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Stimulated Brillouin Scattering in ion implanted semiconductor plasmas having SDDC

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Abstract: A high power laser propagating through ion implanted semiconductor plasma undergoes stimulated Brillouin scattering (SBS) arises due to nonlinear current density and acousto-optical strain of the medium in third-order optical polarization. We have considered that the negatively charged colloidal grains (CGs) are embedded in semiconductor plasma by means of ion implantation. By considering net negative charge of the CGs, we present an analytical study of the effects of CGs on threshold intensity, effective susceptibility and Brillouin gain characteristics. It is found that as the charge on the CGs builds up, the Brillouin gain and threshold are significantly modifies the characteristics for the onset of SBS processes.

Index terms-stimulated Brillouin scattering(SBS),colloidal grains(CGs), strain dependent dielectric constant(SDDC)

1. Introduction:

Stimulated Brillouin scattering (SBS) has numerous applications in diverse areas ranging from optical phase conjugation, real-time holography, optical storing and pulse compression for laser-induced fusion. In laser induced fusion experiments, the SBS is of great concern because it significantly redirects the pump energy away from the target and adversely affects the energy absorption. It is therefore, desirable to minimize SBS process in these experiments [1-5].

The origin of SBS lies in the effective third-order optical susceptibility of the medium. In SBS phenomenon, the maximum scattering occurs in the backward direction [6]. Semiconductors are particularly the most promising materials with highest probability of large third-order nonlinear optical phenomena to occur and are used for fabrication of sophisticated optical devices [7].

Ion implantation a process in which use of ions is made to dope and modify semiconductor materials. The colloids that act as third species or foreign particles are the result of the implantation of any metal ion inside the medium. Colloidal plasmas are a new and fascinating field of plasma physics. These colloids acquire a negative charge through the sticking of high mobility free electrons on them. The negatively charged colloidal grains (CGs) are assumed to be of uniform size and smaller than both the wavelength under study and the carrier Debye length [8-9].

In the present paper, we investigate the effects of negatively charged CGs on the SBS through third order optical susceptibility, originating from induced current density and acousto-optical polarization, in a transversely magnetized n-type ion implanted semiconductor plasmas. The presence of charged CGs in semiconductor plasma medium add new dimensions to the analysis presented in n-doped magneto-active semiconductors with strain dependent dielectric constants (SDDC). It is found that ion implantation modifies the properties of material.

2. Theoretical Farmulation:

We have considered the well-known hydrodynamic description of a homogeneous, ion-implanted n-type semiconductor plasma having SDDC (for which $k_a l \ll 1$, k_a and l being the acoustic wave number and mean free path of an electron, respectively).In order to make an analytical study of the threshold pump field, threshold intensity and effective gain constant of Brillouin cell made of a homogeneous, ion-implanted n-type crystal. The theoretical formulation starts with the derivation of the total current density $\vec{J}$ for the resonant Stoke's component arises due to nonlinear interaction of the waves, followed by deduction of the effective Brillouin susceptibility through nonlinear polarization arising due to nonlinear induced current and acousto-optical strain. We apply the pump electric field $\overrightarrow{E_0}\exp[i(\overrightarrow{k_0}x-\omega_0 t)]$ parallel to the acoustic wave $\overrightarrow{k_a}$ (along the x-axis), and dc magnetic field $\overrightarrow{B_o}$ normal to $\overrightarrow{k_1}$ (along the z-axis).

The basic equations are employed for analysis:

$$\frac{\partial v_0}{\partial t}+\upsilon v_0=-\frac{eE_{eff.}}{m} \qquad (1)$$

$$\frac{\partial v_1}{\partial t}+\upsilon v_1+\left(v_0\frac{\partial}{\partial x}\right)v_1=-\frac{e}{m}(E_1+v_1\times B_0)-\frac{k_BT}{mn_{0e}}.\nabla n_1 \qquad (2)$$

$$\frac{\partial n_1}{\partial t}+\delta_d n_0\frac{\partial v_1}{\partial x}+v_0\frac{\partial n_1}{\partial x}=0 \qquad (3)$$

