Short Papers

Experimental Simulation of Plasma Using Strip Medium

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Abstract —**A technique for the plasma simulation using a two-dimensional strip medium is developed. The experimental results for X-band rectangular waveguide and cavity filled with the strip simulated plasma are in good agreement with the theoretical results and thus validate the simulation.**

I. Introduction

Experimental techniques for simulating the plasma are of much interest for studying the interaction of electromagnetic waves with a plasma environment. Therefore, it has drawn the attention of many researchers. Several methods have been suggested and used for the plasma simulation. Bracewell [1] and Antonucci [2] have suggested electric elements and mechanical analogs for the plasma simulation. Karas and Antonucci [3] used two contiguous dielectric media to simulate plasma-covered slots on cylinders and cones. "The relative index of refraction of less than unity between the plasma and free space was maintained for the model by an analog tank, in which free space was represented by a high-dielectric constant liquid and plasma by a lower dielectric material." Golden and Smith [4] used a single plane of equally spaced wires to simulate a thin plasma sheath. Rotman [5], Golden [6], and Kalluri and Prasad [7] simulated the behavior of the plasma by a rodded medium.

In this paper, the simulation of isotropic, low-loss, stationary plasma using the two-dimensional strip medium is discussed. The propagation characteristics of an X-band rectangular waveguide and the resonant characteristics of an X-band rectangular cavity, filled with a strip simulated plasma are experimentally investigated. Experimental results are compared with the theoretical results and they are in good agreement.

II. Two-Dimensional Strip Medium

The theory of the strip medium consisting of a two-dimensional rectangular lattice of conducting strip grids may be found in numerous texts [8]. For the two-dimensional structure of Fig. 1, inductive loading is produced when the applied electric field is parallel to the strips. For this polarization, the resulting array will behave as a dielectric with a refractive index less than unity. This tends to simulate the oscillating induction currents in a plasma, which makes simulation possible.

It is also observed that the relationship between the propagation constant and the characteristic impedance of a plasma medium is maintained by the strip medium. Equation (5), for the complex propagation constant in a strip medium with resistive

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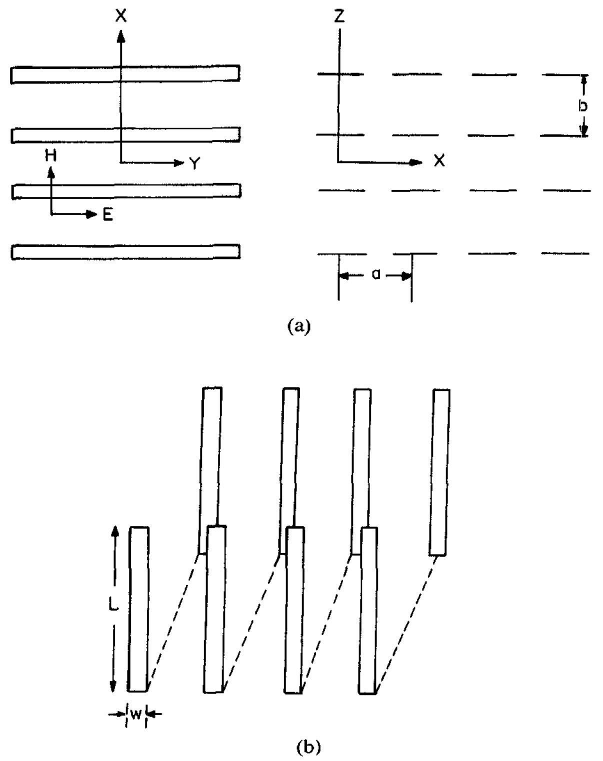

Fig. 1. (a) Strip medium (b) Typical two-dimensional strip medium.

strips, can be easily obtained and is given by

$$\cosh \gamma_s b = \cos \frac{2\pi b}{\lambda_0} + j \frac{Z_0}{2Z_t} \sin \frac{2\pi b}{\lambda_0} \tag{1}$$

where $\gamma_s(\alpha_s + j\beta_s)$ is the complex propagation constant of the strip medium, α_s is the attenuation constant of the strip medium, β_s is the phase shift constant of the strip medium, b is the spacing between two successive planes in the direction of propagation, λ_0 is the free-space wavelength, Z_0 is the free-space characteristic impedance, Z_t ($= Z_i + Z_g$) is the grid impedance, Z_i ($= R_i + jX_i$) is the internal impedance of the strip, Z_g ($= jX_g$) is the reactive impedance of a grid of equivalent lossless strips, and R_i and X_i are the resistive and reactive components of the internal impedance of a single strip, respectively. For the low-loss case ($\alpha_s/\beta_s \ll 1$), (1) becomes

