



CAVITY PERTURBATION MEASUREMENT OF COMPLEX PERMITTIVITY OF DIELECTRIC MATERIAL AT MICROWAVE FREQUENCIES

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Abstract: This paper presents dielectric constant and loss factor of dielectric materials using cavity perturbation technique in X-Band. In this technique, a rectangular cavity resonator is designed to load the sample under test. The values of S-parameters are measured experimentally by placing the sample in the center of the cavity resonator. Experimental measurements of shift in resonant frequency and Q-factor provide ϵ' and ϵ'' values. Accurate results are obtained using Teflon, Rubber & Plexiglass samples. An additional advantage of the technique is that it does not require any prior calibration with known standards.

Key words: Cavity perturbation Technique, Cavity resonator, complex permittivity, Dielectric Constant, Loss factor, Loss tangent

I. Introduction

The measurement of complex permittivity is required not only for scientific but also for industrial applications. It has found significant applications in recent microwave and radar tracking systems. Various resonance measurement techniques for measuring dielectric properties of material at microwave frequencies have been discussed by previous researcher [1-11]. These techniques are associated with design and fabrication of microwave devices (cavity resonators, waveguides etc). Therefore in present work an attempt is made to explore the existing knowledge of various resonance techniques and to develop a new resonance technique. In cavity perturbation technique the dielectric sample in the cavity causes only a perturbation on the field distribution in the metal cavity. In this technique the sample material is used to load a resonant cavity [8-9] and the complex permittivity is measured from the shift in resonant frequency (f_0) and quality factor (Q). We need to calculate Q values for the empty cavity and sample loaded cavity (Q_0 & Q_s). This approach is based on the perturbation theory, thus it requires the sample to be small enough so that field distribution inside the empty cavity changes slightly when the cavity is loaded. The cavity perturbation method is different from other methods and it is very sensitive. It involve approximations in their formulation which lead to acceptable results only under very restricted conditions: (i) The sample must be very small compared with the cavity itself so that a frequency shift which is small compared with the resonant frequency shift of the empty cavity is produced by the insertion of the sample. (ii) The cavity without and with sample must be very much alike. This measurement technique is very accurate and particularly beneficial in the determination of loss factor of very low loss materials.

A new rectangular cavity has been designed with very small slot at the center of broader side of the waveguide in order to insert a sample material. Presence of small dielectric sample in the perturbed cavity will cause shift of resonance frequency and a decrease of quality factor. Measuring resonance frequency & quality factor of empty cavity and then measuring the shift in resonance frequency & decrease in quality factor with the sample material placed at its center performs dielectric properties measurement. The dielectric constant is calculated from the shift in resonance frequency and the sample volume whereas the loss factor is calculated from quality factor with and without sample. The material under test is fabricated in the form of a cylinder and inserted into the center of the cavity. The measurement setup uses rectangular waveguide cavity resonator, Network Analyzer and PC. The complex permittivity of Teflon, Plexiglass and Rubber are measured at different resonant frequencies between 8 GHz to 12 GHz using cavity perturbation technique. Present cavity resonator shows its importance for quick measurement of dielectric properties for low loss materials by providing better results than the other methods.

II. Theoretical Analysis

Many researchers have reported theoretical analyses of cavity perturbation techniques. The measurements of ϵ and μ are performed by inserting a small, appropriately shaped sample into a cavity and determining the

properties of the sample from resultant change in the resonant frequency and loaded quality factor. The basic idea of the cavity perturbation is the change in the overall geometric configuration of the electromagnetic fields upon the insertion of a small sample must be small. Based on this assumption, a detailed derivation of the perturbation equation for the frequency shift upon the insertion of a sample into a cavity was given by Harrington [1].

When a small sample is inserted in a cavity which has an electric field E_0 and magnetic field H_0 in the unperturbed state, the fields in the interior of the object are E and H . For loss less sample, the variation of resonance frequency is given by [1,3] as

$$\frac{f_s - f_0}{f_s} = - \frac{\int (\Delta\epsilon E \cdot E_0^* + \Delta\mu H \cdot H_0^*) d\tau}{\int (\epsilon E \cdot E_0^* + \mu H \cdot H_0^*) d\tau} \quad (1)$$

where ϵ and μ are the permittivity and permeability of the medium in the unperturbed cavity, respectively. $d\tau$ is the elementary volume and $\Delta\epsilon$ and $\Delta\mu$ are the changes in the above equations due to the introduction of the sample in the cavity. Without affecting the generality of Maxwell's equations, the complex frequency shift due to lossy sample in the cavity is given by [3] as

