Original Research Article

Influence of Quantum Effects on Amplitude Modulation in n-InSb Semiconductor

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ABSTRACT

The effect of quantum mechanical corrections in semiconductor plasma has been analytically investigated through amplitude modulational instability in unmagnetized piezoelectric semiconductor crystals. In a semiconducting crystal, each energy level can be occupied at most by two electrons owing to the spatial overlap of the wave functions. The Fermi-Dirac distribution rather than Maxwells-Boltzmann distribution functions describe the occupation of the energy level of electrons and incorporate the new quantum forces associated with the quantum Bohm potentials. In this paper, our main aim was to explore the modification in the modulational characteristics of semiconductor plasmas using the QHD model. The results show significant changes in the amplitude modulational characteristics due to the quantum mechanical effects, highlighting the importance of considering quantum hydrodynamic models in semiconductor plasma studies. This research provides valuable insights for understanding the behavior of n-type InSb crystals under laser illumination at low temperatures.The numerical estimates are made for n-type InSb crystal at 77K duly shoneby pulsed 10.6 μm CO_2 laser.

Keywords:Quantum Plasma; Laser-plasma interaction; Modulational Instability;

1. INTRODUCTION

The field of modulational amplification can be traced from early experiments in communications between satellites, where a modulational signal is impressed on the optical beam using an electro-optic modulator [1]. Nowadays, the maximum bandwidth that can be achieved is limited to hundreds of MHz by commercially available external phase or intensity modulators [2–3]. The use of nonlinear optics' theoretical and experimental tools has sparked a resurgence of interest and increased activity in the field [4-5]. The ability to achieve higher bandwidths in modulational amplification is crucial for high-speed data transmission and advanced optical communication systems. Researchers are actively exploring new techniques and materials to overcome the limitations of current modulators and push the boundaries of achievable bandwidths even further. The majority of this interest stems from possible uses in mode-locking, optical beam deflection, and Q-switching of lasers to produce giant optical pulses [6]. Sound waves' ability to diffract light was first proposed by Brillouin in 1922 [7] and experimentally verified in 1932 [8].

A sound wave consists of a sinusoidal perturbation of the density of the material or strain that travels at the sound velocity. The sound wave causes a propagating modulation of the medium's refractive index. This modulation interacts with the fields of incident and diffracted beams, resulting in additional electric polarization of the medium and power exchange between the incident and diffracted beams. The phenomenon of modulational instability in a semiconducting medium can be described using electric polarization equations, which are cubic functions of the electric field amplitude. The third-order nonlinear optical susceptibility is a complex quantity that can describe the interaction of various resonant and nonresonant processes [9]. The third-order susceptibility tensor is a useful tool for explaining modulation in a Kerr active medium [10]. It provides a mathematical framework for understanding how the medium responds to intense light fields, leading to effects such as self-focusing and self-phase modulation.

In semiconducting crystals, each energy level can accommodate a maximum of two electrons due to the spatial overlap of wave functions and adherence to the Pauli exclusion principle. This limitation on the number of electrons per energy level is crucial for understanding the behavior of semiconductors in electronic devices, as it determines their conductivity and optical properties. The distribution of electrons follows the Fermi-Dirac distribution, which reflects quantum concepts and the statistical behavior of fermions at various energy states. The concept of electron gas in a metal or highly dense semiconductor is the most obvious example in which both plasma and quantum mechanical effects work concurrently. There has been an increasing interest in quantum mechanical effects in semiconductors, motivated by applications in ultrasmall electron devices [11] and in laser-plasma interactions [12].

In highly dense plasmas, new quantum forces, the quantum Bohm potential, and Fermi pressure are associated with the Fermi-Dirac distribution functions. These forces significantly alter the collective behavior of dense quantum plasmas. It is well known [13] that in quantum plasmas, the de Broglie wavelength of the majority of charge carriers is comparable to the dimension of the plasma. This leads to the manifestation of quantum effects on a macroscopic scale, impacting the overall dynamics and properties of the plasma. Understanding these quantum phenomena is crucial for advancing various technological applications and fundamental research in plasma physics.

