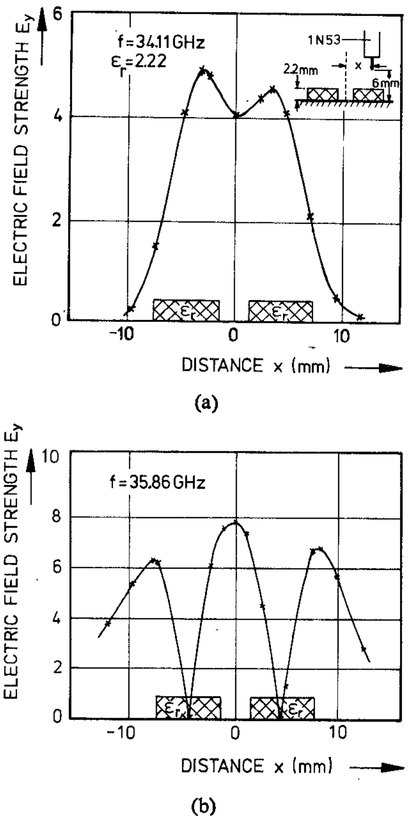

Fig. 2. Measured field distribution in the cross section of two coupled dielectric image lines. (a) EH_{11} (E_{11}^y) even mode. (b) EH_{21} (E_{21}^y) even mode.

structed using a 1N53 diode. The coaxial inner conductor couples to the electric field of the lines since the outer conductor is partly removed. This field probe is much more sensitive than those which use a metal waveguide with a coupling probe [8]. Since the probe is relatively small, the disturbance of the electromagnetic field is tolerable. From the measured maxima of the electric field strength along the line and in the cross section, the guide wavelength and mode of the wave can be detected.

In Fig. 2 the field distribution of the electric field for (a) the E_{11}^y even mode and (b) the E_{21}^y even mode on two coupled image lines of paraffin wax at 34 GHz are shown. The field can be detected very accurately, which can be seen especially from the detection of the zeros of the E_{21}^y mode.

The even mode can be detected symmetrically. The odd mode normally is not as symmetrical as the even mode if the line is excited by only one coupling probe. The field distribution of the odd mode differs from that of the even mode by a zero between the lines, so that both modes can be distinguished very easily.

In Fig. 3 the decay of the electromagnetic field in two dimensions near the edges of a single image line is drawn. As can be seen, the fields decay like an exponential function. The decay coefficients depend on the frequency.

An approximate calculation for the phase constant of the waves on a dielectric image line is described in [1] and [2]. In both papers it has been assumed that the electromagnetic field in the region $x > w, y > h$ ($2 \cdot w$ = width of one dielectric image line, h = height of the line) is zero. As can be seen from Fig. 3, this assumption is verified very well if the frequency is so high that the electromagnetic wave is well guided by the image line, i.e., λ_0/λ_g is at least greater than 1.1.

Corresponding to this result, the measured phase constants of the image lines are in good agreement with the predicted values

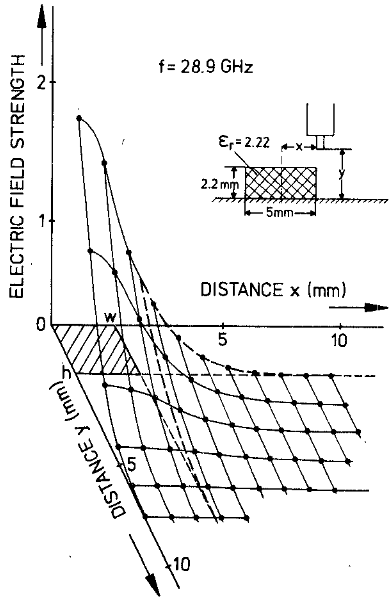

Fig. 3. Measured decay of the electromagnetic field of a single dielectric image line near the edges of the line (λ_0/λ_g = 1.12).

of Toulios and Knox's theory [1] as has been shown in [9]. The wavelengths of the even mode as well as those of the odd mode agree well with the theory as long as the ratio λ_0/λ_g is greater than 1.1.

