels through the barrier formed by the Coulomb potential and the laser field; second, it oscillates almost freely in the laser field; and third, it may recombine with the parent ion and release its kinetic energy by emitting high-order harmonics. This process periodically occurs every half optical cycle of the fundamental field and produces an attosecond pulse train (APT) with a repetition period of half the fundamental cycle. By controlling the high-order harmonic emission within half optical cycle of the fundamental field, an isolated attosecond pulse can be generated.

Different methods have been reported to generate isolated attosecond pulse. One method is through the interaction of atoms and a phase-stabilized few-cycle laser pulse [5,7]. In this method, the harmonics at the cutoff are emitted within half optical cycle where the laser field reaches its maximum, and become continuous, from which an isolated attosecond pulse can be filtered. The disadvantage of this method is that the bandwidth of the continuous harmonics is limited by the available shortest laser pulse, which prevents further compression of the attosecond pulse. Furthermore, the yield of the attosecond pulse is low since the intensities of the continuous harmonics drop rapidly. Much effort has been devoted to compress the duration [9,11–13] and enhance the yield [14–18] of the attosecond pulse. By using a single-cycle laser pulse, the bandwidth of the continuous harmonics is broadened and the duration of the attosecond pulse is compressed below 100 as [13]. However, the laser pulse can only be achieved with a state-of-the-art laser system and the attosecond pulse is generated from the continuous harmonics in the cutoff, of which the intensities decline more rapidly than those in the plateau. The scheme of two-color field [11,12] seems to be an efficient method to generate isolated attosecond pulse since it can broaden the bandwidth of the continuous harmonics and compress the duration of the attosecond pulse. In this method, the continuous harmonics originate from the electron ionized in the half cycle with the second-strongest electric peak. However, the ionization rate of the electron ionized in this half cycle is lower, leading to the much lower yield of the continuous harmonics because the amplitude of the second-strongest peak is much lower than that of the strongest peak. The scheme of attosecond ionization control [15–18] proved to be a promising method to broaden the bandwidth and enhance the yield of the isolated attosecond pulse. In this method, punctual “turn on” of an isolated attosecond uv pulse can trigger the ionization process, which in turn leads to significant enhancement of the photoionization and HHG. By superimposing an isolated attosecond uv control pulse to a few-cycle ir driving laser pulse, the yield of the harmonic is enhanced by two or three orders of magnitude and the bandwidth of the supercontinuum in the cutoff region is extended from 20 to 45 eV [17]. Moreover, when an isolated attosecond uv control pulse is superimposed onto a fundamental and subharmonic two-color field, the intensity of the supercontinuum in the second plateau is enhanced significantly and is about equal to the intensity of the spectrum in the first plateau. Simultaneously, the bandwidth of the supercontinuum is also extended. In addition, the duration of the driving laser pulse can be extended to multicyle [18].

As in many other nonlinear processes, the HHG also intensively depends on the propagation and phase matching in macroscopic medium [19–21]. However, the scheme of attosecond ionization control has been considered only for single atom [15–18] and a careful study of macroscopic effects is required. In this paper, we consider the harmonics generated by a gas jet of helium atoms exposed to a few-cycle ir laser pulse or a multicycle synthesized two-color ir

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laser pulse in combination with an isolated attosecond uv pulse. We intend to investigate whether the efficient broadband supercontinua reported at microscopic level can be maintained after propagation through the gas jet. To answer this question, we calculate the macroscopic harmonics by solving the Maxwell wave equation (MWE) coupled with the time-dependent Schrödinger equation (TDSE). The results show that the efficient broadband supercontinua can be maintained after propagation in the gas jet when the harmonics emitted from the short quantum path are phase matching. The yields of the supercontinua in the combined ir and uv laser pulse are enhanced by two or three orders of magnitude compared to that in the ir laser pulse alone. Moreover, the modulations of the supercontinua are eliminated and the bandwidths of the supercontinua are broadened after propagation through the gas jet. These efficient broadband supercontinua have important applications in attosecond science [22,23].

