# Measurements of the Transmitting and the Receiving Patterns of a Dipole Antenna for an Electron Plasma Wave

TAKAYUKI ISHIZONE, MEMBER, IEEE, KUNIO SAWAYA, SABURO ADACHI, SENIOR MEMBER, IEEE, AND YASUTO MUSHIAKE, SENIOR MEMBER, IEEE

*Abstract*—**The transmitting and the receiving patterns of a dipole antenna for an electron plasma wave have been measured by using the interference method. The results agree fairly well with the theoretical patterns that were predicted from the fluid model analysis and also experimentally prove the reciprocity relationship between the transmitting and the receiving patterns, which is theoretically found to be valid in the plasma wave approximation. The characteristics of the transmitting and the receiving efficiencies versus the dc bias voltage applied to the dipole antenna have been also experimentally investigated.**

## I. INTRODUCTION

THE BEHAVIOR of antenna characteristics in a plasma has been extensively investigated in recent years. Cohen [1], Chen [2], Wait [3], Kuehl [4], and many others have theoretically analyzed the radiation characteristics of an electric dipole immersed in a homogeneous warm electron plasma of infinite extent which can support the propagation of an electron plasma wave in addition to the usual electromagnetic wave. Wunsch [5], Galejs [6], and Lin and Mei [7] have investigated a dipole antenna as a boundary value problem in which an antenna current distribution and an ion sheath effect were taken into account.

As to the experimental investigations, Judson and Chen [8] and Ishizone *et al.* [9] have measured the current distribution on a monopole antenna. Balmain [10], Graf and Jassby [11], Ito and Mushiake [12], Scott and Rao [13], Ancona [14], and Maxam and Chen [15] have measured the input impedance of the cylindrical antenna and they have compared the results with available theories. As to the detection and the propagation properties of an electron plasma wave, Malmberg and Wharton [16], [17], Hoven [18], and Derfler and Simonen [19] have experimentally investigated by using the grid type of exciter and detector and have compared with the classical Bohm and Gross theory [20] and the Landau theory [21]. However, the experimental studies of the transmitting and the receiving characteristics of a dipole antenna for an electron plasma wave do not seem to have been performed insofar as the authors know.

It is the purpose of this study to measure the transmitting and the receiving patterns of a dipole antenna for an electron plasma wave, to compare the results with the existing theory obtained from the fluid model, and also to discuss the reciprocity relationship between the transmitting and the receiving antennas for plasma waves. Furthermore, the measurement of the effect of the antenna dc bias voltage on the transmitting and the receiving efficiencies is also one of the purposes of the present study.

Experimental studies, which are closely related to the present study, were performed by Shen *et al.* [22] and Ishizone *et al.* [23]. The former measured the transmitting patterns of the disk antenna for the ion acoustic waves and the latter was a preliminary experiment of the present one. Recently, Nakamura *et al.* [24] have measured the transmitting patterns of a monopole antenna for an electron plasma wave. However, they have not examined a dipole antenna and also the receiving pattern characteristics.

Manuscript received January 2, 1974; revised March 4, 1974.

The authors are with the Department of Electrical Communications, Faculty of Engineering, Tohoku University, Sendai, Japan.

## II. EXPERIMENTAL SETUP

The experiments were performed in the space chamber (2.5 m$^\phi$ $\times$ 4 m) shown in Fig. 1. The experimental setup and the measuring systems are illustrated schematically in Fig. 2, which shows the setup for measuring the transmitting pattern of a dipole antenna. The plasma used in this experiment is the back-diffused one. The plasma source is composed of a plane anode, two sheets of meshed grids (control grid and accelerating grid), and the cathode assembly, which consists of seven directly heated oxide coated ribbon cathodes. The total size of the plasma source is about 45 cm in length and 17 cm in diameter. The pressure of Argon as a discharging gas is normally set to about $5 \times 10^{-5}$ torr. Fig. 3 shows the typical spatial distribution of plasma parameters ($f_p$: electron plasma frequency, $N_e$: electron density, $T_e$: electron temperature, $V_p$: plasma potential) in the horizontal radial direction in which the antenna is moved. The plasma parameters were obtained by using the Langmuir probe (5 cm in diameter). The homogeneity of the plasma is considered to be satisfactory for the present measurement. The typical Debye length and the mean free path of the electron are about 1 cm and 100 m (corresponding collision frequency is 4 kHz), respectively.

