Permittivity and Permeability Measurements Using Stripline Resonator Cavities—A Comparison

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***Abstract*—The permittivity and permeability of five materials were measured during a comparison of the stripline resonator cavity technique. The National Institute of Standards and Technology (NIST) organized this intercomparison in which a total of seven organizations participated. Each participant measured two dielectric materials and three magnetic materials. Results for this comparison suggest that when the stripline resonator is used, dielectric property measurements are not as accurate as magnetic property measurements, provided that a correction for demagnetization is made. The results are compared to 7 mm coaxial transmission line measurements which have an uncertainty of less than 10% for the relative permittivity, $\epsilon_r' < 15$.**

***Index Terms*— Dielectric materials, ferrites, intercomparison, measurements, permeability, permittivity, stripline resonator.**

I. Introduction

The stripline resonator cavity is illustrated in Fig. 1. It consists of a center-strip conductor mounted equidistantly between two ground planes and terminated by two end plates. Fig. 1 also shows the locations for the material specimen under test required for measurements of complex permittivity $\epsilon_r^* = \epsilon_r' - j\epsilon_r''$ (axial mid-point) and complex permeability $\mu_r^* = \mu_r' - j\mu_r''$ (adjacent to the end plate). Stripline cavities are used primarily for microwave measurements of magnetic materials. Typical samples include sheet stock, thin films, and substrates. Stripline cavities are used because sample geometries are compatible with those of the cavity, thus requiring little or no machining of the sample, and because circuit connections need not be broken to insert or remove a sample from the cavity.

A comparison among seven organizations, including NIST, was initiated to determine the uncertainty of complex permittivity and permeability measurements being provided by industry. The frequency range of interest is from 50 MHz to 5 GHz. Two dielectric samples having low and medium loss and three samples having magnetic properties that vary significantly over this frequency range were selected.

Five commercially supplied specimens were distributed to the participants. The manufacturer's specified values of the permittivity and permeability were disclosed to the participants at the beginning of the comparison and are summarized here in Table I. A measurement data sheet was supplied with each specimen to record sample dimensions, measurement results, and methods of measurement correction. Any details of the correction were given by the participants at their discretion and will briefly be discussed in the Section IV. After completion of the comparison, participants were mailed graphs of the results and were told the letter code of their results only. To maintain their anonymity for this publication, each organization has been designated with a number code (1–6). Table II matches symbol types with organizational number codes.

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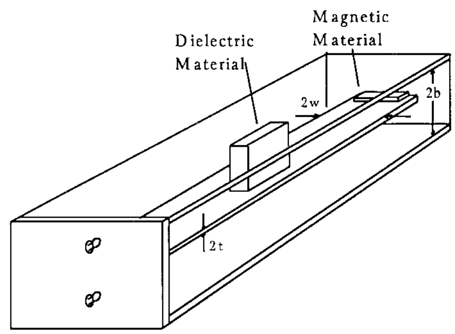

Fig. 1. Stripline cavity showing required specimen locations for measurement of complex permittivity (axial mid-point) and complex permeability (adjacent to end plate).

TABLE I
Material Composition, Permittivity and Permeability Data of Comparison Materials. Permeability Data From Measurements Made in 7 mm Coaxial Transmission Line at 500 MHz. Permittivity Data Provided by Supplier @ 9.4 GHz

Material	Composition	ϵ_r'	$\tan\delta$	μ_r'	μ_r''
A	Cross-linked Polystyrene	2.53	0.001	--	--
B	Ceramic	9.34	0.0001	--	--
C	Ferrite-Loaded Polymer*	15.80	0.125	4.04	0.426
D	Nickel Ferrite	9.28	0.00125	4.39	0.308
E	Yttrium Iron Garnet	14.82	0.0001	2.02	10.126

*Measurement data from coaxial transmission line data @ 500 MHz.

