INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

RESEARCH REPORT

NAGOYA, JAPAN

Red-Shift of the Frequency Spectra of High-Power Microwaves Reflected from a Magnetized Plasma

K. Minami[*], Y. Mori[*] and K. Ishii

IPPJ-229 August 1975

Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

---

[*] Permanent address: Department of Electrical Engineering,
Nagoya University, Nagoya, 464, Japan.

Abstract

Frequency spectra of high-power microwaves reflected from and/or transmitted through a magnetized plasma are measured. The red-shifts of the spectra for reflected waves are found in such a case that the incident microwave is totally reflected from the plasma. No appreciable frequency shifts are observed in reflected and transmitted waves, when the incident microwave can transmit through the plasma. The red-shifts we observe are attributed to a Doppler-shift caused by a deformation of the plasma column, previously reported by the authors, due to the incident high-power microwaves.

I. Introduction

In recent years, interactions between a high-power laser and target plasmas have been studied experimentally as well as theoretically.[1)] Goldman et al.[2)] and Ripin et al.[3)] reported the red-shifts of the spectrum of the scattered laser light. Yamanaka et al.[4)] observed that the back=scattered light around the incident wavelength showed the spectrum broadening with two satellites in red and blue sides.

The phenomena in laser-produced plasmas, however, are not always easy to observe, since they occur in a small spatial region in a short period of the order of nsec. The laser-plasma interactions are occasionally simulated by a high-power microwave and a plasma whose density is much less than that of the laser-produced plasma. Since the frequency of the microwaves are about 10^{-4} time less than that of the lasers, the corresponding density can be 10^{-8} times less than that of the laser-produced plasmas. Thus, one can use the steady-state highly-ionized plasmas which is familiar in laboratory experiments. The characteristic scale and time of the phenomena are about 10^{4} times stretched in microwave=plasma interactions. In this case, many of the electronic devices can be used as diagnostic tools which are not available in laser-plasma interactions.

Ikezi et al.[5)] observed the formation of a plasma cavity, i.e., an envelope soliton, at the cut-off point of an inhomogeneous plasma due to applied microwaves. The plasma cavity accompanied by the localized HF field was observed to move at a velocity closer to that of the ion acoustic wave.

However, they did not investigate the reaction to the applied microwave caused by the formation of the plasma cavities. They used the microwave at a frequency of 640 MHz whose wavelength in vacuum was greater than the size of the plasma. In such a case, the reflectivity and/or the frequency spectrum of the scattered waves are not conveniently observed. In the present paper, we describe an experimental evidence of the red-shift of the frequency spectra of high-power, X-band microwaves reflected from a magnetized plasma.

The experimental setup, procedure and results are presented in Sec.II. In Sec.III, the discussions and interpretations are described with some concluding remarks.

II. Experimental Methods and Results

A steady-state highly-ionized plasma$^{6)}$ called "TPD= machine" at the Institute of Plasma Physics is used in our experiment. The plasma is produced in the helium gas at 10^{-3} Torr. The electron density where the present experiment is made can be changed from 10^{11} (cm^{-3}) to 10^{14}, varying the discharge current I_d at the plasma source. The plasma column has a Gaussian radial distribution with 1 cm half-width. A uniform magnetic field B of several thousand Gauss is applied axially to keep the electron density high. The experimental setup is shown in Fig.1, where the reflection and the transmission of the high-power microwaves are measured. The standard X-band rectangular waveguides are inserted in the radial direction of the plasma column. The end faces of the waveguides are made close each other as possible as we can without disturbing the plasma. The waveguides are coupled to the plasma in such a way that the direction of polarization of the microwave electric field is perpendicular to the static magnetic field B. Then, the extraordinary modes$^{7)}$ can be excited in the plasma. Microwave pulses up to several kW and the time-width 2 μsec at a frequency of 9234 MHz are launched into the plasma through the directional coupler to observe the reflected microwaves and the power-meter which monitors the incident power.

