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Amplitude Modulation and Demodulation in Magnetized Quantum Plasma with SDDC

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Abstract: *Amplitude modulation as well as demodulation of an electromagnetic wave in transversely magnetized quantum plasma with strain dependent dielectric constant is analyzed in different wave number regions over a wide range of carrier cyclotron frequency. The consideration of quantum effects in modulation and demodulation is of prime importance for the adding of new dimensions in acousto-electric magnetized semiconductor plasma. It is found that quantum effects modify the amplitude modulation and demodulation processes effectively. Numerical estimates are made for n-$BaTiO_3$ crystal at 77K duly shined by a pulsed 10.6 µm CO_2 laser .Complete absorption of the wave takes place in all the possible wavelength regimes when the cyclotron frequency ω_c becomes nearly equal to ω_0.*

Keywords: *Acoustoelectric effect, Strain dependent dielectric constant, Quantum effects*.

I. Introduction

Motivated by the extensive researches in the field of semiconductor quantum plasma from the different researchers, [1-3] in present paper analytical investigations are made for the amplitude modulation and demodulation of an electromagnetic wave in material with strain dependent dielectric constant (SDDC) using quantum hydrodynamic model (QHD). Amplitude modulation (AM) is modulation technique used in communication process in which the amplitude of high frequency carrier wave is changed in accordance with the message or information signal. AM generation involves mixing of a carrier and an information signal. The modulation of an electromagnetic wave propagating through plasma is nothing but the periodic variations of the propagation parameters. When an unmodulated electromagnetic wave propagates through plasma medium with periodically varying parameters, it gets modulated or demodulated in terms of amplitude or frequency. This periodic variation in the propagation parameter has been caused by time-varying charge carrier density and collision frequency of plasma. Modulation or demodulation of pump wave is the process of changing amplitude or frequency or phase. In contrast to frequency modulation and phase modulation, AM technique was the earliest form of modulation used to transmit audio signals. This type of modulation when utilized to best advantage, its efficiency can either equal or exceed that of all other modulation processes. In many complex modulation schemes, the phenomenon of modulation of an electromagnetic wave by an acoustic wave is very useful in large number of applications involving the transmission, display and processing of information. An AM type system transmits the carrier and both side bands with equal efficiency. This is often used for maximum simplicity and economy, particularly at low outputs [4].

The fabrication of some acoustoelectrical devices is based on the interaction of acoustic vibrations and the mobile carriers. This interaction gives useful information regarding the physical properties of the host medium. In the study of possible interactions in media where wave functions of the neighboring particles overlapped, quantum corrections that may be estimated by QHD model of plasmas, plays an important role. These wave function overlapping becomes possible only when the deBroglie wave length of the charged particles becomes comparable to the dimensions of the plasma system. There is noticeable interest for quantum plasmas due to their wide-ranging applications in ultra small electronic devices [5-7].

The intense pump beam electrostrictively generates an acoustic wave within the SDDC medium that induces an interaction between free charge carriers and the acoustic phonons. This interaction induces strong space charge field that modulates the pump beam. Thus, the applied optical and generated acoustic wave in an electrostrictive modulator can produce amplitude modulation and demodulation effect at acoustic wave frequency. Several reports on modulation in semiconductor plasmas has been reported by a number of workers [8-11]. Nimje and his coworkers [12] reported the amplitude modulation and demodulation of an electromagnetic wave in presence of hot carriers in magnetized diffusive semiconductor plasmas using hydrodynamic model. Yadav and Ghosh [13] have observed the amplitude modulation and demodulation in strain dependent diffusive semiconductors. The diffusion of carriers shows the strong influence on the nonlinearity of high mobility III-V compounds semiconductor. The semiconductor technology is generally based on the high mobility of excited charge carriers through diffusion processes. The modulation of a laser beam produced due to certain plasma effect in semiconductor was reported by Sen and Kaw [14]. Recently, extensive studies with quantum correction on parametric interactions and longitudinal phonon Plasmon interactions have been reported [15-16]. The concept of amplitude modulation and demodulation in semiconductor plasma has reported by many researchers but the study of such process in quantum plasma systems seems to be theoretically unexplored. Hence, inspired by the above status in the present paper, authors studied quantum effects on amplitude modulation and demodulation of electromagnetic wave in SDDC material. For the study of quantum effect in such process, author used QHD model which is an embracing model developed for quantum plasma through the pioneering works of Manfredi and Hass [17].

