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NEW SPIN-DEPENDENT NONLINEAR WAVE MODES IN MAGNETIZED QUANTUM PLASMA

In the present paper, the authors report analytically on the nonlinear instability and the modifications in the spectra of acoustic wave modes in magnetized semiconductor quantum plasma. The modification resulted from the emergence of new spin-dependent acoustic wave modes that can be controlled and manipulated through external magnetic fields. We consider that the origin of the nonlinearity lies in the nonlinear induced current density in an n-type InSb semiconductor irradiated by CO_2 laser at 77 K. The QMHD (Quantum MagnetoHydrodynamic) model is extended for spin effect to investigate the dynamics of acoustic waves and a novel way to utilize the spin properties of electrons in semiconductor devices for various applications.

Keywords: quantum plasma, laser-plasma interaction, parametric interaction.

1. Introduction

The advancement of high-peak-power lasers made nonlinear optics to be a prominent field of research, being expanded into a famous branch of physics. The nonlinear interactions of co-propagating beams have generated considerable attention due to the requirement of optoelectronic devices and quantum computing. These interactions give rise to novel phenomena, including self-focusing, self-phase modulation, and parametric processes. These phenomena have been thoroughly investigated, and the results have been very helpful in understanding how intense laser beams behave themselves in various media and play a crucial role in developing various nonlinear optical devices [1, 2].

A spin electron acoustic wave (SEAW) mode has been reported by considering the separate spin evolution of spin-up and spin-down electrons in degenerate magnetized plasma [3]. It was demonstrated that, in the presence of an ambient magnetic field, the equilibrium concentration of spin-up and spin-down electrons are different, which, in turn, is responsible for the difference in Fermi pressures and gives birth to a spin electron acoustic wave. These spin-dependent modes can have a significant impact on the propagation, and the characteristics of generated waves in magnetized plasmas are also influenced by the plasma density. Furthermore, the spin electron acoustic wave can exhibit different dispersion properties depending on the strength of the ambient magnetic field.

The interaction of laser light by sound or a low-frequency electromagnetic wave in the semiconductor medium has become important because it can generate new frequencies. The magnetohydrodynam-

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ical model allows for a more accurate analysis of different wave interactions and fluid behavior in the medium. The quantum magnetohydrodynamic model (QMHD) adds two quantum forces to the classical fluid model, the Bohm force and the spin force with Fermi pressure [4, 5]. When the temperature approaches the electron Fermi temperature, the equilibrium electron distribution function changes from the Maxwell–Boltzmann one to the Fermi–Dirac on. The Fermi pressure and Bohm potential are expected to play a key role in the behavior of the systems of charged particles [6, 7].

Specifically, spin plays a vital role in exposing the plasma to an external magnetic field, which interacts with the magnetization in the plasma due to the electron spin [8, 10]. The magnetic properties of a substance depend on the number of unpaired electrons and on how they interact with one another, i.e., spin pairing, etc [11, 12]. In magnetized plasmas, electrons align the spin magnetic dipole moment along the external magnetic field, which enhances the strength of the external magnetic field and significantly changes the propagation characteristics of low-frequency modes [13, 14].

In this paper, we use analytic methods to investigate the spin-dependent nonlinear acoustic wave modes of the propagation of the generated wave in an n-type InSb semiconductor plasma medium. The quantum force is used in the QMHD model to include the spin term, which is very important for understanding how nonlinear waves propagate and spread out in the medium. The modified modes of propagation give a deeper understanding of the spin-electron interaction and its effects on the nonlinear interaction and transport properties of the medium. Additionally, the modification resulted in new spin-dependent modes, which can be controlled and manipulated through external magnetic fields.

2. Theoretical Formulation

To describe the wave interaction analytically in doped (n-type) piezoelectric semiconductor plasma, we are considering the QMHD model (sets of equations that includes continuity equation, momentum transfer, and equation of state) in which the spin forces play a crucial role in determining the overall behavior of the plasma, as they contribute to the momentum transfer equations. The QMHD Model can successfully explain the collective motion of quantum particles in magnetic fields. We start with the following sets of equations to analyze the spin effect on the magnetized plasma

$$\frac{\partial \upsilon_0}{\partial t} + \nu\upsilon_0 = -\frac{e}{m}\left(E_0 + \upsilon_0 \times B_0\right), \quad (1)$$

