

# Phase mismatched optical parametric generation in semiconductor magnetoplasma

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**Abstract.** Optical parametric generation involves the interaction of pump, signal, and idler waves satisfying law of conservation of energy. Phase mismatch parameter plays important role for the spatial distribution of the field along the medium. In this paper instead of exactly matching wave vector, a small mismatch is admitted with a degree of phase velocity mismatch between these waves. Hence the medium must possess certain finite coherence length. This wave mixing process is well explained by coupled mode theory and one dimensional hydrodynamic model. Based on this scheme, expressions for threshold pump field and transmitted intensity have been derived. It is observed that the threshold pump intensity and transmitted intensity can be manipulated by varying doping concentration and magnetic field under phase mismatched condition. A compound semiconductor crystal of n-InSb is assumed to be shined at 77 K by a 10.6 $\mu$ m CO<sub>2</sub> laser with photon energy well below band gap energy of the crystal, so that only free charge carrier influence the optical properties of the medium for the I.R. parametric generation in a semiconductor plasma medium. Favorable parameters were explored to incite the said process keeping in mind the cost effectiveness and conversion efficiency of the process.

## 1. Introduction

New generation of nonlinear optical crystals revived intensive research interest in the field of nonlinear optics and transformed parametric devices from evidence of principle demonstrations to variable sources of coherent light for practical applications. Now a day's operating domain of parametric devices has been extended from selected spectral and temporal regimes to new U.V. well into the mid I.R. and encompassed all time scale from continuous wave (CW) to ultrafast femtosecond regime. At the same time availability of high power laser sources with enhanced spectral and spatial coherence has enabled the development of parametric devices at record power levels and established them as an important class of practical coherent light sources.

Optical parametric frequency conversion based on second and third order nonlinearities are achieved by mixing coherent waves, e.g. light beams from lasers, in a nonlinear material. The strongest parametric processes, and consequently the first to be discovered, are those generated in nonlinear materials possessing a non-zero second order nonlinearity. There are a lot of challenges in harnessing large  $\chi^{(2)}$  coefficient of compound semiconductors near their band gap. Most of the semiconductor materials are isotropic so that no birefringence phase-matching scenario are accessible [1]. Nonlinear optical processes



require high intensity light beams to make their effects observable and useful. Although coherent light can distort the oscillating polarization, Fourier components of these distortions can create or enhance new fields that then radiate from the oscillating nonlinear polarization [2].

In nonlinear optical interactions, because of the dispersive nature of crystal, the fundamental frequency and the generated frequency travel at different speeds in the material, so there is a phase mismatch between the interacting waves. Achieving phase matching in semiconductors with significant dispersion and large  $\chi^{(2)}$  is quite difficult. However main concern is to get larger conversion efficiency in case of optical parametric generation process [3-4].

There have been many efforts to achieve phase matching through poling, birefringence of the medium. But it seems that uptill now no studies were undertaken to study the parametric generation process which is phase mismatched. Hence present paper describes a way to identify and quantify the various implications of the optical phase mismatching on IR generation in the presence of external magnetic field. Parametric process pumped by 10.6 $\mu\text{m}$  CO<sub>2</sub> laser where bulk  $\chi^{(2)}$  nonlinearity is considered as phase mismatched for optical parametric generation process as a consequence of three wave mixing. The process gets initiated by a single intense pump field at frequency  $\omega_0$  at the input to a nonlinear crystal. This field provided by CO<sub>2</sub> laser in turn mixes through the nonlinear susceptibility with a signal field at  $\omega_1 = \omega_0 - \omega_a$ . The idler field so generated in turn mixes back with the pump to produce additional signal and the generated signal mixed with the pump to produce more idler. The process continues in this way until power is gradually transferred from the strong pump at the initially weak signal and idler fields through the nonlinear interaction mediated by  $\chi^{(2)}$ . This wave mixing process is well analyzed by using coupled mode theory and expressions for threshold pump field, transmitted intensity have been derived.