Many authors have theoretically investigated the amplitude modulational instability of propagating beams because of its enormous technological potential [14–18]. The present authors performed research into the impact of quantum effects on the parametric amplification properties of semiconductor plasmas [19]. To the best of the authors' knowledge, no attempt has been made to study modulational characteristics in quantum semiconductor plasmas. Therefore, this study aims to fill this gap by analyzing the amplitude modulational instability in semiconductor plasmas considering quantum effects. The modification in the modulational characteristics of unmagnetised semiconductor plasmas as a result of the quantum correction, the authors hereby used the quantum hydrodynamic model developed by Manfredi, Haas, and others [20-23] to simulate the main characteristics of quantum mechanical effects.

Thus, in the present paper, we have obtained the third-order nonlinear susceptibility leading to the growth of the modulated waves and the threshold field required to incite the transverse amplitude modulation instability process with the influence of the quantum effect as presented in Section 2. Moreover, the study also investigates the impact of quantum corrections on the growth rate and stability of modulated waves in unmagnetised n-InSb semiconductor crystals. Section 3 deals with the numerical estimations of the growth rate of the modulated signal wave influenced by the external parameters. The n-InSb semiconductor crystals used in these analyses were properly illuminated by a CO2 laser.

2. THEORETICAL FORMULATION

To explore the amplitude modulation interaction and the amplification of modulated waves in a highly doped unmagnetized piezoelectric semiconductor, the study considers a homogeneous semiconductor plasma of infinite extent. This analysis focuses on the effects of nonlinear optical third-order susceptibility, which plays a key role in the observed phenomena.The classical hydrodynamic model of homogeneous semiconductor plasma of infinite extent (i.e. *kl*<<1, *k* being the wave number of the acoustic wave and *l* the mean free path of the electron) has been extended to include the necessary quantum mechanical corrections resulting in a component quantum plasma described by the following QHD model. The spatially uniform (wave vector $\left|\vec{k}_0\right| \approx 0$) pump electric field $E_0 \exp(-i\omega_0 t)$ is applied parallel to the wave vector $\vec{k}$ along the *x*-axis.

The de Broglie wavelength of the charge carriers can be comparable to the system's dimension when plasma is cooled to an exceptionally low temperature. In these circumstances, ultracold plasma behaves similarly to Fermi gas, and it is anticipated that quantum mechanical effects will be crucial in determining how charged particles behave. The most obvious instance of both plasma and quantum effects operating simultaneously is the electron gas in a metal or semimetal. On the other hand, statistical mechanics becomes crucial when the temperature falls below the Fermi temperature TF, the quantum effect becomes more significant, and the relevant statistical distribution shifts from Maxwell-Boltzmann to Fermi-Dirac [24].The QHD model used for one-component quantum plasma here includes thequantum pressure term and quantum Bohm potential. Quantum statistics is included in the model through the equation of state, which takes into account the Fermionic character of the electrons. The basic equations following Guha et. al. [25] and Manfredi [26] are as follows.

$$\frac{\partial \upsilon_0}{\partial t} + \nu \upsilon_0 = \frac{-e}{m} E_0 \tag{1}$$

$$\frac{\partial \upsilon_l}{\partial t} + \nu \upsilon_l + \left(\upsilon_0 . \frac{\partial}{\partial x} \right) \upsilon_1 = \frac{-e}{m_l} E_1 - \frac{1}{mn} \frac{\partial P}{\partial x} + \frac{\hbar^2}{4m^2 n_0} \frac{\partial^3 n_1}{\partial x^3} \tag{2}$$

$$\upsilon_0 \frac{\partial n_1}{\partial x} + n_0 \frac{\partial \upsilon_1}{\partial x} = -\frac{\partial n_1}{\partial t} \tag{3}$$