$$\frac{\partial^2 u}{\partial t^2}=\frac{c}{\rho}\frac{\partial^2 u}{\partial x^2}-\frac{(\varepsilon gE_{eff.})}{\rho}.\frac{\partial E_1^*}{\partial x} \qquad (4)$$

$$\frac{\partial E_1}{\partial x}=-\frac{n_1 e}{\varepsilon}+gE_{eff.}\frac{\partial^2 u^*}{\partial x^2} \qquad (5)$$

and

$$P_{ao}=-\varepsilon gE_{eff}\nabla u^* \qquad (6)$$

where $\overrightarrow{E_{eff.}}=\overrightarrow{E_0}+\overrightarrow{v_0}\times\overrightarrow{B_0}$

Equations (1) and (2) represent the zeroth and first order oscillatory fluid velocities of electrons with effective mass m and charge e; υ is the collision frequency. In equation (1), $\overrightarrow{E_{eff.}}$ represent the effective electric field which includes the Lorentz force $(\overrightarrow{v_0}\times\overrightarrow{B_0})$ in presence of external magnetic field $\overrightarrow{B_0}$.

Equation (3) is the continuity equation, where n_0 and n_1 are the equilibrium and perturbed carrier densities. In III-V semiconductor plasmas (i.e. $n_{0e}\approx n_{0h}\approx n_0$) embedded with CGs, the electrons and holes from all directions colloidal with CGs and get stick onto them. However, greater number of electrons sticks onto the CGs as compared to holes in given time interval. The charge imbalance parameter is defined as $\delta_d=\frac{Z_d e n_{0d}}{n_{0h}}$. The plasma is quasi neutral and the conservation of particle number density must always holds. Thus charged should be hold: $n_{0e}e=n_{0h}e-Z_d e n_{0d}$

Where n_{0d} is concentration of CGs and Z_d is charge state of colloids. [10-12].

The equation (4) describes the lattice vibration in ion implanted semiconductor plasma in which ρ, u and c being mass density of the crystal, lattice displacement and crystal elastic stiffness, respectively. The space charge field $\overrightarrow{E_1}$ is determined by the Poisson's equation (5) in which $\vec{D} = \varepsilon \vec{E}(1 + gS)$ and $\varepsilon = \varepsilon_0 \varepsilon_s$ where $\vec{D}$ is the electric displacement, ε_s is dielectric constant in absence of any strain, $S\left(= du/dx\right)$ and $g\left(= \varepsilon_s/3\right)$ is coupling constant due to SDDC. Equation (6) shows that the acoustic wave generated due to acousto-optic strain.

The interaction of the pump with the generated acoustic wave produces an electron density perturbation, which in turn drives an electron plasma wave and induces current density in the Brillouin active medium. In an n-typesemiconductor, this density perturbation can be obtained by using the standard approach [13]. Differentiating equation (3) and using Equations (1) and (5), we obtain.

$$\frac{\partial^2 n_1}{\partial t^2} + \upsilon \frac{\partial n_1}{\partial t} + \bar{\omega}_p^2 n_1 + \frac{\delta_d \omega_p^2 k^2 \varepsilon g E_{eff}.u^*}{e} = ikn_1\bar{E} \tag{7}$$

Where, $\bar{\omega}_p^2 = \left[\delta_d\left(\omega_p^2 + \frac{k_1^2 k_B T}{m}\right)\right], \omega_p^2 = \left(\frac{n_0 e^2}{m\varepsilon}\right), \quad \omega_c = \left(\frac{e.\left|\overrightarrow{B_0}\right|}{m}\right)$ and $\bar{E} = \frac{e\overrightarrow{E_{eff.}}}{m}$

Here, ω_c is cyclotron frequency and ω_p is the plasma frequency of the medium. We neglect the Doppler shift under the assumption that $\omega_0 >> \upsilon >> k_0 v_0$.

