



Excitation of large amplitude electron plasma wave by beating of two laser beams in nanoparticles

S P Mishra^a

^aDepartment of Physics, K. N. Govt. P. G. College, Gyanpur, Bhadohi-221304, India

Abstract

The counterpropagation interaction between two distinct laser beams and a medium of spherical nanoparticles is utilized to stimulate the electron plasma wave. The high-power radiation from the laser beams ionizes the atoms within the nanoparticles, subsequently transforming them into plasma plume balls. The gradient present in the field of each laser beam is responsible for generating a nonlinear ponderomotive force acting on the conduction electrons associated with the nanoparticle cloud. This nonlinear force possesses significant potential to couple and drive a substantial amplitude of the electron plasma wave. Due to the presence of surface plasmon resonance, when the beat wave of the two electromagnetic beams approaches $1/\sqrt{3}$ times the electron plasmon frequency, resonant coupling of the electron plasma wave occurs. The power amplitude of the excited electron plasma wave is heavily influenced by the laser parameters (such as Hermite polynomial mode index, source field, beam decentered parameter, and initial beam width of each laser beam) as well as the interaction medium parameters (including electron-ion collisional frequency, inter-particle separation, and radii of the nanoparticles). By optimizing and controlling these parameters, the desired power amplitude of the electron plasma wave can be attained. This significant amplitude excitation of the electron plasma wave process may be applicable for achieving enhanced laser harmonic generation, anomalous electron heating, self-focusing, and laser absorption processes.

Keywords: Electron plasma wave, Nanoparticles, Beam decentered parameter, Ponderomotive force, Collisional frequency, Laser beams, Surface plasmons resonance

1. Introduction

The process of multiwave mixing in nonlinear media plays a vital role for studying the interesting phenomenon such as electrostatic wave excitation, anomalous electron heating [1], charged particle acceleration, parametric instability, terahertz radiation generation [2], and harmonic generation process [3]. The interacting media (plasma, clustered gas, and nanoparticles) having different conducting and optical properties changed the nonlinear phenomenon [4-5]. Owing to



have enormous surface to volume ratio, the nanoparticles exhibit unique environment as compared with bulk particles. The nonlinear interaction of intense laser beam (electromagnetic radiation) with plasmonic nanoparticles promises the resonant interaction due the presence of effective surface plasmon resonance [6]. Various nonlinear phenomenon were investigated by taking the different shape of laser beams. By using the paraxial optical ABCD system, a theoretical investigation on the propagation properties of Hermite cosh-Gaussian laser beams has been well demonstrated [7]. In this, the spatial lobes of laser beam intensity profile has acquired multi and intensified peaks by varying the mode index associated with Hermite polynomial function and beam decentered parameter correlated with hyperbolic cosine term.

Electron plasma wave is a special kind of electrostatic waves and its wave vector aligned along the magnetic field. It means that this electrostatic wave propagate along the external magnetic field and which is also famously known as Langmuir wave [8]. Several important applications of electron plasma wave has been experimentally and theoretically investigated by various research group such as electron acceleration, electron heating , self-focusing, harmonic generation [9-10], and determination of electron density and electron temperature [20]. Rosenbluth and Liu [11] firstly theoretically presented a scheme of large amplitude electron plasma wave excitation by beating of two laser beams in plasma. They depicts that the relativistic effect and plasma inhomogeneity cause to strong excitation. As the detuned beat wave frequency of two counterpropagating laser beams become twice times the electron plasma frequency, the growth rate of fast and slow plasma wave has been found resonant [12].

In this present work, immense amplitude of electron plasma wave excitation is theoretically investigated by the counterpropagating interaction of Hermite cosh-Gaussian and cosh-Gaussian laser beams with spherical nanoparticles. The collision effect is taken into the account. The schematic diagram of electron plasma wave excitation process in this considered medium is shown in Fig. 1. The two laser beams having slight difference frequency causes to generation beat wave and with influence of laser field with medium oscillate the electrons. Thus, in the inhomogeneity, a nonlinear ponderomotive force will be act on the conducting electrons of spherical nanoparticles and has efficient potential to drive the pre-existed space charge wave and couple the electron plasma wave. The analogy of coupling and excitation of this wave can be seen in the fraction of power amplitude profile of electron plasma wave with respect to total

incident power of two different profile laser beams. This research paper is organised as follows: the introduction is given in Sec. 1. The nonlinear coupling of two laser beams is governed in Sec. 2. The basic equation for power going into the electron plasma wave (excitation process) is presented in Sec. 3. Sec. 4 provides the results and discussion of this excitation method. Finally, the summary and conclusion of this theory is elaborated in Sec. 5.