$$\frac{\partial E_1}{\partial x} + \frac{\beta}{\varepsilon} \frac{\partial^2 u}{\partial x^2} = \frac{-e n_1}{\varepsilon} \tag{4}$$

$$\rho \frac{\partial^2 u}{\partial t^2} - 2\rho \gamma_s \frac{\partial u}{\partial t} + \beta \frac{\partial E_1}{\partial x} = C \frac{\partial^2 u}{\partial x^2} \tag{5}$$

$$P = \frac{m V_F^2 n_1^3}{3n_0^2} \qquad (6)$$

where P is the Fermi pressure with $V_F = \left(\frac{2K_B T_F}{m}\right)$ as the Fermi speed in which K_B is the Boltzmann constant and T_F is the Fermi temperature. n_0 and n_1 are equilibrium and perturbed carrier densities, respectively. ρ is the mass density of the crystal, u is the displacement of the lattice, C is the elastic constant, and γ_s is the electrostriction coefficient of the crystal. First and second equations. explain the equations of motion for the carriers with zeroth and first-order oscillatory fluid velocities (υ_0, υ_1) of carriers with an effective mass m and charge e. The quantum mechanical effects which areknown asthe Bohm potential is represented by the $\hbar$ dependent term in Eq. (2).The Bohm potential is accountable for tunneling and differential resistivity in semiconductor physics. ν is the phenomenological electron collision frequency. The space charge field E_1 is determined by the Poisson eq. (4) where ε is the dielectric constant of the semiconductor.

In this process, an acoustic perturbation formed in the medium under the influence of a strong pump field gives rise to an electron density perturbation at the acoustic frequency, which combines nonlinearity with the pump wave and drives the acoustic wave at modulated frequencies. Following, Guha et al. [25] and using Eqs. (1) - (6) in the collision-dominated regime ($\nu >> k\upsilon_0$) we obtain,

$$\frac{\partial^2 n_1}{\partial t^2} + \overline{\omega}_p^2 + \nu\frac{\partial n_1}{\partial t} + \frac{n_0 e\beta}{m\varepsilon}\frac{\partial^2 u}{\partial x^2} = -\overline{E}\frac{\partial n_1}{\partial x} \qquad (7)$$

$$\overline{E} = -\frac{e}{m}E_0, \overline{\omega}_p^2 = \omega_p^2 + k^2 V_F^{'}, \; V_F^{'} = V_F\sqrt{1+\gamma_e}, \; \gamma_e = \frac{\hbar^2 k^2}{8mk_B T_F}$$

Where $\omega_p = \sqrt{n_0 e^2/m\varepsilon}$ is the plasma frequency and the Doppler shift has been ignored here under the assumption ($\omega_0 >> \nu > k\upsilon_0$).

The density perturbation associated with phonon mode n_s is assumed to vary as $\exp[i(k_s x - \omega_s t)]$ with angular frequency ω_s, and wave number k_s. The initial laser beam thus oscillates with this density perturbation to produce enforced wave disturbance at the upper $\omega_0 + \omega_s$ and lower $\omega_0 - \omega_s$ sideband frequencies [27]. This modulation process under consideration must fulfill the phase-matching conditions, $k_0 = k_1 \pm k_s$, $\omega_0 = \omega_1 \pm \omega_s$ known as the momentum and energy conservation relations.

Here, we have taken into considerationonly the resonant sideband frequencies ($\omega_0 \pm \omega_s$) (by considering the crystal to be of infinite extent) and higher-order scattering terms, being off-resonant, are neglected [28]. Using eq. (7) the density perturbations oscillating at the forced wave frequencies, i.e. upper and lower sideband frequencies may be expressed as.

