Broadband Coaxial Cavity Resonator for Complex Permittivity Measurements of Liquids

U. Raveendranath, S. Bijukumar, and K. T. Mathew

***Abstract*—A novel cavity perturbation technique using coaxial cavity resonators for the measurement of complex permittivity of liquids is presented. The method employs two types of resonators (Resonator I and Resonator II). Resonator I operates in the frequency range 600 MHz–7 GHz and resonator II operates in the frequency range 4 GHz–14 GHz. The introduction of the capillary tube filled with the sample liquid into the coaxial resonator causes shifts in the resonance frequency and loaded *Q*-factor of the resonator. The shifts in the resonance frequency and loaded *Q*-factor are used to determine the real and imaginary parts of the complex permittivity of the sample liquid, respectively. Using this technique, the dielectric parameters of water and nitrobenzene are measured. The results are compared with those obtained using other standard methods. The sources of errors are analyzed.**

I. Introduction

A THOROUGH knowledge of the dielectric properties of a material is essential for its proper use in industrial, scientific, and medical applications. Various techniques in frequency as well as in time domain have been adopted to measure the complex permittivity of materials. Among the available methods, the cavity perturbation technique has a unique place due to many attractive features. The earliest treatment of cavity perturbation theory was given by Bethe and Schwinger [1]. According to them the perturbation was caused 1) by the insertion of small dielectric sample into a cavity and 2) by a small deformation of the boundary surface of the cavity. It was Bimbaum and Franeu [2] who developed a measurement technique based on cavity perturbation theory for the first time. In their experimental arrangement, a small cylindrical sample was placed in a rectangular cavity. Slater [3] discussed the applications of cavity perturbation technique. Casimir [4] extended the cavity perturbation theory for the determination of the magnetic parameters of small sphere. Artman and Tannenwald [5] proposed an experimental technique for measuring the magnetic susceptibility tensor components in microwave cavities. General expressions for the perturbation of microwave cavities by the ferrite materials were developed. Waldron [6] modified Casimir's treatment to suit its application to the anisotropic magnetic materials namely ferrites. Artman [7] considered the effect of sample size on the apparent properties of ferrites observed by using cavity perturbation methods. Perturbation effects associated with propagation of electromagnetic waves within the specimen were also considered. Spencer *et al.* [8] suggested a criterion for the applicability of cavity perturbation theory for measuring dielectric constants and permeabilities of materials. Kohane *et al.* [9] suggested cavity perturbation techniques for material characterization. None of the researchers mentioned above gave the derivation for perturbation formula in detail. A detailed perturbation formula with necessary approximations was given by Waldron [10]. He concluded that the high accuracy perturbation formula would only be realized if the specimen is suitably shaped and positioned in the cavity. Estin and Bussey [11] suggested correction factors for sample insertion holes for cavity perturbation technique. Harrington [12] gave a detailed study of perturbation due to cavity walls and the insertion of the material into the cavity field region. Champlin and Krongard [13] developed a cavity perturbation technique for the measurement of conductivity and permittivity of small spherical samples. Roussy and Felden [14] suggested a cavity perturbation method for studying the dielectric properties of powders under controlled pressure. Waldron [15] showed that the uncertainty principle leads to errors in the cavity perturbation methods. Ho and Hall [16] measured the dielectric properties of sea water and NaCl solutions using a cylindrical cavity in the TM_{010} mode. Cavities of special shapes with strong fields in some regions have also been used to increase the sensitivity of measurement. Blume [17] studied the dielectric properties of polluted water with reflection type cavity. For the measurements of losses of small samples, Martinelli *et al.* [18] suggested a cavity perturbation technique. Chao [19] reviewed the theory and technique of cavity perturbation method. For measuring the complex permittivity of thin substrate materials, Dube *et al.* [20] suggested a cavity perturbation technique. Henry *et al.* [21] studied the polymer latex coalescence by dielectric measurements at microwave frequencies using cavity perturbation technique. Akyel *et al.* [22] suggested a cavity perturbation technique in which high temperature measurements can be conducted. For the measurement of complex permittivity of highly polar liquids like water, Mathew *et al.* [23] proposed a new cavity perturbation method. Raveendranath *et al.* [24] suggested a novel cavity perturbation technique for the complex permeability measurement of ferrite materials. Generally cavity perturbation techniques are used for low-loss and medium-loss materials. But the present technique based on cavity perturbation theory gives good results even for high-loss liquid like water.

