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)

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***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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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 55 000. 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].

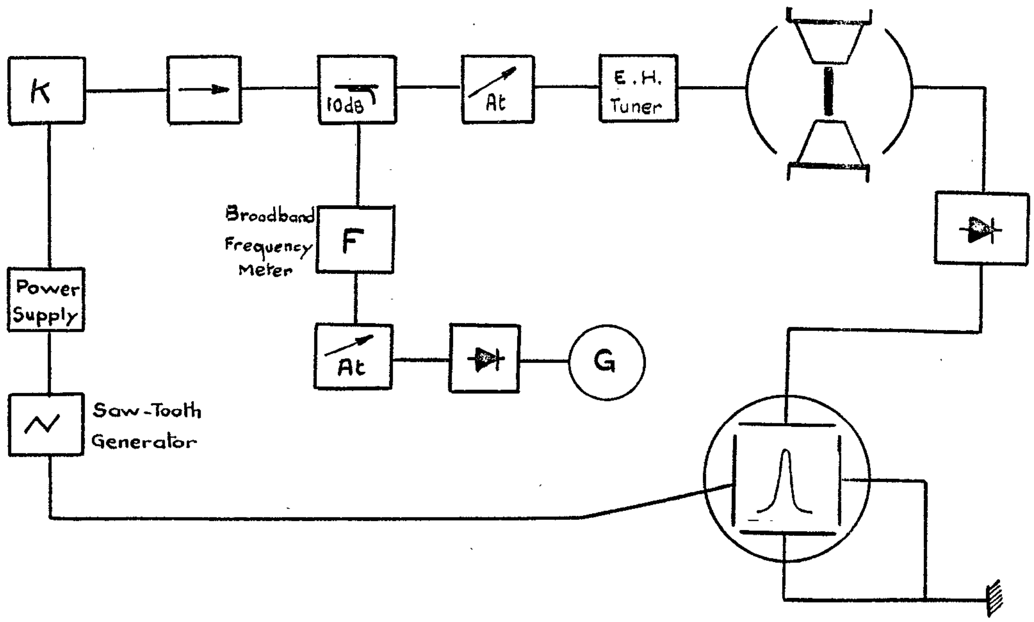

Fig. 1. ε_f' and $tg\delta$ measurement setup.

