Effect of Relativistic Mass Variation of Electron on Nonlinear Absorptionin Magnetised Semiconductor Plasmas

Subhash Chouhan[a)], Swati Dubey, and S Ghosh

School of Studies in Physics, Vikram University, Ujjain(M.P.) India 456010
[a)]Corresponding author: Subh.chouhan2008@gmail.com

Abstract. Hydrodynamic model and coupled mode theory has been used to study effect of relativistic mass variation of electron on parametric interactions in magnetised semiconductor plasma. Expressions for nonlinear second order susceptibility and nonlinear absorption coefficient of the medium have been derived. Effects of various parameters on absorption coefficient have been plotted for relativistic case. Numerical estimations were made for InSb crystal duly irradiated by 1.06 μm Nd:YAGlaser at 77K. Proposed mathematical model successfully examines nonlinear absorption characteristics of the medium. Reported results may be utilized for the construction of optical switches and other optical manipulations devices.

Keywords: Semiconductor plasma, Parametric interaction, Nonlinear absorption coefficient

INTRODUCTION

When an electromagnetic wave propagating through a plasma system is strong enough to drive the electrons to relativistic speed modifies optical nonlinearities arises due to three wave mixing process in plasma. For such plasma, it becomes important to consider the relativistic effects [1,2]. The consequences of such nonlinear effects can induce the considerable change in the refractive index across intensity profile of laser beam and causes the self-focusing of laser beam in plasmas [3,4] .

Theoretical and experimental investigations of relativistic effects have increased continuously during recent decades [5-7]. Various relativistic phenomena and their empirical manifestations developed a diverse field of research linking together widespread activities ranging from high-energy heavy-ion collision physics, atomic or molecular physics and chemistry of heavy elements to solid state physics.

The phenomena of parametric interaction (PI) manifests a peculiar role in nonlinear optics (NLO). Parametric processes have been extensively used as frequency shifter to get tunable laser like radiation in a nonlinear crystal at a frequency unavailable from a laser source [8,9].Although some earlier works [10,11] investigated about the gain profile of parametrically generated signal/idler wave in non-relativistic regime, butamplification characteristics of acoustic wave in relativistic regime are yet to be explored.

Therefore we study nonlinear absorption characteristics of the medium during relativistic laser-plasma interaction. Consequent effect of mass variation on parametric gain profile is the main focus of present investigation.Numerical investigation of problem underneath study and the consequences of results have been discussed.In this work a mathematical model is developed for three wave interactions in an infinite plasma medium using well known hydrodynamic model. We first introduce the basic sets of equations which are used to derive the second order susceptibility . Modern development of intense laser beams made possible relativistic oscillations of plasma electrons. For that purpose, a laser light of 1μm wavelength with an irradiance just above $10^{18} W/cm^2$may enable electrons to driftat relativistic velocities resulting in relativistic mass changes exceeding the electron rest mass with momentum nearly equals to $m_e c$. These specifications allow us to use Nd:Yag laser-plasma system for the theoretical and numerical formalisms in our model.

THEORETICAL FORMULATION

In this section, authors consider the well known hydrodynamic model of homogenous n-type semiconductor plasma of infinite extension with electrons as carriers subjected to the electromagnetic pump wave$\overrightarrow{E_0}\,(exp\,(k_0x - i\omega_0 t)$ and external magnetic field$B_0(\hat{z})$ across the propagation vector $k_0(\hat{x})$ under thermal equilibrium.

Basic equations used for analysis are as follows:

$$\frac{\partial \overrightarrow{V_0}}{\partial t} + (\overrightarrow{V_0}.\nabla)\overrightarrow{V_0} + \nu.\overrightarrow{V_0} = \frac{-e}{\Gamma_0 m}(\overrightarrow{E_0} + \overrightarrow{V_0} \times \overrightarrow{B_0}) \quad (1)$$

$$\frac{\partial \overrightarrow{V_1}}{\partial t} + (\overrightarrow{V_0}.\nabla)\overrightarrow{V_1} + \nu.\overrightarrow{V_1} = \frac{-e}{\Gamma_0 m}\left(\overrightarrow{E_1} + \overrightarrow{V_1} \times \overrightarrow{B_0}\right) - \frac{\vartheta_{th}^2 \nabla n_1}{n_0} \quad (2)$$

