RESEARCH ARTICLE | JULY 01 1989

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Comput. Phys. 3, 49–54 (1989)
https://doi.org/10.1063/1.168330

Computer interfacing of a microwave resonant cavity for temperature measurements during dielectric relaxation

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(Received 24 February 1988; accepted 27 January 1989)

A temperature probe attached to a microwave resonant cavity is interfaced to a microcomputer. The microcomputer allows temperature data to be taken very rapidly as a dielectric undergoes a phase change over a small temperature interval. This technique is shown to improve temperature measurements during dielectric relaxation studies in polar molecules near their phase transition temperatures.

INTRODUCTION

A number of experiments have been performed to investigate the dielectric properties of solids, liquids, and gases at various frequencies. Resonant circuit methods have been used up to a frequency of 100 MHz, but these methods are not suitable beyond this frequency range because of energy losses into space. Various techniques have been used to investigate the dielectric behavior of polar and nonpolar liquids at low frequencies. The dielectric constant values of water were determined by capacitance measurements made at frequencies varying from 500 Hz to 50 kHz.[1]

During the late 1930s some investigations of the dielectric constant of water were done in the MHz region and some idea of the relaxation process was obtained. The rapid development of microwave values and guided wave techniques during World War II made possible the detailed investigation of the GHz or microwave region. Definitive measurements were made by a number of authors.[2–7]

The present investigation involves the design of a microwave resonant cavity and the computerization of it to monitor rapid variations in temperature for dielectric relaxation studies. For the benefit of the continuity of this paper, a brief discussion of the electromagnetic field equations and field patterns of the microwave resonant cavity in TE_{011} mode along with design is given here. A brief discussion of the microwave spectrometer is also given as the temperature probe attached to the resonant cavity is tested by taking some data on dielectric relaxation using the spectrometer.

A microwave resonant cavity displays the same resonant characteristics as a tuned circuit; the basic difference between the two is that the current and voltage of the tuned circuit are replaced by electromagnetic fields. As a waveguide forms the microwave analogy for the transmission line of ordinary circuit theory, so a hollow cavity forms the analogy for a circuit element.

Because of the low resistances in a resonant cavity, a large value for the quality factor Q can be obtained as compared to a resonant circuit that has a low value of Q. As the sample to be studied is placed in the cavity, it perturbs the electric or magnetic field in the cavity depending on what mode the cavity is in, and from this either the electric permittivity or magnetic permeability can be determined. The cavity resonator technique is a standard technique and has been used by several workers. Chatterjee[8] used a circular cavity resonanting in the E_{010} mode with a capillary tube specimen and tuning plunger. Collie *et. al.*[3,4] made use of a circular cavity resonanting in the H_{011} mode with capillary tube specimen. Kobayashi and Ogawa[9] used a resonant cavity in TE_{103} mode to measure the dielectric constant of Mn–Zn ferrite powder at a microwave frequency of 8.935 GHz. Hong and Roberts[10] used a cylindrical cavity resonating near 10 GHz in the TM_{010} mode to determine the dielectric properties of liquids and solids. Jani *et al.*[11] studied the dielectric relaxation in hyaluronate solutions using a cylindrical resonating cavity. Dahiya *et al.*[12] used a similar cavity to study the dielectric properties of some polar molecules near their phase change.

The dielectric behavior of polar molecules from the solid to the liquid phase is of great interest. The dielectric constant of the polar molecules drops abruptly near their phase transition temperatures. In some of the polar molecules like water and nitrobenzene, the drop is so rapid that it is very difficult to record the exact temperature at the phase change.

To monitor rapid temperature changes, the microwave resonant cavity is computerized by using microcomputer interfacing techniques. A temperature probe is attached to the resonant cavity and is monitored by a microcomputer. The probe consists of a set of thermistors designed to produce a linear voltage response. The microcomputer is programmed to record the rapid changes in temperature as the molecule under investigation goes through the phase change. The number of temperature measurements taken during the rapid phase change is a great improvement over earlier measurements where the

temperature near the phase change was only estimated. The temperature probe attached to the resonant cavity can be used for other temperature-dependent studies without changing the hardware or electronics. Only the software has to be modified to fit the experiment.

