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DIELECTRIC STUDIES OF CORN SYRUP FOR APPLICATIONS IN MICROWAVE BREAST IMAGING

G. Bindu, A. Lonappan, V. Thomas, C. K. Aanandan, and K. T. Mathew

Microwave Tomography and Material Research Laboratory
Department of Electronics
Cochin University of Science and Technology
Cochin, Kerala, 682 022, India

Abstract—Permittivity and conductivity studies of corn syrup in various concentrations are performed using coaxial cavity perturbation technique over a frequency range of 250 MHz–3000 MHz. The results are utilized to estimate relaxation time and dipole moments of the samples. The stability of the material over the variations of time is studied. The measured specific absorption rate of the material complies with the microwave power absorption rate of biological tissues. This suggests the feasibility of using corn syrup as a suitable, cost effective coupling medium for microwave breast imaging. The material can also be used as an efficient breast phantom in microwave breast imaging studies.

1. INTRODUCTION

Materials suitable for use in vivo as artificial organs and tissues have been an intriguing topic of research for the past few years [1, 2]. There have been studies on the microwave dielectric properties of materials forming urinary calcifications [3] and various body fluids [4, 5]. Microwave medical imaging has gathered momentum in recent years due to the characterization of tissues in terms of its complex permittivity [6–8]. Here, the object immersed in a coupling medium is subjected to microwave illumination and the collected reflected/scattered energy is analyzed to study the dielectric profile of the object. The specific use of suitable coupling medium is to enhance the coupling of electromagnetic energy to the object as well as to increase the resolution. It is desirable that the medium should respond to microwaves in a similar fashion to the anatomical areas they represent, particularly in tests which measure or calibrate microwave exposures, or when used for optimization of system parameters over the required frequency range. Also the material should be well adapted when intermediate compositions are desired. The stability of the material over variations of time is also an important criteria.

However dielectric permittivity and conductivity values of conventional coupling media like water, saline and gel samples roughly meet these requirements [9] and exhibit high contrast with that of the object to be imaged. Hence there is significant importance in the development of a suitable coupling medium for microwave breast imaging [10].

The present paper reports an independent and complete characterization of the dielectric studies of corn syrup in various concentrations in the frequency range of 250 MHz–3000 MHz. The results are compared with the in vitro breast tissue data and good agreement is obtained. This suggests the feasibility of using corn syrup as an efficient, cost-effective coupling medium for microwave breast imaging.

2. METHODOLOGY

2.1. Sample Preparation

Corn flour mixed with water in the ratio 1:1 is heated till it changes in to a thick consistent jelly like form. This jelly form is treated as Sample 1. Samples 2, 3 and 4 are sample 1 diluted with 30%, 55% and 80% water.

Water used in the study has a permittivity of 77.2 and conductivity of 1.9 S m^{-1} at 3000 MHz.

2.2. Coaxial Cavity Perturbation Technique

Dielectric properties of samples are measured using cavity perturbation technique [11]. The experimental set up consists of Agilent 8714 ET vector network analyzer, interfaced with Compaq workstation SP 750 and cavity resonator . The coaxial resonator given in Figure 1 consists of a reflection type cylindrical cavity with a movable central conductor located along its axis. The length of the central conductor can be adjusted to obtain suitable resonance frequencies. The resonator is fed by a rectangular loop. The cavity is excited in the TM_{010} mode. A movable sample holder is attached around the resonator and a small hole is drilled in it for inserting a capillary tube filled with the sample into the cavity. On the wall of the resonator, a long narrow slot is made to facilitate the movement of the tube along the length of the cavity. The capillary tube is made of low loss silica ($\tan\delta = 0.0002$).

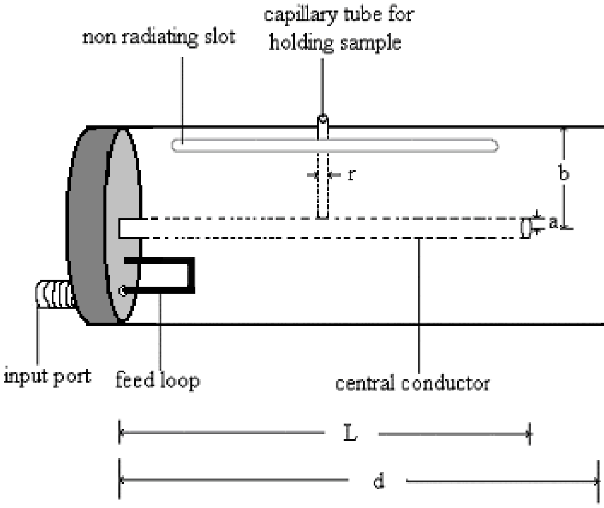

Figure 1. Schematic diagram of the coaxial cavity resonator.

