Brillouin Gain Coefficients of Magnetoactive Doped III-V Semiconductors: Hot Carrier Effects

Renu[1,*], Sanjay[1], Manjeet Singh[2*]
[1]Department of Physics, Singhania University, Pacheri Bari-333515 (Jhunjunu) Rajasthan, India
[2]Department of Physics, Government College, Matanhail-124106 (Jhajjar) Haryana, India
[*]Corresponding Author, Email: renu.singhaniauniv@gmail.com

***Abstract*- Hot carrier effects (HCEs) of an intense pump wave on (steady-state and transient) Brillouin gain coefficients of magnetoactive doped III-V semiconductors are investigated. Numerical analysis is made for n-InSb crystal – CO_2 laser system.**

I. Introduction

Out of various nonlinear optical effects, the study of stimulated Brillouin scattering (SBS) has been active areas of research since last few decades. SBS has been demonstrated in all the four states of matter and hence extensive literature has accumulated on various aspects of this phenomenon. The new development of techniques for the fabrication of nonlinear materials has dramatically contributed to this evolution. Out of various nonlinear media, III-V semiconductors offer greater flexibility in fabrication of optoelectronic devices [1]. In addition, these media exhibit large optical nonlinearities; which can be further enhanced by application of external magnetic field [2]. Thus, the selection of magnetoactive doped III-V semiconductors as Brillouin media for the study of SBS is unquestionable.

In the present paper, we develop a theoretical formulation followed by numerical analysis to study the hot carrier effects (HCEs) induced by pump wave on steady-state (SS) and transient (TR) Brillouin gain coefficients (BGCs) of magnetoactive doped III-V semiconductors. The motivation for this study arises from the fact that HCEs induced by the pump wave may remarkably modify the nonlinearity of the medium and consequently the SBS process. Under high-power pump irradiation, this investigation becomes more important as it leads to better understanding of SBS in magnetoactive doped III-V semiconductors.

II. THEORETICAL FORMULATIONS

In order to excite SBS, the fundamental requirement is to irradiate the Brillouin sample by an intense pump wave. Under the influence of pump field, the electrons (which are mobile charge carriers in n-type doped semiconductor) gain energy and their temperature reaches a value T_e ($>T_0$). Consequently, the momentum transfer collision frequency (MTCF) modifies via relation [3]:

$$\nu = \nu_0 (T_e / T_0)^{1/2} , \tag{1}$$

where T_e/T_0 can be determined from energy conservation relation under SS operation. Following Sodha et.al. [4], the time independent part of power absorbed by a single mobile charge carrier (here electron) from the pump field is given by

$$\frac{e}{2}\mathrm{Re}(\vec{v}_{0x}.\vec{E}_e^*) = \frac{e^2 \nu_0}{2m}\frac{(\omega_c^2-\omega_0^2)}{[(\omega_c^2-\omega_0^2)^2+4\nu_0^2\omega_0^2]}\left|\vec{E}_0\right|^2 , \tag{2}$$

where $\mathrm{Re}(\vec{v}_{0x}.\vec{E}_e^*)$ denotes the real part of the quantity $(\vec{v}_{0x}.\vec{E}_e^*)$.

Following Conwell [5], the power dissipated by a single electron from the pump field in collisions with polar optical phonons (POPs) is given by

$$\left(\frac{\partial \in}{\partial t}\right)_{diss} = eE_{po}(x_0)^{1/2}\kappa_0\left(\frac{2k_B\theta_D}{m\pi}\right)^{1/2}\left(\frac{x_e}{2}\right).\exp\left(\frac{x_e}{2}\right).\frac{\exp(x_0-x_e)-1}{\exp(x_0)-1}, \tag{3}$$

where $x_{0,e} = \hbar\omega_l / k_B T_{0,e}$, in which $\hbar\omega_l$ is the energy possessed by POPs given by $\hbar\omega_l = k_B\theta_D$, where θ_D is the Debye temperature of the Brillouin medium. E_{PO} represents the POPs scattering potential field.

