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Acousto-optic amplitude modulation and demodulation of electromagnetic wave in magnetised diffusive semiconductors

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Abstract. Using hydrodynamical model of semiconductor plasma analytical investigations are made for the amplitude modulation as well as demodulation of an electromagnetic wave in a transversely magnetised acousto-optic semiconducting plasma. The inclusion of carriers diffusion adds new dimension in the analysis presented here. Analysis are made under different wave number regions over a wide range of cyclotron frequency. It has been seen that diffusion of charge carriers modifies amplitude modulation and demodulation processes effectively. Numerical estimations are made for n-InSb crystal irradiated by pump wave of frequency 1.6 $\mathrm{T\,s^{-1}}$. Complete absorption of the waves takes place in all the possible wave lengths regimes when the cyclotron frequency ω_c becomes exactly equal to $(v^2+\omega_c^2)^{1/2}$.

PACS. 52.35.Mw Nonlinear phenomena: waves, wave propagation, and other interactions (including parametric effects, mode coupling, ponderomotive effects, etc.) – 78.20.Hp Piezo-, elasto-, and acoustooptical effects; photoacoustic effects – 72.30.+q High-frequency effects; plasma effects – 42.70.Nq Other nonlinear optical materials; photorefractive and semiconductor materials

1 Introduction

The problem of propagation of optical radiation in crystal in the presence of an electric or acoustic strain field has been an active area of research in the field of modulation of light by sound waves. It is a well-known fact that when an unmodulated electromagnetic wave propagates through a plasma with periodically varying parameters it gets modulated in amplitude. This periodic variation in propagation parameters may be due to the propagation of an acoustic wave in plasmas [1]; the propagation of an acoustic wave in plasmas leads to the periodic variation in its electron density which further leads to modulation at the acoustic wave frequency. The electro-optic and acousto-optic (AO) effects afford a convenient and widely used means of controlling the intensity or phase of the propagating radiation [2–5].

This modulation is used in ever expanding number of applications including the impression of informations onto optical beams, switching of lasers for generation of giant optical pulses, mode locking and optical beam deflection [6,7]. The modulation of electromagnetic beams by surface acoustic wave is also a very active field of interest due to their applicability in communication devices [8]. Acousto-optic interaction in dielectrics and semiconductors is playing an increasing role in optical modulation and beam steering [9,10]. However, in integrated opto-electronic device applications, the AO modulation process becomes a serious limitation due to high acoustic power requirements.

The efficiency of amplitude modulation (AM) can either equal or exceed that of all other modulation processes such as frequency and/or phase modulations. AM is commonly encountered as a preliminary step in many complex modulation schemes. An amplitude modulation type system transmits the carrier and both side bands simultaneously. This often makes for maximum simplicity and economy particularly at low power out-puts. But one of the important problems in communication system is that of developing an effective method for modulation as well as demodulation of waves. It is already predicted by Max *et al.* [11] that finite amplitude electromagnetic wave in nonlinear dispersive medium can become modulationally unstable. The study of modulation can be made with respect to amplitude as well as frequency. The stimulus for the investigation of this type in gaseous plasma stems from the work of Volkov [12] who during the study of the stability of the plane electromagnetic wave propagating through an unmagnetised plasma anticipated self modulation of the electromagnetic waves in plasma. The problem of amplitude modulation in semiconductor plasma has been studied by a number of workers [13–16]. The modulation of microwave while propagating through a piezoelectrically active semiconducting media duly irradiated by an acoustic wave was first predicted by Mathur and Sagoo [13]. The modulation of a laser beam produced due to certain plasma effects in semiconductor was reported by Sen and Kaw [14]. Lashmore-Davies [17] has described

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a mechanism for the spontaneous break up of shear-Alfven wave above a certain threshold and has shown that the same mechanism could be effectively applied to study the modulational instability of other finite amplitude waves in plasmas. The earlier workers [12–14] have found a change in the modulation of an amplitude modulated electromagnetic wave. Two different mechanisms were also proposed by Sodha *et al.* [18] and Ginzberg [19] which were experimentally verified by Cutolo [20]. This particular change in modulation raises the possibility of demodulation of an amplitude modulated wave which in many applications is very much desired.