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22-GHz Measurements of Dielectric Constants and Loss Tangents of Castable Dielectrics at Room and Cryogenic Temperatures

ROBERT W. HAAS, MEMBER, IEEE, AND PETER ZIMMERMANN

***Abstract*—The dielectric constants and loss tangents of a number of castable dielectrics such as different epoxies were measured at 22 GHz at both room temperature and 77 K using a resonant cavity technique. It was found that these high-frequency values differ significantly from published low-frequency values, and that the losses decrease dramatically at cryogenic temperatures.**

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The authors are with the Max-Planck-Institute for Radio Astronomy, 5300 Bonn 1, Germany.

Introduction

The use of dielectrics which can be cast in place rather than being machined to shape is often more convenient in the construction of various microwave devices. Currently, there are also requirements for devices which operate at cryogenic temperatures. However, the electrical properties of available materials are usually measured by the manufacturers at low frequencies and at room temperature. This report summarizes the results of dielectric-constant and loss-tangent measurements at $f \cong 22$ GHz at both room temperature and 77 K.

Measurement Procedure

The basic method involved measuring the resonant frequencies of a rectangular transmission cavity when filled with the unknown material, the insertion loss and VSWR at resonance, and the loaded Q, and then comparing these quantities with those measured for an air-filled reference cavity of the same size. The cavities were sections of WR-42 waveguide, 29.3 mm long, coupled by 3-mm-diam irises at each end.

Normally, in measurements of this type the dielectric constant is simply calculated from the ratio of the resonant frequency in an air-filled cavity to the resonant frequency for the sample-filled cavity, for the same resonant mode. However, in the present case the dielectric constants of some of the materials were so high that it was not possible to observe the same mode as in the air-filled reference cavity. For example, the TE 103, 104, 105 modes were observed for the air-filled cavity while the lowest observable mode for some materials was TE 107. For this reason the following method, which eliminates direct comparison, was used.

In a dielectric-filled waveguide, the dielectric constant, ε', is given by [1]

$$\varepsilon' = \left(\frac{\lambda_0}{\lambda_g'}\right)^2 + \left(\frac{\lambda_0}{\lambda_c}\right)^2$$

where λ_0, λ_g', and λ_c are the free-space wavelength, dielectric-filled guide wavelength, and air-filled waveguide cutoff wavelength, respectively. This applies for all but the most lossy dielectrics. (For the present measurements the error introduced by neglecting the loss amounted to only 0.02 percent in the worst case.) For a test cavity at resonance, the resonant wavelength is measured with a cavity-type wave meter while λ_g is calculated by dividing the cavity length by the third mode index (i.e., n for the TE_{10n} mode) which gives $\lambda_g/2$. The modes were confirmed by later cutting slots in the broad wall of the cavities and counting the nodes at resonance with a detector probe.

The loss tangents were determined by the method given in [2] in which

$$\tan \delta_2 = \frac{1}{Q_{u2}} - \left[\left(\frac{1}{Q_{u1}} - \tan \delta_1\right)\left(\frac{f_{r1}}{f_{r2}}\right)^{1/2}\right].$$

Here Q_{un} are unloaded Q's, $\tan \delta_n$ are loss tangents, and f_{rn} are resonant frequencies of reference and unknown cavities designated by subscripts 1 and 2, respectively. The Q_u are determined from measured values of loaded Q and VSWR and insertion loss at resonance according to [3].

Cooled Measurements

For the cooled measurements the cavities were cooled by conduction through a copper strap to a liquid nitrogen container. Moisture was prevented from forming on the samples by circulating dry nitrogen gas in the coupling waveguides as shown in Fig. 1. Corrections were made for the change in cavity size due to cooling.