II. Comparison Specimens

Comparison specimens were chosen from a list of possible reference materials being studied by NIST for use as standards. The chosen materials were measured using other techniques so that results can be verified. Because of the manufacturing process, variations between batches are a fundamental problem and are most often observed in magnetic materials. Because of these variations, a record of batch number and recipient was carefully kept before samples were sent. Small differences seen between participant data may be partially attributed to these batch-to-batch variations. Participants received bulk

TABLE II
LEGEND KEY GIVING PARTICIPANT CODES AND SYMBOL TYPES

Participant Code	Symbol Type
1	★
2	▲
3	■
4-large cavity	◆
4-small cavity	●
4-large sample	◇
4 small sample	○
5	▲
6	■
NIST 7 mm	×

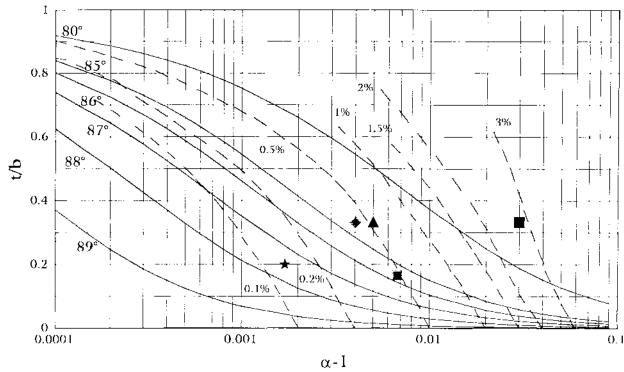

Fig. 2. t/b as a function of α with β as a parameter. β is the sine of the angle given. The dashed curves give the inherent uncertainty in a cavity measurement.

samples and had them machined to fit the dimensions of their particular resonators and as necessary for their correction algorithms. NIST machined 7 mm coaxial specimens from these same batches. A coordinate measuring machine (CMM) with ± 0.0015 mm measurement uncertainty was used to measure specimen diameters so that an accurate gap correction could be made [1]. From knowledge of the relationship between transmission line measurements and our 60 mm cylindrical resonant cavity [2], we can determine the accuracy of the comparison results.

III. MEASUREMENT CONSIDERATIONS

A. Depolarization

In a stripline resonator, an electric field is generated between the center conductor and outer conductor. When a sample is inserted into this region, a discontinuity of the electric field may occur if there are air gaps between the specimen and either conductor. This effect is known as depolarization and results in a smaller measured value of the permittivity than would be measured if the sample filled the space. To reduce this effect, most participants in this comparison machined their sample to achieve a tight fit between the conductors. However, errors in the measurement may result if the sample is too large and distorts the parallel nature of the cavity. Other error mitigation techniques include applying conductive pastes to the ends of the sample to maintain electric field continuity. One participant used shims (small sample pieces) in the gap(s) to decrease the effect of depolarization.

B. Demagnetization

Another error source, demagnetization, occurs when a specimen does not surround the center conductor and creates a discontinuity in the magnetic field, causing a lower measured value of permeability. For magnetic materials, the measurement can be as much as six times lower than expected. There are several theories in the literature used to correct for this effect. One commonly used theory to calculate the demagnetization factor is that given by Osborn [3] based on an ellipsoid within a magnetic field. Since most samples inserted into the cavity are rectangular, the model is only approximate. Another approach is given by Stoner [4] and/or Becker [5], and a final reference for these correction factors is that given by Browning and Westbrook [6]. Once the demagnetization factors have been calculated, the theory developed by Waldron and Maxwell, [7] and Musal [8] is used to obtain the final value of permeability. Most participants used some form of correction based on an ellipsoidal model. One participant, however, used antenna measurements and two different specimen sizes to calculate the demagnetization correction.

C. Algorithms for Data Reduction

The algorithms for data reduction require the resonant frequency shift and change in quality factor upon insertion of the sample [9]–[12]. Because these equations are based on perturbation theory [13] and not exact analytical formulas, samples must be made small so that the fields inside the cavity are not overperturbed. If overperturbation occurs, fields that radiate from the open sides of the resonator will decrease the quality factor and thus increase the apparent loss in the sample. Another important factor is uniformity of the fields across the thickness of the sample. The uniformity of the fields is dependent upon the width of the center conductor and the separation between the ground plane and center conductor [9].

IV. COMPARISON RESULTS

The cavity design is based on a conformal mapping, as described by Waldron [9]. Approximations must be made in this mapping which causes inherent uncertainties in the measurement results. For a well-designed cavity these uncertainties will be small. One can minimize these inherent uncertainties by use of Figs. 2 and 3 [9]. The dashed lines show the inherent uncertainty associated with each measurement. The thickness t and width w of the center conductor and the separation b between the ground plane and center conductor are related to the parameters α and β from the mapping (see Fig. 1). Included on these graphs are points showing where participants 1, 2, 3, and 6 chose to design their resonator and Table III provides a summary of all the participants' dimensions. Only participants 3 and 6 supplied values for α, so the points on the graph are exact. By working backward, we could approximately determine α and β from the values of t, w, and

