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Beat wave excitation of electron plasma wave by cross-focusing of intense cosh-Gaussian laser beams in collisionless plasma with upward density ramp

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ABSTRACT

This paper presents theoretical investigation of the effect of cross-focusing of two coaxial cosh-Gaussian (ChG) laser beams on beat wave excitation of electron plasma wave (EPW) in an under dense plasma with upward density ramp. The plasma wave is generated on account of beating of two coaxial laser beams of frequencies ω_1 and ω_2. The mechanism for laser induced nonlinearity is assumed to be a ponderomotive force. Following moment theory approach in Wentzel–Kramers–Brillouin (W.K.B) approximation nonlinearly coupled differential equations governing the evolution of spot size of the laser beams with distance of propagation have been derived. The ponderomotive nonlinearity depends not only on the intensity of first laser beam but also on that of second beam. Therefore, the behavior of first laser beam affects that of second laser beam and hence cross focusing of two laser beams takes place. By changing the decentred parameter, the peak intensity of the laser beam can be shifted in the transverse direction and a noticeable change is observed on the cross-focusing of the two laser beams as well as on the power of generated plasma wave. The results are presented in the form of graphs for typical set of laser-plasma parameters.

1. Introduction

Invention of laser by Maiman [1] in 1960, led to a renaissance in the field of plasma physics by giving birth to several new possibilities like laser driven particle accelerators [2,3], inertial confinement fusion [4,5], generation of mono-energetic electron bunches [6], X-ray lasers [7,8] etc. For the successful realization of many of these applications, it is highly necessary that laser beam propagate extended distances (up to several Rayleigh lengths) into plasma while maintaining its intensity. In the absence of an optical guiding mechanism the propagation distance is limited approximately to a Rayleigh length due to diffraction divergence. Therefore, diffraction broadening is one of the fundamental phenomena that negate the efficient coupling of laser energy with plasmas. In conventional optics diffraction of laser beam can be prevented either by using optical fibers or relying on the phenomenon of self-focusing. The self-focusing phenomenon arises due to nonlinear response of material medium to the field of incident laser beam leading to modification of its dielectric properties in such a way that self-contraction of transverse dimensions of laser beam takes place. In collisionless plasmas this modification of dielectric properties occurs on account of ponderomotive force that expels electrons from high field region to the low field region [9].

Several nonlinear effects such as stimulated Raman scattering [10,11], stimulated Brillouin scattering [12,13], excitation of plasma waves [14,15], filamentation of laser beam [16], etc. come into play during the transit of intense laser beams through plasmas. Some of these phenomenon lead to anomalous electron and ion heating and others to scattering of electromagnetic energy out of the plasma or to degradation of symmetrical energy deposition to plasma. These nonlinear phenomenon are therefore of paramount importance in laser driven fusion studies. In order, to have a deep understanding of laser-plasma interaction physics there have been ongoing conscious efforts to investigate numerically or analytically some of these nonlinear effects.

The propagation of intense laser beams through plasmas can excite natural modes of vibration of plasma i.e., electron plasma waves or ion acoustic waves. The plasma waves can be driven either by beating two co-propagating laser beams, differing in frequencies by the plasma frequency, or by a single short laser pulse of duration equal to the plasma period. Excitation of plasma waves is of particular interest in inertial confinement fusion, since these waves have very high phase velocity (of the order of light) and hence

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can preheat the fuel and reduce the implosion efficiency by producing energetic electrons. Nonlinear interactions of high power laser beams with electron plasma waves have been considered as an application in various situations [17,18]. Specifically in higher harmonic generation the nonlinear interaction of electron plasma wave with pump beam leads to generation of higher harmonics of incident laser beam [19]. Stimulated Raman scattering is one of the most important resonant three wave interaction process in laser fusion plasmas involving electron plasma waves, which is responsible for depleting and redirecting the incident laser flux [10,11]. Similarly, in beat wave process, the electron plasma wave generated at difference frequency may again nonlinearly interact with the incident laser beam and particle acceleration may be affected [20]. There have been considerable studies on electron motion in plasma wave and electrons can be heated up to a temperature much higher than the corresponding laser ponderomotive potential [21].

A lot of theoretical and experimental work has been reported related to the beat wave excitation of electron plasma waves. Rosenbluth and Liu [22] investigated the growth and saturation of large amplitude plasma wave in cold homogeneous collisionless plasma due to beating of two laser beams with frequencies much above the plasma frequency, by taking into account the modulation of Lorentz force. Darrow et al., [23,24] have reported a model for beat wave excitation of electron plasma waves in rippled density plasma. Leemans et al. [25], have examined the nonlinear dynamics of the laser driven plasma beat wave in the presence of a strong short wavelength density ripple using the relativistic Lagrangian oscillator model. Sharma and Chauhan [20] investigated the effect of cross focusing of two coaxial laser beams on beat wave excitation in relativistic plasmas.

