9-GHz Complex Permittivity Measurements of High-Loss Liquids Using a Variable-Length Reflection Cavity and a Dual-Channel, Double Superheterodyne Signal Processing System

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***Abstract*—This paper evaluates those factors which limit the accuracy with which microwave complex permittivity measurements of high-loss liquids can be made using a variable-length reflection sample cell spectrometer. Measurements made at 0.001-in increments from a cell length of 0.11 in to 0.31 in were found to be statistically independent of the reflector diameter in the interval 0.5 in to 4.25 in. The data were analyzed using expressions for the amplitude and phase derived assuming a plane wave model. It is found that the permittivity ϵ' and the loss ϵ'' can be determined typically to a precision of 0.3 percent and 0.5 percent, respectively, using a 9.354-GHz dual-channel, double superheterodyne signal processing system. However, there is a discrepancy of about two standard deviations between the values of ϵ' and ϵ'' obtained from the phase data and those obtained from the amplitude data. Moreover, it is also found that the values of ϵ' and ϵ'' calculated from these data differ by more than three standard deviations from those obtained using a variable-length transmission sample cell and the same signal processing system. These discrepancies, which exceed 1 percent are attributed to deficiencies in the plane wave model. It has been confirmed using 0.011 and 0.051 mol l^{-1} KCl solutions that the sensitivity achievable with the reflection cell is less by a factor of 100 than that with a transmission sample cell, which is in agreement with the estimated precision obtainable with these two different types of sample cells.**

I. Introduction

VARIABLE-LENGTH, nonresonant reflection sample cells have been used to measure the complex permittivity of high-loss liquids at microwave frequencies [1] because they are easier to design and construct than variable-length transmission sample cells [2]. The advantages of the former become more evident for microwave frequencies above 26 GHz. At these frequencies, it is very difficult to construct two thin-wall waveguides that "trombone" with an alignment accuracy of ~ 0.001 in and to attach a very low VSWR solderable window to the inner waveguide. Moreover, microwave electron paramagnetic resonance spectrometers [3] can be modified easily to permit complex permittivity measurements to be made using variable-length reflection cells, particularly if they employ a superheterodyne signal processing system and microwave phase-lock frequency stabilizers [4]. This modification could be a logical and economical extension of a relatively common but expensive laboratory instrument. Consequently, it is important to evaluate the advantages of using a variable-length reflection sample cell relative to those for a variable-length transmission cell. Recently, Buckmaster [2] has reviewed the measurement of high-loss liquid dielectrics at microwave frequencies using variable-length reflection transmission sample cells.

This paper reports the results of a comprehensive evaluation of the factors that limit the precision with which microwave measurements of amplitude and phase can be made using a variable-length nonresonant reflection sample cell containing a high-loss liquid. Buckmaster *et al.* [5] assessed that a 1-percent was obtainable using the spectrometer configuration described by Zanforlin [1] at 9 GHz. Their measurements also revealed that there may exist a discrepancy between the values of the permittivity ϵ' and the loss ϵ'' obtained using a variable-length reflection sample cell and those obtained using a variable-length transmission sample cell. Zaghloul and Buckmaster [6] have shown that the values of ϵ' and ϵ'' can be determined to an average precision of ~ 0.03 percent for water in the temperature interval from 10 to 40°C using a variable-length transmission sample cell incorporated into a microwave complex permittivity spectrometer using a dual-channel, double superheterodyne signal processing system. It was deemed essential to make a comparison of the values of ϵ' and ϵ'' for water obtainable using both types of variable-length sample cells with the same dual-channel, double superheterodyne signal processing system.

II. Theory

The complex permittivity, $\epsilon = \epsilon' - i\epsilon''$, where ϵ' is the permittivity and ϵ'' is the loss, can be calculated from the attenuation per unit length α and the phase shift per unit

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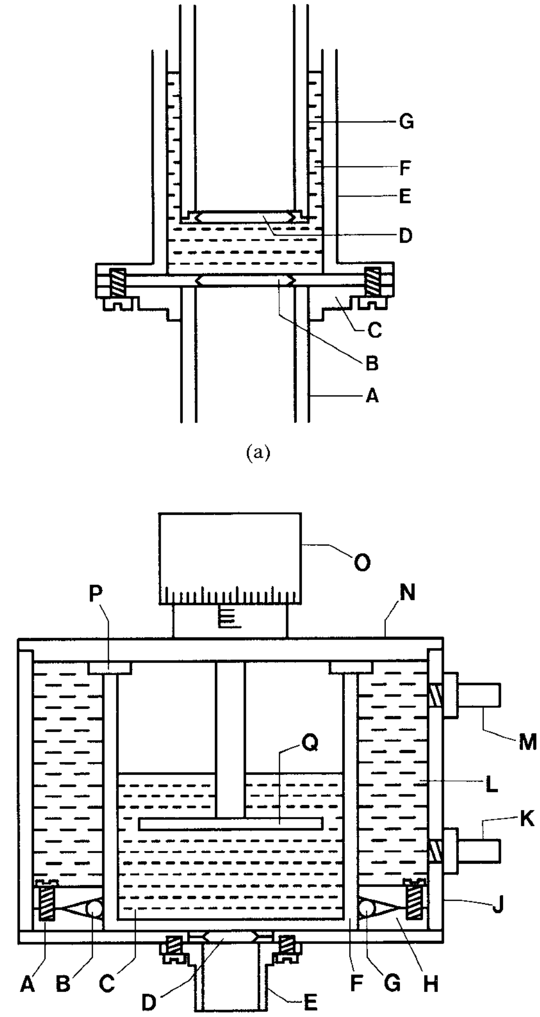

