Harmonic and attosecond pulse enhancement in the presence of noise*

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In this paper, we theoretically investigate the effect of noise on the photoionization, the generation of the high-order harmonic and the attosecond pulse irradiated from a model He^+ ion. It shows that by properly adding noise fields, such as Gaussian white noise, random light or colored noise, both the ionization probabilities (IPs) and the harmonic yields can be enhanced by several orders of magnitude. Further, by tuning the noise intensity, a stochastic resonance-like curve is observed, showing the existence of an optimal noise in the ionization enhancement process. Finally, by superposing a properly selected harmonic, an intense attosecond pulse with a duration of 67 as is directly generated.

Keywords: high-order harmonic generation, isolated attosecond pulse, photoionization

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1. Introduction

Extreme ultraviolet attosecond pulse trains (APTs) or isolated attosecond pulses have been investigated for many years as an effective tool to probe the electronic dynamics deep inside atoms and molecules,.[1,2] So far, these ultrashort attosecond pulses can be generated using several approaches, such as stimulated Raman scattering,[3] Thomson scattering,[4] high-order harmonic generation (HHG),[5,6] etc. However, among them only the HHG scheme can generate the isolated attosecond pulse[7−11] which is more useful for practical applications. Thus, over the past two decades, the HHG process has been investigated in detail and the most well-known theory for understanding it is the semi-classical 'three-step' model,[12] consisting of ionization, acceleration, and recombination. A supercontinuum is then formed with the maximum harmonic energy given by $E_{\rm cutoff} = I_{\rm p} + 3.17U_{\rm p}$, where $I_{\rm p}$ is the ionization potential and $U_{\rm p}$ is the ponderomotive energy of a free electron ($U_{\rm p} = e^2E^2/4m_{\rm e}\omega^2$). Further, the attosecond pulse could be produced by making an inverse Fourier transformation of several harmonics. For instance, a pulse as short as 80 as has been experimentally realized by Goulielmakis *et al.*[13] by using the extremely short 3.3-fs pulse (which is the shortest pulse obtained recently).

However, the applications of these ultrashort attosecond pulses[7−11,13] are limited due to the low output energy. As is well known, the harmonic yields and the attosecond pulse intensities are strongly dependent on the ionization probabilities (IPs). Therefore, much effort has been devoted to the enhancement of the IPs and the harmonic yields.[14−16] Among them, the most successful methods are the coherent superposition initial state,[17,18] and the introduction of an ultrashort high-order harmonic pulse.[19,20]

Recently, the introduction of a noise field as a more promising way to enhance the IPs has been sufficiently investigated in atoms.[21,22] As a result, whether these noise fields would also result in harmonic enhancement becomes an interesting issue. Therefore, in this paper, we further investigate this noise effect on the photoionization and the HHG spectra. And we utilize the fundamental chirped pulse to extend the harmonic cutoff energy. The results show that with the introduction of noise fields, not only the IPs but also the harmonic yields are remarkably enhanced by several orders of magnitude. Moreover, we

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find an optimal noise-laser ratio for each noise field. Finally, an intense 67-as pulse is directly obtained (at least 4 orders of magnitude higher than the single laser field case).

2. Computational aspects

Our theoretical calculations are carried out by numerically solving the time-dependent Schrödinger equation with the help of the splitting-operator fast-Fourier transforms technique, which is well described in the previous studies.[23–34] The soft Coulomb potential $V(x) = -2/\sqrt{0.5+x^2}$ is used to match the ionization potential of the He^+ ion. The stochastic laser field can be expressed as $E(t) = E_0 \exp(-4\ln(2)t^2/\tau^2)\cos(\omega_0 t - \beta \tanh(t/200)) + N(t)$, where E_0, ω_0, and τ are the pulse intensity, the frequency and the pulse duration of the fundamental chirp pulse; β is the chirp parameter; $N(t)$ represents the noise field. Here, we use three kinds of noises, that is, the Gaussian white noise with the properties of[35] $\langle N_1(t)\rangle = 0$, $\langle N_1(t)N_1(s)\rangle = 2D_1^2\delta(t-s)$; the random light[21] consists of a normalized sum of N closely spaced oscillators expressed as

