Threshold and Gain characteristics of Stimulated Brillouin Scattering in n-InSb Crystal

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Abstract- Based upon the electromagnetic treatment, Stimulated Brillouin scattering (SBS) in a strain dependent n-InSb crystal which is subjected to a transverse magnetic field is investigated analytically. The origin of this nonlinear interaction is considered to be found in the third-order nonlinear optical susceptibility arising due to nonlinear current density and strain dependent polarization of the medium. The threshold condition is obtained for onset of the SBS process. The effective Brillouin susceptibility and gain is determined using coupled mode scheme of interacting waves. The effects of magnetic field and doping on threshold and SBS gain are studied. Numerical estimations are made at 77K duly shined by a pulsed 10.6 µm CO2 laser. In the highly doped regime the transverse magnetic filed effects a significantly decrease in the threshold and an appreciable enhancement in the SBS gain is obtained. When cyclotron frequency is nearly equal to the applied field frequency minimum threshold and maximum gain of SBS process is achieved. The numerical value of third-order nonlinear optical susceptibility by our analysis is well agreed with previously obtained theoretical as well as experimental values.

Index Terms- Nonlinear interaction, Semiconductor plasma, Stimulated Brillouin Scattering, Strain dependent dielectric constant, Piezoelectricity, Polar optical phonon.

I. INTRODUCTION

In the present work we have studied some interesting and important nonlinear (NL) effects related to propagation of electromagnetic waves with gaseous and solid state plasmas, a number of nonlinear phenomena play important role on the propagation and coupling of the electromagnetic waves with plasmas. Due to vast technological utility, large numbers of reports were made on the nonlinear interactions in semiconductor plasma [1-10].But very few reports were made on the nonlinear interactions in materials with strain dependent dielectric constants.

Here we intend to put the method developed by Ghosh and Saxena [11] for third order optical nonlinearities to test possible third order interactions such as stimulated Brillouin scattering etc. in semiconductor plasmas.

The object of our present work is two fold: one to look whether the said method is tenable for all possible third order interactions and second to achieve steady state gain in suitable semiconductors. In most of previous studies in nonlinear effects, the dielectric constant of the material is assumed to be constant, but such assumption is not justified and dielectric constant depend upon the deformation of material; which can be true for both piezoelectricity active as well as inactive materials. Taking this effect in to account Ghosh and Saxena [11] have pointed out that in case of nonlinear interactions, the large growth rates can be achieved in materials with high dielectric constants, which are otherwise not possible with piezoelectric materials.

II. SCOPE OF THE PRESENT WORK

Here we have investigated potentially useful nonlinear interactions of electromagnetic waves with semiconducting plasmas. During the interactions, the dielectric constant of the materials does not remains constant and infects depends upon the deformation of the materials. Due to this dependency of the dielectric constants on the deformation of the material shows that the interaction is a result of strain dependent dielectric constant (SDDC) in such materials with piezoelectric interactions [11, 12]. Thus the substances having large dielectric constant can be more efficient in the study of nonlinear interaction than piezoelectric substances. So we have confined our self to the study of substances having large dielectric constants.

In the earlier studies we found that propagation of pump wave infinite semiconductor plasma must have components that are both parallel and perpendicular propagation direction [13-14]. On this account we have considered a case in which hybrid mode is propagating obliquely to the external magnetic field. As for as our study, know such attempt has been made to determine the third order susceptibility arising due to induced current density and other material properties in semiconductor plasma with strain depend dielectric constant.

By the proper selection of material the electric density distribution and deformation by nuclear motion as well as interaction of ions with other elementary excitation can be studied by nonlinear susceptibility.

Motivated by the intense interest in the field stimulated scattering, we have reported the analytical investigation of stimulated Brillouin scattering for different parameters depending upon SDDC in medium.