(a)

(b)

Fig. 1. (a) Schematic diagram of a variable-length transmission sample cell. This cell can be realized at 9 GHz if A and G are WR90 (0.500 in × 1.000 in O.D.) waveguide and E is WR102 waveguide (0.510 in × 1.020 in). A ≡ waveguide, B ≡ waveguide window, C ≡ waveguide flange, D ≡ waveguide window, E ≡ waveguide, F ≡ sample liquid, and G ≡ waveguide. (b) Schematic diagram of the variable-length reflection sample cell. A ≡ tension bolt for sample cell sealing assembly, B ≡ O-ring, C ≡ sample liquid, D ≡ waveguide window, E ≡ waveguide, F ≡ cylindrical glass sample cell, G ≡ brass bottom plate, H ≡ sample cell sealing assembly, J ≡ cylindrical brass outer wall, K ≡ cooling fluid inlet, L ≡ cooling fluid, M ≡ cooling fluid outlet, N ≡ brass top plate, O ≡ micrometer, P ≡ neoprene gasket, Q ≡ brass reflector plate.

length β using the equations

$$\epsilon' = (\lambda/2\pi)^2[\beta^2 - \alpha^2] + (\lambda/\lambda_c)^2 \tag{1a}$$

$$\epsilon'' = (\lambda/2\pi)^2 2\alpha\beta \tag{1b}$$

where λ is the free-space wavelength and λ_c is the cutoff wavelength [6].

A. *Variable-Length Transmission Sample Cell*

Fig. 1(a) is a schematic diagram of a variable-length transmission sample cell. The attenuation and phase constants for this type of sample cell are obtained by measuring the amplitude and the phase of the microwave power which passed through the variable-length transmission sample cell. The expressions for α and β are

$$\alpha = (1/z)\ln[(V(z)/V(0)] \tag{2a}$$

$$\beta = (1/z)[\phi(z) - \phi(0)] \tag{2b}$$

where $V(z)$ is the signal amplitude and $\phi(z)$ is the signal phase at an incremental sample length z. $V(0)$ is the signal amplitude and $\phi(0)$ is the signal phase at $z = 0$. For a TE_{mn} mode in a waveguide of dimensions a and b, the cutoff wavelength $\lambda_c = [(m/2a)^2 + (n/2b)^2]^{-1/2}$ (see [7]). It is assumed that only the fundamental mode TE_{10} is excited so $\lambda_c = 2a$.

B. *Variable-Length Reflection Sample Cell*

Fig. 1(b) is a schematic diagram of a variable-length reflection sample cell. The square of the output voltage $v(t)$ from the linear microwave mixer in the complex permittivity instrumentation system using a variable-length reflection sample cell described in this paper is given by [1]

$$v(t)^2 = C\left[\frac{1-\exp(-2\gamma t)}{1+n\exp(-2\gamma t)}\right]^2 = A(t)\exp[i\theta(t)] \tag{3}$$

where t is the distance of the plunger from an arbitrary origin, γ is the propagation constant in the liquid, n is a complex constant determined by the reflection coefficients of the air–glass, glass–dielectric, and dielectric–piston interfaces, C is a constant, $A(t)$ is the amplitude of $v(t)^2$, and $\theta(t)$ is the phase of $v(t)^2$. Equation (3) was derived by assuming that 1) only TEM plane waves propagate in the sample cell, 2) there is a single propagation mode in the sample cell, 3) multiple reflection within the sample cell can be neglected when measurements are made on high-loss liquids, and 4) the incident microwave power level is time independent. If $\gamma = \alpha + i\beta$ and $n = a + ib$, then it can be shown that the amplitude $A(t)$ and the phase $\theta(t)$ are given by

$$A(t) = C\left[\frac{(1-\text{ECOS})^2 + \text{ESIN}^2}{(1 + a\,\text{ECOS} + b\,\text{ESIN})^2 + (b\,\text{ECOS} - a\,\text{ESIN})^2}\right] \tag{4a}$$

$$\theta(t) = C\left[\arctan\left(\frac{\text{ESIN}}{(1-\text{ECOS})}\right) - \arctan\left(\frac{(b\,\text{ECOS} - a\,\text{ESIN})}{(1 + a\,\text{ECOS} + b\,\text{ESIN})}\right)\right] \tag{4b}$$

where

$$\text{ESIN} = e^{-2\alpha t}\sin 2\beta t \tag{5a}$$

and

$$\text{ECOS} = e^{-2\alpha t}\cos 2\beta t. \tag{5b}$$

The cutoff wavelength is infinite for a variable-length reflection sample cell if the mode of propagation is assumed to be plane wave.