$$N_2(t) = \sqrt{\frac{2}{N}} \sum_{n=1}^{N=1024} D_2 \sin(\omega_n t + \phi_n),$$

where ω_n and ϕ_n denote the frequency and the phase of the n-th mode; the colored noise with the properties of[32] $\langle N_3(t)\rangle = 0$, $\langle N_3(t)N_3(s)\rangle = D_3^2\lambda\, \mathrm{e}^{(-\lambda|t-s|)}$, where λ^{-1} is the correlation time for the colored noise. D_i (i = 1–3) are the root-mean-square amplitudes of $N_i(t)$ (i = 1–3).

3. Results and discussion

3.1. Noise effect on photoionization

We first investigate the noise effect on the photoionization. The laser field is chosen to be 5 fs/800 nm, $I_0 = 1.0\times10^{15}$ W/cm^2, and $\beta = 0.0$. Figure 1(a) shows the IPs each as a function of Gaussian white noise-to-laser intensity ratio (D_1/E_0). In order to take average of the physical quantities, the following results are all averaged over 50 different realizations. Clearly, the IPs of the combined field ($P(L+N)$) produce no distinct change when $D_1/E_0 < 0.001$ due to the weak contribution from the single noise field ($P(N)$). With the increasing of the intensity ratio, the IPs of both the combined field and the single noise field are enhanced by several orders of magnitude. Moreover, the ionization of the combined field is much higher than the simple sum of the IPs of the single laser field and the noise field case ($P(L)+P(N)$). The physical origin of this enhancement phenomenon can be understood with a stochastic resonance two-step model, that is, the electron is first excited to the excited state by the noise field, and then it is ionized from the excited state by the later laser field. Further, with the continuous increasing of the noise intensity, the speed is enhanced much more quickly for the single noise field than that for the combined field, which means that the ionization will be gradually dominated by the noise field. Thus, there should be an optimal intensity ratio to reach a maximum ionization enhancement. Therefore, in the inset of Fig. 1(a), we present the enhancement factor as a function of intensity ratio, which is defined as

$$\eta = \frac{P(L+N) - (P(L)+P(N))}{(P(L)+P(N))}.$$

Clearly, the curve begins around a zero value of η, which denotes the $P(L) \gg P(N)$ at first. Then, it rapidly increases to a maximum point around $D_1/E_0 = 0.1$, and finally it gradually drops down to the zero again until $D_1/E_0 = 2.1$. However, in this time, the zero value implies that the ionization has been dominated by the noise field ($P(L) \ll P(N)$). Figures 1(b)–1(d) show similar results to that in Fig. 1(a) but for the cases of the random light and the colored noise with $\lambda^{-1} = 2.0$ and 1.0, respectively. Clearly, most of the enhancement phenomena remain intact. However, there are some distinct differences. For instance, for the random light case (Fig. 1(b)), the IPs present no change until $D_2/E_0 > 0.03$, which is one order of magnitude higher than that in the Gaussian white noise case. And the enhancement factor drops down to zero around $D_2/E_0 = 1.5$, which means the random light is much easier to dominate the ionization than the white noise. While for the colored noise cases (Figs. 1(c) and 1(d)), the optimal intensity ratio for the enhancement factor is around $D_3/E_0 = 0.01$, which is one order of magnitude lower than those for the white noise and random light cases. Moreover, with the decreasing of the correlation time λ^{-1}, the IPs of both $P(L+N)$ and $P(L)+P(N)$ will be enhanced more or less.