III. THEORETICAL FORMULATION

This section deals with the theoretical formulation of third order effective nonlinear optical susceptibility $\chi^{(3)}$, for the signal electromagnetic waves in magnetized semiconductor plasma. Here we consider sample of n-type Centro symmetric semiconductors, viz., n-InSb immersed in a uniform magneto static field $\overrightarrow{B_s}$ applied along z-axis. The semiconductor is assumed to be the source of a homogeneous and infinite plasma which is subjected to an externally driven large amplitude spatially uniform electromagnetic wave (pump wave) viz. a high frequency laser or micro propagating along x-axis. The electric field of the spatially uniform pump wave is described by $E_o = E_0 \exp.(-i\omega t)$. Here authors have chosen Centro symmetric crystal so that the nonlinearities originated due to piezoelectricity and electro-optical effects can safely be ignored. Here we have considered the well known hydro dynamical model of homogenous one component plasmas. In order to study the effective nonlinear susceptibilities, we consider the propagation of an electromagnetic pump waves.

$$E_0 = E_0 \exp.[i(kx - wt)] \qquad (3.1)$$

Here we also employed the couple mode scheme to obtain the nonlinear polarization. Thus the dielectric constant of the medium is given by

$$\varepsilon = \varepsilon_0(1 + gS) \qquad (3.2)$$

Where ε is dielectric constant in absence of any strain S and the coupling coefficient $g\left(= \varepsilon_0 / 3\right)$ is due to strain dependent dielectric constant. The basic equation consider for analysis are

$$\frac{\partial v_0}{\partial t} + \nu v_0 = \frac{e}{m}[E_0 + v_0 \times B_0] = \frac{e}{m}E_{eff}. \qquad (3.3)$$

$$\frac{\partial v_1}{\partial t} + \nu v_1 + \left(v_0 \frac{\partial}{\partial x}\right)v_1 = \frac{e}{m}[E_1 + v_1 \times B_0] \qquad (3.4)$$

$$\frac{\partial n_1}{\partial t} + n_0 \frac{\partial v_1}{\partial x} + v_0 \frac{\partial n_1}{\partial x} = 0 \qquad (3.5)$$

$$\frac{\partial E_1}{\partial x} = \frac{n_1 e}{\varepsilon} - \left(\frac{gE_{eff}\varepsilon_0}{\varepsilon}\right)\frac{\partial^2 u^*}{\partial x^2} \qquad (3.6)$$

$$\rho\frac{\partial^2 u}{\partial t^2} + 2\gamma\rho\frac{\partial u}{\partial t} = C\frac{\partial^2 u}{\partial x^2} - (\varepsilon_0 g E_{eff})\frac{\partial E^*}{\partial x} \qquad (3.7)$$

where,

$$E_{eff} = E_0 + \vartheta_0 \times B_0$$

Equation (3.3) and (3.4) are the momentum transfer equation for the electrons under the influence of pump and product wave, respectively. In which e, m and ν are the charge, effective mass and phenomenological collision frequency of the electrons. Equation (3.5) is the continuity equation with n_0 and n_1 as equilibrium and perturbed carriers density respectively. Equation (3.6) represent the Poisson's equation where ε is dielectric constant of the semiconductor, ε_0 is absolute permittivity of the crystal and g is coupling constant due to SDDC . Equation (3.7) shows the equation of motion lattice in the crystal here C, ρ are linear elastic modulus of the crystal and mass density respectively, ϒ is the phenomenological damping constant. The last terms of RHS of equation give the contribution due to SDDC. In equation (3.4) we have neglected the effect due to ($v_0 \times B_0$) by assuming that the acoustic phonon mode is propagating along such a direction of the crystal, which produces a longitudinal electric field, e.g. if k_a is taken along (011) and the lattice displacement u is along (100), the electric field induced by the wave is longitudinal field. At very high frequencies of the field, which is quite large as compared to the frequencies of motion of the electrons in the medium, the polarization of the medium is considered on neglecting the interactions of the electrons with one another and with the nuclei of the atoms. Thus the electric induction in the presence of the external magneto static field [15] is given by

$$D = \varepsilon E_{eff}.$$

On differentiating equation (3.5) with respect to time and using equation (3.3) and (3.4) we get

$$\frac{\partial^2 n_1}{\partial t^2} + \nu\frac{\partial n_1}{\partial t} + \varpi_p^2 n_1 + \frac{n_0 e k_a^2 (\varepsilon_0 g E_{eff}) u^*}{m\varepsilon} = -\overline{E}\frac{\partial n_1}{\partial x} \qquad (3.8)$$

Where $\varpi_p = \left[\omega_p^2\left(\frac{\nu^2}{\nu^2 + \omega_c^2}\right)\right]^{1/2}$, $\overline{E} = \frac{e}{m}E_{eff}$, $\omega_p = \left(\frac{e^2 n_0}{m\varepsilon}\right)^{1/2}$ and $\omega_c = \left(\frac{eB_0}{m}\right)$ are the plasma frequency and cyclotron frequency of the electron respectively. Here we have neglected the Doppler shift under assumption that $\omega_0 >> \nu >> k_0 v_0$.