As a dipole antenna under the test, two kinds of stainless wires (17 cm and 12 cm in length, and 2 mm in diameter) are used. As a confronting plasma wave detector (or an exciter in the case of measuring a receiving pattern of a dipole), the three parallel plane grid antenna shown in Fig. 1 was used in order to reduce the direct coupling with

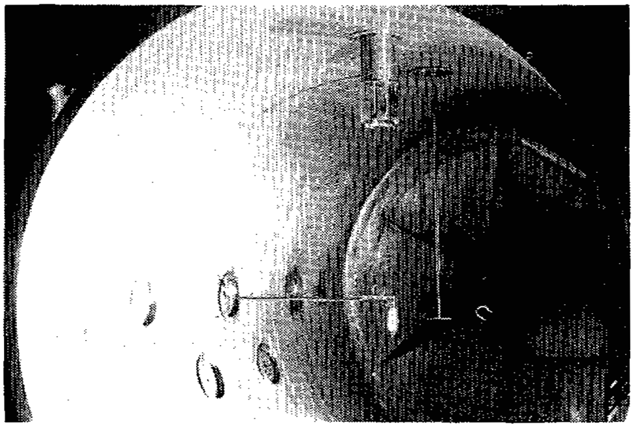

Fig. 1. Photograph of dipole antenna, grids antenna, and plasma source in plasma chamber.

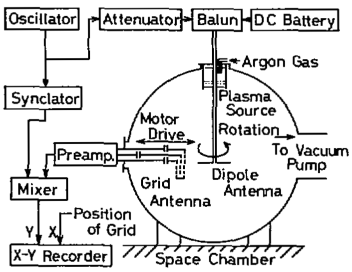


Fig. 2. Experimental setup and block diagram for measuring transmitting properties of dipole antenna.

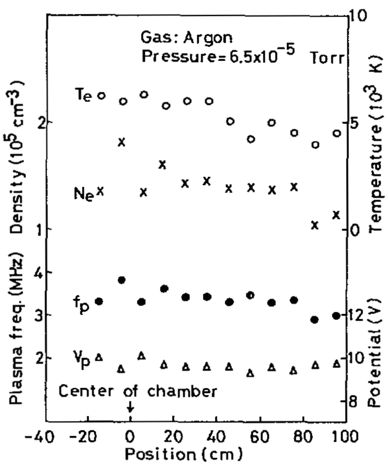


Fig. 3. Distribution of plasma parameters in horizontal radial direction.

the dipole. Each grid is 12 cm in diameter and is fabricated from a stainless mesh having 15 lines (0.3 mm in diameter) per in. The spacing between each grid is 1 cm. The inner grid and the outer two grids are connected to the inner and the outer conductor of the 50 Ω coaxial line through the 0.5 μF capacitors, respectively, so that the grids antenna has a floating dc potential. In order to control the dc potential of the dipole antenna, the dc bias is impressed to the dipole, which is separated electrically from the chamber.

## III. METHOD OF MEASUREMENT

Fig. 2 shows the measuring system used to detect the plasma wave excited by a dipole antenna using the interference method, which detects the phase and the amplitude of the received signal simultaneously. The synclator, which is a synchronized oscillator, is used as a variable phase shifter in order to suppress the output component induced by the direct capacity-coupling between the transmitting dipole antenna and the receiving grid antenna.