The perturbed electron concentration n_1 will have slow and fast components, such that $n_1 = n_s + n_f$. The slow component is associate with the low frequency acoustic wave ω_a ,while the fast component with high frequency electromagnetic wave $\omega_0 \pm \omega_a$. Considering only the Stoke's component of the scattered electromagnetic wave into account we shall have $\omega_1 = \omega_0 - \omega_a$ and $k_1 = k_0 - k_a$. For spatially uniform laser irradiation $|k_0| \approx 0$ yields $k_1 = k_a = k$, (say) we obtain the following coupled equations from equation (7) under rotating wave approximation (RWA),

$$\frac{\partial^2 n_s}{\partial t^2} + \upsilon \frac{\partial n_s}{\partial t} + \bar{\omega}_p^2 n_s = ikn_f^* \bar{E} \tag{8a}$$

$$\frac{\partial^2 n_f}{\partial t^2} + \upsilon \frac{\partial n_f}{\partial t} + \bar{\omega}_p^2 n_f + \frac{k_a^2 \delta_d \omega_p^2 \varepsilon g E_{eff}.u^*}{e} = ikn_s^* \bar{E} \tag{8b}$$

Equations (8a) and (8b) indicate that the slow and fast components of the density perturbations are coupled to each other via the pump field. Thus, it is obvious that the presence of the pump field is the fundamental necessity for SBS to occur.

The slow component n_s^* may be obtained from Equations (4) and (8) as

$$n_s^* = -\frac{mk^2\delta_d\omega_p^2\varepsilon^2 g^2 E_{eff.}^* . E_1}{e^2\rho\left(\omega_a^2 - k^2 v_a^2\right)}\left[1 - \frac{\left(\Delta_a^2 + i\omega_a\upsilon\right)\left(\Delta_1^2 - i\omega_1\upsilon\right)}{k^2\overline{E}^2}\right]^{-1} \tag{9}$$

where , $v_a = \sqrt{\frac{c}{\rho}}$, $\Delta_a^2 = \left(\overline{\omega}_P^2 - \omega_a^2\right)$ and $\Delta_1^2 = \left(\overline{\omega}_P^2 - \omega_1^2\right)$.

It is evident from the above expression that n_s strongly depends upon magnitude of the input pump intensity. The density perturbation thus produced subsequently affects the propagation characteristics of the generated waves.

The Stoke's component of the induced current density may be obtained from the relation

$$J(\omega_1) = \delta_d n_0 e v_{1x} + n_s^* e v_{0x} \tag{10}$$

The preceding analysis under RWA yields

$$J(\omega_1) = -\frac{i\delta_d n_0 e^2 E_1}{m\left(\omega_1^2 - \omega_c^2\right)} + \frac{ik^2\delta_d\omega_p^2\varepsilon^2 g^2\omega_0^3\left|E_0\right|^2 E_1}{\rho\left(\omega_a^2 - k^2 v_a^2\right)\left(\omega_0^2 - \omega_c^2\right)^2} A \tag{11}$$

where $A = \left[\frac{k^2\overline{E}^2 - \left(\Delta_a^2 + i\omega_a\upsilon\right)\left(\Delta_1^2 - i\omega_1\upsilon\right)}{k^2\overline{E}^2}\right]^{-1}$ and $F_{0x} = \frac{e}{m}\left(E_{eff.}\right)_x = \frac{eE_0\omega_0^2}{m\left(\omega_0^2 - \omega_c^2\right)}$

$$\text{Thus } \left(E_{eff.}\right)_x = \frac{E_0\omega_0^2}{\left(\omega_0^2 - \omega_c^2\right)} \tag{12}$$

The first term of the equation (11) represents the linear component of the induced current density and the second term represents nonlinear coupling amongst the three interacting waves *via* total nonlinear current density. The induced polarizations as the time integral current density can be written as

$$P_{cd}(\omega_1) = \int J(\omega_1)dt = -\frac{k^2\delta_d\omega_p^2\varepsilon^2 g^2\omega_0^3\left|E_0\right|^2 E_1}{\rho\omega_1\left(\omega_a^2 - k^2 v_a^2\right)\left(\omega_0^2 - \omega_c^2\right)^2} A \tag{13}$$

