Optik 127 (2016) 5452–5461

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Second harmonic generation of self-focused Cosh-Gaussian laser beam in collisional plasma

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ARTICLE INFO

Article history:
Received 13 January 2016
Accepted 16 February 2016

Keywords:
Self-focusing
Chromatic dispersion
Cosh-Gaussian beam
Collisional plasma
Plasma wave

ABSTRACT

This paper presents theoretical investigation of effect of self-focusing of Cosh-Gaussian (ChG) laser beam on second harmonic generation (SHG) in collisional plasma. Due to non uniform intensity distribution along the wave front of ChG laser beam non uniform Ohmic heating of plasma electrons takes place. Non uniform heating of plasma the laser beam leads to self-focusing of the laser beam which in turn produces strong density gradients in the transverse direction. The generated density gradients excite electron plasma wave at pump frequency that interacts with the incident laser beam to produce its second harmonics. Following moment theory approach in Wentzel–Kramers–Brillouin (W.K.B) approximation second order differential equation governing the evolution of spot size of laser beam with distance of propagation has been derived. Numerical simulations have been carried out to investigate the effect of laser intensity as well as plasma parameters on self-focusing of the laser beam and also on yield of second harmonics. Results predict that ChG laser beams show smaller divergence as they propagate and, thus, lead to enhanced conversion efficiency of second harmonics.

1. Introduction

Since the invention of lasers, the physics of nonlinear interaction of intense laser beams with plasmas is a rapidly growing field of research attracting more and more research groups. Propagation of intense laser beams through plasmas is relevant to a wide range of potential applications including fast ignition schemes for inertial confinement fusion [1,2], plasma based particle accelerators [3–6], X-ray lasers [7], higher harmonic generation [8–12], super continuum generation [13,14], etc. The feasibility of all these applications rely on the fact that the intense laser beams should propagate in a controllable manner over long distances through plasmas while maintaining their intensity. As several nonlinear phenomenon such as stimulated Raman scattering, filamentation of laser beam, self-focusing, self phase modulation, etc. come into play during the propagation of laser beams through plasmas. Therefore, it becomes essential to investigate analytically or numerically some of these phenomenons, to get deep insight into laser–plasma interaction physics.

Ever since first reported by Askaryan, the nonlinear phenomenon of self-focusing of electromagnetic beams in nonlinear media is gaining interest of researchers worldwide because of its relevance to a number of newly discovered processes. Self-focusing is a highly nonlinear phenomenon that arises due to nonlinear response of material medium to the field of electromagnetic beam. Due to modification of dielectric properties of medium, it starts behaving like a convex lens. In collisional plasmas this modification of dielectric properties occur on account of non uniform Ohmic heating of plasma electrons due to non uniform intensity distribution along the wave front of laser beam.

Generation of higher harmonics of electromagnetic radiations in laser produced plasmas is an important nonlinear process and has become an important field of research. Harmonic generation has strong influence on the nature of laser propagation through plasmas. It allows penetration of laser power to over dense region and has thus become an important diagnostic tool for obtaining information of plasma parameters such as local electron density, expansion velocity, electrical conductivity, opacity, via interferometry or absorption spectroscopy [15]. A classic example of this is second harmonic generation, which is routinely used to track the passage of high intensity laser pulses through under dense plasma targets [16]. Ultra short pulse duration and good spatial and temporal coherence of harmonic radiations make them good candidate for applications in the vacuum ultraviolet (VUV) or extreme ultraviolet (XUV) region [17]. This includes investigations of ultrafast atomic [18,19] and molecular [20,21] spectroscopy, ultrafast holography to investigate dynamics of surface deformations [22].

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http://dx.doi.org/10.1016/j.ijleo.2016.02.039

Laser produced plasmas can produce higher harmonics of incident laser beams by a number of mechanisms. These include ionization fronts [23], photon acceleration [24], resonance absorption [25], parametric instabilities [26], and plasma wave excitation [27–30]. In case of second harmonic generation the main mechanism is excitation of electron plasma wave at pump frequency that interacts with the pump beam to produce its second harmonics.

Second harmonic generation in laser–plasma interaction has been investigated extensively both experimentally as well as theoretically by a number of workers [31–33]. Burnett et al. [34] observed harmonics up to 11th from planar solid targets. Carman et al. [35] observed harmonic orders up to 27, and then 49 in a second experiment [36]. Hora and Ghatak [37] derived and evaluated second harmonic resonance for perpendicular incidence at four times the critical density, from hydrodynamics, including unrestricted electric field. Singh et al., investigated the effect of self focusing of Gaussian laser beam on second harmonic generation in collisional [29], collisionless [30], relativistic [38] plasmas by using moment theory approach [39,40]. Pallavi and Ekta [41] investigated the second harmonic generation of p-polarized laser beam in under dense plasma.