The perturbed electron density produced in the medium will have two components which may be recognized as fast and slow components. The fast component n_f correspond to the stocks component of the scattered light and varies as $\exp.[i(k_1 x - \omega_1 t)]$, whereas the slow component n_s is associated with the acoustic waves and varies as $\exp.[i(k_a x - \omega_a t)]$. Such that $n_1 = n_f + n_s$. From equation

(3.8) we obtain the following coupled wave equation under the rotating wave approximation.

$$\frac{\partial^2 n_f}{\partial t^2} + \nu \frac{\partial n_f}{\partial t} + \varpi_p^2 n_f + \frac{n_0 e k_a^2 (\varepsilon_0 g E_{eff}) u^*}{m\varepsilon} = -\overline{E}\frac{\partial n_s}{\partial x} \quad (3.9)$$

$$\frac{\partial^2 n_s}{\partial t^2} + \nu \frac{\partial n_s}{\partial t} + \varpi_p^2 n_s = -\overline{E}\frac{\partial n_f}{\partial x} \quad (3.10)$$

Thus, generated acoustic wave and stocks component coupled each other by the pump Centro symmetric medium. The slow component n_s may be obtained from equation (3.7) and (3.10) as

$$n_s^* = \frac{n_0 k \varepsilon_0 g (\varepsilon_0 g E_{eff}^*) E_1}{\varepsilon\rho (\delta_a^2 - 2i\gamma\omega_a)}\left[1 - \frac{(\delta_1^2 - i\nu\omega_1)(\delta_a^2 - i\nu\omega_a)}{k^2 |\overline{E}|^2}\right]^{-1} \quad (3.11)$$

Where

$$A = \left[1 - \frac{(\delta_1^2 - i\nu\omega_1)(\delta_a^2 - i\nu\omega_a)}{k^2 |\overline{E}|^2}\right]^{-1}$$

Now, stocks component of induced current density may be obtained from the relation

$$J_1 = e v_{0x} n_s \quad (3.12)$$

which yields,

$$J_1 = \frac{-ik^2 \omega_p^2 \varepsilon_0^2 g^2 \omega_0^3 E_0 E_0^* E_1}{\rho(\omega_0^2 - \omega_c^2)^2 (\delta_a^2 - 2i\gamma\omega_a^2)} (A) \quad (3.13)$$

The induced polarization may be expressed at the time integral of the induced current density. The Polarization may therefore be obtained from equation (3.13) as

$$P_{cd} = \frac{k^2 \omega_p^2 \varepsilon_0^2 g^2 \omega_0^3 E_0 E_0^* E_1}{\rho\omega_1 (\omega_0^2 - \omega_c^2)^2 . (\delta_a^2 - 2i\gamma\omega_a)} (A) \quad (3.14)$$

which yield to the third order optical susceptibility as,

$$P_{cd} = \varepsilon_0 \chi^{(3)} E_0 E_0^* E_1 \quad (3.15)$$

$$\chi^{(3)} = \frac{\varepsilon_0 k^2 \omega_p^2 g^2 \omega_0^3 E_0 E_0^* E_1}{\rho\omega_1 (\omega_0^2 - \omega_c^2)^2 . (\delta_a^2 - 2i\gamma\omega_a)} (A) \quad (3.16)$$

and strain dependent Polarization can be given as

$$P_{sd} = -\frac{k^2 \varepsilon_0^2 g^2 \omega_0^4 E_0 E_0^* E_1}{\rho(\omega_0^2 - \omega_c^2)^2 . (\delta_a^2 - 2i\gamma\omega_a)} \quad (3.17)$$