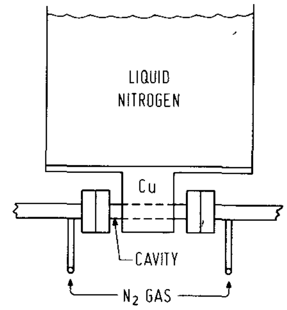

Fig. 1. Cavity cooling device.

TABLE I
MEASURED MATERIALS AND MANUFACTURERS

	Material	Manufacturer
1.	Epoxy-LMB 1386, HY 951	CIBA-GEIGY
2.	Teflon-Vergussmasse, CHS-Type 1542	Carl Huth & Söhne
2a.	(2) plus 1/8 volume Eccospheres FTF-15	Emerson & Cuming, Inc.
2b.	(2) plus 1/4 volume Eccospheres FTF-15	Emerson & Cuming, Inc.
3.	Scotchcast 830	3M Co.
4.	Epoxy-LMB 1386, LMB 1387, DY 067 (mixed by weight)	CIBA-GEIGY
4a.	(4) plus 1/8 volume Eccospheres FTF-15	
4b.	(4) plus 1/4 volume Eccospheres FTF-15	
5.	Epoxy-LMB 1386, LMB 1387, DY 067 (mixed by volume)	CIBA-GEIGY
6.	Epoxy-Araldit CY 220, HY 951	CIBA-GEIGY
7.	Epoxy-Araldit F, HY 951	CIBA-GEIGY
8.	Eccofoam SIL	Emerson & Cuming, Inc.
9.	Epoxy-Araldit CY 209, HY 951	CIBA-GEIGY
10.	Epoxy-Araldit D, HY 956	CIBA-GEIGY
10a.	Epoxy Araldit D, HY 956 plus 17 % Eccospheres	CIBA-GEIGY
10b.	Epoxy-Araldit D, HY 956 plus 20 % Quartzmeal	
10c.	Epoxy-Araldit D, HY 956 plus 44 % Quartzmeal	
11.	Paraffin 52° - 54°	Merck
12.	Solid Teflon	Dupont

Results

Tables I and II show the materials measured and the results for both temperatures along with the published values when available. Solid Teflon and paraffin were also measured as well-known materials in order to check the measurement procedure. Sufficient cold measurements were performed to show up any differences between the various materials. Paraffin was not measured here because it cracks upon cooling. The samples which are mixtures with Eccospheres or quartzmeal resulted from attempts to tailor material to a desired dielectric constant. An analysis of the quantifiable error sources and an estimation of nonquantifiable ones resulted in the conclusion that the measured values of dielectric constant and loss tangent are accurate to within 2 and 5 percent, respectively.

TABLE II
MEASURED AND PUBLISHED DIELECTRIC CONSTANTS AND LOSS TANGENTS

Material	300 °K		77 °K		Published (300 °K)	
	ε'	tan δ	ε'	tan δ	ε'	tan δ
1	4.33	n.m.				
2	3.00	0.019	2.92	0.0048		0.0021/1 kHz
2a	2.77	0.021				
2b	2.61	0.019				
3	3.03	0.021	2.92	0.0051	3.8 / 50 Hz	0.008
4	4.38	0.011				
4a	2.96	0.008				
4b	2.67	n.m.				
5	4.55	0.011	4.45	0.006		
6	2.97	0.025	2.89	0.0042	4.3 / 50 Hz	0.003
7	3.08	0.034	2.90	0.0043	4.1 / 50 Hz	0.003
8	2.91	0.026	2.87	0.010	1.4 / 10 GHz	< 0.01
9	2.96	0.023	2.87	0.0041	4.3 / 50 Hz	0.007
10	2.99	0.024	2.90	0.0039	4.1 / 50 Hz	0.016
10a	2.06	0.012	2.04	0.0028		
10b	3.05	0.017	2.98	0.0035		
10c	4.38	0.013			4.5 / 50 Hz	0.038
11	2.27	0.0003			2.3 / 25 GHz	0.0003
12	1.96	0.0005	1.96	< 0.0003	2.08/25 GHz	0.0006

It is noticeable that at 22 GHz the electrical properties of these materials differ significantly from their low-temperature values. Of particular importance is the fact that the losses decrease dramatically at cryogenic temperatures.