II. THEORETICAL MODEL

A theoretical description of HHG in atomic gases involves calculation of the single-atom dipole response (SADR) induced by the laser pulse and simulation of the copropagation of the laser and harmonics beams. In our model, the SADR is calculated by numerical solution of one-dimensional TDSE, which has been widely used in previous works [24]. The copropagation of the laser and harmonics beams is simulated by numerically solving MWE for the fields of the laser pulse \( E_l \) and the harmonics \( E_h \). Assuming that the linear polarized laser pulse propagates along the \( z \) axis and the system possesses cylindrical symmetry, the model includes a self-consistent solution of three equations [25,26] (in atomic units)

\[
\frac{i}{\Delta} \frac{\partial}{\partial \tau} \psi(x, z, \rho, \tau) = \left[ \frac{-\partial^2}{2 \Delta x^2} + V(x) - E_l(x, z, \rho, \tau)x \right] \psi(x, z, \rho, \tau),
\]

\[
\left( \Delta - \frac{2}{c} \frac{\partial^2}{\partial z^2} \right) E_l(x, z, \rho, \tau) = \frac{N_h(x, z, \rho, \tau)}{\epsilon_0 c^2} E_l(x, z, \rho, \tau),
\]

\[
\left( \Delta - \frac{2}{c} \frac{\partial^2}{\partial z^2} \right) E_h(x, z, \rho, \tau) = \frac{N_h(x, z, \rho, \tau)}{\epsilon_0 c^2} E_h(x, z, \rho, \tau) + \frac{1}{\epsilon_0 c^2} \frac{\partial^2}{\partial \tau^2} [N_h(x, z, \rho, \tau) d(z, \rho, \tau)],
\]

where the moving reference frame \( \tau = t - z/c \) is introduced, \( x \) denotes the coordinate of an active electron in the frame of an atom, and \( z \) and \( \rho \) are the longitudinal and transverse coordinates of an atom in the interaction gas medium, respectively. In the one-dimensional TDSE (1), \( V(x) \) is the Coulomb potential which can be described by \( V(x) = -1/\sqrt{x^2 + \alpha^2} \) in the soft-core model and the single-active-electron approximations. Although our work is not intended to model a specific experiment, in order to make the discussion concrete, \( \alpha \) is set to be 0.485 to retrieve the ionization energy of helium. In the MWEs (2) and (3), \( \Delta \equiv (\partial/\partial \rho)(\partial^2/\partial \rho \partial) \) is the transverse Laplace operator, \( N_h(x, z, \rho, \tau) \) is the free-electron density, \( N_h \) is the density of atoms, and \( d(z, \rho, \tau) \) is the single-atom dipole moment. The ionization probability \( P(z, \rho, \tau) \) is extracted by projecting the electron wave function on the initial seven lowest states. Note that this model takes into account both temporal plasma-induced phase modulation and spatial plasma-lensing effects on the laser pulse. The procedures of solution of the one-dimensional TDSE (1) and MWEs (2) and (3) have been clearly described in [27,25,26]. Briefly, we first calculate the ionization probability and single-atom dipole moment on the initial plane via TDSE (1). Subsequently, we insert the ionization probability and single-atom dipole moment into Eqs. (2) and (3) to obtain the laser field and high-order harmonics on the next plane. Repeating this procedure, the laser field and the high-order harmonics on the final plane can be obtained.