$$n_1(\omega_+, k_+) = \frac{ik^3\beta^2 n_0 e E_1}{m\varepsilon\rho\,(\omega_s^2 - k^2 V_s^2 + 2i\gamma_s\omega_s)}[\overline{\omega}_p^2 - \omega_+^2 - i\nu\omega_+ + ik_s\overline{E}] \qquad (8a)$$

$$n_1(\omega_-,k_-)=\frac{ik^3\beta^2 n_0 eE_1}{m\varepsilon\rho(\omega_s^2-k^2V_s^2+2i\gamma_s\omega_s)}[\overline{\omega}_p^2-\omega_-^2-i\nu\omega_-+ik_s\overline{E}]$$

(8b)

where $\omega_+ = \omega_s + \omega_0$ and $\omega_- = \omega_s - \omega_0$

when deriving Eqs. (8), it has been considered that the sideband waves $n_1(\omega_\pm, k_\pm)$ vary as $\exp[i(\omega_\pm t - k_\pm x)]$. Equation (8) shows that the sideband waves are coupled to the acoustic mode via density perturbation produced by a strong pump field.

It is also evident from the above expression that $n_1(\omega_\pm, k_\pm)$ depends upon the magnitude of the pump intensity.The density perturbations resulting at the sideband frequencies affected the amplification and dispersion characteristics of the generated waves. The effect of the transition dipole moment has been neglected to study the contribution of nonlinear current density on the induced polarization of the medium.

The induced nonlinear current densities for the upper and lower sidebands are given by

$$J(\omega_\pm) = -n_1(\omega_\pm)e\upsilon_0 \tag{9}$$

Henceforth treating the induced polarization at the modulated frequencies $P(\omega_\pm)$ as the time integral of the nonlinear current density $J(\omega_\pm)$, we may write

$$P(\omega_\pm) = \int J(\omega_\pm)\,dt \tag{10}$$

The total effective nonlinear polarization of the modulated wave is obtained as

$$P_{eff} = P(\omega_+) + P(\omega_-) \tag{11}$$

To achieve resonant modulation, both sidebands must contribute equally, and the modulation is then transferred to the acoustic mode that is amplified.In highly doped regime by assuming $\omega_p \approx \omega_0 (\approx \omega_\pm)$ and $\omega_p >> \nu, \omega_s$, we obtain total effective polarization using Eqs. (8) to (9) as

$$P_{eff} = \frac{2\omega_p^2 e^2 \varepsilon A k^2 |E_0|^2 E_s(\delta^2+\nu^2)}{m^2\omega_0^2(\omega_s^2-k^2V_s^2+2i\gamma_s\omega_s)}\left[\left(\delta^2+\nu^2-\frac{k^2\overline{E}^2}{\omega_0^2}\right)^2+4\frac{k^2\overline{E}^2\delta^2}{\omega_0^2}\right]^{-1} \tag{12}$$

where $\delta = \omega_0 - \overline{\omega}_p$ $A = k^2K^2V_s^2$, $K = \beta^2/\varepsilon C$

To initiate modulational amplification in the medium, the pump amplitude must exceed a certain threshold value $E_{0,th}$ to supply the minimum amount of energy to the medium.Todetermine the threshold value of the pump amplitude required for the onset of the modulational amplification, we set $P_{eff} = 0$ and obtain,

$$E_{0,th} = \frac{m\omega_0}{ek}\sqrt{\delta^2+\nu^2} \tag{13}$$

Eq. (13) shows that the transverse modulational instability of the signal wave has a nonzero intensity threshold, which is influenced by the quantum effect through the term $\delta\left(= \omega_0 - \overline{\omega}_p\right)$. The polarization due to modulated frequencies ($\omega_\pm$) is defined as

$$P_{eff} = \varepsilon_0 \chi_{eff}^{(3)} |E_0|^2 E_s \tag{14}$$

From Eqs. (12) and (14), We may obtain effective third-order nonlinear susceptibility, which includes quantum mechanical effects as

$$\chi_{eff}^{(3)} = \frac{2\omega_p^2 e^2 \varepsilon A k^2 (\delta^2 + \nu^2)}{m^2 \omega_0^2 (\omega_s^2 - k^2 V_s^2 + 2i\gamma_s \omega_s)} \left[\left(\delta^2 + \nu^2 - \frac{k^2 \overline{E}^2}{\omega_0^2} \right)^2 + 4 \frac{k^2 \overline{E}^2 \delta^2}{\omega_0^2} \right]^{-1} \quad (15)$$