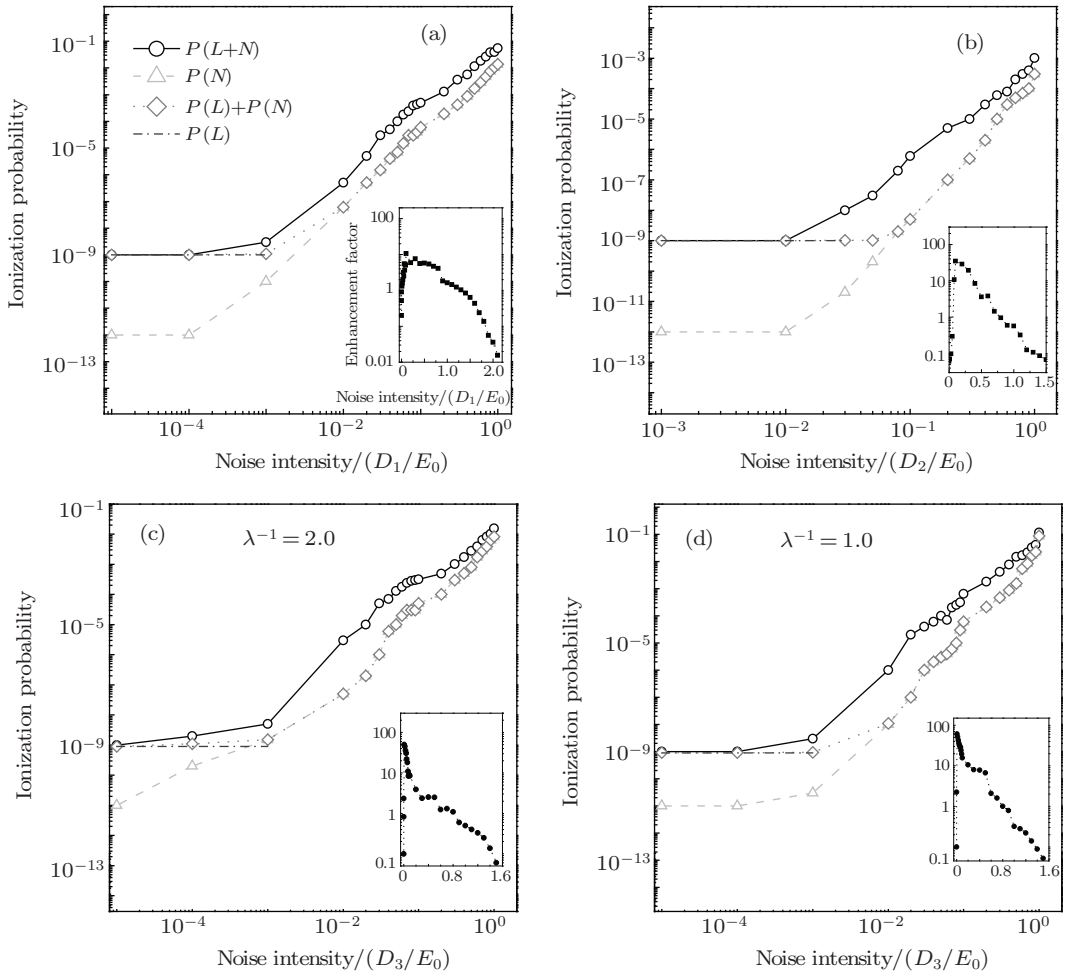


Fig. 1. (a) Evolutions of the IPs with Gaussian white noise-to-laser intensity ratio. Each of the insets shows the enhancement factor of the combined Gaussian white noise-laser field. Panels (b), (c), and (d) show similar results as those in panel (a) but for the cases of the combined random light-laser field, the combined colored noise-laser field with $\lambda^{-1} = 2.0$ and 1.0, respectively.

3.2. Noise effect on harmonic emission and attosecond pulse generation

From the above results, we can confirm that the IPs can be remarkably enhanced with the introduction of the noise fields. Next, we will investigate this stochastic-enhancement-ionization mechanism in the HHG process.

