STUDY ON PHANTOM MODEL FOR SAR MEASUREMENT

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FACULTY OF ENGINEERING AND TECHNOLOGY

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CERTIFICATE

This is to certify that the dissertation entitled **" STUDY ON PHANTOM MODEL FOR SAR MEASUREMENT"** has been carried out by **SRIPARNA DE** (**University Registration No: 128927 of 2014-2015**) under my guidance and supervision and be accepted in partial fulfilment of the requirement for the degree of **Master of Electronics and Telecommunication Engineering** of Jadavpur University, Kolkata, India. The research results presented in the thesis have not been submitted to any other University/Institute for the award of any Degree or Diploma.

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CERTIFICATE OF APPROVAL*

The foregoing thesis is hereby approved as a creditable study of an Engineering subject, carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

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for the evaluation of the Thesis

Signature of the Supervisor

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC THESIS

I hereby declare that this thesis entitled "STUDY ON PHANTOM MODEL FOR SAR MEASUREMENT**"** contains literature survey and original research work by the undersigned candidate, as a part of her degree of **Master of Electronics and Telecommunication Engineering of Jadavpur University.** All information have been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all the materials and results that are not original to this work.

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INTRODUCTION

1.1 Preface:

In recent days, with the increase in the number of mobile phone users, health risk posed by the presence of electromagnetic field due to cell phone as well as the base station towers have become a major public concern, and thus has become an important issue for the researchers and scientists in Electromagnetic Interference and Electromagnetic Compatibility (EMI and EMC) research field. But it is important to notice that a cell phone emits typically 1 watt power for establishing a communication link whereas GSM and Wi-Fi base station towers emit several hundred times more Effective Integrated Radiated Power (EIRP) for radio coverage. Recently, in May 2011, the WHO's International Agency for Research on Cancer (IARC) has classified electromagnetic fields from mobile phones and other sources "possibly carcinogenic to human" and advised the public to adopt safety measures to reduce exposures, like use of hand-free devices or texting. Some international safety guidelines are introduced by International Commission on Non-Ionizing Radiation Protection (ICNIRP), Federal Communications Commission (FCC) and American National Standards Institute/Institute of Electrical and Electronics Engineers (ANSI/IEEE) in terms of Specific Absorption Rate (SAR), Maximum Permissible Exposure (MPE) limits, restriction on multiple frequency exposures etc. as a precaution for humans exposed to Electro Magnetic Radiation (EMR) caused by those cell phone towers [1-3].

But very few studies have been conducted on plant kingdom viz. fruits, vegetables, flowers and different parts of a plant. Nelson S.O. and his team have characterized various dielectric properties of multiple fruits and vegetables [4] in the context of studying the maturity level of the fruits in terms of moisture content and soluble solid content etc. Among those specimens, some have very high permittivity and conductivity even more than that of the human brain tissue due to high water content and ionic concentration of those specimens; this initiates further scope of research in this particular field so as to propose some safety guidelines for the plant kingdom as well, in order to protect them from the adverse effect of electromagnetic exposure. The research is all the mere necessary because indirectly human being and the rest of the animal kingdom also get affected when they consume different agricultural products and even a huge part of animal kingdom and birds depend on this green part of the environment for habitat purpose.

1.2 Objective of the thesis:

The trees and plants around us, the agricultural field and forestry get continuous exposure to Radio Frequency (RF) due to the cell phone towers and that too without any shield and also throughout the whole day. So, main focus of the thesis is on that part of the environment (mainly the fruits). It is strongly expected that those plant tissues get affected due to RF exposure as high permittivity and loss parameters are observed in plants, fruits etc. due to high water content and ionic concentration. Indian climate has a huge variety of vegetation which includes large variety of fruits growing throughout the whole year. In comparison to that variety, dielectric properties of a small number of Indian fruits have been characterized in the context of SAR measurement which gives a thrust to research on this particular topic. Moreover, to protect the agricultural resources of India, it is highly recommended to incorporate such SAR limits for the plants, fruits and vegetables as well in the revised RF exposure guideline.

In case of human beings, SAR is determined by measuring the electric field distribution in an artificial head (Phantom Model) made of a head-shaped shell filled with tissue-equivalent dielectric liquid which is very costly. In India, the phantom liquid is imported from SPEAG (Schmid & Partner Engineering AG, Zurich, Switzerland), SATIMO (France) and SAR measurement of the mobile phone equipment are performed for compliance testing only at Telecommunication Engineering Center (TEC), Delhi. So, it would be a great achievement if we can prepare the phantom liquids in indigenous way.

The focus area of the thesis work is concentrated on fruits. Hence, for SAR measurement of a fruit, a phantom model made of the fruit shaped shell filled with the fruit-tissue equivalent dielectric liquid is required which is not yet done anywhere according to the literature review. After collecting the information about the dielectric properties of the fruits (some from Literature Review and some from experimental results obtained in the Microwave Engineering Laboratory at Jadavpur University), it is required to propose the recipes of the corresponding tissue equivalent liquids to meet the target values of the dielectric parameters. Only the preparation of customized phantom liquids is not enough, further study of their stability is also necessary. Hence the stability of the phantom liquids needs to be studied in terms of frequency, temperature and time. If the liquids are stable from all the aforementioned respects, then only the recipes can be suggested for preparing the customized phantom models of the fruits.