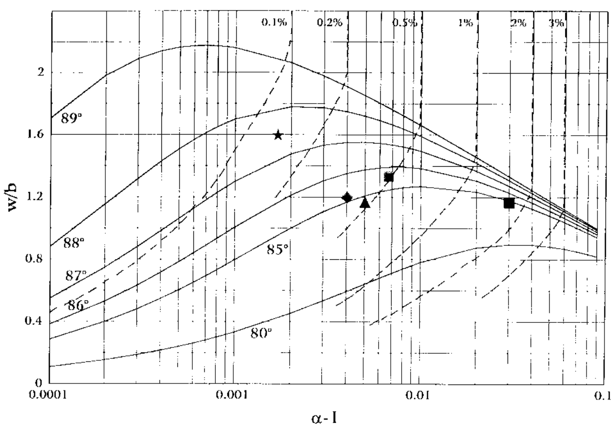

Fig. 3. w/b as a function of α with β as a parameter. β is the sine of the angle given. The dashed curves give the inherent uncertainty in a cavity measurement.

TABLE III
RESONATOR DIMENSIONS FOR INTERCOMPARISON PARTICIPANTS

Participant	t/b	w/b	α	$\sin^{-1}\beta$	A
1	0.2000	1.596	1.0017	87.5°	0.232
2	0.2222	2.222			
3	0.1667	1.333	1.0067	85.6°	0.265
4-large cavity	0.3333	1.200	-		0.289
4-small cavity	0.3333	1.000	–	–	0.320
5	0.3333	1.167	1.0050	84.0°	0.308
6	0.3333	1.167	1.0300	77.5°, 85°	0.292

b for the other participants. Dimensions given by participants 4 and 5 did not correspond to any one value of α and β, so this information is left blank for participant 4 and a value for participant 5 is inferred. If we look at participant 6 on the graph, we see that their values $t/b, w/b$, and α correspond to two different values of β, two different uncertainty bounds, and two different values of A (a geometrical constant). If these results were used in the equations [9],

$$A = \frac{\pi\alpha}{2(\alpha+\beta)K(1/\alpha)}\sqrt{\frac{\alpha^2-\beta^2}{\alpha^2-1}} \tag{1}$$

$$\frac{\delta\omega}{\omega} + \frac{j}{2}\left[\frac{1}{Q_1} - \frac{1}{Q_0}\right] = -A(\epsilon^* - 1)\frac{2yl_1}{bl_0} \tag{2}$$

then there would be a large uncertainty in ϵ^*. In (1) and (2), $\epsilon^* = \epsilon' - \epsilon''; K(1/\alpha)$ is the complete elliptic integral of the first kind with modulus $1/\alpha$; the dimensions of the sample are y, l_1, and $l_0; \delta\omega/\omega$ is the frequency shift with respect to the resonant frequency; and $1/Q_1 - 1/Q_0$ is the change in inverse quality factor of the resonator upon insertion of a sample. From a design standpoint, α, β, and the inherent uncertainty of the cavity should be the same in both graphs. For participant 6, we could do the following: choose values of α and the inherent uncertainty, for instance $\alpha = 1.03$, uncertainty = 2%. Next choose a value for t/b or β, for instance $\beta = \sin(85°)$, which then leads to values of t/b and w/b, or vary β until t/b becomes 0.3333 and determine a value for w/b. The

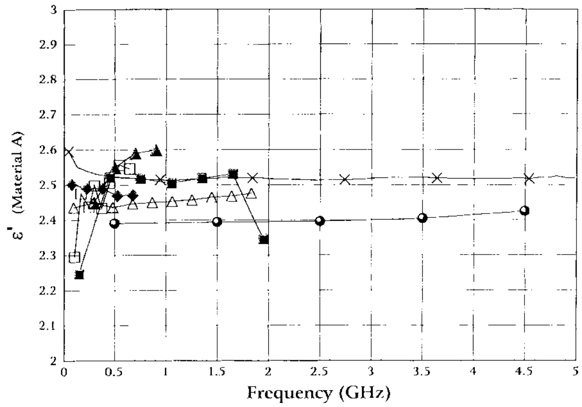

Fig. 4. Measured relative permittivity (ϵ_r') of material A, cross-linked polystyrene.