The effective third-order nonlinear susceptibility is influenced by the quantum mechanical correction through $\delta\left(= \omega_0 - \overline{\omega}_p\right)$. The above formulation reveals that the third-order optical susceptibility is also influenced by the carrier concentration through $\omega_p \neq 0$. Rationalization of Eq. (15) gives the real and imaginary parts of the effective third-order optical susceptibility as

$$\mathrm{Re}\left[\chi_{eff}^{(3)}\right] = \frac{2\omega_p^2 e^2 \varepsilon A k^2 (\delta^2 + \nu^2)(\omega_s^2 - k^2 V_s^2)}{m^2 \omega_0^2 \left[(\omega_s^2 - k^2 V_s^2)^2 + 4\gamma_s^2 \omega_s^2\right]} \left[\left(\delta^2 + \nu^2 - \frac{k^2 \overline{E}^2}{\omega_0^2} \right)^2 + 4 \frac{k^2 \overline{E}^2 \delta^2}{\omega_0^2} \right]^{-1} \quad (16)$$

$$\mathrm{Im}\left[\chi_{eff}^{(3)}\right] = \frac{4\omega_p^2 e^2 \varepsilon A k^2 (\delta^2 + \nu^2)\gamma_s \omega_s}{m^2 \omega_0^2 \left[(\omega_s^2 - k^2 V_s^2)^2 + 4\gamma_s^2 \omega_s^2\right]} \left[\left(\delta^2 + \nu^2 - \frac{k^2 \overline{E}^2}{\omega_0^2} \right)^2 + 4 \frac{k^2 \overline{E}^2 \delta^2}{\omega_0^2} \right]^{-1} \quad (17)$$

By using the real part of effective third-order optical susceptibility, one can study the modulated wave's dispersion characteristics.It can be identified from equation (16) that there is an intensity-dependent refractive index $\left[\mathrm{Re}\left[\chi_{eff}^{(3)}\right]\right]$leading to the possibility of focusing or defocusing the propagating beam. However, for nondispersive mode, i.e. for $\omega_s = k\upsilon_s$, we observe an anomalous dispersion characteristic of the medium.

The gain characteristics of the modulational instability process can be obtained by eq. (17) using the imaginary part of effective third-order optical susceptibility.In order to study the possibility of modulational amplification in a semiconductor, we employ the relation

$$\alpha_{eff} = \frac{-k}{2\varepsilon_1} \left[\chi_{eff}^{(3)}\right] \left|E_0\right|^2 \quad (18)$$

where α_{eff} is the effective nonlinear absorption coefficient of third order. The nonlinear steady-state growth of the modulated signal is possible only if α_{eff}, obtainable from Eq. (18) is negative.

Thus,Equations (17) and (18) provide the growth rate of the modulated beam for pump amplitudes significantly above the threshold electric field as

$$g_{QE} = \frac{2\omega_p^2 e^2 A k^3 (\delta^2 + \nu^2)\gamma_s \omega_s}{m^2 \omega_0^2 \left[(\omega_s^2 - k^2 V_s^2)^2 + 4\gamma_s^2 \omega_s^2\right]} \left[\left(\delta^2 + \nu^2 - \frac{k^2 \overline{E}^2}{\omega_0^2} \right)^2 + 4 \frac{k^2 \overline{E}^2 \delta^2}{\omega_0^2} \right]^{-1} \left|E_0\right|^2 \quad (19)$$

It hasbeen seen that both amplification as well as dispersion characteristics of modulational instability are effectively modified by quantum effect through $\delta\left(= \omega_0 - \bar{\omega}_p\right)$.