1.3 Organization of the thesis:

The thesis is divided into eight chapters. A brief introduction about the work and the objective of the thesis has been already discussed in **chapter 1**.

Chapter 2 depicts the literature review about studies reported on the adverse effects of RF exposure on the environment and a brief study of human phantom model. In the concluding part of the chapter, dielectric characterization of some agricultural products is also portrayed.

Chapter 3 deals with the description of the SAR measurement procedure and phantom model. In the later part, a theory for measurement procedure of dielectric properties is presented.

Chapter 4 illustrates the dielectric characterization of some common Indian fruits in the context of SAR measurement at GSM 900MHz frequency band.

Chapter 5 elaborates different recipes for the preparation of phantom liquids of different fruit specimens whose dielectric parameter values are already well known and set as the target values of the dielectric parameters, needed to be achieved by the prepared phantom liquids.

Chapter 6 enlightens the variation of dielectric properties for the prepared tissue equivalent phantom liquids with the variation in temperature along with frequency.

Chapter 7 presents the study of the stability of the prepared phantom liquids with time in terms of their dielectric parameters.

Chapter 8 concludes the work done in this dissertation and provides a brief discussion on the future scope of the work.

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3. IEEE Std C95.1™- 2005, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz. Piscataway, NJ, USA.

4. Stuart O. Nelson , "Dielectric Spectroscopy of Fresh Fruits and Vegetables", *IMTC 2005 – Instrumentation and Measurement Technology Conference Ottawa, Canada.*

LITERATURE REVIEW

2.1 Introduction:

This chapter depicts a review of some important works on adverse effects of RF exposure on the environment which are discussed chronologically. A number of studies reported by various researchers are presented here. Different works on human phantom model have been reviewed. In later parts of the chapter, some references are drawn regarding the dielectric properties characterization of various agricultural products. Finally requirement of the present work is analyzed to prepare the customized phantom models for some specific fruits for the purpose of SAR measurement.

2.2 Adverse Effects of RF Exposure on the Environment:

2.2.1. Human Beings:

Concern about biological effects of RF/microwave exposure started long time ago. In 1925, Cazzamalli. F studied the effects of RADAR on human body [1]. In 1934, Abstracts of the 1st Internet Congress of Electro-radio-biology reported various biological effects of high frequency fields on human beings [2-5]. Hopkins A.L. developed a method for direct estimation of binding of water in biological system in 1960 [6]. The preliminary data showed that neither pure ice nor frozen dry biological materials absorbed high frequency radio energy. However, frozen protein solution or tissues showed a strong heating at −60°C temperature. In 1964, Lyutov. A.I. cited the effects of RF on the central nervous system of human brain [7]. After a decade, Adams R.L. and Williams R.A. studied the effects of RF radiation on blood, cardiovascular system, cells, central nervous system, digestive system, glands, metabolism, reproduction, visual system and internal sound perception [8]. In 1980, Schwan H.P. and Foster K.R. summarized electrical properties of human tissues, macromolecular solutions and cell membranes at frequencies from the Extra Low Frequency (ELF) to microwave range [9]. In June 1988, Bolen S.M did a review on 'Radiofrequency/Microwave Radiation Biological Effects and Safety Standards' and set an RF exposure safety guideline [10]. At the end of 20th century, various researchers cited causing of cancer in relation to Electro-Magnetic Radiation (EMR) [11], [14]. French P.W. et al. and Freude G. et al. cited that microwave emitted by cellular phones changes the morphology and inhibits proliferation of a human astrocytoma cell line and affects human slow brain potentials [12, 13]. Afterwards in the beginning of 21st century, the implications for the epidemiology of cancer and cardiac, neurological and reproductive effects were found to be pronounced. Even more current evidence was reported in The National medical journal of India [15]. Later studies illustrate that increase of risk of acoustic neuroma, sleeping problems, hearing function problem and reproduction problems arise due to EMR [16-19]. In 2009, Kumar N. and Kumar G. cited several examples indicating various biological effects on human being in a report [20]. In other studies it was also suggested that behavioural problems in young children and Alzheimer's disease were also increasing due to the effect of EMR [21-22].

2.2.2. Other animals and wildlife:

Phone masts located in the living areas of animals and birds are continuously irradiating some species that could suffer long-term effects, like reduction of their natural defenses, deterioration of their health, problems in reproduction and reduction of their useful territory through habitat deterioration.

2.2.2.1. Mice:

In 1961, some researchers started different studies on the effects of microwave radiation on mice in the University of California [23]. Moos. V. also studied some effects of acute and chronic microwave irradiation on mice in 1964 and 1968 respectively [24, 25]. Yao K.T.S. and Jiles M. N. also reported the effects of 2450 MHz microwave radiation on cultivated rat kangarco cell in 1969 [26]. In 1994, Lai H et al. pointed that after microwave exposure the rats showed retarded learning while performing in the radial-arm maze to obtain food rewards, situated at the end of each arm [27]. After 4 years, another study of rats' water-maze performance was published by the same group where rats were exposed to 1 mT, 60 Hz magnetic field for one hour and then trained to locate a submerged platform in a circular water-maze. One hour after the last training session, they were tested in a probe trial during which the platform was removed and the time spent in the quadrant of the maze in which the platform was located during the training sessions was scored. Their swim speed was less than that of the non-exposed rats and their swim pattern was also different [28]. Later Yurekli A et al. found oxidative stress in rats due to electromagnetic radiation from GSM base station in 2006 [29]. In 2008, Eberhardt J.L. et al. noticed blood-brain barrier permeability and nerve cell damage in rat brain 14 and 28 days after exposure to microwaves from GSM mobile phones [30]. In 2010, Ntzouni M.P. Stamatakis A., Stylianopoulou F. & Margaritis L.H. found that short-term memory in mice is affected by mobile phone radiation [31].