$$\frac{\partial \upsilon_1}{\partial t} + \nu\upsilon_1 + \left(\upsilon_0 \frac{\partial}{\partial x}\right)\upsilon_1 = = -\frac{e}{m}\left(E_1 + \upsilon_1 \times B_1\right) - \frac{1}{mn_0}\frac{\partial P}{\partial x} + F_Q, \quad (2)$$

where

$$F_Q = \frac{2\mu_{\rm B}}{\hbar m}\nabla\left(B_1 \cdot S_\alpha\right) + \frac{\hbar^2}{4m^2 n_0}\frac{\partial^3 n_1}{\partial x^3}.$$

Equations (1) and (2) describe the electron motion of the fields associated with the pump and the sideband waves under the influence of a magnetostatic field, respectively. $B_0\upsilon_0$ and $B_1\upsilon_1$ are the equilibrium and perturbed magnetic fields and oscillatory fluid velocities of the electrons of effective mass m and charge e. The quantum force F_Q on an electron in Eq. (2) includes two terms. The first term represents the Bohm potential associated with quantum diffusion of electrons and the second term is the spin magnetization energy due to the spin interaction with magnetic field. Here, S_α is the spin of species α, $\alpha =\uparrow$ and $\downarrow$ denotes the spin-up and spin-down electrons, respectively, with $\mu = -\frac{g\mu_{\rm B}}{2}\mu_{\rm B} = \frac{e\hbar}{2m}g = 2.0023192$ is the electron g-factor, n_1 and n_0 are the perturbed and unperturbed number densities. It is well known that the linearly polarized transverse electromagnetic wave is not affected by the quantum effects. We consider the equation of state for the spin-up and spin-down electrons $P = \frac{mV_{\rm F}^2 n_1^{5/3}}{5n_0^{2/3}}$, where $V_{\rm F} = \sqrt{\xi_{3D}\hbar}\,(n_0^{1/3})/m$ is the Fermi velocity. ξ_{3D} is the degree of spin polarization given by $\xi_{3D} = [(1-\eta)^{5/3} + (1+\eta)^{5/3}]/2$ with spin polarization (η) defined by $\eta = |n_\uparrow - n_\downarrow|/|n_\uparrow + n_\downarrow|$,

$$\upsilon_0\frac{\partial n_1}{\partial x} + n_0\frac{\partial \upsilon_1}{\partial x} + \frac{\partial n_1}{\partial t} = 0, \quad (3)$$

$$\frac{\partial E_1}{\partial x} + \frac{n_1 e}{\varepsilon} = \frac{\beta}{\varepsilon}\frac{\partial^2 u}{\partial x^2}, \quad (4)$$

$$\rho\frac{\partial^2 u}{\partial t^2} + 2\gamma_s\rho\frac{\partial u}{\partial t} + \beta\frac{\partial E_1}{\partial x} = C\frac{\partial^2 u}{\partial x^2}, \quad (5)$$

$$\nabla \times \nabla \times E_1 = -\frac{1}{c_l^2}\frac{\partial^2 E_1}{\partial t^2} - \mu_0\frac{\partial J_1}{\partial t}. \quad (6)$$

The continuity equation (3) contains sources of particles. These sources are caused by the interactions of spins with magnetic fields. The spin-spin interaction is the dipole-dipole interaction of the magnetic moments via the magnetic field created by the magnetic moments. The spin current interaction contribution in this term. It comes via the magnetic field created by the electric currents and acting on the magnetic moments. The space charge field E_1 is determined from the Poisson equation (4) in which the last term on r.h.s. represents the contribution of piezoelectricity (through β, the piezoelectric coefficient) of the medium. Equation (5) describes the lattice vibrations of material density ρ in a piezoelectric crystal and elastic constant C. γ_s is the acoustic damping constant of the medium; u is the lattice displacement under the influence of the interfering electromagnetic fields.