The principle of the measurement is as follows. Let this capacity-coupled signal component be denoted as $A_e(r) \angle \varphi_e$ whose amplitude is a function of the distance $r$ between the dipole and the grid antenna, but whose phase angle $\varphi_e$ is considered as a constant since the distance $r$ is negligibly small compared to a free space wavelength. Now let the signal as an electron plasma wave be expressed as $A_p \cdot (1/r) \cdot \exp(-k_i r - jk_r r)$, where $k_r$ and $k_i$ are the phase and attenuation constants of a plasma wave, respectively, then the dc output of the mixer is proportional to

$$A_m \propto A_e(r) A_s \cos(\varphi_s - \varphi_e - \varphi_1) + A_e(r) A_p \frac{\exp(-k_i r)}{r} \cos(\varphi_e - k_r r - \varphi_2) + A_s A_p \frac{\exp(-k_i r)}{r} \cos(\varphi_s - k_r r - \varphi_3) \tag{1}$$

where $A_s \angle \varphi_s$ is the reference signal to the mixer, and $\varphi_1$, $\varphi_2$, and $\varphi_3$ are constant phase. By varying the phase angle $\angle \varphi_s$, the first term in the right side of (1) can be eliminated. Further, by letting the amplitude of the reference signal be large enough as $A_s \gg A_e(r)$ holds, we obtain

$$A_m \propto A_s A_p \frac{\exp(-k_i r)}{r} \cos(k_r r - \varphi). \tag{2}$$

Accordingly, the interference pattern between a plasma wave and a fixed reference signal can be drawn on an $X$–$Y$ recorder when the grid antenna is moved in a radial direction of the space chamber. In this measurement, the grid antenna is moved in the range of 10 cm ∼ 80 cm from a dipole antenna. The exciting voltage of the antenna is kept as small as 0.3 ∼ 1 V (peak to peak) so that the linear approximation holds in a plasma.

By including the directional pattern function $D(\theta)$ of the dipole antenna in (1), we should obtain the interference pattern expressed as

$$E = A \cdot \frac{D(\theta) \exp(-k_i r) \cos(k_r r - \varphi)}{r} \tag{3}$$

where, $A$ and $\theta$ are a proportional coefficient and the angle between the dipole axis and the propagation direction, respectively, and $\varphi$ is an initial phase angle.

Fig. 4 shows one example of measured interference patterns and the state of the attenuation expressed in (3), when a signal of 0.325 V (peak to peak) and of

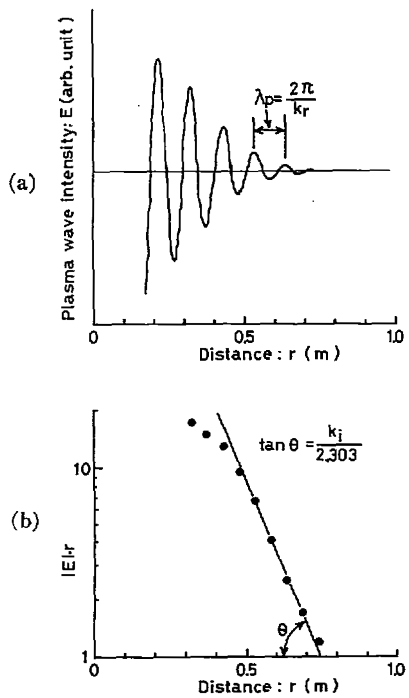


Fig. 4. (a) Interference pattern between plasma wave and reference signal. (b) Product of plasma wave amplitude and distance between antennas versus distance.

$f = 7$ MHz was applied to the dipole antenna. By this procedure shown in Fig. 4, the phase constant $k_r$ and the attenuation constant $k_i$ can be determined.

By having such an interference pattern for each fixed rotation angle of the test dipole antenna, we obtained the transmitting patterns $D(\theta)$ of a dipole antenna for an electron plasma wave. The receiving patterns of the dipole antenna can likewise be obtained by interchanging the exciting terminal and the receiving terminal.