2.2.2.2. Other animals:

In 1957, Yacin.N.V. noticed changes in the blood of animals subjected to a SHF-UHF field in USSR [32]. Tolgskaya. H. S. and Fukalova P. P. found some morphological changes in experimental animals under the action of electromagnetic fields in the HF and VHF ranges in the year 1968 [33]. Zaret. M. H started his work from 1943 regarding the biological effects (mainly ocular effect) of electromagnetic exposures on human being. In 1969 his foundation reported the effects of low-level microwave irradiation on heart rate in **rabbits** also [34]. In 1984, Gould, J.L. published report on magnetic field sensitivity in animals in the Annual Review of Physiology [35]. Arguably, the most serious concern about the impact of EMF on the living systems appears to be its long term effects on genes and reproductive fitness of species. Today, there is evidence that EMR is genotoxic [36]. An experiment on **common frog** (Rana temporalis, new name Hylarana temporalis) indicated that radiation emitted by phone masts in a real-time situation may affect the development and may cause rise in mortality of exposed **tadpoles**. This research may have huge implications for the natural world, which is now exposed to high microwave radiation levels from a multitude of phone masts [37]. However, it requires long-term monitoring studies for establishing any causative link between reproductive fitness and EMF and such data is presently lacking. Moreover, available short term studies are grossly inadequate. For instance a recent review that analyzed the literature (till 2001) on the effects of EMF associated with mobile telephony on the prenatal and postnatal development of **vertebrates** reported that the majority of the studies examined indicated no strong impact on the animal reproduction and development[36]. On the other hand, activity of **bats** seems to be much reduced in areas with Electro-magnetic fields with densities more than 2V/m [37]. A study in Germany says that there has been reduction in milk production along with increased health problems and behavioral abnormalities of **dairy cows** due to EMR [38].

2.2.3. Birds:

The earliest reported study on impacts of microwave radiation on birds was by Tanner. J.A., Romero-Sierra C. and Davie S.J. in 1967 on the non-thermal effects of microwave radiation on birds [39]. Later Kleinhaus S et al. studied thermal effects of short radio waves on **migrating birds** in 1995 [40]. In another study, which was carried out by National Research Centre of Canada on interaction of electromagnetic fields and living systems with special reference to birds, it was observed that following the onset of radiation, stabilizing period of the egg production in birds was affected. London has witnessed a 75% fall in **house sparrow** population since 1994, which coincides with the emergence of the cell-phone [41].

2.2.4. Bees:

Many recent studies have linked EMR with an unusual phenomenon in bees known as ‘Colony Collapse Disorder’ that occur when a hive's inhabitants (honeybees) suddenly disappear, leaving only queens, eggs and a few immature workers [42, 43].

2.2.5. Plants:

There are very few citations available regarding the effects of RF radiation on plants or agriculture. In 1934, Ghetii. B. published a report on tests to determine the possible influence of very short electro-magnetic waves (2-3m) on seed germination and plant development in Abstracts of the lst Internet Congress of Electro-radio-biology in Italy [44]. Later some publications pointed to trees as absorber/attenuator of microwave / RF wave propagation which causes microwave / RF link failure. Stephens R.B L and Al-Nuaimi M.O. reported a paper on attenuation measurement and modeling in vegetation media at 11.2 GHz and 20 GHz in 1995 [45] and estimated the effects of singly distributed hilltop trees on the path loss of microwave signals in May, 1997 [46]. Again Balmori M. A. studied the effects of microwaves on the trees and other plants [47] in 2003. Then in 2006, Lee Y.H. and Meng Y.S. reported the attenuation of VHF and UHF energy propagation in coconut plantation [48]. In 2008 , Roux D. et al. depicted that high frequency (900 MHz) low amplitude (5 V/m) electromagnetic field is a genuine environmental stimulus that affects transcription, translation, calcium and energy change in tomato [49]. Next year, Ursache M., Mindru G., Creangă D.E., Tufescu F.M., Goiceanu C. found the effects of high frequency electromagnetic waves on the vegetal organisms [50]. Then Zhao Q, Utku. C., Lang, R.H. reported another work where the trees have been explained as scatterer of microwave energy in 2012, [51]. Different morphological characteristic variations in Capsicum annuum (green chilli) seed germination and sapling growth rate were observed over a period of 50 days’ time by Kundu A., Gupta B., Mallick A.I. and Pal S.K. in 2016 at Jadavpur University [52]. In the study it was observed that in the close vicinity of the GSM cell phone, lesser number of seeds were germinated interestingly with a increased sapling height and leaf length but the leafs were wrinkled. So from the aforesaid citations it can be inferred that the EMR has its effects on human being and other animals, birds as well as on the plants and trees also.

