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A new technique of measuring the complex dielectric permittivity of liquids at microwave frequencies

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A new technique, based on the cavity resonance, of measuring the complex dielectric permittivity of liquid samples is described in detail. The errors in the measurement of the real and imaginary parts of the complex dielectric permittivity are $\sim \pm 1\%$ and $\pm 3\%$, respectively. The complex dielectric permittivity values measured using this method for some standard liquids are also presented. A comparison is made between the present values and the values obtained using standard techniques.

I. INTRODUCTION

There are several methods of finding the complex dielectric permittivity of liquid samples. The most commonly used methods are Surber's plunger[1] and cavity perturbation[2] techniques. The proposed method is a combination of plunger and the cavity resonance technique. Surber's method is based on the reflection coefficient measurement, whereas Dakin and Works[3] used the standing wave pattern formed by the incident wave and the reflected wave from the sample. A further improvement of this method adopting computer curve fitting technique was developed in this laboratory[4] and this is being used for evaluating ϵ' and ϵ'' in several liquids. The line-length variation method[5] also uses the resonance technique. In the line-length variation method, the sample dimension is kept constant and the detector is placed adjacent to the sample. The resonance is formed by adjusting the length of the air column between sample and plunger. The theory used is similar to the other traveling detector methods using standing wave measurements. In the present technique, the sample fills the entire resonator and the cavity resonance sets in when the sample thickness is equal to the half integral multiple of the microwave wavelength inside the sample. The calculations are based on the amount of power absorbed, by the sample filled cavity, at resonance.

The present method aims at mapping the resonance curve in a dielectric waveguide, where an adjustable calibrated plunger moves through the liquid and records several resonances, from which both ϵ' and ϵ'' can be evaluated precisely.

II. THEORY

An adjustable plunger waveguide is converted into a TE_{10p} mode rectangular cavity, where p can be varied as $p=1, 2, 3, ...$etc. The node number p indicates the number of half wavelengths inside the cavity when it resonates.

As one increases the length of the cavity, fixing the input microwave frequency constant, the node number p also increases. The distance through which the plunger is moved between successive cavity resonances gives half of the guide wavelength of the microwave. This gives $\lambda_g/2$ for an air-filled cavity and $\lambda_d/2$ for a sample-filled cavity. At resonance, the standing wave pattern is formed inside the cavity. The electric field amplitude variation forming the standing wave for the TE_{10p} mode in rectangular cavity is given by

$$E_y=E_{0y}\sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{p\pi z}{d}\right)(e^{-\alpha z}+e^{(-p\alpha\lambda_d+\alpha z)}), \quad (1)$$

where E_{0y} is the maximum electric field amplitude, α is the attenuation constant, z is the propagation direction axis, a is the breadth of the cavity, and d is the length of the cavity.

The first exponential factor $e^{-\alpha z}$ describes the traveling wave in the propagation direction and the second exponential factor is for the reflected wave. The total power stored in the cavity can be calculated by double integrating Eq. (1) from 0 to a for the x variable and from 0 to $p\lambda_d$ for the z variable. The power stored per unit area (hereafter mentioned as average power) is calculated by dividing the total power by the area $(a^*p\alpha\lambda_d)$ and remains same for all nodes when $\alpha=0$. But due to the coupling coefficient and the losses due to the walls of the cavity, the average power slightly changes. However, for practical purposes, this is taken as a constant. For nonzero values of the attenuation constant, the average power decreases with an increase in p. For a particular node 'p,' the average power for the case $\alpha=0$ will be greater than that for the case for which $\alpha\neq0$. This difference in the average power between these two cases ($\alpha=0$ and $\alpha\neq0$) yields the attenuation constant of the sample.

The average power (P_{av1}) inside the cavity for TE_{101} mode will be

$$P_{av1}=\frac{P_0}{2\lambda_d}\left(\frac{\beta^2(1-e^{-2\alpha\lambda_d})}{2\alpha(\beta^2+\alpha^2)}+\lambda_d e^{-\alpha\lambda_d}\right) \text{ for } \alpha\neq0 \quad (2)$$

and

$$=P_0 \quad \text{for } \alpha=0, \quad (3)$$

where $P_0=E_{0y}^2$ is the maximum power and $\beta=2\pi/\lambda_d$ is the phase constant.

Normalizing the power values with respect to P_0, the normalized average power stored (P_{nav1}) and the normalized reflected power measured (P_1) may be written as

$$P_{nav1}=P_{av1}/P_0 \quad (4)$$

TABLE I. Dielectric permittivity and loss obtained from different techniques.

