NONLINEAR INTERACTION OF ELECTROMAGNETIC FIELDS WITH PLASMAS

by
Subhash Chandra

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(SUBHASH CHANDRA)

PREFACE

The interaction of electromagnetic waves with gaseous and solid state plasmas has aroused a great deal of interest on account of its numerous applications in many fields of Science and Technology. The response of a plasma to an electromagnetic radiation is governed by free electrons which are characterised by high mobility, long mean free path and slow rate of energy exchange with heavy particles. If the electric field of the wave is weak, the current density in the plasma is directly proportional to the electric field. However, for a moderately strong electromagnetic wave, the current density is a nonlinear function of the electric field of the wave and the plasma behaves as a nonlinear medium.

The criterion for the nonlinear effects to be significant may be expressed in terms of the characteristic plasma field (E_P) as $E \geqslant E_P$; the field E_P is given by[1]

$$E_P = [\, 3\, m_o K_o T_o\, \delta(\omega^2 + \nu^2) / e^2]^{\frac{1}{2}} \quad , \tag{1}$$

where $-e$, m_o and ν are the electron charge, mass and collision frequency respectively, K_o is the Boltzmann's constant, T_o is the temperature of the plasma, ω is the wave frequency and $\delta = 2m_o/M$ is the fraction of the energy transferred by the electrons to the heavy particles (of mass M) per collision. In a gaseous plasma nonlinearity can in fact occur at fields which are quite feasible in laboratory experiments or in the ionosphere by radiation from powerful radio transmitters. However, the plasma fields for solid state plasmas are much higher as compared to those corresponding to gaseous plasmas because of lower carrier mobility and more efficient carrier energy loss mechanisms in semiconductors[2].

As a result of the nonlinear interaction of intense electromagnetic waves with plasmas a large number of interesting phenomena e.g. harmonic generation[3], parametric amplification and self-action of electromagnetic waves[4] (e.g. self-focusing) have been observed. The studies of such phenomena are relevant to laser-plasma interactions, excitations of plasma instabilities, inertial confinement and heating of plasmas, collisionless and anomalous absorption of waves, plasma shocks, discharge physics and communications. Further the investigations of nonlinear processes in solid state plasmas are relevant to the development of various microwave solid state devices[5] e.g. gunn oscillator, parametric converters and wave mixers. Among the various nonlinear phenomena the phenomenon of self-focusing occupies a unique place because of its lower thresholds and relevance to other nonlinear processes e.g. harmonic generation, stimulated

