Quantum Effects on Brillouin Gain Coefficients of Semiconductor Magneto-plasmas

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***Abstract*- Using QHD model, quantum effects (QEs) on (steady-state and transient) Brillouin gain coefficients of semiconductor magneto-plasmas are investigated. Numerical analysis is made for n-InSb crystal – CO_2 laser system.**

I. Introduction

The study of stimulated Brillouin scattering (SBS) is currently an important topic of research because it forms the basis of various optoelectronic devices. Using the classical hydrodynamic (CHD) model, SBS under steady-state (SS) and transient (TR) regimes in semiconductor magneto-plasmas has been studied by one of us [1].

Over the last few years, there has been growing interest of researchers on analytical investigations of QEs in magneto-plasmas. For super cooled Fermi plasma, the de-Broglie wavelengths of the plasma particles become of the order of Debye length [2]. Manfredi and Hass [3] extended the well developed magneto hydrodynamic model to a newly developed quantum hydrodynamic (QHD) model for quantum plasmas [4]. QHD model is significant to simulate electron transport in magneto-plasmas. This model consists of a set of equations describing the transport of momentum, energy and charge in plasmas interacting via self consistent electrostatic potential. This model generalizes the CHD model of plasmas with the inclusion of a quantum correction (Bohm potential) term. Recently, using QHD model, the present authors [5] studied QEs on parametric amplification of acoustical phonons in semiconductor magneto-plasmas. In the present paper, we investigated the QEs on SS and TR Brillouin gain coefficients (BGCs) of semiconductor magneto-plasmas.

II. THEORETICAL FORMULATIONS

SBS occurs due to nonlinear interaction among three coherent fields in a Brillouin medium, viz. an intense pump field $E_0(x,t)=E_0\exp[i(k_0x-\omega_0t)]$, an induced acoustical vibrational mode $u(x,t)=u_0\exp[i(k_ax-\omega_at)]$, and a scattered Stokes component of pump field $E_s(x,t)=E_s\exp[i(k_sx-\omega_st)]$. The Brillouin medium is inserted in an external magnetic field B_0 (at right angles to the direction of propagation of pump wave).

It is well known fact that at extremely low temperature, the de-Broglie wavelength of plasma particles becomes of the order of system dimensions. Under such condition, the ultra-cold plasma acts as a Fermi gas and QEs arise which play significant role in modifying the behavior of plasma particles. Therefore, ultra-cold plasma may be treated as one-dimensional zero temperature Fermi gas. According to Hass et al. [6], the ultra-cold plasma particles in one-dimensional zero temperature Fermi gas follows the pressure law given by

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

where P is Fermi pressure, m is mass of a plasma particle (here electron); n_0 and n_1 are equilibrium and perturbed electron densities respectively. V_F is the Fermi speed given by

$$V_F=\frac{2k_BT_F}{m}, \tag{1b}$$

where T_F is the Fermi temperature of electrons. The Fermi pressure given by Eq. (1a) is interpreted as a consequence of velocity dispersion around mean velocity of plasma particles. It has been obtained by considering the zero-temperature Fermi distribution for the electrons.

Using the coupled mode approach and following the method adopted in Ref. [1], the expression for SS and TR BGCs (above threshold), including QEs, are obtained as:

$$(G_{B,ss})_{QE}=\frac{k_ak_s^2\omega_0^3I_0\delta_{\beta\gamma}[\nu\omega_0\Omega_a^2+\Gamma_a\omega_a(\omega_0^2-\omega_c^2)]}{4\eta^3\varepsilon_0^2c\rho\delta_3\omega_s(\Omega_a^4+4\Gamma_a^2\omega_a^2)[(\omega_0^2-\omega_c^2)^2+4\nu^2\omega_0^2]} \tag{2}$$

$$(G_{B,tr})_{QE}=(\Gamma_a\tau_p)^{1/2}[(2(G_{B,ss})_{QE}L)^{1/2}-(\Gamma_a\tau_p)^{1/2}], \tag{3}$$

where $\delta_{\beta\gamma}=\varepsilon_0\omega_p^2[\beta\gamma\delta_1\delta_2A+\gamma^2(2I_0/\eta\varepsilon_0c)]+\delta_3\omega_s\omega_0\gamma^2$, $\delta_3=1-\delta_4$, in which, $\delta_4=(\Omega_{ps}^2-i\nu\omega_s)(\Omega_{pa}^2+i\nu\omega_a)/k_s^2\bar{E}^2$ $\Omega_{ps}^2=\bar{\omega}_p^2-\omega_s^2$, $\Omega_{pa}^2=\bar{\omega}_p^2-\omega_a^2$, $A=\omega_p^2/(ek_a/m)$, $\bar{\omega}_p^2=[\nu^2\omega_p^2/(\nu^2+\omega_c^2)]+k^2V_F'^2$, in which $V_F'=V_F(1+\gamma_e)^{1/2}$ with $\gamma_e=\hbar^2k^2/8mk_BT_F$, I_0 is the pump intensity, η is the background refractive index of the Brillouin medium, Ω_a represents the acoustic wave dispersion, ω_p is the electron-plasma frequency, ω_c is the electron-cyclotron frequency.