$$\frac{-df^*}{f^*} = \frac{(\epsilon_r - 1)\epsilon_0 \int_{V_s} E \cdot E_0^* dv + (\mu_r - 1)\mu_0 \int_{V_s} H \cdot H_0^* dv}{\int_{V_s} (D_0 \cdot E_0^* + B_0 \cdot H_0^*) dv} \quad (2)$$

where df^* is the complex frequency shift because the permittivity of practical materials is a complex quantity, so the resonance frequency is also complex. B_0 , H_0 , D_0 and E_0 are the fields in the unperturbed cavity and E and H is the field in the interior of the sample [10].

In terms of energy, the numerator of equation (2) represents the energy stored in the sample and the denominator represents the total energy stored in the cavity. The total energy $W = W_e + W_m = 2 W_e = W_m$. Two assumptions are applied in equation (2). The fields in the empty part of the cavity are negligible changed by the insertion of the sample. The fields in the sample are uniform over its volume. Both of these assumptions can be considered valid if the sample is sufficiently small relative to the resonant wavelength. The negative sign in equation (2) indicates that by introducing the sample the resonance frequency is lowered. When a dielectric sample is inserted into the cavity resonator where the maximum perturbation occurs that is at the position of maximum electric field, only the first term in the numerator is significant, since a small change in ϵ' at a point of zero electric field or a small change in μ at a point of zero magnetic field does not change the resonance frequency. Therefore equation (2) can be reduced to

$$\frac{-df^*}{f} = \frac{(\epsilon_r - 1) \int_{V_s} E \cdot E_{0\max}^* dv}{2 \int_{V_s} |E|^2 dv} \quad (3)$$

III. Design and Fabrication of Cavity Resonator

A rectangular cavity resonator is designed and fabricated using standard WR-90 waveguide at X-band with inner dimension of 23 x 10 mm. Depending upon the modes to be propagate, the length has been taken. The fundamental mode is TE type with $10n$ where n is the number of half wavelength along the propagation direction. Two thin conducting sheets are used to close the two ends of the waveguide to form cavity resonator. The inductive coupling is provided with two symmetric holes of diameter 4 mm on these end sheets. The design specifications are given below.

Frequency Range: 8 GHz -12 GHz (X-band)

Cut of wavelength: 46 mm

Modes Propagates: 5 (TE₁₀₅, TE₁₀₆, TE₁₀₇, TE₁₀₈, TE₁₀₉)

Inner dimension of cavity: 23 x 10 x 140 mm³

Outer dimension of cavity: 25 x 12 x 140 mm³

Material used: Brass

Coupling hole: 4 mm

IV. Measurement of Dielectric Constant ϵ' and Loss Factor ϵ''

A sample of complex permittivity $\epsilon^* = \epsilon' - j\epsilon''$ is kept at the maximum electric field location of the cavity. The sample is taken, as cylinder with uniform cross sectional area ' s ' and length is greater than narrow dimension ' b '

so that it will occupy the entire narrow dimension of the cavity. After the introduction of the sample the empty resonant frequency and Q -factor alter, due to the change in the overall capacitance and conductance of the cavity. If f_0 and Q_0 are the resonance frequency and quality factor of the cavity without sample and f_s and Q_s all the corresponding parameters of the cavity loaded with the sample. The complex resonant frequency shift is related to measurable quantities by [2-3]

$$\frac{df^*}{f} = \frac{f_s^2 - f_0^2}{f_s^2} + \frac{j}{2} \left(\frac{1}{Q_s} - \frac{1}{Q_0} \right) \quad (4)$$

On equating real and imaginary parts of equation (3) and (4) we have

For real part:

$$\frac{-(f_s - f_0)}{f_s} = \frac{(\epsilon_r' - 1) \int_{V_s} \mathbf{E} \cdot \mathbf{E}_{0\max}^* d\mathbf{v}}{2 \int_{V_c} |\mathbf{E}_0|^2 d\mathbf{v}} \quad (5)$$

We may assume that $\mathbf{E} = \mathbf{E}_0$ and the value of $\mathbf{E}_0$ in the TE_{10n} mode is $\mathbf{E}_0 = E_{0\max} \sin(p\pi z/l) \sin(p\pi z/l)$ where a is the broader dimension of the wave guide and l is the length of the cavity. Integrating and rearranging the equation (5), we obtain

$$\begin{aligned} \frac{f_0^2 - f_s^2}{f_s^2} &= \frac{4V_s \epsilon_r'}{V_c} \\ \epsilon_r' &= \frac{V_c (f_0^2 - f_s^2)}{4V_s f_s^2} \end{aligned} \quad (6)$$

where V_c is volume of the cavity = $a \times b \times l$ (Dimensions of the cavity) and V_s is the volume of the sample = $\pi r^2 h$ (r is the radius and h is the length of the sample).

