Efficient generation of isolated attosecond pulses with high beam-quality by two-color Bessel-Gauss beams

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The generation of isolated attosecond pulses with high efficiency and high beam quality is essential for attosecond spectroscopy. We numerically investigate the supercontinuum generation in a neutral rare-gas medium driven by a two-color Bessel-Gauss beam. The results show that an efficient smooth supercontinuum in the plateau is obtained after propagation, and the spatial profile of the generated attosecond pulse is Gaussian-like with the divergence angle of 0.1° in the far field. This bright source with high beam quality is beneficial for detecting and controlling the microscopic processes on attosecond time scale. © 2011 Optical Society of America

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The generation of isolated attosecond pulses makes it possible to probe and control the ultrafast electronic processes inside atoms with high time resolution, such as inner-shell electronic relaxation or ionization by optical tunnelling [1]. So far, the most potential way to produce isolated attosecond pulses in experiments is based on high-order harmonic generation (HHG). Many efforts have been made on the spectral and temporal characteristics of HHG in order to broaden the bandwidth of the generated isolated attosecond pulses or enhance the pulse efficiency [2, 3]. Moreover, the spatial characteristics of the isolated attosecond source are also crucial for attosecond science. The good beam quality of the attosecond source leads to micrometer spot size and focused intensities, which are required for applications in nonlinear optics. The generation of efficient single attosecond pulse with high beam quality is still challenging.

The isolated attosecond pulse generation is associated with the electron dynamics in half a cycle of the driving field. The three-step model [4], which well depicts the HHG process at the classical view, implies that HHG process can be controlled via modulating the external driving field or the target to generate a broadband supercontinuum. It has been proposed that a two-color field [5, 6] can control the acceleration process to generate a broadband supercontinuum in the cutoff. Lan et al. [6] also found that two-color scheme can confine the ionization within half a cycle to produce efficient supercontinuum in the plateau.

In the macro aspects of HHG process, the efficiency and the spatial distribution of the generated attosecond pulse intensively depend on the propagation and phase matching in the medium [7]. In a low-ionization medium, the two major factors in phase matching are the intrinsic intensity-dependent phase [8] and the geometrical phase induced by focusing of the fundamental laser beam. Non-Gaussian or modified Gaussian beams have been introduced to modulate the geometry of the driving beams to optimize the phase matching condition for harmonics. Bessel-Gauss (BG) beams offer a slowly varying geometry for enhancement of the phase matching in HHG. T.Auguste et al. [9] reported a higher conversion efficiency and a better spatial profile of the 21st-order harmonic with a BG beam as compared with a Gaussian one in argon. Numerical studies [10] and experiments [11] have been examined in HHG, revealing that BG beams are more efficient than Gaussian beams for generating harmonics in the plateau. In this letter, we adopt a two-color BG beam as a pump pulse to investigate the supercontinuum generation in helium. The results show that an efficient isolated attosecond pulse is produced by the supercontinuum in the plateau after propagation. Moreover, the spatial profile of the generated attosecond pulse is Gaussian-like with a small divergence angle in the far field. This efficient attosecond pulse with high beam quality has important applications in attosecond spectroscopy.

In this work, we perform a quantum simulation of helium in a two-color intense laser field. The single-atom response is calculated with Lewenstein model [12], using the ADK ionization rate [13] and we solve the nonadiabatic 3D light propagation for both fundamental and harmonic fields to simulate the collective response of macroscopic gas. A 5 fs linearly polarized fundamental pulse with a wavelength of 800 nm and a 5 fs linearly polarized control pulse with a wavelength of 400 nm are used to synthesize the two-color driving field. The peak intensities of the fundamental pulse and the control pulse are 6 × 10^14 W/cm^2 and 2.4 × 10^13 W/cm^2, respectively. The electric field of the two-color laser field is given by

E(r, z, t) = E_0(r, z) f(t) cos(ω_0 t) + E_1(r, z) f(t) cos(2ω_0 t + ϕ).

E_0(r, z) and E_1(r, z) are the amplitudes of the fundamental field and the control field, respectively, which
describe the spatial distribution of the electric fields for BG beams. The focusing half-angle of the two-color BG beam is set to 0.5°. The envelope f(t) is a sine squared function and \( w_0 \) is the frequency of the fundamental field. The relative phase of the two fields \( \varphi \) is set to zero to imitate the ionization gating mechanism. The initial peak density of atoms is \( 1.4 \times 10^{18} \text{ cm}^{-3} \) and a 0.8 mm long gas jet with a truncated Lorentzian density profile is placed 1 mm after the laser focus.

The spatiotemporal intensity profile of the synthesized driving field is shown in Fig. 1, and the ionization rate of helium is represented by the red line. For the two-color field, the synthesized field can be modulated by mixing a control laser pulse to the fundamental one. As shown in Fig. 1, the ionization of the electron is enhanced at 2.5T and suppressed in other optical cycles due to the shaping of the synthesized field. Therefore, HHG is confined within half a cycle of the driving field and an efficient supercontinuum can be produced in the first plateau, which is called the the ionization gating scheme [6]. The spatial distribution of the intensity shows that the laser energy is concentrated in the vicinity of the axis.

