oersteds at room temperature and is comparable to other reported results.

The present equipment can be improved to provide greater precision by decreasing the tolerance on the alignment of the probe, the loop and the crystal mount. The ac magnetic field in the experiment was derived from the common 60 cycle power line and while the voltage was well regulated the frequency variations caused some limitation on precision. A limitation on accuracy can be seen in Fig. 3. If the sample is too close to the pickup loop or the walls of the guide, radiation damping causes a broadening of the resonance. This precludes, at the present, an accurate measurement of this type in the millimeter region. The limiting assumption in the analysis is that the square of the damping constant ($\alpha = \Gamma \Delta H/2\omega$) be much less than unity. At 5 Gc the assumption is satisfied even if the line width is in the range of 100 oersteds.

Conclusion

The method for measuring narrow line width ferromagnets has been shown to have the precision necessary to distinguish the anisotropy in a very narrow line width. It is expected that the precision could be improved if necessary.

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Measurement and Standardization of Dielectric Samples*

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Summary—**The selection of a material suitable for use as a standard of dielectric properties at microwave frequencies is discussed, and tests are described which indicate that a glass and a glass ceramic are satisfactory for such standards. The probable accuracy of measurement of the real part of the dielectric constant is estimated at ± 0.3 per cent. Loss measurements are discussed. A correction is developed for the error resulting from the small airgap often present around the sample in transmission-line measurements. The effects of humidity and temperature variations are examined, and preliminary results of measurements to 800°C are given.**

Introduction

STANDARD SAMPLES, *i.e.*, samples with the limits of error well known for the property in question, are useful in a laboratory in order to improve or confirm the accuracy of the measuring procedures and equipment being used.

There are two main requirements for standard samples of dielectric materials. The material properties should be understood sufficiently to avoid such problems as those associated with inhomogeneity, sensitivity to the environment, and chemical changes or aging. After satisfying this first requirement, the measurements then must be investigated sufficiently so that their accuracy can be specified with confidence. The emphasis in this paper is on accurate dielectric measurements. Material problems have been reduced by choosing materials with known isotropy, homogeneity, and long-term stability.

The Material for Dielectric Samples

The main materials of the present investigation are a glass and a glass ceramic, both of which are available in optical quality. This ensures that the homogeneity, isotropy, and aging requirements are satisfied. There remains mostly the dependence of the complex dielectric constant on temperature, pressure, relative humidity, and surface conditions.

The temperature and relative humidity dependence of the glass standard samples were investigated over a reasonable range of values near usual laboratory conditions. In addition, a high temperature measuring system has been developed.

The Measurement of Dielectric Constant

The accuracy of the measuring procedures is determined mainly by comparing several independent methods. Corrections are made for some small departures of the measuring system from the ideal mathematical model.

Dielectric measurements depend upon knowing electromagnetic wave solutions in some space containing the material in question. The different methods investi-

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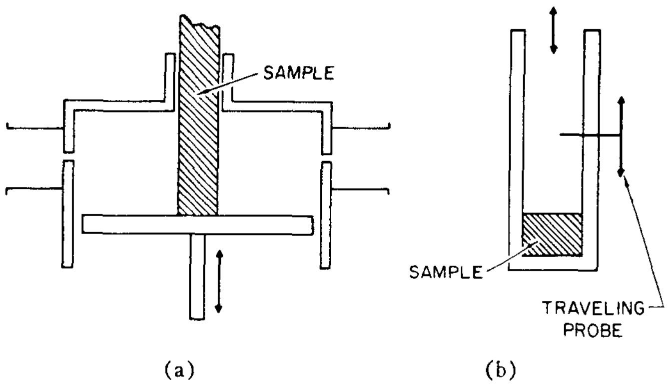

Fig. 1—TE_{01} resonator and TE_{11} line or resonator.

TABLE I

COMPARISON OF TE_{011} RESONANT CAVITY RESULTS FOR k' (PERMITTIVITY) WITH THOSE FROM THE IMPEDANCE METHOD USING TE_{11} MODE CIRCULAR WAVEGUIDE

Sample	TE_{011} resonant cavity, 9200 Mc 0.25-inch diameter rod	TE_{11} line, 8600 Mc, 1.0030-inch diameter		
		Uncorrected	Corrected for airgap	Sample diameter
Glass: from one corner of sheet	6.195	6.128	6.204	1.0001
From another location	6.196	6.127	6.203	1.0000
From another location	6.202	6.139	6.207	1.0004
Glass ceramic, from one corner of sheet	5.730	5.647	5.711	1.0001
From another location	5.708	5.648	5.708	1.0002
From another location	5.731	5.651	5.714	1.0001
Al_2O_3 porcelain (All samples from same batch but random locations in the ceramic body.)	8.784	8.642	8.794	1.0002
	8.775	8.674	8.822	1.0003
	8.775	8.594	8.743	1.0002
Average porcelain	8.778	8.636	8.786	—

gated are represented by the diagrams in Fig. 1. In Fig. 1(a) there is a circular cylindrical dielectric rod centered in a circular cylindrical cavity.[1] For the TE_{011} mode of resonance used, the corrections for imperfections due to the insertion port, the irises, and the gap around the plunger are small and known. These are obtained by perturbation theory using as a basis the exact solution of the ideal resonator with the sample in place.