For Imaginary part:

$$\frac{1}{2} \left(\frac{1}{Q_s} - \frac{1}{Q_0} \right) = \frac{\epsilon_r'' \int_{V_s} \mathbf{E} \cdot \mathbf{E}_{0\max}^* d\mathbf{v}}{2 \int_{V_s} |\mathbf{E}|^2 d\mathbf{v}} \quad (7)$$

Integrating and rearranging the equation (7), we obtain

$$\begin{aligned} \left(\frac{1}{Q_s} - \frac{1}{Q_0} \right) \frac{f_0^2}{f_s^2} &= \frac{4V_s \epsilon_r''}{V_c} \\ \left(\frac{1}{Q_s} - \frac{1}{Q_0} \right) \frac{V_c f_0^2}{4V_s f_s^2} &= \epsilon_r'' \end{aligned} \quad (8)$$

where Q_s is the quality factor of cavity with sample and Q_0 is the quality factor without sample. The measured Q values (Q_0 & Q_s) of the cavity are calculated by the equation given below.

$$Q = \frac{f_{\text{resonant}}}{\Delta f_{3dB}} = \frac{f}{f_R(3dB) - f_L(3dB)}$$

Equation (6) and (8) are of the standard form for the expression for dielectric parameters using perturbation technique.

V. Experimental Set Up

The measurements are done at 8.46GHz, 9.15GHz, 9.96 GHz and 11.64 GHz frequencies. Fig. 1 shows the designed cavity resonator and experimental setup for the measurements.

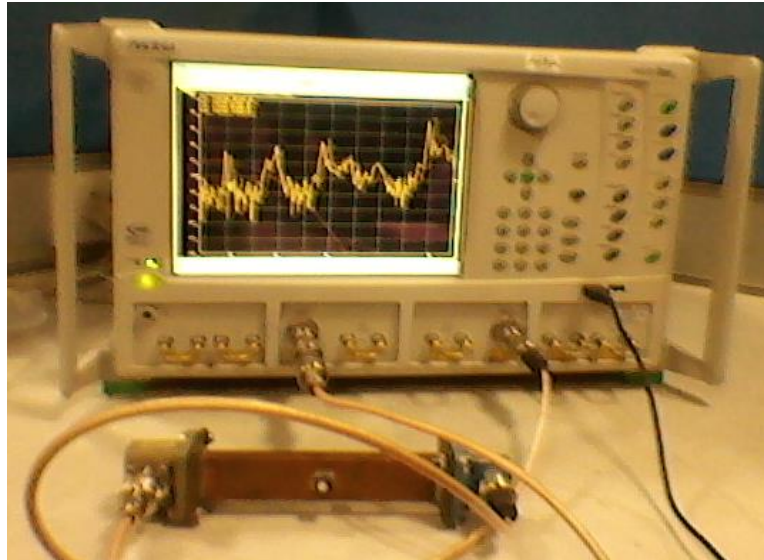


Figure 1- The designed rectangular cavity resonator and Experimental set up.

In order to insert a sample material into the resonator, a slot is constructed at the center of the broader side of the waveguide. The width of the sample hole is equal to the diameter of the cylindrical sample. This rectangular waveguide cavity resonator is connected to the two ports of the vector Network Analyzer s-parameter test set of the measuring system. It is operated in the TE_{10n} modes.

VI. Measurements Results

Using experimental set-up as shown in figure -1 the S-parameter (transmission co-efficient) measurement in X-band is shown in Fig. 3. In figure 3, the left peaks are the resonance peaks of the cavity containing Teflon and right peaks are the empty cavity resonance. The resonance points and then 3dB down point on the resonance curves are noted down to calculate the shift in resonance frequency and quality factor of empty cavity and dielectric filled cavity. The obtained resonance parameters and dielectric calculation are tabulated for TE_{105} to TE_{109} mode. Table 1 shows the calculated values of dielectric constant and loss factor of dielectric sample under test.