I. THEORY

The cavity designed for this investigation is a tunable cylindrical cavity with an internal diameter of 4.9 cm. The cavity is made of brass and the inner surface of the cavity is coated with silver to reduce the Ohmic loss due to wall currents. This silver coating leads to a higher Q value (about 5000) than that for the foundation material. A diagram of the geometry for the cylindrical resonant cavity used in this investigation is shown in Fig. 1. The cavity is designed and constructed for operation in the TE_{011} mode for the frequency range of 6–12 GHz. The field modes are excited in the cavity by two holes corresponding in spacing to $\lambda/2$ for a 9 GHz signal. These holes serve to couple the cavity space with that of the waveguide.

For a cylindrical resonant cavity operating in the TE_{011} mode, the solutions of the frequency-dependent form of Maxwell's field equations yield solutions for the E and H fields which can be expressed as follows:

$$E_r = E_z = 0, \tag{1}$$

$$E_\theta = -D_\gamma J_1(\gamma r)\sin[(\pi/b)z]e^{i\omega t}, \tag{2}$$

$$H_z = D\left(\omega\epsilon - \frac{\pi^2}{\mu\omega b^2}\right)J_0(\gamma r)\sin\left(\frac{\pi}{b}z\right)e^{i(\omega t-\pi/2)}, \tag{3}$$

$$H_r = \frac{-\gamma\pi D}{\mu\epsilon b}J_1(\gamma r)\cos\left(\frac{\pi}{b}z\right)e^{i(\omega t-\pi/2)}, \tag{4}$$

$$H_\theta = 0, \tag{5}$$

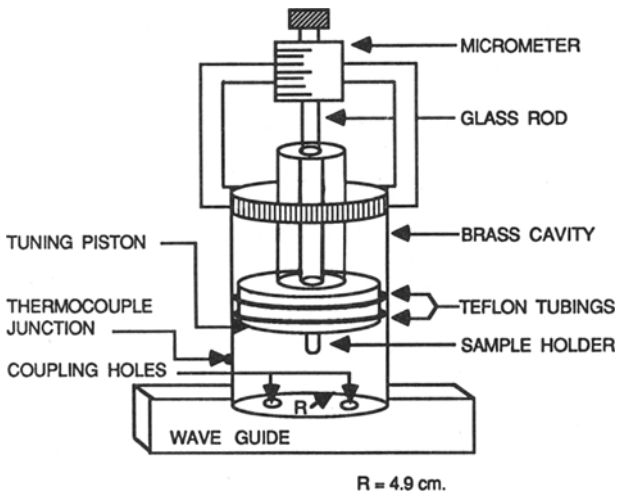

FIG. 1. Tunable cylindrical cavity operated in TE_{011} mode used in this investigation.

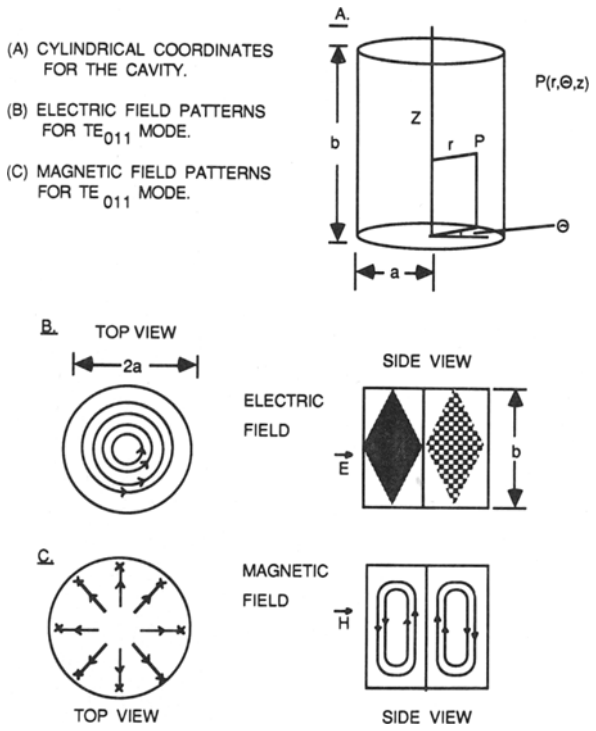

FIG. 2. Microwave cavity geometry and fields.

where J_0 and J_1 are Bessel functions of the first kind, D is a constant, and γ is given by the equation

$$\gamma = [\mu\epsilon\omega^2 - (m\pi/b)^2]^{1/2}, \tag{6}$$

where μ and ϵ are the dielectric permeability and dielectric permittivity of the medium, respectively, and $m = 1$ for TE_{011} mode.