3. RESULTS AND DISCUSSION

Analytical investigations for amplitude modulational instability and the resultant amplification of modulated waves produced from the pump wave to the modulated wave are dealt with in the present section. The study focuses on understanding the conditions under which this instability occurs and how it affects the overall behavior of the system. The analytical outcomes obtained are applied to a centrosymmetric semiconductorsuch as n-InSb at 77K irradiated by a pulsed 10.6μm CO_2 laser. The physical constants involved are $\varepsilon_1 = 15.8$, $\gamma_s = 5\times10^{-10}$ Fm^{-1}, $\rho = 5.8\times10^3$ kgm^{-3}, $\omega_1 = 2\times10^{11}$ s^{-1}, $\omega_0 = 1.78\times10^{14}$ s^{-1}, $\nu = 4\times10^{11}$ s^{-1}, m^{-3}, $\beta = 0.054$ Cm^{-2}.

Figure 1 shows numerical estimates of the wave number dependence on the threshold field required to initiate modulational amplification processes.

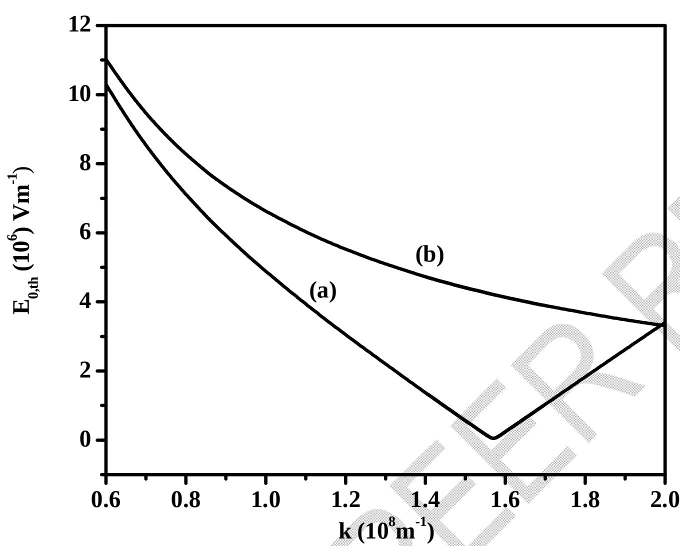

Fig. 1. Variation of threshold electric field $E_{0,th}$ (with quantum effect (curve - a) and without quantum effect (curve-b) of quantum effect) with wave number *k*.

Figure 1 shows thatthe threshold field $E_{0,th}$ continuously decreases with increasing wave number *k* in the absence of quantum effect. From the Eq. (13) for threshold electric field, it may be seen that $k$is present in the denominator as well as in the quantum correction term $\delta = (\omega_0 - \varpi_p)$ through ϖ_p =($\sqrt{\omega_p^2 + k^2 V_F^{'}}$). Therefore,the resonance between ϖ_p and ω_0 will also affect threshold characteristics with the quantum effect.

Hence curve a makes clear, initiallyfor small k values when $\varpi_p < \omega_0$, $(E_{0th})_{QE}$ decreases with *k*. At $k = 1.56\times10^8 m^{-1}$, $\varpi_p \approx \omega_0$ condition is achieved resulting into a minimum $(E_{oth})_{QE} \approx 5.4\times10^4 Vm^{-1}$in the characteristics. Now increasing k, ϖ_p becomes greater than ω_0 and this makes linear increment in the threshold value with *k* in the presence of quantum term. It may also be impliedfrom this figure that the magnitude E_{0th} is always greater than that of $(E_{0th})_{QE}$. As a result, it is possible to interpret that quantum effects play a significant role in reducing the threshold electric field $(E_{0th})_{QE}$ which is important for the fabrication of any nonlinear device.