The origin of the SBS process lies in that component of $P_{cd}(\omega_1)$ which depends on $|E_0|^2 E_1$. The third-order susceptibility corresponding to $P_{cd}(\omega_1)$ is known as Brillouin susceptibility $(\chi_B)_{cd}$. Now, the threshold pump amplitude for the onset of SBS may be obtained by setting $P_{cd}(\omega_1)=0$ (i.e $A=0$) in equation (13), this condition yields,

$$|E_{0th}| = \frac{m}{ek}\left(1-\frac{\omega_c^2}{\omega_0^2}\right)\left[\left(\Delta_a^2 + i\omega_a\upsilon\right)^{1/2}\left(\Delta_1^2 - i\omega_1\upsilon\right)^{1/2}\right] \tag{14}$$

Therefore, the interaction between the pump and the centro-symmetric crystal will be dominated by the SBS phenomena at a pump power level well above the threshold field E_{0th}. The corresponding pump intensity can be obtained by using the relation

$$I_{th} = \frac{1}{2}\eta\varepsilon_0 c|E_{0th}|^2 \tag{15}$$

The Brillouin susceptibility due to induced current density is

$$(\chi_B)_{cd} = -\frac{\varepsilon k^2\delta_d\omega_p^2 g^2\omega_0^3}{\rho\omega_1\left(\omega_a^2 - k^2v_a^2\right)\left(\omega_0^2-\omega_c^2\right)^2}A \tag{16}$$

It is clear from above expression that $(\chi_B)_{cd}$ is a function of material parameters such as carrier concentration n_0 via plasma frequency ω_p, charge imbalance parameter δ_d, and B_0 via cyclotron frequency ω_c. Besides the Brillouin susceptibility $(\chi_B)_{cd}$, the system also possesses an acousto-optical polarization $P_{ao}(\omega_1)$ due to the interaction of the pump with acoustic wave generated in the medium. The acousto optical polarization is obtained from equations (4) and (6) as

$$P_{ao} = -\frac{k^2\varepsilon^2 g^2\omega_0^4|E_0|^2 E_1}{\rho\left(\omega_a^2 - k_a^2v_a^2\right)\left(\omega_0^2-\omega_c^2\right)^2} \tag{17}$$

The induced polarization due to acousto-optic interaction, is given by

$$P_{ao}(\omega_1) = \varepsilon(\chi_B)_{ao}|E_0|^2 E_1 \tag{18}$$

Where $(\chi_B)_{ao}$ is Brillouin susceptibility due to acousto-optic polarization.

Again by keeping the pump intensity well above the threshold, the Brillouin susceptibility foracousto optic process is obtain from equations(17) and (18) as,

$$(\chi_B)_{ao} = -\frac{\varepsilon k^2 g^2\omega_0^4}{\rho\left(\omega_a^2 - k_a^2v_a^2\right)\left(\omega_0^2-\omega_c^2\right)^2} \tag{19}$$

From equations (15) and (17) we obtain the effective Brillouin susceptibility as,

$$(\chi_B)_{eff.} = (\chi_B)_{cd} + (\chi_B)_{ao} \tag{20}$$

$$= -\frac{\varepsilon k_a^2 g^2\omega_0^4}{\rho\left(\omega_a^2 - k_a^2v_a^2\right)\left(\omega_0^2-\omega_c^2\right)^2}\left[1+\frac{\delta\omega_p^2}{\omega_1\omega_0}.A\right] \tag{21}$$