2. Nonlinear Coupling

Herein, we have considered a system of spherical nanoparticles suspended in noble gas (say argon). The noble gas will not easily ionize via the interaction of high power laser radiation. The radii of each spherical nanoparticles can be represented as r_{sn} and the inter particle separation between each nanoparticles is represented as b . The total macroscopic density of spherical nanoparticles is taken as

$$n_e = f_s n_{e0}, \quad (1)$$

where the term $f_s = \frac{4\pi}{3} \left(\frac{r_{sn}}{b}\right)^3$ represents the volume occupied by spherical nanoparticles per unit cell volume and it is also termed as volume fraction and the term n_{e0} represents the equilibrium electron density of nanoparticles. As the two counterpropagating laser beams (Hermite cosh-Gaussian and cosh-Gaussian) with frequencies ω_1 and ω_2 and wave numbers k_1 and k_2 interact with this nano dimension medium, the atoms of nanoparticle get ionize and directly transferred into the plasma plume balls.

The general algebraic form of electric field distribution of Hermite cosh-Gaussian laser beam can be written as

$$\vec{E}_H(y, z) = \hat{y} E_{0H} H_m \left(\sqrt{2} \frac{y}{w_{0H}} \right) \cosh \left(\frac{yd}{w_{0H}} \right) \exp \left(-\frac{y^2}{w_{0H}^2} \right) e^{-i(\omega_1 t - k_1 z)}. \quad (2)$$

where E_{0H} is the initial electric field amplitude of Hermite cosh-Gaussian laser beam at the central position ($x=y=z=0$), the term m is the mode index of Hermite polynomials, w_{0H} is the initial laser beam width parameter associated with Gaussian distribution of laser beam, d is the laser beam decentered parameter correlated with hyperbolic cosine term.

The general algebraic form of electric field distribution of cosh-Gaussian laser beam is written as

$$\vec{E}_c(y, z) = \hat{y}E_{0c} \cosh\left(\frac{yd}{w_{0c}}\right) \exp\left(-\frac{y^2}{w_{0c}^2}\right) e^{-i(\omega_2 t - k_2 x)}, \quad (3)$$

In terms of nonlinear ponderomotive potential, the expression of nonlinear ponderomotive force ($\vec{F}_p^{NL} = e\nabla\phi_p^{NL}$) acting on the conducting electrons can be written as

$$\begin{aligned} \vec{F}_p^{NL} &= \frac{-e^2(E_{0H}E_{0c}^*)(\omega_1\omega_2)\cosh^2\left(\frac{yd}{w_{0c}}\right) \cdot \exp\left[-2\left(\frac{y^2}{w_{0c}^2}\right)\right]}{2m\left(\omega_1^2 + iv_{ei}\omega_1 - \frac{\omega_{pe}^2}{3}\right)\left(\omega_2^2 - iv_{ei}\omega_2 - \frac{\omega_{pe}^2}{3}\right)} \left[(ik)\hat{z}H_m\left(\frac{\sqrt{2}y}{w_{0H}}\right) \cosh\left(\frac{yd}{w_{0H}}\right) \cosh\left(\frac{yd}{w_{0c}}\right) \right. \\ &+ \hat{y} \left\{ \cosh\left(\frac{yd}{w_{0H}}\right) \cosh\left(\frac{yd}{w_{0c}}\right) \left\{ H_m\left(\frac{\sqrt{2}y}{w_{0H}}\right) \times -2y\left(\frac{1}{w_{0H}^2} + \frac{1}{w_{0c}^2}\right) + \left(\frac{\sqrt{2}y}{w_{0H}}\right) 2mH_{m-1}\left(\frac{\sqrt{2}y}{w_{0H}}\right) \right\} \right. \\ &+ H_m\left(\frac{\sqrt{2}y}{w_{0H}}\right) \left\{ \left(\frac{d}{w_{0c}}\right) \cosh\left(\frac{yd}{w_{0H}}\right) \sinh\left(\frac{yd}{w_{0c}}\right) \right. \\ &\left. \left. + \left(\frac{d}{w_{0H}}\right) \cosh\left(\frac{yd}{w_{0c}}\right) \sinh\left(\frac{yd}{w_{0H}}\right) \right\} \right] \times \exp\left\{-y^2\left(\frac{1}{w_{0H}^2} + \frac{1}{w_{0c}^2}\right)\right\} e^{-i(\omega t - kz)}. \quad (4) \end{aligned}$$

