A Simple Method for Accurate Loss Tangent Measurement of Dielectrics Using a Microwave Resonant Cavity

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***Abstract*—A simple yet rigorous method has been developed to enable the loss tangent of dielectrics, having a known relative permittivity, to be accurately measured using a waveguide resonant cavity. The novel method eliminates the need for any physical measurement, either on the cavity or dielectric sample under test. The only electrical parameters that need to be measured are resonant frequencies and Q-factors of a reference cavity and those of the same cavity loaded with the dielectric sample. One of the advantages of the new technique is that dielectrics, of arbitrary shape, can be characterized at very high microwave frequencies. The new method has been verified through measurement over X-band.**

***Index Terms*—Dielectric constant, loss tangent, microwave measurement, perturbation method, resonant cavity.**

I. Introduction

The RAPID development of wireless communication has generated significant interest in the accurate characterization of dielectric materials for use in high frequency components, microwave integrated circuits (MICs) and multichip modules (MCMs) [1]–[4]. The two properties of the dielectric materials that are of particular concern to microwave designers are the relative permittivity and loss tangent. For low loss dielectric materials, the former is almost independent of frequency and relatively easy to measure while the latter is dependent on the frequency and somewhat more difficult to measure. Of the available methods for loss tangent measurement, the resonant cavity technique is probably the most accurate [5].

In the study reported in this letter, the well-known cavity perturbation method has been extended for the measurement of loss tangent in situations where the dielectric constant of the dielectric material under investigation is already known. It has been shown, theoretically, that for this situation, the loss tangent of the dielectrics can be obtained without the need for either the calculation of the electromagnetic field pattern inside the cavity, or physical measurement on the cavity and the dielectric sample. This greatly simplifies the theoretical formula and leads to an increase in the accuracy of the measurement.

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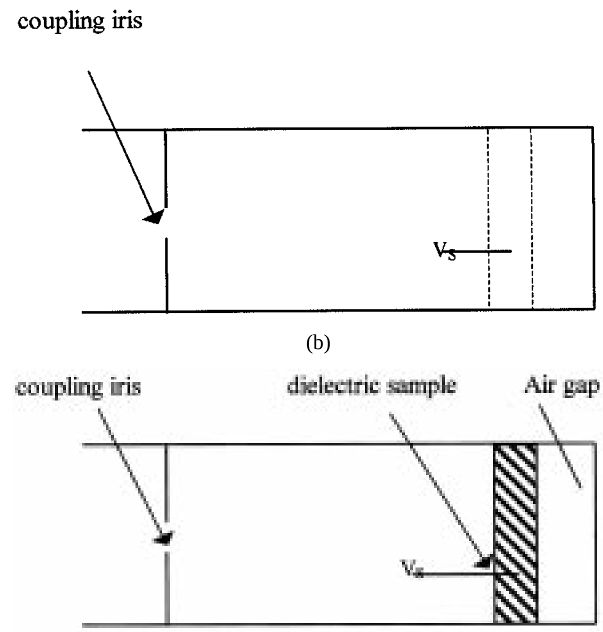

Fig. 1. Configuration of resonant cavity for loss tangent measurement. (a) Empty cavity (reference cavity). (b) Cavity loaded with dielectric sample (perturbed cavity).

II. Theory

Fig. 1 shows the empty cavity (reference cavity) and cavity with sample under test (perturbed cavity). According to cavity perturbation theory [5], we obtain

$$2\left(\frac{f_{r1}-f_{r2}}{f_{r2}}\right)+j\left(\frac{1}{Q_{L1}}-\frac{1}{Q_{L2}}\right)=\frac{\int_{V_S}(\varepsilon_r-1)\mathbf{E}_1\cdot\mathbf{E}_2\,dV}{\int_{V_C}|\mathbf{E}_1|^2\,dV} \tag{1}$$

where f_{r1}, Q_{L1}, $\mathbf{E}_1$ and f_{r2}, Q_{L2}, $\mathbf{E}_2$ are resonant frequencies, loaded Q-factors and electric field strength for the reference cavity and perturbed cavity respectively, ε_r is the complex relative permittivity for the dielectric material under test, V_S is the volume occupied by the sample, as indicated in Fig. 1, and V_C is the total volume of the reference cavity. After rearrangement, (1) can be expressed as

$$\varepsilon_r=\frac{2}{\Gamma}\left(\frac{f_{r1}-f_{r2}}{f_{r2}}\right)+1-j\frac{1}{\Gamma}\left(\frac{1}{Q_{L2}}-\frac{1}{Q_{L1}}\right)=\varepsilon'-j\varepsilon''. \tag{2}$$

Thus the loss tangent is

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\frac{1}{\Gamma}\left(\frac{1}{Q_{L2}} - \frac{1}{Q_{L1}}\right)}{\frac{2}{\Gamma}\left(\frac{f_{r1} - f_{r2}}{f_{r2}}\right) + 1} \quad (3)$$

where

$$\Gamma = \frac{\int_{V_S} \mathbf{E}_1 \cdot \mathbf{E}_2 \, dV}{\int_{V_C} |\mathbf{E}_1|^2 \, dV}. \quad (4)$$

