A NEW METHOD FOR MEASURING DIELECTRIC PROPERTIES OF MATERIAL MEDIA USING A MICROSTRIP CAVITY

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Abstract

A new method for non-destructive testing has been developed for measuring the dielectric constant and the dissipation factor of a slab-type material using a microstrip line cavity. The method has several advantages and yields accurate results with a simple procedure.

Introduction

In this paper, a new non-destructive method is developed for measuring the dielectric properties of slab-type materials. The method uses a simple and rapid substitution procedure that yields accurate results and has a number of advantages over currently available techniques. One begins by measuring the resonance frequency and the Q factor of a microstrip cavity (see Figure 1) with the reference material placed on top of the cavity (Figure 2a). The reference material may be conveniently taken to be the same as the substrate. Then, the reference material is replaced by the unknown dielectric material (Figure 2b), and the measurements for the resonance frequency and the Q factor are repeated. The two sets of data are then processed to derive the dielectric properties of the unknown material.

Theory

Before discussing the measurement procedure we present some basic formulas that relate the resonance frequency and the Q factor of the cavity to the relative permittivity ε and $\tan\delta$ of the unknown material. Under the quasi-TEM approximation, the attenuation and the phase constants of the microstrip line are given by $\alpha = \frac{1}{2}\left(\frac{R}{L} + \frac{G}{C}\right)\sqrt{LC}$, $\beta = 2\pi f\sqrt{LC}$, where f is the operating frequency, and R, L, G and C are the resistance, inductance, conductance and capacitance per unit length of the line, respectively. The resonance frequency and the Q factor of the microstrip line cavity are given by

$$f = \frac{n}{2\ell\sqrt{LC}}, \qquad \frac{2\pi f}{Q} = \frac{R}{L} + \frac{G}{C}, \qquad n = 1,2, \ldots$$

where ℓ is the length of the cavity. If the medium is non-magnetic and the line resistance R is caused by the loss in the conductors, L and R remain unchanged when the dielectric material loading the cavity is changed. Thus, one can write

$$\frac{f_2}{f_1} = \sqrt{\frac{C_1}{C_2}}, \qquad \frac{f_1}{Q_1} - \frac{f_2}{Q_2} = \frac{1}{2\pi}\left(\frac{G_1}{C_1} - \frac{G_2}{C_2}\right) \tag{1}$$

where the subscripts 1 and 2 designate the quantities for the cavities loaded with the reference material and with the unknown material, respectively.

Next, we present the necessary formulas for computing the line capacitance C and the line conductance G under the assumption $G \ll 2\pi fC$ which is valid for dielectric materials that have a low loss tangent $\tan\delta$. These formulas may be extended, if necessary, when this assumption is no longer valid.

For a lossless medium the line capacitance of the microstrip line structure shown in Figure 2b can be expressed in a variational form using a procedure given in Yamashita and Mittra[1] and Yamashita.[2]

The expression reads

$$\frac{1}{C_2} = \frac{1}{2\pi Q^2} \cdot \int_{-\infty}^{\infty} \frac{[1+\varepsilon_2\coth(\beta t_2)]\tilde{\rho}^2(\beta)\, d\beta}{\beta\{\varepsilon_2[\varepsilon_2+\coth(\beta t_2)]+\varepsilon_1\coth(\beta d)[1+\varepsilon_2\coth(\beta t_2)]\}} \tag{2}$$

where Q is the total charge and $\rho(\beta)$ is the Fourier transform of the charge distribution on the strip.

The following choice of $\tilde{\rho}(\beta)$ is known to give good results for C_2:

$$\frac{\tilde{\rho}(\beta)}{Q} = \frac{8}{5}\left[\frac{\sin(\beta w/2)}{\beta w/2}\right] + \frac{12}{5(\beta w/2)^2} \cdot \left[\cos(\beta w/2) - \frac{2\sin(\beta w/2)}{\beta w/2} + \frac{\sin^2(\beta w/4)}{(\beta w/4)^2}\right]. \tag{3}$$

When a perturbation technique is used for the microstrip line filled with a medium that has a small loss ($\sigma \ll 2\pi f\varepsilon$), the following expression for the line conductance can be derived from (2):

$$\frac{G_2}{C_2^2} = \frac{1}{2\pi Q^2} \cdot \int_{-\infty}^{\infty} \frac{\{\sigma_2[2\varepsilon_2+(1+\varepsilon_2^2)\coth(\beta t_2)]+\sigma_1\coth(\beta d)[1+\coth(\beta t_2)]^2\}}{\beta\{\varepsilon_2[\varepsilon_2+\coth(\beta t_2)]+\varepsilon_1\coth(\beta d)[1+\varepsilon_2\coth(\beta t_2)]\}^2} \cdot \tilde{\rho}^2(\beta)\, d\beta \tag{4}$$

where σ_1 and σ_2 are the conductivities of the two dielectric media.

Measurement and Computation Procedure

The next step is to determine the unknowns ε_2 and σ_2 from the measured values of (f_1,Q_1) and (f_2,Q_2).