## IV. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 5 shows the dispersion relation of the electron plasma wave that was obtained from the interference patterns when the dipole antenna and the grid antenna were used as a receiver and a transmitter, respectively. The electron plasma frequency obtained by the extrapolation from the experimental values is 4.5 MHz. This result agrees well with the result $f_p = 4.3$ MHz obtained by the Langmuir probe. In this figure, the theoretical curves obtained from the classical Bohm and Gross equation and the Landau equation are also shown for comparison. The experimental points are mostly located between these two theoretical curves. Thus it is confirmed that the interference pattern obtained in this measurement is certainly an electron plasma wave.

Fig. 6 shows the typical interference patterns of the various rotation angles $\theta$ when the dipole antenna was used as the transmitter.

Now, for the measurement of the directional pattern, the well-known far-field criterion, $r > 2(2L)^2/\lambda_p$ ($2L$: antenna length, $\lambda_p$: plasma wave length) must be satisfied.

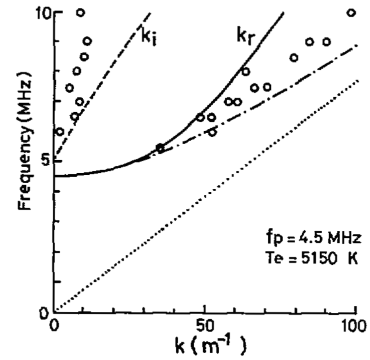


Fig. 5. Dispersion diagram. Circles: experimental measurements. $k_r$ and $k_i$: Landau theory. Dash-dotted curves: Bohm and Gross theory. Dotted curve: thermal speed $\omega/k = (3\kappa T_e/m)^{1/2}$.

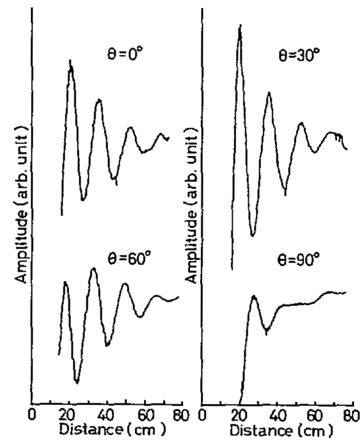


Fig. 6. Interference output of plasma wave from dipole antenna. $\theta$ is angle between dipole antenna axis and propagation direction. $f_p = 4.3$ MHz; $T_e = 5800$ K; $f = 5$ MHz; $V_{ex} = 0.5$ V (peak to peak).

In the present experiment, this criterion is about 17 to 53 cm. In this measurement, the amplitude at the distance of 60 $\sim$ 70 cm was used for determining the directional patterns as a result of the compromise between the far-field criterion, the sensitivity of the measuring system, and the homogeneity of the plasma.

Fig. 7 shows the experimental results of the transmitting and the receiving patterns for various ratios of the antenna length to the plasma wave length. In this measurement, the bias voltage of the dipole antenna was 8 $\sim$ 10 V that was nearly equal to the plasma potential.

The theoretical curves of Fig. 7 are based on the fluid theory by K. M. Chen [2] who gave the transmitting pattern for the plasma wave of a dipole antenna in a lossless plasma with the current distribution

$$I = I_0 \sin [k(L - |z|)] \tag{4}$$

as follows

$$D(\theta) = B \cdot \frac{\cos \theta \cdot [\cos (k_p L \cos \theta) - \cos kL]}{\cos^2 \theta - (k/k_p)^2} \tag{5}$$

where $z$ is the coordinate along the antenna axis, $k$ is the propagation constant of the current along the antenna, and $B$ is the normalizing constant. In (5), $k_p$ is the propa-

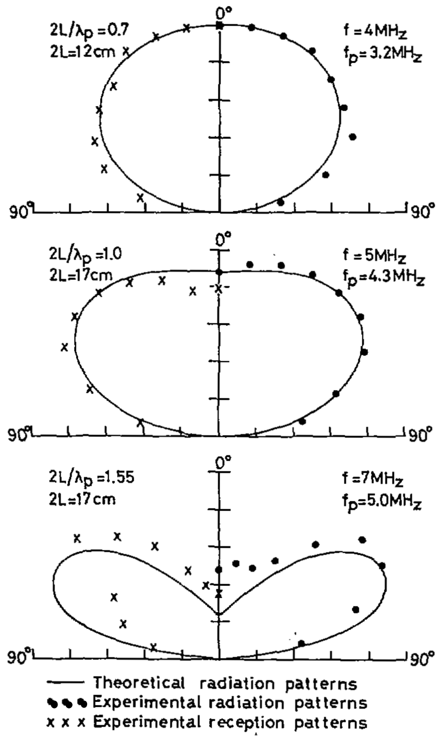


Fig. 7. Theoretical transmitting patterns and experimental transmitting and receiving patterns of dipole antennas for electron plasma wave.