In the above discussed reports of various amplitude modulation mechanisms, the non-local effects such as diffusion of the excitation density that is responsible for the nonlinear refractive index change has been ignored. The study of reflection and transmission of a Gaussian beam incident upon an interface that separates a linear and nonlinear diffusive media has stimulated an effort to include diffusion in computation of nonlinear electromagnetic wave interaction in bulk and nonlinear-nonlinear interfaces [21,22]. It is found that increased diffusion makes light transmission more difficult and tend to wash out the local equilibria of the equivalent potential representing unstable or stable TE nonlinear surface wave [23]. The high mobility of optically excited charge carriers makes diffusion effects particularly relevant in semiconductor technology as they (charge carriers) travel significant distances before recombining. Recently the present authors [24], probably first time reported the diffusion induced acousto-optic frequency modulation interaction in magnetised semiconductors. They have shown that the presence of enhanced diffusion due to excess charge carriers the frequency modulated beam can be effectively amplified in an dispersion-less acoustic wave regime.

Motivated by above discussions in this article we have presented the acousto-optic amplitude modulation of an intense electromagnetic beam in a strain dependent diffusive semiconductor crystal. The effect of diffusion of the charge carriers on the nonlinear interaction of the laser beam adds new dimensions to the analysis presented in n-type semiconductor [25]. The intense pump beam electrostrictively generates an acoustic wave within the semiconductor medium that induces an interaction between the free carriers (through electron plasma wave) and the acoustic phonons (through material vibration). This interaction induces a strong space-charge field that modulates the pump beam. Thus the applied optical and generated acoustic waves in an acousto-optic modulator can produce amplitude modulation and demodulation effect at acoustic wave frequency. It is found that the presence of magnetic field is favourable for the phenomenon under study.

2 Theoretical formulation

This section deals with the theoretical formulation of modulation index of amplitude modulated laser beam in diffusive semiconductor. We have considered hydrodynamical model of a homogeneous semiconductor plasma of infinite extent (*i.e.* $k_\mathrm{a}l < 1$, where k_a is the wave number of acoustic mode and l the mean free path of electron). The medium considered is an n-type InSb plasma immersed in a static magnetic field ($\mathbf{B}_\mathrm{s}$) pointing along z-axis which is irradiated by an intense pump ($\mathbf{k}_0$) and parametrically generated acoustic wave ($\mathbf{k}_\mathrm{a}$; along x-axis). The low frequency perturbations are assumed to be due to the acoustic wave (ω_a, k_a) produced by acoustic polarisation in the crystal. Due to the acousto-optical potential fields accompanying the acoustic wave the electron concentration oscillates at the acoustic frequency. The pump wave then gives rise to a transverse current density at the frequency ω_0 and $(\omega_0 \pm \omega_\mathrm{a})$, where ω_0 is the frequency of the pump wave. 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 $\pm$, where $+$ stands for the mode propagating with frequency $(\omega_0+\omega_\mathrm{a})$ and $-$ stands for $(\omega_0-\omega_\mathrm{a})$ mode.

The equations of lattice dynamics in order to find the perturbed current density in crystal with acousto-optic coupling are

$$\frac{\partial^2 u}{\partial t^2} - \frac{c}{\rho}\frac{\partial^2 u}{\partial x^2} = \frac{\varepsilon(\eta^2-1)}{2\rho}\frac{\partial}{\partial x}(\mathbf{E}_0\cdot\mathbf{E}_1^*) \tag{1}$$

$$\frac{\partial E_1}{\partial x} = \frac{n_1 e}{\varepsilon} + \frac{(\eta^2-1)}{\varepsilon_\mathrm{L}}E_0\frac{\partial^2 u}{\partial x^2}\cdot \tag{2}$$

Equation (1) describes the lattice vibrations in an acousto-optic crystal of material density ρ; c and η are respectively elastic constant and refractive index of the medium. The space charge field E_1 is determined from Poisson's equation (2) in which last term on RHS represents the contribution of acousto-optic polarisation.