2.3 Human Phantom Model and SAR Measurement:

Theoretical studies of **S**pecific **A**bsorption **R**ate (SAR) of electromagnetic energy by biological models have been of increasing interest because of continuing need to evaluate the hazardous levels of EM waves and to refine the presently available safety standards.

In 1979, Durney. C.H., Iskander. M.F., Massoudi. H, Johnson C.C. proposed an empirical relation for calculating average SAR over a broad frequency range for any prolate spheroidal model of human and animal [53]. Durney C.H. [54] continued his calculation to yield a comparative review of EM energy absorptions by different models of human and animals as shown in Fig.2.1. Guy A.W. recommended some safety levels with respect to human exposure to RF electromagnetic fields (300 KHz-100 GHz) in 1980 [55]. In 1982, Michaelson S.M. published some experimental observations on biological effects of EMR on animal and human beings due to different RF exposure duration and also evaluated SAR for human and animals due to RF exposure in the frequency range of 20MHz-10GHz as shown in the table below [56].

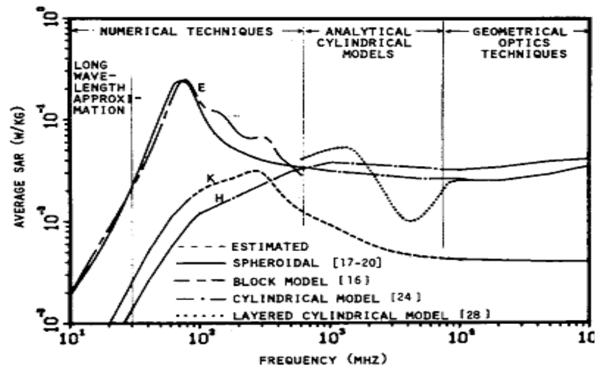


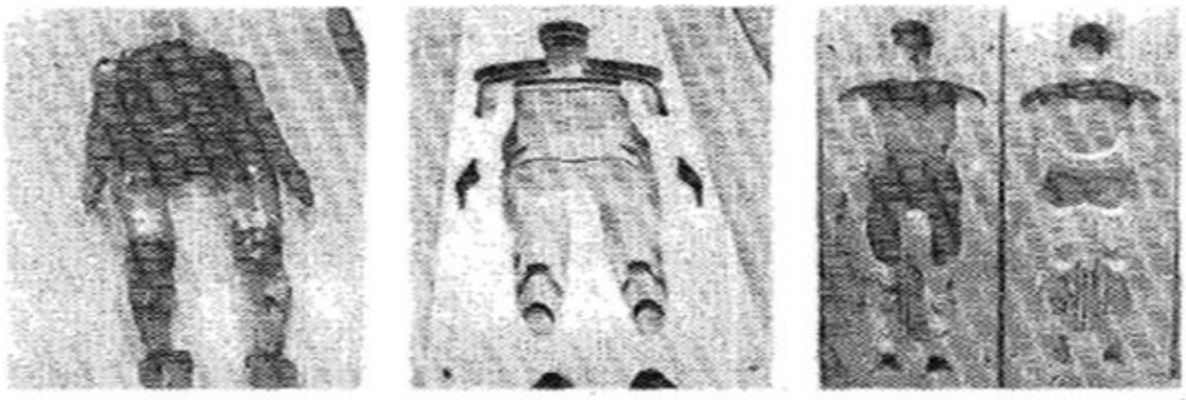
Fig.2.1 Average SAR for different models of the average man irradiated by an EM plane wave of 1mW/cm² power density. E, K, H designate polarizations in which incident electric field vector, propagation vector and magnetic field vector respectively, are parallel to the long axis of the body[54]©IEEE 1980

Table 2.1. SAR for animals and for man (W/kg for 1mW/cm^2 incident Power Density) [56]

Species	Max absorption (MHz)	Frequency(MHz)						
		20-30	70	300	1000	2450	3000	10000
Mouse	2000	8×10^{-4} (0.05)*	0.008 (0.04)	0.06 (1.50)	0.4 (13)	1.00 (36)	0.965 (36.60)	0-322 (12.40)
Rat	600	1.8×10^{-3} (0.12)	0.0125 (0.06)	0.3 (7.50)	0.6 (20)	0.23 (8)	0.26 (9.60)	0.25 (9.60)
Rabbit	320	0.015 (1.00)	0.050 (0.22)	0.80 (20)	0.250 (8.30)	0.15 (5.40)	0.08 (2.96)	0.07 (2.69)
Rhesus	300	1.7×10^{-3} (0.01)	0.0125 (0.06)	0.195 (5.00)	0.10 (3.33)	0.07 (2.50)	0.065 (2.41)	0.060 (2.30)
Dog	200	1.5×10^{-3} (0.10)	0.010 (0.04)	0.100 (2.50)	0.050 (1.67)	0.040 (1.40)	0.037 (1.40)	0.030 (1.15)
Human(1 Y) Man(Av)	150 70	0.004 0.015	0.040 0.225	0.15 0.04	0.065 0.03	0.055 0.028	0.050 0.027	0.042 0.026

*SAR relative to average man.

