PARAMETRIC INSTABILITIES IN PLASMAS

by

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ABSTRACT

This thesis presents an investigation of parametric instabilities of (i) laser radiation in an inertially confined plasma and (ii) radio frequency waves in a magnetically confined plasma, as mechanisms to heat the plasma for fusion applications. In the vicinity of the turning point (or the upper hybrid layer in case of tokamak heating), the upper hybrid laser radiation decays efficiently into lower hybrid waves, fast ion waves, ion acoustic waves and Bernstein waves. It is found that for $|v_{o\perp}|/v_e \geq 0.1$, the nonlinear Landau damping by electrons assumes the largest growth rate; $v_{o\perp}$ and v_e are pump induced electrons velocity perpendicular to the applied magnetic field and thermal speed of electrons. Nonlinear scattering of whistlers in tokamak type plasma has been investigated when the low frequency mode involves long parallel wavelength (lower hybrid and ion Bernstein modes). The decay into lower hybrid wave is possible only for scattering angle exceeding 45^o.

The stimulated Brillouin scattering of laser radiation in a piezoelectric semiconductor (CdS) reveals that threshold laser power is quite low; specifically of the order of 10^6 W/cm^2 for a CO_2 laser and 10^8 W/cm^2 for a Nd:glass laser. The dc bias enhances the growth rate by one order of magnitude. The growth rate for SBS of helicon waves ($\sim$20 KW/cm^2) in a piezoelectric n-InSb turns out to be $\sim 10^3$ sec^{-1} for 1 MHz - 10 MHz acoustic perturbation.

We have also derived the dispersion relation for the electrostatic waves in a semimetal, i.e. bismuth in presence of magnetic field by incorporating the effects of many valley band structure, anisotropy in the carrier mass and degeneracy in the distribution function. Bernstein modes are explicitly analysed.

The phenomenon of nonlinear second harmonic generation of laser radiation in n-InSb filled rectangular waveguide is investigated. It is seen that the power conversion efficiency is greatly enhanced by the dimensional resonances. For a typical, 1KW, CO_2 laser, the second harmonic conversion efficiency can be as high as 1%. In addition, we have also studied the phenomena of nonlinear wave propagation and self focusing of electromagnetic beams.

PREFACE

Thermonuclear fusion seems to provide the most promising answer to the global problem of energy crisis in compliance with the needs of industrial civilisation. The fuel for fusion, viz. deuterium which is contained in the sea water in large proportions would be available to the planet for millions of years almost at the zero cost. The basic reactions would be

$$ {}_1D^2 + {}_1D^2 \longrightarrow {}_1T^3 (1\,\mathrm{MeV}) + {}_1P^1 (3\,\mathrm{MeV}) \qquad (1)$$

$$ {}_1D^2 + {}_1D^2 \longrightarrow {}_2He^3 (0.8\,\mathrm{MeV}) + {}_0n^1 (2.5\,\mathrm{MeV}) \qquad (2)$$

Both these reactions proceed with equal probability. However, the ignition temperature for these reactions is very high and the requirements on the plasma confinement are quite stringent. Consequently, the first generation fusion reaction should rely upon deuterium-tritium reaction

$$ {}_1D^2 + {}_1T^3 \longrightarrow {}_2He^4 (3.5\,\mathrm{MeV}) + {}_0n^1 (14.1\,\mathrm{MeV}) \qquad (3)$$

which has low ignition temperature and puts less difficult conditions on plasma confinement. The well known Lawson criterion for D-T reaction demands that

$$N\tau \gtrsim 10^{14}\ cm^{-3}\ sec. \qquad (4)$$

where N is the electron density and τ is the confinement time of the plasma. The ignition temperature for this reaction is about 4 KeV.

There are two schemes to achieve condition (4):
(i) Inertial confinement, i.e., laser driven fusion,
(ii) Magnetic confinement, i.e. magnetic fusion.

In the inertial confinement scheme D-T pallet is irradiated symmetrically by high power laser pulses and one plans to have enough fusion reaction before the plasma diffuses. As a matter of fact, in the initial phase of irradiation, the plasma is compressed[1] to very high densities (10^2-10^3 times the solid densities) by the self-generated shockwaves. The diffusion of the plasma takes place after a relatively much longer time ($\sim$ 1 n sec. for typical pallet sizes). Recent experiments with Shiva laser[2] have attained the goal within an order of magnitude of Lawson criterion. During the heating phase of the plasma, one observes self-generated magnetic fields, parametric instabilities and harmonic generation of laser radiation. Some experiments have also shown the self-focusing of laser beams[3].