Figure 2(a) shows the HHG spectra of the single chirped pulse ($\beta = 4.0$, this is what we find, i.e., the optimal value for the extension of the cutoff energy under the present laser field) and the combined chirped-Gaussian white noise field. For a comparison, we also present the HHG spectrum of the single chirp-free pulse ($\beta = 0.0$). Clearly, with the introduction of the chirp, the cutoff energy of the chirped pulse (solid black line) is remarkably extended compared with that in the chirp-free case (dash-dot dark-gray line). Moreover, with the introduction of the noise, the harmonic yield is also reinforced. However, when the noise intensity is too high, such as $D_1/E_0 = 0.3$ (dot-gray line), not only does the supercontinuum on the harmonic spectrum becomes unsmooth, but also the interference structures between the two quantum paths, namely the short and the long quantum paths[36] are reinforced, which is not beneficial to the generation of an isolated attosecond pulse. We find that the optimal Gaussian white noise-to-chirped ratio for the enhancement of the harmonic yield is $D_1/E_0 = 0.09$ (dash-light-gray line), with five orders of magnitude higher than that of the single chirped pulse case. Figures 2(b) and 2(c) show the HHG spectra in the combined chirped-random light field and chirped-colored noise field (with the correlation time $\lambda^{-1} = 2.0$), respectively. Clearly, harmonics enhancement phenomena also occur. Particularly,

the harmonic intensities are enhanced by four and five orders of magnitude with optimal intensity ratios of $D_2/E_0 = 0.32$ and $D_3/E_0 = 0.1$ for the above two cases, respectively. Note here that for the case of the combined chirped-colored noise field with a small correlation time (such as $\lambda^{-1} = 0.2$ as shown in the inset of Fig. 2(c)), although the harmonic intensity is much more enhanced, the interference structures on the HHG spectrum are much more obvious compared with the case for $\lambda^{-1} = 2.0$. This is because with the decreasing of the correlation time λ^{-1}, the profile of the combined field is deteriorated due to the remarkable enhancement of the noise intensity.

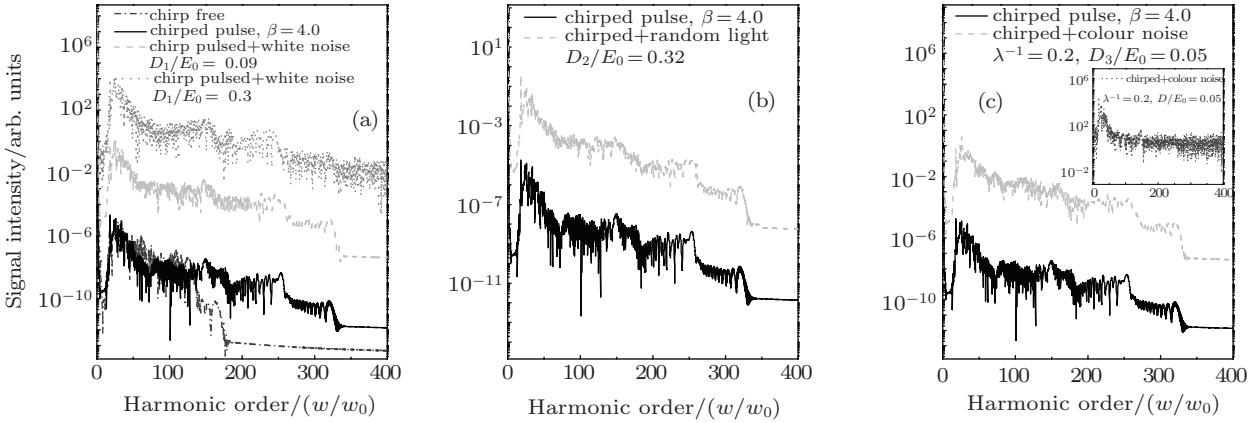


Fig. 2. HHG spectra with adding (a) the Gaussian white noise field, (b) the random light, and (c) the colored noise field.

To better understand the harmonic characteristics, in Figs. 3(b) and 3(c), we present the time-frequency distributions by the wavelet transform of the induced dipole acceleration[37] for the cases of the single chirp-free pulse and the combined chirped-Gaussian white noise field, respectively (here, only one combined field is shown, owing to the fact that the others are similar to it). Clearly, there are three main peaks on the harmonic emission spectrum for both cases, which should be caused by three times 'three-step process' for the present short pulse,[23] marked as M_1 (1st peak), M_2 (2nd peak), and M_3 (3rd peak) in the profiles of the laser fields in Fig. 3(a). It is known that the maximum energy-peak value $(I_\mathrm{p} + nU_\mathrm{p})$ is determined by either the amplitude intensity (pulse intensity) or the width (pulse frequency) of this process. Thus, the extension of the cutoff energy with $\beta = 4.0$ is due to the broadened process of M_2 (or the instantaneous reduction of the frequency of the laser pulse) by the chirp.[24,25] Moreover, due to the noise effect, the harmonic yield is enhanced in comparison with the single laser field case, which will support the generation of a favourable intense attosecond pulse.