In a Centro symmetric semiconductor the total Polarization can be written as,

$$P = P_{cd} + P_{sd} \quad (3.18)$$

Then we get,

$$\chi^{(3)} = -\frac{\varepsilon_0 k^2 g^2 \omega_0^4}{\rho(\omega_0^2 - \omega_c^2)^2 . (\delta_a^2 - 2i\gamma\omega_a)} \times \left[1 + \left(\frac{\omega_p^2}{\omega_0 \omega_1}\right)(A)\right] \quad (3.19)$$

The threshold pump amplitude for the onset of stimulated Brillouin scattering may be obtained as

$$E_{oth} = {}^{m}\!/_{ek}\left(1 - \frac{\omega_c^2}{\omega_0^2}\right)\left[(\delta_1^2 - i\nu\omega_1)(\delta_a^2 - i\nu\omega_a)\right]^{1/2} \quad (3.20)$$

where $\delta_1^2 = \varpi_p^2 - \omega_1^2$ and $\delta_a^2 = \varpi_p^2 - \omega_a^2$

In order to investigate the effective Brillouin gain we used the following relation,

$$g_{eff} = -\frac{k}{2\varepsilon_1}\left[\chi_{eff}^{(3)}\right]_i |E_0|^2 \quad (3.21)$$

Carrier heating and temperature dependence of electron collision frequency to inside SBS, the fundamental requirement is to apply the pump field above the threshold value. Intense pump when passes threw a high mobility semiconductor, ions rema passive on account of their large inertia while due to low effective masses, the electron interacts with the pump and gain energy. As a result, the electron temperature (T_e) starts rising above the lattice temperature (T_o). The electron temperature T_e may be determined from the energy balance equation under steady state conditions.

Following Sodha et al. [16] for the said geometry, the power absorbed per electron from the pump is

$$e/_m R_e(v_0.E_0^*) = \frac{e^2\nu}{2m}\left[\frac{(\omega_c^2 + \omega_0^2)}{\left[(\omega_c^2 + \omega_0^2)^2 + 4\nu_0^2\omega_0^2\right]}\right] E_0 E_0^* \quad (3.22)$$

Where * denotes a complex conjugate of the quantity while R_e stands for the real part of the quantity concerned. The x component of v_0 used in the above relation may be evaluated from equation (3.3).

The electron lose that energy in collision with polar optical phonon following Conwell's [17] the average power loss per electron in the polar optical phonon scattering is given by

$$\langle P\rangle_{pop} = \left[\frac{2k_\beta\theta_D}{m\pi}\right]^{1/2} eE_{po}x_e^{1/2}k_0\left(\frac{x_e}{2}\right)\times\exp\left(\frac{x_e}{2}\right)\frac{\exp(x_0-x_e)-1}{\exp(x_e-1)}, \quad (3.23)$$

where, $x_{e,o} = \left(\frac{\eta\omega_l}{k_\beta T_{o,e}}\right)$ in which $\eta\omega_l$ is the energy of polar optical phonon (*pop*) given by $\eta\omega_l = k_\beta\theta_D;\theta_D$ being Debye temperature of the medium. $E_{po} = \frac{me\eta\omega_l}{\eta^2}\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_1}\right)$ is the field of *pop* scattering potential in which ε_1 and ε_∞ are the respective static and high frequency permittivity of the medium. $k_0\left(\frac{x_e}{2}\right)$ is the zero order Bessel function of first kind.

Equation (3.23) infers that with rise in electron temperature, power lost per electron in collisions with the *pop* also increases. A steady state is therefore, reached when the power lost in the *pop* scattering {equation (3.23)} becomes equal to the power gained {equation (3.22)} from the pump. Consequently, the electron plasma attains a steady temperature (T_e) somewhat above the lattice temperature (T_0). Hence using equations (3.22) and (3.23), one readily obtains

$$\frac{T_e}{T_0} = 1 + \frac{e^2\nu_0\tau(\omega_c^2-\omega_0^2)}{2m\left[(\omega_c^2-\omega_0^2)^2+4\nu_0^2\omega_0^2\right]}E_0E_0^* \quad (3.24)$$

where $$\tau^{-1} = \left(\frac{2k_\beta\theta_D}{m\pi}\right)^{1/2} eE_{po}x^{3/2}k_0\left(\frac{x_0}{2}\right)\frac{\exp\left(\frac{x_0}{2}\right)}{\exp(x_0)-1} \quad (3.25)$$

Thus, the pump energy dependent electron collision frequency (ECF) may be given by

$$\nu = \nu_0\left(T_e/T_0\right)^{1/2}, \quad (3.26)$$

where, T_e is the effective temperature of electron, T_0 is the lattice temperature, and the ECF when $T_e = T_0$.