Eqs. (2) and (3) reveal that both $(G_{B,ss})_{QE}$ and $(G_{B,tr})_{QE}$ are influenced by QEs by the quantum terms in $\bar{\omega}_p^2$ (via δ_3). Both, the electron concentration n_0 (via ω_p) and magnetic field B_0 (via ω_c) play important role in modifying the term $\bar{\omega}_p^2$. In low doping and high magnetic field regime when $\nu\omega_p/(\nu^2+\omega c^2) << k^2V_F^2$, either with increasing n_0 or decreasing B_0, the terms $\bar{\omega}_p^2-\omega_s^2$ and $\bar{\omega}_p^2-\omega_a^2$ become less negative and the parameter δ_3 decrease. Thus in this regime QEs dominate over plasma mode dispersion thereby enhancing $(G_{B,ss})_{QE}$ and $(G_{B,tr})_{QE}$. In high doping and low magnetic field regime when $\nu\omega_p/(\nu^2+\omega c^2) >> k^2V_F^2$, the terms $\bar{\omega}_p^2-\omega_s^2$ and $\bar{\omega}_p^2-\omega_a^2$ become more and more positive and plasma mode dispersion dominates over QEs and inclusion of QEs enhances $(G_{B,ss})_{QE}$ and $(G_{B,tr})_{QE}$.

III. RESULTS AND DISCUSSION

For numerical analysis, we choose n-InSb crystal – CO_2 laser system; the material parameters are given in Ref. [1].

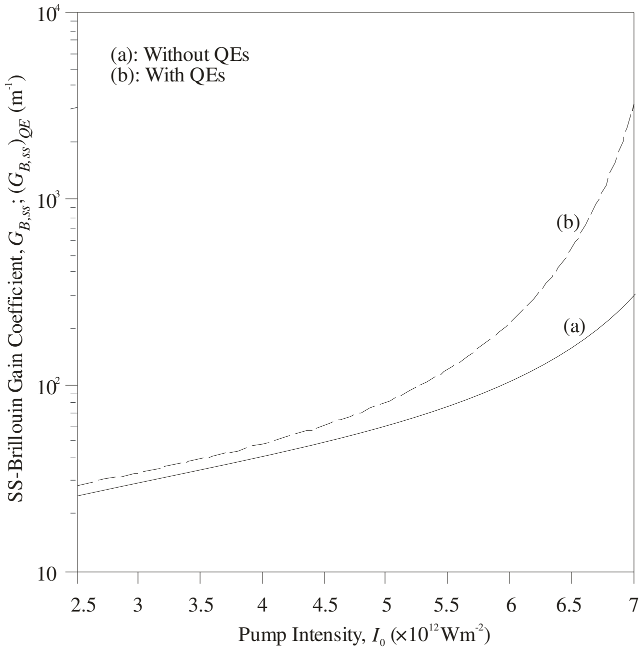

Fig. 1. Variation of SS BGC (without and with QEs) with pump intensity.

Fig.1 shows the variation of $G_{B,ss}$ and $(G_{B,ss})_{QE}$ with pump intensity I_0. For $I_0 < 4\times10^{12}$ Wm^{-2}, when QEs are insignificant, the curves corresponding to $G_{B,ss}$ and $(G_{B,ss})_{QE}$ are closer and show a linear variation with I_0. However, for $I_0 > 4\times10^{12}$ Wm^{-2}, QEs become significant, the curves gradually start deviating and show a parabolic variation with I_0. This indicates that QEs on SS BGC of semiconductor-plasmas are more pronounced at higher excitation intensity. This behaviour can be easily understood from intensity dependence of SS BGC. In Eq. (2), I_0 appears in numerator directly and denominator (via $\bar{E}^2$ in δ_3). The quantum term is included in δ_3 (via $\bar{\omega}_{ps}^2$ and $\bar{\omega}_{pa}^2$). For $I_0 < 4\times10^{12}$ Wm^{-2}, $\bar{E}^2$ is small so that $\delta_3(=1-\delta_4) \sim 1$ and hence $G_{B,ss} \propto I_0$. For $I_0 > 4\times10^{12}$ Wm^{-2}, $\bar{E}^2$ increases significantly so that $\delta_3(=1-\delta_4) \sim -\delta_4$ and the contributions arising due to quantum terms (via product term $\bar{\omega}_{ps}^2\bar{\omega}_{pa}^2$ in δ_4) contribute significantly, consequently resulting in dependence $G_{B,ss} \propto I_0^2$ and subsequently enhancing $(G_{B,ss})_{QE}$. The deviation of $G_{B,ss}$ and $(G_{B,ss})_{QE}$ curves from the parabolic shape at high pump intensity emphasis the necessity of incorporating QEs in SBS.