Recently, broadband coaxial probe techniques [25]–[27] have been employed for complex permittivity measurement. Though these methods give good results, they require elaborate calibration procedures, and significant errors may occur due to improper contact at the probe-material interface for solids. In an

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earlier paper [28], the authors suggested a coaxial cavity resonator technique. This paper discusses in detail the theoretical and experimental aspects of this technique.

II. Design and Fabrication of the Coaxial Resonator

Coaxial cavity resonators are sections of coaxial lines with both or one end shorted by a good conductor. Electromagnetic fields excited in the resonator are reflected from the ends and the waves add in phase. For resonance the total phase shift in the propagating waves must be 2π or its multiple. If ϕ_1 and ϕ_2 are the phases introduced due to the reflections at the two ends and "d" is the length of the resonator, then the condition for resonance will be

$$\phi_1 + \phi_2 + 2\beta d = 2\pi n \qquad \text{where } n = 1, 2, 3, \cdots. \tag{1}$$

For an open-end resonator,

$$\phi_1 = 0, \qquad \phi_2 = \pi,$$

so

$$2\beta d = (2n-1)\pi \qquad \lambda_r = \frac{4d}{(2n-1)} \tag{2}$$

where λ_r is the resonant wavelength. β is the phase shift constant. Thus, the coaxial line section with one end open acts as a resonator in the vicinity of the frequency for which its length is an odd multiple of a quarter wavelength. Various modes are possible for a resonator of given length. The field configurations of these modes may easily be inferred from the propagating TEM mode in a coaxial line. However, care must be taken that higher order TE and TM modes are not excited in such a resonator. The basic condition is $\lambda_r > (\pi/2(b+a))$ where "a" is the radius of the inner conductor and "b" is the inner radius of the outer conductor. In an open-end resonator, there is a possibility of radiation loss from the open end, resulting in poor quality factor. In order to overcome this, the outer conductor is extended beyond the end of the inner conductor such that it forms a cylindrical waveguide operating below cutoff in the TM_{01} mode.

The cutoff frequencies for circular waveguide can be calculated from the separation equations [12].

For TM mode

$$\left[\frac{X_{np}}{b}\right]^2 + k_z^2 = k^2. \tag{3}$$

For TE mode

$$\left[\frac{X'_{np}}{b}\right]^2 + k_z^2 = k^2 \tag{4}$$

where

- k wave number;
- k_z wavenumber in the propagation direction;
- X_{np} and X'_{np} pth order zero of the Bessel functions of the first kind and order n.

In the present investigation, the basic coaxial resonator consists of a circular waveguide with a removable center conductor located along its axis. From Table I, it is clear that comparatively wide range of frequencies can be covered by using the center conductors of different lengths. The TEM mode propagates upto the end of the center conductor. The resonator is fed by a rectangular feed loop. The coupling mechanism will generate spurious higher order modes, which are usually cut off and have an evanescent nonpropagating nature. Since the energy is coupled into or out of the cavity through the same coupling mechanism, the resonator is one-port reflection type. The physical dimensions of the coaxial cavity resonators are shown in Table II. Resonator I has TM_{01} mode cutoff at 6.96 GHz and TE_{11} mode cut off at 5.3 GHz. For resonator II, the values are 19.1 GHz and 14.6 GHz, respectively. Table I shows the characteristic features of resonators I and II. The schematic diagram of the resonator is shown in Fig. 1.

TABLE I
Characteristic Features of Coaxial Resonators

Type of cavity	Length of centre conductor (mm)	Characteristics of resonators	
		Resonance Frequency (GHz)	Loaded Q-factor (Q_L)
Resonator I	168	0.424	542
		1.299	1104
		2.171	1542
		3.035	1011
		3.840	728
		4.760	682
		5.620	814
		6.453	2401
	113	0.622	1363
		1.858	1279
		3.147	1128
		4.396	1150
		5.983	658
		7.301	428
	88	0.861	512
		2.560	468
		4.004	1210
		5.364	2682
		6.541	4365
		7.279	2426
Resonator II	120	0.630	582
		1.550	678
		3.130	406
		4.360	794
		5.632	826
		6.550	625
		9.265	1100
		10.495	2409
		12.951	4531
		14.177	2200
	100	0.748	688
		2.256	741
		3.684	323
		5.260	454
		6.780	772
		8.053	1283
		9.565	6547
		11.021	1223
		13.934	1624