The authors are interested in studying the spin-dependent nonlinear wave modes in second-order optical nonlinearity induced through a generated nonlinear current density. The present approach in the presence of spatially uniform pump (i.e., pump wave vector $|k_0| \approx 0$); thus, the pondermotive force term and the electron exchange-correlation potential are neglected safely. In a doped piezoelectric semiconductor, the low-frequency acoustic wave ω_s, as well as the pump electromagnetic waves ω_0, produce a density perturbation n_1 at the respective frequency in the medium. Following the standard approach [15, 16] and using Eqs. (1)–(6), the density perturbation may be derived as

$$\frac{\partial^2 n_1}{\partial t^2} + \bar{\omega}_p^2 n_1 + n_0 \left(\frac{2\mu_{\rm B}}{\hbar m} \frac{ik^2 E_1}{\omega_0} S_{\alpha 0} + \frac{\beta}{\varepsilon} \frac{\partial^2 u}{\partial x^2} \right) + + \nu \frac{\partial n_1}{\partial t} = \bar{E} \frac{\partial n_1}{\partial x}, \tag{7}$$

where

$$\bar{E} = \frac{e}{m} E_0 \left(1 + \frac{\omega_c (\nu - i\omega_0)}{(\omega_c^2 - \omega_0^2 - 2i\omega_0 \nu)} \right).$$

In the derivation of Eq. (7), we have neglected the Doppler shift under the assumption that $\omega_0 \gg \gg v > kv_0$; $\omega_p = \left(\frac{n_0 e^2}{m\varepsilon}\right)^{1/2}$, $\bar{\omega}_p^2$ is the modified plasma frequency is strongly influenced by the Bohm potential and Fermi pressure. The quantum forces and the Fermi pressure are included in the second term on l.h.s. of Eq. (7). In further calculations, we will study the combined effect of both the quantum correction terms.

The perturbed electron concentration ($n_1 = n_{1\uparrow} + + n_{1\downarrow}$) has two components, known as fast and slow $n_1 = n_f + n_s$. The slow component n_s (viz., $n_s \propto \exp\left[i\left(k_s x - \omega_s t\right)\right]$) is associated with the phonon mode (ω_s, k_s) and the fast component n_f (viz., $n_f \propto \exp\left[i(k_1 x - \omega_1 t)\right]$) is associated with the high-frequency scattered electromagnetic wave ($\omega_1 k_1$), arising due to the three-wave parametric interaction. These waves will propagate at generated frequencies ω_s and $\omega_0 \pm \omega_1$ respectively. We assume that the energy transfer between the pump and produced signal and idler waves satisfy phase matching conditions which are $\omega_0 = \omega_1 - \omega_s$ and $k_0 = k_1 - k_s$. Now, for spatially uniform laser radiation $|k_0| \approx 0$, we obtain $|k_1| = |k_s| = k$. By resolving Eq. (7) into two components (fast and slow) under the rotating wave approximation, we obtain the respective coupled equations as

$$\frac{\partial^2 n_f}{\partial t^2} + v \frac{\partial n_f}{\partial t} + \bar{\omega}_p^2 n_f = \bar{E} \frac{\partial n_s^*}{\partial x}, \tag{8a}$$

$$\frac{\partial^2 n_s}{\partial t^2} + \bar{\omega}_p^2 n_s + n_0 \left(\frac{2\mu_{\rm B}}{\hbar m} \frac{ik^2 E_1}{\omega_0} S_{\alpha 0} + \frac{\beta}{\varepsilon} \frac{\partial^2 u}{\partial x^2} \right) + + \nu \frac{\partial n_s}{\partial t} = \bar{E} \frac{\partial n_f^*}{\partial x}. \tag{8b}$$

Subscripts s and f stand for slow and fast components, respectively. Asterisk (*) represents the complex conjugate of the quantity. We restrict our analysis only for the Stoke's component ($\omega_0 - \omega_s$) of the scattered electromagnetic waves. It is inferred from Eq. (8) that the slow and fast components of the density perturbations are coupled to each other via the pump electric field. Thus, the presence of the pump field is a fundamental necessity for the parametric interactions to occur. From Eqs. (8a), (8b), and (5), we get

$$n_1 = n_0 \frac{\frac{2\mu_{\rm B}}{\hbar m} \frac{ik^2 E_1}{\omega_0} S_{\alpha 0} + \frac{e\beta}{m\varepsilon} \frac{\partial^2 u}{\partial x^2}}{\delta_1^2 - i\omega_s \nu - \frac{k^2 \bar{E}^2}{\delta_2^2 + i\omega_1 v}}. \tag{9}$$

The number density of our expected piezoelectric quantum plasma medium is influenced by both spin-up and spin-down species and quantum Bohm potential and component of piezoelectricity. Now, we also simplified our analysis by assuming that the medium is sufficiently cooled, the temperature is below the Fermi temperature, and the degenerate plasma state is reached [17]. We set $s_{\uparrow 0} = -s_{\downarrow 0} = \left(\frac{\hbar}{2}\right)\hat{z}$ and $n_\uparrow - n_\downarrow = 3n\frac{\mu_B B_0}{2k_B T_F}$ $(T \ll T_F)$.