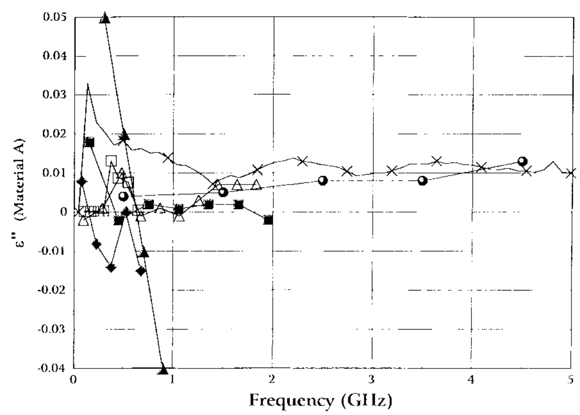

Fig. 5. Measured loss factor (ϵ_r'') of material A, cross-linked polystyrene.

most desirable choice is to choose an uncertainty, for instance <0.2%, as participant 1 did and then choose α and β close to 1, which will then automatically determine t/b and w/b and give the most accurate results. The main point in this discussion is that in the design will be an underlying uncertainty and nothing can be done to correct this uncertainty source after the stripline has been designed. Further, if dimensions are chosen inconsistently with Figs. 2 and 3, the uncertainty will not be defined. Other possible sources of uncertainty are discussed later.

Measurement results from the participating organizations are shown in Figs. 4–13. Figs. 4–7 show results of the dielectric materials, cross-linked polystyrene and the ceramic. The last six graphs are measurements of the permeability of the magnetic materials. Coaxial transmission line measurements are shown as $\times$'s. Figs. 4 and 5 show the real and imaginary parts of the permittivity of cross-linked polystyrene. Results from all participants fall within ±5% of the accepted values as given by von Hippel [14], $\epsilon_r' = 2.55$ @ 100 MHz for the real part of permittivity and $\epsilon_r'' = 0.000\,38$ @ 100 MHz for the imaginary part of permittivity. Although the values quoted in Table I are quoted at a frequency of 9.4 GHz, these values will be within 1% of those at 100 MHz for low-loss materials such as specimens A, B, D, E as verified by previous measurements.

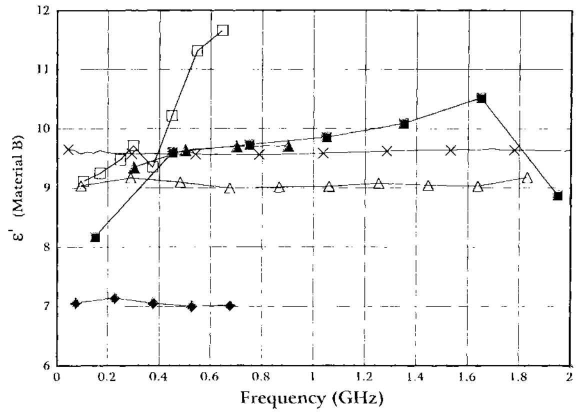

Fig. 6. Measured relative permittivity (ϵ_r') of material B, ceramic.

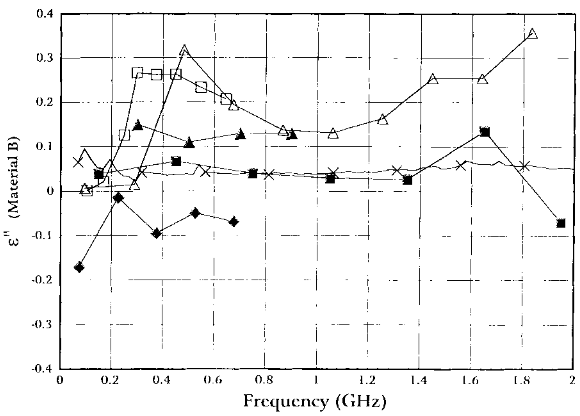

Fig. 7. Measured loss factor (ϵ_r'') of material B, ceramic.

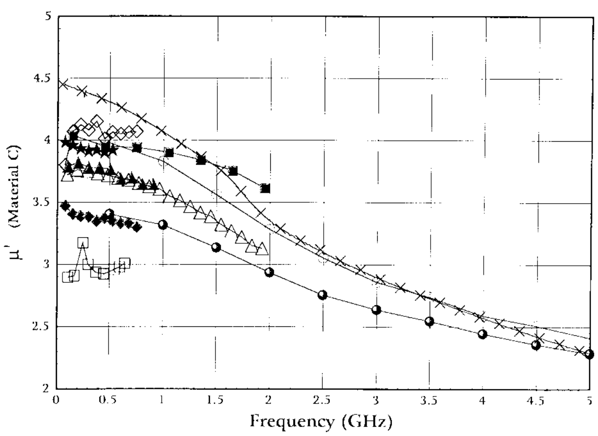

Fig. 8. Measured relative permeability (μ_r') for material C, ferrite-loaded polymer.