III. RESULT AND DISCUSSION

We first consider the method of attosecond ionization control in a few-cycle laser pulse. In this method, by superimposing an isolated attosecond uv control pulse to a few-cycle ir driving pulse, an efficient broadband supercontinuum can be obtained at microscopic level [17]. To make clear the underlying physics, we analyze the electron dynamics process of helium atom in the synthesized laser pulse, i.e., a 5-fs, 800-nm ir driving laser pulse in combination with a 0.6-fs, 100-nm uv control pulse. The intensities of the ir and the uv pulses are \( 3 \times 10^{14} \) and \( 2 \times 10^{13} \) W/cm\(^2\), respectively. The electric field of the synthesized laser pulse is expressed by \( \mathbf{E} = E_{0 \text{uv}}(t) \cos(\omega_{\text{uv}}(t-T/2) + \phi_{\text{uv}}) + E_{0 \text{ir}}(t-T/2 - \tau_d) \cos(\omega_{\text{ir}}(t-T/2 - \tau_d) + \phi_{\text{ir}}) \). Here, \( E_0 \) and \( E_0 \) are the amplitudes and \( \omega_0 \) and \( \omega_0 \) are the frequencies of the ir and the uv pulses, respectively. \( \phi_{\text{ir}} \) is the carrier-envelope phase of the ir pulse and is chosen to be 0 to generate the broadest supercontinuum. \( \phi_{\text{uv}} \) is the carrier-envelope phases of the uv pulses and is also chosen to be 0. \( f_{\text{ir}}(t) = \sin^2(\pi t/T) \) and \( f_{\text{uv}}(t) = \exp(-2 \ln(2)(t-T/2 - \tau_d)^2/\tau_p^2) \) present the temporal profiles of the ir and the uv pulses, where \( T = 5T_0 \) (\( T_0 \): optical cycle of the ir pulse) and \( \tau_p = 0.6 \) fs denote the duration of the two pulses. \( \tau_d \) is the relative delay between the ir and the uv pulses and is chosen to be \( -0.55T_0 \). In Fig. 1(a), we present the dependence of the classical electron energy on the ionization (\( \mathbb{C} \)) and recombination (\( \mathbb{O} \)) times in the ir pulse alone. In Fig. 1(b), we present the ionization probability (red dashed line) in the ir and uv synthesized pulse. The electric fields of the ir (blue dotted line) and the uv (green solid line) pulses are also presented in Fig. 1(b). As shown in Fig. 1(a), the harmonics above 31\( \omega_0 \) in the ir pulse alone are emitted from the recombination electrons around \( P_1, P_2, \) and \( P_3 \). According to the three-step model [10], the harmonic efficiency is mainly determined by the first step, i.e., the ionization. As shown in Fig. 1(b), the ionization probability steeply increases between \( t = 1.8T_0 \) and \( t = 2.4T_0 \) and varies slightly at other times. This indicates that the ionization occurs mainly when the isolated uv pulse is introduced, i.e., \( 1.8T_0 \) to \( 2.4T_0 \).
around the two laser pulses are all 25 μm, which give the confocal parameters \( T_\text{ir}=2.5 \text{mm} \) and \( T_\text{uv}=20 \text{mm} \), respectively. The atomic density is isotropic to a gas pressure of 75 Torr at room temperature. Other parameters are the same as in Fig. 1. Comparing the single-atom (blue dotted line) and macroscopic (blue solid line) high-order harmonic spectra generated by the ir and uv synthesized laser pulse, we can find that the regular modulations in the single-atom high-order harmonic spectrum are almost eliminated in the macroscopic high-order harmonic spectrum and a smooth broadband supercontinuum (60 eV) is formed for the harmonics above 20\( \omega_0 \) in the macroscopic high-order harmonic spectrum. It can be interpreted with phase matching and the selection of quantum paths in propagation. When laser pulse is focused before the gas jet, the phase matching is in favor of the short quantum path [19,21]. Since only the short quantum path survives, the interferences between the long and the short quantum paths are avoided and a smooth broadband supercontinuum is formed. Comparing the high-order harmonic spectra generated by the ir and uv synthesized laser pulse (blue solid line) and the ir laser pulse alone (red solid line) after propagation through a 0.75 mm helium gas jet, we can also find that the yield of the harmonics over the whole spectral range is enhanced by two to three orders of magnitude by superposing an isolated uv pulse to a few-cycle ir laser pulse. Moreover, the intensity of the harmonics in the supercontinuum is almost constant. It results from two factors, i.e., ionization and phase matching. As described above, the ionization probability is significantly enhanced by the uv pulse, which makes the yields of the single-atom harmonics enhanced by two orders of magnitude. The phase matching of the short quantum path is accomplished for the high-order harmonics above 20\( \omega_0 \), generated by the ir and uv synthesized laser pulse, which makes these harmonics emitted from the short quantum path survive and increase constructively but earlier recombination times is called short trajectory. The interferences between the long and the short trajectories lead to the regular modulations of the supercontinuum [28]. While in the ir pulse alone, the ionization occurs mainly around the electric peaks at \( t=2.0T_\text{ir}, 2.5T_\text{ir}, \) and \( 3.0T_\text{ir} \), indicating that the harmonics are mainly emitted around \( P_1, P_2, \) and \( P_3 \). Therefore, the harmonic spectrum generated in the ir laser pulse alone is irregular for the harmonics below 52\( \omega_0 \) and is smooth for the harmonics in the cutoff as shown in Fig. 2 (red dotted line). Comparing the two spectra, one can also find that the yields of the harmonics in the ir and uv synthesized laser pulse are about two orders of magnitude higher than that in the ir driving laser pulse alone. This benefits from the increase of the ionization probability, which is enhanced from less than 0.1% up to about 4.5% by the uv pulse.

