Dielectric Properties of Water at Microwave Frequencies

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***Abstract*— The complex permittivity of water was measured, in terms of the dielectric constant (ε') and dielectric loss factor (ε'') over the frequency range from 1 GHz to 50 GHz and temperatures ranging from 30^{0}C to 60^{0}C. The PNA network analyzer model E8364C and open ended coaxial probe 85070E were used for the analysis. ε'-f and ε''-f curves plotted at different temperatures. ε' decreases with increasing frequency at all temperatures. In frequency range 9-10 GHz, dispersion region is found. ε'' increase with increasing frequency, a peak value is obtained at frequency about 19.5 GHz (relaxation frequency) and then show decreasing trend with increasing frequency at lower temperature (30^{0}C). As the temperature increases, reduces the drag to the rotation of the water molecules, so reducing the friction and hence the dielectric loss. As the temperature increases, the relaxation time decreases, and the loss factor peak shift to higher frequencies. In this frequency range re-orientation process of water molecules is observed.**

Keywords*— dielectric constant, dielectric loss factor, relaxation frequency, temperature, water.

I. INTRODUCTION

The dielectric behaviour of pure water has been the subject of study in numerous laboratories over the past fifty years. As a result there is a good understanding of how the complex permittivity ε* = ε′ - jε '' varies with frequency from DC up to a few tens of GHz and it is generally agreed that the dielectric dispersion in this range can be represented either by the Debye equation or by some function involving a small distribution, of relaxation times [1]. The interactions of electromagnetic fields with materials are described through the fundamental electrical property i.e., relative permittivity of the material. The relative permittivity (ε*) is also a complex quantity with real and imaginary components given by Risman [2].

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \qquad [1]$$

where, ε′ is the real component of ε* (called as dielectric constant) and ε″ = imaginary component of ε* (called as dielectric loss factor), and j appearing in equation 1.2 is a imaginary unit (= √-1). The real component of the permittivity (i.e., dielectric constant - ε′) represents the effective capacitance of a substance and serves as a measure of the ability of the substance to store electrical energy. The imaginary component, (i.e., the dielectric loss factor - ε″) is related to various mechanisms of energy absorption, responsible for energy dissipation in the material and is always positive and usually much smaller in magnitude than dielectric constant. The substance is lossless if dielectric loss factor ε″= 0 [3-4].

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II. MATERIAL AND METHOD

Distilled water as needed for the present research was obtained from the Chemistry lab CEERI, Pilani. The dielectric constant (ε') and loss factor (ε'') of the water were measured in the frequency range 1 GHz to 50 GHz by using a PNA network analyzer, model Agilent E8364C. The test probe consists of an open ended coaxial probe system (Agilent, 85070E). The system software calculates the dielectric properties of the sample from the changes in the phase and amplitude of the microwave signal delivered by the probe of open-ended coaxial line due to reflection at the interface with the sample to be analyzed. The calibration of the Network analyzer was done by using three different loads, viz., (i) air, (ii) a short circuit with the metal contacts, and (iii) distilled water at room temperature. After calibration, the analyzer and the probe system were tested by taking measurements on a standard liquid (methanol, in the present case) of known dielectric properties. The measured values of dielectric constant (ε') and loss factor (ε'') for methanol at frequencies 1 to 50 GHz at room temperature (25^{0}C) are displayed in Fig. 1, along with standard dielectric data (up to 5 GHz) reported by Gregory and Clarke [5] and the values reported by Mishra et al. [6] up to 20 GHz. The values of dielectric parameters for methanol above 20 GHz are not available in literature for a meaningful comparison.