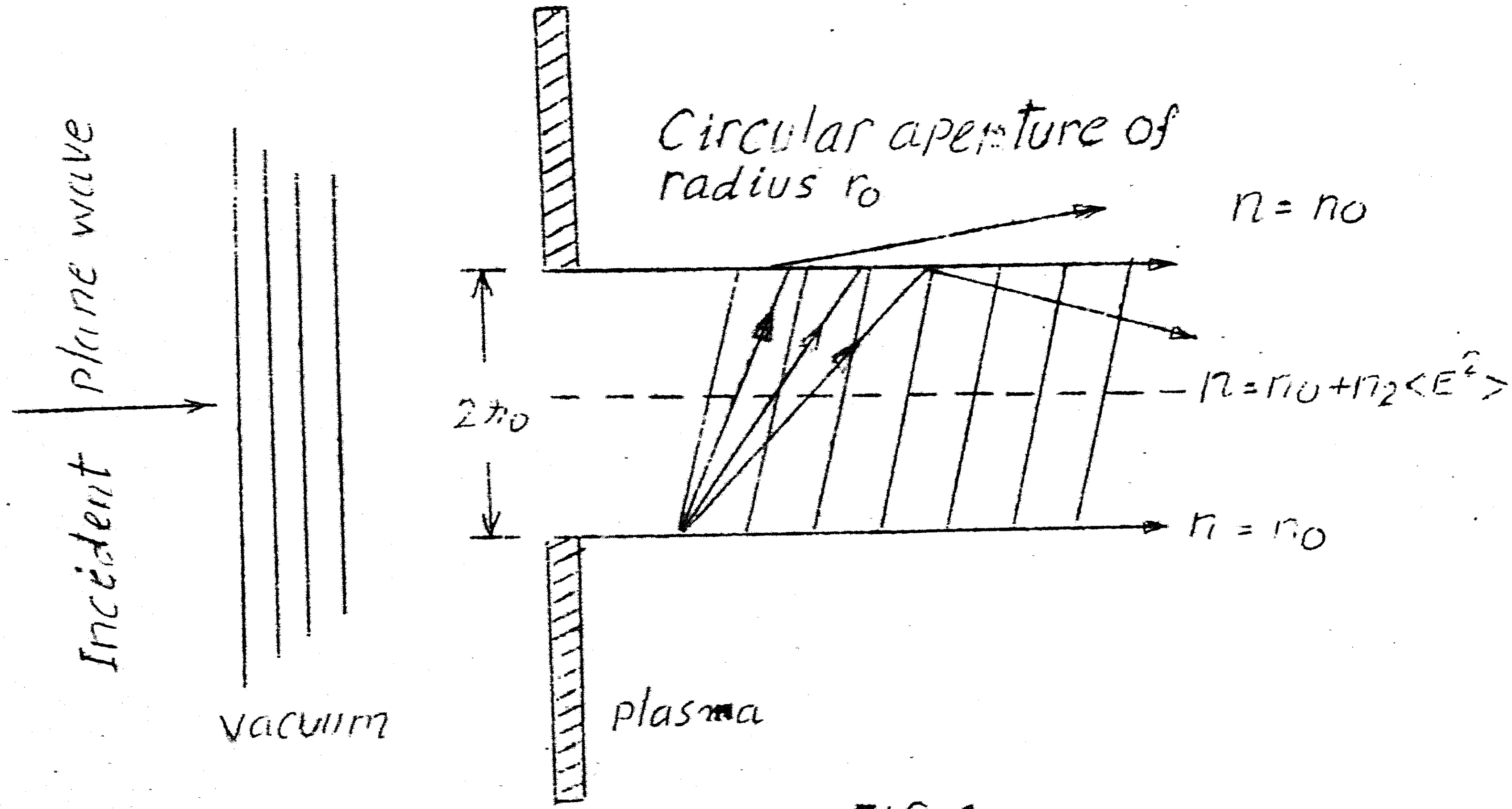
Incident
plane wave
vacuum
$2r_0$
Circular aperture of
radius r_0
$n = n_0$
$n = n_0 + n_2 \langle E^2 \rangle$
$n = n_0$
plasma

FIG. 1

scattering and parametric excitations; the magnitude of these effects is enhanced by self-focusing effects.

It is instructive here to visualise the phenomenon of self-focusing in a nonlinear medium[6] having refractive index variation as (See Fig. 1)

$$n = n_o + n_2 EE^* \qquad , \qquad (2)$$

We consider a plane uniform wave front incident on a circular aperture (of radius r_o) in a nonlinear medium. The portion of the medium illuminated by the beam $(r < r_o)$ has a refractive index $(n = n_o + n_2 EE^*)$ higher than that of the non-illuminated portion $(r > r_o)$. Therefore rays making an angle θ with the direction of propagation suffer total internal reflection at the boundary of the cylinder of radius r_o when

$$\theta < \theta_c$$

where

$$\theta_c = \cos^{-1}\{ \frac{n_o}{n_o + n_2 EE^*} \} \qquad , \qquad (3)$$

corresponds to the critical angle. It is also known from the diffraction theory that a very large fraction of the power will be carried by rays making an angle less than θ_D with the axis, where

$$\theta_D \simeq \frac{0.61\,\lambda_o}{2\, r_o\, n_o} \qquad , \qquad (4)$$

and λ_o is the wavelength of the radiation in free space. The condition that the beam does not lose power appreciably is thus equivalent to the condition that rays making an angle less than θ_D with the axis are not lost from the beam; this is only possible when $\theta_c > \theta_D$, so that such rays will suffer total internal reflection at the boundary and hence returned to the beam.

The critical power of the beam for self-focusing corresponds to $\theta_c = \theta_D$, which leads to

$$P_{cr} = \pi r_o^2 \left(\frac{c}{n_o}\right) \cdot \frac{\epsilon_o}{8\pi} \cdot E_o^2 = \frac{(1.22\ \lambda_o)^2\ c}{128\ n_2} \qquad (5)$$

where the power of the beam is defined as the intensity multiplied by the area of cross-section of the beam and P_{cr} denotes the critical power of the beam. Thus

(i) when $P < P_{cr}$, $\theta_c < \theta_D$ and hence the beam will diverge.