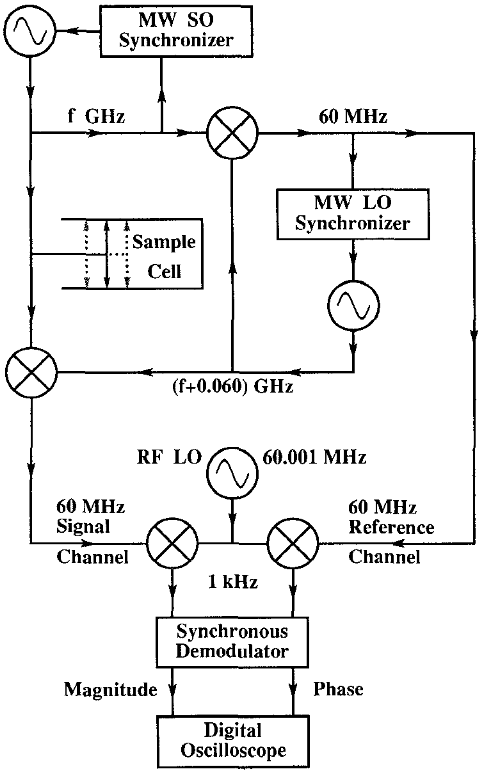

Fig. 2. Conceptual operations block diagram for a microwave complex permittivity instrumentation system using a variable-length reflection sample cell and a dual-channel, double superheterodyne signal processing system (adapted from [2, fig. 1]).

III. Instrumentation

The instrumention system used to perform the experiments described in this paper consists of an integration of the design concepts outlined by Buckmaster *et al.* [4] and McAvoy and Buckmaster [7] and summarized by Buckmaster [2]. The conceptual operations block diagram for a microwave complex permittivity instrumentation system is shown in Fig. 2. This signal processing system was developed to enable microwave amplitude and phase data to be measured to 0.001 dB and 0.01°, respectively, by translating the microwave amplitude and phase data from 9 GHz to 60 MHz and, finally, to 1 kHz by using quasi-phase-coherent or synchronous demodulation at each frequency. This approach has been discussed in detail by Warner [8] and is the basis of all microwave primary attenuation standard measurement procedures.

The system diagram for the dual-channel, double superheterodyne signal processing system used with the variable-length reflection sample cell is given in Fig. 3. The dual-channel, double superheterodyne signal processing system has already been detailed by McAvoy and Buckmaster [7] and McAvoy [9]. Refinements and improvements have been described by Zaghloul [10] and Zaghloul and Buckmaster [6]. Precision rotary vane attenuators (HP-382A) and phase shifters (HP-885A) were incorporated into both arms of the balanced bridge to minimize the resultant temperature coefficient. The bridge arms were wrapped in fiberglass insulation to stabilize the temperature gradients. This was found necessary to achieve a bridge balance and stability in excess of 80 dB. The input power to the bridge was ~ 1.0 mW so the residual reflected bridge power is ~ 90 dBm, which compares favourably with the value of ~ 128 dBm reported by Buckmaster and Dering [11] as part of their study of the achievable bridge balance for various microwave components. They showed that the degree of bridge balance for thermally stable components is determined by the frequency stability and spectral purity of the bridge input microwave power.

The measurements reported in this paper were made using a Varian V-153C reflex klystron, an HP-716A klystron power supply, and a MOS-1 microwave oscillator synchronizer (Microwave Systems Inc.), which provided ~ 100 mW of power at 9.3544 GHz with a frequency stability of better than $1:10^8$/hr and spectral purity of better than 10 Hz. This frequency stability and spectral purity were transferred to the Gunn diode local oscillator with 60 MHz difference using a PLS 2600 microwave oscillator synchronizer (Microwave Systems Inc.). The frequency was measured to $1:10^8$ using an EIP 351D frequency counter, and the spectral purity was monitored using a Tektronix 7603 spectrum analyzer with a 7L18 plug-in. This degree of frequency stability and spectral purity was essential in order to use a 1-kHz second intermediate frequency with a 400-Hz bandwidth to make phase measurements to $\pm 0.01°$. The amplitude and phase outputs of the Ithaco 391 lock-in amplifier operating at 1 kHz were digitized with 14 bits resolution and stored in a Data Precision 6000 universal waveform analyzer.

Fig. 1(b) is a schematic diagram of the variable-length reflection cell used to make the measurements described in this paper. The glass sample cell had an inner diameter of 15 in and a height of 4 in, and the thickness of the water jacket was 1 in. The temperature of the cell was controlled by the water bath surrounding the sample cell. The water in this bath was circulated and its temperature determined by a Haake F4-C refrigerated bath and circulator, which enabled the temperature to be set to 0.01°C and controlled to 0.001°C using a digital microprocessor. The temperature of the water in the sample cell was monitored using a Guildline 9540 digital platinum resistor thermometer with an absolute accuracy of 0.01°C and a resolution of 0.001°C. It was found that the bath temperature was stable to 0.05°C during a 5-minute measurement. Double-distilled, deionized water was used for the complex permittivity measurements.

