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STUDY OF PLASMA SHEATH EFFECTS ON ANTENNAS

BY

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COLLEGE OF ENGINEERING
ENGINEERING EXPERIMENT STATION
TUCSON, ARIZONA

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ABSTRACT

This is the Final Report under contract AF19(628)-3834 and it summarizes the work carried out during the period 1 January 1964 - 31 March 1967 in the Engineering Experiment Station, The University of Arizona. The work covers experimental and theoretical investigations into the problem of plasma sheath effects on antennas.

In the area of experimental investigations, the effects of plasma sheath inhomogeneities and nonuniformities on the radiation pattern and input impedance were assessed.

In the area of theoretical investigations, the effects of the structure curvature and the radiation patterns were assessed. The effect of plasma compressibility was also investigated.

CONTRIBUTORS

The following individuals have been engaged in research under contract AF19(628)-3834 for various periods of time.

Faculty:

Associate Professor George Tyras. Principal Investigator

from 1 January 1964 - until 31 March 1967

Graduate Students:

Advanced degrees in Electrical Engineering were or will be awarded by The University of Arizona to the following individuals whose theses or dissertations were based either entirely or in part on the research supported by the Contract:

Master of Science in Electrical Engineering

Peter C. Bargeliotes	June 1964
Willard P. Webster	June 1966
Udo Karst	June 1967 (expected)
John R. Goltz	June 1967 (expected)

Doctor of Philosophy in Electrical Engineering

Robert R. Schell	February 1967
John M. Hamm	June 1968 (expected)
Eric W. Rahneberg	June 1969 (expected)

INTRODUCTION

Our principal effort in this research project was centered on the following areas:

1. Development of a valid plasma sheath simulation technique.
2. Experimental assessment of the effects of plasma sheath inhomogeneities and nonuniformities on the radiation pattern and input impedance of slot antennas.
3. Theoretical assessment of the effects of curvature of a plasma covered structure on a slot radiation pattern.
4. Effects produced by a plasma inhomogeneity and compressibility.

A brief description of each research topic is given in this final report. More comprehensive discussion of each topic can be found in the Scientific Reports and published papers listed in the final pages of this report.

1. EXPERIMENTAL STUDY OF PLASMA SHEATH EFFECTS ON ANTENNAS

By necessity, most investigations into wave propagation through plasma sheath are of theoretical nature and deal with idealized geometries. In order to experimentally verify the theoretical work and to obtain results applicable to more realistic radiating systems and plasma sheath configurations, a laboratory simulation of a plasma sheath appeared desirable. Because of inherent limitations, the earlier attempts of plasma sheath simulation by means of artificial dielectrics were not successful in reproducing of theoretically known results satisfactorily.

1.1 Plasma Simulation Technique

The difficulty that arises in the plasma simulation attempts stems from the fact that the real part of the plasma dielectric constant is less than unity, namely, $\varepsilon_p/\varepsilon_a < 1$ where ε_p is the plasma dielectric constant and ε_a is the dielectric constant of free space. If, however, $\varepsilon_p/\varepsilon_a = \varepsilon_{ps}/\varepsilon_{as} < 1$ where the subscripts "ps" and "as" denote plasma simulation and air simulation, respectively, it is seen that a simulated plasma environment depends on the ratio of the dielectric constants and not on their absolute values. Thus an artificial plasma environment can be created by covering a radiator or a scatterer under investigation with a medium having a dielectric constant less than that of the free space simulator.

A major requirement of the free space simulator is that it be in the liquid form to allow movement of measuring equipment through it. Furthermore, it should have a low loss tangent to minimize signal attenuation in the medium. The plasma sheath simulator can be any foamy material with $\varepsilon_r \sim 1$ or simply air itself. Such a combination of dielectric materials will simulate a plasma with $0 < \varepsilon_p < 1$.

With such a simulation technique, the plasma parameters can be scaled and properly defined. It suffices to require that the two ratios $c_1 = \mu\varepsilon(l/\tau)^2$ and $c_2 = \mu\sigma l^2/\tau$ where τ is the characteristic period and l denotes the length, remain invariant. In the case considered $\sigma \to o$, hence only c_1 needs to be satisfied which leads to

$$\mu_s \varepsilon_s l_s^2 \omega_s^2 = \mu \varepsilon l^2 \omega^2, \qquad (1)$$

as the basic scaling equation.

The study of a table of dielectric materials at 10 GHz has revealed that the requirements of the free space simulating medium, i.e., low loss-tangent, noncorrosiveness, and stability are satisfactorily met by Aroclor 1232. The combination of air and Aroclor 1232 ($\varepsilon_r = 2.78$ and $\tan\delta = 0.008$) will result in an $n_s = 0.60$ corresponding to an electron density per cubic centimeter $N = 7.83 \times 10^9 f_0^2$, where f_0 is the actual antenna operating frequency in GHz. With the simulating frequency $f_s = 10$ GHz, air layer $a_s = 2.9$ cm, slot mean radius $b_s = 0.675$ cm, and the simulating tank containing Aroclor 1232, it follows that $a/\lambda_0 = 1.612$ and $b/\lambda_0 = 0.375$. As a consequence of the scaling defined in (1) and since the plasma's index of refraction is a function of the wave frequency, the plasma environment that can be represented by this system will depend on the wave frequency chosen.