3. Electron plasma wave excitation

Further, we have considered that this nonlinear ponderomotive force has sufficient potential to drive and couple the pre-existed electron plasma wave in collisional nano plasma medium. The beating of two laser beams couple the electron plasma wave with harmonic potential profile as

$$\phi = \phi_0 e^{-i(\omega t - \vec{k} \cdot \vec{r})}. \quad (5)$$

4. Results and Discussion

Numerical results of electron plasma wave excitation by nonlinear interaction of two different profile laser beams in spherical nanoparticles have been theoretically investigated. The angular frequencies of two different profile laser beams are considered as $\omega_1 \sim 2.3 \times 10^{14} \text{ Hz}$, $\omega_2 \sim 1.8 \times 10^{14} \text{ Hz}$ respectively. Having electrostatic nature of electron plasma waves, these waves are excited along the laser electric field. Herein, we have taken beat wave of two different profile laser beams for excitation process instead of single laser beam radiation. As the beating



of two counterpropagating laser beams interacts with spherical nanoparticles, the atoms associated with nanoparticles are ionized and quickly converted into plasma plume balls. The nonlinear ponderomotive force has efficient potential to couple and excite the electron plasma wave. Along the polarizing direction of each different profile laser beams, a considerable amplitude of electron plasma wave can be excited.

In Fig. 2, we have plotted the variation of normalized power amplitude of electron plasma wave as a function of normalized transverse distance of laser beam from y-axis for different values of Hermite polynomial mode index m . For laser beam decentered parameter $d=1$, and mode index $m=0$, the two laser beam profile acquired purely hyperbolic cosine-Gaussian profile. The power amplitude profile has two resonant peaks at laser beam transverse propagation distance around $y/w_0 \sim 0.48$ and $y/w_0 \sim 1.70$ respectively. It is to be noted that the power amplitude at second one peak is much greater (approximately 241 %) than first one peak. Now, for laser beam decentered parameter $d=1$, and mode index $m=1$, the first laser beam has acquired purely Hermite cosh-Gaussian laser beam and second one laser beam has acquired purely cosh-Gaussian laser beam. In this, the combined effect of two laser beams excited large amplitude electron plasma wave as compared with mode index $m=0$. We can see that the presence of Hermite polynomial mode index m in laser beam, the coupling and excitation is very strong. The resonant peaks are appeared at laser beam transverse propagation distance around $y/w_0 \sim 0.40$ and $y/w_0 \sim 1.80$ respectively. The power amplitude of electron plasma wave at first one peak is much greater as compared with second one peak. In the presence of Hermite polynomial mode index m , the field envelop of laser beam profile is much enhanced and this enhanced field of laser beam causes to impartation of large oscillations to conducting electrons associated with spherical nanoparticles. This depicts that gradient in the field amplitude of laser beams produces strong nonlinear ponderomotive force to the conducting electrons and couples the large amplitude electron plasma wave.

The variation of normalized power amplitude of electron plasma wave as a function of normalized transverse distance of laser beam from y-axis for different values of beam decentered parameter d has been shown in Figs. 3 (a)-3 (b). For Hermite polynomial mode index $m=2$ and



beam decentered parameter $d=0$ (the first one laser beam acquired purely Hermite-Gaussian profile and second one laser beam acquired purely Gaussian profile), the power amplitude profile of electron plasma wave has acquired two resonant peak at laser beam transverse propagation distance around $y/w_0 \sim 0.48$ and $y/w_0 \sim 1.18$ respectively. In the off-resonant position of laser beam transverse propagation distance, there is very sharp decrease in power amplitude profile of electron plasma wave. The laser beam decentered parameter d is also known as waist width parameter. This parameter is dimensionless parameter associated with hyperbolic cosine term present in both type of laser beam. It is point to be noticed that as the beam decentered parameter is increased ($0 \leq d \leq 1$) (shown in Fig. 3 (a)), the power amplitude profile of electron plasma wave is enhanced. Further, with increased in laser beam decentered parameter ranges ($1 \leq d \leq 2$) (shown in Fig. 3 (b)), the rate of enhancement of power amplitude profile of electron plasma wave is found much more as compared with Fig. 3 (a). The Physics behind this effect of beam decentered parameter on electron plasma wave excitation can be understood by properties of field envelop of laser beams. The increased values of beam decentered parameter causes to enlarge the vortex of field envelop of laser beam. This leads to much more transfer for energy and momentum to the conducting electrons of spherical nanoparticles and produced strong nonlinear ponderomotive force to couple the large amplitude electron plasma wave. Furthermore, one can also notice that as the beam decentered parameter is varied, the two resonant peaks profile is shifted slight outward from origin of laser beam transverse propagation distance. By tuning and optimizing the values of beam decentered parameter, one can enhanced the resonant position of power amplitude of electron plasma wave.