Using equations (1, 2) one can obtain the perturbed carrier concentration as

$$n = \left[2\rho u\{k_\mathrm{a}^2 v_\mathrm{a}^2(1+A^2) - \omega_\mathrm{a}^2\}\right]\left[e(\eta^2-1)E_0\right]^{-1} \tag{3}$$

in which v_a is the shear acoustic speed in the crystal lattice given by $v_\mathrm{a} = (c/\rho)^{1/2}$ and

$$A^2 = \frac{\left[\epsilon_0(\eta^2-1)E_0\right]^2}{2c\epsilon_0} = \frac{(\epsilon_0\beta)^2}{2c\epsilon_0}$$

is the dimensionless acousto-optic coupling coefficient due to acousto-optic interaction.

The oscillatory electron fluid velocity in presence of the pump electric field E_0 as well as that due to the fields of the sideband modes $E_\pm$ can be obtained by using the electron momentum transfer equation including diffusion effects as

$$\frac{\partial \mathbf{v}_j}{\partial t} + (\mathbf{v}_j\cdot\nabla)\mathbf{v}_j + \nu\mathbf{v}_j = \frac{e}{m}\left[\mathbf{E}_j + \mathbf{v}_j\times\mathbf{B}_s\right] - D\nu\frac{\nabla n_j}{n_j} \tag{4}$$

in which $D = (k_\mathrm{B}T/e)\mu$ (Diffusion coefficient).

The subscript j stands for 0, + and − modes and m is the effective mass of the electrons and ν is the phenomenological electron collision frequency. Using equation (4) the velocity components can be obtained as

$$\nu_{jx} = \frac{eE_j(\mathrm{i}\omega_j + \nu)}{m\left[\omega_\mathrm{c}^2 + (\mathrm{i}\omega_j + \nu)^2\right]}\left[1 + \frac{D\nu k^2}{\omega_\mathrm{p}^2}\right] \quad (5)$$

$$\nu_{jy} = \frac{-eE_j\omega_\mathrm{c}}{m\left[\omega_\mathrm{c}^2 + (\mathrm{i}\omega_j + \nu)^2\right]}\left[1 + \frac{D\nu k^2}{\omega_\mathrm{p}^2}\right] \quad (6)$$

in which $\omega_\mathrm{c} = eB_0/m$, is the electron cyclotron frequency and $\omega_\mathrm{p} = (n_0e^2/m\varepsilon)^{1/2}$ is the plasma frequency. Here we have assumed an $\exp\left[\mathrm{i}(\omega_j t - k_j x)\right]$ dependence on the field quantities. The total transverse current density in the medium is given by

$$\mathbf{j}_\mathrm{total} = e\left[\sum_j n_0\mathbf{v}_j + \sum_j n\mathbf{v}_0 \exp\left\{\mathrm{i}\left(\omega_j t - k_\mathrm{a}x\right)\right\}\right], \quad (7)$$

where $n\mathbf{v}_0 \exp\left\{\mathrm{i}(\omega_j t - k_\mathrm{a}x)\right\}$ represents the current generated due to interaction of the pump with acoustic wave. Using equations (7, 8), in the wave equation given by

$$\frac{\partial^2\mathbf{E}}{\partial x^2} - \mu\epsilon\frac{\partial^2\mathbf{E}}{\partial t^2} = \mu\frac{\partial\mathbf{j}_\mathrm{total}}{\partial t} \quad (8)$$

and neglecting $\exp(\pm\mathrm{i}k_\mathrm{a}x)$ in comparison to 1 we obtain the expressions for modulation indices as

$$\frac{E_\pm}{E_0} = \frac{2\mathrm{i}\omega_0\mu k_\mathrm{a}A^2ecu}{m\beta(k_\mathrm{a} \pm 2k)}\frac{(\mathrm{i}\omega_0 + \nu)}{\left[\omega_\mathrm{c}^2 + (\mathrm{i}\omega_0 + \nu)^2\right]}\left[1 + \nu Dk^2/\omega_\mathrm{p}^2\right]. \quad (9)$$