gation constant of an electron plasma wave that is expressed by

$$k_p = \left(\frac{m}{3\kappa T_e} (\omega^2 - \omega_p^2)\right)^{1/2}. \tag{6}$$

In (6), $\kappa$ is Boltzmann's constant, $m$ is the electron mass, $T_e$ is the electron temperature, and $\omega_p$ and $\omega$ are the electron plasma and the driving frequencies, respectively. The theoretical studies on the propagation constant $k$ of the current along a dipole antenna have been performed by Wunsch [5], Galejs [6], Schiff [25], and others, while, the experimental studies on this subject have been done by Judson *et al.* [8] and Ishizone *et al.* [9]. As a result, except in the vicinity of the plasma frequency, the following representation is found to be of good approximation:

$$k = k_e \tag{7}$$

where $k_e$ is the propagation constant of the plane electromagnetic wave in a cold plasma. In the present experiment, we have $k_eL \ll 1$, and $k_e/k_p \sim 10^{-3}$ since $T_e \sim 5000$ K. Consequently, the transmitting pattern is approximated as follows:

$$D(\theta) = B \cdot \frac{\cos (k_pL \cos \theta) - 1}{\cos \theta}. \tag{8}$$

Equation (8) was calculated and is shown by the solid curve in Fig. 7. Although the phase constant $k_p$ given by (6) is not correct because of the Landau effect as indicated in the phase measurement of Fig. 5, Fig. 7 indicates that the measured transmitting patterns of the electron plasma wave agree fairly well with the theoretical patterns, particularly for the first two patterns. Discrepancy in the third pattern is considered to be partly due to the insufficiency of the distance between the two antennas. Further, we find from Fig. 7 that the measured receiving patterns are almost identical to the corresponding transmitting patterns. It was shown by Chen and Cheng [26], that the reciprocity relationship in a compressible plasma does not hold in general if $\nabla \cdot J_e \neq 0$ ($J_e$: impressed electric current). But, in some special cases, it is shown that this relationship approximately holds. Adachi *et al.* [27] have treated the case where antennas are isolated from the plasma by the ion sheath and have concluded that the reciprocity relationship is approximately valid in the vicinity of the plasma frequency. Recently, Ishizone *et al.* [28] have discussed the same problem and have concluded that the reciprocity relationship is valid in the quasistatic approximation (the electromagnetic fields are neglected). As the electromagnetic field is greatly reduced by the shielding of the transmitting grid, and only the electron plasma wave is detected by the interference method in this measurement, it is expected that the reciprocity relationship holds, that is, the transmitting and the receiving patterns for an electron plasma wave are identical. The results of the above pattern measurement are considered as the first experimental proof of the reciprocity relationship.

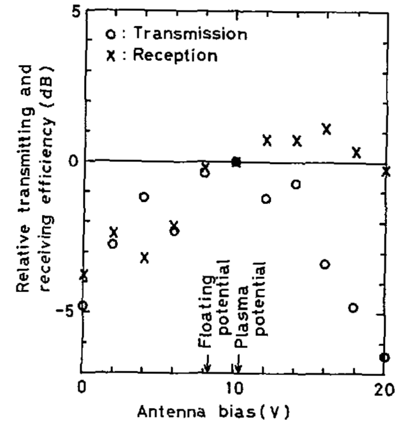


Fig. 8. Relative transmitting and receiving efficiencies of dipole antenna versus antenna bias voltage, $f_p = 4.5$ MHz; $T_e = 5150$ K; $f = 6$ MHz; $\theta = 50°$; $2L = 17$ cm.

