Microwave-Power Absorption by Rectangular-Shaped Conductive Dielectric Samples in Stripline

W. T. JOINES, G. DAKERMANDJI, R. L. SEAMAN, AND H. WACHTEL

***Abstract*—A general method of calculating the power absorbed by a rectangular sample of material within the microwave field of a stripline is developed. Equations which account for the sample's disturbance of the otherwise uniform plane-wave field of the stripline are given, and restrictions on sample size for best accuracy are stated in terms of stripline dimensions. Power absorption measurements are made on a 0.775 × 1.04 × 1.7-cm sample of seawater over the 1–2-GHz range and compared with calculations made using the equations developed.**

I. Introduction

For microwave power incident upon an absorptive material, the total absorption depends upon the size, shape, and electrical properties of the material, as well as the frequency. The microwave power absorbed by a rectangular sample of seawater (in a Plexiglas® container) within the uniform field of a stripline is calculated and measured over the 1–2-GHz range. Seawater is used for convenience and because its electrical properties are comparable to various types of biological tissue.

Most applications where this method of determining the total absorbed power in a rectangular sample may be useful will involve the irradiation of biological materials. For example, excised tissue held in a dielectric container to study microwave interactions with individual nerve cells [1] or with tumor cells, and whole animal studies [2], [3] where the animal is assumed to have a rectangular shape, would be appropriate applications for using the results presented. Within reason, the results are also applicable to any sample size because if all cross-sectional dimensions of the stripline and sample are scaled by the same amount the relative absorption cross section of the sample remains unchanged.

A simple sketch of the stripline with the rectangular sample in position is shown in Fig. 1. Letter designations for important dimensions are also given. The dimensions b and $w + 2s$ should be less than a half wavelength at the operating frequency to suppress higher order modes.

II. Development of Theory

Before the sample is placed in the stripline, there exists between the central conductor (of width w and thickness t) and the upper and lower ground planes (of separation b) a region of uniform electromagnetic field. For a 50-Ω air-filled stripline, the width of this central uniform-field region is about $0.65(b - t)$ [4]. Hence, if

$$w_s \leq 0.65(b - t) \tag{1}$$

the sample placed as indicated in Fig. 1 should be subjected to the same field configuration as encountered in the far field of an antenna, and the ratio of abosrbed to incident power should be the same in either case.

Near the edges of the central strip in Fig. 1 the field becomes nonuniform due to fringing effects and causes an apparent width increase of amount [5]–[7]

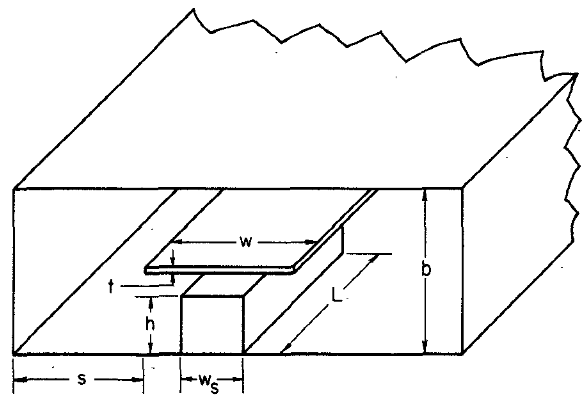

Fig. 1. Stripline with rectangular sample in position for microwave irradiation.

$$\Delta w = \frac{2b}{\pi}\left[\log\frac{2b - t}{b - t} - \frac{t}{2b}\log\frac{t(2b - t)}{(b - t)^2}\right] \cdot \frac{\log\left(1 + \coth\frac{\pi s}{b}\right)}{\log 2}. \tag{2}$$

Hence, the effective area through which power flows within the stripline is

$$A = (w + \Delta w)(b - t). \tag{3}$$

In a similar manner, the sample of width w_s and height h disturbs the uniformity of the field and causes the sample to appear electrically wider than its actual width by the amount [5], [8]

$$\Delta w_s = \frac{r(b - t)}{\pi}\left[\frac{1 + r^2}{r}\log\left(\frac{1 + r}{1 - r}\right) - 2\log\left(\frac{4r}{1 - r^2}\right)\right] \tag{4}$$

where $r = 1 - 2h/(b - t)$. Hence the effective cross-sectional area of the sample in the field is

$$A_s = (w_s + \Delta w_s)h. \tag{5}$$

Equation (4) was determined by conformal mapping techniques under the assumption that the sample conductivity (σ) is much larger than the conductivity of the surrounding medium. This assumption allows the sample surface to be treated as an equipotential. In deriving (4) it was also necessary to assume that fringing effects on each side of the sample are independent. This assumption is valid, and the error in determining electric-field intensity on the sample surface does not exceed 1 percent, if

$$w_s \geq b - t - 2h. \tag{6}$$

Note that (1) and (6) bracket the range of sample widths for which these developments yield the most accuracy.