In the following, we investigate the influences of propagation effects on the efficient broadband supercontinuum described in the above paragraph. Figure 2 shows the high-order harmonic spectra generated by the ir and uv synthesized laser pulse (blue solid line) and the ir laser pulse alone (red solid line) after propagation through a 0.75 mm helium gas jet. The ir and the uv pulses are assumed as Gaussian beams and are focused 1.5 mm before the entrance of the gas jet. The beam waists at focus of the two pulses are 25 μm, which give the confocal parameters \( b_{\text{ir}}=2.5 \text{mm} \) and \( b_{\text{uv}}=20 \text{mm} \), respectively. The atomic density is isotropic and equal to \( 2.5 \times 10^{18} \text{ atoms/cm}^3 \), which corresponds to a gas pressure of 75 Torr at room temperature. Other parameters are the same as in Fig. 1. Comparing the single-atom (blue dotted line) and macroscopic (blue solid line) high-order harmonic spectra generated by the ir and uv synthesized laser pulse, we can find that the regular modulations in the single-atom high-order harmonic spectrum are almost eliminated in the macroscopic high-order harmonic spectrum and a smooth broadband supercontinuum (60 eV) is formed for the harmonics above 20\( \omega_0 \) in the macroscopic high-order harmonic spectrum.
during propagation. Thus, an efficient broadband supercontinuum is obtained at the exit of the gas jet.

We further investigate the temporal characteristics of the supercontinuum after propagation via applying a square window with a width of ten harmonics to the supercontinuum at different orders. The results are shown in Fig. 3(a). One can see that there is only one attosecond pulse along the time axis and the emission time of the attosecond pulses increases with the central frequency, indicating that these attosecond pulses are emitted from the short quantum path [29]. It is again shown that the phase matchings of the short quantum path are well accomplished for the harmonics in the supercontinuum after propagation through the gas jet. The results in Fig. 3(a) also indicate that isolated attosecond pulses with tunable central wavelengths can be directly filtered out from the supercontinuum. To further shorten the duration of the attosecond pulse, we have superposed more harmonics in the supercontinuum. As shown in Fig. 3(b), an efficient isolated 135 as pulse was obtained by filtering the harmonics from 31st to 50th harmonics in the supercontinuum.