$$\cos\left(\frac{2\pi nb}{\lambda_0}\right) \approx \cos \frac{2\pi b}{\lambda_0} + \frac{x_t}{2(x_t^2 + r_t^2)} \sin\left(\frac{2\pi b}{\lambda_0}\right) \tag{2}$$

$$(\alpha_s b) \sin\left(\frac{2\pi nb}{\lambda_0}\right) \approx \frac{r_t}{2(x_t^2 + r_t^2)} \sin\left(\frac{2\pi b}{\lambda_0}\right) \tag{3}$$

where n ($= (\lambda_0/2\pi)\beta_s$) is the refractive index of the strip medium, and z_t ($= r_t + jx_t = Z_t/Z_0$) is the normalized grid impedance.

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III. Strip Impedance

As mentioned in the previous section, the shunt impedance Z_t of a grid of lossy strips is composed of two parts, Z_i the internal impedance of the strips, and Z_g the reactive impedance of a grid of equivalent lossless strips. The internal impedance term may now be found for the strip. The internal impedance per unit length is the quotient of the electric field at the surface and the total current. The total current (J_w) flowing in the strip for a unit width is found by integrating the current density (J) over the thickness t of the strip.

Current density per unit width is given by [9]

$$J_w = \int_0^t J\,dx = \int_0^t J_0 e^{-(1+j)(x/\delta)}\,dx. \tag{4}$$

Upon integration (4) reduces to

$$J_w = \frac{J_0 \delta}{1+j}\left[1 - e^{-(1+j)t/\delta}\right] \tag{5}$$

where $\delta\ \{=1/(\pi f \mu_0 \sigma)^{1/2} = (\lambda_0/\pi Z_0 \sigma)^{1/2}\}$ is the skin depth, J_0 is the current density at the surface, σ is the conductivity of the strip, and f is the frequency. The electric field at the surface is given by

$$E_0 = J_0/\sigma. \tag{6}$$

Using (5) and (6), the resistive part (r_i) and reactive part (x_i) of the normalized internal impedance ($z_i = Z_i/Z_0$) are given by

$$r_i = \text{Real part of } \{(E_0/J_w)(L/w)(1/Z_0)\}$$
$$= \frac{L\left[1 - e^{-t/\delta}\left(\sin\frac{t}{\delta} + \cos\frac{t}{\delta}\right)\right]}{w\sigma\delta Z_0\left[1 + e^{-2t/\delta} - 2e^{-t/\delta}\cos\frac{t}{\delta}\right]} \tag{7}$$

and

$$x_i = \text{Imaginary part of } \{(E_0/J_w)(L/w)(1/Z_0)\}$$
$$= \frac{L\left[1 - e^{-t/\delta}\left(\sin\frac{t}{\delta} + \cos\frac{t}{\delta}\right)\right]}{w\sigma\delta Z_0\left[1 + e^{-2t/\delta} - 2e^{-t/\delta}\cos\frac{t}{\delta}\right]} \tag{8}$$

where L is the length and w the width of the strip. The normalized reactive impedance of a grid of equivalent lossless conducting strips is given by [10]

$$x_g = X_g/Z_0 \approx (a/\lambda_0)\ln(2a/\pi w) \tag{9a}$$

where a is the spacing between two strips. The approximation is valid for

$$(w/a) < 1 \quad \text{and} \quad (2a/\lambda_0) < 1. \tag{9b}$$

Therefore

$$r_t = r_i \quad \text{and} \quad x_t = x_i + x_g. \tag{10}$$

IV. Plasma Simulation

The design equations for the low-loss (under the condition: $[(\nu/\omega)^2 \ll (\omega^2/\omega_p^2 - 1)]$) isotropic stationary plasma, using two-dimensional strip medium, are obtained on the same lines as in [7] and given by

$$1 - \cos\frac{2\pi b}{\lambda_0} - \frac{x_t}{2(r_t^2 + x_t^2)}\sin\frac{2\pi b}{\lambda_0} = 0 \tag{11}$$

and

$$\frac{\pi b^2 \nu}{\lambda_p c} = \frac{r_t}{2(r_t^2 + x_t^2)}\sin\frac{2\pi b}{\lambda_p} \tag{12}$$