Since Δw and Δw_s account for the nonuniformity of the field, if these widths are added to w and w_s, the field can be correctly assumed to be uniform for impedance and absorption cross-section calculations. If P_0 W are incident within the stripline cross section, then the power incident upon the sample is

$$P_i = (A_s/A)P_0. \tag{7}$$

Manuscript received June 12, 1975; revised February 13, 1976.
W. T. Joines and G. Dakermandji are with the Department of Electrical Engineering, Duke University, Durham, NC 27706.
R. L. Seaman and H. Wachtel are with the Department of Biomedical Engineering, Duke University, Durham, NC 27706.
® Registered service mark of Rohm and Haas, Philadelphia, PA.

The amount of incident power reflected from the sample is

$$P_r = |\rho|^2 P_i \tag{8}$$

and the amount transmitted through the sample is

$$P_t = |T|^2 P_i \tag{9}$$

where ρ is the reflection coefficient at the air–sample interface and T is the transfer function of the sample. Using (8) and (9), the power absorbed within the sample may be expressed as

$$P_a = (1 - |\rho|^2 - |T|^2)P_i \tag{10}$$

and substituting (3), (5), and (7) yields

$$P_a = \frac{(w_s + \Delta w_s)h}{(w + \Delta w)b}(1 - |\rho|^2 - |T|^2)P_0 \tag{11}$$

where T and ρ, which are functions of the electrical properties and length of the sample, are to be determined.

All of P_i is incident within a rectangular cylinder of height h and width $w_s + \Delta w_s$. Since the top and bottom of the cylinder are equipotentials separated by the height h, it is convenient to represent the region before, within, and after the sample by equivalent transmission lines.

A wave propagating through the equivalent transmission line represented by the sample sees a characteristic impedance

$$Z_0' = \sqrt{\frac{j\omega\mu_0}{\sigma + j\omega\varepsilon}}\,\frac{h}{w_s + \Delta w_s} \tag{12}$$

whereas, the characteristic impedance of the same cross section in air, before and after the wave encounters the sample, is

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}\,\frac{h}{w_s + \Delta w_s} \tag{13}$$

where μ_0 is the free-space permeability, ε_0 is the free-space permittivity, σ is the sample conductivity, ε is the sample permittivity, ω is the radian frequency, and $j = \sqrt{-1}$. Taking into account the length of the sample,[1] the $ABCD$ or transfer matrix of the sample is

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh \gamma L' & z_0' \sinh \gamma L' \\ \dfrac{\sinh \gamma L'}{z_0'} & \cosh \gamma L' \end{bmatrix} \tag{14}$$

where

$$\gamma = \sqrt{j\omega\mu_0(\sigma + j\omega\varepsilon)} = \alpha + j\beta \tag{15}$$

is the propagation constant of the sample and $z_0' = Z_0'/Z_0$. Hence, with the equivalent transmission line of the cross section before and after the sample normalized to unity characteristic impedance, the reflection coefficient and the transfer function may be expressed as

$$\rho = \frac{A + B - C - D}{A + B + C + D} \tag{16}$$

and

$$T = \frac{2}{A + B + C + D}. \tag{17}$$

Since $|\rho|^2$ and $|T|^2$ represents the fractional reflection and transmission of the sample, any additional power must be absorbed within the sample. The absorbed power is expressed as a fraction of the power incident upon the sample cross section as in (10), or as a fraction of the total power within the stripline cross section as in (11).

III. Calculation of Absorbed Power

From the foregoing development, it is seen that if the dimensions of the stripline and sample are specified, together with the sample electrical properties (σ and ε), the fraction of power absorbed by the sample (P_a/P_0) can be calculated from (11) at any desired signal frequency.

As determined from data given by Saxton and Lane [9], the conductivity (σ) of seawater (equivalent to 0.62-M NaCl) at room temperature varies with frequency as

$$\sigma = 0.06\left[\frac{1 + 10.6(f/20)^2}{1 + 0.8(f/20)^2}\right] \text{mhos/cm} \tag{18}$$

where f is in gigahertz. For comparison, the frequency-dependent conductivity of biological tissue with high water content has been expressed as [10], [11]

$$\sigma = 0.01\left[\frac{1 + 62(f/20)^2}{1 + (f/20)^2}\right] \text{mhos/cm} \tag{19}$$

with f in gigahertz. The permittivity (ε) of seawater as well as biological tissue may be taken as $63\varepsilon_0$ within the frequency range of interest.