![Fig. 1. Spatiotemporal intensity profile of the driving laser pulse and the ionization rate of helium.](image)

The harmonic spectrum with the two-color BG beam after propagation is presented by the red curve in Fig. 2(a). For comparison, the harmonic spectrum with two-color associated Gaussian beam [9] (blue curve) and the single-atom result (black curve) are also presented, respectively. As shown in Fig. 2(a), the harmonic spectrum for single-atom response in two-color field is regularly modulated through the plateau to cutoff. The fringes in the supercontinuum originate from the interference between two quantum trajectories. After propagation, in the case of the two-color Gaussian beam, there are still obvious modulations in the supercontinuum. However, the interference in the supercontinuum is largely removed and a smooth supercontinuum is obtained in the first plateau (from 22th to 50th) for the two-color BG beam case. Besides, the intensity of harmonics from 22th to 50th in the plateau with the two-color BG beam is enhanced by about one order compared with the two-color Gaussian one. The characteristics of the supercontinuum are associated with the phase matching conditions in propagation. In our scheme, the calculated ionization probability is below 0.1%. Thus the two governing factors in phase matching are the intrinsic intensity-dependent phase and the geometrical phase of the driving beam. Since the geometry of the BG beam is different from Gaussian beam, phase matching conditions for the quantum paths (long and short) differ between the two beams. In our simulation conditions, in the case of two-color BG beam, for low-order harmonics, good phase matching of only one path can be fully satisfied and a single quantum path is macroscopically selected after propagation. Thus the harmonics in the plateau are well phase matched and the spectrum becomes continuous. As in the two-color Gaussian beam case, both long path and short path survive after propagation. The interference between quantum trajectories may limit the efficiency of HHG and result in the modulations in the harmonic spectrum. Fig. 2(b) shows the isolated attosecond pulse generated in our scheme. By superposing the harmonics in the plateau (from 22th to 50th), a single 250as pulse is obtained using two-color BG beam. The intensity of the attosecond pulse in the case of two-color Gaussian beam is one order of magnitude lower and the inset in Fig. 2(b) is the enlargement of its temporal profile. Moreover, the temporal profile in two-color Gaussian
beam case contains two or more pulses, due to the poor phase matching for both short and long quantum paths.

The far-field spatial characteristics of the attosecond source is essential for its applications. We further investigate the spatial profile of the isolated attosecond pulse in the far field through a Hankel transformation [14]. The results are shown in Fig. 3. For comparison, the far-field spatial profile of the attosecond pulse with the two-color Gaussian beam is also presented. Figure 3(a) and (b) are the spatial images of the attosecond pulses with the two-color Gaussian and BG beams, respectively. For the case of the Gaussian beam, the far-field spatial distribution shows a annular-like structure. This implies a large amount of the energy is radiated off axis and the generated attosecond pulse is divergent, which may limit its potential applications. For the case of the two-color BG beam, the far-field spatial distribution shows a small size spot with focused intensity and two annular rings with much lower intensities. The divergence angle of central spot is approximately 0.1° from our calculation. The intensities of the two additional annular rings are approximately 15% and 10% of the central spot, respectively. These two rings can be filtered by a aperture. Figure 3(c) and (d) present the far-field spatial intensity profiles of the attosecond pulses with Gaussian and BG beams, respectively. It is shown that the spatial intensity profile with the two-color BG beam is Gaussian-like and its intensity is nearly one order higher than that with the two-color Gaussian beam. These spatial properties are related to the good phase matching of the continuous harmonics near the axis. This bright source with high beam quality is beneficial for many potential applications, such as nonlinear studies and plasma diagnostics.

In summary, we have investigated the supercontinuum generation in helium driven by a two-color BG beam based on the ionization gating mechanism. It is shown that an efficient smooth supercontinuum in the plateau (from 22th to 50th) is obtained after propagation. In contrast to the conventional two-color Gaussian beam, our calculations show that the beam quality of the generated isolated attosecond pulse is significantly improved in our scheme. The far-field spatial profile of the generated attosecond pulse is Gaussian-like and the divergence angle is approximately 0.1°. In addition, the intensity of the attosecond pulse generated is nearly one order higher than that with the two-color Gaussian beam. This bright attosecond source with high beam quality can benefit many practical applications in attosecond science. Experimentally, our scheme can be carried out with a Ti:sapphire laser system. The laser beam is split into a strong one and a weak one. The strong one is used as the fundamental field. The weak one is used to produced the control field via frequency multiplication technology. The driving beam may be obtained by focusing a two-color Gaussian beam with an axicon.

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Fig. 3. The far-field profiles of isolated attosecond pulses with different driving beams for the cases of two-color Gaussian beam (c) and two-color Bessel-Gauss beam (d), and the corresponding spatial images of the pulses are presented in (a) and (b). The far-field position is located 1 m from the laser focus.
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