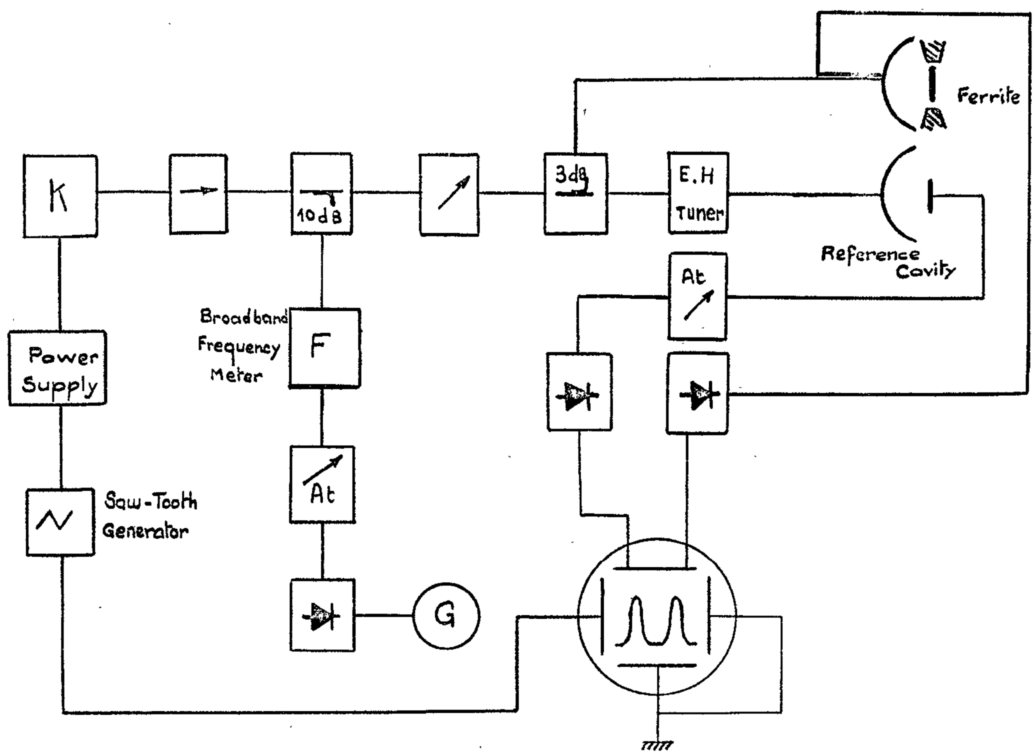

Fig. 2. ΔH measurement setup.

B. ΔH Measurement

The ΔH measurement principle is issued from the saturation magnetization $(4\pi M_s)$ measurement method studied by Ermert [4]. The ferrite sample is magnetized by an external magnetic field perpendicular to the propagation direction. In this case, during the propagation of the extraordinary wave, one can define a reflection coefficient relative to the ferrite–air interface by the equation

$$r = |r| \quad e^{j\phi} = \frac{\sqrt{\mu_{\text{eff}}} - \sqrt{\varepsilon_f}}{\sqrt{\mu_{\text{eff}}} + \sqrt{\varepsilon_f}} \tag{1}$$

where

$$\mu_{\text{eff}} = \mu'_{\text{eff}} - j\mu''_{\text{eff}}.$$

For a magnetic field verifying

$$H_i = \frac{f}{|\gamma|} - 4\pi M_s, \qquad \gamma = \text{the gyromagnetic ratio} \tag{2}$$

one can obtain $\mu'_{\text{eff}} = 0$ and, in a first approximation,

$$\mu''_{\text{eff}} \simeq \frac{\Delta H}{4\pi M_s}. \tag{3}$$

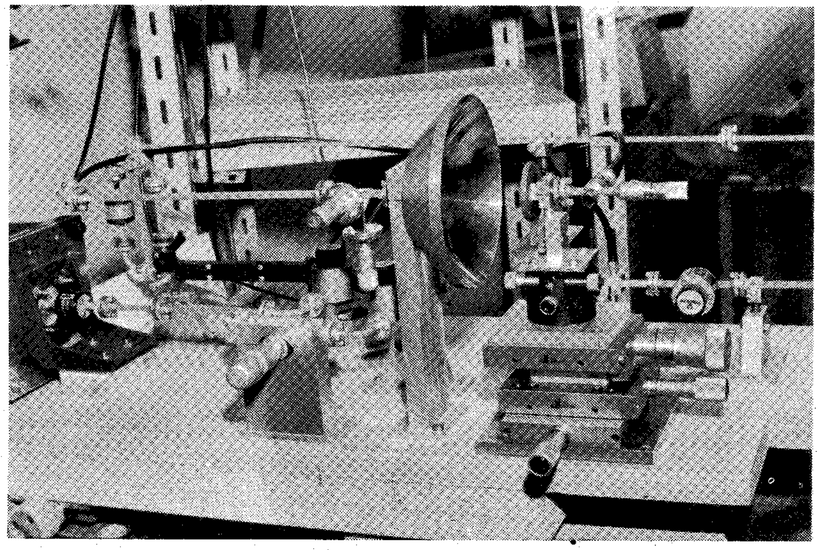

Fig. 3. Partial view of ΔH measurement setup showing the reference branch with a transmission hemispherical resonator.

For ferrites with small dielectric losses ($\varepsilon'' \ll \varepsilon'$) we can see, from (1), (2), and (3), that the phase of the reflection coefficient is given by the relation

$$\phi \simeq \sqrt{\frac{2\Delta H}{\varepsilon_f' 4\pi M_s}}. \tag{4}$$

Indeed, this quantity represents the phase shift due to the ferrite magnetic losses. If these are equal to zero, ϕ will be equal to zero and the ferrite–air interface will behave as a plane mirror with a total reflection.

In the case of materials with small dielectric losses, the ΔH measurement reduces to the measurement of the phase shift $\Delta\phi$, where $4\pi M_s$ and ε_f' are known.