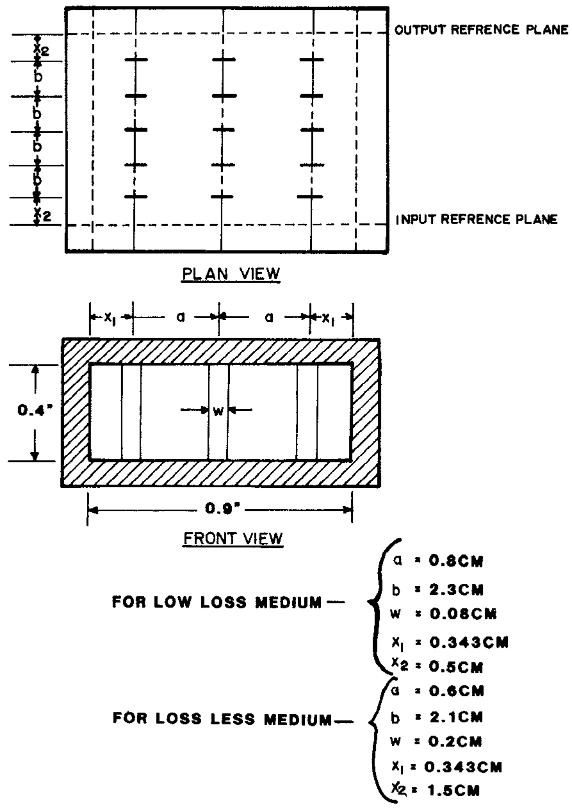

Fig. 2. Strip medium in a waveguide.

TABLE I
Lossless Strip Medium

Results	Waveguide filled with lossless plasma		Cavity filled with lossless plasma	
	Cut-off frequency (GHz)	Dispersion Characteristics	Resonance Frequency (GHz)	Quality Factor
Theoretical	9.16	Shown in Fig. 3	9.257	4112.28
Experimental	9.07		9.15	4072.98

TABLE II
Low-Loss Strip Medium

Results	WAveguide filled with low-loss plasma	Cavity filled with low-loss plasma	
	Dispersion Charecteristics	Resonance Frequency (GHz)	Quality Factor
Theoretical	Shown in Figs. 4 & 5	8.49	224.26
Experimental		8.51	225.478

where ω_p is the angular plasma frequency, ν is the angular collision frequency of the plasma, λ_p is the plasma wavelength, and c is the velocity of the light in the free space.

The relationship between the plasma parameters (plasma frequency $f_p = c/\lambda_p$ and collision frequency ν) and the strip medium parameters (w, t, a, and b) is described by (11) and (12). The plasma wavelength corresponds to the longest cutoff wavelength of the strip medium and can be obtained by solving (11) for λ_0. Thus, for an isotropic low-loss plasma simulation, the strip medium can be designed using (11) and (12) and also for a given strip medium, the equivalent plasma parameters (ω_p and ν) can be determined.

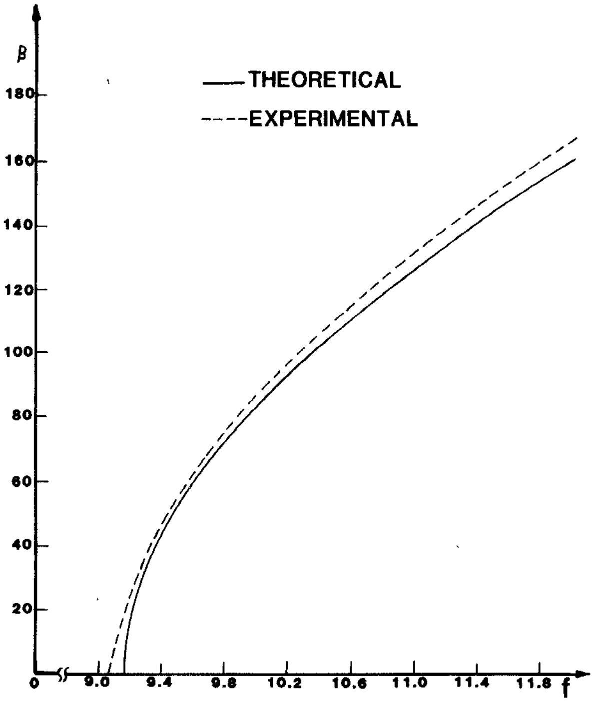

Fig. 3. β (radians/meter) versus f (GHz) diagram of a waveguide filled with lossless strip medium.

