Amendment of cavity perturbation method for measuring dielectric properties of medium loss sample at microwave frequencies

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The conventional cavity perturbation method of placing the sample on the broad wall of a rectangular cavity resonator is altered by placing the sample on a narrow wall of the cavity and an analytical formula is proposed for measuring the dielectric properties of medium loss materials at microwave frequencies. Advantages and limitations of the analytical technique over earlier approaches of calibration techniques are also presented.

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1. Introduction

In the cavity perturbation method the dielectric constant and loss factor of the material has been determined by measuring the shift in resonance frequency and quality factor with respect to the unloaded cavity [1]-[6].

In the general approach, the sample is placed on one of the broad walls of the cavity. In our approach the sample is placed on one of the narrow walls of the cavity (Fig. 1) as this satisfies the following conditions, viz:

1) Electromagnetic fields in the cavity are changed negligibly due to the introduction of the sample, and the stored energy in the empty cavity equals that in the cavity with the sample.

2) Differences between the cavity wall losses with and without the sample is negligible.

3) Q_1 and Q_2 are measured at the same frequency and with the same coupling condition.

Fig. 1 shows clearly the advantage of placing a sample having dimension (5 mm × 5 mm × 4 mm) on one of the narrow walls of a cavity with dimension (22.9 mm × 10.2 mm × 27.5 mm), the change in resonance frequency is only of the order of MHz from that of the empty cavity, whereas in the case when the sample is placed on a broad wall, the change in resonant frequency is of the order of a few GHz, which leads to serious measurement inaccuracy [7].

2. Analytical method and its advantage

In the cavity perturbation formula [8]

$$2\frac{f_1 - f_2}{f_2} = \left(\varepsilon_r^{'} - 1\right) C \tag{1}$$

$$\frac{1}{Q_2} - \frac{1}{Q_1} = \varepsilon_r^{''} C \tag{2}$$

$$C = \frac{\iiint_{v_s} \boldsymbol{E_1^*} \cdot \boldsymbol{E_2}\, dv}{\iiint_{v_c} |\boldsymbol{E_1}|^2\, dv} \tag{3}$$

In the general approach of the perturbation technique, C is usually obtained by calibration using a standard sample of known permittivity, like Teflon, and from the changes observed in the resonant frequency and quality factor due to the introduction of the standard sample, $\varepsilon_r^{'}$ and $\varepsilon_r^{''}$ can be calculated using (1) and (2). It should be noted that the standard sample used in calibration is required to be of similar configuration with the samples to be measured. This constraint therefore poses certain difficulties when samples of the same size and shape are not available, especially when measurements are to be taken for polymer composites.

Dielectric properties of the materials depend on various factors like frequency, homogeneity, anisotropy, temperature and surface roughness. Dependence on these factors will render the measurements using a standard sample inaccurate, leading to a high disagreement in the dielectric properties as shown below in the graphs.

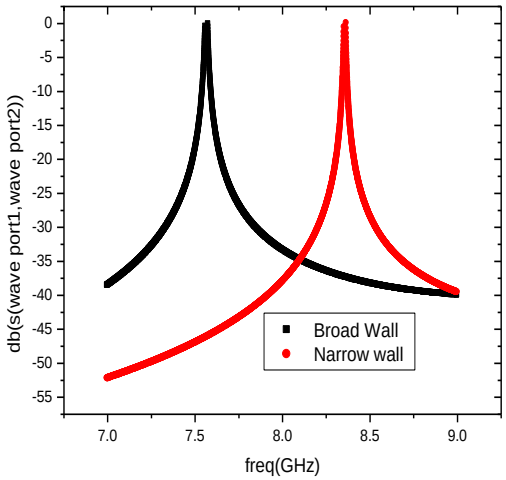

Fig. 1. Shift in resonant frequency when Teflon is placed on a broad wall and a narrow wall respectively of an empty cavity having resonant frequency is 8.512GHz.

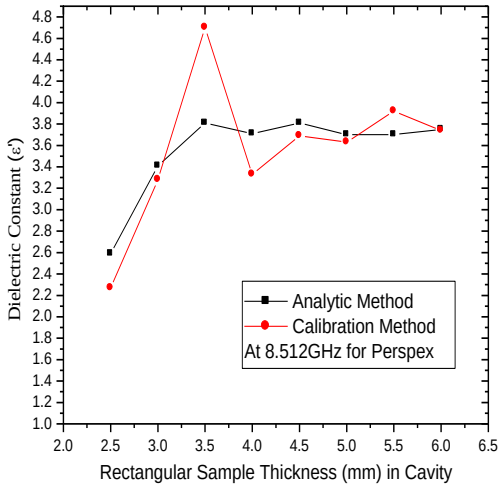

Fig. 2. Dielectric Constant vs. Thickness of a rectangular Perspex sample at 8.512 GHz.