By equating the real parts of above equation, we find

$$\left(\frac{E_\pm}{E_0}\right)_\mathrm{real} = \frac{-2\omega_0^2\mu k_\mathrm{a}A^2ecu}{m\beta(k_\mathrm{a} \pm 2k)} \times \frac{(\omega_\mathrm{c}^2 - \omega_0^2 - \nu^2)}{\left[(\omega_\mathrm{c}^2 + \nu^2 - \omega_0^2)^2 + 4\nu^2\omega_0^2\right]}\left[1 + \nu Dk^2/\omega_\mathrm{p}^2\right]. \quad (10)$$

It can be inferred easily from this equation that diffusion modifies the index of modulation effectively.

3 Results and discussion

In this section we analyse equation (10) to discuss the amplitude modulation and demodulation due to acousto-optic interaction in the presence and absence of carrier diffusion. One can see that diffusion process modifies the results effectively. Equation (10) for the modulation index in semiconductor materials can be analysed for two different wave number regimes *viz.* (i) $k_\mathrm{a} > 2k$, and (ii) $k_\mathrm{a} < 2k$.

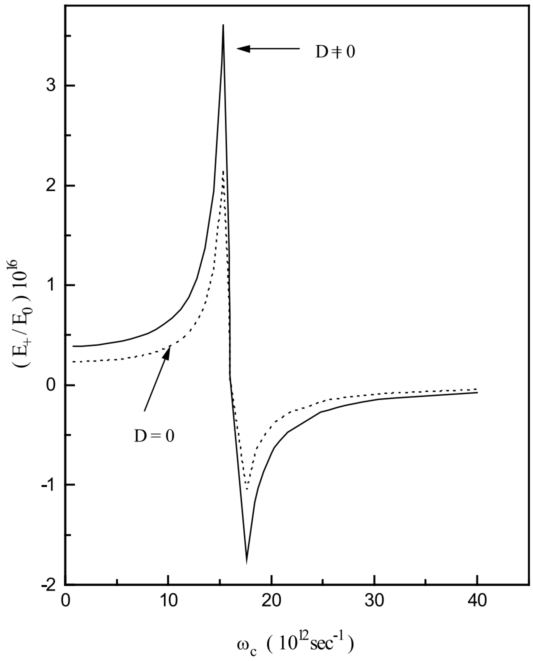

Fig. 1. Variation of modulation index of plus mode (when $k_\mathrm{a} > 2k$) with magnetic field (ω_c) for $\nu = 4 \times 10^{11}$ s^{-1}, $\omega_0 = 1.6 \times 10^{13}$ s^{-1}, $\rho = 5.8 \times 10^3$ kg m^{-3}, $\omega_\mathrm{a} = 10^{12}$ s^{-1}, $n_0 = 10^{24}$ m^{-3}, $v_\mathrm{a} = 4.8 \times 10^3$ m s^{-1} and $u = 10^4$ W m^{-2}; [for $D = 0$ (- - -); for $D \neq 0$ (—)].

3.1 When $k_\mathrm{a} > 2k$

The amplitude of the side band modes (E±) are in phase only under the condition $\omega_\mathrm{c} < (\omega_0^2 + \nu^2)^{\frac{1}{2}}$. However, when the carrier frequency becomes equal to the cyclotron frequency, complete absorption of waves takes place, provided one neglects the collision term in equation (10). In the range defined as $\omega_\mathrm{c} > (\omega_0^2 + \nu^2)^{\frac{1}{2}}$ the amplitudes of the modulated wave and the pump wave get out of phase. Under this condition, the side bands again interact with the pump wave to produce a demodulated acoustic wave. Thus in this region demodulation occurs.