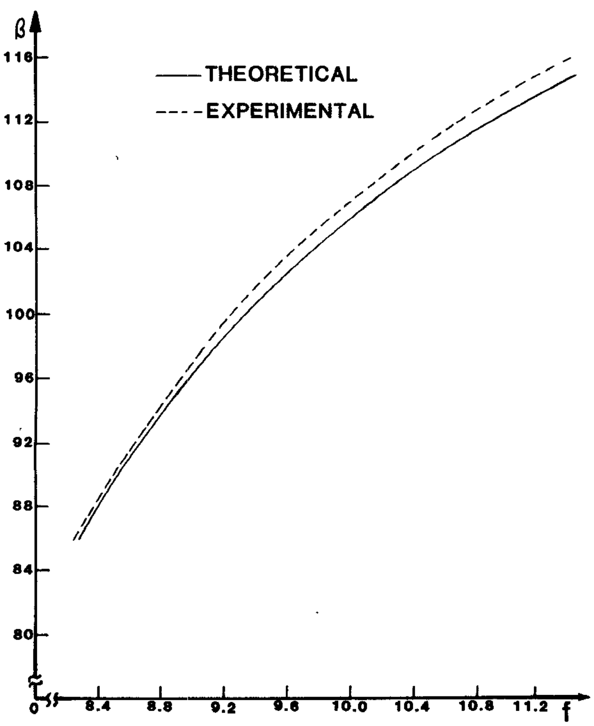

Fig. 4. β (radians/meter) versus f (GHz) diagram of a waveguide filled with lossy strip medium.

For a lossless strip medium ($\alpha_s = 0$), (11) reduces to

$$1-\cos\frac{2\pi b}{\lambda_0}-\frac{\lambda_0}{2a\ln\frac{2a}{\pi w}}\sin\frac{2\pi b}{\lambda_0}=0. \tag{13}$$

A relation between the plasma frequency and the parameters of the strip medium for the lossless plasma simulation is given by (13).

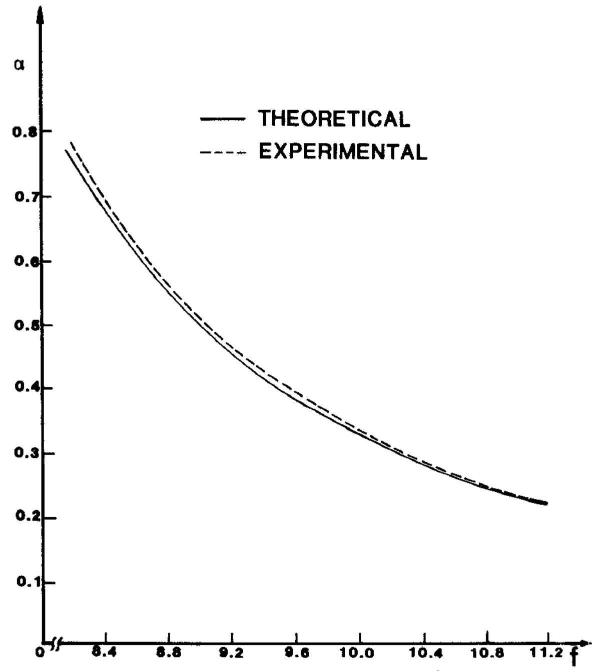

Fig. 5. α (Nepers/meter) versus f (GHz) diagram of a waveguide filled with lossy strip medium.

For $(b/\lambda_0) \ll 1$, (13) becomes

$$\lambda_p^2 = 2\pi ab\ln(2a/\pi w). \tag{14}$$

The value of λ_p obtained from (14) can serve as an initial guess for solving the transcendental (11) or (13) numerically.

V. Experimental Study

The strip simulation of the plasma is verified by comparing the experimental characteristics of the waveguide and the cavity filled with the strip medium, with the theoretical results when filled with the plasma medium. The measurement techniques and the theoretical calculations are the same as those given in [7] and, therefore, will not be repeated here.

The experimental model for simulating the lossless isotropic plasma has been realized, as illustrated in Fig. 2, using 0.004-cm-thick (t) copper strips with $a = 0.6$ cm, $b = 2.1$ cm, and $w = 0.2$ cm. The equivalent plasma frequency f_p has been obtained from the transcendental (13) and is 6.396 GHz. In the cavity experiment, the length of the cavity (L_3) is 11.4 cm.