The dependence of the gain coefficient (with and without quantum effect) with pump field E_0 is shown in Fig. 2. In both cases, the gain coefficient decreases as the pump's electric field increases. It is found that the gain coefficient is strongly affected by the quantum correction. It increases the magnitude of the gain coefficient as evident from curve a. This demonstrates the importance of considering quantum effects when analyzing the behavior of the gain coefficient in these systems.

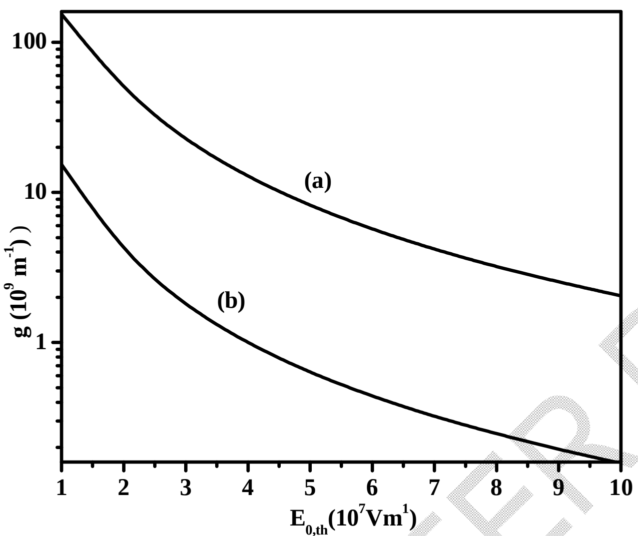

Fig. 2. Variation of gain coefficient g (with quantum effect (curve – a) and without quantum effect (curve – b) of quantum effect) with pump electric field E_0.

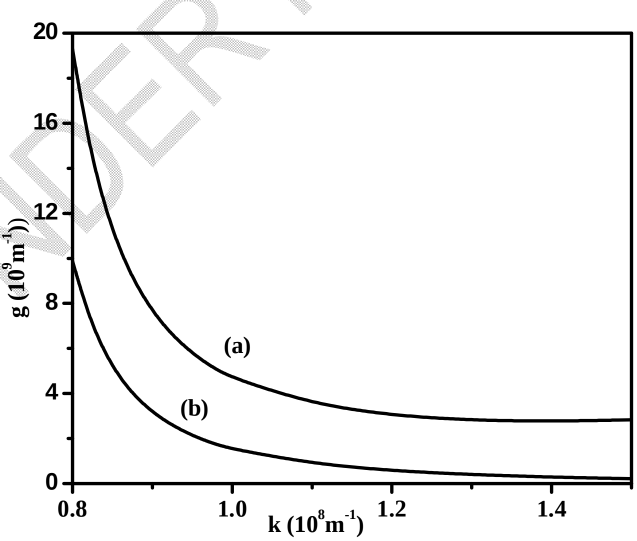

Fig. 3. Variation of gain coefficient g (with quantum effect (curve - a) and without quantum effect (curve -b) of quantum effect) with wave number *k*.

Fig. 3 illustrates the variation of gain coefficient (with quantum effect and without quantum effect) with wave number k. The presence of the quantum effect is found to be favorable in achieving a higher gain. In both cases, gain coefficient decays parabolically with increasing k value, becoming nearly independent of k as wave number increases.