$$\frac{\partial^2 u}{\partial t^2} + \beta\frac{\partial \overrightarrow{E_s}}{\partial x} + 2i\gamma_s\frac{\partial u}{\partial t} = \mathrm{C}\frac{\partial^2 u}{\partial x^2} \quad (3)$$

$$\frac{\partial \overrightarrow{E_s}}{\partial x} = \frac{-en_1}{\varepsilon} - \frac{\beta}{\varepsilon}\frac{\partial^2 u}{\partial x^2} \quad (4)$$

$$\frac{\partial n_1}{\partial t} + n_0\left(\frac{\partial \overrightarrow{V_1}}{\partial x}\right) + \overrightarrow{V_0}\left(\frac{\partial n_1}{\partial x}\right) + n_1\left(\frac{\partial \overrightarrow{V_0}}{\partial x}\right) = 0 \quad (5)$$

here $\Gamma_0 = \left(1 - {\vartheta^2}/{c^2}\right)^{-1/2}$ is the relativistic factor.

Equations (1) and (2) are the zeroth- and first- order momentum transfer equations. Relativistic factor Γ_0 has been included in the equations with the momentum term. A crude pressure term $\frac{\vartheta_{th}^2\nabla n_1}{n_0}$ with thermal velocitiesϑ_{th} of electrons, has been added to relativistic equation (2). Equation (3) represents the equation of motion of the lattice in the piezoelectric crystal. Equation (4) is the Poisson's equation which describes piezoelectric contribution to polarization. Equation (5) represents the equation of continuity. Meaning and notations used in remaining basic equations are explained in [12].

Following standard approach [13], with the aid of equations (1) to (5), time evolution of perturbed carrier density may be obtained as

$$\frac{\partial^2 n_1}{\partial t^2} + \nu\frac{\partial n_1}{\partial t} + \omega_R^2 n_1 + \overline{\omega_p}^2\frac{k_a^2\beta u}{e} = -i(k_0 + k_1)n_1\bar{E} \quad (6)$$

Here$\bar{E} = \frac{-e}{\Gamma_0 m}\overrightarrow{E_0} + \omega_c\overrightarrow{V_{0x}}$, the plasma frequency,the relativistically modified plasma frequency andcyclotron frequencies are$\omega_R^2 = \left[\overline{\omega_p}^2 + k_a^2\vartheta_{th}^2\nu/(\nu + \omega_c\right]$,$\omega_c = \left(\frac{-eB_0}{\Gamma_0 m}\right)$ and$\omega_p = \left(\frac{n_0 e^2}{\Gamma_0 m\varepsilon}\right)^{\frac{1}{2}}$,magnetic field modified plasma frequency is $\overline{\omega_p}^2 = \omega_p^2\left(\frac{\nu^2}{\nu^2+\omega_c^2}\right)$.

By defining induced current density and nonlinear induced polarization and following the well defined procedure,one may deduce the following expression for second order nonlinear susceptibility as

$$\chi^{(2)} = \frac{Ae\varepsilon_L k_a\omega_0\overline{\omega_p}^2}{2\Gamma_0 m\omega_s\omega_a\gamma_s(\omega_0^2-\omega_c^2)}\left[\Delta_1^2 + i\nu\omega_a - \frac{(k_0+k_1)^2\bar{E}^2}{\Delta_2^2 - i\nu\omega_s}\right]^{-1} = \chi_r^{(2)} + \chi_i^{(2)} \quad (7)$$

Here $\Delta_1^2 = \omega_R^2 - \omega_a^2$,$\Delta_2^2 = \omega_R^2 - \omega_s^2$,$K^2 = \frac{\beta^2}{\varepsilon C}$,$A = k_a^2K^2\vartheta_s^2$, $\vartheta_s = \left(\frac{C}{\rho}\right)^{1/2}$is the acoustic velocity of the crystal medium, $\chi_r^{(2)} and \chi_i^{(2)}$are real and imaginary parts of second order susceptibility. Above equation displays the dependence of nonlinear susceptibility on various parameters namely charge carrier concentration, applied external magnetic field, pump intensity etc.