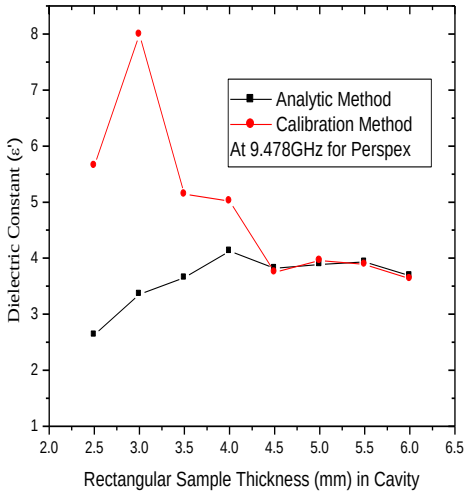

Fig. 4. Dielectric Constant vs. Thickness of a rectangular Perspex sample at 9.478 GHz.

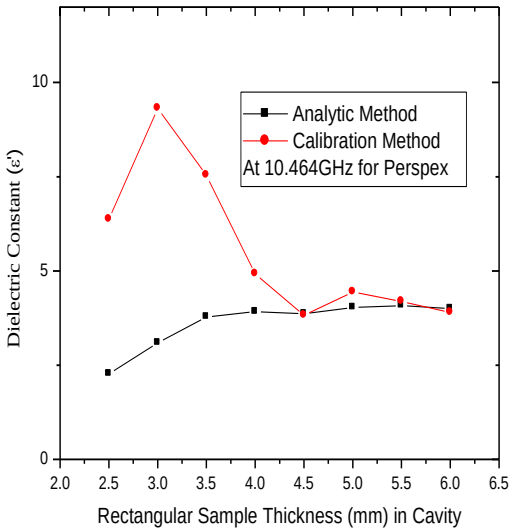

Fig. 3. Dielectric Constant vs. Thickness of a rectangular Perspex sample at 10.464 GHz.

Hence from the above graph we can clearly see that an analytical method based on the placement of a sample on one of the narrow walls of the cavity is advantageous. Determination of the permittivity and loss tangent analytically can be performed without taking recourse to calibration by using standards of known permittivity.

3. Theory and experimental set-up

If a rectangular sample of length, W, breadth, B and thickness, d, is inserted in a rectangular cavity resonator having corresponding dimensions c, b and a respectively and excited in the TE_{011} mode, then the values for ε_r' and σ can be expressed analytically as [8]

$$\varepsilon_r' = \left[\frac{f_1^3 - f_1^2 f_2}{f_2^3} \cdot \frac{3a^3bc}{2WB\pi^2 d^3} \right] + 1 \qquad (4)$$

$$\sigma = \frac{Q_1 - Q_2}{Q_1 Q_2} \cdot \frac{f_1^2}{f_2} \varepsilon_0 \cdot \frac{3a^3bc}{2WB\pi\ d^3} \qquad (5)$$

where the resonant frequencies of the cavity without and with the sample are f_1 and f_2 respectively, and Q_1 and Q_2 are the corresponding loaded Q's of the empty cavity and that with the sample.

Measurements are done using the experimental arrangement shown below.

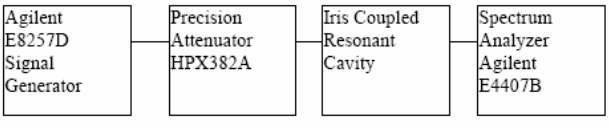

Fig. 5. Experimental set-up.

The values of the dielectric constant for Perspex (3.7) obtained are in good agreement with those given by Dube and Verma [9].

4. Error

In the measurements taken, there are two possible sources of error. These error types are commonly known as random error and systematic error. The difference between these error types lies in the fact that systematic errors occur in a somewhat repeatable manner for a given system, while random errors are occur randomly and cannot be related in any manner. These errors are dealt with in completely different ways. Random errors are dealt with statistically, since they can be reduced by applying clever averaging techniques. Systematic errors, on the other hand, must be specifically characterized for the given system. While random errors are largely unexplainable and unrepeatable, systematic errors result from human factors or instrument biases.