The configuration of the focus of the laser pulse relative to the gas jet influences the phase matching of the high-order harmonics largely. As discussed above, the phase matching of the short quantum path is accomplished when the laser pulse is focused before the gas jet. We then change the configuration by focusing the laser pulse 0.5 mm after the entrance of the gas jet, which is in favor of the phase matching of the long quantum path [19,21]. Figure 4 shows the macroscopic high-order harmonics generated by focusing the laser pulse 1.5 mm (blue line) before the entrance of the gas jet and 0.5 mm (red line) downstream from the entrance of the gas jet. Other parameters are the same as in Fig. 2. As shown in Fig. 4, a supercontinuum with a bandwidth of about 23 eV (35ω0−50ω0) is obtained when the laser pulse is focused 0.5 mm downstream from the entrance of the gas jet. The bandwidth of the supercontinuum is much narrower than that obtained by focusing the laser pulse 1.5 mm before the entrance of the gas jet. The reason is that the phase matchings of the long quantum path are only accomplished for the harmonics between the 35th-order and the 50th-order harmonics. This also leads to different yields of harmonics for the two configurations. In the two configurations, the yields of the harmonics are usually higher when the laser pulse is focused 1.5 mm before the entrance of the gas jet. However, for the harmonics which are all phase matching in the two different configurations, the yields are almost equal. Therefore, efficient broadband supercontinuum is favor of being obtained by focusing the laser pulse before the entrance of the gas jet and selecting the short quantum path. Thus in the following, we will only investigate the propagation effects for the supercontinuum which is phase matching for the short quantum path.

The single-atom high-order harmonic spectrum is sensitively dependent on the relative time delay τd between the ir pulse and the isolated attosecond uv pulse. The quantum paths can be selected by adjusting the delay at single-atom process [17]. As discussed above, the quantum paths can also be selected by phase matching during propagation through the gas jet. To investigate whether the delay influences the macroscopic high-order harmonic spectrum significantly, we calculated the macroscopic high-order harmonic spectra by changing the delay. Figure 5 shows the results when the delay is τd=−0.55T0 (blue solid line) and τd=−0.47T0 (red dashed line). Other parameters are the same as in Fig. 2. As discussed in [17], both the short and the long quantum paths

FIG. 3. (Color online) (a) The attosecond pulses centered at different frequencies generated by filtering ten harmonics in the supercontinuum shown by the blue solid line in Fig. 2. (b) The attosecond pulse generated with the supercontinuous harmonics (31–50ω0) shown by the blue solid line in Fig. 2.

FIG. 4. (Color online) On-axis high-order harmonic spectra generated by focusing the ir and uv synthesized laser pulse 1.5 mm before (blue line) or 0.5 mm after (red line) the entrance of the gas jet. Other parameters are the same as in Fig. 2.

FIG. 5. (Color online) On-axis high-order harmonic spectra generated by the ir and uv synthesized pulse for two different values of the delay between the two pulses, τd=−0.55T0 (blue solid line) and τd=−0.47T0 (red dashed line). Other parameters are the same as in Fig. 2.
contribute to the single-atom high-order harmonics almost equally when \(r_p = -0.55T_0\) and the contribution from the long quantum path becomes weak while the contribution from the short quantum path is dominant when the delay decreases to \(r_p = -0.47T_0\). Therefore, the short quantum path has been selected at microscopic level. However, we can find that the two macroscopic high-order harmonic spectra are almost the same as shown in Fig. 5. This phenomenon can be explained as follows: the difference of the two single-atom spectra is induced by the high-order harmonics emitted from long quantum path, but the difference is eliminated during propagation and has no contribution to the macroscopic high-order harmonic spectra. Therefore, selecting of the quantum path at microscopic level does not influence the selecting of the quantum path at macroscopic level significantly. This characteristic allows some variations of the relative delay between the ir and uv pulses, which may make this scheme experimentally implemented easily.