In Fig.2, the transmitted microwave powers through the plasma are recorded as a function of B, using a crystal detector and a boxcar integrator. The abscissa is the normalized magnetic field ω_c/ω, where ω_c and ω are, respectively, the electron cyclotron and the microwave angular frequencies. Since $\omega/2\pi = 9.234 \times 10^9$, $\omega_c/\omega = 1$ corresponds to B = 3298 (Gauss). The discharge currents $I_d = 10$ (A) and 20 correspond, respectively, to the normalized electron densities $(\omega_p/\omega)^2 = 0.2$ and 0.5, where ω_p is the electron plasma frequency on the axis of the plasma column. It is shown in Fig.2, that the transmitted microwave disappears somewhere $\omega_c/\omega < 1$, whereas it can be observed always for $\omega_c/\omega > 1$.

Next, we measure the frequency spectra of the incident and reflected microwaves as functions of I_d and B. The Panoramic Spectrum Analyser (Model RF-4a) is used in our experiment. An example is shown in Fig.3, where the microwave pulses of 1.15 kW are incident on the plasma for I_d = 20 (A). In the figure, (a) is the spectrum of the incident microwave. Since the incident pulse has a shape of square wave with time-width of 2 μsec, the spectrum has a dispersion around the center frequency of 9234 MHz. The spectral pattern of (a) directly corresponds to the Fourier components of the microwave modulated by the square wave. The Fig.3(b), (c) and (d) are the spectra of the reflected microwave for $\omega_c/\omega = 0.881$, 0.969 and 1.03, respectively. These three pictures are measured at ω_c/ω shown, respectively, by arrows (b), (c) and (d) in Fig.2. The former two pictures are taken in the evanescent condition, where no transmitted microwave powers are observed. The last picture corresponds to the transmission condition. The red-shift of the spectra of the reflected microwave in comparison with that of the incident wave can be observed only for the evanescent conditions, as is shown in (b) and (c). Whereas, no appreciable frequency-shift in the reflected microwave is observed for transmission condition, i.e., $\omega_c/\omega > 1$, as is shown in (d). When a small incident power of the order of mW from CW klystron oscillator is used, we do not observe any frequency-shift in the reflected microwaves. Furthermore, (b) shows a spectral broadening which is similar to those previously reported in the laser-plasma interactions.2-4)

The frequency spectra of the transmitted microwaves are also examined. An example is shown in Fig.4. Here, (a) is the spectrum of the transmitted wave, when the plasma is put out, i.e., $I_d = 0$. This spectrum is just the same as that of the incident microwave for $I_d \neq 0$. The apparent discrepancy between Fig.3(a) and Fig.4(a) is due to the slow frequency-drift of the microwave oscillator. The effect of the drift can be eliminated in each run of the measurements, since the effect becomes serious in a period of the order of a minute. Our primary concern is the differences between (a), (b), (c) and (d) in each figure. Fig.4(b), (c) and (d) are the spectra for I_d = 20 (A) and ω_c/ω = 0.881, 1.03 and 1.18, respectively. Fig.4(b) is under the evanescent condition. In this case, the attenuation before the input terminal of the spectrum analyser is reduced by an amount of 12 db, in comparison with the cases of Fig.4(a), (c) and (d). Then, the observed signal in (b) is very small and is dominated by the white noise. Fig.4(c) and (d) correspond, respectively, to the transmission condition, i.e. $\omega_c/\omega > 1$ with appreciable observed signals. We do not detect any frequency-shift in transmitted microwaves for $\omega_c/\omega > 1$.

The center-frequencies of the red-shift in the reflected microwaves are plotted for I_d = 10 (A) and 20, as a function of ω_c/ω in Fig.5. We conclude that the red-shift is detected only in the reflected wave for the plasma in the evanescent condition.

III. Discussions

In order to explain our results in Fig.2, we calculate numerically the transmission coefficients of the one=dimensional plasma slab, on which a uniform magnetic field B is applied parallel to the plasma boundary. For simplicity, we make use of the linear theory of extraordinary modes in a cold plasma where the effects[8)] of the thermal electrons are ignored. We assume a parabolic density distribution. Solving the Maxwell equations with usual Runge-Kutta method and using the boundary conditions, we obtain the transmission coefficient of the incident microwaves, as a function of the peak density and B. We find that the calculated values fairly agree with the observations shown in Fig.2.

