Effect of Decentred Parameter on Self-Focusing in the Interaction of Cosh-Gaussian Laser Beams with Collisionless Magnetized Plasma

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Abstract. In this paper, we have exploited self-focusing of cosh-Gaussian laser beams in collisionless magnetized plasma. The nonlinearity in dielectric constant considered herein is mainly due to the ponderomotive force. Differential equations for beam width parameters in two transverse dimensions of the beam have been established by using WKB and paraxial approximations under parabolic equation approach. These equations are solved numerically by using fourth order Runge-Kutta method. The effect of decentred parameters in both transverse dimensions of the beam on self-focusing has been presented graphically and discussed.

INTRODUCTION

The interaction of high power laser beams with plasmas has known to produce various nonliner effects [1] such as sum and difference frequency generation, parametric amplification, stimulated Raman scattering, self-phase modulation, self-focusing etc. Study of these nonlinear effects has been a subject of experimental and theoretical research related to laser-plasma interaction due to their wide applications in laser-based plasma accelerators [2, 3], fast ignition for inertial confinement fusion [4, 5] etc. The propagation of laser beams over several Rayleigh lengths without loss of energy is essential requisite in such applications while keeping an efficient interaction with plasmas. The development of high intense laser beams now days makes feasibility of investigating such interesting nonlinear optical effects in plasmas. In plasmas, the self-focusing of laser beams [6] perennially fraught and spans the gamut to many self-action effects. In general, three types of nonlinearities [7], viz., relativistic, ponderomotive, and collisional have been identified in laser-plasma interaction. The role of these nonlinearities in the self-focusing of the beams has received considerable attention in the last 50 years. In case of collisionless plasma, the ponderomotive force on the electrons is proportional to the gradient of the irradiance. As such at moderate fields of laser beam, there is a modification of electron density and subsequent alteration in dielectric function of the plasma causing self-focusing /defocusing of the beam [7]. Combined effect [8, 9, 10, 11] of relativistic and ponderomotive nonlinearities is also important in self-focusing of laser beams in plasmas.

The theoretical analysis based on paraxial approach for self-focusing of laser beams in nonlinear medium [6] has been extended by Sodha, et al. [7] for plasmas. In most of the investigations on self-focusing of laser beams in plasmas, cylindrically symmetric Gaussian beam [12, 13] have been taken into consideration. Such fundamental beam plays a vital role on account of its specific characteristics. This beam produces the less beam divergence and the high brightness with a simple Gaussian intensity distribution along its wavefront. As such the laser beam with such profile possesses the great spectral purity and high degree of coherence. These salient features are advantageous in simplifying the mathematical complexities involved in the theoretical treatment of various nonlinear optical effects, which are experimentally observed with a Gaussian laser beam.

For the purpose of general scientific work, lasers are required to be utilized in different capacities. This is achieved by designing the laser systems in large variety of configurations [14]. For this requirement, the laser systems are sup-

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plied with cavity mirrors having different output-coupling apertures. Beam selection techniques are available to isolate the desired beam to suit a particular application. Consequently, different type of laser beams are also important in the field of laser-plasma interaction. The beam shaping technology has has made different beams available practically. It is well known that the nonlinear effects arrived by laser beams in plasmas are highly sensitive to the distribution of intensity along the wavefronts of the beam and laser-plasma coupling parameters.

Recently, a new class of laser beams known as cosh-Gaussian beams [15] has received significant interest as these beams possess high power and low divergence in comparison to the Gaussian beam [16, 17, 18]. Such beams thus can be utilized to achieve efficient interaction with the plasmas. The investigations [19, 20, 21, 22, 23] on interaction of such laser beams with plasmas have received considerable interest in self-focusing of laser beams in different situations. Till date, to the best of authors knowledge such studies are limited to their intensity profile by considering decentred paramater varied along radial direction of the beam.

The aim of this paper is to study the self-focusing of cosh-Gaussian laser beams in collisionless magnetized plasma by taking into account two decentred parameters in transverse dimensions of the cosh-Gaussian beams. We have done theoretical study concerned with beam-width parameter changes which are related to the transverse dimensions of the beam during the propagation through plasma. Present study employs WKB and paraxial approximations under usual parabolic equation approach [6, 7]

SELF-FOCUSING

In the slowly varying envelope approximation, the evolution of the electric field (for right circularly polarized also called extraordinary mode) in a collisionless magnetized plasma can be written as,

$$\frac{\partial^2 E_+}{\partial z^2} - 2ik_+\frac{\partial E_+}{\partial z} + \delta_+\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)E_+ + \frac{\omega^2}{c^2}\,(\epsilon_+ - \epsilon_{0+})E_+ = 0 \tag{1}$$

where, $\delta_+ = [1 + (\epsilon_{0+}/\epsilon_{0zz})]/2$ with $\epsilon_0 zz = 1 - \Omega_p^2$. The effective dielectric function ϵ_+ of the plasma can be expressed as

$$\varepsilon_+ = \varepsilon_{0+} + \phi(E_+E_+^*), \tag{2}$$

where, ε_{0+} and $\phi(E_+E_+^*)$ is the linear and nonlinear part of ε_+, respectively with