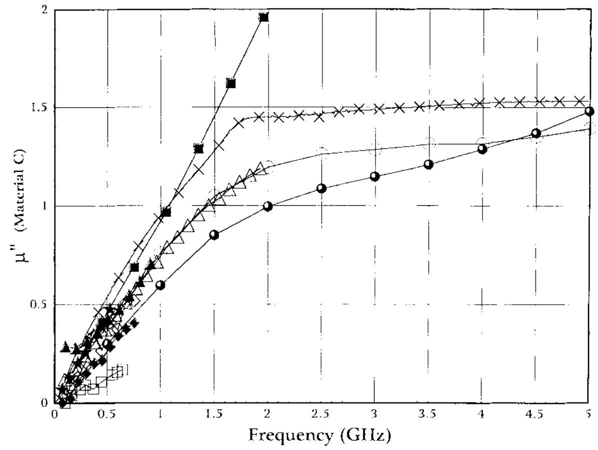

Fig. 9. Measured magnetic loss factor (μ_r'') for material C, ferrite-loaded polymer.

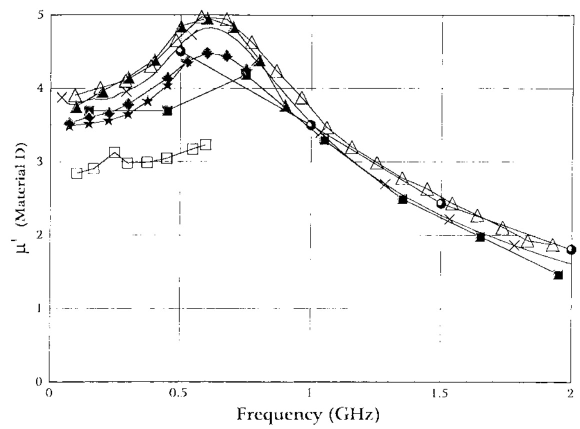

Fig. 10. Measured relative permeability (μ_r') for material D, nickel ferrite.

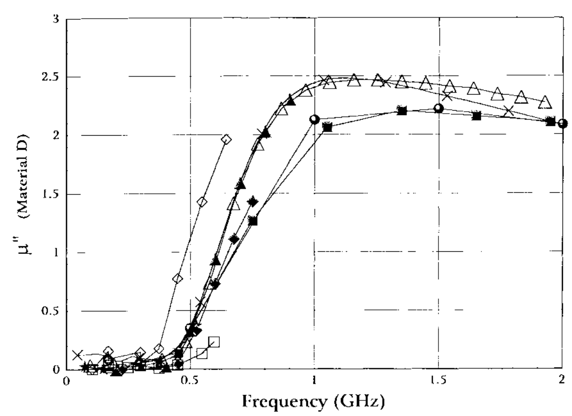

Fig. 11. Measured magnetic loss factor (μ_r'') for material D, nickel ferrite.

Participants measuring lower values could have an air gap between the sample and the conductor(s). An explanation for the variability in ϵ_r'' is radiation from the open sides of the resonator. This radiation is thought to be the result of placing a sample on only one side of the center conductor thus creating an asymmetrical field distribution. As a test of this hypothesis, participant 3 used two samples, one on either side of the center conductor, and, did in fact, obtain values that were closer to the accepted value. Participant 2 uses doors on the open sides of their resonator to minimize leakage of these fields. Some results show a negative value for ϵ_r'', which could be the result of an overperturbation of the fields because the sample was too large.

Figs. 6 and 7 show measurement results for the ceramic material. One participant's measurement for the real part of permittivity was much lower than the other measurements. This again could be the result of an air gap; as we increase

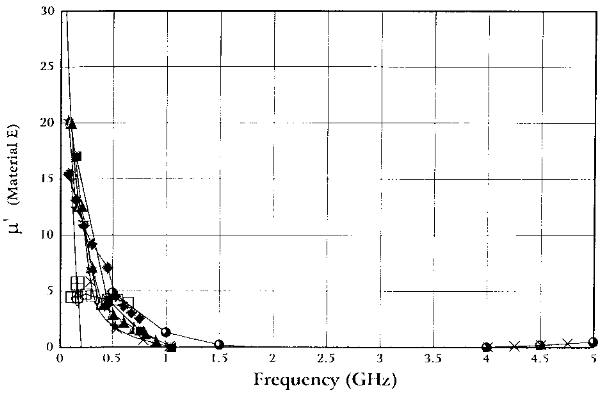

Fig. 12. Measured relative permeability (μ_r') for material E, yttrium iron garnet.