Under SS condition, the power absorbed by an electron from the pump field is exactly equal to the power dissipated by it in collisions with POPs. Consequently, the electron-plasma attains a steady temperature T_e ($>T_0$). For average heating of electron-plasma, Eqs. (2) and (3) yield

$$\frac{T_e}{T_0} = 1+\alpha\left|\vec{E}_0\right|^2 , \tag{4}$$

where $\alpha = \frac{e^2\nu_0}{2m\tau\Omega_0^2}\frac{(\omega_c^2-\omega_0^2)}{[(\omega_c^2-\omega_0^2)^2+4\nu_0^2\omega_0^2]}$, in which

$$\tau = eE_{po}\kappa_0\left(\frac{2k_B\theta_D}{m\pi}\right)^{1/2}\left(\frac{x_0}{2}\right)\frac{(x_0)^{1/2}\exp(x_0/2)}{\exp(x_0)-1}.$$

Using Eqs. (1) and (3), the modified MTCF is given by

$$\nu = \nu_0\left(1+\alpha\left|\vec{E}_0\right|^2\right)^{1/2} \approx \nu_0\left(1+\frac{1}{2}\alpha\left|\vec{E}_0\right|^2\right). \tag{5}$$

Using the coupled mode approach and following the method adopted in Ref. [6], we derived an expression for SS and TR BGCs as:

$$G_{B,ss} = \frac{k_a k_s^2 \omega_0^3 I_0 \delta_{\beta\gamma}[\nu\omega_0\Omega_a^2+\Gamma_a\omega_a(\omega_0^2-\omega_c^2)]}{4\eta^3\varepsilon_0^2 c\rho\delta_3\omega_s(\Omega_a^4+4\Gamma_a^2\omega_a^2)[(\omega_0^2-\omega_c^2)^2+4\nu^2\omega_0^2]} \tag{6}$$

$$G_{B,tr} = (\Gamma_a\tau_p)^{1/2}[(2G_{B,ss}L)^{1/2}-(\Gamma_a\tau_p)^{1/2}] , \tag{7}$$

where $\delta_{\beta\gamma} = \varepsilon_0\omega_p^2[\beta\gamma\delta_1\delta_2 A+\gamma^2(2I_0/\eta\varepsilon_0 c)]+\delta_3\omega_s\omega_0\gamma^2$,
$\delta_3 = 1-[(\Omega_{ps}^2-i\nu\omega_s)(\Omega_{pa}^2+i\nu\omega_a)/k_s^2\bar{E}^2]$, in which,
$\Omega_{ps}^2 = \bar{\omega}_p^2-\omega_s^2$, $\Omega_{pa}^2 = \bar{\omega}_p^2-\omega_a^2$, $A = \omega_p^2/(ek_a/m)$,
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, and c is speed of light.

III. RESULTS AND DISCUSSION

For numerical analysis, we choose n-InSb crystal – CO_2 laser system; the material parameters are given in Ref. [6].

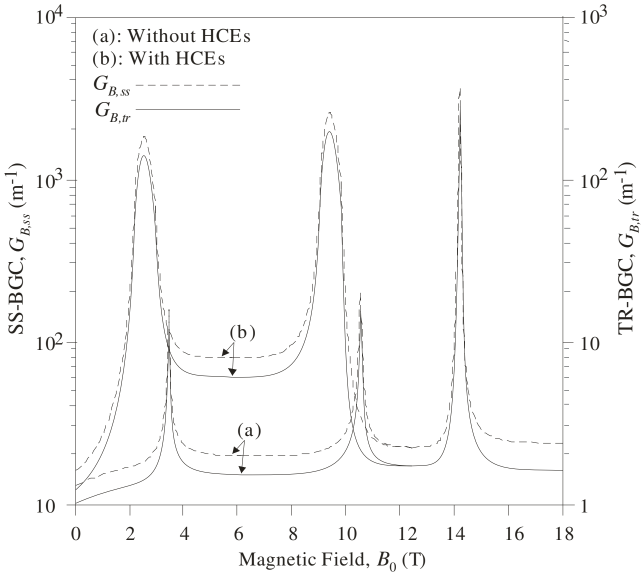

Fig. 1. Variation of SS and TR BGCs with external magnetic field at $n_0 = 2\times10^{19}$m^{-3}, $I_0 = 6.5\times10^{12}$Wm^{-2}.