$$\varepsilon_{0+} = 1 - \frac{\Omega_p^2}{1-\Omega_c}, \tag{3}$$

$$\phi_+ = \frac{\Omega_p^2}{2(1-\Omega_c^2)}[1 - exp(-(\gamma_+\alpha E_0^2))], \tag{4}$$

where $\gamma_+ = [1-(\Omega_c/2)]/(1-\Omega_c)$, $\alpha = 3m\alpha_0/4M$, $\alpha_0 = e^2/6m\omega^2 K_B T_0$, $\Omega_p = \omega_p/\omega$, $\Omega_c = \omega_c/\omega$, $\omega_p = (4\pi N_0 e^2/m)^{1/2}$ is the plasma frequency, $\omega_c = e/B_0/mc$ is the electron cyclotron frequency, e and m are the electronic charge and its rest mass respectively. N_0 be the unperturbed density of plasma electrons, m is the mass of ion, ω is the angular frequency of laser used, K_B is the Boltzmann constant, B_0 is static magnetic field and T_0 is a equilibrium plasma temperature.

Within the framework of WKB and paraxial approximations, for $z > 0$, energy conserving ansatz for the intensity distribution of cosh-Gaussian beams propagating along z axis is given by

$$A_{0+}^2 = \frac{E_{0+}^2}{f_{1+}f_{2+}}exp\left[-2\left(\frac{x^2}{r_{0+}^2 f_{1+}^2} + \frac{y^2}{r_{0+}^2 f_{2+}^2}\right)\right]cosh^2\left(\frac{b_1 x}{r_0 f_{1+}}\right)cosh^2\left(\frac{b_2 y}{r_0 f_{2+}}\right) \tag{5}$$

where E_{0+} is the initial amplitude of the Gaussian laser beam with initial beam-width r_{0+}, b_1 and b_2 are the decentred parameters of cosh-Gaussian beams with f_1 and f_2 as the corresponding beam-width parameters in x and y dimensions respectively.

Following the paraxial approach given by Akhmanov et al. [6] and its extension by Sodha et al. [7], we have obtained the dimensionless beam-width parameters f_{1+} and f_{2+} as

$$\frac{d^2 f_{1+}}{d\zeta^2} = \frac{A_1}{2}\frac{\delta_+^2}{f_{1+}^3} + \frac{B_1\delta_+}{(1-\Omega_c)}\frac{\rho_{0+}^2\gamma_+ P_{0+}}{f_{1+}^3 f_{2+}^2}exp\left(-\frac{\gamma_+ P_{0+}}{f_{1+}f_{2+}}\right) \tag{6}$$

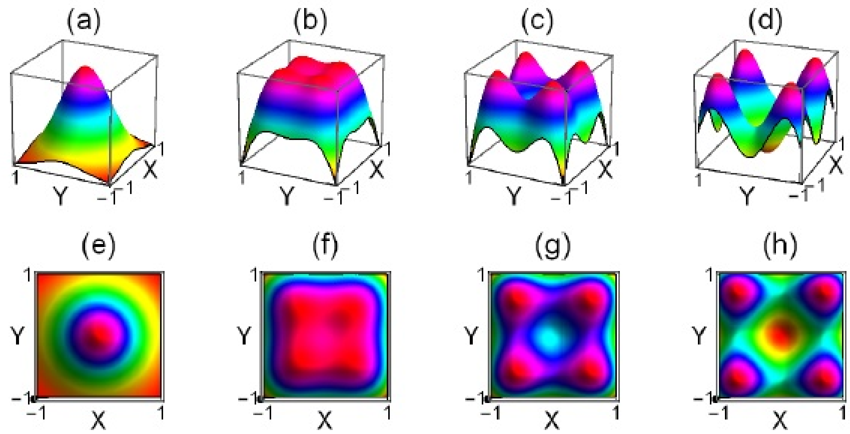

FIGURE 1. 3D intensity profile of cosh-Gaussian laser beam for (a) $b_{1,2} = 0.0$, (b) $b_{1,2} = 1.5$, (c) $b_{1,2} = 1.6$ and (d) $b_{1,2} = 1.7$. The above orthographic views of the profile for (e) $b_{1,2} = 0.0$, (f) $b_{1,2} = 1.5$, (g) $b_{1,2} = 1.6$ and (h) $b_{1,2} = 1.7$.

$$\frac{d^2 f_{2+}}{d\zeta^2} = \frac{A_2}{2}\frac{\delta_+^2}{f_{2+}^3} + \frac{B_2\delta_+}{(1-\Omega_c)}\frac{\rho_{0+}^2\gamma_+ P_{0+}}{f_{2+}^3 f_{1+}^2} exp\left(-\frac{\gamma_+ P_{0+}}{f_{2+} f_{1+}}\right) \tag{7}$$

where, $A_{1,2} = 4(1 - b_{1,2}^2)$, $B_{1,2} = b_{1,2}^2 - 2$, $P_{0+} = \alpha E_{0+}^2$, $\rho_{0+} = r_{0+}\omega/c$ is the equilibrium beam radius, $\zeta_+ = z/k_+ r_{0+}^2$ is the dimensionless distance of propagation.