## 2. Theoretical Formulations

This section deals with the theoretical formulation of induced nonlinear polarization and transmitted intensity in doped semiconductor magnetoplasma medium. The model used in the analysis is the well-known hydrodynamic model of one component plasma. A pump electric field  $E_0 \exp(k_0 x - \omega_0 t)$  is assumed to be incident on a semiconductor sample, parallel to the wave vector  $k$  (along  $x$  axis) and external magnetic field is applied along  $z$  axis. In the presence of a strong input pump, the signal and idler fields in the parametric interaction can experience growth as they propagate through the nonlinear crystal. Generation of signal and idler are also hoped to be strongly dependent functions of the phase mismatch parameter  $\Delta k = k_0 - k_1 - k_a$  where  $k_0$ ,  $k_a$  and  $k_1$  are wave vectors of pump, acoustic and signal modes respectively. This corresponds to the more realistic case as exact phase matching is very difficult to achieve experimentally. Following basic equations are used for analysis:-

$$\frac{\partial \mathcal{G}_0}{\partial t} + \mathcal{G}_0 \left( \frac{\partial \mathcal{G}_0}{\partial x} \right) + \nu \mathcal{G}_0 = \frac{e}{m} (E_0 + \mathcal{G}_0 \times B_0) \quad (1)$$

$$\frac{\partial \mathcal{G}_1}{\partial t} + \mathcal{G}_0 \left( \frac{\partial \mathcal{G}_1}{\partial x} \right) + \mathcal{G}_1 \left( \frac{\partial \mathcal{G}_0}{\partial x} \right) + \nu \mathcal{G}_1 = \frac{e}{m} (E_1 + \mathcal{G}_1 \times B_0) \quad (2)$$

$$\frac{\partial n_1}{\partial t} + n_0 \frac{\partial \mathcal{G}_1}{\partial x} + n_1 \frac{\partial \mathcal{G}_0}{\partial x} + \mathcal{G}_0 \frac{\partial n_1}{\partial x} = 0 \quad (3)$$

$$\rho \frac{\partial^2 u}{\partial t^2} + 2\gamma_s \rho \left( \frac{\partial u}{\partial t} \right) + \beta \frac{\partial E_s}{\partial x} = C \frac{\partial^2 u}{\partial x^2} \quad (4)$$

$$\frac{\partial E_s}{\partial x} + \frac{\beta}{\varepsilon} \frac{\partial^2 u}{\partial x^2} = \frac{n_1 e}{\varepsilon} \quad (5)$$

Meanings of all the symbols are given in [6]. Following standard approach of the Neogi and Ghosh [5] and utilizing equations (1)-(5) a simplified expression for the density perturbation is obtained as

$$\frac{\partial^2 n_1}{\partial t^2} + \nu \frac{\partial n_1}{\partial t} + \overline{\omega_p}^2 n_1 + n_0 e \beta \frac{\partial^2 u}{\partial x^2} \left( \frac{\nu^2}{\omega_c^2 + \nu^2} \right) = -i(k_0 + k_1) n_1 \overline{E} \quad (6)$$

$$\overline{E} = \frac{e}{m} E_0 + \omega_c \mathcal{G}_{0y}, \quad \mathcal{G}_{0y} = \frac{-e \omega_c E_0}{m(\omega_c^2 - \omega_0^2)} \quad \text{and} \quad \overline{\omega_p}^2 = \omega_p^2 \left( \frac{\nu^2}{\omega_c^2 - \nu^2} \right) \quad (7)$$

Induced nonlinear polarization may be obtained as

$$P_1(\omega_1) = \frac{ieAk\varepsilon\overline{\omega_p}^2 E_1^* E_0}{m\omega_1 \left( \frac{c}{\rho} k_a^2 - \omega_a^2 + 2i\gamma_s \omega_a \right)} \left( \frac{\nu^2}{\omega_c^2 + \nu^2} \right) \left[ \left( \overline{\omega_p}^2 - \omega_a^2 + i\nu\omega_a \right) - \frac{(k_0 + k_1)^2 |\overline{E}|^2}{(\overline{\omega_p}^2 - \omega_1^2 - i\omega_1\nu)} \right]^{-1} = \varepsilon_0 \chi^{(2)} E_1^* E_0 \quad (8)$$

Threshold pump field required for the onset of I.R. generation can be obtained by setting imaginary component of the second order susceptibility  $\chi^{(2)}$  equals to zero

$$E_{0th} = \frac{m}{e(k_0 + k_1)} \frac{\omega_c^2 - \omega_0^2}{\omega_0^2} \sqrt{\frac{(\overline{\omega_p}^2 - \omega_1^2)^2 \omega_a + \nu^2 \omega_1^2 \omega_a}{\omega_1}} \quad (9)$$

If the sample length is 10 to  $10^2$  orders greater than the pump wavelength [6], one can easily use the expression for induced polarization ( $P_1$ ) deduced for an infinite medium, to express the transmitted intensity ( $I_T$ ) in a crystal length  $L$  given by

$$I_T = \frac{1}{2} \eta \varepsilon_0 c |E_T|^2 \quad \text{where} \quad E_T = -\frac{ik_1 L}{\varepsilon} P_1(\omega_1) \quad (10)$$

Equations (8), (9) and (10) may be used to determine induced polarization, transmitted electric field amplitude and transmitted intensity respectively.