(ii) when $P = P_{cr}$, $\theta_c = \theta_D$ the beam will propagate uniformly without any convergence or divergence and

(iii) when $P > P_{cr}$ and hence $\theta_c > \theta_D$ the convergence or self-focusing of the beam will occur. The characteristic lengths of diffraction divergence and self-focusing for a Gaussian beam are given by

$$R_d = K r_o^2 = (\frac{\omega}{c})\, n_o\, r_o^2 \qquad (6)$$

and

$$R_n = r_o \left(\frac{n_o}{2n_2\, E_o^2} \right)^{\frac{1}{2}} \qquad (7)$$

where K and ω are the wave vector and frequency, respectively.

The self-focusing of electromagnetic waves in nonlinear media has been investigated both theoretically and experimentally by various workers[7-10]. The earlier studies on self-focusing were confined to dielectrics where the self-focusing occurs on account of the nonlinear dependence of the displacement vector on the electric field of the wave. The various nonlinearities responsible for self-focusing are electrostriction[7], Kerr effect[8] and thermal heating effects[9,10]. In the typical case of a ruby laser beam of initial diameter 0.05 cm propagating in nonlinear dielectric CS_2 the critical power P_{cr} is 25 Kw and a beam of power $(P \geq P_{cr})$ 90 Kw is focused to a spot size of diameter 0.005 cm in a distance of 12 cm. The critical and threshold powers for the thermal self-focusing are found to be rather small ($P_{cr} \sim 0.1$ to 10 watt) which are now available with the commercial CW gas lasers.

Recently the self-focusing of intense electromagnetic waves in gaseous and solid state plasmas has attained considerable importance. The critical powers for self-focusing in plasmas/semiconductors are several orders of magnitude smaller than those in dielectrics and hence the laboratory experiments on plasmas/semiconductors should be easier to undertake. Such a study leads to better understanding of free carrier nonlinearities in plasmas/semiconductors. In a recent experiment with a decaying plasma with $N_o = 5x10^{11}$ cm^{-3}, $T_o = 2.5x10^{3}$°K and $\nu = 10^{8}$ sec^{-1}, an electromagnetic beam of initial width r_o = 10 cm, wavelength λ_o = 3 cm and incident power P = 100 watt is focused in a distance of z_f = 70 cm; the critical power for self-focusing was found to be P_{cr} = 10 watt.

In the present thesis the author has investigated the mechanisms of nonlinearity (relevant to the phenomenon of self-focusing) in plasmas and semiconductors. This study of nonlinearity is then used to study the self-focusing of electromagnetic waves under stationary and nonstationary conditions by following the technique developed by Akhmanov, Sukhorukov and Khokhlov[6]. The hot carrier phenomena in a semi-metal and effect of hot carriers on the propagation and instability of EM waves in solid state plasmas have been studied. Besides these investigations the problem of steady state and transient thermal blooming of laser beams in a nonlinear absorbing moving medium (e.g. CS_2) has also been investigated.

In case of plasmas/semiconductors the nonlinearity arises due to the nonlinear dependence of the free carrier current density $\underline{J}$ on the electric vector $\underline{E}$. For such conducting media, the current density and the effective dielectric constant are given by

$$\underline{J} = \sigma\,\underline{E} = (\sigma_r - i\,\sigma_i)\underline{E} \quad , \tag{8}$$

and

$$\epsilon_{eff} = \epsilon_\ell - \frac{4\pi i\sigma}{\omega} = \epsilon_r - i\epsilon_i \quad , \tag{9}$$

where

$$\begin{aligned} \epsilon_r &= \epsilon_\ell - \frac{4\pi(\sigma_i)}{\omega} \quad , \\ \epsilon_i &= \frac{4\pi\,\sigma_r}{\omega} \end{aligned} \tag{10}$$

and ϵ_ℓ is the lattice dielectric constant or dielectric constant in the absence of free carriers. The conductivity σ is a function of carrier concentration, collision frequency and mass. The field dependence of each of these parameters leads to a nonlinear current density.

The self-focusing of intense electromagnetic beams in gaseous and solid state plasmas arises on account of free carrier nonlinearities. When an intense electromagnetic wave propagates through a plasma/semiconductor, the electrons acquire momentum and energy from the wave, which are lost in collisions with heavy particles/lattice.