The resonant frequency f_0 and the corresponding quality factor Q_0 of each resonant peak of the cavity resonator with the empty capillary tube placed at the maximum of electric field are noted. The position of the tube is adjusted for maximum perturbation (i.e., maximum shift of resonant frequency with minimum amplitude for the peak). Similarly f_s and Q_s are determined for the cavity loaded with the samples. Dielectric studies of the samples are also performed at different time intervals.

The real and imaginary parts of the complex permittivity are calculated using the following relation,

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

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

where ε_r' is the dielectric constant and ε_r'' is the dielectric loss of the sample.

The absorption coefficient α of the material is given by

$$\alpha = \frac{\pi\varepsilon_r'' f_s}{c\sqrt{\left({\varepsilon_r'}^2 + {\varepsilon_r''}^2\right)}} \tag{3}$$

where c is the velocity of light.

2.3. Dielectric Spectrum of the Tissue

The main features of the dielectric spectrum of the biological tissues have been reviewed and reported [12, 13]. The dielectric spectrum of a tissue is characterized by three main relaxation regions α, β and γ at low, medium and high frequencies and other minor dispersions are reported as δ dispersion. When an electromagnetic field is applied, the polarization of the sample will relax towards the steady state as a first order process characterized by the relaxation time τ. The complex permittivity ε is represented as a function of angular frequency ω by the Debye equation [9],

$$\varepsilon_r' = \varepsilon_{r\infty} + \frac{\varepsilon_{rs} - \varepsilon_{r\infty}}{1 + (\omega\tau)^2} \tag{4}$$

where ε_{rs} is the static permittivity and $\varepsilon_{r\infty}$ is the optical permittivity.

However, the complexity of both the structure and composition of biological material is such that each dispersion region may be broadened by multiple contributions to it. The broadening of dispersion could be empirically accounted for by introducing a distribution parameter, thus giving an alternative to the Debye equation known as the Cole-Cole equation [9],

$$\varepsilon_r'' = \varepsilon_{r\infty} + \frac{(\varepsilon_{rs} - \varepsilon_{r\infty})\omega\tau}{1 + (\omega\tau)^2} \tag{5}$$

where α represents the distribution parameter which is a measure of the broadening of dispersion.

In the present study the frequency range of interest falls in the tail end of β and beginning of γ dispersion regions. In this region, the dipolar orientation of water molecules is the dominant polarization mechanism in biological tissues.

3. RESULTS AND DISCUSSIONS

The permittivity and conductivity studies of corn syrup in various concentrations and at different time intervals are done using coaxial cavity perturbation technique. The measured data is compared with the available literature data on normal, benign and malignant breast tissues [14] and is given in Table 1. Good agreement is observed. The dielectric parameters of conventional coupling media like water, saline and SMS gel, in the frequency range of 250 MHz–3000 MHz are compared with that of corn syrup samples and are also shown in the table. While water and saline [15] exhibit a higher range of permittivity

Table 1. Comparison of the dielectric properties of various breast tissues with corn syrup samples, water and saline in the frequency range of 250–3000 MHz.

Sample		Range of dielectric constant (average)	Range of conductivity S m^{-1} (average)
Normal breast tissue (water content varies from 40 - 50 % by weight)		46 – 17	0.37 - 3.4
Benign breast tumor (water content varies from 70 - 74 % by weight)		67 – 35	0.7 – 4.9
Malignant breast tumor (water content varies from 70 - 78 % by weight)		65 - 30	0.2 – 3.4
Corn syrup	Sample 1	44.5 – 18.7	0.30 – 0.64
	Sample2	49. 8 – 27.9	0.74 – 0.98
	Sample 3	54.8 - 35.7	1.02 - 1.43
	Sample 4	56.2 – 39.8	1.15 - 2.20
Water		77.5 – 76.7	1.6 – 2.05
Saline (0.5 % NaCl)		71.78 – 67.4	0.63 - 0.74
SMS gel		16.6 – 8.2	0.52 – 0.71

than that of the breast tissue samples, SMS gel [16] exhibits a lower range. Hence these media provide poor coupling of the electromagnetic energy and significant reflections. A frequency range of 250 MHz–3000 MHz is selected for the study to include the Industrial Scientific and Medical applications (ISM) band. However static permittivity ε_{rs} is measured at 693 KHz and the optical permittivity $\varepsilon_{r\infty}$ is fixed as 4 for high water content biological samples for a frequency of 100 GHz [13].