In the scheme of magnetic fusion, the plasma is confined by a network of static magnetic fields. Out of the various configurations of confinement, the tokamak has attained highest importance. The confinement times in this device are of the order of a second and one deals with relatively much lower electron densities ($\sim 10^{13}-10^{15}$ cm^{-3}). In this case, one needs to provide supplementary heating of plasma by radio-frequency fields, e.g. lower hybrid heating, electron cyclotron heating, ion cyclotron heating etc. Evidences of ion heating in various small and large scale experiments have been obtained recently. The ion heating is seen to be accompanied by the appearance of a low frequency spectrum showing the existence of parametric instabilities.

Thus in the both the schemes of fusion, one deals with the nonlinear interaction of high power radio waves/ laser beams with plasmas and one is looking forward for various ways of enhancing the absorption coefficient[4-7] of the plasma for electromagnetic radiation. Parametric instabilities might provide an effective mechanism of anomalous absorption. However, it needs to be explored in great details.

In the present thesis we have studied the parametric instabilities of laser radiation and radiowaves in fusion plasma, laboratory plasma and solid state plasmas and examined the relative predominance of various channels of decay. We have also studied other nonlinear effects, e.g. harmonic generation, nonlinear propagation and self-focusing of Gaussian laser beams in plasmas in considerable detail. Before proceeding further, it would be useful to have a physical understanding of these phenomena.

A: Parametric Instabilities

In the presence of a high power electromagnetic wave $(\omega_0, \underline{k}_0)$ the electrons of a plasma acquire an oscillatory drift velocity. A low frequency density perturbation $(\omega, \underline{k})$ interacts with the oscillatory drift velocity of electrons and the magnetic field of the pump to produce high frequency sidebands $(\omega \pm \omega_0, \underline{k} \pm \underline{k}_0)$. The sidebands inturn interact with the pump wave to produce a low frequency ponderomotive force which then drives the original density perturbation. When this positive feedback process is strong enough to overcome the damping of these modes, instability results and both the low frequency mode and the sideband modes grow at the same rate, at the expense of the pump energy. The decay modes are eventually absorbed by electrons or ions through Landau damping and cyclotron damping giving rise to anomalous heating of the plasma.

The process of decay may be categorised as follows:

a) Resonant Decay: When the low frequency perturbation $(\omega, \underline{k})$ and the high frequency lower sideband $(\omega_1, \underline{k}_1;$ $\omega_1 = \omega - \omega_0,\ \underline{k}_1 = \underline{k} - \underline{k}_0)$ are the normal modes of the linear system and the upper sideband ($\omega_2, \underline{k}_2$; $\omega_2 = \omega + \omega_0, \underline{k}_2 = \underline{k} + \underline{k}_0$) is off-resonant, the decay process is known as the resonant three wave decay. In this process the linear dampings of decay waves is small as compared to the growth rate of the low frequency perturbation. The growth rate well above the threshold is proportional to E_0 (E_0 is the pump amplitude). Resonant decay is known as the decay instability when both the decay waves are electrostatic modes. If the high frequency sideband is an electromagnetic wave, the decay process is known as stimulated scattering. Further, if the electrostatic mode ($\omega, \underline{k}$) is an electron plasma wave, the scattering is known as the stimulated Raman scattering. When the electrostatic mode ($\omega, \underline{k}$) is an acoustic mode, the decay is known as the stimulated Brillouin scattering. If the low frequency perturbation ($\omega, \underline{k}$) is not a normal mode, the density perturbation can still exist if the pump is large enough to maintain it against diffusion. This has been called reactive quasimode scattering.

b) <u>Non-resonant Decay/Nonlinear Landau Damping</u>: When the low frequency perturbation has a phase velocity of the order of thermal speed of electrons/ions, the perturbation is heavily Landau damped and could exist only in the presence of the pump. Such perturbations are called as quasimodes ($\omega \simeq \underline{k} \cdot \underline{v}$). The decay of the pump into a quasimode and a high frequency sideband is known as nonlinear

