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Original Research Article

Amplitude modulation and demodulation in carrier-heated magnetized semiconductor plasma

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ABSTRACT
In communication systems, amplitude modulation (AM) is widely used for efficient power utilization through single-band transmission. This study employs the hydrodynamical model of semiconductor plasma to analytically examine both amplitude modulation and demodulation of electromagnetic waves, taking into account carrier heating (CH) effects in acousto-optic magnetized semiconductor plasma. The inclusion of CH effects introduces additional complexity and depth to the analysis. Investigations are carried out across different wave number regions and a broad range of cyclotron frequencies. Results indicate that the presence of CH effects significantly influences the AM and demodulation behavior. Numerical calculations are performed for a III–V semiconductor crystal subjected to a pump wave of frequency 1.6×10^{13} s^{-1}. Complete absorption of the waves occurs across all considered wavelength ranges when the cyclotron frequency ω_c approaches the pump frequency ω_0, assuming the collision term is neglected in the modulation and demodulation indices.

1. Introduction

It has been proposed that periodic changes in the propagation parameters of a plasma can induce modulation of an electromagnetic wave traveling through it. These periodic variations, arising from time-dependent fluctuations in carrier density and collision frequency, can result from a modulated magnetic field, variations in power within an RF discharge, or the passage of an acoustic wave. The modulation of electromagnetic waves by acoustic waves is particularly significant in communication technologies, as scattering of light by sound or low-frequency electromagnetic waves provides a practical way to control the frequency, intensity, and direction of an optical beam. Such modulation techniques enable numerous applications in the transmission, display, and processing of information [1, 2].

Certain optical devices, such as acousto-optic modulators, rely on the interaction between an acoustic or low-frequency electromagnetic wave and an incident laser beam [3, 4]. The acoustic wave generates a refractive index grating, which diffracts the laser beam and thereby modulates it. Both electro-optic and acousto-optic (AO) effects have proven to be effective for controlling the intensity and phase of propagating radiation [5, 6]. AO interactions in dielectrics and semiconductors are increasingly important for optical modulation and beam steering. However, in integrated optoelectronic devices, AO modulation can be limited by its high-power demands. A promising solution is the development of new materials engineered to possess improved AO properties.

Modulation can be analyzed in terms of amplitude, frequency, or phase. Among these, amplitude modulation (AM) is one of the earliest and most widely used forms. A key challenge in communication systems is to develop efficient techniques for both modulation and demodulation of waves. Several researchers [7-10] have investigated modulation in semiconductor plasmas. Notably, Mathur and Sagoo [11] were the first to predict microwave modulation during its propagation through a piezoelectrically active semiconductor medium exposed to an acoustic wave. Later, Sen and Kaw [12] demonstrated that certain plasma effects in semiconductors can induce modulation of a laser beam.

When a strong pump beam propagates through a medium, it leads to significant heating of the charge carriers, raising their temperature above that of the lattice in steady-state conditions. This carrier heating substantially alters the electron momentum transfer collision frequency (MTCF), which in turn affects key properties such as carrier mobility, diffusion, and the medium's conductivity, resulting in notable modification of these characteristics.

In many studies of amplitude modulation mechanisms, non-local effects—such as the diffusion of excitation density responsible for nonlinear refractive index changes—have often been neglected. Investigations of the reflection and transmission of a Gaussian beam at the interface between linear and nonlinear diffusive media have prompted the inclusion of diffusion effects in modeling nonlinear electromagnetic wave interactions in both bulk and nonlinear–nonlinear interfaces [13, 14]. It has been observed that increased diffusion hinders light transmission and tends to smooth out the local equilibria of the effective potential, which represents stable and unstable TE nonlinear surface waves [15]. The high mobility of optically excited charge carriers makes diffusion effects particularly significant in semiconductor technologies, as these carriers can travel considerable distances before recombination.

In this work, we examine how hot carriers influence the amplitude modulation and demodulation of a strong electromagnetic wave through acousto-optic interaction in a diffusive semiconductor crystal. Incorporating carrier heating effects in a diffusive semiconductor plasma introduces new aspects to the analysis. The intense pump beam generates an acoustic wave within the semiconductor via electrostrictive effects, leading to interactions between free carriers (through electron plasma waves) and acoustic phonons (through lattice vibrations). This interaction creates a substantial space-charge field that modulates the pump beam. Consequently, the combination of applied optical waves and generated acoustic waves in an acousto-optic modulator can produce amplitude modulation and demodulation at the acoustic wave frequency. The results indicate that both the presence of a magnetic field and hot carriers enhance the modulation effects under investigation.