For biological materials, relaxation time τ decreases and dipole moment increases with the increase in water content of the tissues [12, 13]. To substantiate this, these parameters are calculated for corn syrup samples at a frequency of 3000 MHz and are reported in Table 2. The frequency is so selected that it matches with the resonant frequency of the designed antennae for our microwave imaging experimental studies. It is observed from Table 2 that increasing the water content of the sample makes a decrease in the relaxation time. This reduction is caused by the decrease in viscosity and hence the reduction in the hindering forces. The highly polar nature of the water molecule contributes more to the intramolecular relaxation process, thereby reducing the most probable relaxation time [9]. The dipole moments of the samples are calculated using the Onsager equation

Table 2. Relaxation time, dipole moment and Specific Absorption Rate of corn syrup samples at 3000 MHz.

Sample	τ ps	Dipole moment μ x 10^{-29} C m	Specific Absorption Rate W / kg
Sample 1	13.8	0.30	0.835
Sample 2	9.54	0.32	0.855
Sample 3	6.52	0.37	0.873
Sample 4	5.48	0.4	0.885

given by,

$$p^2 = \frac{9kT\varepsilon_0}{N}\frac{(\varepsilon_{rs} - \varepsilon_{r\infty})(2\varepsilon_{rs} + \varepsilon_{r\infty})}{\varepsilon_{rs}(\varepsilon_{r\infty} + 2)^2} \tag{6}$$

where k stands for Boltzman constant, ε_0 dielectric permittivity of free space, N Avagadro number, and T the period of the applied field.

As the water content of the sample is increased, the polarity increases and the dipole moment approaches towards that of the water molecule which is 0.69×10^{-29} cm. The increase of dielectric constant with the dilution of water also causes an increase of the dipole moment.

The complex relative permittivity of the medium can be written as

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{7}$$

where ε_r' is the dielectric constant and ε_r'' is the dielectric loss of the medium The conductivity σ is given by

$$\sigma = \omega\varepsilon_0\varepsilon_r'' \tag{8}$$

The loss tangent

$$\tan\delta = \varepsilon_r''/\varepsilon_r' \tag{9}$$

The propagation constant

$$\gamma = \sqrt{j\omega\mu_0(\sigma + j\omega\varepsilon)} = \alpha + j\beta \tag{10}$$

where a represents the attenuation factor and b the phase factor.

Substituting Eqns. (7), (8) and (9) in (10) and simplifying, we get

$$\alpha = 2\pi f\sqrt{\mu_0\varepsilon_0\varepsilon_r'\left[\sqrt{1 + \tan^2\delta} - 1\right]} \tag{11}$$

