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Quantum effect on parametric amplification characteristics in piezoelectric semiconductors

S. Ghosh *, Swati Dubey, R. Vanshpal

School of Studies in Physics, Vikram University, Ujjain 456010, India

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ABSTRACT

Using QHD model the parametric interaction of a laser radiation in an unmagnetised piezoelectric semiconductor has been studied. It is found that the Bohm potential in the electron dynamics enhances the gain coefficient of parametrically generated modes whereas reduces the threshold pump intensity.

1. Introduction

By employing the quantum hydrodynamic (QHD) model for the electron dynamics in the semiconductor plasma, in the present Letter optical parametric amplification (OPA) is analytically investigated in an unmagnetised n-type piezoelectric semiconductor. We have considered that the origin of nonlinear interaction lies in the second order susceptibility arising from the nonlinear induced current density. In the present work the classical hydrodynamic model has been extended by incorporating the quantum corrections. Influence of quantum effects on optical parametric amplification has been explored via determination of threshold electric field required for the onset of OPA process and parametric gain coefficient.

Second order nonlinear optics continues to be a topical area of research because of its tremendous potential in the design of photon based new materials for optical switching, data manipulating and information processing. The phenomenon of parametric interactions exhibits a distinctive role in nonlinear optics. Parametric processes have been widely used to generate tunable laser light at a frequency that is not directly available from a laser source; these frequency conversion techniques extend the spectral range covered by coherent sources [1–3]. Parametric oscillators, amplifiers, optical phase conjugators, etc. [4–6], are the outcome of parametric interactions in a nonlinear medium.

If the amplitudes of interacting waves are relatively small, the linear theory plays an important role in studies of waves and instabilities in the medium. However if the amplitude of the waves are sufficiently large, then one cannot ignore the nonlinearities. The nonlinearities contribute to localization of waves and lead to different types of nonlinear structures i.e. solitons, shocks, vortices, etc. The nonlinear interaction of large amplitude electromagnetic waves in metals, semimetals and semiconductors has been a subject of great interest in the past several decades [7–12]. The response of semiconductor plasmas to the intense light has been a fascinating field of research [13–17]. Semiconductors are used in most of the sophisticated, sensitive and ultrafast optoelectronic devices due to their compactness [18], provision of control of material relaxation time and highly advanced fabrication technology. Second order nonlinearity due to carrier diffusion current was reported [19] in magnetised diffusive semiconducting plasma.

However, in all these studies, quantum mechanical effects were not taken into account. Of late, microscopic optical phenomena such as generation of three wave parametric interactions have attracted keen attention of a large number of workers in the field of quantum optics [20–22]. Many investigations are based upon the nonlinear optical response in a semiconducting medium [21,22]. In recent years, there has been a growing interest on the quantum mechanical effects in plasma physics. For super cooled Fermi plasma, the de Broglie wavelengths of the plasma particles may be comparable to the Debye length [23]. Using the magneto hydrodynamic model for plasmas, Haas, Manfredi, and others [24,25] have developed the quantum hydrodynamic model (QHD) model for quantum plasmas. Recently, the derivation of such QHD model

* Corresponding author. Tel./fax: +91 9425984816.
E-mail address: drsanjayghosh.ssp@gmail.com (S. Ghosh).

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from first principle has attracted a lot of interest in the mathematical and physical literature [26–29]. The interest relies on the need of accurate efficient simulations of quantum semiconductor devices like lasers and tunneling diodes. These models proved to be computationally less expensive. Recently QHD model is applied to the dynamics of free electron laser in the quantum regime [30].

The quantum transport models have also received great attention in recent years mainly due to their relevance for describing quantum effects in plasmas and in microelectronic devices. Quantum plasmas [31] have immense applications which include quantum plasma echoes [32], the expansion of a quantum electron gas into vacuum [33], quantum plasma instabilities [34]. Self consistent fluid model for a quantum electron gas is a useful tool for the study of quantum transport in solid state plasma [35].

Quantum hydrodynamic models become important and necessary to model and simulate electron transport, affected by extremely high electric fields. The QHD model consists of a set of equations describing the transport of charge, momentum and energy in a charged particle system interacting through a self consistent electrostatic potential. Mathematically, the QHD model generalizes the fluid model for plasmas with the inclusion of a quantum correction term, i.e. Bohm potential. This extra term can appropriately describe negative differential resistivity in resonant tunneling diodes [28]. Such kind of quantum mechanical phenomena cannot be simulated by classical hydrodynamical models. The advantage of the macroscopic quantum hydrodynamical model is that they are able to describe directly the dynamics of physical observable and simulate the main characters of quantum effects. This motivates the development of quantum transport model for charged particle systems.

As far as we know, study of optical parametric amplification incorporating quantum corrections in semiconductor plasma has yet to be made. Hence motivated by the above state of art, in the present Letter we have analytically investigated the quantum effects on parametric amplification in one component semiconductor plasma. Here we have obtained the second order susceptibility arising from nonlinear induced current density of mobile electrons in a doped semiconductor crystal. Effect of Bohm potential on the parametric gain coefficient is studied through the quantum corrections in classical hydrodynamic equations. In Section 2, we first derive the linear response of semiconductor plasmas in the presence of high frequency electromagnetic waves. The nonlinearity is due to the interaction of the high frequency incident pump and the generated sideband waves. In Section 3, numerical estimations are made for n-CdS crystal duly irradiated by a CO_2 laser.