If the dielectric constant, i.e., the real part of ε_r in (2) is unknown, the electric field distribution in the reference cavity has to be calculated to find Γ in (4). This will necessitate the accurate data for the geometric size of both the cavity and the dielectric sample under test. If the value of the dielectric constant, ε', is known, then Γ can be obtained directly from (2) as

$$\Gamma = \frac{2}{(\varepsilon' - 1)}\left(\frac{f_{r1} - f_{r2}}{f_{r2}}\right). \quad (5)$$

Therefore, (3) can be rewritten as

$$\tan\delta = \frac{(\varepsilon' - 1)}{2\varepsilon'} \frac{f_{r2}}{(f_{r1} - f_{r2})}\left(\frac{1}{Q_{L2}} - \frac{1}{Q_{L1}}\right). \quad (6)$$

Equation (6) shows that only the resonant frequencies and loaded Q-factors of the reference cavity and perturbed cavity need to be measured. Actually the physical information for the cavity and dielectric sample have already been reflected in the change of the resonant frequencies.

III. Experimental Results and Discussion

In order to demonstrate the new technique, tests were made on two materials: 1) standard 99.6% alumina and 2) a new printed dielectric from Heraeus, Inc. The samples under test were cut to size and positioned in waveguide test cavity as shown in Fig. 1. The resonant cavity was formed from X-band (8–12 GHz) rectangular copper waveguide. The details of cavity length, sample loading position and the diameter of the coupling iris are given in Table I. The precise size of the coupling iris is not critical but it should be chosen to be in the region that gives a high loaded Q-factor (typically around 2000 for empty cavity). The diameters of the coupling iris in Table I are determined experimentally. The air gap between the sample and the cavity end is needed to create sufficient perturbation to the cavity. On the other hand, the air gap should be in a range where the change of resonant frequency due to perturbation is less than 1% to ensure the validity of the cavity perturbation approach. Also shown in this table are the resonant frequencies at which measurements were performed. The physical data in Table I is provided for interest, but it is a feature of the present method that none of these data are required for the calculation of the loss tangent following the microwave measurement.

The measurement procedure is, firstly, to measure the resonant frequency and Q-factor for the empty cavity and, secondly, to repeat these measurements with the cavity loaded with sample under test. After the two measurements the loss tangent of the dielectric sample can be easily obtained from (6).

TABLE I
SETUPS OF RESONANT CAVITIES FOR LOSS TANGENT MEASUREMENT

Frequency (GHz)	Cavity length (mm)	Iris diameter (mm)	Air gap (mm)
8.2	29.95	6	1.5
9.2	44.95	6	2
10.0	37.95	5.5	2
11.5	29.95	5.5	1.5

TABLE II
MEASURED LOSS TANGENT OF TWO DIELECTRIC MATERIALS

Frequency (GHz)	Alumina (99.6%)	Printed dielectrics
8.2	7.4×10^{-4}	5.8×10^{-3}
9.2	6.9×10^{-4}	5.5×10^{-3}
10.0	7.1×10^{-4}	5.6×10^{-3}
11.5	7.2×10^{-4}	5.6×10^{-3}

Table II shows the measured results for the two dielectric materials. The dielectric constant for alumina was taken as 9.8 and a value of 7.9 was used for the sample from Heraeus, Inc. Examination of the measured loss tangent values for alumina shows that the measured values consistently converge at around 7.1×10^{-4}. In previously published data for 96% alumina, the loss tangent increases by a factor of 3 from 3×10^{-4} to 9×10^{-4} when the frequency increases from 1 MHz to 10 GHz [6]. According to the data provided by Coors, the loss tangent of 99.6% alumina at 1 KHz and 1 MHz are 2×10^{-4} and 3×10^{-4} respectively. Although the loss tangent data for 99.6% alumina at high frequency region is not available from the manufacturer, it can be seen that the values obtained here are realistic. To confirm the validity of the new technique, we also carried out accurate physical measurements on the cavity and dielectric samples, and these physical data were used in the standard cavity technique given in [5] for loss tangent calculation. If the same raw measured data are used for the calculation of loss tangent, for both materials the loss tangent values resulting from the standard cavity technique are within 1% of the values obtained using the new technique. These results, using two materials of significantly different loss tangent, clearly confirm the validity of the new method. The overall accuracy of the loss tangent measurement using the new method is estimated to be better than 5%.

IV. Conclusions

A new technique has been established for accurately measuring the loss tangent of a dielectric material with known dielectric constant. The simplicity of the measurement, which results from not having to measure the physical parameters of the resonant cavity and dielectric sample, and not having to machine the test samples to accurately fit the cavity, makes it very powerful. Moreover, the new technique should be particularly useful for the accurate characterization of dielectric materials at very high microwave frequencies.

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