The effect of the dc bias voltage of the antenna on the transmitting and the receiving efficiencies has been studied experimentally by varying the antenna bias voltage referred to the plasma potential and thus by varying the sheath produced around the dipole antenna.

In Fig. 8, both transmitting and receiving intensities are shown as relative efficiencies, which are normalized by the intensities when the antenna bias voltage is equal to the plasma potential. It is found from these results that both efficiencies increase with increasing antenna bias voltage when the bias voltage is lower than the plasma potential and take the maximum values near the vicinity of the plasma potential, although the variation of both efficiencies is moderate. It is worthwhile to note that the behavior of Fig. 8 is different from that of the grid type detector tested previously by Ishizone *et al.* [23] or that of the

Faraday cup type detector tested by Nakamura *et al.* [24]. Both previous results showed the curve of the efficiency versus the bias voltage, which resembled the $V$–$I$ characteristic of the dc Langmuir probe. This fact may suggest the difference of the reception mechanism between the dipole antenna and others. The reason of this difference is not known at the present stage of this study and it should be clarified in the future.

## V. CONCLUSION

We have measured, for the first time, the transmitting and receiving directional patterns of a dipole antenna for an electron plasma wave and have found that these patterns agree fairly well with those predicted theoretically based on the simple fluid model of a plasma. The experimental verification of the reciprocity relationship between the transmitting and receiving antennas in a compressible plasma has been also established in this paper. Finally, the effect of the dc bias voltage on the transmitting and receiving efficiencies has also been investigated experimentally.

## ACKNOWLEDGMENT

The authors wish to thank the late Prof. K. Kamiryo for his helpful advice and H. Ishikawa for his assistance in carrying out the experiments. Part of the experiment reported in this paper was performed at the space chamber of the Institute of Space and Aeronautical Science, University of Tokyo, Tokyo, Japan. The helpful advice and assistance of Prof. T. Itoh and S. Kojima are greatly appreciated.

## REFERENCES

[1] M. H. Cohen, "Radiation in a plasma III," *Phys. Rev.*, vol. 126, pp. 398–404, Apr. 15, 1962.

[2] K. M. Chen, "Interaction of a radiating source with a plasma," *Proc. IEE*, vol. 111, pp. 1668–1678, Oct. 1964.

[3] J. R. Wait, "On radiation of electromagnetic and electroacoustic waves in a plasma," *Appl. Sci. Res.*, vol. B-11, pp. 423–432, 1964.

[4] H. H. Kuehl, "Resistance of a short antenna in a warm plasma," *Radio Sci.*, vol. 1 (New Series), pp. 971–976, Aug. 1966.

[5] A. D. Wunsch, "The finite tubular antenna in a warm plasma," *Radio Sci.*, vol. 3 (New Series), pp. 901–920, Sept. 1968.

[6] J. Galejs, "Insulated cylindrical antenna immersed in a compressible plasma," *Radio Sci.*, vol. 4 (New Series), pp. 269–278, Mar. 1969.

[7] S. H. Lin and K. K. Mei, "On the effect of sheath, collision, and absorptive surface on the performance of a linear antenna in a compressible plasma," *IEEE Trans. Antennas Propagat.*, vol. AP-18, pp. 672–679, Sept. 1970.

[8] H. Judson and K. M. Chen, "Measurement of antenna current distributions in a hot plasma," *Proc. IEEE* (Lett.), vol. 56, pp. 753–754, Apr. 1968.

[9] T. Ishizone, K. Taira, S. Adachi, and Y. Mushiake, "Sheath effects on the current distribution along an antenna in a plasma," *IEEE Trans. Antennas Propagat.* (Commun.), vol. AP-17, pp. 398–400, May 1969.

[10] K. G. Balmain, "The impedance of a short dipole antenna in a magneto plasma," *IEEE Trans. Antennas Propagat.*, vol. AP-12, pp. 605–617, Sept. 1964.