The field patterns for the TE_{011} mode in the cylindrical cavity are assumed to be as shown in Fig. 2. We see from this figure that the E field has a circular component in this mode. It does not have a z or an r component and is a maximum at $r = a/2$ and $z = b/2$. The magnetic field has no θ dependence. Just like the electric field, it is also symmetric with respect to θ.

There are basically two main advantages in using this kind of field configuration in this investigation. First, the resonant cavity can be tuned at the desired frequency of interest in the klystron's frequency range simply by moving the piston in the vertical direction and hence changing the "b" parameter of the cavity. Second, the electric field near the symmetry axis has a very small value, and hence, by introducing the sample along the axis, the perturbation produced can be made small enough for the first-order perturbation equations to be valid.

Relaxation may be defined as the time lag in the response of a system to a change in the physical forces to which it is subjected. The term relaxation mainly applies to linear systems where a response and a stimulus are proportional to one another in equilibrium. In dielectrics the stimulus is almost always an electrical field and the response is a polarization of the dielectric molecules. The time lag be-

tween the application of the field and the polarization of the molecule implies an irreversible degradation of free energy to heat. The relaxation time may be defined as the time in which this polarization is reduced to $1/e$ times its original value, where e is the natural logarithmic base.

Debye[13] in his theory of polar molecules explained the relaxation phenomenon and showed that the polarization of a dielectric medium in an electric field might arise from the partial orientation of permanent molecular dipoles by the field as well as from the distortion of electronic orbits in the molecules. The theory starts with an assumption about the time variation of the polarization in response to a step function removal of field. The simplest assumption is of an exponential decay:

$$P(t) = P_0 e^{-t/\tau}, \tag{7}$$

where τ is the relaxation time. The physical meaning of such a decay is that the rate of change of polarization is proportional to the difference between the instantaneous polarization and its final value. This relaxation assumption is often used to explain the return to equilibrium of a perturbed system.

For the application of a harmonically time-dependent field of angular frequency $\omega = 2\pi f$ described by

$$E(t) = E_0 e^{j\omega t}, \tag{8}$$

where E_0 is independent of time t, the frequency-dependent complex dielectric constant, which is defined as

$$\epsilon^* = \epsilon' - j\epsilon'', \tag{9}$$

can be shown to be

$$\epsilon^* = \epsilon_\infty + (\epsilon_s - \epsilon_\infty)/(1 + j\omega\tau), \tag{10}$$

where ϵ_s is the static dielectric constant for time-invariant fields and ϵ_∞ is the residual dielectric constant appropriate to frequencies much higher than that of the relaxation process. At sufficiently high frequencies permanent dipoles make no contribution to the dielectric constant. Only atomic and electronic polarizations contribute at these high frequencies.

Debye obtained the expression given in Eq. (10) using a very specialized model, that of spherical molecules in a viscous fluid; a quantity containing the viscosity of the fluid, ϵ_s, ϵ_∞, and other factors replace τ.

Rationalizing Eq. (10) yields

$$\epsilon' = \epsilon_\infty + (\epsilon_s - \epsilon_\infty)/(1 + \omega^2\tau^2) \tag{11}$$

and

$$\epsilon'' = (\epsilon_s - \epsilon_\infty)\omega\tau/(1 + \omega^2\tau^2). \tag{12}$$

These are known as the Debye equations for relaxation of a medium driven by a time-dependent field as given by Eq. (8).

Experimentally one usually measures the quantities ϵ' and ϵ'' and calculates the relaxation times using Debye's equations (11) and (12).