IV. Experimental Procedure

The measurements of the complex permittivity of the double-distilled, deionized water and KCl solutions were performed using the instrumentation system described in the previous section. The sample cell length was incremented in 0.001-in steps from 0.111 to 0.311 in. After each increment the phase and amplitude of the microwave signal were recorded and stored in the Data Precision 6000 memory. The amplitude at the starting displacement was

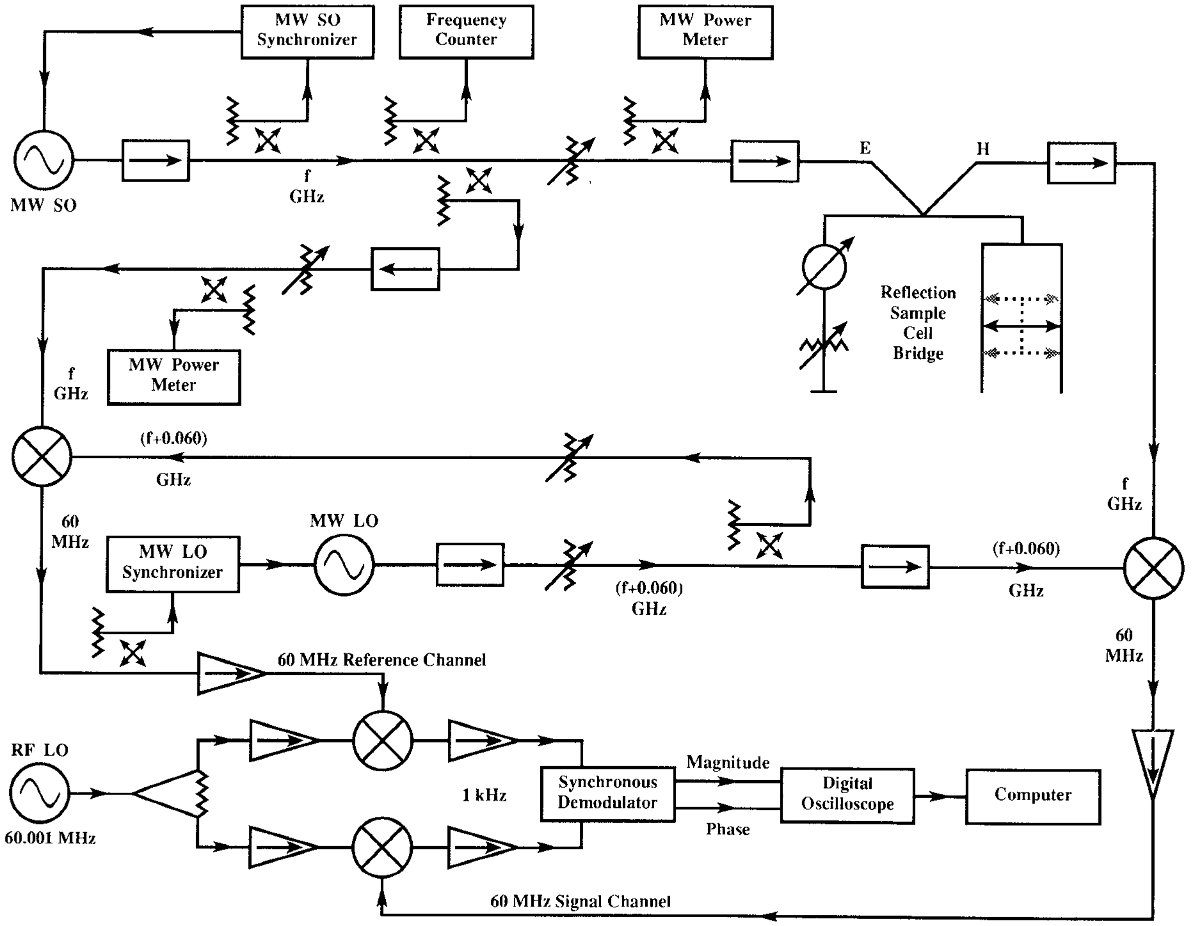

Fig. 3. System diagram of the dual-channel, double superheterodyne signal processing system for making microwave complex permittivity measurements using a variable-length reflection sample cell (adapted from [2, fig. 2(b)]).

set to zero by adjusting the attenuator and phase shifter in the reference arm. The 200 point phase and amplitude spectra were transferred from the Data Precision 6000 to a CYBER 175 for analysis. Fig. 4(a) and (b) shows the typical phase and amplitude spectra obtained by this method. The spectra were fitted to the six-parameter expressions $(\alpha, \beta, a, b, C, t)$ for the amplitude and phase given by (4a) and (4b), respectively, using the grid search method [12]. The measure of the goodness-of-fit was defined as $\Sigma_i[y_i - y(t_i)]^2$, where y_i is the measured value of y at t_i and $y(t_i)$ is the calculated value of y at t_i. It was less than 0.01 in all measurement data sets. Consequently, if the analytical functions for the amplitude and phase were also plotted in Fig. 4(a) and (b), respectively, then the superposition error with the experimental data cannot be resolved. The permittivity and the loss for each measurement data set were calculated from the parameters α and β using (1a) and (1b). All values of ϵ' and ϵ'' reported in this paper are the average of ten consecutive amplitude or phase measurement data sets. Experiments were performed to determine the effect of using different minimum cell lengths on the values of ϵ' and ϵ''. It was found that these values were statistically insensitive to this length in the interval 0.075 in to 0.250 in. The minimum length of 0.111 in was chosen because the reflected microwave power level yielded an output signal-to-noise ratio of about a thousand and avoided possible multimodal effects for short cell lengths.