In equalibrium, the temperature of the electrons is the same as that of the heavy particles/lattice so that net energy exchange between them is zero. In the presence of electric field, the electrons attain a temperature higher than the equilibrium value such that in the steady state the rate of power absorption from the field becomes equal to the rate of power lost by the electrons by thermal conduction and/or by collisions with heavy particles/lattice. Such carriers whose temperature is higher than the equilibrium value are known as hot carriers and have been extensively investigated by Ginzburg[1] and Conwell[2] in the literature. The field dependent rise in electron temperature, in turn, modifies other free carrier parameters (e.g. collision frequency, mass and concentration of electrons), hence the current density is a nonlinear function of the electric field vector of the wave.

The different mechanisms of nonlinearity responsible for self-focusing in plasmas and semiconductors can be understood as follows:

(i) Nonlinearity due to Change in Collision Frequency

This nonlinearity arises on account of the temperature/energy/velocity dependence of the electron collision frequency and has been investigated in considerable detail[1,3]. Dubey and Paranjape[11] have studied the self-focusing of electromagnetic waves on account of this nonlinearity but neglected absorption. Tripathi, Tewari, Pandey and Agarwal[12] have shown that this nonlinearity is not significant in causing self-focusing of the waves at optical frequencies because of enhanced absorption of the wave. For typical parameters of a semiconductor the absorption length is found to be smaller than the self-focusing length.

Recently Stenflo and Yu[14] and Chandra and Tripathi[14] investigated nonlinearity in gaseous and solid state plasmas showing Ramsauer effect. According to the Harp model, we may assume the collision frequency to be very low below some critical speed of the electron $v = v_o$ and infinite above v_o. Thus only those electrons contribute to the current density which have speed below v_o. When the electric field of a wave acts on a plasma some electrons from the low velocity range $v < v_o$ (on assuming ν to be small but finite) are transferred to high velocity range $v > v_o$. Thus the effective number density of electrons responsible for current density is reduced. This nonlinearity predicts self-focusing of the Gaussian beam for reasonable powers of the beam but is based on the Harp model, which has limited applicability.

(ii) Nonlinearity on account of Energy Dependence of Carrier Mass

The field dependent temperature rise of the electrons may also modify the mobility and conductivity of the carriers on account of the energy dependence of the carrier mass which is important for semiconductors having non-parabolic energy bands (e.g. InSb). This nonlinearity is effective in causing self-focusing of the beam as shown by Tzoar and Gersten[15] and Sodha, Tewari, Tripathi and Kamal[16].

Another interesting nonlinearity on account of the relativistic velocity dependence of the electron mass has been discussed by Kaw and Dawson[17] and Max, Arons and Langdon[18]. According to them, when an intense laser beam propagates through plasma, the electrons acquire so much energy from the beam that their drift velocity becomes comparable to the velocity of light; hence the electron mass increases with the intensity of the beam; thus the effective dielectric constant of the plasma is a function of the intensity of the wave. This mechanism is effective in causing the self-focusing of laser beams at very high powers ($\simeq 10^{15}$ watt).

(iii) Nonlinearity on account of Change in Electron Density

Litvak[19], Prasad and Tripathi[20] and Sodha, Tewari, Kamal, Pandey, Agarwal and Tripathi[21] have recently proposed a new mechanism of nonlinearity in plasmas/semiconductors. When an intense electromagnetic beam having a nonuniform intensity distribution propagates through a plasma/semiconductor, the electron temperature has a variation along the wave front. This temperature gradient results in the redistribution of carriers through ambipolar diffusion. For a Gaussian beam the heating of the electrons is maximum on the axis and hence the depletion of the plasma from the axial region is maximum. The change in electron density leads to the dependence of the effective dielectric constant on the electric vector. This nonlinearity is most dominant in causing self-focusing in collisional plasmas.