Our interpretations of the results in Fig.2 are as follows. When $\omega_c/\omega < 1$, there is a cut-off region in the plasma column where the electron density changes in radial direction, as is well known in the linear theory.[7,8)] Here, the term "cut-off" means the region where the local refractive index is imaginary. Then, the wave can not propagate through the cut-off region. When the cut-off region exists somewhere in the plasma, the incident microwave can not transmit through the plasma column. The evanescent condition, where no transmitted wave is observed in Fig.2, always appears when ω_c/ω increases to unity. The evanescent condition for $\omega_c/\omega < 1$ increases with the plasma density, i.e., I_d as is shown in Fig.2. On the other hand, there is no cut-off region anywhere in the plasma for $\omega_c/\omega > 1$. Then, the transmitted power can be detected always for $\omega_c/\omega > 1$.

Next, we consider the physical reason of the red-shift we observe. The stimulated Brillouin scattering[9)] is not likely to happen, since the threshold intensity of the pumping microwave is much greater than that used in our experiment. The incident power of 1.15 kW corresponds to $(v_d/v_t)^2$ =

$e^2E^2/2m_e\omega^2KT_e = 0.0137$, where $v_d = eE/m_e\omega$ and $v_t = (2KT_e/m_e)^{1/2}$ are, respectively, the HF drift and thermal velocities of electrons. Here, $T_e = 10$ (eV) is assumed. In our plasma, the stimulated Brillouin scattering can be expected for $(v_d/v_t)^2 >> 1$.

We believe that the red-shift we observe is a Doppler=shift caused by a deformation of the plasma column, in other words, the formation of the density rarefaction wave previously reported by the authors.6) Recently, Marhic10) analysed a transient response of under-dense plasmas along the applied magnetic field B to an incident laser pulse. When the incident power is considerably small, he showed that the density perturbation moves away from the perturbed region in both directions along B, with the velocity of the ion acoustic wave. Although the density perturbation may propagate across B in our case, the direction of propagation will not be exactly perpendicular to B, since our experiment is not one-dimensional. Then, the electrons which can move only along B will completely neutralize the ion perturbation moving across B. Then the characteristic speed of the moving perturbation will be again that of the ion acoustic wave in our case. If so, we can estimate the Doppler-shift Δf of the reflected frequency as,

$$\Delta f = \{1 - (1 - a/c)^2\} f_0 \simeq (2a/c) f_0$$

where f_o is the incident frequency, a and c are, respectively, the velocities of the ion acoustic wave and light in vacuum.

Taking the electron temperature as $T_e = 10$ (eV) in helium ions,[6)] we obtain $\Delta f = 1.35$ (MHz) which is surprizingly close to the observed red-shift, as is shown in Fig.5. The simple theoretical model of the Doppler-shift described above is shown with the chained line in Fig.5. It is shown in Fig.5 that the red-shifts are insensitive to I_d. This fact is the further evidence that the perturbation is closely related to the ion acoustic velocity which is independent of the plasma density.

We cannot measure directly the density perturbation moving across B, since the diameter of the plasma column is just 1 cm. We only observe the density rarefaction wave[6)] moving along B. We are not successful to determine how the red-shift is dependent on the incident power. It should be noted that the observed red-shifts were just the time-averaged ones over the period of incidence of the microwave pulse. Thus, one cannot know how is the instantaneous spectra. The question is left unsolved at this moment.

Although the microwave scattering[11)] is a fully developed diagnostic tool for the plasmas in laboratory and/or ionosphere, it has been limited to the small incident powers. It might be interesting to examine what would happen in the scattered signals in the usual diagnostics, when the incident power increased. It will offer valuable informations to understand the experimental results currently obtained in the laser=plasma interactions.

References

1) See for example, Laser Interaction and Related Plasma Phenomena, Vol.3 edited by H. Schwarz and H. Hora, (Plenum, New York, 1974).

2) L.M. Goldman, J. Soures and M.J. Lubin, Phys. Rev. Letters 31 (1973) 1184.

3) B.H. Ripin, J.M. McMahon, E.A. McLean, W.M. Manheimer and J.A. Stamper, Phys. Rev. Letters 33 (1974) 634.

4) C. Yamanaka, T. Yamanaka, J. Mizui and H. Yamaguchi, Phys. Rev. A-11 (1975) 2138.