II. EQUIPMENT CONFIGURATION

A block diagram of the microwave spectrometer used in this investigation is shown in Fig. 3. The microwave signal

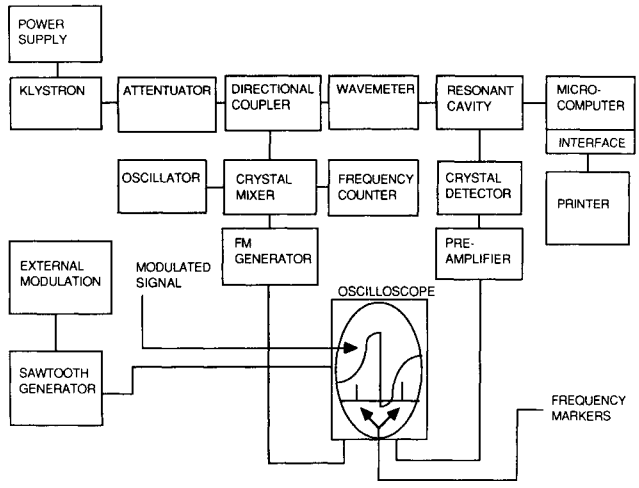

FIG. 3. Block diagram of the microwave spectrometer used in this investigation.

generated by a klystron is transmitted through the waveguide and is modulated. The directional coupler divides the signal in two parts. A part of the signal goes to the resonant cavity. The reflected signal is detected by a diode in the reflectometer, amplified by a 31 kHz tuned amplifier, and then displayed on the oscilloscope. The other part of the signal goes to the directional coupler where the mixing process takes place. The lower-order harmonics are increased to the higher-order harmonics through frequency multiplication techniques.

The radio receiver responds to only the difference between the klystron frequency and an nth harmonic from the crystal oscillator. This results in two markers which are displayed on the oscilloscope. With the help of these markers the frequency shift and the width changes are recorded.

The temperature monitor for the microwave cavity consists of a calibrated temperature transducer, a signal conditioning amplifier, an analog to digital converter, and a Commodore VIC-20 microcomputer as shown in Fig. 4. Although the specific computer was chosen to be a VIC-20 for convenience, the circuit described can easily be adapted to any 6502- or 6510-based microcomputer with a minimum of effort.

The temperature transducer is an Omega Thermistor Composite #44020. This transducer contains three thermistors and three precision resistors (0.1%) arranged as shown in Fig. 5. This arrangement provides a good linear-

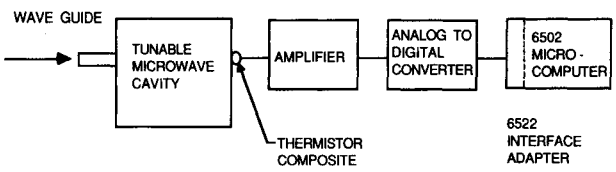

FIG. 4. Block diagram of temperature measurement interface.

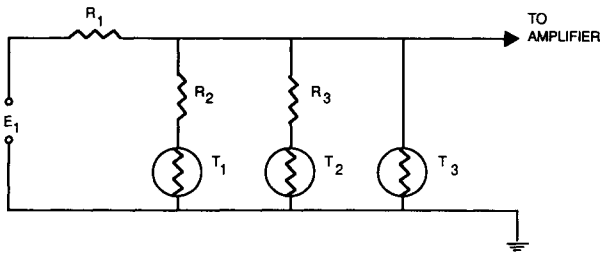

FIG. 5. Schematic of omega thermistor composite #44020 used in this investigation: $R_1 = 23.1$ K, $R_2 = 88.2$ K, $R_3 = 32.0$ K, $T_1 = 2$ K @ 25 °C, $T_2 = 15$ K @ 25 °C, $T_3 = 45$ K @ 25 °C, and $E_1 = 1.000$ v.