Hora[22], Lindl and Kaw[23] and Sodha, Mittal, Virmani and Tripathi[24] have considered another interesting mechanism of nonlinearity viz. the ponderomotive force arising from the interaction of electron drift velocity with the magnetic field of the wave and the motion of electrons in the inhomogeneous electric field; this nonlinearity is important for collisionless plasmas. When the intensity distribution of the beam is nonuniform, the force on account of this interaction has a finite time independent component in a direction transverse to that of propagation. This force leads to a redistribution of electronic concentration; the ions are also dragged by the electrons on account of Coulomb interaction. This effect makes the dielectric constant of the plasma to depend on the electric vector leading to self-focusing. This nonlinearity is dominant even in collisional plasmas when the duration time of the electromagnetic beam (τ) is much smaller than the energy relaxation time (τ_E) of electrons; such situation occurs in the case of fast pulsed lasers. The nonlinearity due to ponderomotive force is set up in a time of the order of r_o/v_S where v_S is the ion sound speed. This time is usually nonsmaller than the time required by the hot carrier nonlinearity to set up.

It must be mentioned here that the electron density in a plasma/semiconductor may also change by the ionisation breakdown[25] and ionisation recombination imbalance[26] etc. But this nonlinearity does not lead to self-focusing because an increase in electron concentration with field is synonymous with a decrease in effective dielectric constant and thus defocusing the Gaussian beam.

The steady state self-focusing of intense electromagnetic waves in plasmas has been discussed by Askar'yan[27] Talanov[28], Litvak[19] and others[29]. In these investigations, the conditions for self-channelisation of waves (i.e. uniform wave guide propagation) in plasmas were investigated. Litvak[19] and Prasad and Tripathi[20] investigated the self-focusing of microwaves in a weakly ionised plasma; they considered the nonuniform heating and consequent redistribution of electrons. These treatments were phenomenological in nature and applicable only in the perturbation approximations. Sodha, Tewari, and Tripathi[30] studied the same problem with a rigorous kinetic treatment. The velocity dependence of collision frequency governs the redistribution of carriers. It was shown that at high powers the nonlinear dielectric constant of the plasma is a saturating function of the wave intensity which, in turn, results in periodic focusing of the beam i.e. the wave propagates in a selfmade oscillatory wave guide. Sodha, Khanna and Tripathi[31] studied the self-focusing of laser beams in a strongly ionised plasma, where thermal conduction plays a dominant role in the loss of excess electron energy; the analysis predicted periodic focusing of the beam even when the dielectric constant is not in the saturating region.

Lindl and Kaw[23], Hora[22] and Sodha, Mittal, Virmani and Tripathi[24] investigated self-focusing in a collisionless plasma by the ponderomotive force nonlinearity which is found to be less significant (smaller by four or five orders of magnitude) as compared to nonuniform heating and redistribution type nonlinearity except when the duration of the pulse $\tau << \tau_E$, the energy relaxation time. The nonstationary self-focusing of e.m. waves in collisional and collisionless plasmas have also been studied by Sodha, Sharma and Tripathi[32] and Sodha, Prasad and Tripathi[33] where the finite relaxation time of the nonlinearity is found to affect the self-focusing considerably more in a collisional plasma than in a collisionless plasma.

Recently experimental evidence of self-focusing of microwaves in a weakly ionized discharge tube plasma has been presented by Batanov and Silin[34] and Eremin, Litvak and Poluykhtov[35]. The plasma was, however, of decaying in nature and hence a comparison with earlier investigations could not be made. The available literature on self-focusing of electromagnetic waves in plasmas is applicable to stationary (i.e. plasmas at rest) and time-independent plasmas. However, many of the laboratory and natural occurring plasmas are time-dependent (i.e. decaying/growing) and have a finite flow velocity. The first two chapters of the proposed thesis are concerned with (i) Steady state self-interaction of laser beams in a moving plasma and (ii) Nonstationary propagation of microwaves in a time dependent plasma.

The analyses of these problems are based on phenomenological considerations. The convection effects in a moving plasma and relaxation effects in a time dependent plasma play a significant role in the process of self-focusing and lead to non-symmetrical and time dependent convergence of the beam respectively in the two cases. The study of steady state self-focusing in a moving plasma is applicable to plasma jets and streams where a flow velocity of the order 10^5-10^7 cm/sec is encountered. The nonstationary self-focusing in a time dependent plasma may be useful in determining the characteristic times of electron heating and redistribution. This treatment is also relevant to the explanation of the classic experiment of Eremin, Litvak and Poluyakhtov[35].