In 1984, Kraszewskl A., Stuchly M.A., Stuchly S.S., George H., Adamski D. found SAR distribution in over 650 locations of a Full-Scale Human Phantom Model at 350 MHz [57] as shown in Fig.2.2. In the next year, the same group measured the whole-body average, the body-parts average, and the distributions of the SARs which are compared (Fig.2.3) for different wave polarizations for the far and the near-field exposures [58].



(a) (b) (c)

Fig.2.2 Phantom model of man-design details, (a) plastic model of an average man (b) set of templates and (c) styrofoam mold [57]©IEEE 1984.

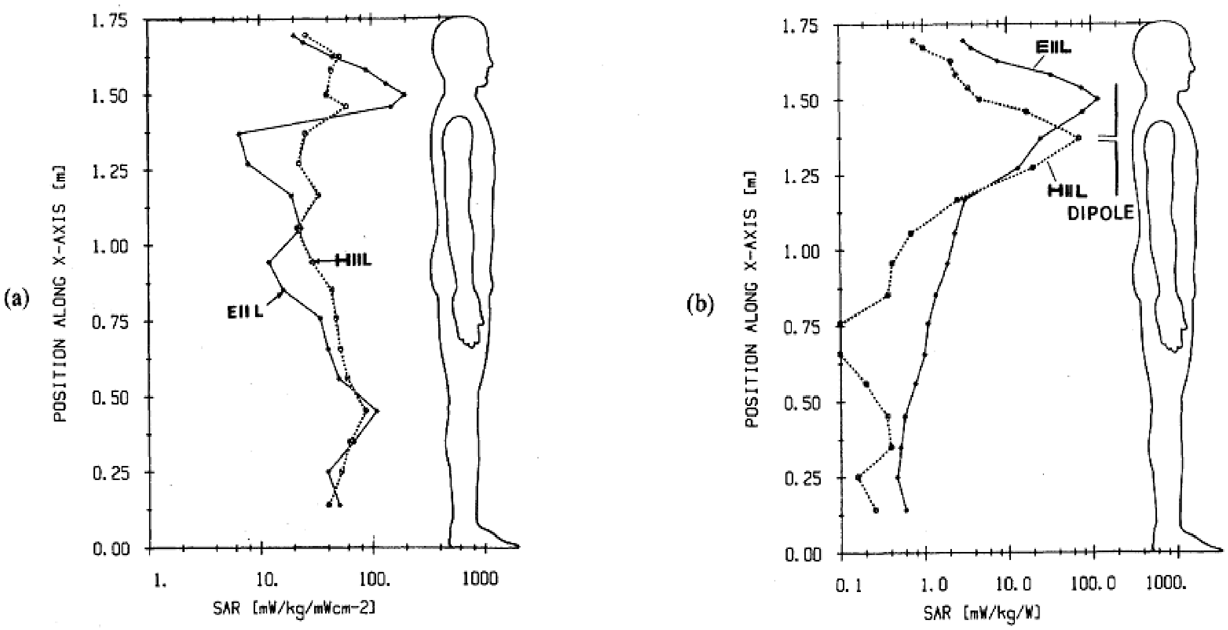


Fig.2.3 SAR averaged over tissue layers perpendicular to the body axis for two polarizations, E-polarization (E||L)-solid lines and H-polarization (H||L)-dashed lines, f=350MHz. (a) Far-field exposure 1 mW/cm^2. (b)Near-field exposure, a resonant dipole placed 8 cm from the body surface and 137cm from the foot base [58] ©IEEE 1985.

Later Hsing-Yi Chen and Hou-Hwa Wang evaluated current and SAR induced in a human head model by the electromagnetic fields irradiated from a cellular phone using FDTD (Finite Difference Time Domain) method [59]. In the beginning of 21st century, Stevens N. and Martens L studied the effect of the position of averaging volume on the averaged SAR values at the typical European cellular telephone frequencies around 900 and 1800 MHz [60].

In 2005, Edwards R.M. and Whittow W.G. investigated relative changes in SAR owing to perturbing metallic spectacles in proximity to the face [61]. In 2010, an interesting study was performed by Akimoto S. et al. where they evaluated SAR in a fetus that was exposed to EM waves from a portable radio terminal when used in vicinity of the maternal abdomen [62]. In the next year, Sabbah A. I., Dib N.I. and Al-Nimr M.A. evaluated SAR and temperature elevation in a multi-layered human head model exposed to RF radiation using FDTD method and found that at the same levels of radiated power, SAR levels in the tissues are less than the safety limit recommendations, except in skin and cerebrospinal fluid (CSF) tissues [63]. In the latter half of 2011, Lee A. and Yun J. compared SAR in Specific Anthropomorphic Mannequin (SAM) phantom for 7-year-old Korean and 5 and 9 year old European child head models for mobile phone exposure at 835 and 1900 MHz [64]. At the end of the year, Gosselin M.C. et al. estimated formulas for SAR in humans exposed to base-station antennas. They validated the formulas numerically using three anatomical human models exposed to 12 generic base-station antennas in the frequency range varying from 300 MHz to 5 GHz at six distances between 10 mm and 3m and found that the estimation formulas for adult models were conservative in predicting the SAR exposure values of the two adults, but not for the child [65]. In the following year, Leung S.W. et al. evaluated SAR induced in mobile phone users inside a vehicle, using different scenarios, including handedness, passenger counts and seating locations as illustrated in figure 2.4 [66].

