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Resonant second harmonic generation in plasma under exponential density ramp profile

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ABSTRACT

Resonant second harmonic generation of a relativistic self-focused laser beam in plasma under exponential density ramp profile is investigated. It has been found that the self-focusing of Gaussian laser beam becomes stronger in plasma with exponential density ramp profile hence, leads to enhance the resonant second harmonic generation. The periodic variation of the normalized second-harmonic amplitude with normalized distance has been analyzed for different laser and plasma parameters. Therefore, enhanced second harmonic generation on account of relativistic self-focusing of fundamental laser beam in plasma under plasma density transition is observed. One may notice that exponential density ramp plays an important role in making the self-focusing stronger which in turn enhances the second harmonic generation in plasma.

1. Introduction

With the advancement in laser technology various non-linear phenomena like frequency up-conversion, harmonic generation, signal processing etc. [1–5], can be seen due to the interaction of high power laser beams with semiconductors and plasmas. Different techniques are used by various researchers to produce resonant harmonic generation during laser-plasma interaction [6–9]. Further, it was observed that when ultra-intense laser beam interacts with plasma, it gives rise to second harmonic generation by inducing transverse plasma currents which are highly relativistic and nonlinear, causing in the generation of current density at second harmonic which leads to the second harmonic generation.

Harmonic generation during laser plasma interaction has been become a great area of interest for last few decades. However, the efficiency of harmonic generation observed during laser plasma interaction is reasonably low and hence a number of techniques have been used to enhance the efficiency of harmonic generation. The phenomenon of self-focusing has shown great importance in the efficient harmonic generation [10,11]. The relativistic self-focusing of laser beam in plasma has been studied in detail both experimentally as well as theoretically [12]. Further, as we know the process of harmonic generation is non-resonant, so different techniques were proposed by various scientists [3,13] to make the process resonant. Additional momentum required for the phase matching condition is provided by density ripple or wiggler magnetic field to the harmonic photon to make the process resonant which further enhances the efficiency of harmonic generation.

In the past years, in order to make the self-focusing stronger during laser plasma interaction, a great interest has been shown by introducing slowly increasing plasma density ramp. A lot of work has been reported in which tangent density ramp profile [14–18] has been introduced due to its upward increasing nature, but self-focusing by using this type of profile is

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limited to the value of $\xi < \xi_d$, where ξ_d is that value of propagation distance at which density will shoot to infinity. Therefore, in order to overcome this limit exponential density ramp profile has been proposed by Sen et al. [14].

In the present work, we purpose a scheme to increase the efficiency of second harmonic generation on account of relativistic self-focusing of laser in plasma with exponential density ramp profile. The dependence of plasma density and relativistic self-focusing on second harmonic generation has been studied. Under the influence of the exponential density ramp, it has been found that the fundamental laser beam propagates up to longer distance without getting diverged. Due to this the relativistic self-focusing of fundamental laser beam becomes stronger which greatly increases the intensity and hence the efficiency of the second harmonic generation. Similar results are found by Valkunde et al. [19]. They have compared the results for both exponential density ramp as well as tangent density ramp and noticed the stronger self-focusing for the exponential density ramp as compared to tangent density ramp profile. Because in case of exponential density ramp profile, laser beam propagates up to several Rayleigh length without so much divergence.

In Section 2, we derive the equation of beam width parameter of the fundamental laser beam, and the equation describing the variation of normalized amplitude of the second-harmonic wave $A_{20}^{''}$ with normalized propagation distance ξ. The numerical results are discussed in Section 3, and the conclusion is presented in Section 4.

2. Theoretical considerations

The field of the laser beam propagating in plasma with exponential density ramp profile can be written as

$$\vec{E}_1 = \hat{x}A_1(z,t)\exp[-i(\omega_1 t - k_1 z)], \tag{1}$$

$$A_1^2 = \frac{A_{10}^2}{f_1^2(z)}\exp\left[\frac{-r^2}{r_0^2 f_1^2}\right], \tag{1a}$$

$$\vec{B}_1 = \frac{c\vec{k}_1 \times \vec{E}_1}{\omega_1}, \tag{1b}$$

$$\vec{B}_W = \hat{y}B_0\exp(ik_0 z), \tag{1c}$$

where A_1 is the amplitude of the fundamental laser pulse inside plasma, A_{10} is the constant amplitude of the fundamental laser pulse, f_1 is the beam width parameter of the fundamental laser pulse, r_0 is the spot size of the fundamental laser pulse at $z = 0$, ω_1 and k_1 are the frequency and wave number of fundamental laser beam and k_0 is the wiggler wave number. The pump wave and the second-harmonic wave obey the linear dispersion relation, $k^2 \approx (\omega^2/c^2)(1 - \omega_p^2/\omega^2)$. The wave vector $\vec{k}$ increases more than linearly with frequency ω, hence $k_2 > 2k_1$. The difference of momentum can be provided to the second- harmonic photon by the wiggler magnetic field when $\vec{k}_2 = 2\vec{k}_1 + \vec{k}_0$; the value of $\vec{k}_0$ required for the phase matching can be obtained as $k_0 = (2\omega_1/c)[(1 - \omega_p^2/4\omega_1^2)^{1/2} - (1 - \omega_p^2/\omega_1^2)]$, where $\omega_P = (4\pi\ n(\xi)e^2/m)^{1/2}$ is the plasma frequency which is a function of propagation distance, $m = m_0\gamma$, and $\gamma = 1/\sqrt{1 - v^2/c^2}$. We consider the plasma density profile as $n\left(\xi\right) = n_0\exp\left(\xi/d\right)$, where $\xi = z/R_d$; $R_d = kr_0^2$ is the diffraction length, n_0 is the equilibrium electron density, c is the velocity of light in vacuum, and e & m_0 are the charge and rest mass of the electron respectively.

Let us consider the dielectric constant of the plasma as,

$$\varepsilon = \varepsilon_0 + \phi(EE^*) \tag{2}$$

Therefore, the plasma frequency can be written as,

$$\omega_p^2 = \left(\frac{4\pi n_0 e^2}{m_0\gamma}\right)\exp\left(\frac{\xi}{d}\right) = \left(\frac{\omega_{p0}^2}{\gamma}\right)\exp\left(\frac{\xi}{d}\right) \tag{3}$$

where $\gamma = \sqrt{1 + e^2EE^*/c^2m_0^2\omega_0^2}$. The nonlinear part of dielectric constant is given by

$$\phi(EE^*) = \frac{\omega_{p0}^2}{\omega_1^2\gamma}\exp\left(\frac{\xi}{d}\right)\ \left[1 - \exp\left(\frac{3m_0}{4M}\alpha_1 EE^*\right)\right] \tag{4}$$

2.1. Relativistic self-focusing

Wave equation for fundamental wave can be deduced by using Maxwell's equations

$$\nabla^2\vec{E} - \frac{\varepsilon}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = \frac{\omega_P^2}{c^2}\vec{E} \tag{5}$$

The solution of this equation can be assumed as,

$$\vec{E} = A(x,y,z)\exp[i(\omega_1 t - k_1 z)], \tag{6}$$