In Fig. 1(b) there is a circular transmission line operated in the TE_{11} mode with a disk sample at a shorted end. Either by impedance measurement with a traveling probe or by resonating the line with another short, or both, the dielectric properties may be determined. The main error here is due to airgaps between the sample and the walls of the line. Such gaps not only permit the insertion and removal of the sample, but also leave it free to rest squarely on the short circuit, a condition which must be met if an even larger error is to be avoided.

A comparison of the two methods showed that the airgap around the disk sample contributed a significant error to the real part of the permittivity. The results in Table I show that when the TE_{11} data for the disk are corrected for the fit of the sample in the line there is good agreement with the TE_{011} rod data. The glass showed the best agreement. The glass and glass ceramic used were not of optical quality, but both are available in such quality. The results of such measurements on optical quality material are not expected to differ from those given here, except that the scatter of measured values may be less as a result of greater homogeneity of the optical quality material. The Al_2O_3 ceramic body, as might be expected, shows some variation from sample to sample, but the averages show good agreement between the two methods.

A general treatment of the error due to an airgap around a sample is not available, though some specific cases are covered.[2,3] Therefore, a general treatment based on perturbation theory, which seems to be adequate for practical cases, will be given.

[1] H. E. Bussey, "Cavity resonator dielectric measurements on rod samples," *1959 Annual Rept. of the Conf. on Electrical Insulation*, Pocono Manor, Pennsylvania, October 26–28, 1959, publication 756 of the Nat'l Research Council of the Nat'l Acad. of Sci.

[2] W. B. Westphal, "Techniques of Measuring the Permittivity and Permeability of Liquids and Solids in the Frequency Range 3 c/s to 50 kMc/s," M.I.T. Laboratory for Insulation, Cambridge, Mass., Res. Tech. Rept. No. 36; 1950.

[3] E. S. Hotston, "Correction term for dielectric measurements with cavity resonators," *J. of Sci. Instr.*, vol. 38, pp. 130–131; April, 1961.

Correction for Gap Around a Disk Sample

The complex propagation constant γ in the section of transmission line containing the sample is obtained from appropriate measurements and calculations and then the relative permittivity $k=\epsilon/\epsilon_0$, which may be complex to indicate losses, is obtained from

$$(\omega/c)^2 k = \gamma^2 + k_c^2, \qquad (1)$$

where k_c is the characteristic or cutoff wave number for the mode and cross section of the line.

Based on perturbation theory[4,5] the change in the propagation constant of a TE or TEM line, due to an airgap between the dielectric cylinder and the cylindrical wall, is

$$\gamma_{\text{gap}}^2 - \gamma_{\text{no gap}}^2 = \Delta(\gamma^2) = (k-1)\left(\frac{\omega}{c}\right)^2 \frac{\int_{\text{gap}} \boldsymbol{E}_1 \cdot \boldsymbol{E}_2 dS}{\int_S |\boldsymbol{E}_1|^2 dS}, \qquad (2)$$

where $\boldsymbol{E}_1$ is the electric field of the dielectric filled line with no gap, $\boldsymbol{E}_2$ is the electric field with an airgap present, S is the cross section of the line and dS is an element of S. When k is complex the change in γ is complex, and a loss correction is obtained concomitantly.

For a first-order theory the normal (n) and tangential (t) components of E_2 are obtained from E_1 by satisfying boundary conditions at the dielectric interface. These require that $E_{2,n}=k'E_{1,n}$ and $E_{2,t}=E_{1,t}$, where k' is the real part of k. Using these components in (2)

$$\Delta(\gamma^2) = (k-1)(\omega/c)^2 \frac{\int_{\text{gap}} \{k'|E_{1,n}|^2 + |E_{1,t}|^2\} dS}{\int_S |E_1|^2 dS}. \qquad (3)$$

The second term becomes appreciable only for large gaps because E_t vanishes at the conducting wall. Very large gaps are only practicable when using the TE_{0m} modes, in which case the usually predominant term in E_n vanishes; a case already treated.[3] From (1) and (3), the error in a measurement of permittivity k due to an airgap is

$$\Delta k = -(k-1)\frac{\int_{\text{gap}} \{k'|E_{1,n}|^2 + |E_{1,t}|^2\} dS}{\int_S |E_1|^2 dS}. \qquad (4)$$

[4] H. A. Bethe and J. Schwinger, "Perturbation theory for cavities," NDRC, Washington, D. C., Rept. No. DI-117; 1943.
[5] The general method is described by E. L. Ginzton in "Microwave Measurements," McGraw-Hill Book Co., Inc., New York, N. Y., ch. 10; 1957.