II. Theoretical Formulation

Authors have used the QHD model to get the objective established in introduction section. Authors have considered a homogeneous n-type crystal (n-$BaTiO_3$) for the theoretical formulation of amplitude modulated laser beam. The medium is immersed in a static magnetic field (B_0) pointing along z-axis that is normal to the propagation vector of parametrically generated acoustic wave (k_a) along x-axis ;. Here, we have assumed $\exp\{i(kx-\omega t)\}$ dependency of the field quantities. The low-frequency perturbations are assumed to be due to the acoustic wave (ω_a, k_a) produced by acoustic polarization in the crystal. The electron concentration oscillates at the acoustic wave frequency due to the SDDC field associated with the acoustic wave. The pump wave then gives rise to a transverse current density at the frequencies ω_0 and $(\omega_0 \pm \omega_a)$ where ω_0 is the pump wave frequency. The transverse current densities produced at frequency $(\omega_0 \pm \omega_a)$ are known as first order side band current densities. These side band current densities produce side band electric field vectors and this way the pump wave gets modulated. In the subsequent analysis the side bands will be represented by the suffixes ±, where + stands for the mode propagating with the frequency $(\omega_0 + \omega_a)$ and – stands for $(\omega_0 - \omega_a)$ mode.

The equation of motion for $u(x,t)$ is considered in order to find the perturbed current density in SDDC crystal which describes the lattice vibration and is given by,

$$\rho \frac{\partial^2 u}{\partial t^2} = C \frac{\partial^2 u}{\partial x^2} - (\varepsilon g E_0) \frac{\partial E_1^*}{\partial x} \tag{1}$$

where ρ and C are the mass density and the elastic constant respectively, ε is the dielectric constant when the strain is zero and g is coupling constant is given by $g = \varepsilon/3$. The * over a quantity represents its complex conjugate.

The space charge field E_1 is determined by the Poisson equation as

$$\frac{\partial E_1}{\partial x} = \frac{e n_1}{\varepsilon} + \frac{(\varepsilon g E_0)}{\varepsilon} \frac{\partial^2 u^*}{\partial x^2} \tag{2}$$

where last term on RHS represents the SDDC contribution. To compute the perturbation current density in n-type SDDC crystal using equations (1) and (2), one obtains the perturbed carrier concentration as

$$n_1 = -\frac{\rho \varepsilon u\left[-k_a^2 V_a^2 \left(1 + A^2\right) + \omega_a^2\right]}{(\varepsilon g E_0) e} \tag{3}$$

In which V_a is the acoustic speed in the crystal lattice given by $V_a = \left(C/\rho\right)^{1/2}$ and $A = \left[\varepsilon^2 g^2 |E_0|^2 / \varepsilon C\right]^{1/2}$ is the dimensionless coupling coefficient due to SDDC.

The oscillatory electron fluid velocity in presence of the pump electric field E_0 as well as that due to the side band modes $E_\pm$ can be obtained by using the electron momentum transfer equation of the QHD model which is given below

$$\frac{\partial V_j}{\partial t} + \nu V_j + \left(V_0 \frac{\partial}{\partial x}\right) V_j = \frac{e}{m}\left[E_j + \left(V_j \times B_0\right)\right] - \frac{1}{m n_0}\frac{\partial P_f}{\partial x} + \frac{\hbar^2}{4 m^2 n_0}\frac{\partial^2 n_j}{\partial x^2} \tag{4}$$

where, $P_f = m V_f^2 n^3 / 3 n_0^2$ is the Fermi pressure in which Fermi velocity $V_f = \left[2 k_B T_f / m\right]^{1/2}$ with Boltzmann constant k_B and Fermi temperature T_f.

Here, the subscript j stands for 0, + and – modes. The above equation describes the electron motion under the influence of the electric fields associated with the pump and side band modes in which m is the effective mass of the electron and ν is the phenomenological electron collision frequency. n_j stands for perturbed and unperturbed electron density. In the above relation, the pump magnetic field is neglected by assuming that the electron plasma frequency of the medium is of the order of pump frequency. By linearizing equation (4), the velocity components are obtained as,

$$V_{jx} = \frac{\left(eE_j/m\right)(\nu - i\omega_j)}{\left[(\nu - i\omega_j)^2 + \omega_c^2\right]} \cdot \left[1 + \frac{V_f'^2 k^2}{\omega_p^2}\right] \tag{5}$$

$$V_{jy} = -\frac{\left(eE_j/m\right)\omega_c}{\left[(\nu - i\omega_j)^2 + \omega_c^2\right]} \cdot \left[1 + \frac{V_f'^2 k^2}{\omega_p^2}\right] \tag{6}$$

with $V_f'^2 = V_f(1+\Gamma_e)$ and $\Gamma_e = \dfrac{\hbar^2 k^2}{8mk_B T_f}$ represents the inclusion of quantum effect in the interaction process.