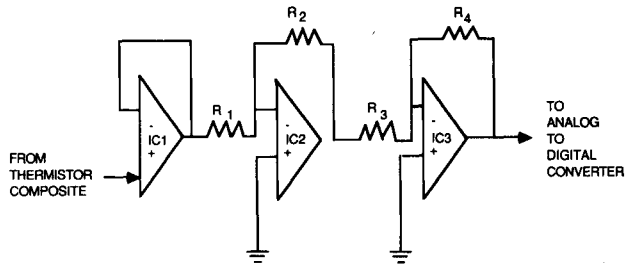

FIG. 6. Schematic of signal conditioning amplifier used in this investigation: $R_1 = 1005\ \Omega$, $R_2 = 6883\ \Omega$, $R_3 = 1016\ \Omega$, $R_4 = 1016\ \Omega$, and IC1, IC2, IC3 = LM351.

ity of ± 0.10 °C over the operating range -50 °C to $+50$ °C. The algorithm used to calculate the temperature was supplied by the manufacturer and is given below:

$$E_o = (-0.00559149\,E_i)T + 0.59300\,E_i \qquad (13)$$

where E_i = input reference voltage, E_o = measured output voltage, and T = temperature in °C.

This algorithm was checked against the temperature measured by a digital thermometer using a thermocouple sensor and was found to produce results well within the specifications of the measuring devices.

The signal processing amplifier consists of a voltage follower and a simple voltage amplifier. The voltage follower is used to minimize loading effects on the output of the thermistor composite circuit, and the gain of the amplifier can be chosen so that the maximum allowable input to the analog to digital converter corresponds to the minimum temperature to be measured. Note that it is the minimum temperature to be measured that is the ruling factor since the slope of the curve described by the temperature algorithm is negative. In this design the minimum temperature was arbitrarily chosen to be -23 °C. The zero-effect voltages of each of the amplifiers were measured and corrected in the software. This eliminated the need for balancing potentiometers to correct for zero offset effects. A schematic of the amplifier is shown in Fig. 6.

The analog to digital converter (ADC) is the National Semiconductor ADC 0809. This chip was chosen for several reasons. It has an on-board eight-channel analog multiplexer. This allows for future expansion of up to eight analog inputs. The channel selector is controlled by the microcomputer. The clock input of the 0809 is compatible with the 6502 or 6510 microprocessor clock output. Therefore, no external clock is necessary. This reduces the timing problems between the ADC and the microcomputer. The ADC can convert an analog voltage to an 8 bit binary number in under 100 μs operating from the system clock. The 8 bit output has a resolution of 1 part in 2^8 which allows a precision of less than one-half of one percent. This translates to a precision of approximately ± 0.5 °C over the full 100 °C range of the temperature transducer.

The ADC is a standard successive approximation type converter. The output pins of the 0809 are connected to the data input pins of the 6522 interface adapter on the VIC-20. The handshake lines from the 6522 are connected to the start and end of conversion (EOC) pins of the 0809 (Fig. 7). When a start signal is sent from the microcomputer to the ADC, the conversion process begins. The microcomputer waits until it receives a signal from the EOC line and then stores the data and sends another start signal and the process is repeated. (Note: If a different interface chip is used, e.g., a 6526 on a Commodore 64, the wiring and software must be modified. However, if a different computer is used and the interface chip is still a 6522, only the software must be changed.) The circuit can be updated in the future. One modification is to use one of the unused analog inputs to monitor the input reference voltage to the thermistor composite. This would be a check against errors due to reference voltage drift. Another improvement would be to use one of the inputs to generate an interrupt at critical times during the experiment, e.g., at a phase transition. The VIC-20 is severely limited in memory size. The interface can easily be modified to work with a Commodore 64/128 microcomputer. The software necessary to drive the interface is relatively simple and straightforward. A copy is available upon request.

III. TEMPERATURE-DEPENDENT STUDIES

As the sample is introduced into the cavity it perturbs the electric field in the cavity, and as a result the resonant frequency shifts and the Q of the cavity changes. According to Slater's perturbation equations shown below, the resonant frequency shift and the Q of the cavity are functions of the

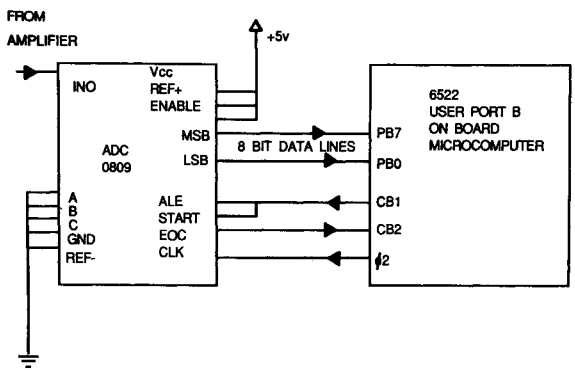

FIG. 7. Schematic of analog to digital interface used in this investigation.