### 3. Results and discussions

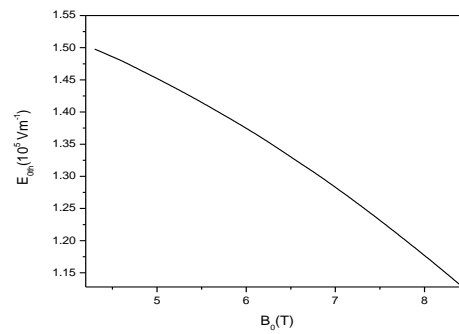
This section deals with the numerical appreciation of the theoretical formulations for different parameters in previous section. Data of a compound semiconductor crystal of InSb pumped by 10.6 $\mu\text{m}$  CO<sub>2</sub> laser at 77K is used [7] for the calculations.

Figure 1 illustrates the variation of  $E_{0th}$  with the magnetic field  $B_0$ . It is clear from this graph that threshold field linearly decreases with increasing magnetic field at constant carrier concentration  $n_0 = 2 \times 10^{23} \text{ m}^{-3}$ . This observation fulfills the prime requirement of lower threshold field at higher external magnetic field which is beneficial for a cost effective I.R. generation.

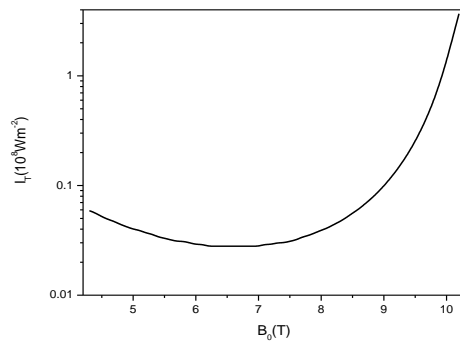
Figure 2 displays the variation of transmitted intensity  $I_T$  with respect to external magnetic field  $B_0$ . It is found that transmitted intensity first decreases with increasing external magnetic field till 6.7T and beyond this magnitude, transmitted intensity increases. Resonance between modified plasma frequency and idler wave frequency ( $\omega_a$ ) causes minimum transmission at 6.7T. Beyond this magnetic field modified plasma frequency becomes greater than  $\omega_a$  and hence the transmitted intensity also increases with increasing magnetic field.

Figure 3 illustrates the variation of transmitted intensity  $I_T$  and carrier density  $n_0$  at various cell lengths. Maximum transmitted intensity is envisaged for higher cell length and at higher carrier densities.

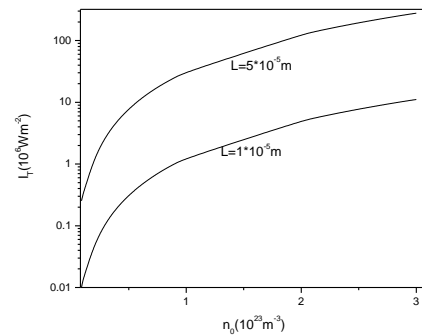
Phase mismatching condition is found to increase threshold pump requirements by a factor of 10 as compared to earlier study [6] done with phase matching in highly doped regime. It can be concluded that highly doped semiconductor plasma with high magnetic field may be helpful for a cost effective I.R. generation with improved conversion efficiency.



**Figure 1.** Variation of threshold field  $E_{0th}$  with magnetic field  $B_0$  at  $k = 5.5 \times 10^8 \text{ m}^{-1}$  &  $n_0 = 2 \times 10^{23} \text{ m}^{-3}$ .



**Figure 2.** Variation of Transmitted Intensity  $I_T$  with external magnetic Field  $B_0$  at  $L = 5 \times 10^{-5} \text{ m}$ ,  $k = 5.5 \times 10^8 \text{ m}^{-1}$ ,  $E_0 = 3 \times 10^5 \text{ Vm}^{-1}$  &  $n_0 = 2 \times 10^{23} \text{ m}^{-3}$ .



**Figure 3.** Variation of Transmitted Intensity  $I_T$  with carrier density  $n_0$  at magnetic field  $B_0 = 10 \text{ T}$ ,  $k = 5.5 \times 10^8 \text{ m}^{-1}$ ,  $E_0 = 3 \times 10^5 \text{ Vm}^{-1}$  &  $n_0 = 2 \times 10^{23} \text{ m}^{-3}$ .

### Acknowledgment

One of the authors (KJ) is thankful to UGC, New Delhi, India for the award of Maulana Azad fellowship for Minority.

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