Laser beams with different intensity profiles behave differently in plasmas. A review of literature reveals the fact that most of the theoretical investigations on excitation of electron plasma waves have been carried out under the assumption of uniform laser beam or laser beams having Gaussian irradiance of intensity along their wave fronts. In contrast to this picture there is currently interest in a new class of laser beams known as ChG laser beams since they possess high power and low divergence as compared to Gaussian laser beams [26–28]. The main incentive behind this paper is to present for the first time, a more cogent approach together with numerical simulations to investigate the cross-focusing of two coaxial ChG laser beams in collisionless plasmas with density ramp and to delineate its effect on beat wave excitation of electron plasma wave.

The outline of this paper is as follows:

In Section 2 the dielectric function of plasma has been obtained. In Section 3 the nonlinear coupled differential equations governing the evolution of spot size of laser beams with distance of propagation have been derived. In Section 4 the expression for normalized power of the generated plasma wave has been obtained. Sections 5 and 6 describe the detailed discussion and conclusions of the results obtained, respectively.

2. Dielectric function of plasma

Consider the propagation of two coaxial, linearly polarized laser beams having ChG intensity distribution along their wavefront [27,28], through an underdense plasma of equilibrium electron density $n_0(z)$

$$\mathrm{E_j}(r,z,t) = E_j(r,z)e^{-\iota(\omega_j t - k_j z)}\mathrm{e_x} \tag{1}$$

$$E_jE_j^{\star}|_{z=0} = E_{j0}^2 e^{-(r^2/r_j^2)}\cosh^2\left(\frac{b_j}{r_j}r\right) \tag{2}$$

where, $j = 1, 2$ and ω_j, k_j respectively are the angular frequency and vacuum wave numbers of the fields of the laser beams, $\mathbf{e}_x$ is the unit vector along x-axis, $\frac{b_j}{r_j}$ is the factor associated with cosh function and is termed as cosh factor and r_j is the initial spot size of the laser beams. Eq. (2) can be written as

$$E_jE_j^{\star}|_{z=0} = \frac{E_{j0}^2}{4}e^{b_j^2}\left[e^{-\left(\frac{r}{r_j}+b_j\right)^2} + e^{-\left(\frac{r}{r_j}-b_j\right)^2} + 2e^{-\left(\frac{r^2}{r_j^2}+b_j^2\right)}\right]$$

from which it is clear that ChG laser beam can be produced in the laboratory by the superposition of two Gaussian laser beams with same spot size and in phase, whose centers are located at positions $(\frac{b_j}{2}, 0)$ and $(-\frac{b_j}{2}, 0)$ respectively. Hence, the parameter b_j is also termed as decentered parameter.

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

$$E_jE_j^{\star} = \frac{E_{j0}^2}{f_j^2}e^{-\frac{r^2}{r_j^2 f_j^2}}\cosh^2\left(\frac{b_j}{r_jf_j}r\right) \tag{3}$$

where, r_jf_j is the instantaneous spot size of the laser beams. Hence, the function f_j is termed as dimensionless beam width parameter which is measure of both axial intensity and spot size of laser beams. For $b_j = 0$, the ChG distribution gets converted into usual Gaussian distribution.

When such high amplitude ChG laser beams propagate through the plasma, due to nonuniform intensity distribution along their wavefronts, the plasma electrons experience ponderomotive force

$$\mathrm{F_p} = -\frac{e^2}{4m\omega_j^2}\nabla\sum_j E_jE_j^{\star} \tag{4}$$

where e and m respectively are charge and mass of electrons, which results in their ambipolar diffusion from high field region to low field region. The electron density n responds to the wave electric field according to

$$n = n_0(z)e^{-\sum_j \beta_j E_j E_j^{\star}} \tag{5}$$

where $\beta_j = \frac{e^2}{8m\omega_j^2 T_0 K_0}$ is the coefficient of ponderomotive nonlinearity, T_0 is the equilibrium temperature of plasma, K_0 is the Boltzmann constant. In this paper we shall be considering the case where light beam varies in space, but propagate in a steady state manner in time. Consequently, the ponderomotive force completely dominates ion inertia, and must be balanced by pressure forces. The formal conditions for Eq. (5) to be valid are: macroscopic scale length L must satisfy $L \gg \lambda_d$; macroscopic velocities must be small compared with the sound speed $c_s = \left(\frac{T_e}{M_i}\right)^{1/2}$ and macroscopic time scales must be long compared with (L/c_s)

The redistribution of electrons results in modification of dielectric properties of plasma. The modified dielectric function of plasma can be written as

$$\epsilon_j = 1 - \frac{\omega_{p0}^2(z)}{\omega_j^2}e^{-\sum_j \beta_j E_j E_j^{\star}} \tag{6}$$

where,

$$\omega_{p0}^2(z) = \frac{4\pi e^2}{m}n_0(z)$$

Eq. (6) can be written as

$$\epsilon_j = \epsilon_{0j} + \phi_j(E_1E_1^{\star}, E_2E_2^{\star})$$