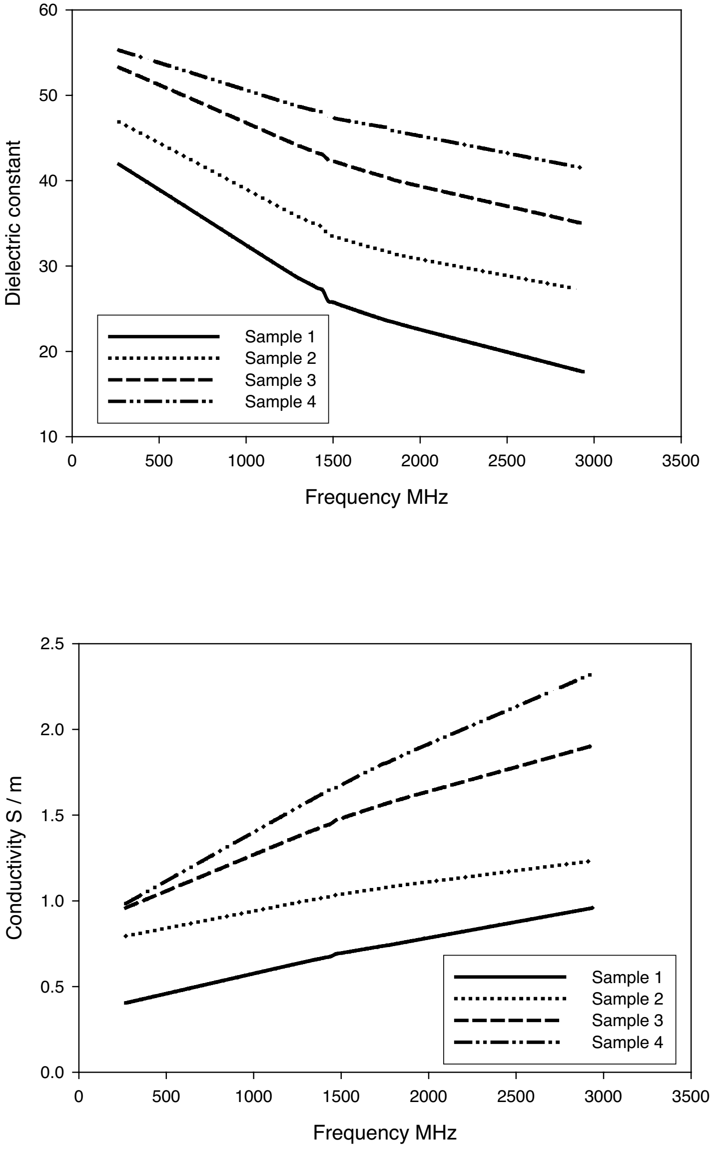

Figure 2. Variation of dielectric parameters with frequency for corn syrup samples in the frequency range of 250 MHz–3000 MHz.

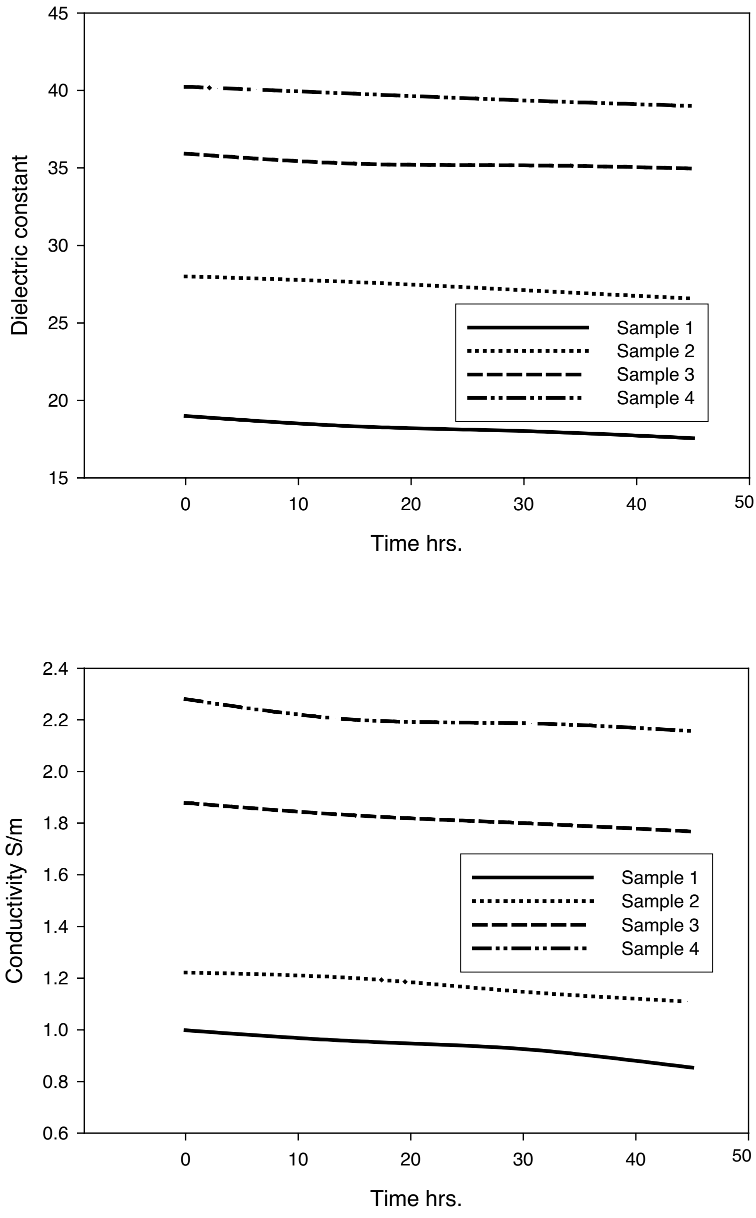

Figure 3. Variation of dielectric parameters with time for various corn syrup samples measured at 3000 MHz.