A schematic diagram and a photograph of the ΔH measurement are shown in Figs. 2 and 3, respectively. The measurement setup is composed of two branches: a reference and measurement branch.

The former is composed of a transmission hemispherical resonator. The latter is composed of a similar hemispherical resonator operating in reflection, whose plane mirror is the ferrite sample placed in the electromagnetic air gap. Both resonators have the same length, and the spherical reflector has a curvature of 100 mm in radius. This measurement setup allows us to use smaller size slabs of ferrite (25-mm sides).

In these specific experiments, the phase shift ϕ of (4) corresponds to a resonance frequency shift ΔF of the measurement resonator in comparison with the reference resonator. The quantity ΔF is given by

$$\Delta F = \frac{C}{4\pi D}\,\phi \tag{5}$$

where C is the velocity of the light and D is the length of the resonators. Using (4) and (5), we deduce that

$$\Delta H = \frac{4\pi M_s \varepsilon_f'}{2C^2}(4\pi D)^2(\Delta F)^2. \tag{6}$$

ΔF is measured from the reference cavity when measuring ε_f' and $tg\delta$ ($\Delta F = F \cdot \Delta D/D$).

In our experiments, the conditions of (2) were realized with a magnetic field of 19.2–19.5 kG for ferrite slabs about 2 mm thick.

TABLE I

L.T.T. FERRITE	$4\pi M_s$	CLOSED CAVITIES 10 GHz			OPEN CAVTTIES 36 GHz		OPEN CAVTTIES 70 GHz		
		ε_f'	$tg\delta.10^{-4}$	ΔH	ε_f'	$tg\delta.10^{-4}$	ε_f'	$tg\delta.10^{-4}$	ΔH Gauss
7270	5098	15,4	2,5	170	15,3	2,4	15,5	2,4	230
7271	5084	15	3,7	153	15,2	3,3	15,4	3,8	240
7272	5126	15,1	3,6	130	15,2	3,4	15,4	4	150
7273	5202	15,3	26,6	135	15,2	10	15,3	12,5	170
7278	5178	15,3	4	129	–	–	15,3	4,4	270
Alumine					9,8	3,6	9,9	4,1	

III. RESULTS

The results of the measurement of ε_f', $tg\delta$, and ΔH are listed in Table I. The measurements at 10 GHz were made by the LTT firm with techniques using closed cavities. The measurements at 36 and 70 GHz were made using open resonators.

It may be noted that the nickel–zinc ferrites with their dielectric and magnetic properties can be used in the millimeter-wave ranges.

IV. CONCLUSION

Measurement techniques using open resonators were proved useful for accurately characterizing the complex permittivity of a material and the resonance linewidth (ΔH) of a ferrite. These methods are not only applicable to dielectrics and ferrites but can also be used for various types of materials (semiconductors, plasmas, etc.).

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Measurement of Surface Resistance in Oversized Circular Waveguide at Millimeter Wavelengths

SATOMI HATANO AND FUMIHIRO NIHEI

***Abstract*—The increase of the surface resistance of oversized circular waveguides has been accurately evaluated at millimeter wavelengths by measuring attenuations of TE_{0n} modes. The ratios of the effective resistances to the ideal resistances of the wall were found to be 1.27, 1.42, and 1.54 at 40, 60, and 80 GHz, respectively.**

I. Introduction

There have been few reports or measurement values about surface resistances of oversized circular waveguides at millimeter wavelengths, since it has been very difficult to measure them directly. The difficulty of the measurement is attributed to the mode conversion from the signal mode to spurious modes. Then, in the calculation of attenuation in the circular waveguide, the surface resistance at the waveguide wall has been estimated by $R = \sqrt{\pi f \mu / \sigma}$ with conductivity of copper $\sigma = 5.8 \times 10^7$ ℧/m. Measured losses, however, are usually greater than those theoretically determined by the formula. The discrepancies between them have been regarded as mode conversion losses caused by waveguide imperfections.

Such consideration is reasonable only when the waveguide wall has ideal conductivity and has a relatively smooth surface compared with skin depth. The surface of the practical waveguide wall is generally rough, and the conductivity of the wall, which is electroplated with copper, is not always equal to the ideal one in the region of millimeter wavelengths. Therefore, it is assumed that the surface resistance increases on account of the inferiority of the waveguide wall caused mainly by roughness.