Equation (21) may be separated into real and imaginary parts $(\chi_B)_{eff.} = (\chi_B)_{eff.} + i(\chi_B)_{eff.}$ as,

$$[[\chi_B]_{eff.}]_{real.} = -\frac{\varepsilon k^2 g^2 \omega_0^4}{\rho(\omega_a^2 - k^2 v_a^2)(\omega_0^2 - \omega_c^2)^2}\left[1 + \frac{\delta_d \omega_p^2}{\omega_1 \omega_0}.\left[\frac{k^2 \bar{E}^2 [k^2 \bar{E}^2 - \Delta_1^2 \Delta_a^2 - \omega_1 \omega_a \upsilon^2]}{[k^2 \bar{E}^2 - \Delta_1^2 \Delta_a^2 - \omega_1 \omega_a \upsilon^2]^2 + \upsilon^2 [\omega_a \Delta_1^2 - \omega_1 \Delta_a^2]^2}\right]\right] \quad (22)$$

and

$$[[\chi_B]_{eff.}]_{imag.} = -\frac{\varepsilon k^2 g^2 \omega_0^4}{\rho(\omega_a^2 - k^2 v_a^2)(\omega_0^2 - \omega_c^2)^2}\left[1 + \frac{\delta_d \omega_p^2}{\omega_1 \omega_0}.\left[\frac{\upsilon k^2 \bar{E}^2 [\omega_a \Delta_1^2 - \omega_1 \Delta_a^2]}{[k^2 \bar{E}^2 - \Delta_1^2 \Delta_a^2 - \omega_1 \omega_a \upsilon^2]^2 + \upsilon^2 [\omega_a \Delta_1^2 - \omega_1 \Delta_a^2]^2}\right]\right] \quad (23)$$

The effective Brillouin gain coefficient $[g_B]_{eff.}$ of SBS process in ion implanted semiconductor crystal can be computed by employing the well known relation,

$$[g_B]_{eff.} = -\frac{k}{2\varepsilon}[[\chi_B]_{eff.}]_{imag.}|E_0|^2 \quad (24)$$

3. Results and Discussion:

The numerical calculations are performed for the n-type semiconductor sample ($BaTiO_3$) at 77 K duly irradiated by 10.6 μm CO_2 laser.

The following material parametershave been considered as follows: $m = 0.0145 m_0$ (m_0 being the free electron rest mass), $m_d = 1.67 \times 10^{-27} kg$. $\varepsilon_s = 2000$, $\rho = 4 \times 10^3 kg.m^{-3}$, $\eta = 3.9$ $n_0 = 10^{25} m^{-3}$, $\upsilon = 5 \times 10^{11} s^{-1}$, $\omega_0 = 1.78 \times 10^{13} s^{-1}$, $\omega_a = 1.6 \times 10^{13} s^{-1}$, and $v_a = 3 \times 10^3 m.s^{-1}$

The threshold characteristics are illustrated in figures 1 and 2. Figure 1 shows the variation of threshold intensity I_{th} with wave number k. The I_{th} decreases abruptly as the k increases in ion implanted semiconductors with chosen values of charge imbalance parameter δ_d .It can be seen that at $k \approx 1 \times 10^7 m^{-1}$ the intensity is $I_{th} \approx 5.1 \times 10^{13} Wm^{-2}$ .The I_{th} decreases abruptly with wave number k up to $k >> 4 \times 10^7 m^{-1}$ and then afterwards decreases slowly. It is evident from the figure that as the fraction of negative charge stick on to the CGs δ_d ,decreases (i.e. $\delta_d \approx 1 > 0.90 > 0.80$), the I_{th} gets lowered.

Figure 2 depicts the variation of threshold pump fields E_{0th} with the function of cyclotron frequency ω_c. The value of theratio ω_c/ω_0 can be changed for various value of the cyclotron frequency ω_c. It is found that initially at the ratio $\left(\omega_c/\omega_0 \approx 0.477\right)$, the threshold pump field is $E_{0th} \approx 1.48 \times 10^6 Vm^{-1}$. As we increase the ω_c , the E_{0th} decreases slowly. When ω_c become nearly equal to ω_0 (i.e. $\omega_c \approx \omega_0$), the threshold pump field gets the minimum value at $E_{0th} \approx 8.84 \times 10^4 Vm^{-1}$ for the chosen value of δ_d. The increase in cyclotron frequency (i.e.