A semicylindrical tank of 22 in. inside radius and 24 in. high was designed and subsequently built to the design specifications. The wall material was plexiglass, $\varepsilon_r = 2.59$. The flat wall of the tank was made of one inch plexiglass plate and the curved wall of 0.25 inch plexiglass. The tank held 78 gal. of Aroclor 1232 oil, $\varepsilon_r = 2.78$. At the operating frequency of 10 GHz, the tank allowed a separation of the transmitting and the receiving antennas by at least 28 wavelengths.

Since the relative dielectric constants of the tank material and the oil were so close in value, the interface between them had negligible effect on the wave propagation. The reflections from the curved plexiglass-air interface were successfully reduced to a desirable level by placing high performance microwave absorber against the outside wall of the tank.

1.2 Homogeneous, Uniform Plasma Layer

Using the simulation technique developed earlier, experiments were conducted with linear and annular slot antennas in the presence of a simulated uniform and homogeneous plasma sheath. The obtained experimental antenna radiation patterns agreed very well with theoretical predictions.

The input admittance of slot antennas was also measured. Reference to theoretical curves showed that the experimental curves were of the same general shape as those predicted. One notable discrepancy was seen in the curve for the normalized conductance. The theory predicted approximately a 5:1 ratio between the maximum and minimum values of G/Yo, while the experimental curves showed approximately a 1.1:1 ratio.

It was concluded that the most serious limitation of the technique was the fact that the method was not capable of simulating plasmas characterized by a negative dielectric constant. Moreover, the effective simulated dielectric constant of 0.36 achieved with Aroclor 1232-air combination could not be readily lowered because of the lack of suitable liquid dielectrics with $\varepsilon_r > 2.8$.

1.3 Inhomogeneous Stratified and Discontinuous Plasma Layers

The same plasma sheath simulation technique was also used to investigate the effects of various types of sheath discontinuities and inhomogeneities on a slot-antenna radiation pattern and input admittance. The results are applicable to re-entry environments.

In the case of semi-infinite and finite-extent homogeneous plasma sheaths, the radiation pattern and the impedance characteristic were investigated with regard to the geometry of the discontinuity and its proximity to the slot antenna. It was found that the radiation pattern is unaffected by the discontinuity as long as the ratio of the distance between the source and discontinuity to the sheath thickness was of the order of 20 or greater. When the sheath was made finite in extent, with a discontinuity on each side of the slot, the resulting pattern was seen to be a superposition of the effects of each discontinuity acting separately. Investigation of the input impedance of the slot showed essentially no variation with discontinuity separation for separation-to-thickness ratios of at least 4. For smaller separations, the impedance exhibited significant variations, strongly dependent on the geometry of the discontinuity. The effects produced by inhomogeneities were found to be similar to those of a homogeneous sheath with a certain equivalent dielectric constant.

For both the homogeneous and inhomogeneous sheaths, favorable comparisons with the available theory was obtained.

2. THEORETICAL STUDY OF PLASMA SHEATH EFFECTS ON ANTENNAS

The existing literature dealing with the assessment of the plasma sheath effects on antennas, although not scarce, is somewhat limited in scope. The analyses are limited to (a) planar geometries with uniform homogeneous plasma layer, (b) planar geometries with stratified plasma consisting of a series of homogeneous discrete layers, (c) circular cylindrical geometries with uniform, homogeneous layer applicable to large cylinders, (d) circular cylindrical geometries with inhomogeneous layer applicable to small cylinders only. In this research effort, answers were sought to problems of plasma covered antennas when some of the foregoing restrictions were relaxed. Specifically, the problem of a radiating slot on a circular cylinder clad with an inhomogeneous, continuously stratified plasma layer was solved for cylinders of arbitrarily large radii.

While problems dealing with incompressible homogeneous plasmas received considerable attention in the past, little has appeared on the problem of propagation through a plasma that is both compressible and inhomogeneous. Furthermore, one finds that frequent use is made of the boundary condition that the normal component of the electron velocity shall vanish at the free space-plasma interface. While the application of this boundary condition may yield useable answers, it is doubtful that such a rigid interface can be realized in situations relevant to reentry communication. In this research effort this questionable boundary condition was avoided by suitably choosing a profile which was continuous at the air-plasma interface. Consequently, since the electron density is zero at the interface, the vanishing of the normal component of the electron velocity is satisfied there automatically. Additional boundary conditions for the pressure and its normal derivative, however, must be introduced to specify the problem uniquely.