III. Theoretical Analysis

In the cavity perturbation technique, the "perturbation"—a gradual disturbance—of the field inside the cavity is generated by changing the dielectric medium inside the cavity. If ε_1 is the dielectric constant of the medium inside the empty cavity and ε_2 that of the medium after the introduction of a small sample, the change in dielectric constant is $\varepsilon_1 \sim \varepsilon_2 = \Delta\varepsilon$. If E^0_{ps} and E_{ps} are the fields inside the cavity before and after the introduction of sample in the cavity, theory of perturbation states that $E_{ps} \rightarrow E^0_{ps}$ when $\Delta\varepsilon \rightarrow 0$. This is the fundamental and very reasonable assumption [12] of the theory of perturbation. This

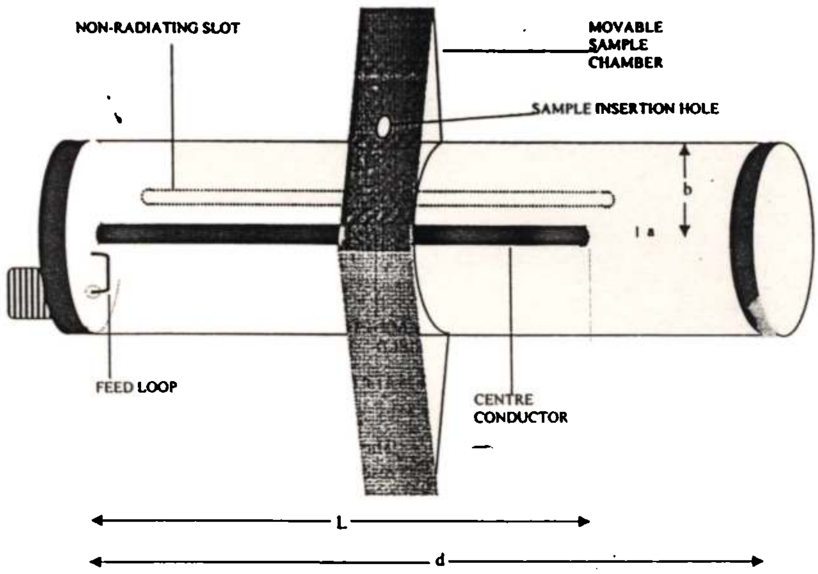


Fig. 1. Schematic diagram of the coaxial cavity resonator.

TABLE II
DESIGN PARAMETERS OF COAXIAL TRANSMISSION LINE RESONATORS

Dimension (mm)	Resonator I	Resonator II
Length of the resonator (d)	250	140
Lengths of the centre conductors (L)	168 113 88	120 100
Inner radius of the resonator (b)	16.25	6.64
Radius of the centre conductor (a)	3.0	1.36
Distance from the centre conductor to feed loop (c)	3.0	0.75
Feed loop, inner dimension (h x l)	2 x 8	1 x 2

fundamental assumption is applied in the theory of coaxial resonator.

The coaxial transmission line resonator consists of a circular waveguide which operates below cutoff for the TM_{01} mode. Along the axis of the waveguide there is a removable center conductor. Thus the TEM mode can propagate upto the end of the center conductor.

The standing wave field components of the resonant TEM mode are obtained by combining the forward and backward propagating waves (in cylindrical coordinate system $\{\rho, \phi, z\}$) as [12], [29]

$$E^0_{\rho s} = \frac{Ae^{j\beta z}}{\rho} + \frac{Be^{-j\beta z}}{\rho} \quad (5)$$

$$H^0_{\phi s} = -\frac{Ae^{j\beta z}}{\eta\rho} + \frac{Be^{-j\beta z}}{\eta\rho} \quad (6)$$

where η is the free space impedance and A and B are constants. The boundary conditions require that $E^0_{\rho s}$ must vanish at $z = 0$ which is the fixed end of the center conductor. At $z = L$, (where L is the length of the center conductor) the maximum field corresponding to resonance occurs. The first condition gives $A = -B$, while the second gives the resonance condition. Now, (5) and (6) become

$$E^0_{\rho s} = 2j\frac{A}{\rho}\,\text{Sin}\,\beta z = jE_{av}\text{Sin}\,\beta z \quad (7)$$

$$H^0_{\phi s} = -2\frac{A}{\eta\rho}\,\text{Cos}\,\beta z = -\frac{E_{av}}{\eta}\,\text{Cos}\,\beta z. \quad (8)$$