IV. Results and Discussion

A close look at equation (3.21) reveals that the effective Brillouin susceptibility is a sensitive function of carrier concentration via plasma frequency ω_p and momentum transfer collision frequency through the factor (A). At lower concentration this magnitude of $(\chi_\beta)_{eff}$ is lowered by about five orders and become potentially non-usable for the fabrication of cubic NL devices. The magnitude of the third order susceptibility due to total current density (conduction as well as diffusion) agrees reasonably well with experimentally observed [18] and theoretically quoted values [19] using conduction current only.

A detailed numerical analysis of Brillouin gain is made in a Centro symmetric III-V semiconductor crystal at 77 K duly shined by 10.6 μm nanosecond CO_2 Laser. The material constant are taken as: $m = 0.015m_0$ (m_0 being the free electron mass), $\rho = 5.8\times10^3 kgm^{-3}$, $\nu = 3\times10^{11}\sec^{-1}, \omega_0 = 1.78\times10^{14}\sec^{-1}$, $\eta = 3.9$ $\nu_a = 4.8\times10^3 m\sec^{-1}$, and $\omega_a = 10^{12}\sec^{-1}$.

Figure 1 shows the dependence of threshold on carrier concentration via plasma frequency. Figure shows that the threshold electric field decreases with increase in plasma frequency ω_p,at the resonant condition $\omega_p^2 \approx \omega_1$, the threshold electric field attains its minimum value at $\omega_p \approx 3.8\times10^{13}s^{-1}$ or $E_{oth} \approx 0.01\times10^4 Vm^{-1}$. Further when we increase plasma frequency via carrier concentration beyond this critical value the threshold required for stimulated Brillouin Scattering increases.

In figure 2, we have plotted threshold pump amplitude as a function of magnetic field B_0 (In terms of ω_c/ω_0). It is clear from figure 2 that the threshold pump amplitude decreases continuously with increasing ω_c up to $\omega_c > \omega_0$. At resonance $\omega_c = \omega_0$, it attained its minimum value. Above this value of $\omega_c(\omega_c > \omega_0)$, the threshold pump amplitude increase with ω_c.

In figure 3, we shows the dependence of Stimulated Brillouin scattering gain (SBSG) on the carrier density (concentration) (in terms of ω_p) for $k \approx 2.5\times10^8 m^{-1}$ and $\omega_c \approx 3.14\times10^{13}$ and $E_0 = 10^7$. It is found that the gain of stokes mode (i.e. SBSG) in both the cases increases with increase in carrier concentration of the medium via ω_p. Hence, enhanced SBS gain of stokes mode can be achieved by increasing the carrier concentration of the medium by n-type doping. Therefore, it may be concluded that the heavily doped semiconductors are most suitable host for achieving the SBS process in semiconductor crystal.

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Variation of SBSG with magnetic field (in terms of ω_c / ω_0) is depicted in figure 4 at $E_0 = 10^7$ when $n_0 = 10^{24} m^{-1}$ and $k = 2.5\times10^8 m^{-1}$. From figure 4, it is clear that for weak magnetic field $(\omega_c << \omega_0)$ the SBSG are nearly independent but suddenly shows characteristic $\omega_c \to \omega_0$. At the resonant condition $\omega_c \approx \omega_0$. SBSG attends its maximum value $(g \approx 1.73\times10^{13})$. Further if we increase $\omega_c.(\omega_c > \omega_0)$, SBSG decease sharply with ω_c.