2. Theoretical formulations

For the theoretical formulation of the modulation index of an amplitude-modulated laser beam in n-type diffusive semiconductor plasma, we have employed the hydrodynamic model of a homogeneous semiconductor plasma of infinite extent. The medium is subjected to a static magnetic field $\vec{B}_0$ along the *z*-axis and is irradiated by an intense pump wave ($\vec{k}_0$) as well as a parametrically generated acoustic wave propagating ($\vec{k}_a$ along the *x*-axis). The field quantities are assumed to vary as: $\exp[i(\omega_j t - k_j x)]$. Using the hydrodynamic model at a crystal temperature of 77 K (liquid nitrogen temperature) allows the streaming electrons to be treated as an electron fluid characterized by macroscopic parameters such as average velocity and carrier density. This simplification facilitates the analysis without significant loss of accuracy. However, the validity of this approach is limited to the condition $k_a l << 1$, where k_a is the acoustic wave number and l is the carrier mean free path.

The low-frequency perturbations are assumed to originate from the acoustic wave $(\omega_a, \vec{k}_a)$ generated by acoustic polarization within the crystal. The acousto-optical potential fields associated with this acoustic wave cause the electron concentration to oscillate at the acoustic frequency. As a result, the pump wave induces a transverse current density at frequencies ω_0 and $(\omega_0 \pm \omega_a)$, where ω_0 is the pump wave frequency and ω_a is the acoustic wave frequency. The transverse current densities at these frequencies are referred to as first-order sideband current densities. These sideband currents generate corresponding sideband electric fields, leading to modulation of the pump wave. In the subsequent analysis, the sidebands are denoted using the suffixes "+" and "–," where "+" corresponds to the mode propagating at $(\omega_0 + \omega_a)$ and "–" corresponds to the mode at $(\omega_0 - \omega_a)$.

To determine the perturbed current density in the crystal under acousto-optic coupling, we start by considering the lattice dynamics equation, which is expressed as follows:

$$\frac{\partial^2 u}{\partial t^2} - \frac{C}{\rho}\frac{\partial^2 u}{\partial x^2} + 2\gamma\frac{\partial u}{\partial t} = \frac{\varepsilon(\eta^2 - 1)}{2\rho}\frac{\partial}{\partial t}(\vec{E}_0 \vec{E}_1^*) \quad (1)$$

$$\frac{\partial E_1}{\partial x} = \frac{n_1 e}{\varepsilon} + \frac{(\eta^2 - 1)}{\varepsilon_L} E_0 \frac{\partial^2 u^*}{\partial x^2}. \quad (2)$$

Equation (1) represents the lattice vibrations in an acousto-optic crystal with material density ρ. Here, C, η and γ denote the elastic constant, refractive index, and phenomenological damping constant of the medium, respectively. The space-charge field E_1 is obtained from Poisson's equation (2), where the last term on the right-hand side accounts for the contribution of acousto-optic polarization. The symbol "*" indicates the complex conjugate of the corresponding quantity.

Using Eqs. (1) and (2), the perturbed current densities in an n-type diffusive semiconductor under acousto-optic coupling can be expressed as follows:

$$n_1 = \frac{2\rho u[k_a^2 v_a^2(1 + A^2) - \omega_a^2 + 2i\gamma\omega_a]}{e(\eta^2 - 1)E_0}. \quad (3)$$

Here, $v_a = (C/\rho)^{1/2}$ represents the shear acoustic velocity in the crystal lattice, and $A^2 = [\varepsilon_0(\eta^2 - 1)E_0]^2 / 2c\varepsilon_0$ denotes the dimensionless acousto-optic coupling coefficient arising from the acousto-optic interaction.

The electron momentum transfer equation, accounting for diffusion effects, is given by

$$\frac{\partial \vec{v}_j}{\partial t} + (\vec{v}_0.\vec{\nabla})\vec{v}_j + \nu\vec{v}_j = \frac{e}{m}(E_j + (\vec{v}_j \times \vec{B}_0)] - \nu D\frac{\nabla \vec{n}_j}{n_j}. \quad (4)$$

The subscript *j* refers to the 0, +, and − modes. The above equation describes the motion of electrons under the influence of electric fields associated with the pump and sideband modes. Here, *m* and ν denote the effective electron mass and the phenomenological electron collision frequency, respectively, while n_j represents the electron density. *D* is the carrier diffusion coefficient, which can be expressed using Einstein's relation:

$$D = (k_B T_e / e)\mu_e,$$

where k_B is Boltzmann's constant, T_e is the electron temperature, μ_e is the electron mobility, and *e* is the electron charge. In this analysis, the effect of the pump magnetic field is neglected by assuming that the electron plasma frequency of the medium is comparable to the pump frequency.