Since "ρ" varies from "a" to "b" (from the surface of the center conductor to the inner radius of the resonator) the average field acting on the sample may be considered. Thus E_{av} is the average electric field. The electrical energy stored in the cavity is

$$W_e = \frac{\varepsilon_0}{2}\int_{V_c} E^{0^2}_{\rho s}\,dV. \quad (9)$$

On substituting the value of E^0_{rs} from (7) in (9) we get

$$W_e = \frac{\varepsilon_0}{2}\int_0^{2\pi}\int_a^b\int_0^L E^2_{av}\,\text{Sin}^2\,\beta z\rho\,d\rho\,d\phi\,dz. \quad (10)$$

Here "b" is the inner radius of the outer conductor and "a" is the radius of the center conductor.

When the sample is introduced into the cavity, the relative complex frequency shift of the resonator is given by Waldron [10] as shown in (11) at the bottom of the next page. The numerator of (11) represents the total energy stored in the sample and the denominator represents the total energy stored in the cavity.

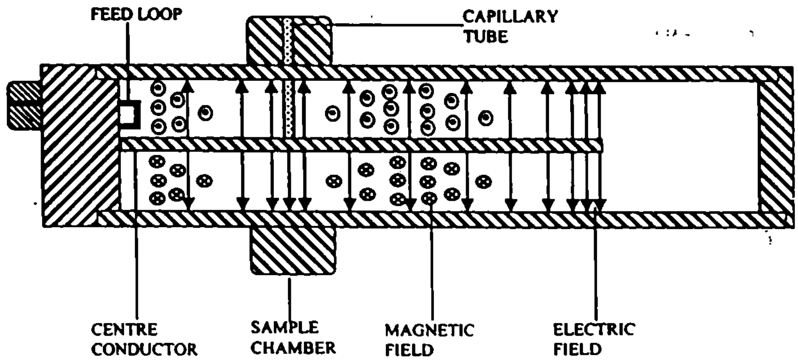


Fig. 2. Cross-sectional view of the coaxial cavity resonator.

The total energy stored in the cavity is

$$\int_{V_c} (D_0 \cdot E_0^* + B_0 \cdot H_0^*)\, dV = 4W_e. \quad (12)$$

When the dielectric sample is introduced at the position of maximum electric field (Fig. 2) the relative frequency shift is given by

$$-\frac{d\Omega}{\Omega} \approx \frac{(\bar{\varepsilon}_r - 1)\int_{V_s} \varepsilon_0 E_{ps\,\max} \cdot E_{ps\,\max}^{0*}\, dV}{4W_e}. \quad (13)$$

Substituting for W_e from (10), (13) becomes

$$-\frac{d\Omega}{\Omega} \approx \frac{(\bar{\varepsilon}_r - 1)\int_{V_s} E_{ps\,\max} \cdot E_{ps\,\max}^{0*}\, dV}{2\int_0^{2\pi}\int_a^b\int_0^L E_{av}^2 \mathrm{Sin}^2\, \beta z \rho\, d\rho\, d\phi\, dz} \approx \frac{(\bar{\varepsilon}_r - 1)V_s}{\pi L(b^2 - a^2)}. \quad (14)$$

For small volume of the sample, $E_{ps\,\max} = E_{ps\,\max}^0 = E_{av}$. $V_s = \pi r^2(b - a)$ where r is the inner radius of the capillary tube. However, $\bar{\varepsilon}_r = \varepsilon_r' - j\varepsilon_r''$. Then, (14) becomes

$$\frac{d\Omega}{\Omega} \approx -\frac{(\varepsilon_r' - 1)r^2}{L(b+a)} + \frac{j\varepsilon_r'' r^2}{L(b+a)}. \quad (15)$$