V. Results

The dual-channel, double superheterodyne signal processing system enables both the microwave amplitude and phase data to be measured simultaneously. In the theory section, it was shown that both the permittivity and the loss of a sample can be calculated from each of these two sets of microwave data. Table I lists the 9.354-GHz calculated values of ϵ' and ϵ'' for double-distilled, deionized water at 20°C. A 2.5-in-diameter plunger was used in the reflection cell for all five entries. The measurements for the first entry were performed on five different days using new water samples on each day. Ten measurement data sets were obtained on each of the five days. Consequently, this entry is the average of all 50 independent measurement data sets. Table I shows that a discrepancy exists between the values of ϵ' and ϵ'' calculated from the amplitude and phase measurement data sets. For all measurement data sets, the phase data produce ϵ' values which are approximately 0.5 percent higher and ϵ'' values which are about

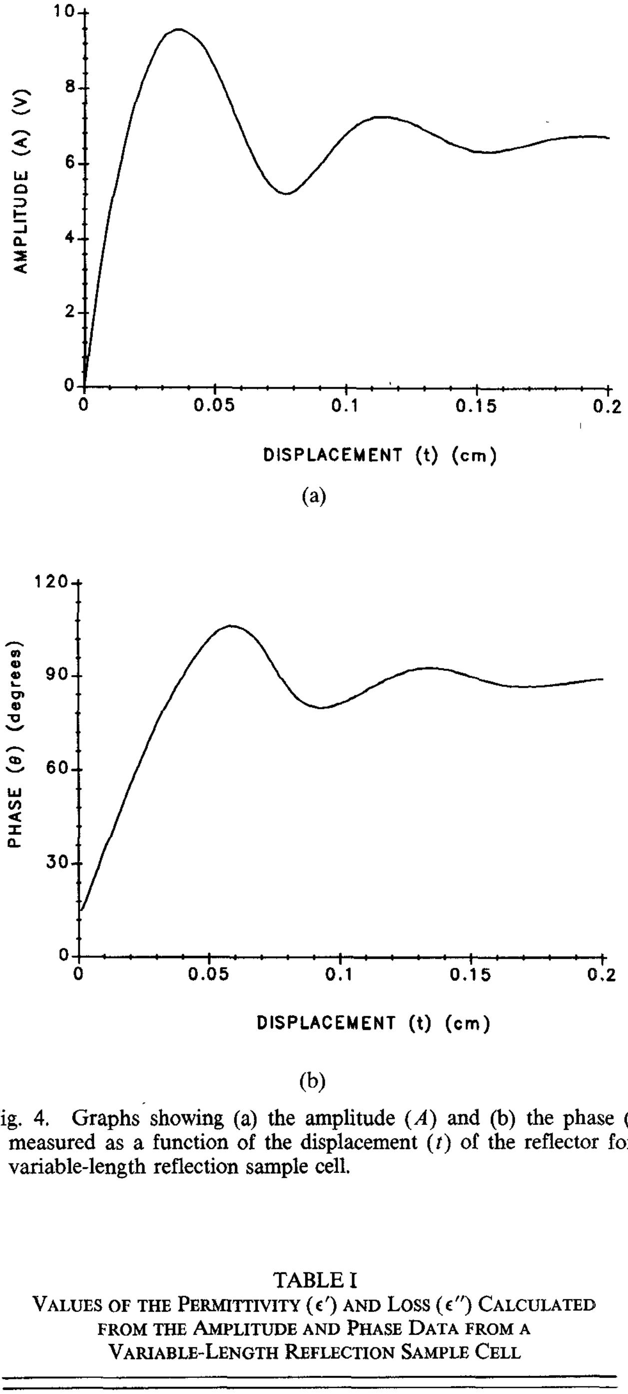

Fig. 4. Graphs showing (a) the amplitude (A) and (b) the phase (θ) measured as a function of the displacement (t) of the reflector for a variable-length reflection sample cell.

TABLE I

VALUES OF THE PERMITTIVITY (ϵ') AND LOSS (ϵ'') CALCULATED FROM THE AMPLITUDE AND PHASE DATA FROM A VARIABLE-LENGTH REFLECTION SAMPLE CELL

NO.	AMPLITIDE		PHASE		T(°C)
	ε'	ε"	ε'	ε"	
1	61.673(0.121)	32.396(0.084)	61.927(0.184)	32.002(0.125)	20.020(0.005)
2	61.578(0.102)	32.388(0.134)	61.919(0.112)	31.985(0.079)	20.018(0.012)
3	61.578(0.102)	32.388(0.134)	61.922(0.109)	32.003(0.078)	20.018(0.012)
4	61.544(0.097)	32.429(0.066)	61.662(0.269)	31.855(0.091)	20.013(0.015)
5	61.104(0.081)	33.149(0.071)	61.046(0.210)	32.599(0.116)	20.040(0.010)
Transmission Cell:					
	ε' = 62.426(0.025)		ε" = 31.575(0 009)		20.0(0.1)

(1) Double-distilled deionized water, (2) same as 1, using phase data from Ithaco phase module, (3) same as 1 using phase data calculated from $A\cos\theta$ and $A\sin\theta$, (4) 0.011 mol l^{-1} KCl solution, and (5) 0.051 mol l^{-1} KCl solution. All measurements were made at 20°C and 9.3544 GHz. The values of ϵ' and ϵ'' reported by Zaghloul and Buckmaster at 20°C and 9.35 GHz using a variable-length transmission sample cell are included for comparison.