The self-focusing of intense electromagnetic waves in solid state plasma has also been investigated in considerable detail during recent years; the critical powers for self-focusing are much larger in solid state plasmas as compared to gaseous plasmas. Tzoar and Gersten[15] investigated the steady state self-focusing of laser beams in InSb invoking the mechanism of change in electron mass on account of drift energy of the electrons. However, in the steady state the drift energy of the electrons is much smaller than the rise in excess thermal energy of the electrons and hence the effect of the former on mass modulation is small. Dubey and Paranjape[11] investigated a new mechanism of nonlinearity viz. the energy dependence of relaxation time. Tripathi, Tewari, Pandey and Agarwal[12] showed that this nonlinearity is not important in self-focusing on account of the attenuation of the wave. Guha and Tripathi[13] analysed laser focusing in GaAs by the mechanism of intervalley transfer of carriers from a lower valley to a higher valley which results in an increase of the effective mass of the carriers. This nonlinearity is effective in causing self-focusing of laser beams in GaAs only and requires a strong d.c. electric field in conjunction with the laser beam.

Sodha, Tewari, Kamal, Pandey, Agarwal and Tripathi[21] proposed a different and efficient mechanism of self-focusing on account of the nonlocal effects. The nonlinearity arises on account of nonuniform heating and redistribution of carriers. Sodha, Khanna and Tripathi[13] showed that this nonlinearity is dominant when both electrons and holes are present in the sample. The analyses mentioned so far are phenomenological in nature. Tripathi, Sodha and Tewari[36] followed a kinetic treatment to study self-focusing in a Ge sample with arbitrary relative concentration of electrons and holes. The available literature mentioned above is restricted to nondegenerate samples and thus applicable to low carrier density and hence, low laser frequencies. The focusing of high frequency waves requires high carrier concentrations which are synonymous with degeneracy. In the third chapter of the present thesis we have investigated the self-focusing of laser beams in degenerate semiconductors viz., (i) a degenerate parabolic semiconductor (Ge), and (ii) a degenerate nonparabolic semiconductor (n-InSb). The nonlinearity arises in the former case due to non-uniform heating and redistribution of carriers and that in the latter through the energy dependence of electron mass in the presence of a Gaussian laser beam.

Besides self-focusing discussed so far the hot carrier phenomena in semiconductors have been a subject of detailed investigations in the past two decades[2,5]. These studies have resulted in very useful microwave solid state devices and provided an effective tool for the characterisation/diagnostics of semiconductors. The earlier theoretical and experimental investigations in this field are restricted to elemental and compound semiconductors only. Similar investigations in metals could not be made because they cannot sustain high electric fields owing to their high electrical conductivity. Such studies are also infrequent for semi-metals. However, hot carriers in semi-metals can be observed because they are characterised by small and equal concentration of electrons and holes and hence have a considerably (four or five orders of magnitude) lower electrical conductivity than that of metals. Such a possibility has not been reported in the literature so far. Further the effect of hot carriers on the propagation and instability of transverse electromagnetic waves in solid state plasmas is also important from the point of view of device applications. In the fourth chapter of the present thesis the author has investigated (i) hot carrier effects and electromagnetic wave propagation in a current carrying semi-metal plasma.

In addition to this the author has carried out two interesting problems in the last miscellaneous chapter of the thesis viz. (i) hot carrier drift induced electromagnetic wave instability in a magnetoactive solid state plasma, and (ii) steady state and transient thermal blooming of laser beams in a nonlinear absorbing moving medium.

A chapterwise summary of the work reported in the thesis is as follows:-

Chapter-I : Steady State Self-interaction of a Laser Beam in a Strongly Ionised Moving Plasma

The steady state self-interaction of a laser beam with a strongly ionised plasma flowing transverse to the direction of beam propagation have been investigated from a phenomenoligical approach, a perturbation theory and using WKB and paraxial ray approximations. The nonlinearity arises on account of the nonuniform heating and consequent redistribution of carriers. The dominant mechanism of loss of electron excess energy is assumed to be thermal conduction. The effect of the transverse motion of the plasma has been taken into account by a convection term in the energy balance equation and is found to result in non-symmetrical heating of the electrons which in turn leads to non-symmetrical self-focusing along the transverse directions and a shift or deflection of the beam in the direction of flow velocity of the plasma. The extent of asymmetry in self-focusing is however, very small and the deflection of the beam increases with the flow velocity. In a typical case of 7.6×10^5 watt laser of $\omega = 10^{13}$ Rad/sec. and initial beam width $r_o = 0.05$ cm the transverse shift $x_p = 0.1 r_o$ is predicted in a distance of propagation $z = 0.34$ cm in a strongly ionized plasma of electron density $N_o = 10^{16}$ cm^{-3} and transverse flow velocity $W_o = 10^7$ cm/sec.