In equations (5) and (6) $\omega_c = {eB_0}/{m}$ is the cyclotron frequency and $\omega_p = \left(n_0 e^2/m\varepsilon\right)^{1/2}$ is the plasma frequency.

The total transverse current density in the medium is given by,

$$J_{total} = e\left[\sum_j n_0 V_j + \sum_j n V_0 \exp\{i(k_a x - \omega_j t)\}\right] \tag{7}$$

where, $nV_0 \exp\{i(k_a x - \omega_j t)\}$ represents the current generated due to the interaction of the pump with acoustic wave. Using equations (5), (6) and (7) in the general wave equation,

$$\frac{\partial^2 E_{total}}{\partial x^2} - \mu\varepsilon \frac{\partial^2 E_{total}}{\partial t^2} - \mu \frac{\partial J_{total}}{\partial t} = 0 \tag{8}$$

where μ is the permeability of the medium and neglecting $\exp(\mp i k_a x)$ in comparison to 1, we obtained the following expressions for modulation indices,

$$\frac{E_\pm}{E_0} = -\frac{i\omega_0 \mu e u C k_a A^2 (\nu - i\omega_0)}{m\beta(k_a \pm 2k)\left[(\omega_c^2 + \nu^2 - \omega_0^2) - i(2\omega_0\nu)\right]}\left[1 + \frac{V_f'^2 k^2}{\omega_p^2}\right] \tag{9}$$

in which $\beta = gE_0$. By rationalization of above equation, one obtains the real part of modulational indices as,

$$\frac{E_\pm}{E_0} = -\frac{\omega_0 \mu e u C k_a A^2 (\omega_c^2 + \nu^2 - \omega_0^2)}{m\beta(k_a \pm 2k)\left[(\omega_c^2 + \nu^2 - \omega_0^2) - 4\omega_0^2\nu^2\right]}\left[1 + \frac{V_f'^2 k^2}{\omega_p^2}\right] \tag{10}$$

It can be inferred from the above equation that quantum effects appear in the parameter V_f' and SDDC contribution contained in A and β play a significant role in deciding the magnitudes of the modulation indices in semiconductor plasma.

III. Result And Discussion

In this section we analyze the above expression (10) to discuss the amplitude modulation/demodulation due to acousto-electric interaction with and without quantum effect in the presence of SDDC in materials with high dielectric constant. To get some numerical appreciation, we use the following parameters of n-$BaTiO_3$ semiconductor crystal assumed to be duly irradiated by 10.6 µm pulsed CO_2 laser at 77K:. $m = 0.0145 m_0$, $\nu = 5\times10^{11} s^{-1}$, $\varepsilon_L = 2000$

$V_a = 2.5\times10^3 ms^{-1}$, $\omega_0 = 1.6\times10^{13}\sec^{-1}$ $\omega_s = 2\times10^{12}\sec^{-1}$, $\rho = 4\times10^3 kgm^{-3}$ $T = 77k$.

Expression (10) for the modulation index in the SDDC material with and without quantum effect can be analyzed for two different wave number regimes viz., (i) $k_a > 2k$ and (ii) $k_a < 2k$

(i) When $k_a > 2k$:

The variation of E_+/E_0 and E_-/E_0 with the applied magnetic field ω_c are depicted in figures 1and 2.It may be inferred from figures that when one applies weak magnetic field, the cyclotron frequency ω_c becomes smaller than the carrier frequency ω_0, then both the modes are in phase with pump wave, which exhibits modulation process. At a particular value of magnetic field when $\omega_c \approx \omega_0$ the modulation indices of both the modes become zero and complete absorption of waves takes place on neglecting the collision term in equation (10). On further increasing the cyclotron frequency $(\omega_c > \omega_0)$ both side band go out of phase. These out of phase side bands then interact with the pump wave under this condition to produce demodulated acoustic wave. We conclude that demodulation process can be observed in the regime $k_a > 2k$ with $(\omega_c > \omega_0)$ in presence and absence of quantum term. It can also be seen that the modulation index of the minus mode is always greater than that of the plus mode.

