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P. S. Neelakantaswamy and R. Govindarajan

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Noninvasive beam-wave spectrometric instrumentation for measuring dielectric constant at microwave frequencies

P. S. Neelakantaswamy[a] and R. Govindarajan

Department of Electrical Engineering, Indian Institute of Technology, Madras 600036, India

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From the characteristics of the reflected Gaussian beam-wave for oblique incidence, measured with a spectrometer arrangement, the dielectric properties of a selectively exposed region of a dielectric slab are ascertained at microwave frequencies. For this purpose, a focused (Gaussian) microwave beam is launched from a suitable applicator to irradiate obliquely a selected portion of the test dielectric and the complex reflection coefficient is measured and analyzed. Further, the magnitude of the angular shift involved in the direction of the reflected beam is also used to calculate the dielectric constant. Application of this method to noninvasive measurements of dielectric properties of selective partial-bodies of commercial dielectrics and biological substances is discussed.

INTRODUCTION

Recently, the necessity to irradiate (to expose) only a part of a whole dielectric body in order to ascertain the dielectric nature of the selectively exposed region was discussed by Neelakantaswamy[1] elsewhere in detail. It was indicated that such partial body measurements are often required in biological experiments wherein, for dosimetric/therapeutic purposes, the dielectric properties of only a small portion of a human body or an animal *in vivo* (or *in vitro*) are to be determined. To meet this requirement, a noncontact measurement technique was evolved by Neelakantaswamy[1] involving a reflectometric instrumentation formed by a microwave Gaussian-beam launcher plus a monostatic bridge arrangement. The launcher is designed to irradiate the test object selectively at normal incidence over a small area and the amplitude-phase characteristics of the reflected beam are measured by a bridge technique, from which the complex permittivity is analytically determined.

Presently, a beam wave spectrometer is proposed for such measurements. This method has two Gaussian-beam launchers, one to transmit and the other to receive the microwave power. The transmitted beam irradiates the test material obliquely (Fig. 1) and the reflected beam is received by an identical launcher. This bistatic arrangement has the following advantages over the monostatic arrangement described in Ref. 1: (i) Oblique incidence allows more than one reflection coefficient measurement, by changing the angle of incidence. This resolves any ambiguity involved in the measured value. (ii) Normal incidence may not always be feasible in practical situations due to the geometrical complexity of the test object. (iii) Dependence of the reflection coefficient on the polarization of the incident beam enables the determination of the incident field polarization versus permittivity characteristics of the test material. (iv) The dielectric constant can be determined from the measured data by two methods in the present setup—by measuring the complex reflection coefficient and by measuring the characteristic angular-shift in the direc-

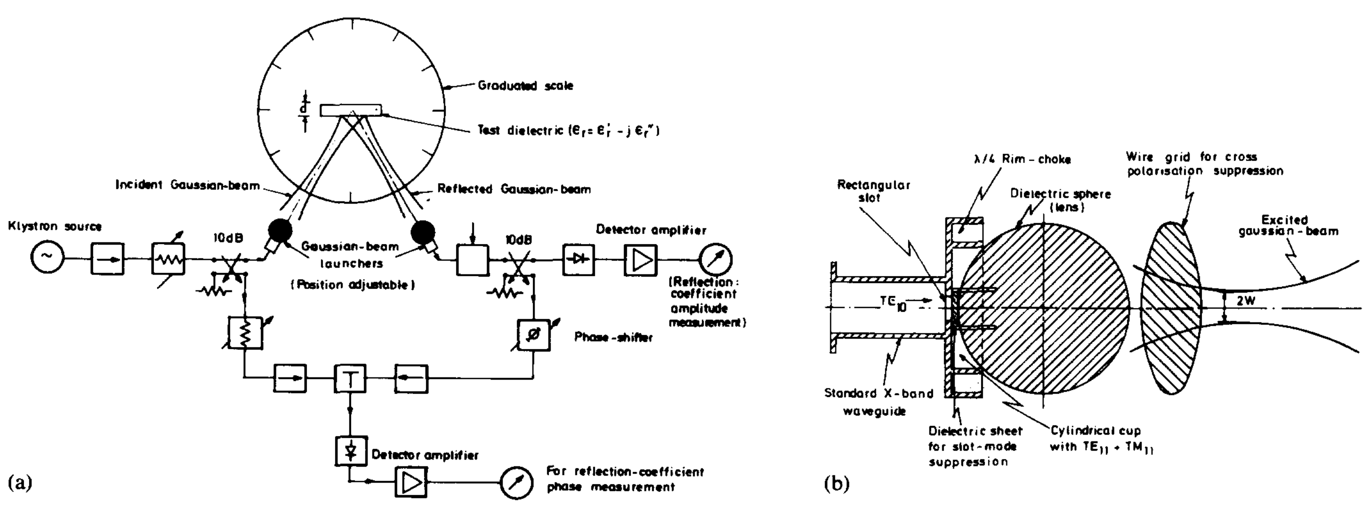

FIG. 1. X-band beam-wave spectrometer and the Gaussian-beam launcher.