The relative complex frequency shift is related to the shifts in resonance frequency and loaded Q-factor by the standard equation [10]

$$\frac{d\Omega}{\Omega} \approx \frac{(f_s - f_0)}{f_s} + \frac{j}{2}\left[\frac{1}{Q_s} - \frac{1}{Q_0}\right] \quad (16)$$

where f_s and f_0 are the resonant frequencies of the cavity with and without the sample. Q_s and Q_0 are the corresponding Quality factors. From (15) and (16), we can write

$$(\varepsilon_r' - 1) = \frac{L(b+a)}{r^2}\frac{(f_0 - f_s)}{f_s} \quad (17)$$

$$\varepsilon_r'' = \frac{L(b+a)}{2r^2}\left[\frac{1}{Q_s} - \frac{1}{Q_0}\right]. \quad (18)$$

If the frequency shift is measured from the resonance frequency f_t of the cavity loaded with empty tube rather than that of the empty cavity alone, the above equations become

$$(\varepsilon_r' - 1) = \frac{L(b+a)}{r^2}\frac{(f_t - f_s)}{f_s} \quad (19)$$

$$\varepsilon_r'' = \frac{L(b+a)}{2r^2}\left[\frac{1}{Q_s} - \frac{1}{Q_t}\right] \quad (20)$$

where Q_t is the quality factor of the cavity loaded with empty tube, f_s and Q_s are the resonance frequency and quality factor of the cavity loaded with capillary tube containing the sample liquid, respectively.

The effective conductivity of the sample under test is given by

$$\sigma_e = \omega\varepsilon'' = 2\pi f \varepsilon_0 \varepsilon_r''. \quad (21)$$

$$-\frac{d\Omega}{\Omega} \approx \frac{(\bar{\varepsilon}_r - 1)\varepsilon_0\int_{V_s} E \cdot E_0^*\, dV + (\bar{\mu}_r - 1)\mu_0\int_{V_s} H \cdot H_0^*\, dV}{\int_{V_c} (D_0 \cdot E_0^* + B_0 \cdot H_0^*)\, dV}. \quad (11)$$

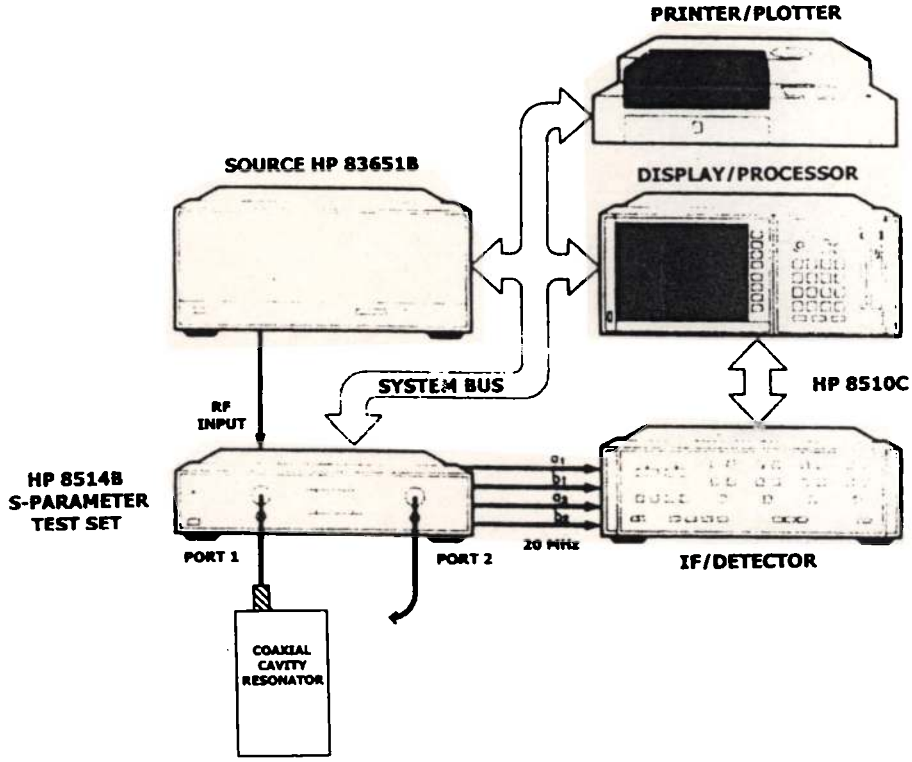


Fig. 3. Block diagram of the experimental setup.