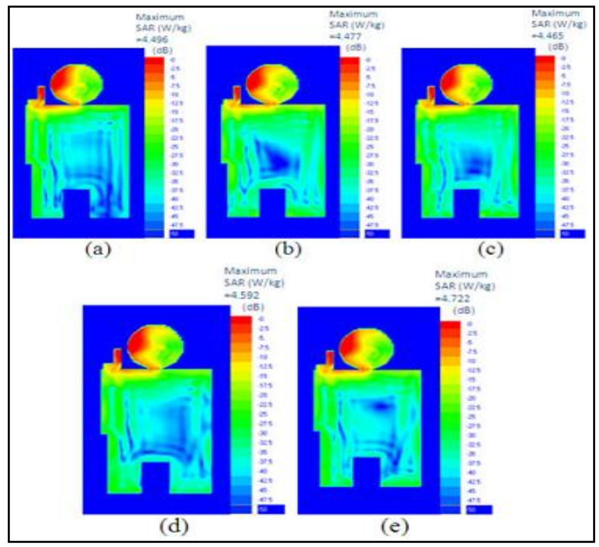


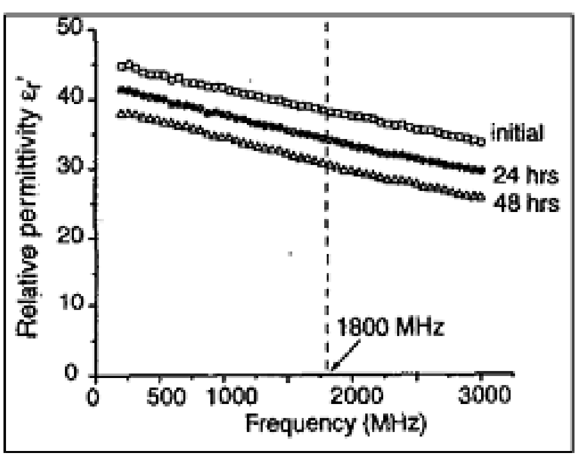
Fig.2.4 SAR distributions for mobile phone user in (a) free space, (b) vehicle with 1 person, (c) vehicle with 2 people (User+P1), (d) vehicle with 3 people (User+P1+P2) and (e) vehicle with 4 people (User+P1+P2+P3).[66]©IEEE2012

2.3.1 Tissue Equivalent Liquid:

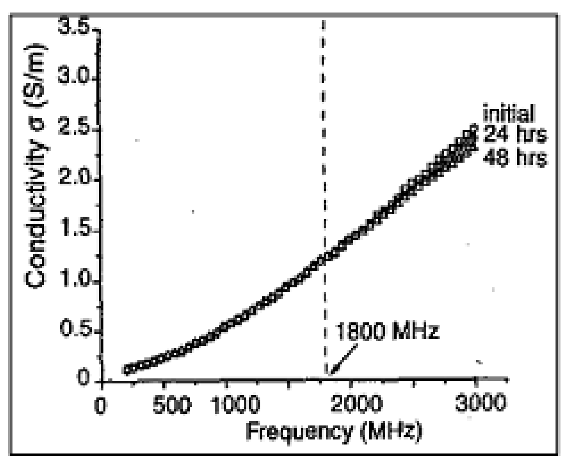
Standard method for SAR measurement has always been a point of discussion among the researchers worldwide. Now, it is equally important to prepare the proper tissue equivalent liquid for human phantom model. So, recipes for tissue-equivalent dielectric liquids have recently been the subject of discussion among international standards organizations.

In 1996, Gabriel C. compiled the dielectric properties of different tissues which constitute the head model [67]. Based on these values of dielectric characteristics of human body, such as the relative permittivities and conductivities of various tissues , various recipes for tissue-equivalent dielectric liquids have been proposed by IEEE and CENELEC [68, 69]. For frequencies about 900MHz, 3 types of tissue-equivalent dielectric liquids are recommended viz. sugar based recipe, glycol based recipe and diacetin based recipe. For 1800MHz, mixtures of de-ionized water and polyhydric alcohol, such as diethylene glycol monobuthyl ether (DGBE) and polyethylene glycol mono phenyl ether (Triton X-100) or mixture of de-ionized water and diacetin are recommended to reach the target value. For more higher frequencies mineral oil and water with TritonX-100 (as surfactant) is used to make an emulsion [70]. In 2002, Monebhurrun V. et al. presented a paper describing FDTD based numerical approach to determine the dielectric properties of the tissue equivalent liquid employed in homogeneous phantoms when testing the SAR compliance of mobile phones [71].

In the same year, Fukunaga K et al. also studied the time dependence of dielectric properties of human body phantoms [72] as depicted in figure 2.5.