Landau damping or stimulated Compton scattering. In this case, the pump transfers energy and momentum to the lower sideband and a bunch of resonant particles. The growth rate lies between γ_L and γ_{L1}, i.e. $\gamma_L > \gamma > \gamma_{L1}$ and goes as the square of the pump amplitude (γ_L and γ_{L1} are the linear damping rates of the quasimode and the high frequency sideband).

c) Oscillating Two-Stream Instability: When the pump interacts with a short wavelength perturbation ($k \gg k_0$) it produces both the high frequency sidebands and one is encountered with a four wave decay process. In this process, the sidebands possess a finite frequency shift from the eigenfrequency of the linear system. The nonlinear interaction between the sidebands and the pump results in a low frequency ponderomotive force which then drives the perturbation. In the limit of $\omega \ll \omega_0$, $k \gg k_0$, the perturbation is a purely growing mode and the process of decay is known as the oscillating two-stream instability (OTSI). This instability effectively results in the formation of small bunches of the pump.

d) Filamentation and Modulational Instabilities: When the low frequency perturbation satisfies the conditions $\omega \ll \omega_0$ $k \ll k_0$, both the high frequency sidebands (viz. the scattered electromagnetic waves) are again important. If $\underline{k}$ is perpendicular to $\underline{k}_0$, the instability is called the filamentation instability and turns out to be a purely growing mode. In the other case of $\underline{k}$ parallel to $\underline{k}_0$ and $\omega/k = \partial\omega_0/\partial k_0$ (i.e. the phase velocity of perturbation is equal to the group velocity of the pump) the decay process is known as the modulational instability.

B: Harmonic Generation

In the presence of a high amplitude electromagnetic wave, the electrons of a plasma experience a strong ponderomotive force having two components (i) a time independent component which results in the redistribution of plasma density and (ii) a time dependent component at twice the frequency of the pump. The oscillatory component of ponderomotive force produces a second harmonic current density and thus results in the generation of second harmonic. In the case of a plane uniform pump wave propagating through a homogeneous plasma, the second harmonic is a purely electrostatic wave. However, in the presence of a gradient either in the intensity of the pump or in the density of the plasma, the second harmonic is a mixture of electrostatic and electromagnetic modes.

The generated second harmonic might interact with the fundamental to produce the third harmonic and so on. The third harmonic is also produced by a different mechanism which is operative in collisional plasmas. In the presence of the pump, the electrons of the plasma absorb energy from the wave ($-e\underline{E}_0\cdot\underline{v}_D$ per electron per second), their temperature rises. In the steady state electron temperature has a component oscillating at twice the frequency of the pump. Since the collision frequency of electrons is a function of electron temperature, it gets modulated. The modulation of collision frequency means the corresponding modulation of the conductivity of the plasma and thus a third harmonic is generated. For highly collisional plasmas, the collisional nonlinearity dominates over the ponderomotive nonlinearity in the generation of third harmonic.

C: Self Focusing

When the high power electromagnetic wave has a Gaussian distribution of intensity ($E_0E_0^*$) along its wave-front, the plasma is pushed away from the regions of high intensity to those of low intensity by (i) the ponderomotive force and (ii) the pressure gradient caused by the non-uniform heating of electrons. This results in the profile for refractive index variation as

$$n = n_0 + n_2 E_0 E_0^* ; \quad n_2 > 0. \qquad (5)$$

Thus, the high intensity portion, i.e. the central portion of the beam would propagate with lower phase velocity than the marginal portion. The wavefront in the course of propagation would attain curvature and the beam would get focused. This phenomenon of focusing is opposed by the diffraction divergence effects, consequently, there exists a threshold for self-focusing. The value of threshold power is, however, quite low and is easily achieved in the present day experiments.