The vast majority of earlier works on second harmonic generation outlined above have been carried out under the assumption of uniform laser beam or laser beams having Gaussian distribution of intensity along their wave fronts. In contrast to this picture a new class of laser beams known as ChG laser beams is gaining much interest among scientific communities because they possess high power and low divergence in comparison to Gaussian beams. A review of literature reveals the fact that no earlier theoretical investigation on SHG has been carried for ChG intensity distribution along the wave front of laser beam for collisional plasma. The aim of this article is to delineate for the first time, the effect of self-focusing of ChG laser beam on SHG in collisional plasmas. The paper is organized as follows:

In Section 2 the dielectric function describing the nonlinear response of the plasma to the field of incident laser beam has been derived. In Section 3 the nonlinear differential equation governing the self-focusing of laser beam has been derived. In Section 4 conditions for self-trapping of the laser beam have been obtained. Sections 5 and 6 describe excitation of electron plasma wave and generation of second harmonics of incident laser beam, respectively. In Section 7 detailed discussion of the results obtained has been given.

2. Nonlinear dielectric response of plasma

Consider the propagation of an intense laser beam having electric field vector

$$\mathbf{E}(r,z,t) = E_0(r,z)e^{\iota(\omega_0 t - k_0 z)}\mathrm{e}_x \tag{1}$$

through an under dense collisional plasma with dielectric constant

$$\epsilon = 1 - \frac{\omega_p^2}{\omega_0^2} \tag{2}$$

where, ω_0 and k_0 respectively are angular frequency and vacuum wave number of the laser beam and

$$\omega_p^2 = \frac{4\pi e^2}{m} n_e \tag{3}$$

is the plasma frequency in the presence of laser beam.

The initial intensity distribution of the laser beam along its wavefront is assumed to be ChG and is given by [42–44]

$$E_0E_0^\star|_{z=0} = E_{00}^2 e^{-(r^2/r_0^2)}\cosh^2\left(\frac{b}{r_0}r\right) \tag{4}$$

where, r_0 is the spot size of the laser beam at the plane of incidence i.e., $z=0$, E_{00} is the axial amplitude of the electric field of laser beam, (b/r_0) is the parameter associated with Cosh function and is known as cosh factor. Such a ChG laser beam can be produced in laboratory by superposition of two decentered Gaussian laser beams having same spot size and which are in phase with each other [43]. Hence, the parameter b is also known as decentered parameter.

for $z>0$, the energy conserving ansatz for the intensity distribution of ChG laser beam propagating along z-axis is given by

$$E_0E_0^\star = \frac{E_{00}^2}{f^2} e^{-(r^2/(r_0^2 f^2))}\cosh^2\left(\frac{b}{r_0 f}r\right) \tag{5}$$

where r_0f is the instantaneous spot size of the laser beam. Hence, the function f is termed as dimensionless beam width parameter which is measure of both axial intensity and spot size of the laser beam. For $b=0$ the intensity distribution of the ChG laser beam attain usual Gaussian distribution.

The nonuniform intensity distribution of laser beam along its wavefront produces nonuniform heating of the plasma electrons as a result of which redistribution of electrons takes place. The resultant distribution of electrons is given by [45]

$$n_e = n_0\left(\frac{2T_0}{T_0+T}\right)^{1-(s/2)} \tag{6}$$

where, n_0 is equilibrium electron density, T_0 is equilibrium plasma temperature and T is the temperature of the plasma in the presence of laser beam which is related to laser electric field by

$$\frac{T}{T_0} = 1 + \beta E_0 E_0^\star \tag{7}$$

where, $\beta = (e^2M)/(6K_0T_0m^2\omega_0^2)$ is the coefficient of collisional nonlinearity. Using Eqs. (3), (5), (6) and (7) in Eq. (2) we get

$$\epsilon = 1 - \frac{\omega_{p0}^2}{\omega_0^2}\left\{1 + \frac{1}{2}\frac{\beta E_{00}^2}{f^2}e^{-(r^2/r_0^2f^2)}\mathrm{Cosh}^2\left(\frac{b}{r_0 f}r\right)\right\}^{(s/2)-1} \tag{8}$$

where, $\omega_{p0}^2 = (4\pi e^2/m)n_0$ is the plasma frequency in the absence of laser beam. The parameter s describes the nature of collisions and can be defined through the dependence of collision frequency ν on electron's random velocity v and temperature T as $\nu \propto (v^2/T)^s$. For velocity independent collisions $s=0$, for collisions between electrons and diatomic molecules $s=2$ and for electron-ion collisions $s=-3$.

Taking

$$\epsilon = \epsilon_0 + \phi(E_0E_0^\star) \tag{9}$$

we get

$$\epsilon_0 = 1 - \frac{\omega_{p0}^2}{\omega_0^2} \tag{10}$$

and

$$\phi(E_0E_0^\star) = \frac{\omega_{p0}^2}{\omega_0^2}\left\{\left(1 + \frac{1}{2}\frac{\beta E_{00}^2}{f^2}e^{-(r^2/r_0^2f^2)}\cosh^2\left(\frac{b}{r_0 f}r\right)\right)^{(s/2)-1}\right\} \tag{11}$$

where ϵ_0 and $\phi(E_0E_0^\star)$ respectively are the linear and nonlinear partes of dielectric function of the plasma.

3. Self-focusing of the laser beam

Starting from Ampere's and Faraday's laws for an isotropic, non-conducting and non absorbing medium ($J=0$, $\rho=0$, $\mu=1$), we get

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} \tag{12}$$