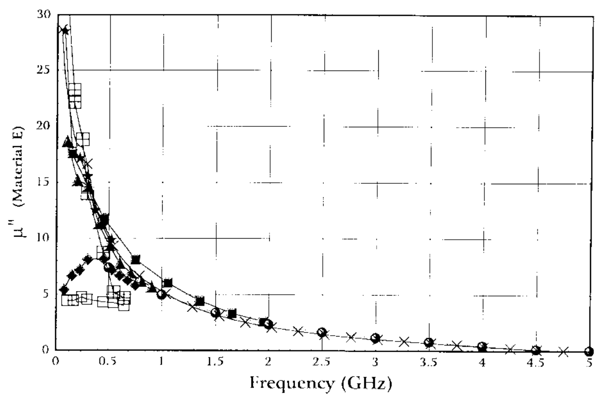

Fig. 13. Measured magnetic loss factor (μ_r'') for material E, yttrium iron garnet.

the value of permittivity, the uncertainties in the measurement also increase. If a conductive paste is applied or the sample is machined very accurately, then we can minimize the effect of air gaps. Permittivity results for the stripline comparison are similar to those in the 7 mm coaxial transmission line round robin [1]. Measurements of the imaginary part of the permittivity have higher uncertainties for the stripline than for the coaxial transmission line, most likely because of radiation leakage.

Fig. 8 shows measurements of the real part of permeability for a ferrite-loaded polymer, and Fig. 9 for the imaginary part of permeability. The results vary by more than ±10% at the lower frequencies. Participant 4 has measured samples of two different sizes in both a large and small cavity. The diamonds show measurements made in the larger cavity, and the circles show measurements made in the smaller cavity. For the smaller sample, the results approach those of the 7 mm coaxial transmission line. The coaxial line has greater accuracy because no demagnetization of the sample occurs. This indicates that the variability in the measurements can be partially attributed to demagnetization. For large samples, the effect of demagnetization is greater than for small samples, and measured results will be lower than expected unless a demagnetization correction is made.

Magnetic materials often display unique properties in the microwave region. Figs. 10 and 11 show measurements of a nickel ferrite that exhibits interesting properties over a very narrow bandwidth. Participants 3 and 4 have resonators with discrete frequencies spaced far enough apart that this narrowband frequency behavior could have been overlooked.

Finally, Figs. 12 and 13 show the results for a lossy magnetic material. Most participants agree within ±10% except participants 4 and 5. This is especially apparent in Fig. 13. These two participants did not correct for demagnetization and thus their measurements were in error by as much as a factor of 6. Both participants have recently received information on demagnetization corrections and corrected data for participant 5 are shown by the plus sign inside the square symbol. Although these measurements still appear to have large uncertainties (possibly due to design uncertainties), they show the importance of the demagnetization correction.

V. Conclusions

For the dielectric materials considered, the spread of the permittivity values obtained using data from different stripline resonators are typically within ±15%. Considering the various uncertainty sources for these measurements, the uncertainty in permittivity using the NIST stripline resonator is expected to be within ±10%. This estimated uncertainty is determined from the uncertainties due to the conformal mapping, the quality factor, the dimensions of the specimen and others [15], [16]. For example, design of the cavity can be a fundamental uncertainty source if dimensions are not carefully chosen. The real part of the permittivity will have uncertainties due to the discontinuity of the electric field that can exist between the specimen and the conductors and the imaginary part will include uncertainties due to the fields that radiate from the cavity. The uncertainty of permeability measurements can be about ±5% if the demagnetization correction is taken into account. The size and shape of the specimen can reduce some of these effects, but a correction must always be made because the sample does not surround the center conductor. If magnetic measurements are made in the stripline, the resonant frequencies must be close enough together that important details of the frequency spectrum are not omitted. Other possible sources of uncertainty include coupling corrections and losses due to the metal surfaces. The sources of uncertainty and their contributions to overall error budgets for permittivity, permeability and loss tangents continue to be studied.

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