(a)



(b)

Fig.2.5 Time dependence of dielectric properties of dielectric liquid at 1800MHz : (a) Permittivity, (b) Conductivity [72]

The same group continued their study further to observe the variation of temperature in the tissue equivalent liquid and consequently the effect on SAR measurement [73] as shown in the following figures:

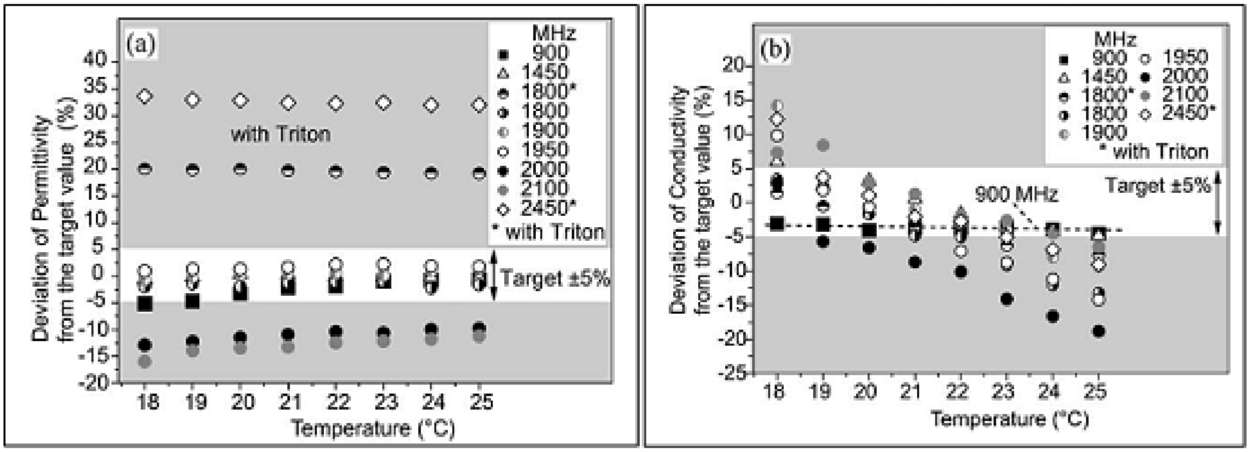


Fig.2.6 Temperature dependence of dielectric properties of tissue equivalent liquids (a) Permittivity (b) Conductivity [73] ©IEEE 2004

IEEE first recommended standard 1528-2003 to practice for determining the peak spatial-average SAR in the human head from Wireless Communications Devices [74]. After few years, Douglas M.G. and Chou C-K. predicted an algorithm which can be used to correct the measured SAR in a homogeneous phantom when its complex permittivity deviates from standardized reference values and analyzed the numerically simulated and measured results over a frequency range of 30–6000 MHz for several antenna sizes and distances to the phantom so as to study a large range of SAR distributions [75] as given by the formula below-

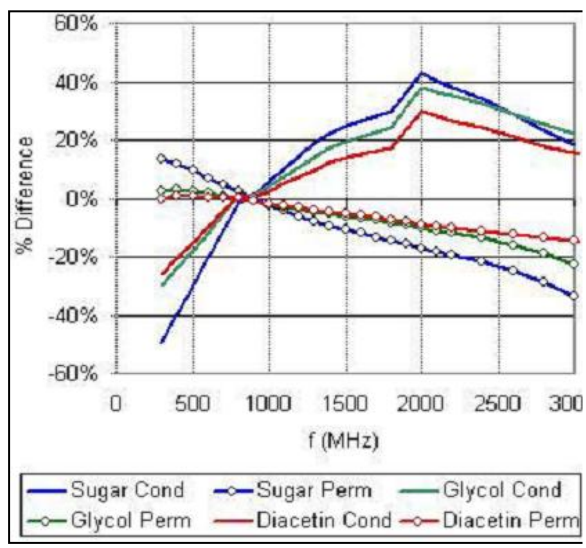


Fig.2.7 Frequency dependence of the permittivity and conductivity of 3 tissue equivalent liquids which meet the targets at 900MHz. The vertical axis represents the percent difference between the permittivity or conductivity from the corresponding target value in IEEE Std 1528-2003

$SAR_m/SAR_t = a + b(\varepsilon_m/\varepsilon_t) + c(\sigma_m/\sigma_t)$

where suffix m represents simulated data and t represents target values.

ε = relative permittivity ; σ = conductivity; a, b = frequency dependent coefficient; $c = 1 - a - b$.

In 2009, Douglas et al. derived a simple prediction algorithm from thousands of simulation results and observed that a linear relationship exists between ΔSAR and both $\Delta\varepsilon_r$ and Δσ. A third order dependence on frequency gives a good fit of the sensitivity coefficients to the data [76]. El wasife K.Y. and Al Batniji A.Y. evaluated electric and magnetic field in tissue equivalent liquids (DGBE type solution) for different EM wave frequencies in 2013 [77]. Next year, Zhang K., Wu T. and Teng J. performed an experiment to test dielectric properties of tissue equivalent liquids using open-ended coaxial sensor based on the transverse electromagnetic (TEM) model [78]. A review of the developed artificial phantoms to emulate human body parts for checking the performance and safety verification of wireless body centric devices and systems was done by Mobashsher A.T. and Abbosh A.M. in 2015 [79].