5) H. Ikezi, K. Nishikawa and K. Mima, J. Phys. Soc. Japan 37 (1974) 766.

6) K. Minami, Y. Mori, S. Takeda and K. Ishii, Phys. Fluids (to be published).

7) W.P. Allis, S.J. Buchsbaum and A. Bers, Waves in Anisotropic Plasmas (MIT Press, 1963) pp 38.

8) S.J. Buchsbaum and A. Hasegawa, Phys. Rev. Letters 12 (1964) 685.

9) H. Motz, in the Proceeding of the Conference of Electrostatic and Electromagnetic Confinement of Plasmas and the Phenomenology of Relativistic Electron Beams (1974) in Annals of the New York Academy of Sciences, Vol.251 (1975) 74.

10) M.E. Marhic, Phys. Fluids 18 (1975) 837.

11) J. Sheffield, Plasma Scattering of Electromagnetic Radiation (Academic, New York, 1975).

Figure Captions

Fig.1 Schematic diagram of the experimental setup. The microwave pulses are launched to the plasma column, where the extraordinary modes can be excited.

Fig.2 The power of the transmitted microwaves vs the normalized magnetic field ω_c/ω, for I_d = 3 (A), 10 and 20. The three arrows are related to Fig.3(b), (c) and (d), respectively.

Fig.3 The frequency spectra of the reflected microwaves from the plasma at I_d = 20 (A): (a), the spectrum of the incident microwave pulse; (b), (c) and (d) are the spectra of reflected microwaves for ω_c/ω = 0.881, 0.969 and 1.03, respectively.

Fig.4 The frequency spectra of the transmitted microwaves: (a) I_d = 0; (b), (c) and (d) are I_d = 20 (A) and ω_c/ω = 0.881, 1.03 and 1.18, respectively.

Fig.5 The red-shift of the reflected microwaves vs the normalized magnetic field ω_c/ω, for I_d = 10 (A) and 20. The chained line is the expected values from a simple theoretical model of Doppler-shift.

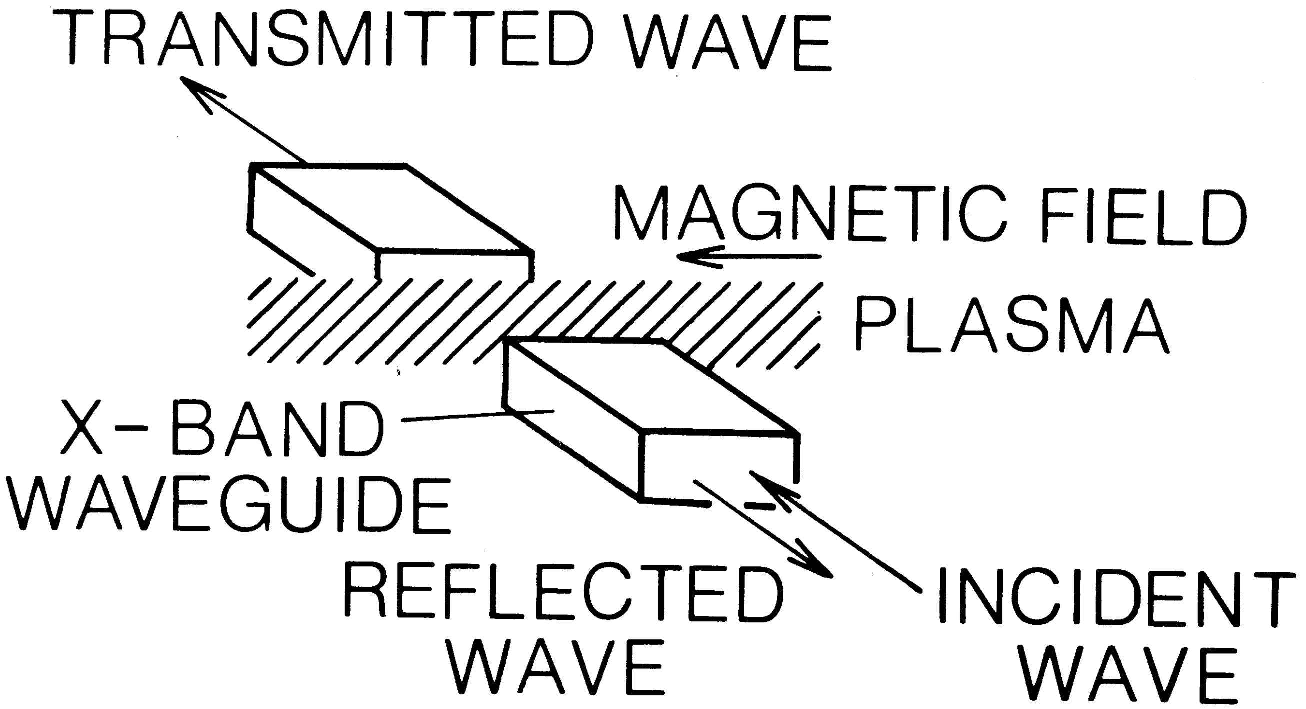
TRANSMITTED WAVE
MAGNETIC FIELD
PLASMA
X-BAND
WAVEGUIDE
REFLECTED
WAVE
INCIDENT
WAVE