1.0 percent lower than those for the amplitude data. The source of this discrepancy can be either experimental or an artifact of the model used in the data analysis.

The Ithaco 391 lock-in amplifier has three outputs, which define the signal: A, $A\sin\theta$, and $A\cos\theta$, where A is the amplitude and θ the phase of the signal. The phase is extracted from the $A\sin\theta$ and $A\cos\theta$ outputs in the Ithaco 391 Phase Option 03 module, and is proportional to the phase difference between the input signals and the reference signal to which the Ithaco 391 lock-in amplifier is synchronized. The phase data can also be calculated from the $A\sin\theta$ and $A\cos\theta$ outputs of the Ithaco 391 lock-in amplifier. The values for ϵ' and ϵ'' obtained from the amplitude A and from the phase data sets using the two different methods to determine θ are also listed in Table I, as entries 2 and 3. Since no statistically significant difference is observed between the ϵ' and ϵ'' values calculated from these two different phase measurement data sets, it is concluded that the phase module is not the source of the discrepancy discussed above. Therefore, it must also be concluded that this discrepancy is attributable either to the method of data analysis or to the assumptions made in deriving the equations for the permittivity and the loss, since this is the only place where the experimental amplitude and phase measurement data obtained using the two different sample cell configurations were handled differently.[1]

The effect of the diameter of the reflector on this discrepancy was also studied. The values for ϵ' and ϵ'' of double-distilled, deionized water obtained from the amplitude measurement data sets at 20°C and 9.35 GHz using reflectors of diameters ranging from 0.5 to 4.25 in are graphed in Fig. 5(a) and (b), respectively. Fig. 6(a) and (b) shows graphs of the values of ϵ' and ϵ'', respectively, obtained from the phase measurement data sets under the same conditions as Fig. 5(a) and (b). As in the case of the 2.5-in reflector, the permittivity for the phase data is consistently higher by about 0.5 percent, whereas the loss is approximately 1.0 percent lower. This discrepancy does not appear to depend upon the reflector diameter. It can also be concluded from a statistical analysis of these data sets that, although there is a weak dependence of ϵ' and ϵ'' calculated from both amplitude and phase data on the reflector diameter, this dependence is not significant statistically.

Inspection of Figs. 5(a) and (b) and 6(a) and (b) indicates that the range of values for ϵ' and ϵ'' for the different diameter reflectors is slightly larger than that observed for the 2.5-in reflector. Since the measurement data sets for the different diameter reflectors were obtained on different days, the broader range can be attributed to variations in the temperature and the purity of the water. This reason may seem to contradict the observations for the 2.5-in reflector, but in that case the sample temperature deviation was less than 0.05°C for each measurement data set, while

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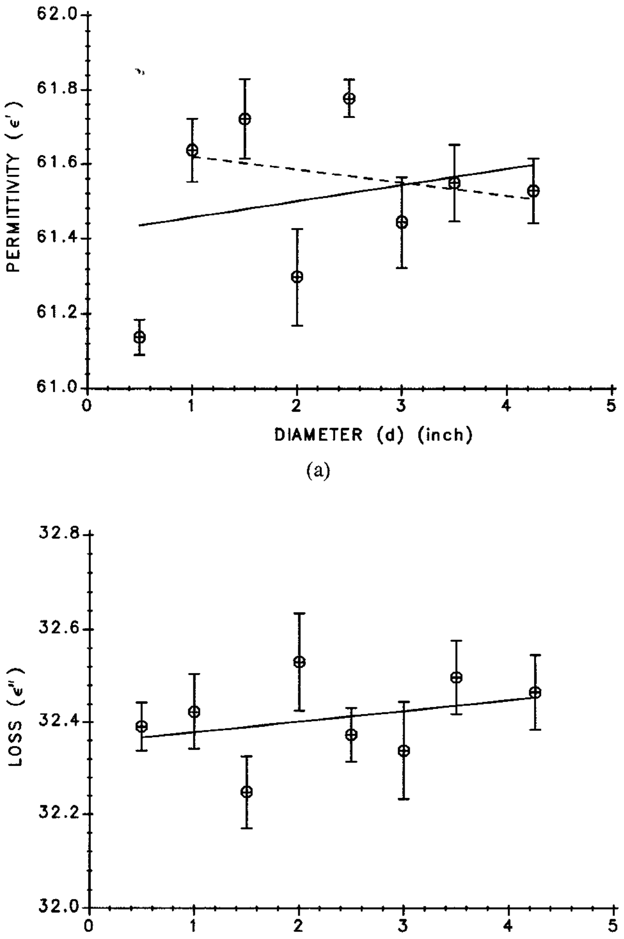
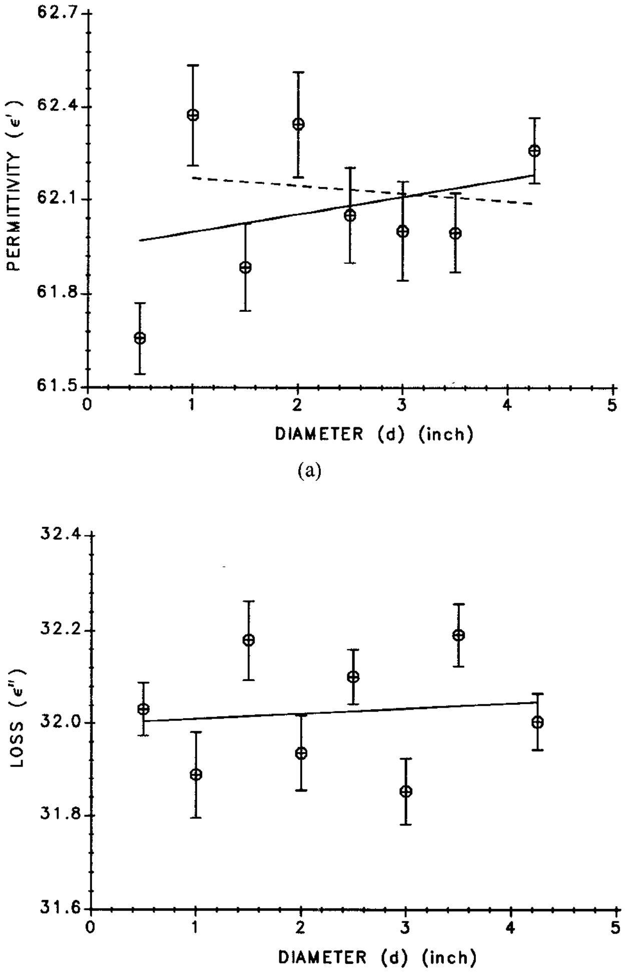
[1] Note added in proof: It has been discovered that $A\cos\theta$ and $A\sin\theta$ deviate from orthogonality by less than 0.5°. However, this fact is not considered to affect the above conclusion.