The errors in the measurements of the resonant frequency and quality factor of the loaded cavity evaluated from its theoretical values considering the dielectric constant of Teflon as 2.08 [10] are demonstrated in the following graphs.

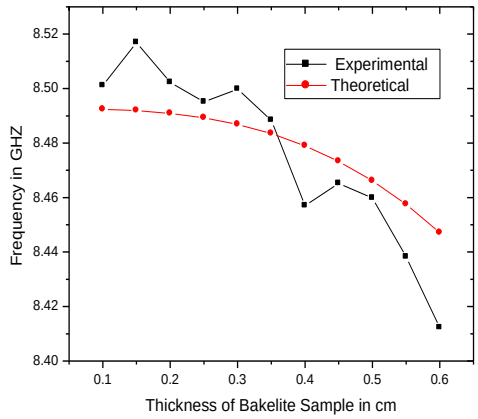

Fig. 6. Variation of resonant frequency as a function of sample thickness (empty cavity resonant frequency = 8.512 GHz).

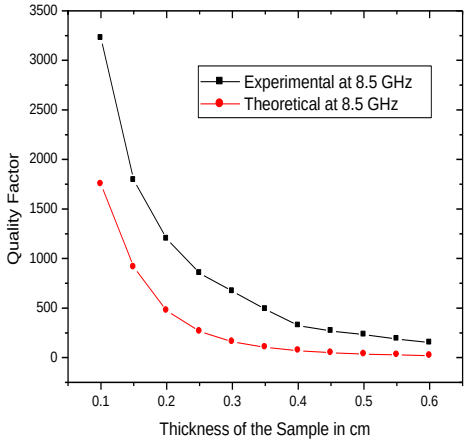

Fig. 7. Variation of Q-factor as a function of sample thickness for the same cavity of fig 6.

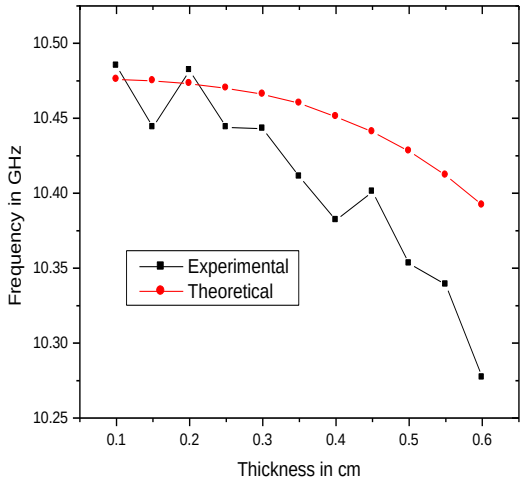

Fig. 8. Variation of Resonant frequency as a function of sample thickness (empty cavity resonant frequency: 10.464GHz).

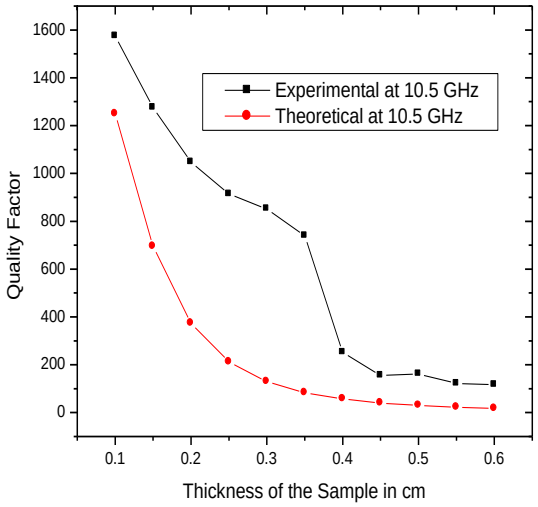

Fig. 9. Variation of Q-factor as a function of sample thickness for the same cavity of fig 8.

5. Conclusion

In the experiments, small samples were chosen to reduce the errors required for the perturbation approximation. However, from the above figures it is observed that the sample size should not be too small, otherwise the sensitivity to changes in the resonant frequency and the Q-factor, due to the insertion of the sample, are poor and the errors calculated for σ and ε resulting from measurement errors of the resonant frequency and Q-factor become very large. It implies that for a given material, due to the conflicting requirements of small size for small perturbation error and large size for small percentage errors in δf_0 and δQ_0, an optimum sample size between 4-6 mm for minimum error should be used [11]. The above results also suggest the advantage of an

analytical technique over the earlier approach of using calibration standards.

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