2. Theoretical formulation

In order to study the parametric amplification in a highly doped semiconductor, arising due to nonlinear effective optical susceptibility χ_{en}, a spatially uniform pump electric field (i.e. pump wave vector $|k_0| \approx 0$) $\hat{x}E_0 \exp(-i\omega_0 t)$ is applied to semiconducting plasma. The classical hydrodynamic model of homogeneous semiconductor plasma of infinite extent (i.e. $kl \ll 1$, k being the wave number of the acoustic wave and l the mean free path of the electron) has been extended to include essential quantum corrections resulting into one component quantum plasma described by the following QHD model.

Due to the fact that when plasma is cooled to an extremely low temperature, the de Broglie wavelength of the charge carriers can be comparable to the dimensions of the system. In such situations, ultracold plasma behaves like a Fermi gas and quantum mechanical effects are expected to play a central role in the behavior of charged particles. Therefore plasma system may be considered as a one-dimensional zero temperature Fermi gas. For definiteness, we assume that the plasma particles in one-dimensional zero temperature Fermi gas obey the pressure law [24,36]

$$P = \frac{mV_F^2 n_1^3}{3n_0^2} \tag{1}$$

where P is the Fermi pressure with $V_F = (\frac{2K_B T_F}{m})$ is the Fermi speed. K_B is the Boltzmann constant, T_F is the Fermi temperature of electrons, n_0 and n_1 are unperturbed and perturbed electron densities respectively. Pressure is interpreted as a result of velocity dispersion around the mean velocity of the fluid. The pressure term chosen here is obtained on assuming a zero-temperature Fermi distribution for the electrons.

Following Guha et al. [37] and Manfredi [38], the other required basic equations are:

$$\frac{\partial \upsilon_0}{\partial t} + \nu\upsilon_0 = -\frac{e}{m}E_0 \tag{2}$$

$$\frac{\partial \upsilon_1}{\partial t} + \nu\upsilon_1 + \left(\upsilon_0 \cdot \frac{\partial}{\partial x}\right)\upsilon_1 = -\frac{e}{m}E_1 - \frac{1}{mn_0}\frac{\partial P}{\partial x} + \frac{\hbar^2}{4m^2 n_0}\frac{\partial^3 n_1}{\partial x^3} \tag{3}$$

$$\upsilon_0\frac{\partial n_1}{\partial x} + n_0\frac{\partial \upsilon_1}{\partial x} = -\frac{\partial n_1}{\partial t} \tag{4}$$

$$\frac{\partial E_1}{\partial x} + \frac{\beta}{\varepsilon}\frac{\partial^2 u}{\partial x^2} = -\frac{n_1 e}{\varepsilon} \tag{5}$$

$$\rho\frac{\partial^2 u}{\partial t^2} + 2\gamma_s\rho\frac{\partial u}{\partial t} + \beta\frac{\partial E_1}{\partial x} = C\frac{\partial^2 u}{\partial x^2} \tag{6}$$

One-dimensional QHD model (Eqs. (1)–(6)) includes two different quantum effects: (1) quantum diffraction and (2) quantum statistics. Quantum diffraction is taken into account by the terms proportional to $\hbar^2$ in Eq. (3), where $\hbar$ is the Planck's constant divided by 2π. These contributions may be interpreted alternatively as quantum pressure terms or as quantum Bohm potentials [39]. The quantum statistics is included in the model via the equation of state (Eq. (1)) which takes into account the fermionic character of the electrons. Eqs. (2) and (3) describe the electron motion under the influence of the fields associated with the pump and side band waves, respectively in which m and ν stand for the effective mass and phenomenological momentum transfer collision frequency of electrons. The pump magnetic field in Eq. (2) is neglected by assuming $\omega_p \approx \omega_0$. Eq. (3) actually represents the equation of motion of the quantum hydrodynamical model (QHD). It is a well-known fact that the linearly polarized transverse electromagnetic wave is not affected by the quantum effects. Thus the pump wave dispersion relation is unaffected by the quantum effect, but the sideband contains this effect. Conservation of charge is represented by the continuity equation (4). Eqs. (3) and (4) are actually first and zeroth moment of the Boltzmann equation under adiabatic conditions (i.e. heat flow vector $\vec{q} = 0$ or small velocity spread $\vec{q} \approx 0$) leading to equations of motion and continuity, respectively. Under above assumptions the sequence of moment equation may safely be terminated to achieve Eqs. (3) and (4). The space charge field E_1 is determined from Poisson equation (5) in which the last term on L.H.S. represents the contribution of piezoelectricity (through β, the piezoelectric coefficient) of the medium. Eq. (6) describes the lattice vibration in a piezoelectric crystal of material density ρ 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. Authors are interested to study the second-order optical effects induced through generated nonlinear current-density approach in presence of spatially uniform pump (i.e., pump wave vector $|k_0| \approx 0$); thus the pondermotive force term is neglected safely.