Brief Summary of the Earlier Work

In the realm of laser driven fusion much work has been reported on stimulated Raman Scattering, stimulated Brillouin scattering, stimulated Compton scattering, filamentation instability and OTSI of laser radiation. Liu and Kaw[8] have given a good review of the growth rates and power thresholds for these channels of decay. The growth rates turn out to be considerably large. In the underdense region of the plasma SRS and SBS predominate whereas, in the vicinity of the plasma resonance ($\omega_0 \sim \omega_p$) the decay instability and OTSI possess largest growth rates. Nonlinear Landau damping possesses relatively smaller growth rate. Filamentation instability has still smaller growth rate. Liu[9] has given a detailed discussion of the effect of inhomogeneity of the plasma on the various channels of parametric decay. The inhomogeneity restricts the region of resonant interactions and gives rise to convective losses. The threshold powers are raised. However, the oscillating two-stream instability and the nonlinear Landau damping might turn out to be an absolute instability when two turning points for the scattered waves exist in the plasma. These studies are mainly restricted to unmagnetised plasmas[10-23]. With the recent observations of self-generated megaGauss magnetic fields[24-36] in pallet fusion, a new dimension is added to the laser fusion processes. A magnetoplasma supports many more modes and offers many new channels of decay. The work in this area is, however, in early stage. . Grebogi and Liu[37] have studied the effect of self-generated magnetic field on the two plasmon decay. They[38] have also studied Brillouin and Raman scattering of extra-ordinary laser radiation in a magnetised plasma. In the present thesis we have studied the various channels of parametric decay of laser radiation in a magnetised plasma.

With reference to magnetic fusion the work on parametric instabilities has been mainly restricted to lower hybrid heating[39-50] and whistler mode heating[51-58] of plasmas. Tripathi, Grebogi and Liu[59] have given a detailed discussion of parametric decay of lower hybrid waves and obtained largest growth rates for the decay into (i) ion cyclotron waves (ii) nonlinear Landau damping and (iii) OTSI. Kaw[54], Lee[53] and Forslund et al.[55] have studied the nonlinear scattering of whistler pump in a plasma. The decay instability of whistler waves with lower hybrid and ion Bernstein sidebands has not been investigated by earlier workers. We have studied these channels of decay and shown that they possess the largest growth rates.

The phenomenon of nonlinear harmonic generation of electromagnetic waves in plasmas has been studied in considerable detail in last two decades[60-65]. Sodha and Kaw[66] have given a review of harmonic generation in unbounded collisional plasmas. Sodha and Sawhney[67] and others considered a plasma slab of thickness comparable to the wavelength of the fundamental wave and optimised the plasma parameters and slab thickness for maximum harmonic conversion efficiency. Sodha et al.[68] have studied the phenomena of harmonic generation of Gaussian laser beams taking the effect of self-focusing into account. The self-focusing enhances the power density of the fundamental beam and hence enhances the harmonic efficiency by 2-3 orders of magnitude. Sharma and Sharma[69-70] have made calculations of harmonic generation in collisionless plasmas due to ponderomotive type nonlinearity. The conversion efficiency could be raised to very high values when resonance conditions could be achieved either by the choice of plasma parameters or by the choice of plasma configuration. A part of the present thesis is devoted to achieve the enhancement of harmonic conversion efficiency by choosing suitable dimensions of the plasma.

Recently the self-focusing of intense electromagnetic waves in gaseous and solid state plasmas has attained considerable interest[71-75]. Earlier theoretical calculations of self-focusing are restricted to time scale larger than τ_D

(diffusion time), and hence, are not relevant to the interesting situations of high power beams of shorter duration. No attempt so far has been made to investigate short time scale self-focusing of electromagnetic beams which are relevant to interesting situations.

The present thesis is devoted to the study of parametric instabilities of (i) laser radiation in an inertially confined plasma and (ii) radio frequency waves in a magnetically confined plasma,as a mechanism to heat the plasma for fusion applications. We have studied in detail the various channels of parametric decay (viz. nonlinear scattering, decay instability, nonlinear Landau and cyclotron damping and OTSI) of (i) laser radiation (upper hybrid) in laser produced plasmas and (ii) whistler waves in tokamak type plasmas. We have also extended these calculations to piezoelectric semiconductors where lattice vibrations play an important role. In addition to this, we have also analysed the phenomena of nonlinear wave propagation, self-focusing and harmonic generation of laser radiation in various situations of interest. We have also developed a rigorous kinetic theory of electrostatic dispersion relation in many valley bismuth (with anisotropic mass tensor) in the presence of a static magnetic field. The Bernstein modes have been analysed in considerable detail.

The thesis has been divided into eight chapters; a chaptersie summary is given below.