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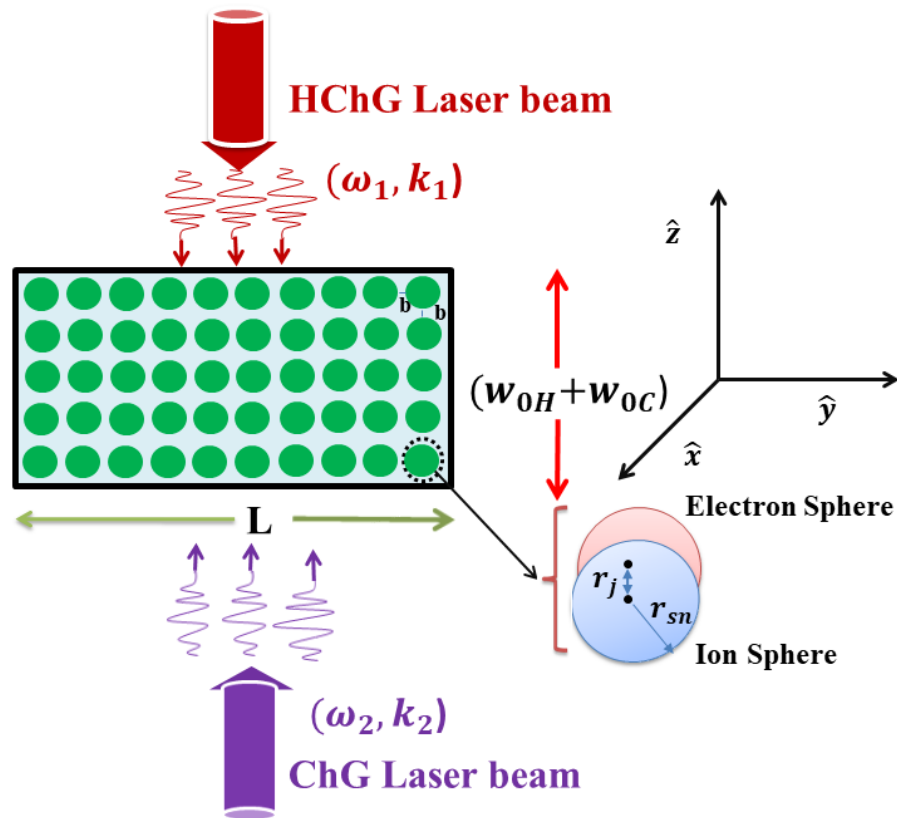


Fig. 1

Fig. 1: Schematic diagram of excitation of electron plasma wave by counterpropagating Hermite cosh-Gaussian (HChG) and cosh-Gaussian (ChG) laser beams in spherical nanoparticles