As a typical case numerical estimations have been made for n-InSb at 77 K using the following physical constants: $m = 0.014m_0$, $\varepsilon_\mathrm{L} = 17.8$, $\nu = 4 \times 10^{11}$ s^{-1}, $\omega_0 = 1.6 \times 10^{13}$ s^{-1}, $\rho = 5.8 \times 10^3$ kg m^{-3}; m_0 being the free electron mass. The crystal is assumed to be irradiated with an acoustic intensity ≈10^4 W m^{-2} at frequency $\omega_\mathrm{a} = 10^{12}$ s^{-1}. The variations of (E_+/E_0) and (E_-/E_0) with the applied magnetostatic field (ω_c) are depicted in Figures 1 and 2 in absence ($D = 0$; - - -) and presence ($D \neq 0$; —) of the carrier diffusion. It may be inferred from Figures 1 and 2 that upto $\omega_\mathrm{c} = \omega_0$ both the modes ($E_\pm$) are in the phase with pump wave and for $\omega_\mathrm{c} > \omega_0$ one obtains the demodulation of both modes. It is also seen that the modulation index for the plus mode is always less than that of the minus mode. The modulation indices for both modes in this region always increases with increase in cyclotron frequency upto $\omega_\mathrm{c} = \omega_0$. A slight tuning ($\omega_\mathrm{c} > \omega_0$) at this resonance point, decreases both

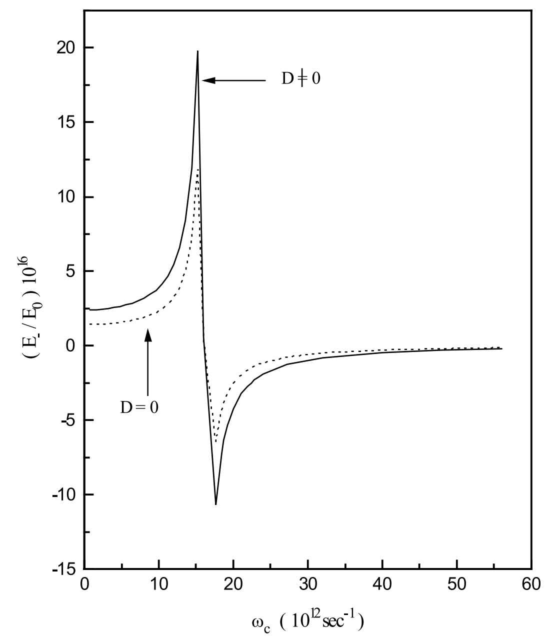

Fig. 2. Variation of modulation index of minus mode (when $k_a > 2k$) with magnetic field (ω_c) for the parameters as in Figure 1.

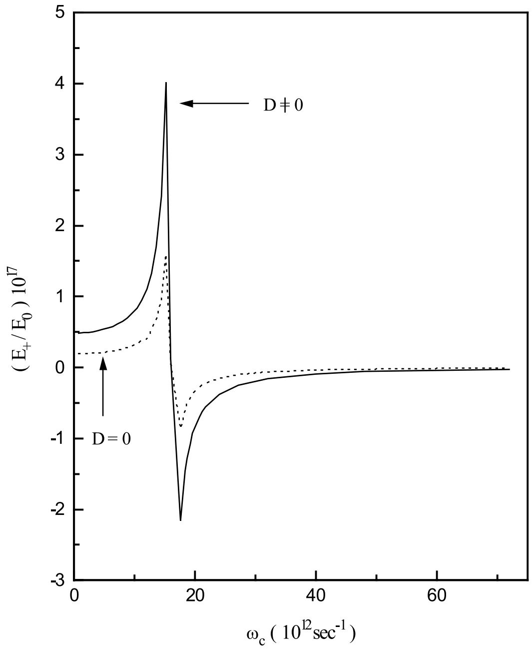

Fig. 3. Variation of modulation index of plus mode (when $k_a < 2k$) with magnetic field (ω_c) for the parameters as in Figure 1.