Using (11), the total power absorbed is, in general, an oscillatory function of frequency because signals internally reflected from the trailing edge of the sample pass back through and interact with signals entering the sample. The maximum and minimum values occur at frequencies where the sample length is approximately an even number of half wavelengths and an odd number of quarter wavelengths, respectively. The oscillatory behavior diminishes with increases in frequency (f), conductivity (σ), and sample length (L); because signal transmission within the sample is attenuated at the rate of 8.686α dB per unit length, and α (the attenuation constant) is an increasing function of σ and f. Hence, when $\alpha L = 2.31$, the leading and trailing edges of the sample are isolated by 20 dB of attenuation, and internal reflections are negligible, as is the case for the seawater sample treated in the following section.

IV. Measurement of Absorbed Power

A thin-walled Plexiglas container was constructed, which, when filled to the proper level with seawater, had the inside dimensions $L = 1.7$ cm, $h/b = 0.29$, and $w_s/b = 0.4$; and the stripline dimensions were $b = 2.65$ cm, $w/b = 1.22$, $t/b = 0.03$, and $s/b = 0.28$. The arrangement used for measuring the power absorbed is shown in Fig. 2. At a number of frequencies from 1 to 2 GHz, the microwave source (AIL 125) was adjusted to yield 1 W of power incident (P_0) upon the stripline, and readings on the three power meters were taken with the seawater sample in the stripline, and with the empty Plexiglas container in the stripline. With the seawater sample in the stripline, the power incident (P_0) must be reflected from the sample (P_r), transmitted past the sample (P_t), absorbed in the stripline (P_{as}), or absorbed

[1] Since the sample disturbs the uniformity of the field at the leading and trailing edges, there is also an apparent length increase ΔL which adds to the actual length L, making the electrical length of the sample $L' = L + \Delta L$. Replacing w_s by L in (4) and (6) gives the equation for determining ΔL and the length restriction for 1-percent accuracy, respectively.

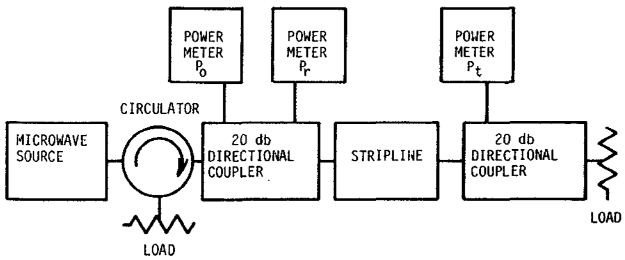

Fig. 2. Equipment arrangement used for measuring power absorbed by a sample in the stripline.

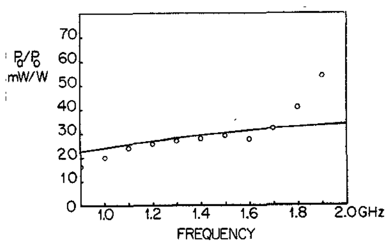

Fig. 3. The measured (circles) and calculated (solid curve) values of power absorbed for a seawater sample with the dimensions: $L = 1.7$ cm, $b = 2.65$ cm, $w/b = 1.22$, $t/b = 0.03$, $s/b = 0.28$, $w_s/b = 0.4$, $h/b = 0.29$.

in the sample (P_a) as

$$P_0 = P_r + P_t + P_{as} + P_a. \tag{20}$$

With the empty Plexiglas container in the stripline, P_0 is set to the value in (20) and P_{as} should remain about the same, so that

$$P_0 = P_r' + P_t' + P_{as} + 0. \tag{21}$$

Subtracting (21) from (20) yields the power absorbed in the seawater sample as

$$P_a = (P_r' - P_r) + (P_t' - P_t). \tag{22}$$

V. Discussion of Results and Conclusions

For the seawater sample of length $L = 1.7$ cm, the measured and calculated results are shown together in Fig. 3. The total power absorbed by the rectangular sample in the stripline was calculated using (11), and close agreement with measurement is noted over most of the 1–2-GHz range. The difference below 1 GHz could be due to measurement errors, since at these lower frequencies the absorbed power is such a small fraction of the incident power.

The equivalent dielectric constant of the stripline cross section is increased by the presence of the seawater sample. Calculations based upon the dimensions given in Fig. 3 and the permittivity of seawater ($\varepsilon = 63\varepsilon_0$) show that higher order modes can exist within the section of stripline occupied by the seawater sample at frequencies above about 1.8 GHz. These higher order modes probably account for the measurement errors above 1.8 GHz in Fig. 3.