Finally, we discuss the influences of the propagation effects on the broadband supercontinuum generated by the method of attosecond ionization control in two-color field. In contrast to the method described above, a broader bandwidth supercontinuum can be generated by this method with multicyle driving laser pulse at microscopic level [18]. To make the underlying physics clear, we analyze the electron dynamics process of helium atom in the synthesized field. The parameters of the isolated attosecond uv pulse are the same as in Fig. 1. The two-color laser pulse is synthesized by a 10 fs, 800 nm driving pulse and a 10 fs, 1600 nm control pulse. The intensities of the ir driving and control laser pulses are \(3 \times 10^{14}\) and \(2.7 \times 10^{13}\) W/cm\(^2\), respectively, then the intensity of the ir control pulse is 9% of the ir driving pulse. The electric field of the synthesized field is expressed by \(E = E_0f_0(t)\cos[\omega_0(t-T/2) + \phi_0] + E_1f_1(t)\cos[\omega_1(t-T/2) + \phi_1] + E_2f_2(t)\cos[\omega_2(t-T/2 - \tau) + \phi_2] + E_3f_3(t)\cos[\omega_3(t-T/2 - \tau) + \phi_3]\). Here, \(E_0, E_1, E_2\), and \(E_3\) are the amplitudes and \(\phi_0, \omega_1, \phi_2\), and \(\omega_3\) are the frequencies of the ir driving pulse, ir control pulse, and uv control pulse, respectively. \(\phi_0, \omega_1, \phi_2\), and \(\omega_3\) are the carrier-envelope phases of the ir driving pulse, ir control pulse, and uv control pulse and are all chosen to be 0. \(f_0(t) = \sin^2(\pi t/T)\), \(f_1(t) = \sin^2(\pi t/T)\), and \(f_2(t) = \exp[-2\ln(2)(t-T/2-\tau)^2/T_0^2]\) present the temporal profiles of the three pulses, where \(T = 10T_0\) (\(T_0\): optical cycle of the ir driving pulse) and \(\tau = 0.6\) fs denote the duration of the three pulses. \(\tau\) is the relative delay between the ir driving pulse and the isolated attosecond uv control pulse and is chosen to be \(-0.55T_0\). In Fig. 6(a), we present the dependence of the classical electron energy on the ionization (○) and recombination (●) times in the two-color field. In Fig. 6(b), we present the ionization probability (red dashed line) in the ir and uv synthesized laser pulse. The electric fields of the two-color laser pulse (blue dotted line) and the isolated attosecond uv pulse (green solid line) are also presented in Fig. 6(b). In Fig. 6, we can see that the electric fields of the two-color field around \(t=4.5T_0\) and \(t=5.5T_0\) are much lower than that around \(t=5.0T_0\), which induces that the highest cutoff of the harmonic is 95\(\omega_0\), whereas the second-highest cutoff is 55\(\omega_0\). This indicates that the harmonics above 55\(\omega_0\) are mainly emitted from the recombination electrons around \(P\). Meanwhile, these electrons are ionized around the electric peak at \(t=4.5T_0\) and their ionization rate is much lower than that around the electric peak at \(t=5.0T_0\). Consequently, there are two plateaus in the high-order harmonic spectrum and the intensity of the harmonics in the second plateau is much lower than that in the first plateau, as shown in Fig. 7 (red dotted line). In Fig. 6(a), we can also find that the harmonics in the second plateau contain two classes of trajectories, the

![Image](https://example.com/image1)

**FIG. 6.** (Color online) (a) The dependence of the classical electron energy on the ionization (○) and recombination (●) times in the two-color field. (b) The electric fields of the two-color laser pulse (blue dotted line) and the uv pulse (green solid line). Red dashed line shows the ionization probability of helium atoms in the two-color field in combination with the uv field. The two-color field is synthesized by a 10 fs, 800 nm driving pulse and a 10 fs, 1600 nm control pulse. The intensities of the driving and control pulses are \(3 \times 10^{14}\) and \(2.7 \times 10^{13}\) W/cm\(^2\), respectively. The carrier-envelope phases of the driving and control pulses are all 0. The parameters of the uv pulse are the same as in Fig. 1.

