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Attosecond pulse generation from relativistic plasma mirror

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Abstract. When an intense relativistic short las ulse in nt on an optically polished surface, it generates a high density plasma th acts as a rela isti lasma mirror. As this mirror reflects the intense laser field, its ce time characteriz changes due to high nonlinear response of the field. This lead to t phase variati both temporally and spatially that could affect the generation of high harmon of the laser an ttosecond pulses. The present theoretical study address the issues of the intens dependent ace-time characteristics on the generation of attosecond pulses fro istic p mir

1. Introduction

The interaction of ultrashort-ultraint nse aser $\geq 10^2$ m^2) pulse with an optically reflected metal surface generates a dense asma tha acts a a plasma mirror(PM). These mirrors specularly reflect the main part e laser pu an can be used as an active optical elements to manipulate the spa a d te ral properties of the high harmonics. The modification in the temporal contras d to ge te an intense attosecond extreme ultraviolet(XUV) or X-ray pulses of energy in the ge 1-10 rough nonlinear harmonic up-conversion of the laser pulse. However, pressure exert y the las r pulse deformed the PM surface non-uniformly This results in the rot he PM fect the spatial and temporal contrast of the reflected laser field and e high monics.

PMs are r tinel used moderate light intensities ($10^{14} - 10^{16} W/cm^2$) as ultrafast witche t nhance e temporal contrast of the femtosecond lasers. For intensities $I \geq 10$ $/cm^2$, linear sponse of the PMs to the laser field results in sub-cycle temporal modula ns of the field , associated to the high harmonic generation in its spectrum (HHG) hese harmonics generated through various mechanism are associated in the time domain to t lses.For lasers with intensity $\geq 10^{18} W/cm^2$, the key HHG results in the r tivistic oscillating mirror where the laser driven oscillation of the plasma surface induces a riodic Doppler effect on the reflected laser field [1, 2, 3, 4, 5, 8],which can result in harmonic o s of several thousands. In these high intensity applications, laser field exerts such a high pres on the plasma ($\cong 5 Gbar for I \approx 10^{19} W/cm^2$) that it induces a significant motion of the PM su ace, even during a femtosecond laser pulse. This leads spatial variation of intensity on the target and hence the deformation in the surface of the PM.

Our present work is based on the spatiotemporal coupling (STC) to the generation of isolated attosecond pulse. We consider deformation in the relativistic plasma mirror surface in the form of an elliptical curvature-which can affect the spatial and spectral properties of the reflected beam.

The intensity dependence of the harmonic spectrum and the attosecond pulse are described in section 2. Conclusions are presented in section 3.

2. Intensity Dependence

It is observed that the wave train of the attoseond pulses can be observed when intensity of the laser beam exceeds to $10^{18} W/cm^2$. It is further concluded that the rotation effect in relativistic oscillating plasma mirror change the denting mechanism of the reflected laser field and phase coherence in the attosecond pulses. The rotation effect of plasma mirror due to $E \times B$ changes the phase parameter of the harmonics and increases the value of f_h. This leads high repetition rate for attosecond pulses with increased intensity.
When an electromagnetic wave reflected from an oscillating mirror, its frequency spectrum extended to high frequency range and the wave breaks-up in the short waves. In relativistic oscillating mirror, harmonics of much higher frequency are generated. The reflected wave's electric field from the oscillating mirror in a reflection time $t' = t - x(t)/c$ is given as

$$\mathbf{E_r} = -\frac{\mathbf{1}}{\mathbf{c}}\frac{\partial \mathbf{A_L}(\mathbf{t}', \mathbf{x}')}{\partial \mathbf{t}'} \tag{1}$$

where x' and t' are the position and time of the reflected waves in observer's frame. The oscillating mirror model implies that the tangential components of the vector potential are zero at the mirror surface. The component of reflected electric field from the oscillating plasma surface will be parallel to incident electromagnetic wave. As a result of it,if the oscillating mirror moves with $\gamma_L \gg 1$ towards the laser pulse with oscillating frequency ω_{osc} and electric field $E_{\shortparallel}$, and duration τ_L, the reflected electric field of the n^{th} harmonics will be given as

$$E_r \propto \gamma_L^2 E_l \tag{2}$$

and the pulse duration will be

$$\tau_L' \propto \frac{\tau_L}{n\gamma_L^2} \tag{3}$$

The Fourier spectrum of the electric field of reflected beam at position x' and time t' is

$$E_r(\omega_r) = \frac{mc\omega}{e\sqrt{2\pi}} \int_{-\infty}^{\infty} \mathbf{a_L}(\mathbf{t}', \mathbf{x}') \\ \times \exp -\iota\omega_L t' - \iota\omega_L(x'/c) \exp(-\iota\phi_r) \tag{4}$$

where

$$t' - x(t')/c = t \tag{5}$$

and ϕ_r is the phase of reflected wave and is given by

$$\phi_r = \int_0^u \Omega_r(u) du = \omega_L[2t'(u) - u] \tag{6}$$

where $u = t' - x'(t')/c$ and spatial position x' and time t' and t'(u) can be obtained from the equation