Fig. 1

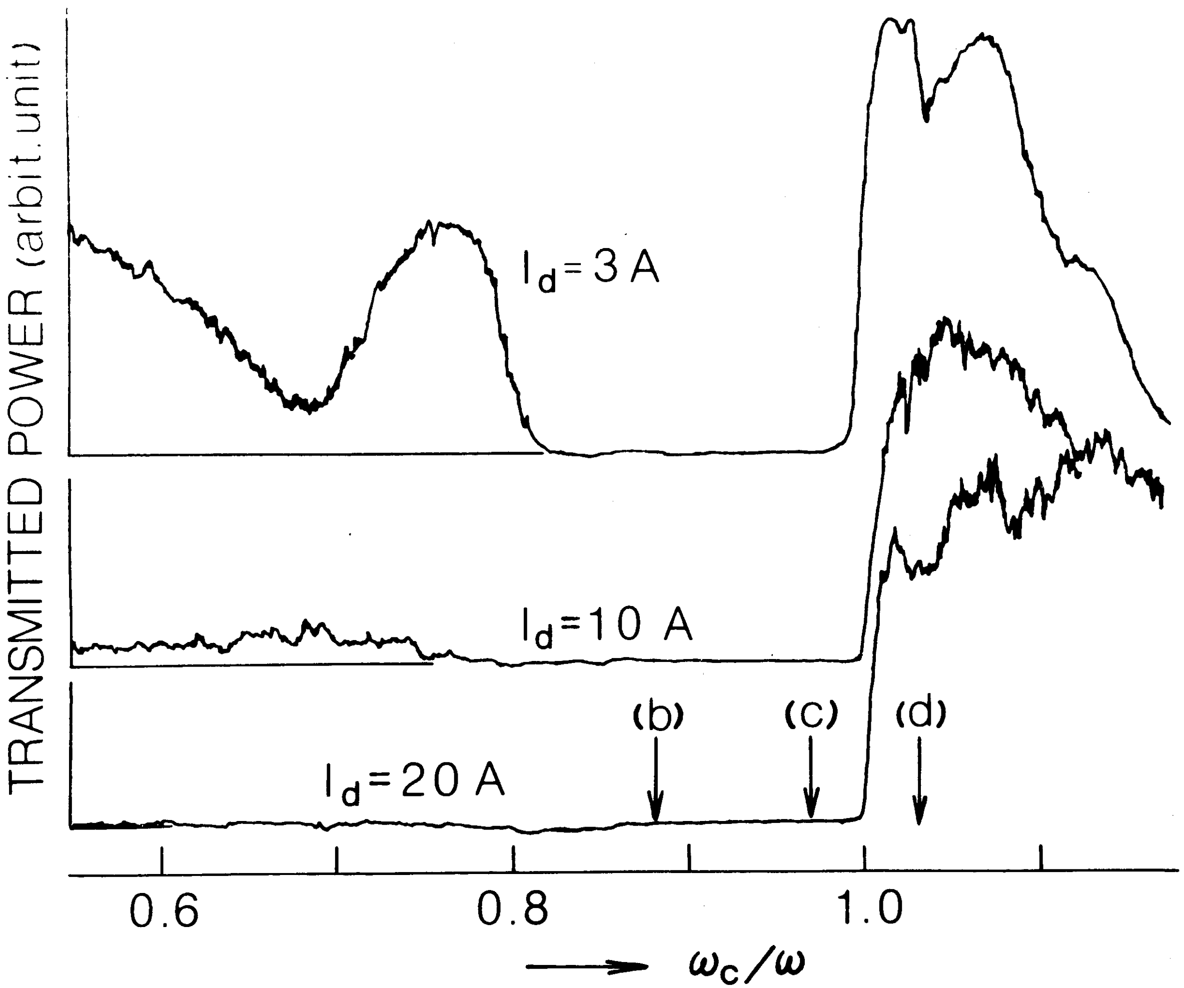
TRANSMITTED POWER (arbit.unit)
$I_d=3$ A
$I_d=10$ A
$I_d=20$ A
(b)
(c)
(d)
0.6
0.8
1.0
ω_c/ω