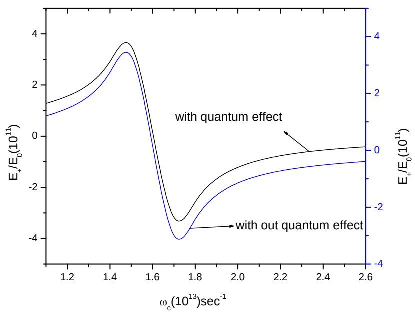

Figure 1. Variation of modulation index of plus mode (when $k_a > 2k$) with magnetic field with and without quantum effects.

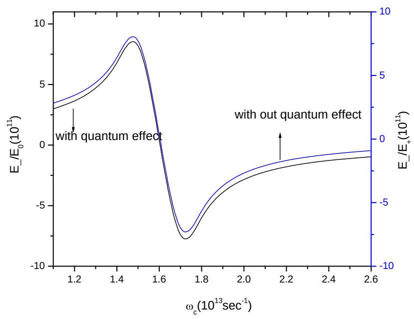

Figure 2. Variation of modulation index of minus mode (when $k_a > 2k$) with magnetic field with and without quantum effects.

(ii) When $k_a < 2k$:

The variation of E_+/E_0 and E_-/E_0 with the applied magnetic field ω_c are depicted in figures 3 and 4. In this wave number regime the behavior of modulation indices for plus and minus modes are (as shown in figures 3 and 4) opposite in nature. In the same wave number regime the amplitude of the plus mode is positive under the condition $(\omega_c < \omega_0)$. Hence under this regime of cyclotron frequency, the amplitude of plus mode is in phase with the pump wave. This side band then interacts with the wave to produce modulated acoustic wave. However, when the carrier frequency becomes nearly equal to the cyclotron frequency, complete absorption of waves takes place on neglecting the collision term in equation (10). In the range defined as $(\omega_c > \omega_0)$, the modulation indices of plus mode is negative. This out of phase side band waves then again interact with the pump to produce a demodulated wave which exhibits demodulation process. From figure 4 we can see that in this wave number regime the amplitude of the minus mode is negative under the condition $(\omega_c < \omega_0)$ and out of phase with pump wave. This side band then interacts with the wave to produce demodulated acoustic wave.

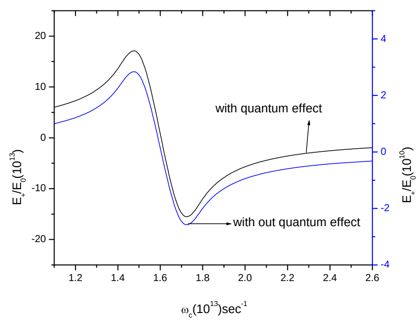

Figure 3. Variation of modulation index of plus mode (when $k_a < 2k$) with magnetic field with and without quantum effects.

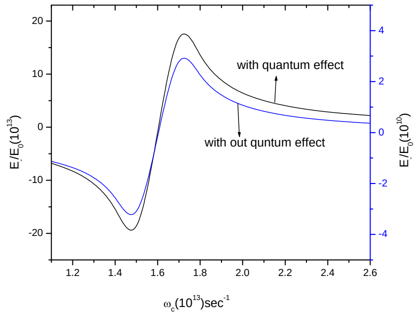

Figure 4. Variation of modulation index of minus mode (when $k_a < 2k$) with magnetic field with and without quantum effects.

When the carrier frequency becomes nearly equal to the cyclotron frequency, complete absorption of waves takes place on neglecting the collision term in equation (10). A slight tuning in the range defined as $(\omega_c > \omega_0)$ at this resonance condition decreases the indices abruptly to zero and exhibits modulation process. Thus, for a particular magnetic field if one gets modulation of plus side band mode then minus side band mode becomes demodulated and vice-versa. It is a very fascinating result.

IV. Conclusions

From the above discussion the modulation and demodulation of the EM wave by the acoustic wave can be easily achieved by using material with high dielectric constant. It is found that quantum effect plays a significant role in deciding the parameter range and selecting the side band mode, which will be modulated by the above mentioned interaction. The quantum correction term alters the result favorably. It always increases the value of modulation/demodulation indices for both the modes around $\omega_c \approx \omega_0$.Thus in presence of quantum term the material with strain dependent dielectric constant offers an interesting medium for the purpose of investigations of different modulational interactions and one hopes to open a potential experimental tool for energy transmission and solid state diagnostics in crystals with high dielectric constant.

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