$$t'(u) = u + x'(t'(u))/c \tag{7}$$

Differentiating above equation, we obtain

$$\phi_r' = \omega_L \frac{1 + \beta'(u)}{1 - \beta'(u)} \tag{8}$$

where $\beta'(u) = dx'(u)/cdt'$ is the mirror velocity normalized by c. Using both power law and the exponential decay parts, and properties of Array's function to analyze the spectrum modulation due to the $E \times B$ effect, we use Eq.(4-6) in Eq(2) to obtain

$$E_r = \left(\frac{\omega_L}{\Omega'_r n}\right)^{5/2} \exp\left(\frac{-16\sqrt{5}\Omega'_r}{5\sqrt{n^3}\omega_L\omega_p^{3/2}}\right) \times Re\frac{\exp(\iota\Omega'_r t - \iota\psi'_r)}{10\sqrt{2}/(5\sqrt{n^3}\omega_p) + \iota\omega_L} \tag{9}$$

where $\Omega'_r = \Omega_r + \Omega_{rot}$.
The amplitude of these reflected pulses decreases fast when Ω_r grows. However, the pulse duration does not depend on Ω_r. Since the fundamental frequency grows as Ω_r, the pulses obtained with an above cut-off filter are filled with electric field oscillations. We use Eq.(9) to obtain the intensity of n^{th} harmonics as

$$I_{rn} \propto \left(\frac{\omega_L}{\Omega'_r n}\right)^{5} \exp\left(\frac{-32\sqrt{5}\Omega_r'^{5/2}}{5\sqrt{n^3}\omega_L\omega_p^{3/2}}\right) \times \frac{\left(n^3\omega_p^2 - \omega_L^2\right)}{8\omega_p^2} \tag{10}$$

The intensity of the reflected pulses decreases with higher harmonics and plasma frequency. However the pulse repetition rate increases when Ω_r grows. It is observed that the intensity of the attosecond pulses depend on the harmonic phases. If v_r is the ultra relativistic velocity of the reflected electric field of a particular harmonics at time $t'(u)$, than the maximum relativistic factor will be given as

$$\gamma_{max} = \frac{1}{\sqrt{1 - \frac{v_r(t'(u))^2}{c^2}}} \tag{11}$$

Consequently, for the surface γ factor during a relativistic spike, the highest harmonic will be generated over the time period

$$\Delta t \approx \frac{1}{\omega_L\gamma_{max}^3} \approx \frac{1}{\omega_L n_{cr}^{3/2}} \tag{12}$$

where n_{cr} is the critical density of plasma surface.
For this duration the reflected fields move with ultra-relativistic velocity in the direction of the emitted [illegible]. The intensity variation over this time interval for n^{th} harmonic can be written as

$$I_n \propto \left(\frac{n_{cr}}{n^3\Omega'_r}\right)^{5} \exp\left(\frac{-32\sqrt{5}\Omega_r'^{5/2}}{5\sqrt{n^3}\omega_L\omega_p^{3/2}}\right) \times \frac{\left(n^3\omega_p^2 - \omega_L^2\right)}{8\omega_p^2} \tag{13}$$

Eq.(13) shows a theoretical result of temporal structure of the intensity of attosecond pulse trains produced on plasma mirrors. The harmonic spectra associated with a train of attosecond pulses

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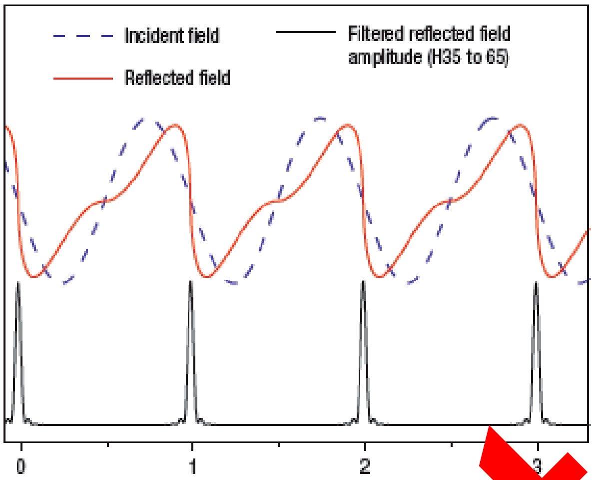

Figure 1. Harmonic spectra from plasma mirror

for different intensities is shown in the figure(1) The harmonic divergence θ_n of n^{th} harmonics is given

$$\theta_n^2 = \left(\frac{\lambda_n}{\pi w_n}\right)^2 + \left(\frac{\lambda_n}{\pi w_n}\right)^2 (n\phi_L)^2$$

$$\theta_n = \theta_n^0\sqrt{1 + (n\phi_L)^2} \tag{14}$$

where $\theta_n^0 = \lambda_n/\pi w_n$ is the harmonic divergence for the source size w_n, in the absence of PM curvature and rotational effect due to $E \times B$.

3. Conclusions

We have presented a simple analytical model for the generation of the attosecond pulse from the relativistic oscillating plasma mirror with $E \times B$ effect that leads rotation in the oscillating plasma mirror. The $E \times B$ effect changes the harmonic divergence which could change the pattern of extended ultra-broadband isolated attosecond pulse spectrum and repetition rate. We have also addressed the temporal characterization of the reflected electric field from plasma mirror, with temporal resolution going down to the attosecond range. It is further observed that the number of harmonics in the reflected laser field increases with intensity of the incident laser beam and electron plasma density.

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