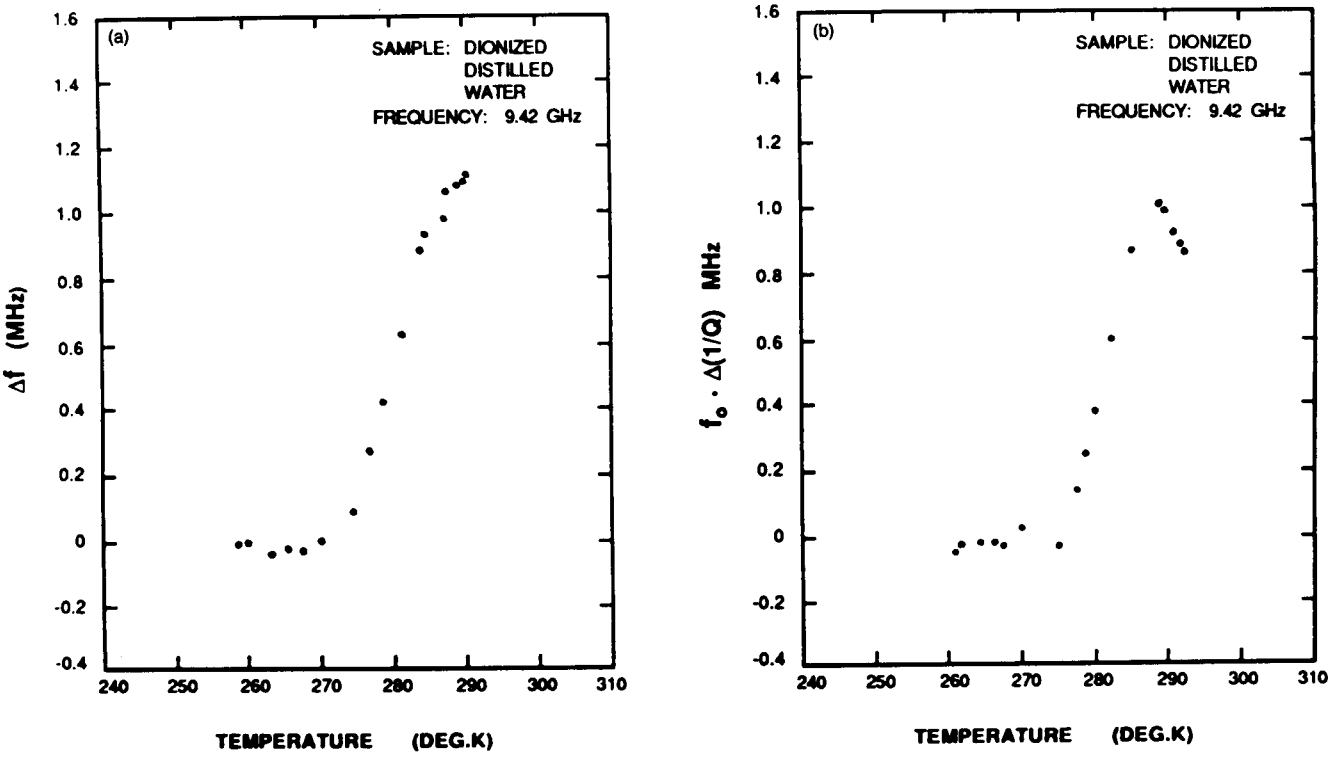

FIG. 8. (a) Frequency shift (MHz) of a resonant cavity without the computerized temperature probe and perturbed by a sample of distilled water as a function of temperature at microwave frequency of 9.42 GHz. (b) Changes in the quantity $f_0 \cdot \Delta(1/Q)$ in MHz of a microwave resonant cavity, without the computerized temperature probe, perturbed by a sample of distilled water as a function of temperature at microwave frequency of 9.42 GHz.