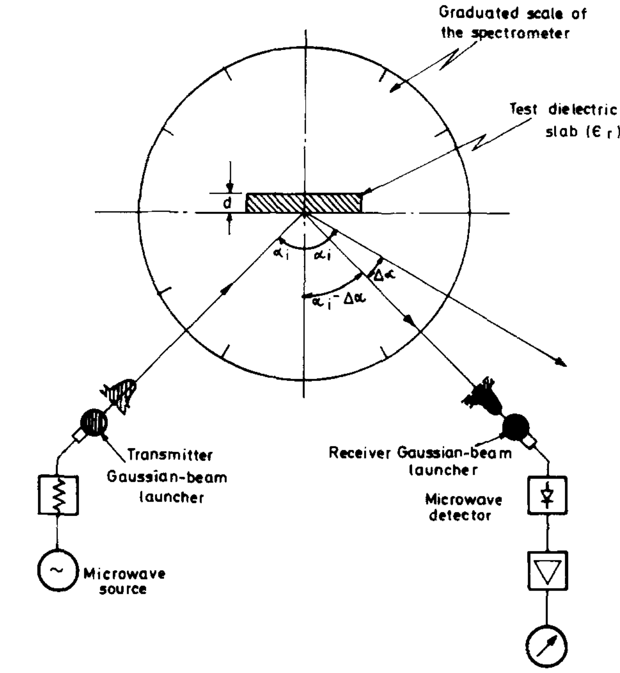

FIG. 2. Angular beam-shift measurement.

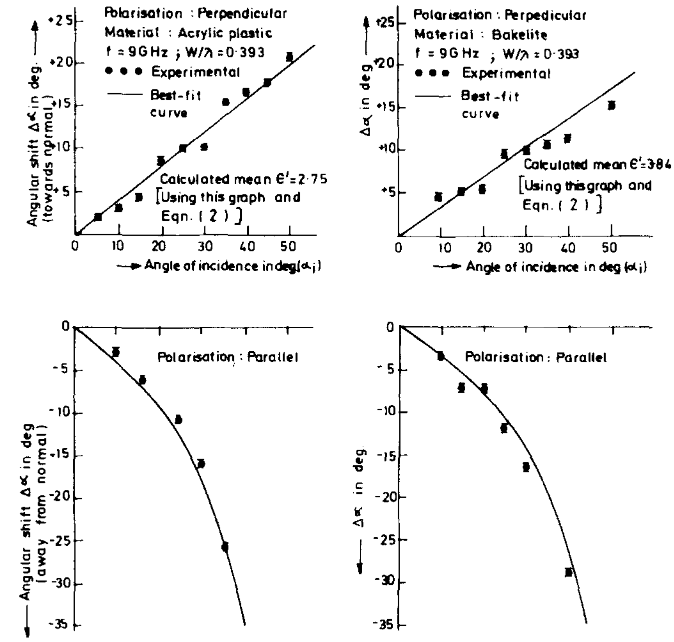

FIG. 3. Angular beam-shift versus angle of incidence.

tion of the reflected beam. These two results can be used to cross-check against each other.

Using the experimental set up to be described and the theoretically formulated results on the complex reflection coefficient/angular beam shift, the test procedure involved in the measurement is presented here along with the relevant calculations.

I. MEASUREMENT TECHNIQUE

Presented in Fig. 1(a) is the beam wave spectrometer under discussion. It utilizes a microwave bistatic bridge arrangement and two identical Gaussian-beam launchers to illuminate and receive a focused Gaussian beam (dominant mode) obliquely at the test dielectric surface. A reflex klystron is used as a microwave source and the complex reflection coefficient is determined by a comparison method. That is, the received beam amplitude-phase characteristics are compared with those found when the reflecting surface is a metallic sheet.

The Gaussian beam launcher [Fig. 1(b)] consists of a Clavin's type horn which supports a balanced mixture of TE_{11} and TM_{11} modes and the aperture of this horn illuminates a dielectric sphere (lens). The resulting diffracted field in the image zone of the lens is a highly focused near-circular Gaussian beam as indicated by Neelakantaswamy elsewhere.[2] A wire grid is placed ahead of the sphere lens in order to allow only one particular polarization of the field to propagate and to suppress any spurious cross-polarized component. This ensures the correctness of the formula for reflection coefficient to be used for a given polarization of the incident beam.

