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Isolated sub-50 attosecond pulse generation in the combined mid-infrared laser field

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Abstract. We theoretically study high-order harmonic and isolated attosecond pulse generation from a model helion ion in the combination of the mid-infrared (mid-IR) laser and an extreme ultraviolet (xuv) pulse. It is shown that, for the low laser intensity, the harmonic cutoff is at about 657th order, and the supercontinuum with a 287-eV bandwidth is formed. For the high laser intensity, the spectral cutoff is enlarged to 1795th order, and the supercontinuum is broadened to 834 eV. In the two cases, both the long quantum path selection and the enhancement of the supercontinuum are achieved. Especially for the relatively high laser intensity, pure isolated sub-50 as pulses can be directly obtained by superposing an arbitrary 87-eV harmonics in the supercontinuum from 450th to 1590th order.

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Key words: high-order harmonic generation, supercontinuum, isolated attosecond pulse, combined field

1 Introduction

Attosecond (as) extreme ultraviolet pulses open the way to a new field of studying and operating basic ultrafast electronic processes in atoms and molecules with an unprecedented precision [1-3]. Thus the generation of attosecond pulse has attracted a great deal of attention in recent years. Since HHG covers a large spectral range from the infrared to soft x-ray region, it has become a candidate for breaking through the femtosecond (fs) limit and a preferred light source for realizing the attosecond pulse generation. Additionally, the HHG is currently the most promising way to produce isolated attosecond

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pulses in experiments [4,5]. The physical mechanism of the HHG can be well understood by semiclassical three-step model [6]. In detail, the electron first tunnels through the barrier formed by the Coulomb potential and the laser field, then it oscillates almost freely in the laser field, and finally it may recombine with the parent ion and emit a harmonic photon with energy up to I_p+3.17U_p, where I_p is the atomic ionization potential and $U_p = 9.38\times10^{-14} I[\mathrm{W/cm^2}](\lambda[\mu m])^2$ is the ponderomotive energy. Since the maximal photon energy scales as the intensity of the driving field or the square of the driving field wavelength, the harmonic cutoff can be extended by enhancing the intensity of the driving field or adopting longer-wavelength driving field. However, on the one hand, too high driving field will result in the ionization saturation of the target atom and limit the harmonic yields; on the other hand, high ionization rate also leads to plasma defocusing of the driving pulse and dephasing of the atomic dipole oscillators, then further decreases the conversion efficiency [7]. Therefore, an efficient method for significantly extending the harmonic cutoff is to adopt a longer-wavelength driving field. With the rapid development of ultrafast laser technology, mid-IR laser pulses with high intensity level can be produced by high-power femtosecond optical parametric amplifiers (OPAs) [8-10]. It has been shown that, by using the mid-IR pulses at wavelengths of 1.51 and 2 μm, the harmonic cutoff energies can be extended to 160 eV [9] and 220 eV [10], respectively. Tate *et al.* [11] has theoretically shown that a mid-IR driving pulse not only produces much more energetic harmonic photons but also reduces harmonic chirps, which is helpful to the attosecond pulse generation.

As is well known, during the recombination in the HHG, a photon is emitted. Usually, this process periodically occurs every half optical cycle, leading to the generation of an attosecond pulse train (APT). For practical application, the straightforward attosecond metrology prefers an isolated attosecond pulse, so much effort has been paid out to obtain an isolated attosecond pulse. It has been shown that an isolated attosecond pulse can be generated by using a few-cycle laser pulse [12,13] or polarization gating technique [14]. In a recent breakthrough work, an isolated attosecond light pulse lasting approximately 80 as were produced with a 3.3 fs, 720 nm laser pulse [15]. However, the duration of isolated attosecond pulse is still significantly longer than the time scale of electron motion in atoms, i.e., 24 as. To broaden the bandwidth of supercontinuum and compress the pulse duration, some other methods have been put forward to reach the desired objectives. It has been proposed that the two-color field can broaden the bandwidth of the supercontinuum spectrum and obtain an isolated attosecond pulse with much shorter duration. Zeng *et al.* [16] theoretically proved that a synthesized two-color field can broaden the bandwidth of the supercontinuum to 148 eV, and then an isolated 65 as pulse was created directly. Lan *et al.* [17] proposed a method for coherently controlling electron dynamics using a few-cycle laser pulse in combination with a controlling field, and also showed that this method not only can broaden the attosecond pulse bandwidth and reduce the harmonic chirp, but also can produce a close-to-Fourier-limit 80-as pulse. An alternative method for generating a broadband attosecond pulse is controlling quantum paths. Macroscopically, the short path can be selected by carefully adjusting the phase-matching