![Image](https://example.com/image2)

**FIG. 7.** (Color online) The high-order harmonic spectra of helium atom generated by the two-color laser pulse in combination with the uv laser pulse (blue dotted line) and the two-color laser pulse alone (red dotted line) and the on-axis high-order harmonic spectra generated by the two-color laser pulse in combination with the uv laser pulse (blue solid line) and the two-color laser pulse alone (red solid line) after propagation through a 0.75 mm helium gas jet. The density of the gas jet is \(2.5 \times 10^{18}\) atoms/cm\(^3\). The laser pulse is focused 1 mm before the gas jet. The beam waists at focus of the three laser pulses are all 25 μm. Other parameters are the same as in Fig. 6.
short and the long trajectories, which lead to regular modulations in the spectrum [28]. When the isolated attosecond uv pulse is introduced, the ionization rate of the atoms is changed significantly. As shown in Fig. 6(b), the ionization probability steeply increases between \( t = 4.2T_0 \) and \( t = 4.8T_0 \) and varies slightly at other times. This indicates that the ionization rate of the electrons recombining around \( P \) increases significantly, leading to an efficient yields of the harmonics above 55\( \omega_0 \). Therefore, a smooth and regularly modulated broadband supercontinuum (70 eV) for the harmonics above 55\( \omega_0 \), with the intensity comparable to that of the lower irregular harmonics in the plateau, is formed in the two-color laser pulse in combination with the isolated attosecond uv laser pulse, as shown in Fig. 7 (blue dotted line). In addition, we can also find from Fig. 7 that the intensity of the whole high-order harmonic spectrum is enhanced by introducing the isolated attosecond pulse. This also benefits from the increase of the ionization probability, which increases from 1% up to 5.4% by the uv pulse. Comparing the two supercontinua in Figs. 2 and 7 (blue dotted line), one can find that the supercontinuum generated by the method of attosecond ionization in two-color laser pulse has a much broader bandwidth than that in few-cycle laser pulse when the intensity of ir driving laser pulse is fixed. Moreover, the ir driving laser pulse is extended from few-cycle to multicycle in two-color laser pulse.

Figure 7 shows the high-order harmonic spectra generated by the two-color laser pulse in combination with the uv laser pulse (blue solid line) and the two-color laser pulse alone (red solid line) after propagation through a 0.75 mm helium gas jet. The parameters of the gas jet are the same as in Fig. 2. The three laser pulses are all Gaussian beams and are focused 1.0 mm before the entrance of the gas jet. The beam waists at focus of the three pulses are 25 \( \mu \)m, which give the confocal parameters \( b_{\omega_0} = 2.5 \) mm, \( b_{\nu_1} = 5.0 \) mm, and \( b_{\nu_x} = 20 \) mm, respectively. Comparing the single-atom high-order harmonic spectrum (blue dotted line) to the macroscopic high-order harmonic spectrum (blue solid line) generated by the method of attosecond ionization control in two-color laser pulse, we can find that the regular modulations in the single-atom high-order harmonic spectrum are almost eliminated after propagation through the gas jet and a smooth broadband supercontinuum (90 eV) is formed for the harmonics above 40\( \omega_0 \) in the macroscopic high-order harmonic spectrum. This can also be explained by the phase matching of the short quantum path is well accomplished for the 55th–75th order harmonics in the ir and uv synthesized laser pulse and for the harmonics above 80\( \omega_0 \) in the ir two-color laser pulse alone. Consequently, the intensity of the supercontinuum is enhanced by about three orders of magnitude for the harmonics around the 65th order harmonic and only one to two orders of magnitude for the harmonics above 80\( \omega_0 \). However, the enhancement for the 40th–50th harmonics is not very intensive. It is because these harmonics come into the first plateau of the single-atom harmonic spectrum in the synthesized two-color pulse alone.