V. CONCLUSION

Based on the above discussion on may arrive to the following conclusion –

1. Threshold pump electric field required for the incite the stimulated Brillouin scattering process can be minimized by adjusting the carrier density and applied magneto static field.
2. By controlling the magnitude of externally applied magnetic field one may time the magnitude of Brillouin gain. It is found that when cyclotron frequency is nearly equal to applied pump frequency maximum gain of SBS process is achieved.

The present analysis on SDDC provides a model most appropriate for the finite laboratory semiconductor plasma. It is expected that the experimental study based on this phenomena would open a new vista of energy conversion devices for developing potentially useful Brillouin cells, high speed optoelectronic, instrumentation etc.

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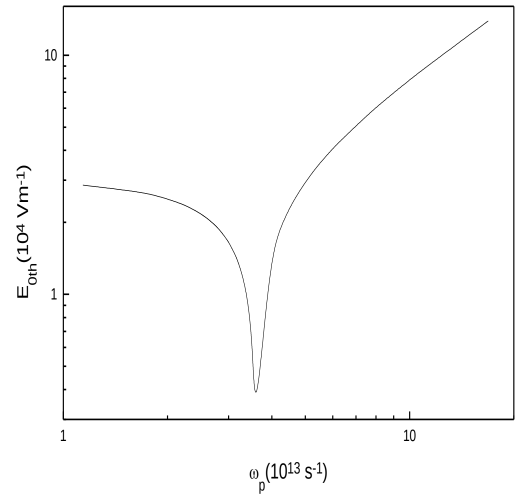

Figure 1:Nature of dependence of threshold pump field E_{0th} on carrier concentration(Through plasma frequency ω_p) in n-InSb crystal.

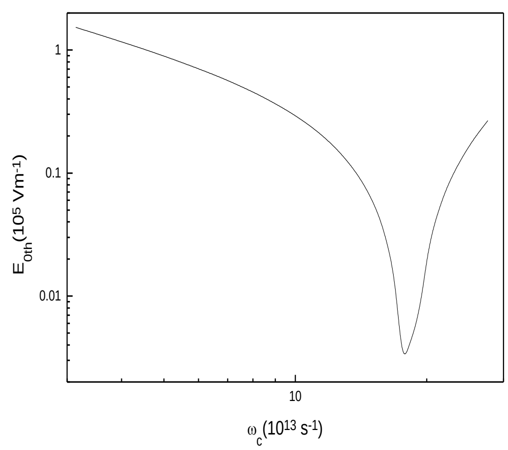

Figure 2: Variation of threshold pump field E_{oth} with cyclotron frequency ω_c

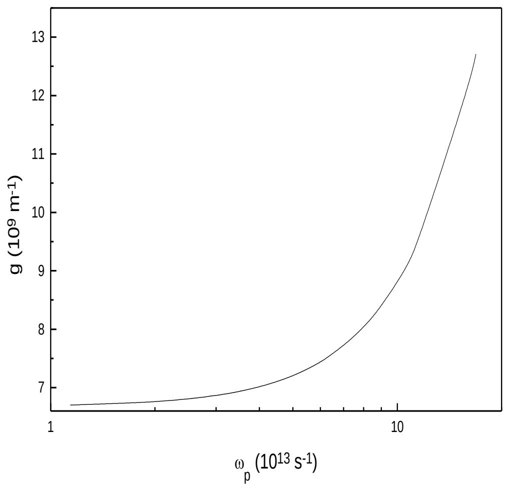

Figure 3: Variation of SBS gain with plasma Frequency ω_p

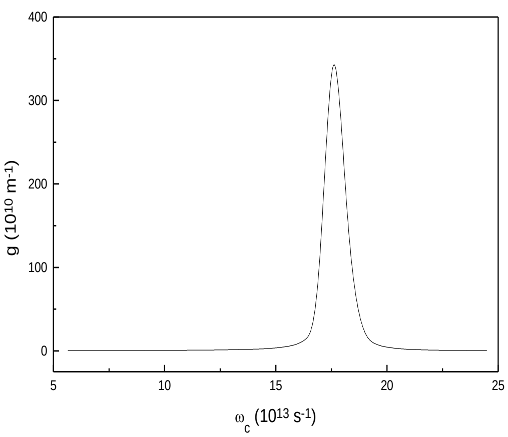

Figure 4: Variation of SBS gain with cyclotron frequency ω_c

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