These assumptions allow us to focus on the key interactions and behaviors of the particles in the system, providing a clearer understanding of the overall dynamics. The effect of spin electrons in the Stoke's component of induced current density is given by

$$J_1 = -n_1^* e v_0. \tag{10}$$

Substituting Eq. (9) into Eq. (10) we get

$$J_1 = \left[\frac{E_0 \varepsilon \omega_P^2 (v - i\omega_0)}{(\omega_c^2 - \omega_0^2 - 2i\omega_0 v)}\right] \times \left[\frac{e\beta^2 k^3}{m\varepsilon\rho\gamma_s\omega_s} - \frac{2\mu_B}{\hbar m}\frac{ik^2}{\omega_0}S_{\alpha 0}\right] \times \left[\delta_1^2 + i\omega_s v - \frac{k^2\bar{E}^2}{\delta_2^2 - i\omega_s v}\right]^{-1}, \tag{11}$$

$\delta_1^2 = \bar{\omega}_p^2 - \omega_s^2$ and $\delta_2^2 = \bar{\omega}_p^2 - \omega_1^2$, $\bar{\omega}_p^2 = \omega_p^2 + \frac{\hbar^2 k^2}{m}\left(\frac{\xi_{3D}}{5} + \frac{k^2}{4m}\right)$, $\omega_0 = \omega_1 - \omega_s$ and $v_0 = \frac{\bar{E}}{(v - i\omega_0)}$, $\Omega_{c0}^2 = \omega_c^2 - \omega_0^2$, $\Omega_{ps}^2 = \bar{\omega}_p^2 - \omega_s^2$.

An acoustic perturbation in the lattice gives rise to an electron density fluctuation at the same frequency. The density perturbation thus produced affects the propagation characteristics of the generated waves, which can be obtained by employing the electromagnetic wave by Eq. (6). This couples nonlinearly with the pump field and drives the electron plasma at the same and difference frequencies which can be adjusted so that they are close to the electron-plasma frequencies. The resulting electron density fluctuation at the plasma frequency also nonlinearly couples with the external field and can reinforce the original electron density perturbation at the acoustic frequency. The modification resulted in new spin-dependent modes, which can be controlled and manipulated through external magnetic fields.

The standard approach [18] provides a modified spin-dependent dispersion relation of generated waves induced through the nonlinear current density

$$\left(\omega_1^2 - k^2 c_l^2\right)\left(\bar{\omega}_p^2 - \omega_s^2 - i\omega_s v - \frac{k^2\bar{E}^2}{\bar{\omega}_p^2 - \omega_1^2 - i\omega_1 v}\right) - \frac{\mu_0 E_0 \omega_P^2 \omega_0^2 c_l^2}{m(\omega_c^2 - \omega_0^2)}\left[\frac{e\beta^2 k^3}{\varepsilon\rho\gamma_s\omega_s} - \frac{2\mu_B}{\hbar}\frac{ik^2}{\omega_0}S_{\alpha 0}\right] = 0. \tag{12}$$

The modified dispersion relation gives a deeper understanding of the spin-electron interaction and its effects on the nonlinear interaction and transport properties of the medium. Additionally, the modification resulted in the emergence of new spin-dependent modes, which can be controlled and manipulated through external magnetic fields. It is evident that Eq. (12) is of fourth degree in complex quantity and may be written in the form of polynomial in ω_1 as

$$D_4\omega_1^4 + D_3\omega_1^3 + D_2\omega_1^2 + D_1\omega_1^1 + D_0 = 0,$$

where

$$D_4 = \left(\Omega_{ps}^2 + i\omega_1^2\omega_s\nu\right)\left(\Omega_{c0}^2\omega_s m\hbar + i\omega_1^2\omega_s\nu\varepsilon\rho\gamma_s\right),$$