The nonlinear absorption coefficient α_R may be obtained through the following relation

$$\alpha_R = \frac{-k_a}{2\varepsilon_L}\left[\chi_i^{(2)}\right]E_0 \quad (9)$$

The nonlinear gain of the signal is possible only if α_R obtainable from above equation is negative. It is found that the negativity of $\alpha_R$is possible only above a particular pump field called threshold field. Therefore It is necessary to determine the threshold value of the pump amplitude required for the onset of the parametric process. Thus by setting equation (7) equals to zero, we may obtain

$$E_{th} = \frac{\Gamma_0 m(\omega_c^2 - \omega_0^2)}{ek_a\omega_0^2}\left[(\Delta_1^2 + i\nu\omega_a)(\Delta_2^2 - i\nu\omega_s)\right] \quad (10)$$

RESULTS AND DISCUSSION

The theoretical formulation presented in the preceding section has been numerically analysed in this section. The following set of parameters has been used to perform numerical appreciation of the results obtained and the n-InSb is assumed to be irradiated by 1.06 μm CO_2 laser.$m = 0.145m_0$ (m_0 being the rest mass of free electrons), $\gamma_s = 5 \times 10^{-10} mksunit$,$\rho = 5.8 \times 10^3 kgm^{-3}$,$\varepsilon_L = 15.8$,$\nu = 3.5 \times 10^{11} s^{-1}$,$\beta = 0.054\ Cm^{-2}$,$\omega_0 = 1.78 \times 10^{13} s^{-1}$,$\omega_a = 2 \times 10^{11} s^{-1}$, and $\vartheta_s = 4 \times 10^3 ms^{-1}$.

By utilizing the above parameters, we have studied the effect of relativistic mass variation on the nonlinear absorption coefficient. Equation (9) is used to study nonlinear absorption coefficient by varying input parameters: n_0 (carrier concentration), B_0 (externalmagnetostatic field), k_a (acoustic wave vector).

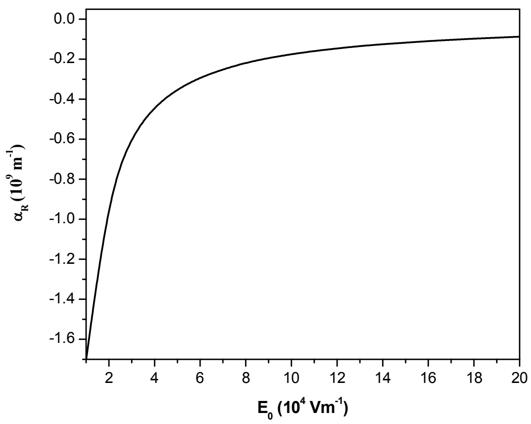


Figure 1. Variation of absorption coefficient with pump amplitude E_0at $10^{24} m^{-3}$&$E_0 = 1 \times 10^4\ Vm^{-1}$

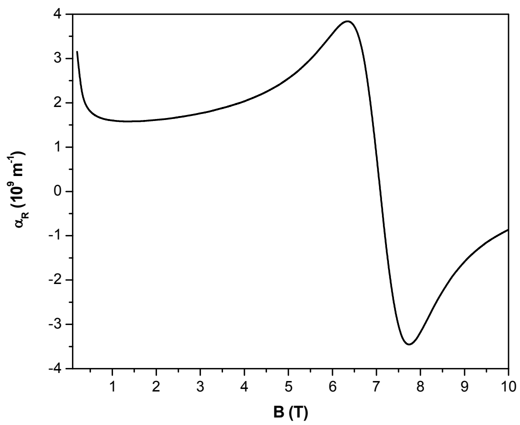
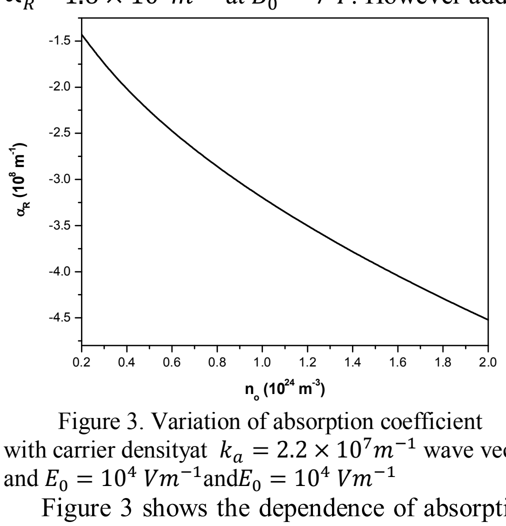