Chapter-I: Decay Instability and OTSI of Upper Hybrid Laser Radiation in a Plasma

In this chapter we have investigated the various channels of parametric decay of upper hybrid laser radiation in laser-pallet fusion plasmas. In the vicinity of the cut off, the pump decays efficiently into (I) lower hybrid + upper hybrid modes (II) ion acoustic + upper hybrid mode (III) fast ion wave + plasma wave and (IV) Bernstein mode + plasma wave. At high pump powers, nonlinear Landau damping and cyclotron damping by electrons possess , largest growth rates. These instabilities are relevant to tokamak type plasmas also, where nonlinear effects are important in the vicinity of upper hybrid resonance. A high power laser radiation (in upper hybrid mode) is unstable for short wavelength purely growing perturbations, viz. oscillating two stream instability. In the limits of long and short perpendicular wavelengths, $k_{\perp}\rho_e < 1$ and $k_{\perp}\rho_e > 1$, the growth rate turns out to $\sim(\underline{k}_{\perp} \cdot \underline{v}_{0\perp})^2$; ρ_e and $\underline{v}_{0\perp}$ are the electron Larmor radius and oscillatory drift velocity.

Chapter-II: Nonlinear Scattering of Whistler by Lower Hybrid and Ion Bernstein Modes

The earlier investigations of nonlinear scattering of whistler involve only short perpendicular wavelengths of the scattered mode. This excludes two important channels of decay which involve lower hybrid waves, and ion Bernstein modes having long perpendicular wavelengths. In this chapter we have studied the parametric decay of a high power whistler into lower hybrid and ion Bernstein modes in a homogeneous plasma. Fluid model approach has been used to obtain the nonlinear response of electrons. The thresholds for these channels are considerably low. However, the decay into lower hybrid waves is possible only for scattering angles exceeding $\pi/4$. The decay into ion Bernstein mode is possible at shorter scattering angles but the growth rate is relatively small and the threshold is high.

Chapter-III: Stimulated Brillouin Scattering of Laser Radiation in a Piezoelectric Semiconductor

This chapter presents an investigation of Stimulated Brillouin Scattering (SBS) of laser radiation in a piezoelectric semiconductor. A high power laser beam propagating through a piezoelectric semiconductor decays efficiently into an acoustic wave (mainly a lattice mode) and a scattered laser wave. The coupling of waves for SBS is provided by the nonlinear response of free electrons and the resonance conditions are easily satisfied over a wide range of scattering angles and semiconductor parameters. The threshold laser power is quite low; of the order of 10^6 W/cm^2 for a CO_2 laser and 10^8 W/cm^2 for a Nd:glass laser. Above the threshold, the growth rate of decay waves is considerably large ($\sim 10^6$ sec^{-1}).

The above analysis is extended to dc biased piezoelectric semiconductor. The dc bias strongly reduces the threshold laser power for parametric decay. In the case $v_d > c_s$ (v_d is the drift due to applied dc field and c_s is the sound speed) the acoustic instability grows at the expense of dc field, however, the laser power enhances the growth rate.

Chapter-IV: Stimulated Brillouin Scattering of Helicon Waves in a Semiconductor

In this chapter we have investigated resonant decay of a right handed circularly polarised helicon (RHCP) wave into low frequency acoustic wave and a scattered helicon wave in a piezoelectric semiconductor. The low frequency nonlinearity arises through the parallel ponderomotive force on electrons whereas the high frequency nonlinearity arises through the equation of continuity. The growth rate of instability turns out to be $\sim 10^3$ sec^{-1} for 1 MHz - 10 MHz acoustic perturbations when a microwave of 20 KW/cm^2 propagates through n-InSb.

Chapter-V: Bernstein Waves in Bismuth

In this chapter we have derived a general dispersion relation for electrostatic waves in bismuth in the presence of a static magnetic field by solving the Vlasov equation for electrons and holes. The technique of integration over the unperturbed trajectories of electrons and holes has been used. The effect of many valley band structure, anisotropy in the carrier mass and degeneracy in the distribution function are incorporated. The dispersion relation is explicitly solved for Bernstein waves. It is found that the anisotropy in the electron mass gives rise to nonequal contribution from three ellipsoids, however, the electrons in all the ellipsoids possess the same gyrofrequency. In the limit of negligible degeneracy, the dispersion relation resembles very closely to the one in gaseous plasma.