2.1 Slotted Circular Cylinder Clad with Inhomogeneous, Incompressible Plasma

Even though the problem of an axial slot on a circular cylinder clad with inhomogeneous plasma was considered before, the resulting solution is not well suited for computations of field patterns of large cylinders.

In the present formulation the dielectric permittivity profile of the form $\epsilon(\rho) = (\rho/b)^{2p}$ $a \leq \rho \leq b$, was considered where 'a' and 'b' denote the radius of the conducting cylinder and the dielectric coating respectively and 'p' is an arbitrary parameter. The assumed profile is capable of representing an inhomogeneous, incompressible plasma when $p > 0$ and a real dielectric when $p < 0$. When $p > 0$, this model can be related to the plasma frequency in the form $(\omega_o/\omega)^2 = 1 - (\rho/b)^{2p}$. Thus, this representation admits the specification of the plasma frequency, ω_o, between the limits of the operating frequency and zero.

The apparen advantage of the present formulation is that the wave equation can be solved in terms of Bessel functions and the solution can be extended to large cylinders.

Field expressions appropriate to small and large cylinders were found using well known methods of harmonic series representation, Watson transformation, and saddle point integration. In the case of large cylinders coated with incompressible plasma, the radiation patterns were plotted for various combinations of the cylinder radius, thickness of the coating, and the inhomogeneity gradient. The radiation patterns were found to be in good agreement with the qualitative arguments of geometrical optics.

An examination of the resulting radiation patterns revealed a resemblance to the radiation patterns of the corresponding planar geometry, homogeneous layer problem. The effect of the cylinder curvature was found to be a compression of the radiation pattern in the forward direction illuminated by the slot. As the radius of the cylinder is allowed to become large, the radiation patterns broadens and in the limit of an infinitely large radius it resembles the radiation pattern pertinent planar geometry, homogeneous layer configuration.

2.2 Compressible, Inhomogeneous Plasma Layer

The set of hydrodynamic equations together with Maxwell's equations describing a nonuniform plasma were applied to a two-dimensional problem where the magnetic field has a single component transverse to the direction of propagation and the profile is of the form exp(-Bx). These assumptions lead to a set of second order coupled electromagnetic and hydrodynamic differential equations which describes the region under consideration. Solutions to this coupled set were obtained and by the application of the method of Frobenius. Considerable simplification in the solutions resulted from the realization that the rms velocity of the electrons was always much smaller than the speed of light. The resulting set of approximate solutions were applied to the problem of obtaining reflection and transmission coefficients for the case of a plane wave incident obliquely from free space upon a layer of compressible inhomogeneous plasma.

LIST OF SCIENTIFIC REPORTS

The following Scientific Reports were published by the Engineering Experiment Station, The University of Arizona, under the sponsorship of the Contract AF19(628)-3834:

Scientific Report No. 1:

"An Experimental Study of Plasma Sheath Effects on Antennas" by G. Tyras, P. C. Bargeliotes, J. M. Hamm and R. R. Schell, December 1964.

Scientific Report No. 2:

"Further Experimental Study of Plasma Sheath Effects on Antennas" by J. M. Hamm and G. Tyras, July 1965.

Scientific Report No. 3:

"Field of an Axially Slotted Circular Cylinder Clad with an Inhomogeneous Dielectric", by G. Tyras, February 1966.

Scientific Report No. 4:

"Plane Wave Propagation Through a Compressible Inhomogeneous Plasma", by E. Rahneberg and G. Tyras, March 1967.

PAPERS BASED ON SCIENTIFIC REPORTS

G. Tyras, P. C. Bargeliotes, J. M. Hamm, and R. R. Schell - "An Experimental Study of Plasma Sheath Effects on Antennas", Radio Science, Journal of Research NBS/USNC-URSI, Vol. 69D, No. 6, June 1965, pp. 839-850.

J. M. Hamm and G. Tyras - "Further Experimental Study of Plasma Sheath Effects on Antennas", Radio Science, Vol. 1 (New Series), No. 11, November 1966, pp. 1263-1271.

G. Tyras - "Field of an Axially Slotted Circular Cylinder Clad with an Inhomogeneous Dielectric", IEEE Transactions on Antennas and Propagation, Vol. AP-15, No. 2, March 1967, pp. 222-226.

PAPERS PRESENTED AT PROFESSIONAL MEETINGS

G. Tyras, P. C. Bargeliotes, J. M. Hamm, and R. R. Schell - "An Experimental Study of Plasma Sheath Effects on Antennas", USNC-URSI Spring Meeting, Washington, D.C., April 20-24, 1965.

J. M. Hamm and G. Tyras - "Further Experimental Study of Plasma Sheath Effects on Antennas", USNC-URSI Fall Meeting, Hanover, New Hampshire, October 4-6, 1965.

G. Tyras - "Field of an Axially Slotted Circular Cylinder Clad with an Inhomogeneous Dielectric", USNC-URSI Spring Meeting, Washington, D.C., April 18-21, 1966.

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