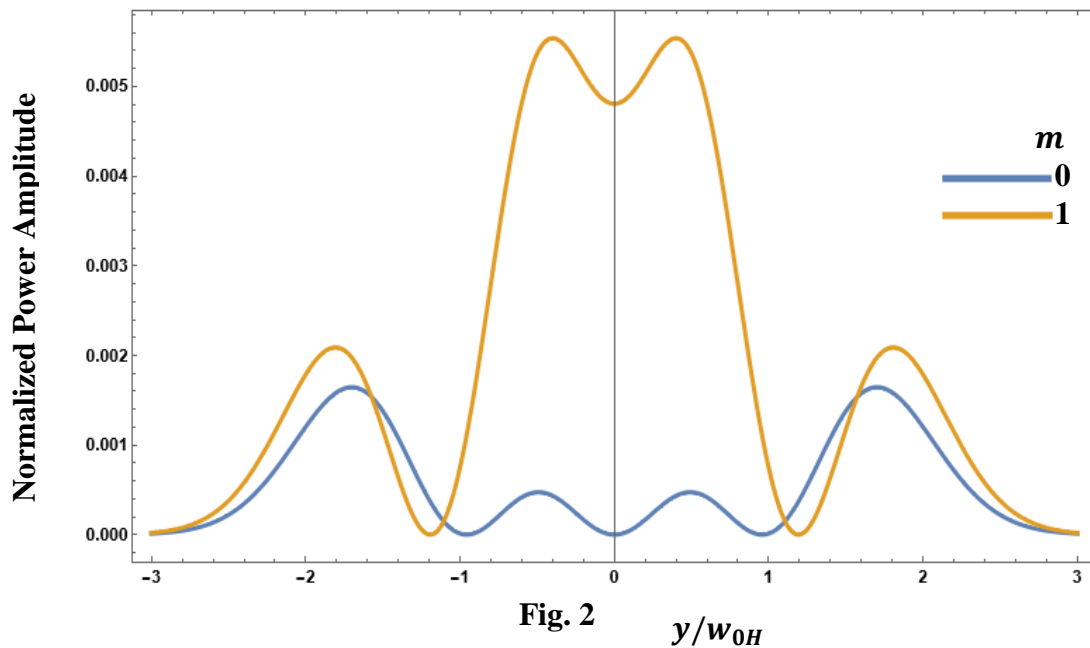


Fig. 2: Variation of normalized power amplitude of electron plasma wave with normalized beam transverse propagation distance from y-axis for different values of Hermite cosh-Gaussian laser beam mode index m when $d=1$, $v_{ei}/\omega_{pe} = 0.01$, $\omega/\omega_{pe} = 0.5$, $r_{ns} = 20 \text{ nm}$, $b = 100 \text{ nm}$ and $w_{0H} = w_{0C} = 10 \mu\text{m}$