(a)

(b)

Fig 5. Graphs showing (a) the permittivity ϵ' and (b) the loss ϵ'' for water at 20°C at 9.345 GHz as a function of the reflector diameter d calculated from the amplitude data obtained using a variable-length reflection sample cell. For (a), the best-fit equation is $\epsilon' = 0.043d + 61.414$ ($\sigma = 0.239$) (——). If the value of ϵ' for $d = 0.5$ in is omitted, then $\epsilon' = -0.35d + 62.653$ ($\sigma = 0.170$) (----). For (b), the best-fit equation is $\epsilon'' = 0.023d + 32.356$ ($\sigma = 0.099$) (——).



(a)

(b)

Fig. 6. Graphs showing (a) the permittivity ϵ' and (b) the loss ϵ'' for water at 20°C and 9.346 GHz as a function of the reflector diameter d calculated from the phase data obtained using a variable-length reflection sample cell. For (a), the best-fit equation is $\epsilon' = 0.056d + 61.942$ ($\sigma = 0.269$) (——). If the value ϵ' for $d = 0.5$ in is omitted, then $\epsilon'' = -0.025d + 62.194$ ($\sigma = 0.202$) (----). For (b), the best-fit equation is $\epsilon'' = 0.011d + 31.999$ ($\sigma = 0.146$) (——).

a maximum deviation of ~ 0.1°C was observed for the measurement data sets made with the different diameter reflectors. Recently, Zaghloul and Buckmaster [6] reported the measurement of the complex permittivity of water at 9.356 GHz as a function of the sample temperature using a variable-length transmission sample cell. They fitted the $\epsilon'(T)$ and $\epsilon''(T)$ values to fourth-order polynomial expressions in the temperature. The differences $\epsilon'(T_1) - \epsilon'(T_2)$ and $\epsilon''(T_1) - \epsilon''(T_2)$ are linear functions in $(T_1 - T_2)$ provided that the temperature difference is less than ~ 0.2°C. It can thus be concluded that the variation in the values of ϵ' and ϵ'' for the different diameter reflectors will be larger than that for the 2.5-in reflector because of the greater sample temperature inhomogeneity and the decreased sample cell temperature reproducibility.

The purity of the water sample will also affect the values of ϵ' and ϵ'', but this is dependent on the sensitivity of the signal processing system. McAvoy and Buckmaster [13] determined the complex permittivity of dilute aqueous KCl solutions at 25°C. It was found that both the permittivity ϵ' and the loss ϵ'' of the KCl solutions exhibit a linear dependence on the concentration, even at the lower limits of the measurements. Their signal processing system used a variable-length transmission sample cavity, which made it possible to achieve a precision of about 0.065 percent and 0.15 percent in the permittivity and the loss for water, respectively [14]. These errors allowed measurements on KCl solutions to be made as weak as 0.001 mol l^{-1}. If the standard deviations for the values of ϵ' and ϵ'' for water obtained using a 2.5-in-diameter reflector variable-length reflection sample are a good indicator of the precision attainable in the present measurement system, then deviations in these values should be detectable for a 0.01 mol l^{-1} KCl solution. Entries 4 and 5 in Table I give the values of ϵ' and ϵ'' for 0.011 and 0.051 mol l^{-1} KCl solutions of water at 20°C and 9.354 GHz. The values of the permittivity and the loss obtained for the 0.011 mol l^{-1} KCl solution cannot be distinguished statistically from the values for pure water, while the permittivity decreased by about 1 percent and the loss increased by approximately 2 percent for the 0.051 mol l^{-1} KCl solution. These deviations are in fair agreement with those reported by McAvoy and Buckmaster [13]. These results lead to the conclusion that the errors in the values of ϵ' and ϵ'' obtained using the variable-length reflection sample cell method are probably not less than 1 percent in contrast to the 0.35 percent derived from the standard deviations of the measurement data sets for these quantities.