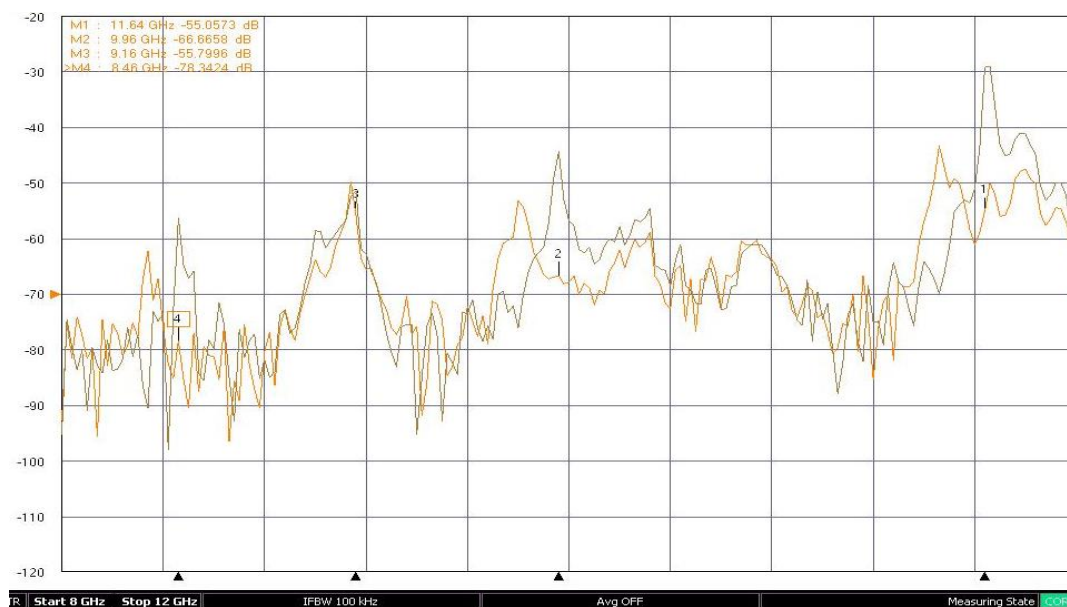


Figure 3 Transmission coefficients of the Cavity measurements in X-band

Table 1 Dielectric Constant, Loss factor and Loss tangent of Teflon, Rubber & Plexiglass

MODE	f_0 GHz)	Teflon			
		f_s (GHz)	ϵ'	ϵ''	$\tan\delta$
TE ₁₀₅	8.46	8.28	1.94	0.004	0.0021
TE ₁₀₆	9.15	8.95	2.001	0.0048	0.0024
TE ₁₀₇	9.96	9.74	2.02	0.0058	0.0029
TE ₁₀₉	11.64	11.38	2.04	0.0069	0.0034
		Rubber			
		f_s (GHz)	ϵ'	ϵ''	$\tan\delta$
TE ₁₀₅	8.46	8.22	2.62	0.0008	0.0003
TE ₁₀₆	9.15	8.88	2.73	0.0009	0.0003
TE ₁₀₇	9.96	9.65	2.89	0.0017	0.0005
TE ₁₀₉	11.64	11.26	3.04	0.0019	0.0006
		Plexiglass			
		f_s (GHz)	ϵ'	ϵ''	$\tan\delta$
TE ₁₀₅	8.46	8.26	2.17	0.0004	0.0002
TE ₁₀₆	9.15	8.91	2.41	0.0006	0.00029
TE ₁₀₇	9.96	9.67	2.69	0.0008	0.0003
TE ₁₀₉	11.64	11.29	2.78	0.0008	0.0003

VII. Conclusion

The complex permittivity of Teflon, Rubber and Plexiglass are measured at various resonance frequencies using new cavity perturbation technique to ensure its accuracy. From the results, it is observed that the values of ϵ' for dielectric sample under test are increasing with the increase of frequency. ϵ'' also increasing with increase of frequency but slightly more as compare to dielectric constant. Loss tangent or dissipation factor (defined as $\tan\delta = \text{loss factor } \epsilon'' / \text{storage factor } \epsilon'$) is also measured that is a good measure of how lossy a dielectric material is. The results are in good agreement with the existing results in literature. It has been observed from the results that the dielectric properties of the material can be measured with existing cavity resonator with good accuracy.

VIII. References

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