Sample	Adjustable (9 GHz) plunger cavity		Cavity (9.1 GHz) perturbation		Plunger (10 GHz) technique		Literature	
	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''
CCl_4	2.23	...	2.23	...	2.23	...	2.23 (Ref. 7)	...
Benzene	2.27	...	2.27	...	2.28	...	2.274 (Ref. 8)	...
Chlorobenzene	4.65	1.64	4.55	1.44	4.60	1.44	4.596 (Ref. 7)	1.44
Acetonitrile	30.1	6.3	31.5	6.1	32.3	6.2	30.24 (Ref. 9)	8.82
Acetone	19.0	3.5	...	...	...	...	19.85 (Ref. 7)	3.21
CBZ in CCl_4								
0.06 MF	2.48	0.156	2.48	0.155	...	...	...	...
0.075 MF	2.57	0.226	2.58	0.225	...	...	...	...

and

$$P_1 = 1 - P_{\text{nav}1} \quad \text{for } \alpha \neq 0, \tag{5}$$

$$= 0 \quad \text{for } \alpha = 0. \tag{6}$$

The same argument can be extended for higher node numbers also. Hence by measuring the values of P_1 and λ_d, one can compute the attenuation constant using Eq. (2).

The dielectric permittivity (ϵ') and loss (ϵ'') of the sample are calculated from the following formulas:[6]

$$\epsilon' = \lambda_{0a}^2 \left(\frac{1}{\lambda_c^2} + \frac{\beta^2 - \alpha^2}{4\pi^2} \right) \tag{7}$$

and

$$\epsilon'' = \frac{\lambda_{0a}^2 \alpha}{\pi \lambda_d}, \tag{8}$$

where λ_{0a} is the free space wavelength of the microwave, λ_c is the cut-off wavelength, and λ_d is the guide sample wavelength.

III. EXPERIMENTAL PROCEDURE

An adjustable plunger waveguide is taken and the free end through which microwave enters is closed by a coupling hole followed by a thin teflon sheet. The reflected power is monitored using an analog to digital converter–microcomputer setup.

The plunger is moved by the computer-controlled stepper motor arrangement, with the step of 0.025 mm in the vertical scale.

The plunger is moved from zero thickness onwards. For an air-filled cavity, the first cavity resonance (for $p=1$) is observed at $\lambda_g/2$. The input power is measured as P_{max}. The reflected power at resonance for $p=1$ is measured as $P_{\text{air}1}$. Now the cavity is filled with the sample and the same procedure is followed. This time one gets $\lambda_d/2$ and $P_{\text{liq}1}$. The zero error (ZE) of the amplifier is also noted down. The power values are in arbitrary units. The normalized reflected power P_1 is calculated as follows:

$$P_1 = \frac{(P_{\text{liq}1} - P_{\text{air}1})}{(P_{max} - \text{ZE})}. \tag{9}$$

By measuring the above-mentioned parameters, the attenuation coefficient can be calculated using Eqs. (2), (4), and (5). One can use a substitution method for computing the coefficient. The complex dielectric permittivity can be calculated using Eqs. (7) and (8).

IV. ERROR ANALYSIS

The absolute error made in the measurements of an air-filled guide wavelength and sample-filled guide wavelength is ± 0.0025 cm and for power values is ± 0.25 (in arbitrary units). The computer program developed here for finding the attenuation constant gives an error percentage less than 0.0001. The error in calculating α is affected mostly by the value of reflected power. Hence a very careful measurement of the reflected power is done using a 12-bit A/D converter. Considering all the above factors, the net error in calculating ϵ' comes around $\pm 1\%$ and in ϵ'' it is around $\pm 3\%$.

V. RESULTS AND DISCUSSION

The present technique requires less readings to be taken. The method, being a cavity method, is sensitive and hence the error percentage is small. The coupling coefficient changes as one goes to higher p values. In order to control this, the first mode alone is taken and the calculations are based on that. The problem of electrical noise and backlash can be avoided by slowly moving the plunger in only one direction. Samples having $\tan \delta (=\epsilon''/\epsilon')$ values less than 0.25 are recommended for this method. For higher values of $\tan \delta$, the resonance curve will be damped and it would be difficult to get the minimum precisely, thereby increasing the error percentage. For pure liquids, the standard reference taken is air. But for nonpolar–polar liquid mixtures, the reference chosen is the nonpolar solvent.