The momentum transfer equation (Eq. (4)) can be employed to determine the oscillatory velocity of the electron fluid under the influence of the pump electric field E_0 and the sideband fields $E_\pm$. By linearizing Eq. (4), the corresponding velocity components are obtained as:

$$v_{jx} = \frac{(eE_j/m)(\nu + i\omega_j)}{[(\nu + i\omega_j)^2 + \omega_c^2]}\left[1 + \frac{\nu D k^2}{\omega_p^2}\right] \quad (5)$$

$$v_{jy} = \frac{(eE_j/m)\omega_c}{[(\nu + i\omega_j)^2 + \omega_c^2]}\left[1 + \frac{\nu D k^2}{\omega_p^2}\right]. \quad (6)$$

Here, $\omega_c = eB_0/m$ denotes the cyclotron frequency, and $\omega_p = (n_0 e^2 / m\varepsilon)^{1/2}$ represents the plasma frequency.

In general, when a high-intensity pump field interacts with a high-mobility n-type semiconductor, the charge carriers gain momentum and energy from the pump, causing the electrons to reach a temperature T_e slightly higher than the lattice temperature.

This electron heating alters the momentum-transfer collision frequency (MTCF), which can be expressed through the relation:

$$\nu = \nu_0 \left(\frac{T_e}{T_0}\right)^{1/2}. \tag{7}$$

Here, T_e represents the effective electron temperature, T_0 is the lattice temperature, and n0 is the momentum-transfer collision frequency when $T_e = T_0$. The electron temperature T_e can be determined using the energy balance equation under steady-state conditions.

Using Eq. (5) for the specified geometry, the time-independent component of the power absorbed per electron from the pump is given by

$$\frac{e}{2}\mathrm{Re}(\vec{v}_0.\vec{E}_0) = \frac{e^2\nu_0}{2m}\frac{(\omega_c^2+\omega_0^2)}{[(\omega_c^2-\omega_0^2)^2+4\nu_0^2\omega_0^2]}E_0E_0^*. \tag{8}$$

Here, the symbol "*" indicates the complex conjugate of the quantity, and "Re" represents the real part.

This power is dissipated through collisions with polar-optical phonons (POP) in the medium. The average power loss per electron due to POP interactions is expressed as:

$$\langle P\rangle_{POP} = \left(\frac{2k_B\theta_D}{m\pi}\right)^{1/2} eE_{po}x_e^{1/2}K_0\left(\frac{x_e}{2}\right) \times\exp\left(\frac{x_e}{2}\right)\times\frac{\exp(x_0-x_e)-1}{\exp(x_0)-1}. \tag{9}$$

Here, $x_{0,e} = \hbar\omega_l / k_B T_{0,e}$, in which $\hbar\omega_l$ is the energy of the polar-optical phonons (POP) given by $\hbar\omega_l = k_B\theta_D$ with θ_D representing the Debye temperature of the medium. $E_{po} = (me\hbar\omega_l/\hbar^2)(\varepsilon_\infty^{-1}-\varepsilon_L^{-1})$ denotes the POP scattering potential, where ε_L and ε_∞ are the static and high-frequency dielectric permittivities of the medium, respectively. $K_0(x_e/2)$ is the zeroth-order Bessel function of the first kind.

In steady state, the power absorbed per electron from the pump equals the power lost per electron through POP scattering. Therefore, for moderate carrier heating, using Eqs. (8) and (9), the electron temperature can be determined, which in turn allows calculation of the modified diffusion coefficient as:

$$\frac{T_e}{T_0} = 1+\frac{e^2\nu_0}{2m}\frac{\tau(\omega_c^2+\omega_0^2)}{[(\omega_c^2-\omega_0^2)^2+4\nu_0^2\omega_0^2]}E_0E_0^* \tag{10}$$

$$D = \frac{k_BT_0}{e}\left[1+\frac{e^2\nu_0}{2m}\frac{\tau(\omega_c^2+\omega_0^2)}{[(\omega_c^2-\omega_0^2)^2+4\nu_0^2\omega_0^2]}E_0E_0^*\right]\mu_e, \tag{11}$$

where $\tau^{-1} = \left(\frac{2k_B\theta_D}{m\pi}\right)^{1/2} eE_{po}x_0K_0\left(\frac{x_0}{2}\right)\frac{x_0^{1/2}\exp(x_0/2)}{\exp(x_0)-1}$.