IV. Experimental Setup and Measurements

The experimental setup consists of HP 8510B network analyzer, S-parameter test set, sweep oscillator, and instrumentation computer (Fig. 3). The resonator is connected to one port of the S-parameter test set. A movable sample chamber is attached around the resonator and a small hole is drilled in it for inserting the sample into the cavity field region. On the wall of the resonator, there is a long narrow slot to facilitate the movement of the sample along the cavity (Fig. 1). This narrow slot is nonradiating and there is negligible field redistribution due to its presence. An empty capillary tube made of low loss fused silica ($\tan\delta = 0.0002$) is introduced into the cavity at the position of maximum electric field corresponding to each resonance frequency, by sliding it along the slot, as shown in Fig. 2. Resonance frequency and Q-factor of the cavity loaded with empty capillary tube are determined. The liquid whose dielectric parameters are to be determined is placed in the capillary tube both ends of which are sealed. The measurements are repeated. From the shifts in the resonance frequencies and Q-values, the real and imaginary parts of complex permittivity can be calculated. For the resonator I, sharp resonance peaks are available from 600 MHz to 7 GHz. Resonance peaks are not very sharp at low frequencies for the resonator II. Hence resonator II is used for measurements in the frequency range 4 GHz–14 GHz. From Table I, it is noted that for a given center conductor, loaded Q-factors are considerably low at certain resonance frequencies. Therefore, the measurements are performed at those frequencies where Q-values are high. All the measurements in this work are performed at constant temperature 27 °C.

V. Sources of Error and Accuracy Conditions

Though accuracy of measurement is the most attractive feature of perturbation techniques, care should be taken to eliminate all possible sources of error. In the present study HP 8510B Network Analyzer was used. Accuracy of the instrument is 0.001 dB for the power measurement, 1 Hz for frequency measurement, 0.01° in the phase measurement, and 0.01 ns for time domain measurement [30]. Main sources of experimental error are 1) high relative resonance frequency shift ($\delta f_r/f_r$); 2) nonuniformity of cross section of tube; 3) high loss tangent of capillary tube; 4) mismatch of coupling loop; and 5) axis tilt of center conductor. To satisfy the perturbation condition, relative resonance frequency shift ($\delta f_r/f_r$) should be of the order of 0.001. So the size of the capillary tubes is properly chosen to give a frequency shift of the order of 0.001 GHz and a decrease in the Q-factor of the cavity from Q_0 by a factor of 10–15%. With these criteria in mind, sample tubes of different diameters

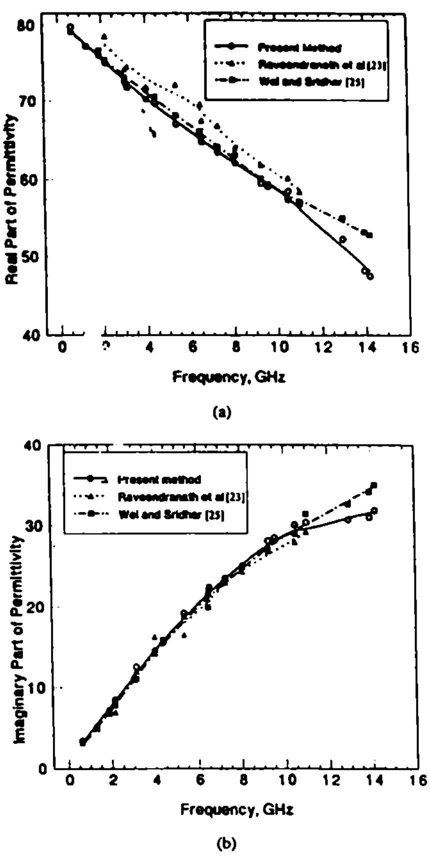


Fig. 4. (a) Real part of permittivity of water versus frequency. (b) Imaginary part of permittivity of water versus frequency.