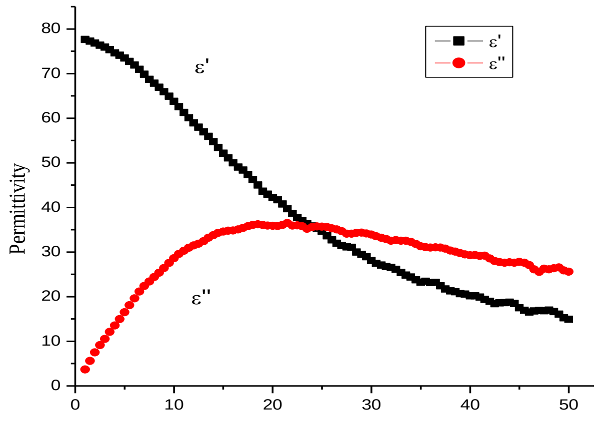

Fig. 1. Variation of dielectric Constant (ε') and loss factor (ε'') of water with frequency at room temperature (25^{0}C)

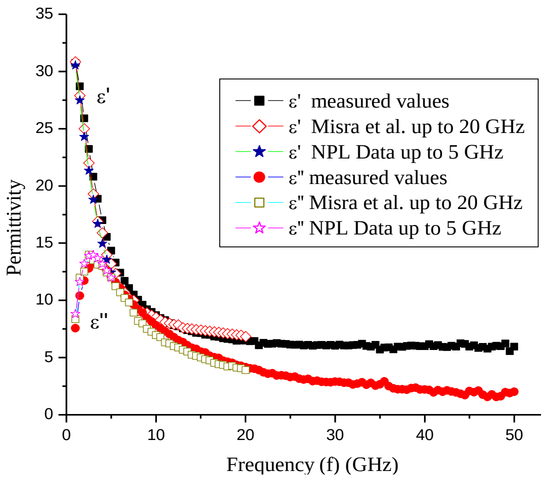

Fig. 2. Variation of dielectric constant (ε') and loss factor (ε") of methanol with frequency at room temperature (25^0C)

Dielectric polarization under the influence of external electric field and lagging of the polarization vector behind the high frequency electric field by virtue of the inertia of the molecules, are the phenomenon responsible for the frequency dependence of dielectric properties [7]. The temperature dependence of the dielectric properties of materials is a complex phenomenon. It may increase or decrease with the temperature depending on the nature of material.

III. RESULT AND DISCUSSIONS

In its pure form, water is a classic example of a polar dielectric. The water molecules behave as dipoles with dipole moment 6.2 x 10^{-30} Coulomb-meter. In Figs. 3 and 4, variation of dielectric constant (ε') and loss factor (ε") respectively of water with frequency is shown for temperatures (30°C to 60°C) over the frequency range 1 GHz to 50 GHz. From Fig. 3, it is observed that as the frequency is increased from 1 GHz to 50 GHz, ε' decreases with frequency at all temperatures, the rate of decrease with frequency being faster at low temperatures and slow at higher temperatures. It is also observed that the ε'-f curves for at 30^0 and 40^0C, intersect each other at frequency 8.5 GHz, while the curves at 50^0 and 60^0C, intersect each other at frequency 14.5 GHz. Thus, the ε'-f curves for different temperatures intersect each other somewhere in the frequency region (8.5 GHz $\leq$ f $\leq$ 14.5 GHz). These curves show dielectric dispersion to this intersection frequency region. Below this frequency region (f < 8.5 GHz) ε' decreases with increasing temperature whereas above this frequency region (f > 14.5 GHz) ε' increases with increasing temperature. This behavior of variation of ε' with frequency at different temperatures may be attributed to the effect of temperature on the dispersion of EM waves in water. Further, it can be noticed from Fig. 4.3 that at low temperature (30^0C), a smooth curve of ε'- f is obtained, but at higher temperatures (40- 60^0C) and at higher frequencies (35- 50 GHz) overlapping of many absorption peaks are observed. When temperature is increased, both the strength and extent of the hydrogen bonding decrease. These results in lowering of dielectric constant at low frequencies but at high frequencies oscillations of dipoles are faster and since at high temperatures molecular agitations also increase. At high temperatures, increased molecular agitations and rapid oscillations under the influence of high frequency EM radiation result in fluctuations in ε' values, giving rise to zig-zag behavior, i.e., ups and downs in ε'-f curves at high temperatures in the high frequency region (35 – 50 GHz).