The total transverse current density can be expressed as:

$$\vec{J}_{total} = e\left[\sum_j n_0\vec{v}_j + \sum_j n\vec{v}_0\exp[i(\omega_j t - k_a x)]\right]. \tag{12}$$

Here, $n\vec{v}_0\exp[i(\omega_j t - k_a x)]$ represents the current generated due to the interaction between the pump and the acoustic wave. To determine the modulation indices of the sideband modes, Eqs. (5), (6), and (12) are applied in the general wave equation:

$$\frac{\partial^2\vec{E}_{total}}{\partial^2 x} - \mu\varepsilon\frac{\partial^2\vec{E}_{total}}{\partial^2 t} - \mu\frac{\partial\vec{J}_{total}}{\partial t} = 0. \tag{13}$$

By neglecting $\exp(\mp ik_a x)$ in comparison to 1, the following expressions for the modulation indices are obtained:

$$\frac{E_\pm}{E_0} = \frac{2i\omega_0\mu ue\Delta(\nu+i\omega_0)(ck_a^2A^2+2i\rho\gamma\omega_a)}{m\beta(k_a^2\pm 2kk_q)[(\omega_c^2+\nu^2-\omega_0^2)+2i\nu\omega_0]}, \tag{14}$$

where $\left(1+\frac{\nu Dk^2}{\omega_p^2}\right)$.

By rationalizing the above equation, the real part of the modulation indices can be expressed as:

$$\frac{E_\pm}{E_0} = \frac{-2\omega_0\mu k_a ue[cA^2\omega_0\delta_1^2+\left(\frac{2\rho\gamma\nu\nu_a}{k_a}\right)\delta_2^2\Delta}{m\beta(k_a\pm 2k)[(\omega_c^2-\omega_0^2+\nu^2)^2+4\nu^2\omega_0^2]}, \tag{15}$$

where $\delta_1^2 = (\omega_c^2-\omega_0^2-\nu^2)$, $\delta_2^2 = (\omega_c^2+\omega_0^2+\nu^2)$.

It is evident that including carrier heating effects (Eq. (10)) increases the carrier diffusion (Eq. (11)) in the medium, which in turn enhances the modulation indices (Eq. (15)). Therefore, carrier heating plays a crucial role in determining the magnitude of the modulation indices in semiconductor plasma. Equation (15) can thus be regarded as the modulation indices of acousto-optic semiconductors modified by the carrier temperature (via the diffusion coefficient) in the presence of a magnetic field.

3. Results and discussion

In this section, amplitude modulation and demodulation resulting from acousto-optic interaction are analyzed both with and without the inclusion of carrier heating (CH) effects, using Eq. (15). It is observed that CH effects alter key dependent parameters such as the momentum-transfer collision frequency (Eq. (7)) and the diffusion of charge carriers (Eq. (11)), thereby significantly influencing the modulation process. The modulation index given by Eq. (15) is examined under two distinct and interesting wave number regimes: (i) $k_a > 2k$, and (ii) $k_a < 2k$.

(i) When $k_a > 2k$.

In this wave number regime, the modulation indices of both sidebands are consistently negative, indicating that the amplitudes of the sideband modes ($E_\pm$) remain out of phase with the pump wave within the cyclotron frequency range.