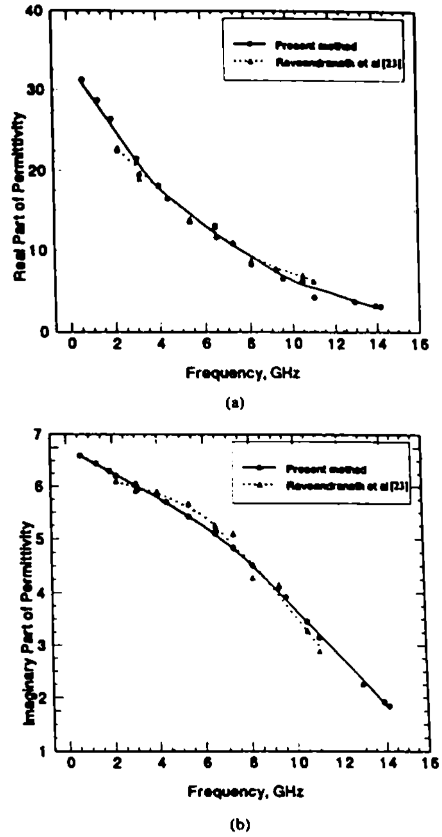


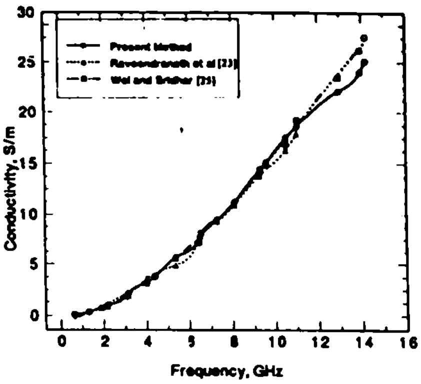
Fig. 5. (a) Real part of permittivity of nitrobenzene versus frequency. (b) Imaginary part of permittivity of nitrobenzene versus frequency.

are selected for different materials (polar, nonpolar, etc.) to enhance the sensitivity of measurement. The significant error that usually occurs in the complex permittivity measurement is due to the nonuniformity of cross-section of the tube. It causes error in the value of V_s. So the diameter of the tube should be accurately measured at different cross-sections of the tube and average value should be taken. An error in the diameter measurement of a capillary tube by a least count of 0.001 mm causes less than 1% variation in the complex permittivity. An error of five least count causes 2.5% variation in the complex permittivity. The thickness of the wall of the tube should be negligibly small and the loss tangent of the material of the tube be very low ($\tan\delta = 0.0002$). Hence, the resonance frequency and Q-factor of the cavity loaded with empty sample tube is almost the same as that of the empty cavity alone. The coupling loop of the resonator must be properly designed for maximum impedance matching. This can be judged from the return loss of the resonator without the sample. Care should be taken to see whether the center conductor remains coaxially. Inclination of the center conductor by 10° and 15° make 2% and 3.5% errors, respectively, in the permittivity measurements.

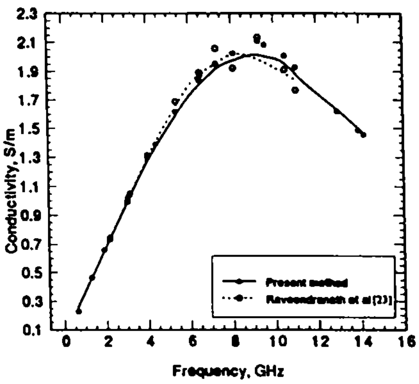
VI. Results and Discussion

Coaxial cavity resonator technique offers an accurate method for measuring the dielectric parameters of all types of liquids. In the present study, water and nitrobenzene were considered. These liquids are polar in nature and consequently have high complex permittivity. As expected, the real part of the complex permittivity of water and nitrobenzene is found to be decreasing with frequency. The imaginary part of complex permittivity of these liquids also varies with frequency. The results are shown in Figs. 4 and 5. Conductivity of water and nitrobenzene are also determined and plotted in Figs. 6(a) and (b).

The technique developed by Wei and Sridhar [25] gives very accurate results in the determination of dielectric parameters of water. A comparative study of the results obtained with the methods suggested by Von Hippel [31], E. H. Grant *et al.* [32], and J. B. Hasted [33] show that their results are not in good agreement with those of Wei and Sridhar [25]. In this context, the present technique is very significant as the dielectric parameters of water measured agree well with the results of Wei and Sridhar. In the case of nitrobenzene, the results are compared with that of rectangular cavity method [23]. The attractive fea-



(a)



(b)

Fig. 6. (a) Conductivity of water versus frequency. (b) Conductivity of nitrobenzene versus frequency.

ture of this method is that the measurement of the dielectric parameters over a wide range of frequencies can be performed. Since the volume of the sample required for the measurement is very small (<0.5 ml), precious liquids available in very small quantities can be studied using the present technique. Thus it finds applications in the fields like Biotechnology and Biochemistry. The present method is very well suited for the measurement of dielectric parameters of low loss and medium loss liquids. This technique may be extended for solids and vapors.

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