$$\Omega D_3 = \left(i\nu\left(\bar{\omega}_p^2 + \omega_s^2\right) - \omega_s\nu\right)\left(\Omega_{c0}^2\omega_s m\hbar\varepsilon\rho\gamma_s\right),$$

$$D_2 = \left(\Omega_{ps}^2\bar{\omega}_p^2 + i\bar{\omega}_p^2\omega_s\nu - k^2\bar{E}^2\right) - \left(k^2c^2\left(\Omega_{ps}^2 + i\omega_s\nu\right)\left(\Omega_{c0}^2\omega_s m\hbar\varepsilon\rho\gamma_s\right) - \left(\mu_0 E_0\omega_P^2\omega_0^2 c_l^2 k^2\left(2i\varepsilon\rho\gamma_s\mu_B S_{\alpha 0} - \hbar e\beta^2\right)\right)\right),$$

$$D_1 = k^2c^2\left(i\nu\left(\bar{\omega}_p^2 + \omega_s^2\right) - \omega_s\nu^2\right)\left(\Omega_{c0}^2\omega_s m\hbar\varepsilon\rho\gamma_s\right) - i\nu\left(\mu_0 E_0\omega_P^2\omega_0^2 c_l^2 k^2\left(2i\varepsilon\rho\gamma_s\mu_B S_{\alpha 0} - \hbar e\beta^2\right)\right),$$

$$D_0 = k^2c^2\left(\Omega_{ps}^2 + i\bar{\omega}_p^2\omega_s\nu - k^2\bar{E}^2\right)\left(\Omega_{c0}^2\omega_s m\hbar\varepsilon\rho\gamma_s\right) - \bar{\omega}_p^2\left(\mu_0 E_0\omega_P^2\omega_0^2 c_l^2 k^2\left(2i\varepsilon\rho\gamma_s\mu_B S_{\alpha 0} - \hbar e\beta^2\right)\right).$$

These spin-dependent modes can have a significant impact on the behavior of propagation, and the characteristics of generated waves in magnetized plasmas are also influenced by the plasma density. Furthermore, the spin electron acoustic wave can exhibit different dispersion properties depending on the strength of the ambient magnetic field. Equation (12) demonstrates that the presence of spin terms in the system induces two new modes of propagation. The third and fourth modes are unaffected by the spin effect. Overall, the inclusion of spin terms in the system introduces new complexities and possibilities for understanding the wave propagation in magnetized plasmas. Further research is needed to fully explore the implications of spin-dependent modes on the plasma behavior and wave characteristics. Now, it may be inferred that the presence of the spin term in wave propagation effectively modifies the wave spectra. This opens new avenues for studying the behavior of waves in magnetized plasmas and could lead to advancements in various fields such as fusion research and space physics. Understanding these spin-dependent modes is crucial for developing more accurate models and predictions for the plasma dynamics.

3. Results and Discussions

The dispersion relation derived in the preceding section can be employed to study the wave spectrum of nonlinear interaction in piezoelectric semiconductors. This relation is solved numerically for complex frequency $\omega(=\omega_r + i\omega_i)$ with real positive values of propagation constant k. The form of perturbations was considered as $\exp\left[i\left(\omega t - kz\right)\right]$. So, the mode may be growing in time, when the imaginary part of the wave angular frequency becomes negative for the real values of k, i.e., $\omega_i < 0$ and decaying when $\omega_i > 0$. The numerical estimations have been made for n-type InSb assumed to be duly irradiated by pulsed 10.6 μm CO_2 laser at 77 k. The physical parameters

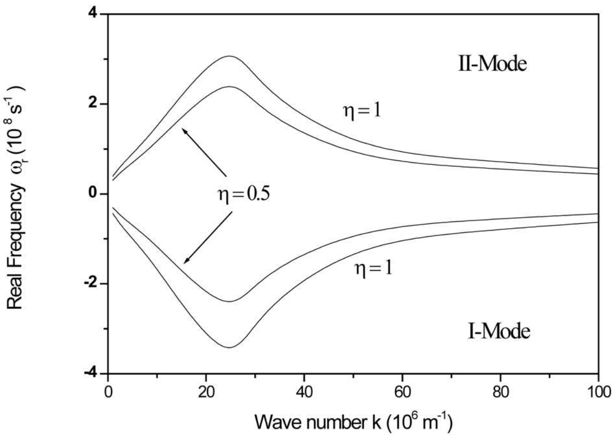

Fig. 1. Variations of real parts of frequencies$\omega_r$of modified modes with wave number k