Chapter-VI: Optical Second Harmonic Generation in n-InSb

In this chapter we have studied the phenomenon of nonlinear second harmonic generation of laser radiation in n-InSb filled rectangular waveguide. The nonlinearity arises through the ponderomotive force on electrons. The generated harmonic possess a very different kind of intensity distribution than that of the normal modes. The efficiency of second harmonic generation is resonantly enhanced at some optimum values of density & size of the waveguide such that

$$2\beta_1 = \beta_2, \text{ i.e. } \frac{\pi^2 n^2}{b^2} + \frac{(l^2-1)\pi^2}{a^2} = \frac{3\omega_p^2}{c^2},$$

where β_1 and β_2 are the propagation constants of fundamental and second harmonic modes, a and b are the x and y-dimensions of the waveguide and n and m are integers. For a typical 1 KW, CO_2 laser the second harmonic conversion efficiency takes on values as high as 1%.

Chapter-VII: Short Time Scale Self-Focusing of Electromagnetic Beams in a Magnetoplasma

A Gaussian electromagnetic beam propagating in a plasma in the direction of the static magnetic field gives rise to (i) a pondoromotive force transverse to the magnetic field and (ii) nonuniform heating of electrons. These effects eventually modify the local magnetic field and thus produce a nonlinearity relevant to self-focusing. The critical power for self-focusing on a time scale shorter than the diffusion time $(t_D > t)$ is v^{th}/c times shorter than that on the longer time scale $(t > t_D)$: v^{th} is the thermal speed of electrons.

Chapter-VIII: Nonlinear Propagation of Laser Radiation in an Inhomogeneous Plasma

This chapter presents an investigation of propagation of a high power Gaussian laser beam at an angle to the density gradient in a plasma. The laser beam suffers from three effects: (i) size reduction due to curvature in the ray trajectories, (ii) size enhancement due to diffraction divergence and (iii) size reduction due to self-focusing. These three competing processes have been incorporated in the wave equation which has been solved analytically. It is seen that as the beam approaches the reflection layer, its intensity decreases due to the predominance of diffraction effects as against the prevailing belief of intensity enhancement due to curvature in the ray trajectories.

The thesis is partly based on the following publications:

1. Short time scale self-focusing of electromagnetic beams in a magnetoplasma, D.P.Tewari and R.R. Sharma, J.Appl.Phys. 50, 751 (1979).

2. Nonlinear propagation of laser radiation in an inhomogeneous plasma, D.P.Tewari and R.R.Sharma, J.Phys.D: Appl.Phys. (In Press 1979).

3. Bernstein Waves in Bismuth, D.P.Tewari and R.R.Sharma, (Communicated).

4. Decay Instability of laser radiation in a magnetoplasma, V.K.Tripathi and R.R.Sharma (Communicated). Phys. Fluids (In Press 1979)

5. Oscillating two stream instability of upper hybrid laser radiation in a plasma, R.R.Sharma (Communicated).

6. Optical second harmonic generation in n-InSb, R.R.Sharma, Phys.Rev.A. (Accepted).

7. Nonlinear scattering of whistlers by lower hybrid and ion Bernstein modes, M.S.Sodha, R.R.Sharma and V.K.Tripathi (Communicated).

8. Stimulated Brillouin Scattering of laser radiation in a semiconductor, R.R.Sharma and V.K.Tripathi (Communicated). Phys. Rev. (In Press 1979)

9. Stimulated Brillouin Scattering of laser radiation in dc biased semiconductor, R.C.Sharma, R.R.Sharma (Communicated).

10. Stimulated Brillouin Scattering of Helicon waves in a semiconductor, M.S.Sodha and R.R.Sharma (Communicated).

In addition to the above mentioned publications the author has also been associated with the following publications which have not been included in the thesis.

1. Microwave harmonic generation in plasma filled waveguides, R.R.Sharma and R.C.Sharma, J.Appl. Phys. (In Press 1979).

2. Nonlinear mixing of microwaves in plasma filled waveguide, R.R.Sharma and R.C.Sharma, J.Phys.D: Appl. Phys. (In Press 1979).

3. Submillimeter harmonic generation in semiconductor waveguides, R.R.Sharma and R.C.Sharma (Communicated).

4. Over modulation of an upper hybrid electromagnetic beam in a plasma, R.C.Sharma and R.R.Sharma (Communicated).

5. Nonlinear distortion of microwave beam in a Waveguide, R.C.Sharma and R.R.Sharma (Communicated).

6. A Note on nonlinear reflection of laser radiation from an overdense plasma, D.P.Tewari, R.R.Sharma and R.C.Sharma (Communicated).

CONTENTS