Chapter-II: Nonstationary Propagation of Electromagnetic Waves in a Time Dependent Plasma

The linear and nonlinear nonstationary propagation of electromagnetic waves in a weakly ionised decaying plasma has been investigated from a phenomenological approach and using perturbation technique; the characteristic time of electron density decay is assumed to be comparable with the duration of the pulse and the energy relaxation time of electrons.

In the linear case of a Gaussian (in time) electromagnetic pulse propagating through a time dependent plasma, the pulse is found to be compressed/broadened in a decaying/growing plasma because different parts of the pulse have different group velocities. In the approximation of zero absorption in the plasma the total energy content of the pulse is shown to be conserved. The effect of absorption on compression/broadening is found to be negligible. However, the peak value of the pulse is suppressed by attenuation. The results are in qualitative agreement with that of Pozwolski[37]. For typical plasma parameters ($\frac{\omega_{po}^2}{\omega^2} = 0.4$, $\nu = 10^8$ sec^{-1}, $\omega = 10^{11}$ Rad/sec, $\gamma\tau = 1.0$ where τ is the duration of the pulse and γ is the decay rate of the plasma) the half width of the pulse is changed by 7-8% when the pulse propagates a distance of $z = 155\lambda_o$ (λ_o is the free space wave length).

In the nonlinear case the self-focusing of microwaves (Gaussian in space) in a weakly ionised decaying plasma has been studied by using WKB and paraxial ray approximations. The nonlinearity arises through the nonuniform heating and redistribution of electrons. For a plasma having decay time (τ_d) comparable to nonlinearity relaxation time (τ_E) the self-focusing of the wave at any time depends on the intensity of the preceding portion of the wave and hence the different parts of the beam get focused by different amounts. It is found that faster the rate of plasma decay, slower is the rate of self-focusing. However, when τ_d is larger than τ_E the quasi-steady state analysis is applicable[30] and the results of our treatment are in substantially good agreement with the experiment of Eremin, Litvak and Poluyakhtov[35] on self-focusing of microwaves in a decaying discharge tube plasma.

Chapter-III: Self-focusing of Laser Beams in Degenerate Semiconductor Plasmas

The free carrier nonlinear dielectric constants of a degenerate parabolic semiconductor (Ge) and a degenerate nonparabolic semiconductor (n-InSb) in the presence of a Gaussian laser beam have been investigated by rigorous kinetic treatments. The nonlinearity arises through the heating and redistribution of carriers in the case of compensated Ge and through the energy dependence of electron mass in n-InSb. The rise in carriers temperatures due to the wave field is almost unaffected by their degeneracy; however, the nonlinearity is considerably affected by this feature. The nonlinearity is larger when ionised impurity scattering is dominant in momentum transfer as compared to the case when acoustical phonon scattering (in Ge) or polar optical phonon scattering (in n-InSb) are important. Further, the increase of degeneracy (by increasing the equilibrium carrier concentration at the fixed lattice temperature) increases the nonlinear dielectric constant and hence the self-focusing of laser beams is enhanced by degeneracy. The critical powers for self-focusing of the beam are found to be: (i) For Ge, $P_{cr} = 10$ watt for $\omega = 10^{13}$ Rad/sec and $r_o = 0.1$ cm and (ii) For n-InSb, $\omega = 2\times10^{14}$ Rad/sec and $r_o = 0.01$ cm., then $P_{cr} = 0.1$ watt.

Chapter-IV: Hot Carrier Effects and Electromagnetic Wave Propagation in a Semi-Metal Plasma

In this chapter the author has investigated the hot carrier effects in a semi-metal (e.g. Bi) by a semi-kinetic treatment using the effective temperature model. The isotropic part of the carrier distribution function is assumed to be Fermi Dirac corresponding to different effective temperatures in each valley; the temperatures are determined by solving the energy balance equation. The many valley model of the band structure and anisotropy of electron and hole mass have been incorporated in the analysis and the carrier relaxation time is assumed to be isotropic. The anisotropy of the d.c. conductivity is studied by orienting the heating electric field along the three crystallographic axes: Trigonal, Binary and Bisectrix. It is concluded that hot carrier effects can be observed in semi-metals also because of their comparatively lower conductivity than that of metals. The hole ellipsoid heating is found to be negligibly small as compared to electron ellipsoid heating. The d.c. conductivity tensor is found to be analogous to electron mass tensor.