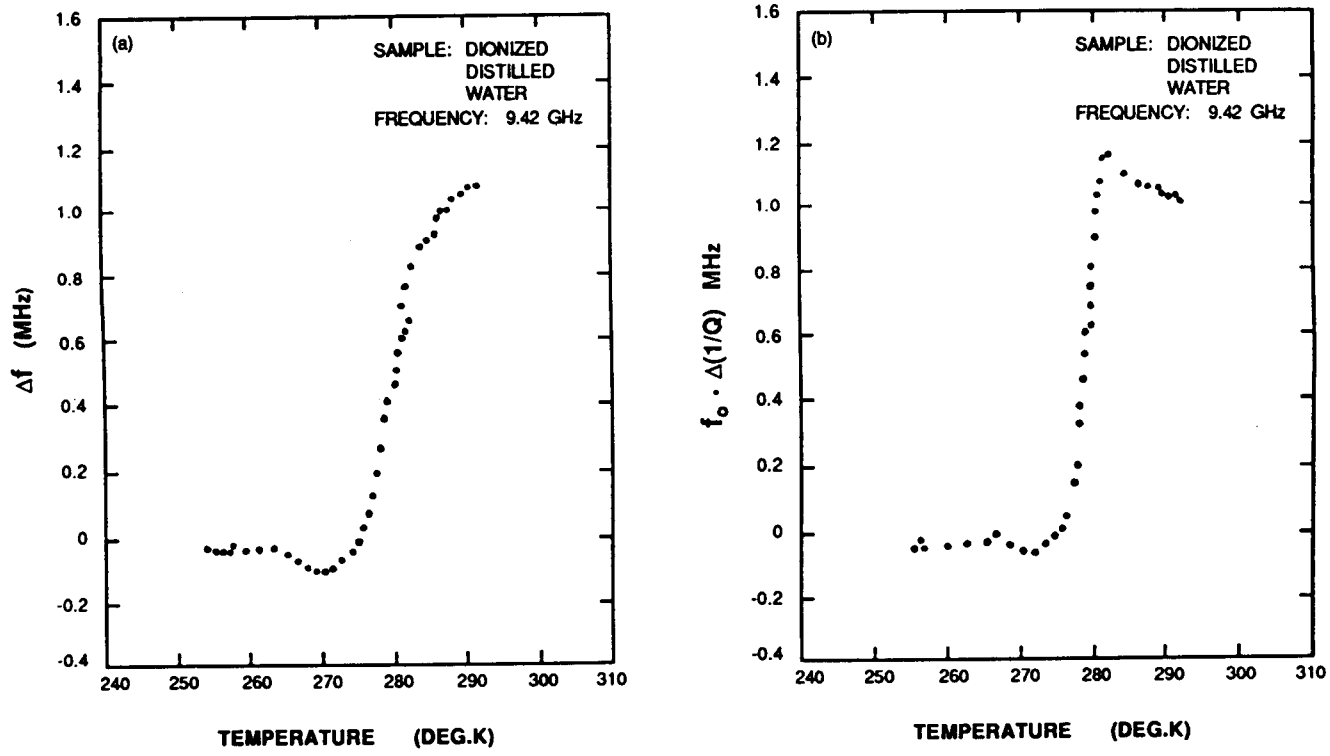

FIG. 9. (a) Frequency shift (MHz) of a resonant cavity, with a computerized temperature probe, perturbed by a sample of distilled water as a function of temperature at microwave frequency of 9.42 GHz. (b) Changes in the quantity $f_0 \cdot \Delta(1/Q)$ in MHz of a microwave resonant cavity with a computerized temperature probe and perturbed by a sample of distilled water as a function of temperature at microwave frequency of 9.42 GHz.

dielectric properties of the cavity media and their perturbation change:

$$\frac{\Delta f}{f_0} = -\frac{\epsilon' - 1}{2} \int \mathbf{E}_s \cdot \mathbf{E}\, dv \Big/ \int \mathbf{E} \cdot \mathbf{E}_A\, dV, \tag{14}$$

$$\Delta\left(\frac{1}{Q}\right) = \epsilon'' \int \mathbf{E}_s \cdot \mathbf{E}\, dv \Big/ \int \mathbf{E} \cdot \mathbf{E}_A\, dV, \tag{15}$$

where ϵ' and ϵ'' are the real and imaginary parts of the complex permittivity, E_s is the field in the sample, E_A is the electric field of the unperturbed cavity, E represents the electric field of the perturbed cavity, Δf is the frequency shift, f_0 is the center frequency of the klystron, v is volume of the sample under test, and V is the volume of the cylindrical cavity.