Fig. 1 shows the variation of SS and TR BGCs with B_0. When HCEs are excluded, BGCs are very small and independent of B_0 except at 3.5T, 10.5T and 14.2T. At these particular values of B_0, both the BGCs exhibit sharp peaks. When HCEs are included, the features of the plot remain unchanged except that: (i) the peak of Brillouin gain coefficients which was previously occurring at 3.5T and 10.5T have now been shifted to 2.5T and 9.4T, respectively; (ii) the peak value of Brillouin gain coefficients now occurring at 2.5T and 9.4T has been further enhanced by one order of magnitude; (iii) the range of B_0 at which sharp enhancement of BGCs occurs (except at 14.2T) has been widened. When HCEs are excluded, the enhancement of BGCs at 3.5T, 10.5T and 14.2T occur due to resonance conditions: (i) $(\omega_p^2\omega_c^2)/\nu_0^2 \sim \omega_s^2$, (ii) $\nu_0^2\omega_p^2/(\nu_0^2+\omega_c^2) \sim \omega_s^2$, and (iii) $\omega_c^2 \sim \omega_0^2$, respectively An important aspect of resonance conditions (i) and (ii) is the interaction between electron-plasmon mode and electron-cyclotron mode driven by MTCF. Let we define this as MTCF driven coupled plasmon-cyclotron mode. When the pump field interacts with this coupled mode, as a consequence, the MTCF driven coupled plasmon-cyclotron mode frequency dependent Stokes mode is generated. Under the influence of HCEs, the MTCF of electrons, which previously was ν_0 now increases to ν. When HCEs are included, resonance conditions (i) and (ii) require that for a fixed n_0, the increase in MTCF of electrons further enhances and shifts the peak value of BGCs towards smaller values of B_0.

Fig. 2 shows the variation of BGCs with I_0. Here, both BGCs exhibit the similar nature of curves with excluding and including HCEs throughout the plotted range of I_0. For $I_0 < 3.5\times10^{12}$Wm^{-2}, when heating of the carriers is insignificant, both the BGCs increase in a parabolic shape with I_0. However, they gradually start deviating from the parabolic shape as the heating of the carriers become significant, in the region $I_0 > 3.5\times10^{12}$Wm^{-2}. This indicates that HCEs on SS and TR BGCs of magnetoactive doped III-V semiconductors are more pronounced at higher excitation intensity.

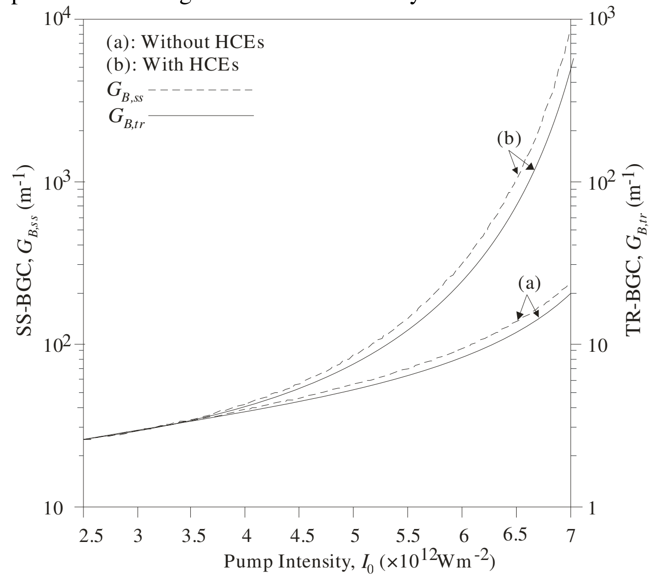

Fig. 2. Variation of SS and TR BGCs with pump intensity at $n_0 = 2\times10^{19}$m^{-3}.

This behaviour can be easily understood in terms of temperature dependence of BGCs via MTCF in Eqs. (6) and (7). This deviation of BGCs curves from the parabolic shape at high pump intensity emphasis the necessity of inclusion of HCEs in SBS and the related phenomena.

IV. CONCLUSIONS

The analysis offers three achievable resonance conditions at which enhancement of SS and TR BGCs by one order of magnitude can be obtained. The HCEs induced by the intense pump wave increases the MTCF of electrons, which consequently enhances the BGCs by one order of magnitude; broadens and shifts the Brillouin gain spectrum arising due to resonance conditions (i) and (ii) towards smaller values of magnetic field.

REFERENCES

[1] S. Mokkapati and C. Jagadish, “III-V compound SC for optoelectronic devices,” *Mat. Today*, vol. 12, pp. 22-32, 2009.

[2] M. Singh, J. Gahlawat, A. Sangwan, N. Singh, and M. Singh, “Nonlinear optical susceptibilities of a piezoelectric semiconductor magneto-plasma,” Springer Proc. Phys., vol. 256, pp. 189-202, ch. 20, (2020).

[3] A.C. Beer, *Galvanometric Effects in Semiconductors: Solid State Physics*, New York: Academic Press, 1963.

[4] M.S. Sodha, A.K. Ghatak, and V.K. Tripathi, *Self-Focusing of Laser Beams in Dielectrics, Plasmas and Semiconductors*, New Delhi: Tata McGraw, 1974, pp. 55-62.

[5] E.M. Conwell, *High Field Transport in Semiconductors*, New York: Academic Press, 1967, pp. 159.

[6] 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. Technol.*, vol. 22, pp. 749-754, 2007.