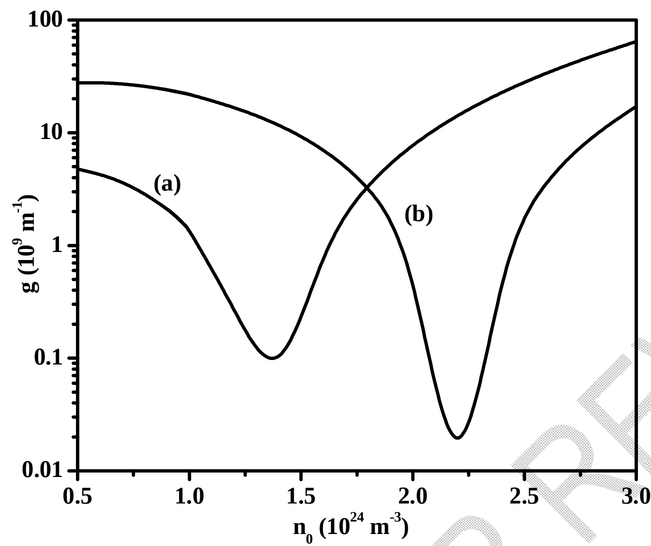

Fig. 4. Variation of gain coefficient g (with quantum effect (curve - a) and without quantum effect (curve - b)) with number density n_0.

Fig. 4 shows the variation of gain coefficient with free carrier density n_0. Again,a close look at the Eq. (17) reveals the critical dependence of gain coefficient on n_0 via $\delta\left(=\omega_0-\bar{\omega}_p\right)$ term. In the low doping regime where $\omega_0>\bar{\omega}_p$, the value of δ is positive and consequently gain decreases with n_0. As we increase doping concentration the value of plasma frequency increases. At a particular doping concentration $\bar{\omega}_p$ resonates with ω_0. At this resonance condition $\omega_0\approx\bar{\omega}_p$ when $n_0=1.3\times10^{24}m^{-3}$ in the presence of quantum correction and $n_0=2.2\times10^{24}m^{-3}$ without quantum terms, modulational gain achieve the minimum value. It is also implied from this figure that the quantum correction shifts the minimumtowarda lower number density value. a little away from this juncture results in $\delta\left(=\omega_0-\bar{\omega}_p\right)$ negative and eventually the gain increases with doping concentration. Both curves exhibit identical qualitative behavior.Carrier densities of this magnitude are highly relevant to III-V semiconductors and have been extensively studied by several researchers [29-30]. These high carrier densities can significantly impact the electronic properties of the material, leading to unique quantum effects and potential applications in high-speed electronics and optoelectronics.

However, the doping should not exceed the limit for which the plasma frequency ω_p exceeds the input pump frequency ω_0, because in the regime when $\omega_p > \omega_0$ the electromagnetic pump wave will be reflected by the intervening medium. It may be thereby implied that moderately doped semiconductors are the most suitable hosts for the amplitude modulational instability process.

It has been found that the magnitude of the threshold electric field for the onset of modulational amplification is $5.4 \times 10^4 Vm^{-1}$ (with quantum effect) and $4.9 \times 10^6 Vm^{-1}$ (without quantum effect) and the respective excitation intensitiesare $2.6 \times 10^9 Wm^{-2}$ to $1.2 \times 10^{11} Wm^{-2}$. Such pump intensities are easily obtainable by using frequency-doubled CW and pulsed 10.6 µm CO_2 laser. The capability to achieve these excitation intensities with commonly used lasers renders the phenomenon of modulational amplification accessible for experimental investigation, with modulational processes potentially being easily excited in moderately doped piezoelectric semiconductors even at lower pump intensities.

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4. CONCLUSION

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

1. The quantum effect in the electron dynamics of the semiconductor plasma significantly increases the gain coefficient of modulational amplification in moderately doped semiconductors.This enhancement in gain coefficient allows for more efficient amplification of signals in these materials, making them ideal for applications requiring high amplification.
2. The inclusion of quantum effects in modulational processes opens new possibilities for improving signal amplification in semiconductor devices. Quantum effects, particularly through the quantum Bohm potential, significantly influence modulational instability and have a substantial impact on the modulational instability characteristics in n-type InSb semiconductor plasmas. These quantum effects alter the amplitude and stability of wave modulations, emphasizing the need to incorporate quantum considerations in analysing semiconductor plasmas.

3. The QHD model is crucial for accurate prediction in laser-illuminated environments. The model reveals modifications in the modulational stability and amplitude due to quantum effects, offering an essential framework for more accurate predictions in applications involving semiconductor crystals exposed to laser fields, particularly at low temperatures.

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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