Table 3. Propagation loss parameters of water, saline and corn syrup at 3000 MHz.

Sample		Total loss dB
Cornsyrup	Sample 1	4.13
	Sample 2	5.88
	Sample 3	6.96
	Sample 4	7.53
Water		180
Saline (0.5% NaCl)		165

and

$$\beta = 2\pi f \sqrt{\mu_0 \varepsilon_0 \varepsilon_r' \left[\sqrt{1 + \tan^2 \delta} + 1\right]} \tag{12}$$

If the wave considered is traveling in the $+z$ direction, $e^{-\alpha z}$ represents the decaying envelope of the wave and $e^{-\beta z}$ represents the sinusoidal nature of the wave whose phase is βz. The total loss encountered by the wave over a distance z consists of dissipation loss L_{diss} due to conduction currents being excited in the medium and diffusion loss L_{diff} due to the spherical spreading of energy [17].

They are given by,

$$L_{diss} = 20 \log_{10} e^{\alpha z} \tag{13}$$

$$L_{diff} = 20 \log_{10}(\beta z) - 29.14(d\beta) \tag{14}$$

Hence the total loss

$$L_{total} = L_{diss} + L_{diff} \tag{15}$$

Table 3 shows a comparison of the loss parameters of corn syrup with that of water and saline. A loss of 4.13 dB to 7.53 dB is an acceptable range when compared to the loss parameters of conventional coupling media like water and saline [17]. As the conductivity of cornsyrup is less, loss tangent decreases and hence the propagation loss. It is seen that losses increase with frequency, which is due to the increase of conductivity.

Microwaves deposit power in tissues when subjected to electromagnetic field. This power deposition heats the tissues. Specific Absorption Rate (SAR) quantifies the amount of power absorbed in a volume of the tissue. The measured values of SAR for various corn syrup samples when exposed to a microwave power of 10 mW at 3000 MHz is reported in Table 2. The data agrees with that of the microwave power absorption rate of biological tissues as per the prescribed safety standards [9, 18].

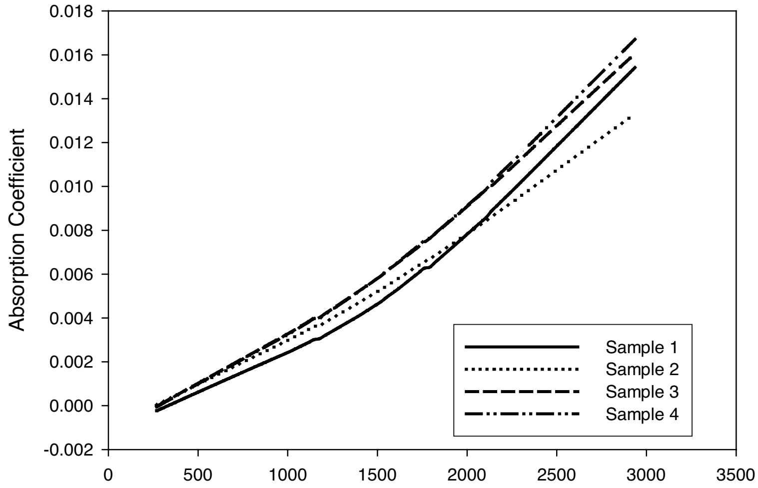

Figure 4. Variation of absorption coefficient with frequency for corn syrup samples.

Figure 2 shows the variation of dielectric constant and conductivity of corn syrup samples with frequency. It is observed from the graphs that coupling medium for any of the breast tissues [14] mentioned in Table 1 can be made from corn syrup by varying its concentration, as good permittivity match is observed. For a given sample the permittivity decreases and the conductivity increases, with the increase in frequency. This result coincides with the studies on dielectric properties of biological tissues [12, 13]. Figure 3 shows that corn syrup samples exhibit almost stable performance over the variations of time.

Figure 4 shows the variation of absorption coefficient of the samples with frequency. It is observed that absorption coefficient increases with frequency which is due to the increase of conductivity.

4. CONCLUSION

Dielectric properties of corn syrup samples exhibit good match with that of the breast tissue samples. Hence usage of this material as the coupling medium minimizes the scattering, enhances coupling of electromagnetic energy and improves the resolution in microwave breast imaging. The material can also be used as an efficient breast phantom as its dielectric parameters are in good match with that of the actual breast tissue samples.

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