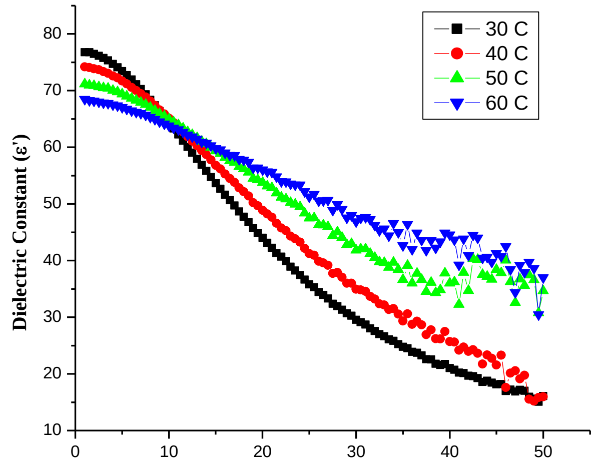

Fig. 3. Frequency dependence of the dielectric constant (ε') of water at indicated temperatures

This is because in liquid water the molecular stretching and molecular librations shift the frequency of molecular vibrations to higher side, on raising the temperature (as hydrogen bonding weakens at higher temperatures, the covalent O-H bonds strengthen causing them to vibrate at higher frequencies) [8].

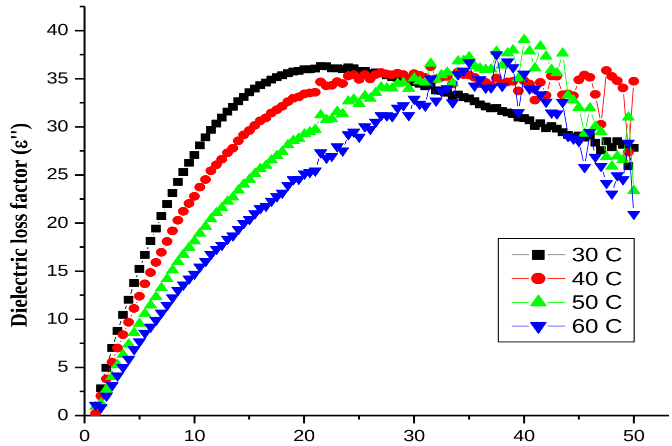

Fig. 4. Frequency dependence of the dielectric loss factor (ε") of water at indicated temperatures

From Fig. 4, it is observed that at low temperature (30^0C) dielectric loss factor (ε") of water increases with increasing frequency, acquires a maximum value at a frequency of about 19.5 GHz (relaxation frequency) and then slowly decreases with increasing frequency. A smooth ε"-f curve is obtained at this temperature (30^0C). An increase in temperature, reduces the drag associated with the rotation of the water molecules, so reducing the friction and hence the dielectric loss. As such, in the low frequency region the value of ε'' at a particular frequency decreases as the temperature is increased as observed from Fig. 4. As the temperature increases, the relaxation time decreases (i.e., relaxation frequency increases) and hence the loss factor maxima shifts to higher frequencies, as evidenced by Fig. 4, from which it is apparent that the maxima in ε''-f curves shifts from 19.5 GHz to about 38.0 GHz as the temperature is increased from 30^0C to 60^0C. In the higher frequency range (30 – 50 GHz) where the operating frequency is greater than the relaxation frequency, re-orientation process of water molecules is becomes active. The re-orientation process may be modeled by using a 'wait-and-switch' process where the water molecules have to wait for a period of time until favorable orientation of neighboring molecules occurs and then the hydrogen bonds switch to the new molecule [9]. At these frequencies (30 to 50 GHz) and at higher temperatures (40 to 60^0C), multiple relaxation losses are observed.

IV. CONCLUSION

The dielectric properties of fresh juice of water can be efficiently and accurately measured by E8364C PNA network analyzer and 85070E coaxial probe in the frequency range 1 GHz to 50 GHz. The present values of ε' and ε'' are found to be in good agreement with the values reported by other researcher. These measurements may be useful in dielectric heating applications and for quality sensing application as well for developing new techniques.

ACKNOWLEDGMENT

The authors are grateful to the Vice Chancellor, The IIS University for providing necessary facilities for this work. They are also grateful to Emeritus Scientist Dr. S. N. Joshi, and Gyrotron Laboratory, CEERI, Pilani, India for useful discussions and permitting use of the Network Analyzer for this work. Ravika Vijay also, thanks Director, Poornima Foundation, Jaipur for permitting her to take up this research work.

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