$\omega_c > \omega_0$), the E_{0th} also increases gradually for all value of δ_d. The decrease in fraction δ_d negative charge stick on to the CGs, the E_{0th} values gets reduced as shown in figure.

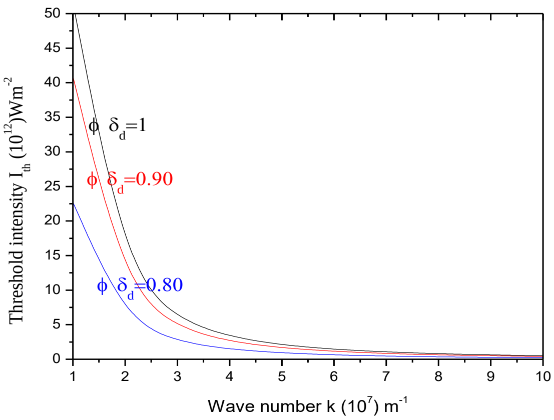

Figure1 Variation of threshold intensity I_{th} Vs wave number k.

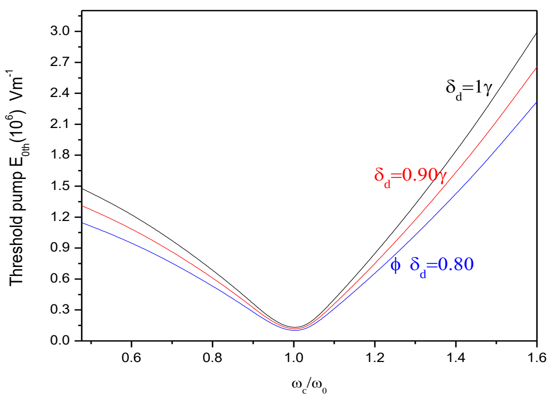

Figure 2 Variation of threshold pump field E_{0th} with magnetic field [in terms of ω_c / ω_0] when $E_0 = 5 \times 10^7 Vm^{-1}$.

The dependence of effective real susceptibility $[\chi_{eff.}]_{real}$ on magnetic field [via cyclotron frequency ω_c] is shown in figure 3.The magnitude of $[\chi_{eff.}]_{real}$ decreases abruptly with increases inthe value of ratio ω_c / ω_0. It is found thatwhen $\omega_c \approx \omega_0$ [i.e.at the ratio $\omega_c / \omega_0 \approx 1$,] the $[\chi_{eff.}]_{real}$ attains minimum value $[\chi_{eff.}]_{real} \approx -1.65 \times 10^{-10} V^2 m^{-2}$. On increase in ratio $\omega_c / \omega_0 > 1$ there is increase in $[\chi_{eff.}]_{real}$. Afterward for further value of $\omega_c / \omega_0 \approx 1.3 >$,saturates the $[\chi_{eff.}]_{real}$. The decrease in charge imbalance parameter $\delta_d << 1$ the minimum value of susceptibility also shifts toward higher.Figure 4 represents the variation of the effective susceptibility with respect wave number k_0. It can be seen that the effective susceptibility $[\chi_{eff.}]_{real}$ usually decreases with increase wave number k_0 .

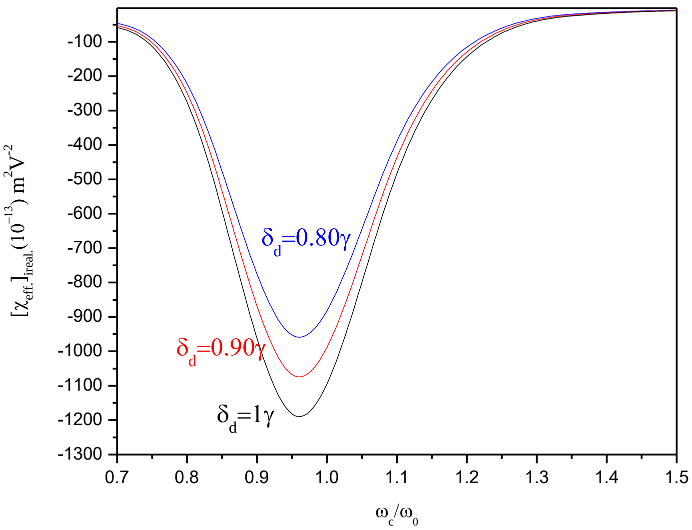

Figure 3 Effective susceptibility $[\chi_{eff.}]_{real}$ Vs cyclotron frequency ω_c at $E_0 = 1\times10^8 Vm^{-1}$ and $n_0 = 10^{25} m^{-1}$.