the indices abruptly to zero and then the situation crosses over to demodulation regimes. It may be also inferred from these figures that diffusion effectively altered the index parameter by increasing their values for both the modes.

3.2 When $k_a < 2k$

The amplitudes of the plus and minus side band modes remain in phase with the pump wave under the condition $\omega_c > (\omega_0^2 + \nu^2)^{\frac{1}{2}}$ and $\omega_c < (\omega_0^2 + \nu^2)^{\frac{1}{2}}$, respectively. Complete absorption of waves takes place when the carrier frequency equals the cyclotron frequency ($\omega_c = \omega_0$) in absence of collision frequency (ν) in this wave number regime, too. These plus and minus modes get out of phase with the pump when $\omega_c < (\omega_0^2+\nu^2)^{\frac{1}{2}}$ and $\omega_c > (\omega_0^2+\nu^2)^{\frac{1}{2}}$, respectively, raising the possibility of demodulation. Thus for a particular magnetic field (ω_c) if one gets modulation of the plus mode, the minus mode gets demodulated and *vice versa.* Hence in this particular wave number regime, both the modes have opposite behaviour. It is a very fascinating result. The numerical estimations in this wave number regime $k_a < 2k$ are drawn in Figures 3 and 4. It can be seen from these figures that the modulation index for the E_+ mode increases, while that of E_- mode decreases with the increase in ω_c. This is so because one gets the modulation of E_+ mode at low magnetic fields when $\omega_c < (\omega_0^2 + \nu^2)^{\frac{1}{2}}$, and in this region one can easily note from equation (10) that the modulation index becomes directly proportional to the square of the cyclotron frequency whereas the E_- mode gets modulated when $\omega_c > (\omega_0^2 + \nu^2)^{\frac{1}{2}}$. The carrier diffusion coefficient always increases the value of modulation index for both the modes.

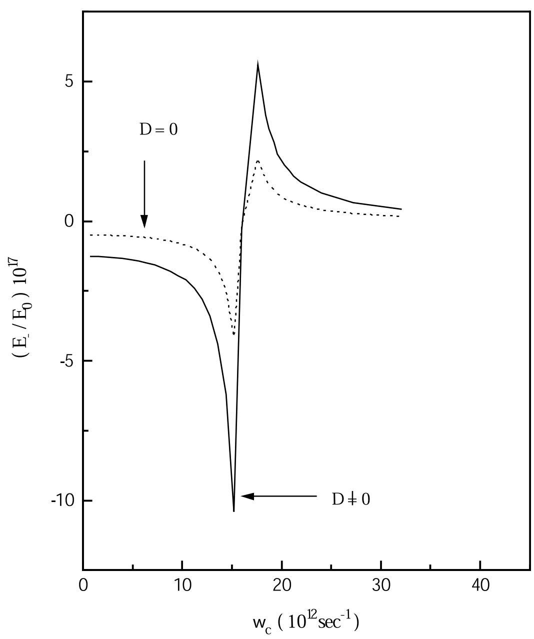

Fig. 4. Variation of modulation index of minus mode (when $k_a < 2k$) with magnetic field (ω_c) for the parametres as in Figure 1.

The above discussion reveals that the amplitude modulation of an electromagnetic wave by an acoustic wave can be easily achieved in acousto-optic crystal. The presence of diffusion altered the result favourably. Hence the consideration of a diffusive crystal with acousto-optic polarisation thus possibly offers an interesting area 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 acousto-optic diffusive crystals.

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