By definition, the quality factor Q of a resonant cavity is related to the width W of its absorption signal by

$$Q = f_0/W, \tag{16}$$

where W is the full width of the signal at half power maximum.

Therefore,

$$W = f_0/Q$$

and

$$\Delta W = f_0 \Delta(1/Q) \tag{17}$$

with a modulation correction Rinehart *et al.*[14] modified Eq. (17) as shown below:

$$\Delta(1/Q) = \sqrt{3}\Delta W/f_0\,. \tag{18}$$

The frequency shift Δf and change in the quality factor $\Delta(1/Q)$ are dependent upon the location as well as the dielectric nature of the perturbing sample. In this investigation the perturbing sample is placed along the symmetry axis of a cylindrical cavity operating in the TE_{011} mode. The resultant change in the frequency and change in Q are monitored as the cavity temperature is varied. The two parameters f and Q are related to the real and imaginary parts of the permittivity of the perturbing sample and measurements on these two parameters enable the values for ϵ' and ϵ'' to be obtained via Eqs. (14) and (15).

The sample to be tested is placed along the symmetry axis of the cavity with the aid of a micrometer drive as shown in Fig. 1. The cavity resonating in the TE_{011} mode is placed into a thermal bath. Temperature control of the sample is achieved by flushing cold nitrogen gas through a copper coil which is wrapped around the cavity, with the nitrogen gas passing through a heat exchanger consisting of a 7 liter dewar filled with liquid nitrogen in which the copper coil is resting. The sample under study is cooled below its freezing point and the temperature is kept constant to ensure temperature equilibrium between the sample and the cavity. This is very important since the thermistor could only be attached to the outer wall of the cavity to avoid additional perturbation of the fields. The temperature is then allowed to rise with the resonant frequency shift Δf and the width change ΔW measured for each temperature until sufficient data are obtained to determine the behavior of the dielectric response of the system over the transition region.

The frequency shifts and the width changes are recorded by using the frequency markers whose position is controlled manually by using the signal generator. For one complete set of readings of Δf and ΔW in MHz, the marker is placed on the left, center, and right peaks of the signal. For each position of the marker on the signal, the keyboard is struck and the computer gives a reading of the temperature at that instant and, finally, for one complete set of readings it gives an average value of temperature.

Figures 8(a) and 8(b) show the dielectric relaxation in dionized distilled water at 9.42 GHz in terms of Δf vs T and $\Delta(1/Q)$ vs T. In this case the temperature was recorded without using the computer interface. Figures 9(a) and 9(b) show the dielectric relaxation in the same water molecule, but in this case the temperature of the phase transition was recorded by using the computer interface.

It can be seen from these phase transition experiments that as the sample under investigation goes from solid to the liquid form, there is a dramatic change in its dielectric properties. It can also be seen that the computer data shows the dielectric relaxation phenomenon very clearly with many more data points and the transition taking place at the correct phase change temperature. Since data can be taken at a very small interval of temperature, the frequency shift (Δf) versus temperature and also the width change (Δw) or $\Delta(1/Q)$ versus T graphs reveal more information before and after the transition has taken place. This can be seen by comparing the computer data shown in Figs. 9(a) and 9(b) with the manual data in Figs. 8(a) and 8(b).

In summary, the temperature probe interfaced to the microcomputer allows several more temperature measurements to be taken during the phase change of the dielectric sample than with previous temperature measurement techniques. As the phase transition takes place very quickly in most polar molecules,[12] this technique is useful in monitoring the fast changes in temperature. Similar techniques will be excellent in studying the dielectric relaxation phenomenon in liquid crystals where there can be more than one phase change and the transition temperatures are very critical.

ACKNOWLEDGMENTS

We would like to thank Phil Mesnier, an engineering physics student, for his contribution to this work.

We would also like to express our appreciation to Southeast Missouri State University Grants and Research Funding Committee for support of this research.

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