TABLE II
Comparison of Loss Tangent Measurements on Rods and Disks

Material	Rod (TE_{011})	Disk
Glass	53×10^{-4}	56* $\times10^{-4}$
Glass	53	56
Glass ceramic	2.4	3.8
Glass ceramic	2.7	3.5
Glass ceramic	2.4	3.6
Al_2O_3 porcelain	9.7 ± 0.2	9.7 ± 0.2†

* Slotted line, except last sample.
† Disk in TE_{113} resonator at room temperature.

TABLE III
Measurement of a Plastic Sample Before and After a Reduction in Diameter to Illustrate the Effect of an Airgap. The Transmission Line Diameter Was 1.0029 Inches

Diameter	k' Uncorrected	k' Corrected	$\tan\delta\times10^4$ Uncorrected	$\tan\delta\times10^4$ Corrected
1.0028	2.5330	2.5332	5.72	5.72
0.9808	2.4694	2.5364	5.17	5.26
0.9601	2.4188	2.5412	5.46	5.65
0.9186	2.3588	2.5525	5.68	6.03
0.8505	2.2085	2.5478	5.27	5.94

TABLE IV
Loss Tangent $\times10^4$ Measured at 9200 Mc vs Temperature and Humidity Variations

Material	4 Per Cent R.H. 24°C	31.5 Per Cent R.H. 35°C	48 Per Cent R.H. 23°C	83 Per Cent R.H. 24°C	Unclean surface 83 Per Cent R.H. 24°C
Glass ceramic	2.2	2.3	2.2	2.5	3.6
Glass ceramic	2.2	2.3	2.3	2.6	3.3
Glass ceramic	2.2	2.3	2.2	2.6	4.3
Glass ceramic	2.2	2.3	2.2	2.5	3.5
Glass	53	52	53	53	55
Glass	53	52	53	53	54
Glass	53	52	53	54	55

TABLE V
Complex Permittivity of Al_2O_3 Ceramic vs Temperature

Temperature °C	Dielectric Constant	Loss Tangent $\times10^4$
23	8.81	9.9
308	9.32	11
505	9.71	14
813	10.58	34

For comparison see M.I.T. Tables.[6]

[6] "Tables of Dielectric Materials," M.I.T. Laboratory for Insulation Research, Cambridge, Mass., Tech. Rept. No. 119, vol. V, p. 40; 1957.

Eq. (4) was applied to a TEM coaxial transmission line and a TE_{01} rectangular line and it agreed with the usual correction[2] for these modes when the gap was small. Eq. (4) may be applied to the important case of a circular TE_{11} transmission line for which no correction for fit was previously available. For a sample with radius $b-\Delta b$ in a waveguide of radius b,

$$\Delta k' = -k'(k'-1)(0.8368)\Delta b/b. \qquad (5)$$

This equation was used to correct the results in Table I, as shown.

Experimental

The samples compared in Tables I and II were obtained as follows. Pairs of samples, a rod and a disk were cut side-by-side from the various corners of a glass and a glass-ceramic sheet about 12 inches square. Samples from the same batch of Al_2O_3 porcelain were available in each shape, but were not pairs from side-by-side locations.

In order to estimate the size of the airgap that may be treated by (4) without too much error, measurements were made with larger airgaps. The results appear in Table III. The same sample was used throughout this experiment, its diameter being cut down in steps as indicated. It was carefully centered in the line to minimize mode conversion.

To determine the effects of temperature and humidity variations on the measured properties, the TE_{011} resonant cavity and samples were enclosed in a glove box where the temperature and humidity could be controlled. The results of these measurements appear in Table IV (loss variation); the real part to two decimal places did not vary.

The high temperature equipment uses the method of Fig. 1(b). A section of silver circular TE_{11} transmission line is closed with a second short circuit which contains a coupling iris, forming a TE_{113} cylindrical resonant cavity whose Q and resonant frequency yield the complex permittivity of the sample. The first measurements made with this system are reported in Table V.

Discussion

The 1723 glass appears to be quite homogeneous and isotropic, based on the results in Table I. It seems probable that the various systems are capable of measurements on k' to an accuracy of 0.3 per cent.

The results shown in Table II confirm the accuracy of the present loss tangent measurements to ± 10 per cent ± 0.0001. It is expected that future work will improve this accuracy.

Based on Table III we estimate that with large gaps, corrections of more than 4 or 5 per cent will leave inaccuracies of 1 per cent or more in the final results for k'. The results make it doubtful whether the imaginary part of (4) should be used. When there is a gap there may be extra mode-conversion losses that makes up for the missing sample material. The dielectric constant at 9200 Mc of these materials, for two decimal accuracy, is independent of temperature and relative humidity over the normal range of laboratory conditions. Relative humidity and surface contamination do alter the apparent loss, as shown in Table IV, presumably by lowering the surface resistivity of the sample. The magnitude of this effect should vary for different measuring systems which may concentrate the applied electric field at the surface of the sample to varying degrees. It does appear, however, that when measurements can be made at low relative humidity, say below 30 per cent humidity, corrections are unnecessary.

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