Fig. 2

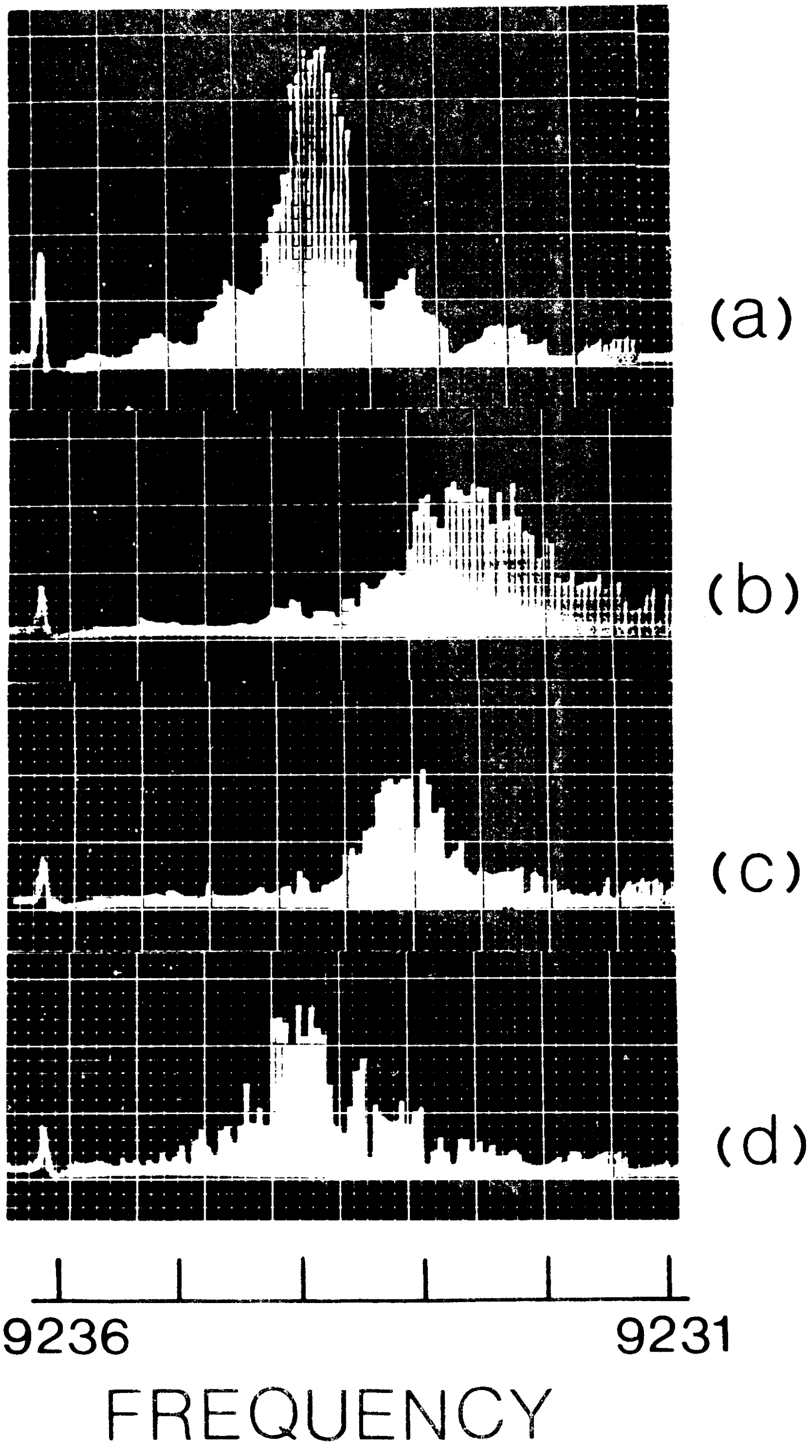

Fig. 3

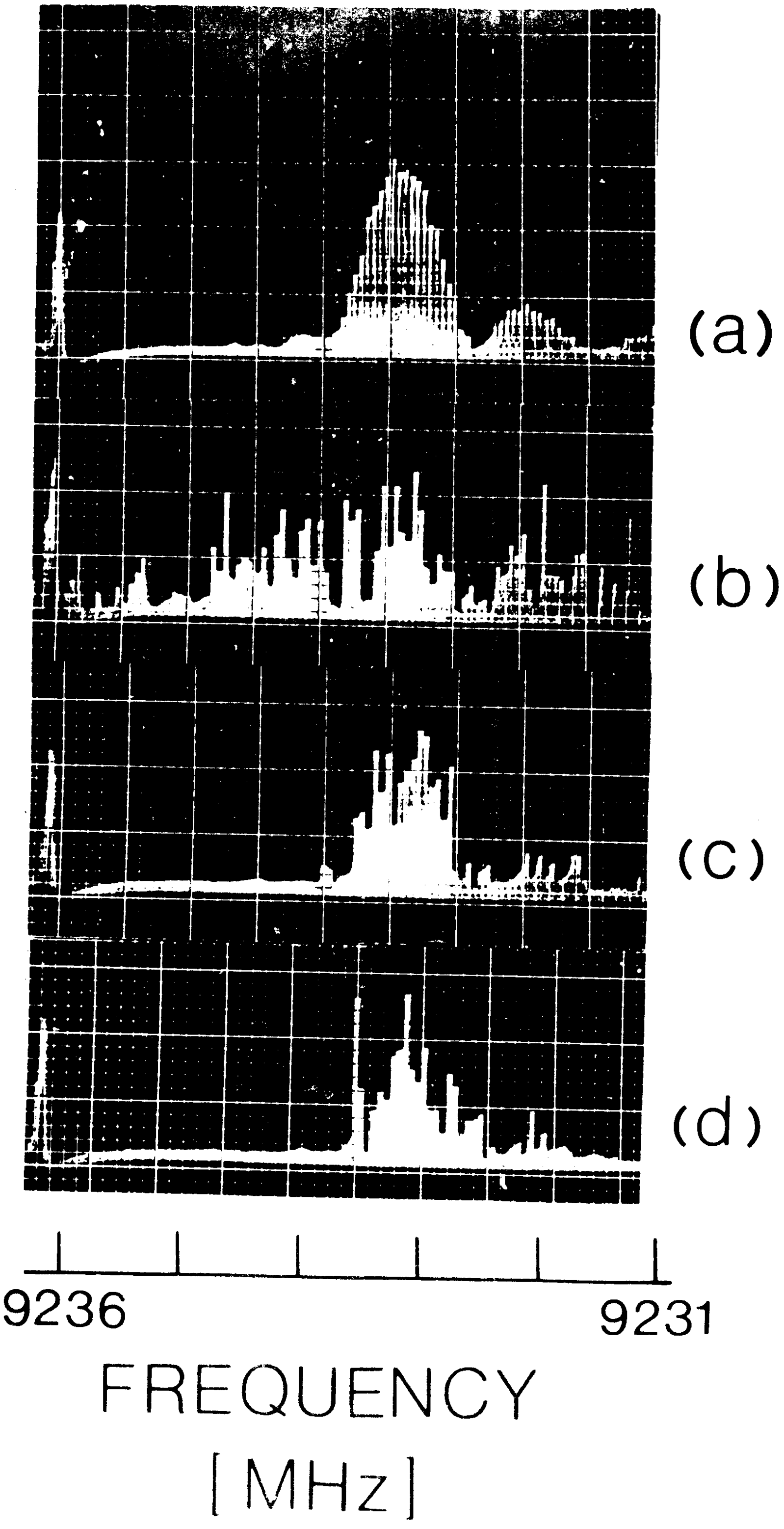

Fig. 4