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Characterization of Magnetic Materials in the Millimeter-Wave Range (60–90 GHz)

B. CHAN SONG LINT AND A. PRIOU, MEMBER, IEEE

***Abstract*—It is shown that the measurement techniques of dielectric samples using open resonators can also be used to characterize ferrimagnetic materials. The parameters that are measured are the complex permittivity ε_f^* and the ΔH ferrite gyromagnetic resonance linewidth. The principle of the techniques used and an evaluation of ferrite material parameters from 10 to 70 GHz are presented.**

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The authors are with the Microwave Department, ONERA, Centre D'Etudes et de Recherches, B.P. 40-25, 31055 Toulouse Cedex, France.

I. INTRODUCTION

The closed (rectangular or circular) cavities generally used in the microwave range to characterize materials are applicable only with difficulty to millimeter waves. In addition to the size problem of the samples, these closed cavities operating in the millimeter-wave range have a Q factor which rapidly decreases. Because of this limitation, the use of open resonators is often preferred at millimeter wavelengths. The first papers concerning measurement techniques adapted to millimeter waves were published by Culshaw [1] and Degenford [2]. Cullen and Yu [3] then showed how to improve these measurement techniques to characterize the dielectric materials with great accuracy. Ermert [4] was among the first to measure parameters of ferrite materials in the 4- and 2-mm range but he considered the lossless state of the materials.

We have adapted the technique of Cullen [3] and Ermert [4] in order to characterize ferrites, from the LTT Society, and look for good materials usable in the 60–90-GHz range. This short paper gives the characteristics of the nickel–zinc ferrite materials at 70 GHz.

II. MEASUREMENT SETUP DESIGN

A. ε_f',$tg\delta$ Measurement

Ermert [4] studied the conditions of Gaussian beam propagation in a ferrite slab magnetized perpendicular to the propagation direction. He showed that two types of waves can be defined: the ordinary wave, with a propagation constant $k = \beta$; and the extraordinary wave, characterized by the propagation constant $k = \beta\sqrt{\mu_{\text{eff}}}$ (μ_{eff} being the effective permeability).

In the case of the ordinary wave, when the ferrite is slightly magnetized, the ferrite material is equivalent to an isotropic dielectric material. This isotropic aspect of the material can be experimentally proved. Indeed when the ordinary wave is excited, the resonance frequency and the Q factor of the loaded resonator are not affected by a variation of the external magnetic field so long as it remains relatively weak (Ha < 2–3 kG).

The measurement techniques used in quasi-optics, as investigated by Cullen and Al [3], [5], adapted to millimeter waves, can be used to measure ε_f' and $tg\delta$ of ferrites. The resonator is made of two spherical quasi-concentric-type reflectors. This allows us to obtain the maximum focusing of the beam in the center of the cavity and use small samples. A schematic diagram of ε_f' and $tg\delta$ measurement is presented in Fig. 1.

Within the 60–90-GHz range, the resonator used had a length of about 250 mm. The spherical mirrors had a 130-mm radius of curvature. The coupling of the rectangular guide to the cavity was obtained with a coupling hole 1.1 mm in diameter. The Q_0 unloaded Q factor was about 55000. Q_0 and Q_L (QL = loaded Q factor) are determined by the quasi-optic formula [3]

$$\frac{f}{\Delta f} = Q = \frac{D}{\Delta D}$$

where D is the length of the resonator and ΔD is the variation of the length corresponding to 3 dB of the resonance line of the loaded cavity.

The samples were ferrite square slabs about 5 mm thick with 35-mm sides. The ferrites characterized by this method are of the nickel–zinc type and were provided by the LTT firm. The saturation magnetization is about 5300 G.

ε_f' and $tg\delta$ values are then obtained by using the equations as developed by Cullen and Yu [3] and the present authors [6].