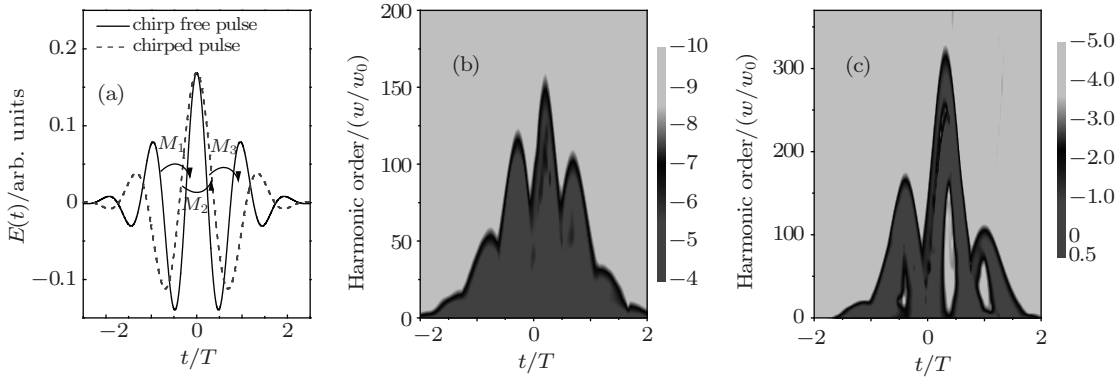


Fig. 3. (a) Profiles of the chirp-free pulse and the chirped pulse. (b) and (c) The time–frequency distributions for the single chirp-free pulse and the combined chirped-Gaussian white noise field, respectively. T is the optical cycle of the 800-nm pulse.

Figure 4 shows the temporal profiles of the attosecond pulses. Due to the fact that the harmonics have no emissions at the same time, the selection of an entire supercontinuum region no longer provides the perfect isolated attosecond pulse. Thus, by properly superposing the harmonics from the 275th to the 320th order in the combined chirped-Gaussian white noise field (Fig. 2(a) dash-light-gray line), an intense isolated 67-as pulse is obtained, which is almost five orders of magnitude higher than that generated from the single chirped field, as shown in the inset of Fig. 4. Note here that if we choose the other two combined field cases, such an intense attosecond pulse can also be obtained, with the four and five orders of magnitude enhancement, respectively.

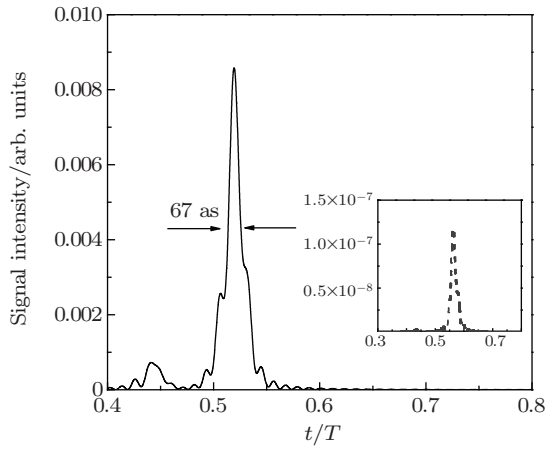


Fig. 4. An attosecond pulse generated from the combined chirped-Gaussian white noise field. The inset shows the attosecond pulse produced from the single chirped pulse.

4. Conclusion

In this paper, we investigated the enhancement of the photoionization, the harmonic emission, and the attosecond pulse generation in the presence of noise. The results show that by properly adding the noise fields, such as the Gaussian white noise, the random light or the colored noise, both the photoionization and the harmonic yield can be remarkably enhanced. Further, through the combination of the chirp pulse, an impressive supercontinuum is obtained. Finally, by properly superposing the harmonics in this supercontinuum, an intense 67-as pulse with four-five orders of magnitude improvement is obtained.

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