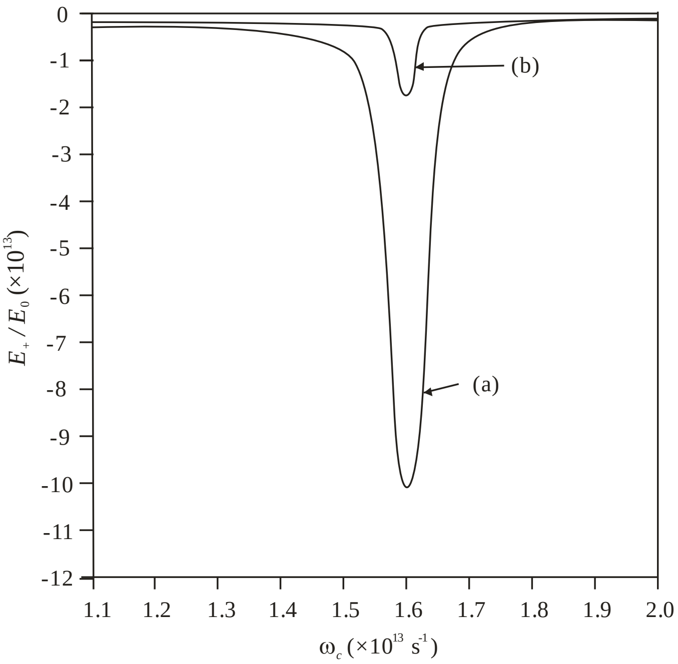

Figure 1: Variation of the modulation index of the plus mode ($k_a > 2k$) with the applied magnetic field. Curve (a) corresponds to CH effects, and curve (b) corresponds to results without CH effects.

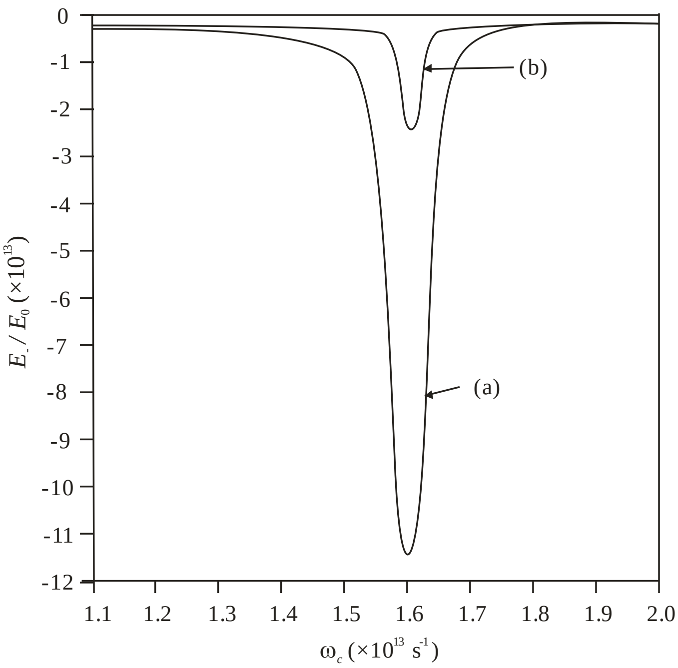

Figure 2: Variation of the modulation index of the minus mode ($k_a > 2k$) with the applied magnetic field. Curve (a) includes CH effects, and curve (b) excludes CH effects.

However, when the carrier frequency matches the cyclotron frequency, complete absorption of the waves occurs, assuming the collision term in Eq. (15) is neglected. Under this condition, the out-of-phase sidebands interact with the pump wave to generate a demodulated acoustic wave. The demodulation index reaches its maximum at a specific value of the magnetic field when $\omega_c \sim \omega_0$.

As a representative example, numerical calculations have been carried out for a III–V semiconductor crystal irradiated by a 10.6 μm pulsed CO_2 laser at 77 K. The physical parameters employed in the analysis are:

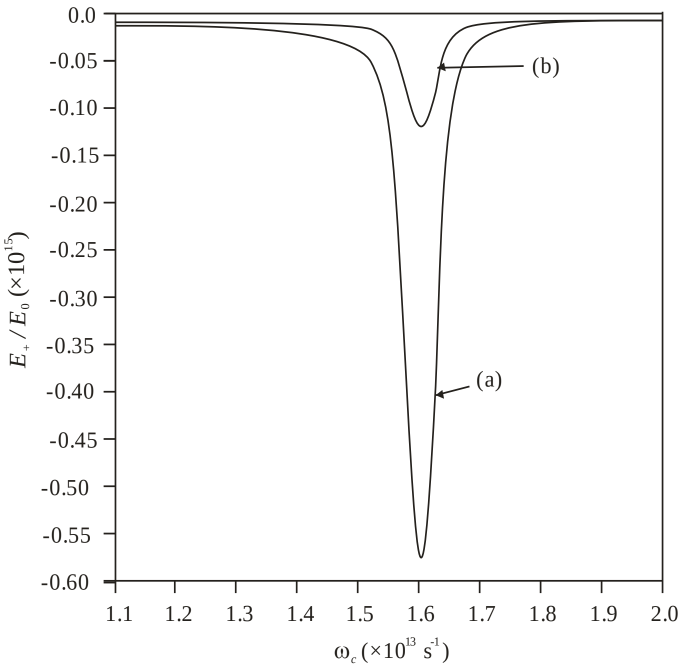

Figure 3: Variation of the modulation index of the plus mode ($k_a < 2k$) with the applied magnetic field. Curve (a) corresponds to CH effects, and curve (b) corresponds to results without CH effects.