Even though the effect of surface roughness has been investigated and a number of results are reported, some are concerned with single-mode rectangular waveguide [1]–[3] and others with small samples of the metal plates [4], [5]. This short paper describes the surface resistance of oversized circular waveguides used as long-distance transmission lines at frequency regions from 40 to 90 GHz. The surface roughness of the waveguide wall is also discussed briefly.

II. Evaluation of Surface Resistance

A. Principles

Nomenclature

α_D	total attenuation in dielectric lined waveguides under ideal conditions;
α_M	measured attenuation in actual waveguides;
α_H, α_H'	heat loss due to surface resistance in ideal and actual waveguides, respectively;
$\Delta\alpha_1$	perturbation of attenuation due to dielectric losses;
$\Delta\alpha_2, \Delta\alpha_2'$	perturbation of attenuation due to additional eddy current caused by the dielectric in ideal and actual waveguides, respectively;
$\delta\alpha$	additional attenuation due to mode conversion;
R, R'	ideal and effective surface resistances, respectively.

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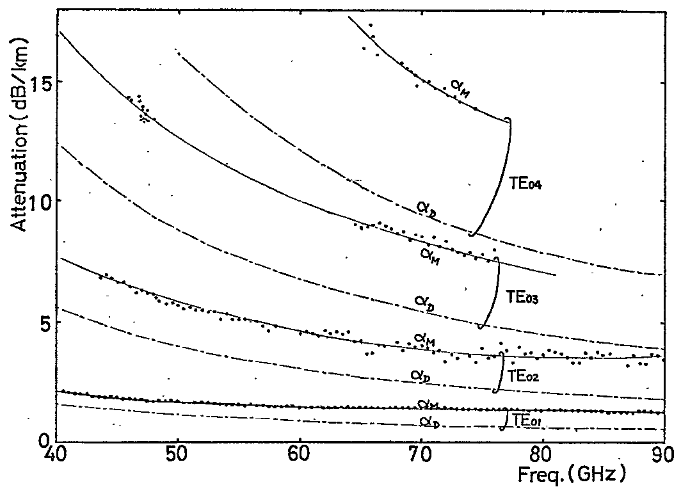

Fig. 1. Measured and calculated attenuation characteristics for TE_{0n} modes. α_M: measured characteristic for experimental guides. α_D: calculated characteristic for ideal guides.

Let us consider the TE_{0n} mode loss in perfectly straight and circular lined waveguides. The loss is given by the following equation [6]:

$$\alpha_D = \alpha_H + \Delta\alpha_1 + \Delta\alpha_2. \tag{1}$$

On the other hand, measured loss α_M in actual waveguides, which is expected to be larger than α_D because of various imperfections including surface roughness, is expressed as follows:

$$\alpha_M = \alpha_H' + \Delta\alpha_1 + \Delta\alpha_2' + \delta\alpha. \tag{2}$$

Here α_H' and $\Delta\alpha_2'$ mean the actual values of α_H and $\Delta\alpha_2$, respectively, and can be written as follows in terms of effective surface resistance R':

$$\alpha_H' = \alpha_H \frac{R'}{R}$$

$$\Delta\alpha_2' = \Delta\alpha_2 \frac{R'}{R}. \tag{3}$$

$\delta\alpha$ accounts for mode conversion loss due to mechanical imperfections in waveguides and joints. Being independent from surface resistance $\Delta\alpha_1$ in actual waveguides is regarded as the same value as in ideal waveguides.

The ratio of effective surface resistance R' to ideal surface resistance R can be carried out by (1)–(3) and then becomes

$$\frac{R'}{R} = \frac{\alpha_M - \Delta\alpha_1 - \delta\alpha}{\alpha_D - \Delta\alpha_1}. \tag{4}$$

B. Measurement of TE_{0n} *Mode Attenuation*

The attenuation characteristics of the 180-m-long experimental waveguide line by the pulse single-reflection method [7] have been measured, which makes it possible to measure low losses with high accuracy. The waveguide line under measurement,