Attosecond pulse generation from relativistic plasma mirror

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Abstract. When an intense relativistic short laser pulse incident on an optically polished surface, it generates a high density plasma that acts as a relativistic plasma mirror. As this mirror reflects the intense laser field, its space time characteristics changes due to high nonlinear response of the field. This lead to the phase variation both temporally and spatially that could affect the generation of high harmonics of the laser and attosecond pulses. The present theoretical study address the issues of the intensity dependent space-time characteristics on the generation of attosecond pulses from relativistic plasma mirror.

1. Introduction

The interaction of ultrashort-ultraintense laser pulse (I ≥ 10¹² W/m²) with an optically polished metal surface generates a dense plasma that acts as a plasma mirror (PM). These mirrors specularly reflect the main part of the laser pulse and can be used as an active optical elements to manipulate the spatial and temporal properties of the high harmonics. The modification in the temporal contrast lead to generate an intense attosecond extreme ultraviolet (XUV) or X-ray pulses of energy in the range 1-10 J through nonlinear harmonic up-conversion of the laser pulse. However, pressure exerted by the laser pulse deformed the PM surface non-uniformly This results in the rotation of the PM surface which affect the spatial and temporal contrast of the reflected laser field and the high harmonics.

PMs are routinely used at moderate light intensities (10¹⁴ − 10¹⁶ W/cm²) as ultrafast optical switches to enhance the temporal contrast of the femtosecond lasers. For intensities I ≥ 10¹⁶ W/cm², the nonlinear response of the PMs to the laser field results in sub-cycle temporal modulations of the pulse field, associated to the high harmonic generation in its spectrum (HHG). These harmonics generated through various mechanism are associated in the time domain to the attosecond pulses. For lasers with intensity ≥ 10¹⁸ W/cm², the key HHG results in the relativistic oscillating mirror where the laser driven oscillation of the plasma surface induces a periodic Doppler effect on the reflected laser field [1, 2, 3, 4, 5, 8], which can result in harmonic orders of several thousands. In these high intensity applications, laser field exerts such a high pressure on the plasma (∼ 5 Gbar for I ≈ 10¹⁹ W/cm²) that it induces a significant motion of the PM surface, 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 attosecond 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. The 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 extends 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 $t' - x(t')/c$ is given as

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

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 $A_L$ 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 $\omega_{osc}$ and electric field $E_i$, and duration $\tau_L$, the reflected electric field of the $n^{th}$ harmonics will be given as

$$E_r \propto n\gamma_L^2 E_i$$

and the pulse duration will be

$$\tau'_L \propto \frac{\tau_L}{n\gamma_L^2}$$

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

$$E_r(\Omega_r) = \frac{m c \omega}{e \sqrt{2\pi}} \int_{-\infty}^{\infty} a_L(t',x') \times \exp(-\omega_L t' - \omega_L (x'/c) \exp(-i\phi_r))$$

where

$$t' - x(t')/c = t$$

and the phase of reflected wave and is given by

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

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

$$t'(u) = u + x'(t'(u))/c$$

Differentiating above equation, we obtain

$$\phi'_r = \omega_L \frac{1 + \beta'(u)}{1 - \beta(u)}$$
where $\beta' = \frac{dx'(u)}{cdt'}$ 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

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

where $\Omega'_r = \Omega_r + \Omega_{rot}$.

The amplitude of these reflected pulses decreases fast when $\Omega_r$ grows. However, the pulse duration does not depend on $\Omega_r$. Since the fundamental frequency grows as $\Omega_r$, 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

$$I_{rn} \propto \left( \frac{\omega_L}{\Omega'_r n} \right)^5 \exp \left( -\frac{32\sqrt{5}\Omega'_r^{5/2}}{5\sqrt{n^3\omega_p^{3/2}}} \right) \times \Re \exp \left( i\Omega'_r t - i\psi'_r - \frac{n^3\omega_p^2 - \omega_L^2}{8\omega_p^2} \right)$$

The intensity of the reflected pulses decreases with higher harmonics and plasma frequency. However, the pulse repetition rate increases when $\Omega_r$ grows. It is observed that the intensity of the attosecond pulses depend on the harmonic phases. $v_r$ 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

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

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

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

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 radiation. The intensity variation over this time interval for $n^{th}$ harmonic can be written as

$$I_n \propto \left( \frac{n_{cr}}{n^3\Omega'_r} \right)^5 \exp \left( -\frac{32\sqrt{5}\Omega'_r^{5/2}}{5\sqrt{n^3\omega_L\omega_p^{3/2}}} \right) \times \Re \exp \left( i\Omega'_r t - i\psi'_r - \frac{n^3\omega_p^2 - \omega_L^2}{8\omega_p^2} \right)$$

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
Figure 1. Harmonic spectra from plasma mirror

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

$$\theta_n^0 = \left( \frac{\lambda_n}{\pi w_n} \right)^2 + \left( n \frac{\phi_L}{\pi} \right)^2 \theta_n = \theta_0 n \sqrt{1 + \left( n \phi_L \right)^2}$$

(14)

where $\theta_0 = \lambda_n/\pi w_n$ is the harmonic divergence of 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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