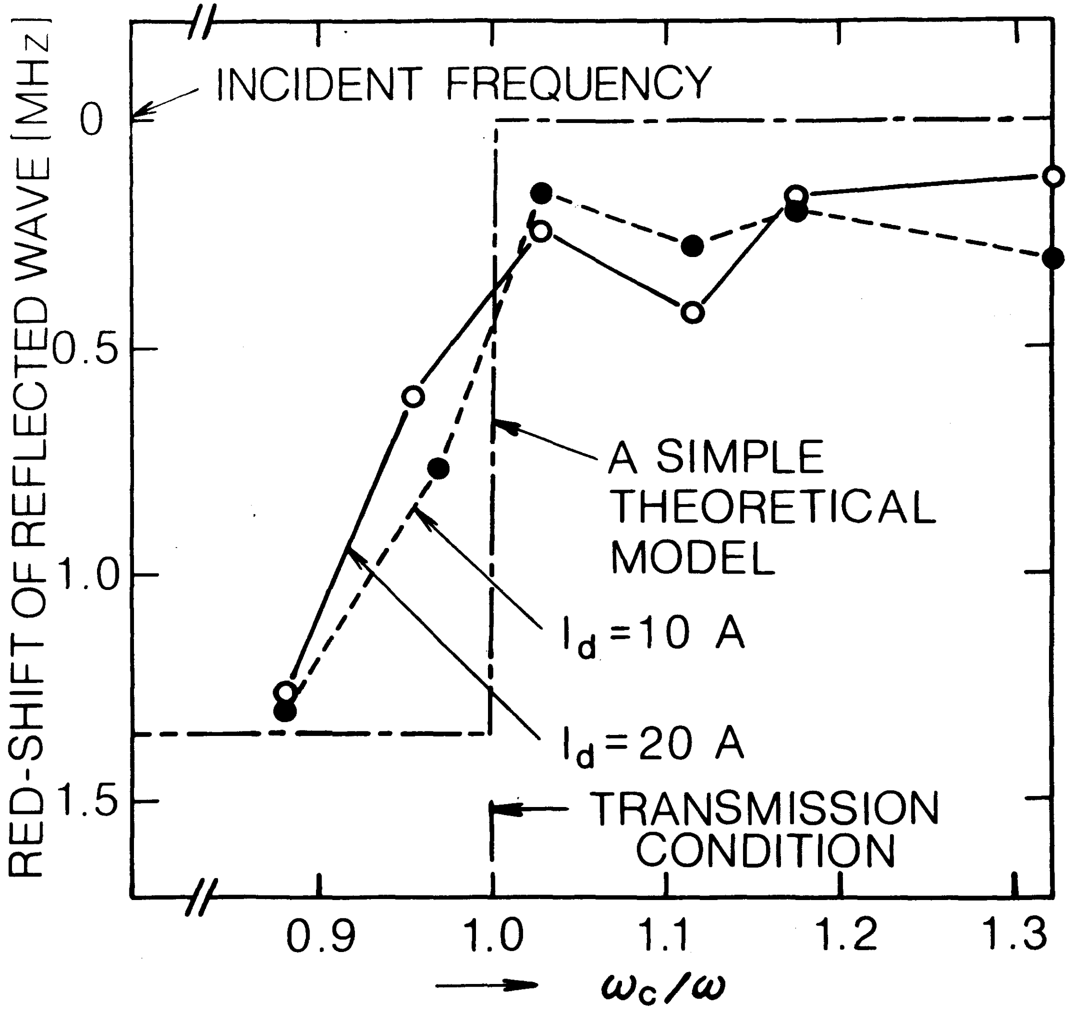
INCIDENT FREQUENCY
A SIMPLE THEORETICAL MODEL
$I_d = 10$ A
$I_d = 20$ A
TRANSMISSION CONDITION
RED-SHIFT OF REFLECTED WAVE [MHz]
0
0.5
1.0
1.5
0.9
1.0
1.1
1.2
1.3
ω_c/ω

Fig. 5