VI. CONCLUSIONS

The measurements reported in this paper show that the assumptions used in deriving (3) are not completely valid and limit the accuracy with which the permittivity and the loss can be calculated to 1–2 percent. In addition, the amplitude and phase measurement data obtained with a variable-length transmission sample cell are a linear function of the sample cell length, whereas the same data obtained using a variable-length reflection sample cell are described by a six-parameter function. Thus, the calculated values of ϵ' and ϵ'' are much more reliable using the former sample cell configuration. Measurements of weak KCl solutions confirm these conclusions, since they show that the sensitivity achieved using a variable-length transmission sample cell is greater by about a hundred than that achieved using a variable-length reflection sample cell and the same dual-channel, double superheterodyne signal processing system. Consequently, it is concluded that the complex permittivity of high-loss liquids can be determined more accurately from 9-GHz amplitude and phase measurements using a variable-length transmission sample cell than using a variable-length reflection sample cell for two fundamental reasons.

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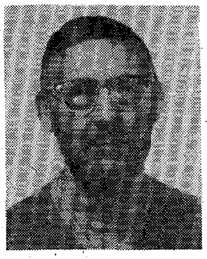

H. A. Buckmaster (S'47–M'60–SM'69) was born in Calgary, Alta., Canada on April 8, 1929. He received the B.Sc. degree (with first class honors) in mathematics from the University of Alberta in 1950 and the M.A. degree in applied mathematics in 1952 and the Ph.D. degree in physics in 1956, both from the University of British Columbia. He held a National Research Council Overseas Post-Doctoral Fellowship at the Cavendish Laboratory, Cambridge University, in 1956–57, where he did radio astronomy research. He was an Assistant Professor of Physics at the University of Alberta from 1957 to 1960 and has been at the University of Calgary since 1960. He was appointed Professor of Physics in 1967.

He has been engaged in the theoretical, experimental, and instrumental aspects of research using the technique of electron paramagnetic resonance to study S-state ions, with particular emphasis on the lanthanide ion gadolinium in a variety of hydrated and deuterated lattices, for 35 years. He has also used this technique to study biological materials, fossil fuels, and clays. More recently, he has been interested in studying the complex permittivity of high-loss liquids such as water at microwave frequencies. This research has resulted in over 120 refereed journal and conference proceedings publications.

Dr. Buckmaster was elected a Fellow of the Institute of Physics in 1966 and was registered as a P. Geophys. in 1967 and a P. Eng. in 1968 by the Association of Professional Engineers, Geologists and Geophysicists of Alberta. He was awarded the Queen Elizabeth II Silver Anniversary Medal for "Service to Canada" in 1978 for his many contributions to his professions and universities as well as to various levels of Canadian society.

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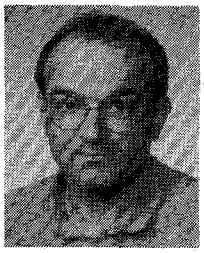

T. H. T. van Kalleveen was born in Amsterdam, The Netherlands, on November 16, 1952. He received the Kandidaats and Doctorandus degrees from the Gemeentelijke Universiteit van Amsterdam in 1973 and 1976, respectively. He obtained the Ph.D. degree in physical chemistry in 1983 from the University of Calgary, Calgary, Alta., Canada.

After spending two and a half years as a Post-Doctoral Fellow in Chemistry at the University of Nebraska, he returned to Calgary, where he is completing the B.Sc. degree in computing science while working as a Post-Doctoral Fellow with the electron paramagnetic resonance group in the Physics Department at the University of Calgary.

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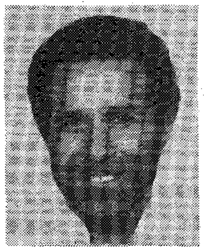

H. Zaghloul was born in Giza, Egypt, on February 1, 1957. He received the B.Sc. (with honors) in electrical engineering from the University of Cairo, Egypt, in 1979. He worked as a logging engineer for Schlumberger Wireline Services in the North Sea until 1983. He received the M.Sc. degree in physics for a study of the temperature dependence on the 9-GHz complex permittivity of water in 1985 from the University of Calgary, Calgary, Alta., Canada, where he is currently studying toward the Ph.D. degree in the area of electron paramagnetic resonance to study phase transitions in ionic lattices.

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C. H. Hansen (A'56) was born in Calgary, Alta., Canada, on August 16, 1930. He graduated in electronic technology from the Provincial Institute of Technology and Art in 1950 and worked in the avionics industry until 1957 and as an audio engineer at the Southern Alberta Jubilee Auditorium until 1961, when he joined the Department of Physics at the University of Calgary.

He was responsible for the design and construction of balloon- and rocket-borne as well as ground-based instrumentation systems until 1970. Since then he has been responsible for the design and maintenance of all instrumentation and data collection and analysis systems in the electron paramagnetic resonance group. He has taught courses in the Department of Computing Science based on his expertise in digital systems design.

Mr. Hansen is at present a member of the IEEE Computer, Test and Measurement, Acoustics, Speech and Signal Processing, and Geoscience and Remote Sensing Societies and is a Chapter Member of the Southern Alberta Section of the IRE.