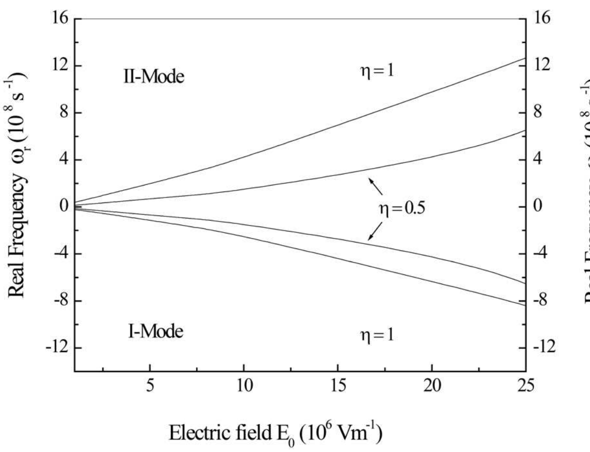

Fig. 2. Variation of real parts of frequencies ω_r of modified modes with electric field strength ($\mathbf{E}_0$) at $k = 2 \times 10^5$ m^{-1}

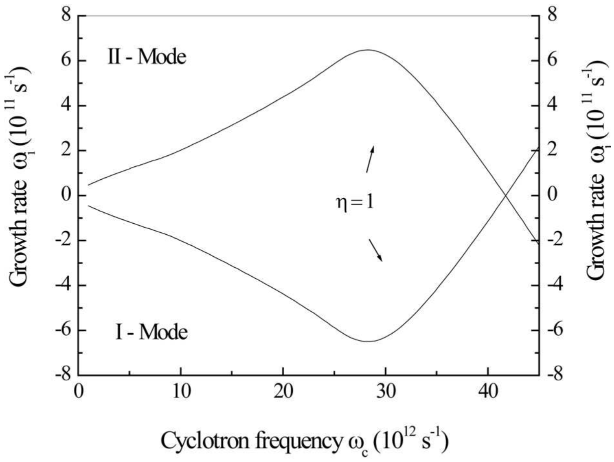

Fig. 3. Variation of modified modes ω_i with cyclotron frequency ω_c

used [19, 20] are:

$m = 0.107m_0$, $\varepsilon_1 = 9.35$, $\nu_s = 1.8 \times 10^3$ ms^{-1},

$\beta = 0.21$ Cm^{-2}, $\rho = 4.82 \times 10^3$ kg m^{-3},

$\omega_s = 2 \times 10^{11}$ s^{-1}, $\omega_0 = 1.78 \times 10^{14}$ s^{-1},

$\nu = 5 \times 10^{13}$ s^{-1}, $n_0 = 2 \times 10^{24}$ m^{-3}, $T_{\rm F} = 77$ K.

Figure 1 displays the variations of real parts of frequencies (ω_r) of two new modes of propagation modified by the spin effect with wave number k. It is found that these two modes are periodic and propagate in opposite directions with equal phase speed. Their phase speeds first increase with k and touch a maximum at $k \approx 2 \times 10^6$ m^{-1}. For $k > 2 \times 10^6$ m^{-1}, phase speeds decrease and saturate at higher wave numbers. Here, we consider two different spin polarization strengths which are included in the formulation via $V_{\rm F}$ fully spin-polarized ($\eta = 1$) and partially spin-polarized ($\eta = 0.5$). The results show that the spin effect significantly influences the propagation characteristics of these modes, with higher spin polarization strengths ($\eta = 1$) leading to greater changes in phase speed and partially spin-polarized ($\eta = 0.5$) leading to more moderate alterations in propagation behavior. The spin effect causes noticeable deviations in the phase speed behavior of the modes, particularly at higher spin polarization strengths. This indicates that the spin polarization plays a crucial role in shaping the propagation characteristics of these waves. Overall, the study demonstrates that the spin polarization strength plays a crucial role in determining the propagation characteristics of these modes. Understanding how spin affects the phase speed can provide valuable insights for applications involving spin-polarized waves.