The strip medium for simulating the lossy plasma using nichrome strips with $t = 0.005$ cm, $a = 0.8$ cm, $b = 2.3$ cm, and $w = 0.08$ cm is shown in Fig. 2. The equivalent plasma frequency (f_p) and the collision frequency (ν) are calculated from (11) and (12), respectively, and it has been found that $f_p = 4.674$ GHz and $\nu = 0.082$ GHz. In the cavity experiment, the length of the cavity (L_3) is 5.6 cm.

The theoretical and experimental results are compared in the Tables I and II and Figs. 3–5. The comparison provides good verification of the strip simulation of the lossless and low-loss plasma.

VI. Comparison of the Rodded Medium with the Strip Medium

Real plasma environment for investigating EM wave interaction is expensive to build. Simulation of this environment through artificial dielectrics permits inexpensive experimentation.

The simulation of a warm plasma is discussed in [16]. The simulation of a warm anisotropic plasma, typical of the plasmas

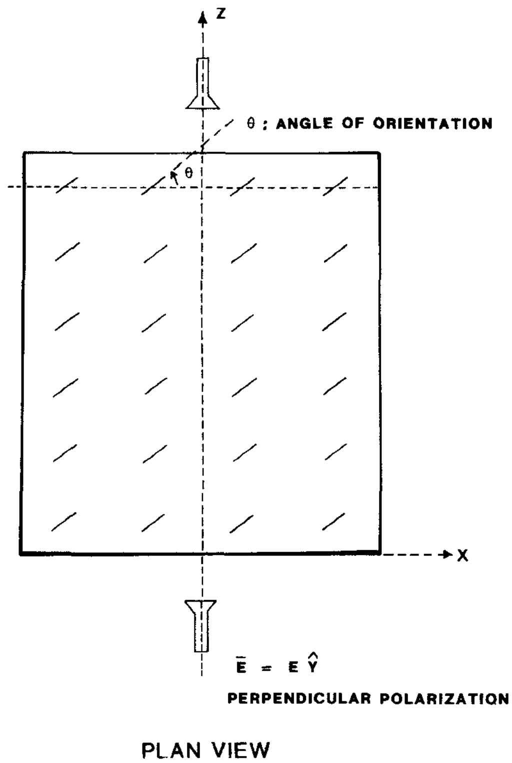

Fig. 6. Strip simulation of an anisotropic plasma. Adjustment of the orientation of the strips can simulate the required anisotropy.

in fusion machines [17], is presently under investigation by the first author. It appears the strips are more suitable than the rods for simulating the anisotropic plasma. The orientation of the strips (Fig. 6) with reference to the direction of propagation can simulate the required anisotropy.

VII. Summary

In this paper, a technique is developed for the simulation of the lossless and low-loss plasma, using the two-dimensional strip medium. The plasma parameters (plasma frequency ω_p and collision frequency ν) are related to the parameters of the strip medium (width of the strip (w), thickness of the strip (t), separation between two strips (a), and spacing between two successive planes in the direction of propagation (b)).

The necessary conditions for the plasma simulation are: 1) the electric vector of the incident wave should be parallel to the strips; 2) the spacing between two successive planes of strips in the direction of propagation should be less than the separation between strips in the transverse plane to avoid the reactive coupling between adjacent planes of elements; 3) the width of the strips should be less than the separation between strips; and 4) the separation between strips should be less than half of the free-space wave length.

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Microwave Radiation from a Magnetic Dipole in an Azimuthally Magnetized Ferrite Cylinder

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***Abstract*—The electromagnetic radiation pattern from a ferrite coated dipole antenna is a torus with a point center. By deriving an expression for the far-field electric field and defining a form factor $F(\theta)$, the dilations and contractions of the radiation pattern were evaluated and demonstrated graphically.**

I. Introduction

Almost all the work on ferrite antennas has been experimental. Attempts to explain the radiation patterns of ferrite radiators have been based on an analysis by Kiely [1] who considered dielectric rods in the hybrid HE_{11} mode. The present paper is concerned with radiation from a magnetic dipole in an azimuthally magnetized ferrite cylinder. Similar problems are found in the literature on antennas immersed in plasmas or with ferrite coatings. The number of these articles [2]–[10] increased when plasma effects began to interrupt communications with space vehicles reentering the Earth's atmosphere.

An oscillating magnetic dipole in a column of azimuthally magnetized ferrite may act as a waveguide and as a radially radiating antenna. A magnetic dipole along the z-axis consists of a loop antenna in the x-y plane with a sinusoidal circulatory current. The loop antenna is a less effective radiator than an electric dipole antenna of the same size and driving current. However, at low frequencies the electric dipole requires a higher

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