The measurement procedures consist of the following steps:

Step 1) The values of C_1 and G_1 are computed by evaluating the integrals in (2) and (4) with $\varepsilon_2 \to \varepsilon_1$, $\sigma_2 \to \sigma_1$, and $t_2 \to t_1$.

Step 2) f_1, Q_1 are measured for the situation where the cavity is loaded with the reference material (Figure 2a).

Step 3) f_2, Q_2 are measured for the cavity loaded with the unknown material (Figure 2b).

Step 4) C_2 and G_2 are computed by substituting the values of f_1, Q_1, f_2, Q_2, C_1 and G_1 into (1).

Step 5) The last step is to substitute the values of C_2 and G_2 computed in the step 4) into (2) and (4), and to solve the resulting equations for ε_2 and σ_2. Although closed-form solutions for these equations are not possible, the desired unknowns ε_2 and σ_2 are easily obtained with the aid of a computer by using a zero-seeking routine.

Results and Discussions

The method developed in this paper has several advantages. First, the experimental procedure is quite simple. In fact, once the microstrip cavity is constructed, all one has to do is to place the material to be measured on the cavity and measure the resonance frequency and the Q of the cavity. Another advantage is that it is not necessary in this method to separate the dielectric loss from the loss in conductors. It is only necessary to measure the total loss (or Q) in each of the measurement steps.

Table 1 shows some of the results for test measurements carried out with this method. The consistency of the procedure has been verified by employing several different cavities, and the reliability of the method has been confirmed experimentally. Some inconsistency is noted between the measured values of tan δ and those supplied by the manufacturer. Possibly, the insufficient accuracy of the measured Q values is one of the contributing factors.

To date the measurements have been done at the UHF range. It is planned to extend the measurements at the low microwave frequencies in the near future.

Conclusions

A new non-destructive method for measuring dielectric properties was presented. The method is simple and yields the results at microwave frequencies with reasonable accuracy.

References

1. E. Yamashita and R. Mittra, "Variational method for the analysis of microstrip lines," IEEE Trans. Microwave Theory and Techniques, vol. MTT-16, pp. 251-256, April 1968.

2. E. Yamashita, "Variational method for the analysis of microstrip-like transmission lines," IEEE Trans. Microwave Theory and Techniques, vol. MTT-16, pp. 529-535, August 1968.

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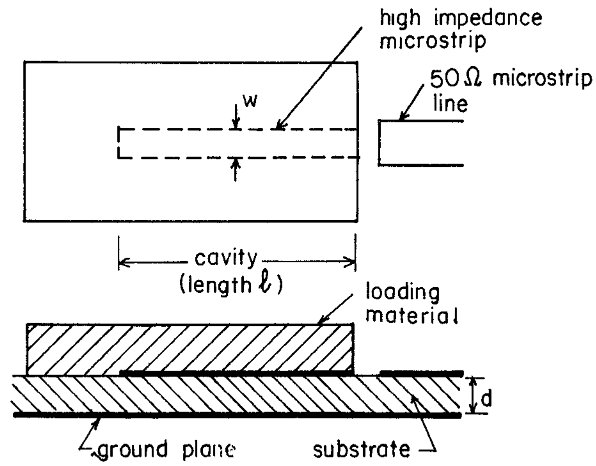

FIG. 1. TOP VIEW AND SIDE VIEW OF THE MICROSTRIP CAVITY

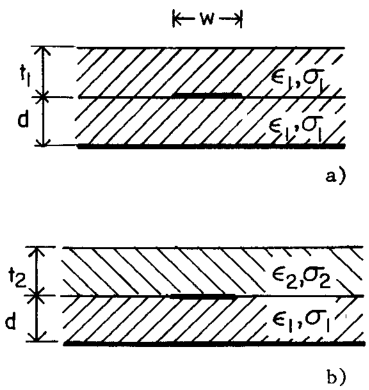

FIG. 2. CROSS-SECTION OF THE MICROSTRIP CAVITY LOADED WITH a) REFERENCE MATERIAL, b) UNKNOWN MATERIAL

Table 1. Test Results (300-500 MHz)

Cavity Structure†		Polystyrene* (7.64 mm thick)		Plexiglass** (5.92 mm thick)	
w(mm)	ℓ(mm)	ε_2	tan δ_2	ε_2	tan δ_2
1.77	210	2.55	0.0009	2.64	0.0073
2.92	210	2.54	0.0010	2.63	0.0059
1.77	185	2.55	0.0011	2.60	0.0042
2.92	185	2.56	0.0011	2.63	0.0068
1.77	160	2.58	0.0012	2.64	0.0067
2.92	160	2.56	0.0007	2.61	0.0066

† Substrate is the Rexolite 2200 with 1.59 mm thickness.
* Values supplied by the manufacturer $\varepsilon = 2.55$, tan $\delta = 0.0002$
** $\varepsilon = 2.68$, tan $\delta = 0.0057$