Assuming only a dominant mode exists in the beam, the complex reflection coefficient is given by[3]

$$\gamma_{00} = \frac{n\cos\alpha_i - \cos\alpha_t}{n\cos\alpha_i - \cos\alpha_t} + \frac{4n\cos\alpha_i\cos\alpha_t}{(n\cos\alpha_i + \cos\alpha_t)^2}\sum_{m=1}^{\infty}\left(\frac{n\cos\alpha_i - \cos\alpha_t}{n\cos\alpha_i + \cos\alpha_t}\right)^{2m-1}\exp(jnk2md\cos\alpha_t)$$
$$\times\exp\left(-\frac{km^2\delta^2}{2kW_s^2 - j2(Z_{10}' - Z_{1m}')}\right)\frac{kW_s^2}{[kW_s^2 - j(Z_{10}' - Z_{1m}')]^{1/2}}\cdot\frac{1}{[kW_s^2 - j(Z_{20}' - Z_{2m}')]^{1/2}}, \quad (1)$$

(Electric vector parallel to plane of incidence), where

n = refractive index of the test material ($=\sqrt{\epsilon_r}$),
d = thickness of the test slab,
δ = $2d\tan\alpha_t\cos\alpha_i$,
k = 2π/free space wavelength,
Z_{lm} = $(Z_{bs,2m+1}) - jmd\tan\alpha_t\sin\alpha_i$,
Z_{lm}' = $(Z_{1s,2m}) - 2md\tan\alpha_i\sin\alpha_i$,
l = 1, 2,
$Z_{1s,2m+1} = Z_s + (2m+1)d\cos^2\alpha_i/n\cos\alpha_t$,
$Z_{2s,2m+1} = Z_s + (2m+1)d/n\cos\alpha_t$,

where α_i and α_t are the angles of incidence and transmission respectively. $2W_s$ is the beam spot-size at Z_s from the source point of the beam.

II. BEAM SHIFT METHOD

The existence of the angular shift (Fig. 2) in the direction of the reflected beam when a bounded beam undergoes partial reflection from a planar dielectric interface between two dielectric media was identified by Ra *et al.*[4] and was later extensively analyzed by Antar and Boerner.[5] The physical mechanism which produces this shift has been pointed out by White *et al.*[6] to be entirely

TABLE I. Measured dielectric constants (complex relative permittivity $\epsilon_r = \epsilon' - j\epsilon''$).

Sl. No.	Dielectric material	Slab thickness (in mm) (mean value)	Measured data (present methods) Temperature 36 °C: Reflection coefficient method: Dielectric constant ϵ'	Reflection coefficient method: Loss tangent $\tan\delta$	Beam-shift method ϵ'	Measured data (other methods): Beam-wave interferometric method (Ref. 1) ϵ'	Beam-wave interferometric method (Ref. 1) $\tan\delta$	von Hippels' method ϵ'	von Hippels' method $\tan\delta$
Commercial dielectric materials: frequency = 9.35 GHz									
1	Acrylic plastic	6.50 4.22	2.79 2.85	0.0119 0.0470	2.75 2.75	2.756	0.04	2.75	0.0228
2	Bakelite	12.90 0.65 1.78	3.99 3.85 3.61	0.060 — 0.0105	3.84	3.676	—	3.84	0.0230
Biological substance: frequency = 9.0 GHz. Nominal values at X band, as given in Ref. 7.									
3	Human skull (in vitro measurements) Right temporal region Left temporal region	6.90	5.92 6.57	0.123 0.132	— —	5.02	0.164	5.00	0.2500

due to the finite width and profile of the beam, since the finite spatial width of the beam requires a range of incident ray directions over which Fresnel's reflection lens is nonuniform.

The angular shift is also dependent on the polarization characteristics of the incident wave. The following are the results of White *et al.*[6] on the angular shift:

$$\Delta\alpha = \frac{2\cos\alpha_i}{(kW_s)^2}\frac{|R(\sin\alpha_i)|'}{|R(\sin\alpha_i)|} \quad \text{for} \quad \alpha_i \neq \alpha_B, \qquad (2)$$

where $\Delta\alpha$ is the angular shift and R is the reflection coefficient when a plane wave is obliquely incident on a dielectric. The prime denotes differentiation with respect to the argument and α_B is the Brewster angle of the test material.

Therefore by measuring the angular shift relative to the expected value of reflected beam (as per Fresnel's law), it is possible to calculate the real part of the complex permittivity through Eq. (2), in terms of the beam parameters. The measured angular shift as a function of incidence angle is depicted in Fig. 3.

The details of the Gaussian beam launchers (Fig. 2) used presently are given in Ref. 2. Dielectric materials like acrylic plastic and Bakelite were used and measurements were carried out at X-band frequencies. To study the suitability of this method to biological experiments, *in vitro* measurements were carried out with a human skull as the test material. Calculations with the measured data substituted in the theoretical expressions of (1) and (2), were carried out with the computer IBM 370/155-II.

Presented in Table I are the results of the investigations along with the relevant comparative results obtained by other methods. The tabulated values are the mean of the results obtained by averaging the results due to the two principle polarizations.

III. DISCUSSION

Referring to Table I, the real parts of the dielectric constants agree closely with the nominal values obtained by other methods.[1,7,8] The loss tangents measured by the present technique differ significantly from the expected value, due to the errors associated with the measurement of phase angle. A detailed analysis of the possible errors is elaborated in Ref. 8, and attempts are being made to reduce these errors.

[a] Presently with the Electronics Section, School of Applied Sciences, University Science Malaysia, Minden, Penang, Malaysia

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