The directional couplers used in the testing arrangement were not 20 dB at all frequencies, but the measured values shown in Fig. 3 were corrected for coupling errors. Also, the walls of the Plexiglas container were thin enough (1 mm) to have a negligible effect upon the experimental results [12].

As a further indication that (11) correctly accounts for the absorption cross section of the rectangular sample, if Δw_s is neglected in (11), P_a/P_0 decreases to 0.73 times the values represented by the solid curve in Fig. 3. Hence Δw_s, as expressed by (4), cannot be neglected in accurate calculations of the power absorbed.

References

[1] H. Wachtel, R. Seaman, and W. T. Joines, "Effects of low intensity microwaves on isolated neurons," *Annals of the New York Academy of Sciences*, vol. 247, pp. 46–62, February 1975.
[2] R. D. Phillips, E. L. Hunt, and N. W. King, "Field measurements, absorbed dose, and biologic dosimetry of microwaves," *Annals of the New York Academy of Sciences*, vol. 247, pp. 499–509, February 1975.
[3] O. P. Gandhi, "Strong dependence of whole animal absorption on polarization and frequency of radio-frequency energy," *Annals of the New York Academy of Sciences*, vol. 247, pp. 532–538, February 1975.
[4] S. B. Cohn, "Characteristic impedance of the shielded-strip transmission line," *IRE Trans. Microwave Theory and Tech.*, vol. MTT-2, pp. 52–57, July 1954.
[5] W. T. Joines, "The characteristic impedance of symmetrical strip transmission lines with undesired modes suppressed," Doctoral Dissertation, Duke University, 1964.
[6] S. B. Cohn, "Shielded coupled-strip transmission line," *IRE Trans. Microwave Theory and Tech.*, vol. MTT-3, pp. 29–38, October 1955.
[7] ——, "Problems in strip transmission lines," *IRE Trans. Microwave Theory and Tech.*, vol. MTT-3, pp. 119–126, March 1955.
[8] S. Ramo, J. R. Whinnery, and T. Van Duzer, *Fields and Waves in Communication Electronics*. New York: Wiley, 1965, p. 192.
[9] J. A. Saxton and J. A. Lane, "Electrical properties of seawater," *Wireless Engineer*, pp. 269–275, October 1952.
[10] H. N. Kritikos and H. P. Schwan, "Hot spots generated in conducting spheres by electromagnetic waves and biological implications," *IEEE Trans. Biomedical Engineering*, vol. BME-19, pp. 53–58, January 1972.
[11] W. T. Joines and R. J. Speigel, "Resonance absorption of microwaves by the human skull," *IEEE Trans. Biomedical Engineering*, vol. BME-21, pp. 46–48, January 1974.
[12] C. M. Weil, "Propagation of plane waves through two parallel dielectric sheets," *IEEE Trans. Biomedical Engineering*, vol. BME-21, pp. 165–168, March 1974.

Additional Information on the Noise-Temperature Behavior of F8T5 Lamps

RONALD E. GUENTZLER

***Abstract*—Noise temperature versus bulb temperature is given for an F8T5 lamp operating at 160-mA dc at bulb temperatures from 0 to 70°C. The new values supplement and correct previously published values. The behavior of the noise temperature is explained in terms of an Ar discharge at low bulb temperatures and the normal Hg–Ar discharge at high temperatures.**

Introduction

A few years ago, a study was made of the noise temperature as a function of bulb temperature for normal and for cataphoretically pumped fluorescent lamps [1]. A second study was made to determine the lower limit on the noise temperature as the mercury-vapor pressure was lowered by "freezing out" the mercury [2]. Finally, the results were compared with those obtained from pure-argon discharges at various pressures [3].

The purposes of this letter are: 1) to show the noise-temperature behavior of a normal F8T5 lamp over the entire range from 0 to 70°C, thus filling in the gaps between the results given in [1] and [2]; 2) to correct some of the values given in [1]; and 3) to indicate the existence of a sharp boundary between the Ar and the Hg–Ar discharge as the bulb temperature is varied.

Bulb-Temperature Control

In the original study, the bulb temperature was controlled by the lamp dissipation and the ambient temperature; the bulb temperature was measured by means of a thermocouple. Recently,

Manuscript received November 12, 1975; revised February 6, 1976.
The author is with the Department of Electrical Engineering, Ohio Northern University, Ada, OH 45810.