Further, the effect of a static magnetic field on the heating of carriers and propagation of electromagnetic waves in bismuth have been studied when the direction of d.c. electric field, static magnetic field and of the propagation of waves are all along the trigonal axis. In this case the three electron ellipsoids are equally heated as in the absence of the magnetic field. The presence of magnetic field effectively cools the carriers due to the finite off-diagonal component of the electron mass tensor. The hole heating is not affected by the presence of magnetic field. Further, the enhanced heating of the carriers with increasing d.c. electric field causes progressive decrease in the refractive index and the absorption coefficients; this effect is more pronounced in the case of upper band microwaves. The effects of heating of carriers on Faraday rotation and ellipticity for high frequency waves have also been investigated.

Chapter-V: Miscellaneous Topics

Section A: Hot Carrier Drift Induced Electromagnetic Wave Instability in a Magnetoactive Solid State Plasma

In this section the effect of a strong longitudinal static electric field on the propagation and instability of transverse circularly polarised electromagnetic waves (both left and right handed) has been studied under hot carrier conditions in the presence of a static magnetic field along the direction of propagation in an InSb plasma by a phenomenological approach. The exact dispersion relation has been derived and numerically analysed. The results indicate the possibility that both left and right handed circularly polarised waves can experience spatial growth in intrinsic InSb at room temperature and extrinsic InSb at liquid nitrogen temperature. The growth rate decreases with the heating d.c. electric field and increases slightly with the static magnetic field. The present study may be useful in designing an amplifier using InSb plasma even at room temperature.

Section B: Steady State and Transient Thermal Blooming of Laser Beams in a Nonlinear Absorbing Moving Medium

In this section the author has investigated the steady state and transient thermal self-focusing/defocusing of a Gaussian laser beam (TEM_{00} mode) in an absorbing nonlinear dielectric (e.g. CS_2) medium moving transverse to the direction of beam propagation. The effect of the transverse wind is included in the heat conductivity equation and is found to result in a symmetrical heating of the medium and hence in asymmetric focusing along the transverse directions and a deflection of the beam into the wind. The deflection of the beam is in the wind direction if $\frac{dn_o}{dT} = +ve$ and opposite to it if $\frac{dn_o}{dT} = -ve$. The deflection of the beam increases with increasing wind velocity in the former case and decreases with wind velocity in the latter case. For typical parameters of CS_2 the deflection is appreciable even for small wind velocity. The results are substantially in agreement with that of experimental observations[38] and earlier theoretical treatments. In the non-steady state case the time dependent convergence/divergence and deflection of the beam occur .

The work reported in the thesis has partially appeared in the following publications:-

1. Self-focusing of electromagnetic waves in a degenerate-electron-hole plasma, Appl. Phys. 3, 141 (1974).
2. Hot carrier anisotropic conductivity of a current-carrying bismuth, J.Phys.Chem. Solids 35, 521 (1974).
3. Hot carrier drift induced EM wave instability in a magnetoactive solid state plasma, J.Phys.Chem.Solids, In Press (1975).

4. Steady state and transient self-interaction of a laser beam in a strongly ionised moving plasma, Appl.Phys., In Press (1975).
5. Thermal self-focusing/defocusing of laser beams in an absorbing moving medium: convection effects, Optica Acta, In Press (1975).
6. Nonstationary propagation of a Gaussian EM pulse in a decaying/growing plasma, J.Phys. D: Appl. Phys. (Communicated).
7. Transient self-focusing of electromagnetic waves in a decaying plasma, Opto Electronics (Communicated).
8. Self-focusing of laser beams in a degenerate nonparabolic semiconductor: Kinetic approach, J.Phys.Chem.Solids (Communicated).

In addition to the above work, the author has also been associated with the following publications:

1. **Nonlinear Scattering of a Gaussian Laser beam from a turbulent plasma. (J.Appl. Phys., comminicated).**
2. **Collapse of Langmuire waves by the pump wave. (communicated).**

CONTENTS

APPENDIX