The complex dielectric permittivities of some standard liquids measured using this method are presented in Table I. Complex dielectric permittivities of two binary liquid mixtures are also presented in the same table. The reference taken in this case is carbon tetrachloride (CCl_4).

The reflected power versus the thickness of the sample for a nonpolar liquid, benzene (C_6H_6), is shown in Fig. 1. The zero thickness taken does not correspond to zero cavity length. Figure 2 is for a lossy sample, acetonitrile. The maximum power comes down as one goes from $p=1$ to 2. The reason is that the cavity resonance itself is so broad

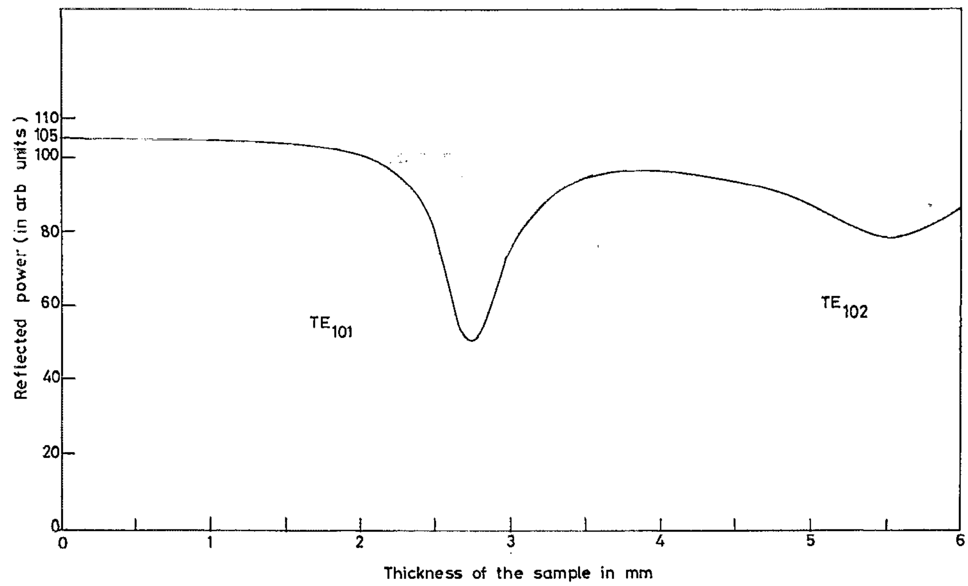

FIG. 1. The cavity resonances obtained for a nonlossy sample, benzene. The zero reading in x axis does not correspond to the actual zero thickness of the sample.

that the first resonance curve intrudes the second resonance curve and so on.

A comparison of this method with conventional measurement procedure of reflected power[1,4] shows that the cavity resonance is a more precise technique than the other techniques. A comparison with the cavity perturbation technique, mostly adopted for a small amount of samples, shows that the cavity perturbation technique is very sensitive to the location of the sample in the cavity and requires the availability of a precision frequency counter to measure the resonance frequency and quality factor. In this present method, the positioning error of the sample does not arise and there is no need to find the quality factor of the cavity. For these reasons, this present technique is more suitable for liquid samples. If one includes the coupling coefficient change with respect to the node number 'p' into account, the attenuation coefficient can be calculated more accurately.

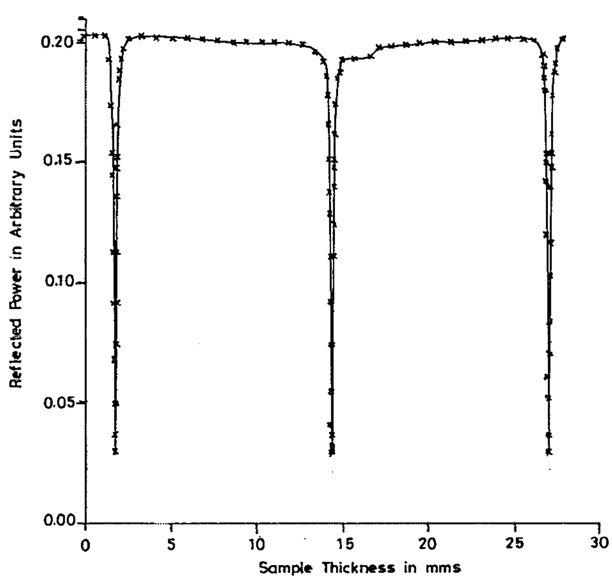

FIG. 2. The cavity resonances obtained for a lossy sample acetonitrile.

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