Fig. 2 shows the variation of $G_{B,tr}$ and $(G_{B,tr})_{QE}$ with pump pulse duration τ_p. When QEs are excluded, $G_{B,tr}$ increases with τ_p and at a certain value of τ_p, $G_{B,tr}$ attains a certain maximum value which remains constant over a certain range of τ_p. Such regimes may be regarded as quasi-SS regime. If τ_p is chosen beyond the quasi-SS regime, $G_{B,tr}$ diminishes very rapidly. The value of τ_p above which no transient gain could be achieved is known as optimum value of pump pulse duration $\tau_{p,opt}$. On the other hand, when QEs are included, the features of $(G_{B,tr})_{QE} - \tau_p$ plot are similar to $G_{B,tr} - \tau_p$ plot except that the inclusion of quantum terms: (i) enhances $(G_{B,tr})_{QE}$, (ii) broadens the transient Brillouin gain spectrum by shifting the quasi-SS regime and $(\tau_{p,opt})_{QE}$ towards higher values.

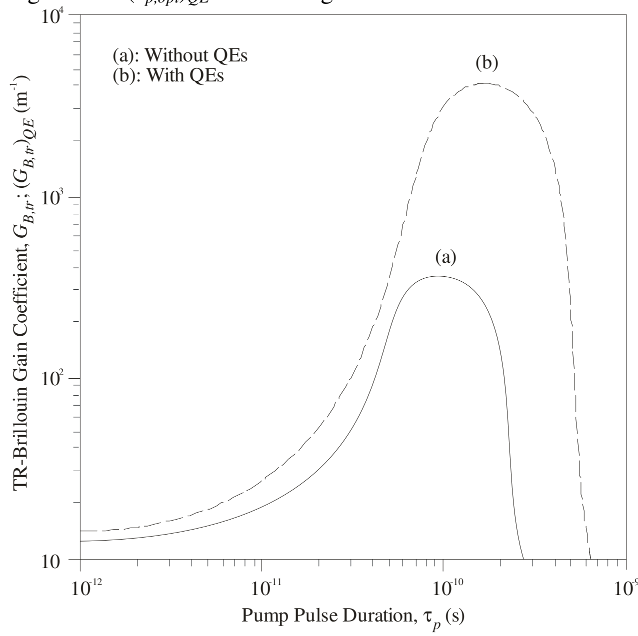

Fig. 2. Variation of TR BGC (without and with QEs) with pump pulse duration

In addition to QEs, $(\tau_{p,opt})_{QE}$ can be increased by increasing pump intensity. A calculation for n-InSb-CO_2 laser system for Eq. (3) yields $(\tau_{p,opt})_{QE} \sim 10^{-22}I_0$ s. This value of $(\tau_{p,opt})_{QE}$ not only explains the washing out of Brillouin gain at large pulse duration but also suggests that optimum pulse duration can be increased by increasing the pump intensity.

IV. CONCLUSIONS

The analysis deals with QEs on BGCs of semiconductor magneto-plasmas. Both, electron concentration and magnetic field play important role in modifying the quantum term. In low doping and high magnetic field regime, QEs dominate over plasma mode dispersion and vice versa; thereby enhancing SS and TR BGCs. The inclusion of QEs enhances the TR BGCs and broadens the transient Brillouin gain spectrum by shifting the quasi-saturation regime and the cut-off value of pump pulse duration towards higher values.

REFERENCES

[1] P. Aghamkar, M. Singh, N. Kishore, S. Duhan, and P.K. Sen, "Steady-state and transient Brillouin gain in magnetoactive narrow band gap semiconductors," *Semicond. Sci. Tech*., vol. 22, pp. 749-754, (2007).

[2] P.K. Shukla and S. Ali, "Dust acoustic waves in quantum plasmas," *Phys. Plasmas*, vol. 12, pp. 114502, 2005.

[3] G. Manfredi and F. Haas, "Self consistent fluid model for a quantum electron gas," *Phys. Rev. B*, vol. 64, pp. 075316, 2001.

[4] F. Hass, "A magnetohydrodynamic model for quantum plasmas," Phys. Plasmas, vol. 12, pp. 062117, 2005.

[5] D. Singh, B.S. Sharma, and M. Singh, "Parametric amplification of acoustical phonons in semiconductor magneto-plasmas: quantum effects," *Mat. Today: Proc*., 2021. https://doi.org/10.1016/j.matpr.2021.07.066.

[6] F. Haas, L.G. Garcia, J. Goedert, and G. Manfredi, "Quantum ion-acoustic waves," Phys. Plasmas, vol. 10, pp. 3858-3866, 2003.