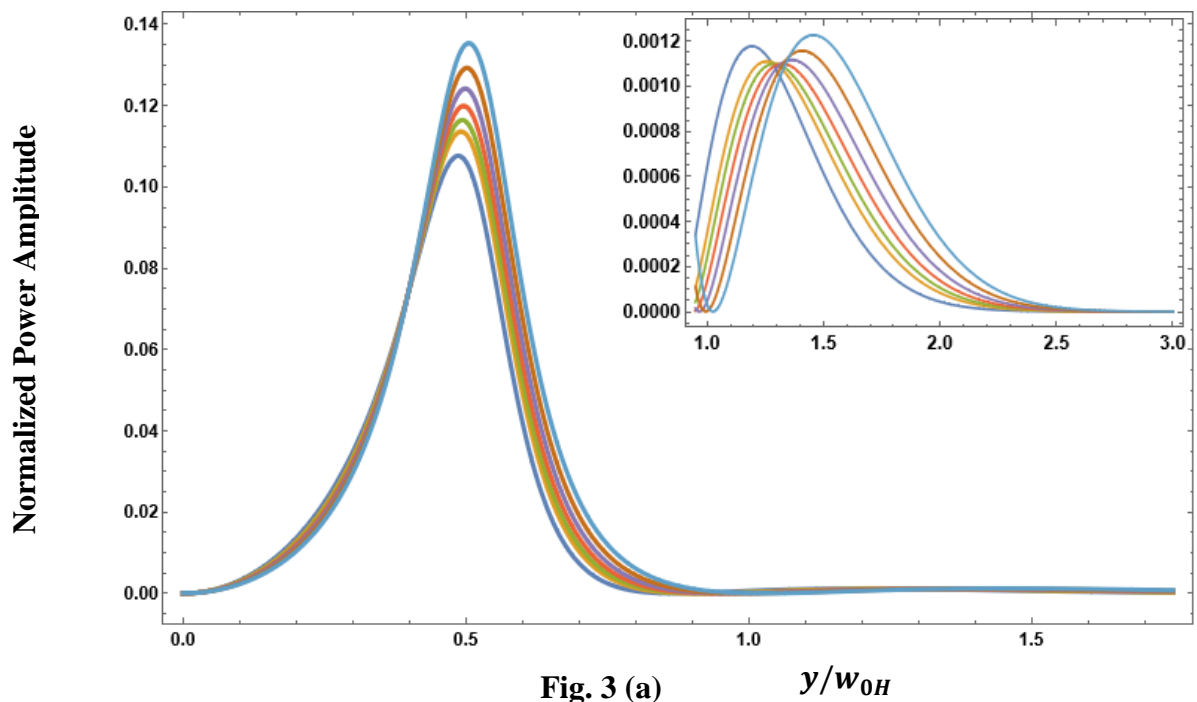


Fig. 3 (a): Variation of normalized power amplitude of electron plasma wave with normalized beam transverse propagation distance from y-axis for different values of laser beam decentered parameter $0 \leq d \leq 1$ when $m=2$, $v_{ei}/\omega_{pe} = 0.01$, $\omega/\omega_{pe} = 0.5$, $r_{ns} = 20 \text{ nm}$, $b = 100 \text{ nm}$ and $w_{0H} = w_{0C} = 10 \mu\text{m}$

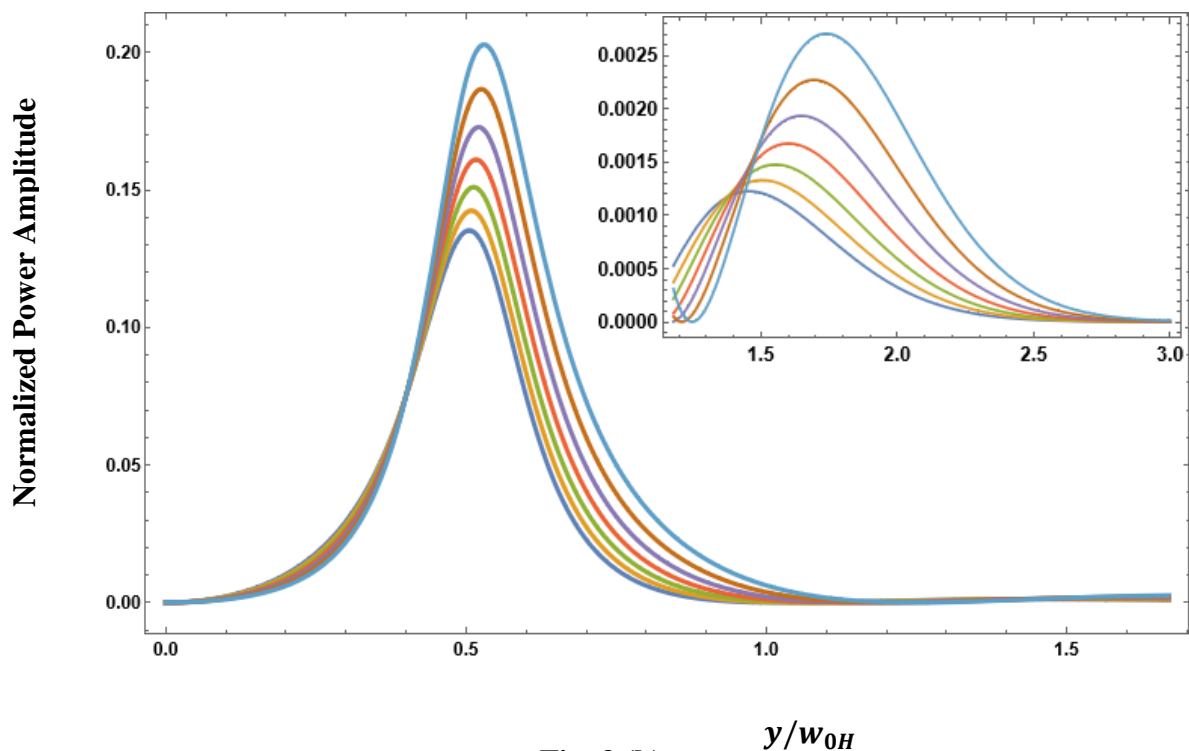


Fig. 3 (b)

Fig. 3 (b): Variation of normalized power amplitude of electron plasma wave with normalized beam transverse propagation distance from y-axis for different values of laser beam decentered parameter $1 \leq d \leq 1.6$ when $m=2$, $v_{ei}/\omega_{pe} = 0.01$, $\omega/\omega_{pe} = 0.5$, $r_{ns} = 20 \text{ nm}$, $b = 100 \text{ nm}$ and $w_{0H} = w_{0C} = 10 \mu\text{m}$