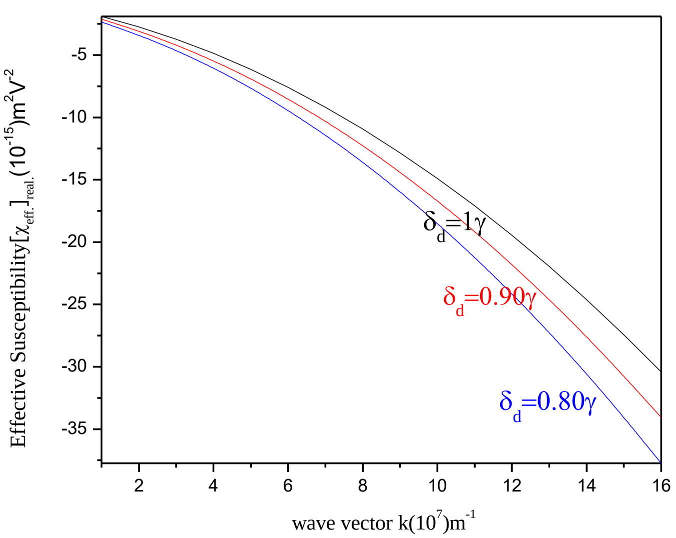

Figure 4Variation of effective susceptibility real $[\chi_{eff.}]_{real.}$ Vs wave number $k_0$at $E_0 = 1\times10^8 Vm^{-1}$

The dependence of effective Brillouin gain via ω_p, on carrier concentration (n_0) is shown in figure 5. It is seen that gain is nearly independent of n_0, but on the higher value ($>10^{25} m^{-3}$) of n_0 when $\omega_p^2 > \omega_0\omega_1$, the gain increases rapidly with small increase in n_0. The roll of charge imbalance parameter δ_d shows unusual characteristics initially when ($>5\times10^{25} m^{-3}$)the gain is high for $\delta_d = 1$ but at $<5\times10^{25} m^{-3}$ gain is high for $\delta_d = 0.80$.

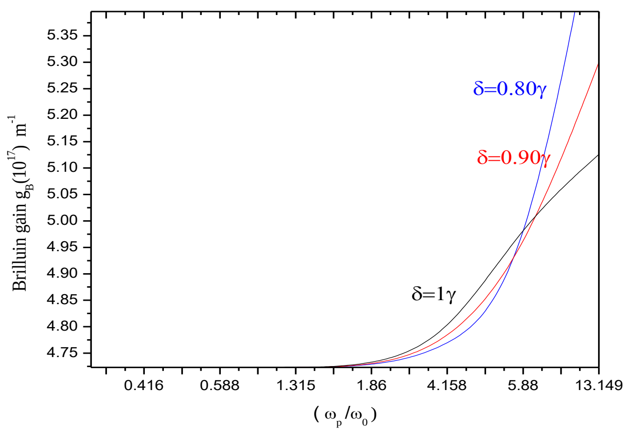

Figure 5 Variation of effective Brillouin gain $[g_B]_{eff}$ with carrier concentration [in terms of ω_p/ω_0]when $E_0 = 5\times10^7 Vm^{-1}$.

4. **Conclusion:**In present analysis, we have analytically studied the influence of CGs on the threshold intensity, effective susceptibility and Brillouin gain of the Stokes component. It is observed from the study that significant change inthreshold and gain characteristics when the charge imbalance parameter is slightly changed. The presence of CGs plays a strong catalyzing effect in changing the Brillouin gainand the threshold value.

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