[11] K. A. Graf and D. L. Jassby, "Measurements of dipole antenna impedance in an isotropic laboratory plasma," *IEEE Trans. Antennas Propagat.*, vol. AP-15, pp. 681–688, Sept. 1967.

[12] H. Ito and Y. Mushiake, "Impedance of an antenna in anisotropic plasma," *Trans. Inst. Electron. Commun. Eng. Japan*, vol. 51-B, pp. 69–75, Feb. 1968.

[13] L. D. Scott and B. R. Rao, "A short cylindrical antenna as a diagnostic probe for measuring collision frequencies in a collision-dominated non-Maxwellian plasma," *IEEE Trans. Antennas Propagat.*, vol. AP-17, pp. 777–786, Nov. 1969.

[14] C. Ancona, "Antenna impedance measurements and sheath effects in an RF generated plasma," *IEEE Trans. Antennas Propagat..* vol. AP-19, pp. 237–246, Mar. 1971.

[15] G. L. Maxam and K. M. Chen, "An experimental and theoretical study on the circuit properties of a cylindrical antenna in a hot lossy plasma," *IEEE Trans. Antennas Propagat.*, vol. AP-20, pp. 347–353, May 1972.

[16] J. H. Malmberg and C. B. Warton, "Collisionless damping of electrostatic plasma wave," *Phys. Rev. Lett.*, vol. 13, pp. 184–186, Aug. 10, 1964.

[17] J. H. Malmberg and C. B. Warton, "Dispersion of electron plasma wave," *Phys. Rev. Lett.*, vol. 17, pp. 175–178, July 1966.

[18] G. V. Hoven, "Observation of plasma oscillation," *Phys. Rev. Lett.*, vol. 17, pp. 169–172, July 1966.

[19] H. Derfler and T. C. Simonen, "Landau waves: An experimental fact," *Phys. Rev. Lett.*, vol. 17, pp. 172–175, July 1966.

[20] D. Bohm and E. P. Gross, "Theory of the plasma oscillations. A. Origin of medium-like behavior," *Phys. Rev.*, vol. 75, pp. 1851–1864, June 15, 1949.

[21] L. D. Landau, "Oscillations of an electron plasma," *J. Phys.* (USSR), vol. 10, p. 25, 1946.

[22] K. Shen, S. Aksornkitti, H. C. S. Hsuan, and K. E. Longren, "Radiation characteristics of longitudinal waves from an antenna in a plasma," *Radio Sci.* (New Series), vol. 5, pp. 611–615, Mar. 1970.

[23] T. Ishizone, S. Adachi, Y. Mushiake, and K. Sawaya, "Experiments on electron plasma wave radiation and reception by some simple antennas," Summaries of papers, *Int. Symp. Antennas and Propagation* (Sendai, Japan), p. 65, Sept. 1971.

[24] N. Nakamura, M. Nakamura, and T. Itoh, "Reception characteristics of monopole antennas for electron plasma waves," *IEEE Trans. Plasma Sci.*, vol. PS-1, pp. 100–106, Sept. 1973.

[25] M. L. Shiff, "Current distribution on a grid type dipole antenna immersed in a warm isotropic plasma," *Radio Sci.* (New Series), vol. 6, pp. 665–671, June 1971.

[26] H. C. Chen and D. K. Cheng, "Reciprocity relations in a compressible plasma," *IEEE Trans. Antennas Propagat.* (Commun.), vol. AP-13, pp. 989–990, Nov. 1965.

[27] S. Adachi, T. Kasahara, and Y. Mushiake, "Receiving characteristics of antennas in an isotropic compressible plasma," *Trans. Inst. Electron. Commun. Eng. Japan*, vol. 55-B, pp. 220–225, May 1972.

[28] T. Ishizone, S. Adachi, and Y. Mushiake, "Reciprocity relation on plasma waves and antenna receiving voltage," *Trans. Inst. Electron. Commun. Eng. Japan*, vol 57-B, pp. 149–150, Feb. 1974.