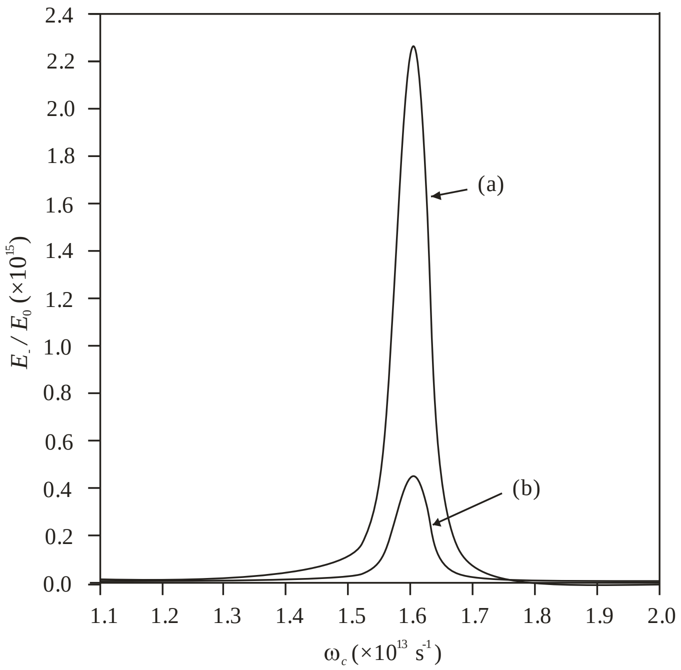

Figure 4: Variation of the modulation index of the minus mode ($k_a < 2k$) with the applied magnetic field. Curve (a) shows results with CH effects, and curve (b) shows results without CH effects.

$m = 0.014\, m_0$ (m_0 being the free electron mass),
$\varepsilon_L = 17.54$, $\varepsilon_\infty = 15.7$, $\eta = 3.9$, $\rho = 5.8\times10^3$ kg m^{-3},
$\gamma = 2\times10^{10}$ s^{-1}, $T_0 = 77$ K, $\theta_D = 278$, $\nu_0 = 4\times10^{11}$ s^{-1},
$\omega_a = 10^{12}$ s^{-1} and $\omega_0 = 1.6\times10^{13}$ s^{-1}.

The variations of (E_+/E_0) and (E_-/E_0) with the applied magnetostatic field (ω_c) are shown in Figs. 1 and 2, with curve (a) representing results including carrier heating (CH) effects and curve (b) representing results without CH effects. From these figures, it can be seen that the demodulation indices of both sidebands increase with cyclotron frequency when $\omega_c < \omega_0$, reaching a maximum near $\omega_c \approx \omega_0$. As the cyclotron frequency is further increased ($\omega_c > \omega_0$), the indices drop sharply to zero. The curves also indicate that the presence of CH effects significantly enhances the demodulation indices of both modes. Therefore, incorporating carrier heating is essential for accurate analysis of nonlinear interactions in high-mobility diffusive semiconductors.

(ii) When $k_a < 2k$:

In this regime, the modulation indices of the plus and minus modes exhibit opposite behaviors. Figure 3 shows the variation of (E_+/E_0) with the applied magnetostatic field (ω_c) for $k_a < 2k$. From the figure, it is evident that the amplitude of the plus mode is out of phase with the pump, indicating a demodulation process. The magnitude of this demodulation reaches its maximum near $\omega_c \approx \omega_0$. Figure 4 presents the variation of (E_-/E_0) with ω_c, showing that the amplitude of the minus sideband mode remains in phase with the pump, resulting in modulation.

4. Conclusions

The present study demonstrates that amplitude modulation and demodulation of an electromagnetic wave can be effectively achieved in an acousto-optic III–V semiconductor crystal. Carrier heating (CH) effects consistently enhance the modulation and demodulation indices for both sideband modes, indicating that hot carriers are beneficial for the modulation process. Therefore, incorporating CH effects in a diffusive semiconductor crystal with acousto-optic polarization provides a promising platform for investigating various modulational interactions. This approach also holds potential as an experimental tool for energy transmission and solid-state diagnostics in acousto-optic diffusive crystals.

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