For an initially plane wavefront $df_{1+,2+}/d\zeta_+ = 0$ and $f_{1+,2+} = 1$ and $\zeta_+ = 0$, the condition $d^2 f_{1+,2+}/d\zeta_+^2 = 0$, leads to the propagation of cosh-Gaussian laser beams without convergence or divergence.

DISCUSSION OF RESULTS

Equations (6) and (7) are the second-order, nonlinear, coupled, differential equations which govern self-focusing and defocusing of cosh-Gaussian laser beam in collisionaless magnetized plasma for extraordinary mode. The first term on right hand sides of the these equations represents diffraction effect which is responsible for divergence of laser beams while the second term is due to the ponderomotive nonlinearity in dielectric function which is responsible for convergence of the laser beams. Subsequently, self-focusing/de-focusing of the beam depends on relative magnitude of both the terms.

Figure 1 represents the initial intensity profiles of cosh-Gaussian laser beams for different decentred parameter values. Figs.1(a), (b), (c) and (d) portray the initial beam profile for $b_{1,2} = 0, 1.5, 1.6, 1.7$ respectively and figs.1(e), (f), (g) and (h) depict corresponding above orthographic views. These figures show that with increase in the value of b for $0 < b_{1,2} < 1$ the top of the beam profile becomes flatter and for $b_{1,2} > 1$, energy is concentrated in the wide lobes of the beam. Such intensity distribution in widely spaced lobes makes cosh-Gaussian beams interesting in the field of laser-plasma interaction. Figure 2 describes the variation of beam-width parameters f_{1+} and f_{2+} as a function of dimensionless distance of propagation ζ_+ for decentred parameters $b_{1,2} = 0, 1.5, 1.6, 1.7$. The requisite laser-plasma parameters are; $N_0 = 10^{19} cm^{-3}$, $\omega = 1.778 \times 10^{14} rad/s$, $B_0 = 0.10MG$, $\rho_{01+,02+} = 12$ and $P_0+ = 0.5$. From this figure it is clear that beam-width parameters f_{1+} and f_{2+} merge together due to identical values of decentred parameters in both the dimensions of the beam. Solid curve for which $b_1 = b_2 = 0.0$, the exact synchronized periodic oscillations of f_{1+} and f_{2+} is clear. Such type of synchronized periodic attenuation has been reported by Takale et al. [24] for Gaussian beam. Further, with increase in decentred parameter $b_1 = b_2 = 1.5, 1.6$ and 1.7 in both dimensions, defocusing nature of beam-width parameters f_{1+} and f_{2+} is observed. This is due to the fact that with increase in decentred parameters $b_{1,2} > 1$, energy is concentrated off the axis of the beam.

In conclusion, an impact of decentred parameters on self-focusing and defocusing of symmetric cosh-Gaussian laser beams is studied by taking into account ponderomotive nonlinearity in collisinless magnetized plasma. The following important conclusions are drawn from the present study:

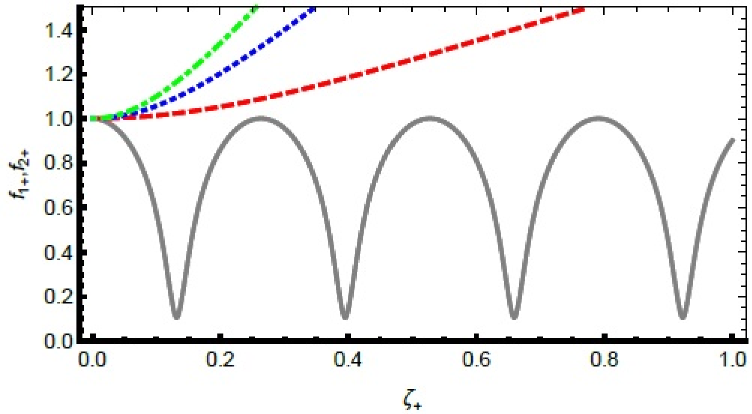

FIGURE 2. Variation of beam-width parameters f_{1+} and f_{2+} with dimensionless distance of propagation ζ_+ in collisionless magnetized plasma; $b_{1,2} = 0.0$ (solid curve), $b_{1,2} = 1.5$ (dashed curve), $b_{1,2} = 1.6$ (dotted curve) and $b_{1,2} = 1.7$ (dot-dashed curve). The laser-plasma parameters are; $N_0 = 10^{19} cm^{-3}$, $\omega = 1.778 \times 10^{14} rad/s$, $B_0 = 0.10MG$, $\rho_{01+,02+} = 12$ and $P_0+ = 0.5$.

- With increase the decentred parameter $b > 1$, the beam profile becomes flatter and central dip appears in the intensity profile. As a result, beam defocuses in both transverse dimensions of the beam.
- With identical decentring of beam profile, corresponding beam-width parameters variation in both transverse dimensions overlap with each other.

Our results may be helpful for many applications related to laser-plasma interaction requiring the propagation of laser beams with decentred intensity distribution is requisite.

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