We further investigate the temporal characteristics of the supercontinuum after propagation. Figure 8(a) shows the intensity normalized harmonics pulses produced by superposing ten harmonics at different orders. One can see that there is only one attosecond pulse along the time axis, corresponding to the short quantum path. This validates that the phase matching of the short quantum path is well accomplished for the harmonics in the supercontinuum after propagation through the gas jet and shows that isolated attosecond pulses with tunable central wavelengths can be generated from the supercontinuum. In addition, by synthesizing more harmonics in the supercontinuum, the duration of the attosecond pulse can be further compressed. As shown in Fig. 8(b), an efficient isolated pulse with a duration of 110 as is obtained by synthesizing the harmonics from 65th to 90th harmonics in the supercontinuum.

In addition, we have also investigated the influences of the configuration and the relative time delay on the macroscopic high-order harmonic spectra, especially on the supercontinuum generated by the method of attosecond ionization control in a two-color laser pulse. The results are similar to

FIG. 8. (Color online) (a) The attosecond pulses centered at different frequencies generated by filtering ten harmonics in the supercontinuum shown by the blue solid line in Fig. 7. (b) The attosecond pulse generated with the supercontinuous harmonics (65–90\( \omega_0 \)) shown by the blue solid line in Fig. 7.
that generated by the method of attosecond ionization control in a few-cycle IR laser pulse: the long quantum path can be selected by focusing the laser pulse after the entrance of the gas jet and some variation of the relative time delay will not influence the macroscopic supercontinuum largely.

It must be noted that the intensities of the few-cycle IR laser pulse and the synthesized two-color laser pulse cannot be too high in the schemes discussed above. The intensity of the few-cycle IR laser pulse needs to be lower than $4.5 \times 10^{14}$ W/cm$^2$. The intensity of the fundamental laser pulse of the two-color field even needs to be lower than $3.5 \times 10^{14}$ W/cm$^2$. Too high intensities would induce large numbers of atoms to be ionized, which may lead to the saturation of the enhancement induced by the attosecond ionization control scheme. Large numbers of ionized electrons may also influence the propagation of the laser pulse and the high-order harmonics significantly, even destroy the scheme of two-color field [30]. Though the bandwidth of the supercontinuum can be broadened by increasing the intensity of the control pulse of the two-color laser pulse, the intensity of this control pulse also needs to be lower than $4.5 \times 10^{13}$ W/cm$^2$ when the intensity of the fundamental laser pulse is $3 \times 10^{14}$ W/cm$^2$. The intensity of the isolated attosecond UV pulse does not influence the structure of the supercontinuum, while it has a little influences on the yield of the supercontinuum. When the intensity of the isolated attosecond UV pulse is lower than $2 \times 10^{13}$ W/cm$^2$, the yield of the supercontinuum increases continuously and reaches saturation with increasing intensity of the isolated attosecond UV pulse. Moreover, the carrier-envelop phase of the isolated attosecond UV pulse does not influence the supercontinuum.

In conclusion, we have investigated the influences of propagation effects on the supercontinuum generated by the method of attosecond ionization control in a few-cycle laser pulse and in a two-color laser pulse. The results show that an isolated attosecond UV pulse is a robust tool for producing efficient broadband supercontinuum at macroscopic level. The efficient broadband supercontinuum generated by single atom can be maintained after propagation through the gas jet when the phase matching of short quantum path is achieved. Moreover, the modulations in the supercontinuum are eliminated and the bandwidths of the supercontinuum are broadened after propagation. In addition, these efficient smooth broadband supercontinua are not sensitive to the relative time delay between the IR and UV pulses and support the generation of efficient isolated broadband attosecond pulse.

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