Figure 2. Variation of absorption coefficient with magnetic field B$_0$at$k_a = 2 \times 10^7 m^{-1} k_a = 2 \times 10^7 m^{-1}$&$n_0 = 2 \times$

Absorption coefficient $\propto_R$ is plotted as a function of pump amplitude E_0 and magnetic field B_0in figures 1 &2 respectively. In figure 1, maximum gain ($\propto_R = 1.7 \times 10^9 m^{-1}$) is attained at smaller pump fields which sharply decreases and saturates beyond $E_0 > 10^4 Vm^{-1}$. It should be noted that favourable pump field amplitude is quite small for large gain.

From figure 2 it can be seen that external magnetic field significantly affects nonlinear absorption characteristics of the medium. Initially at lower magnetic field absorptioncharacteristicsare prominent till $B_0 = 6.9\,T$. Beyond which amplification gets initiated leading to increase in gain with increments in magnetic field upto maximum gain $\propto_R = 1.6 \times 10^9 m^{-1}$ at $B_0 = 7\,T$. However additional increments in magnetic field again reduces gain appreciably.



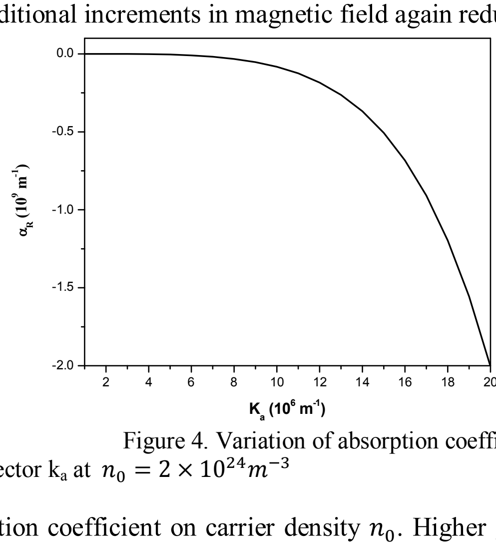


Figure 3. Variation of absorption coefficient with carrier densityat $k_a = 2.2 \times 10^7 m^{-1}$ and $E_0 = 10^4\ Vm^{-1}$

Figure 4. Variation of absorption coefficientwith wave vector k$_a$ at $n_0 = 2 \times 10^{24} m^{-3}$ and$E_0 = 10^4\ Vm^{-1}$

Figure 3 shows the dependence of absorption coefficient on carrier density n_0. Higher gain coefficients can be attained through incrementsin carrier concentration of the medium.Hence n-type doping in the crystal is found to be beneficial. However, the doping should not exceeds the limit for which the plasma frequency (ω_p) exceeds the input pump frequency (ω_0), because in this regime where $\omega_p^2 < \omega_0^2$, the electromagnetic pump wave will be totally reflected back by the intervening medium.

The nature of variation of nonlinear absorption coefficient with acoustic wave number ka is plotted in figure 4. one may notice that with increments in the magnitude of k_a , absorption coefficient is found to increase and reaches a maximum $\propto_R = 4 \times 10^9 m^{-1}$ at $k_a = 2 \times 10^7 m^{-1}$. Hence we can conclude that maximum acoustic wave number is found favourable.

It may be concluded that heavily doped semiconductors are the appropriate hosts for the study of relativistic effects and relativistic optical properties of semiconductor plasma medium. This fact could drastically reduce the operating cost of parametric amplifiers and other related nonlinear devices based on this interaction. Sudden transition from absorption to gain profile with respect to varying external magnetic field could be utilized in optical switching devices and other optical manipulation mechanisms.

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