Figure 2 depicts the variation of ω_r with electric field strength ($\mathbf{E}_0$) at $k = 2 \times 10^5$ m^{-1}. It was found that both the modes are contra-propagating to each other with electric field strength. In the presence of electric field both the spin-modified modes propagate in opposite directions but with larger phase speeds. This indicates that the electric field has a significant impact on the propagation of the spin-modified modes, causing them to travel in opposite directions with increased speed. The observed contra-propagating behavior suggests a complex interaction between the modes and the electric field. The results show that the degree of spin polarization, represented by η, influences the behavior of the modes. Fully spin-polarized ($\eta = 1$) and partially spin-polarized ($\eta = 0.5$) exhibit identical characteristics of contra-propagating behavior, but with varying phase speeds. This demonstrates that the level of spin polarization plays a central role in determining the propagation characteristics of the spin-modified modes.

Figure 3 depicts the variations of growth rate with cyclotron frequency ω_c. Variation of both the modes increases with increasing cyclotron frequency, reaches to maximum at $\omega_c \approx 3 \times 10^{12}$ s^{-1} and then starts decreasing. This trend suggests that there is an optimal cyclotron frequency for maximizing the real parts of frequency. Beyond this point, the real parts begin to decrease, indicating a shift in behavior. We consider higher spin polarization strengths ($\eta = 1$) in both cases. Spin polarization strength is included in the study through V_{F}, which modifies the plasma frequency. In the magnetized plasma medium, the cyclotron frequency via the magnetic field strength also plays a crucial role in determining the behavior of the system. The interplay between spin polarization strength, plasma frequency, and cyclotron frequency is effectively clarified by this curve. The peak of real parts occurs at a specific combination of parameters at 3×10^{12} s^{-1}, providing valuable insight into the system's dynamics. This curve highlights the complex relationship between these key factors and their impact on the behavior of the system in a magnetized plasma medium. This curve provides valuable insights into the complex dynamics of magnetized plasma systems.

4. Conclusions

Based on the above discussions, the following conclusions may be drawn:

1. Studying the spin-dependent nonlinear wave modes in magnetized quantum plasma is important, from the diagnostics point of view, since the observation of the propagation characteristics of the wave modes may be used to understand the behavior of magnetic fields in quantum plasma.

2. Furthermore, analysing the spin-dependent nonlinear wave modes can provide valuable insights into the interaction between particles and magnetic fields within plasma. This research can ultimately contribute to advancements in plasma diagnostics and magnetic field manipulation techniques.

3. It can be observed from results that, at high spin polarization strengths, the phase velocities of contra-propagating modes increase with electric field strength, and this behavior indicates a complex interplay between magnetic fields and spin-dependent nonlinear wave propagation in quantum plasma.

4. New modes of wave propagation may emerge as a result of nonlinear interactions, providing insights into the fundamental dynamics of quantum plasma systems. Exploring these complex interactions can potentially lead to advancements in fields such as quantum computing and magnetic confinement fusion.

5. By investigating these wave modes, researchers can gain a deeper understanding of how magnetic fields influence plasma behavior and potentially develop more efficient ways to control and manipulate these fields. This knowledge could lead to advancements in various fields, such as fusion energy research and space exploration.

6. This analysis established that the electron's spin effect in magnetized quantum plasma, which includes quantum effects (Bohm potential, quantum pressure, and spin effects), can also lead to a better understanding of how magnetic fields influence particle behavior at the quantum level.

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НОВІ СПІН-ЗАЛЕЖНІ
НЕЛІНІЙНІ ХВИЛЬОВІ МОДИ
В НАМАГНІЧЕНІЙ КВАНТОВІЙ ПЛАЗМІ

Ми аналітично досліджуємо нелінійну нестабільність та зміни спектрів акустичних хвильових мод у намагніченій напівпровідниковій квантовій плазмі. Ці зміни пов'язані з появою нових спін-залежних акустичних мод, які можна контролювати зовнішніми магнітними полями. Ми вважаємо, що цю нелінійність викликано нелінійною залежністю густини індукованого струму в n-напівпровіднику InSb, який опромінюється CO_2 лазером при 77 К. Квантову MHD модель узагальнено на інші спінові ефекти – для вивчення динаміки акустичних хвиль та дослідження спінових властивостей електронів для застосування у напівпровідникових пристроях.

Ключові слова: квантова плазма, взаємодія лазерного випромінювання з плазмою, параметрична взаємодія.