2.3.2 Phantom shells:

In 1984, Kraszewskl A et al. estimated SAR distribution in a full scale human plastic phantom model at 350MHz [57]. The templates shown in figure 2.2 were used to prepare 2.5-cm-thick styrofoam layers, which were glued together to obtain a hollow phantom of man that was filled with a sugar based solution later to perform the experiment. IEEE Std 1528 ™-2003 recommended that the phantom shell should be constructed from chemical-resistant, low-permittivity and low-loss material with relative permittivity less than 5 and loss tangent less than 0.05 [74]. In any area within the projection of the handset, the shell thickness should be 2 mm ± 0.2 mm, except for the ear and the extended perimeter walls. The phantom shell should be made of materials resistive to compounds used for making tissue-equivalent liquids. In 2005, Onishi T. and Uebayashi S. presented in a paper that the shell had marginal influence in electromagnetic field within the liquid at low frequency whereas above 3GHz the SAR is affected by the shell, though the shell was thin and had dielectric properties much lower than the tissue equivalent liquid [80]. After 3 years, Gabriel C. and Chadwick P. developed whole body shell and solid phantoms and their experience of fabrication indicated that 2mm wall thickness would not be sufficiently strong for the body when filled with tissue-equivalent liquid. So they decided to use 3mm wall thickness and used fiberglass resin for the shell [81]. In 2013, Behari J. and Nirala J.P. developed a SAR measurement system for compliance testing of personal mobile phones where they used perpex (fabricated by plexiglass material) box which contained the brain phantom liquid [82].

2.4 Dielectric Properties Characterization of Various Agricultural Products:

The need for quantitative values of dielectric properties arose from research on the application of RF dielectric heating to agricultural problems. In 1953, Nelson S.O., Soderholm L.H., Yung F.D. first reported quantitative data on dielectric properties of grain (for barley) in 1 to 50MHz frequency range [83]. Similar types of data were soon reported in Russia (1959) for wheat and other grain and crop seeds by Knipper [84]. The other principle application was the possible selective dielectric heating for control of insects that infest stored grain and it took one decade for extensive data measurement as reported by Nelson [85,86].

So far dielectric properties were discussed in detail from an electrical circuit viewpoint, Nelson reported an article [87] in terms of electromagnetic field concepts in 1977. Another earliest applications of such electrical properties was the study of dc electrical resistance of grain for rapidly determining its moisture content [88]. In 1980, because of the need for rapid nondestructive quality measurements for fresh fruits and vegetables, Nelson measured the dielectric properties of some fruits and vegetables at microwave frequencies [89].In 1984, Nelson found that dielectric properties of whole-kernel wheat and ground wheat of the same density are very similar and because of much lower moisture content, the dielectric properties of wheat are much lower than those of the high moisture fruits and chicken breast meat [90]. Noh S. H. and Nelson S. O. measured dielectric properties of rice at frequencies from 50 Hz to 12 GHz in 1989 [91]. Nelson studied variation of the dielectric constant and loss factor with variables such as frequency, moisture content, temperature and product density, important in selecting the best conditions and techniques for either measurement or power applications of some agricultural products[92].

In 1995, Tulsidas T.N., Raghavan G.S.V., Vroot F. and Girard R. determined dielectric properties of water based sugar solution of different concentration at varying temperature and compared the values with that of the grapes of corresponding moisture concentration [93]. They also predicted a model to explain real and imaginary part of relative permittivity (ε' and ε'') of grape as a function of both moisture content (M) in percentage and temperature (t) in °C given below:

$$\varepsilon' = 44.32 + 25.63M - 0.50t - 6.18M^2 + 6.67Mt - 2.07t^2$$

$$\varepsilon'' = 14.36 + 4.13M - 1.69t - 5.40M^2 - 3.13Mt - 0.017\, t^2$$

In 2003, Nelson obtained temperature dependent permittivity data [94] from 5°C to 95°C in the frequency range of 10MHz to 1.8GHz as shown in figure 2.8.

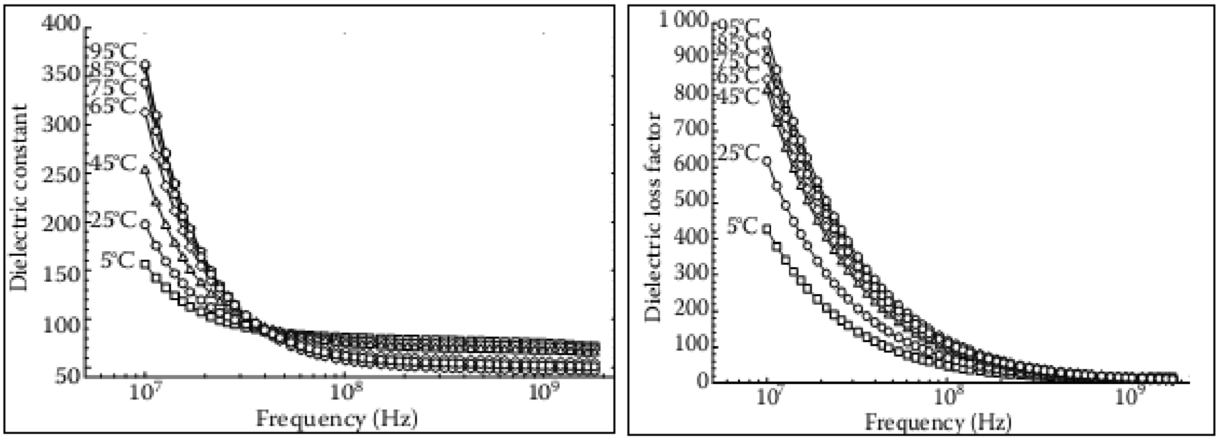


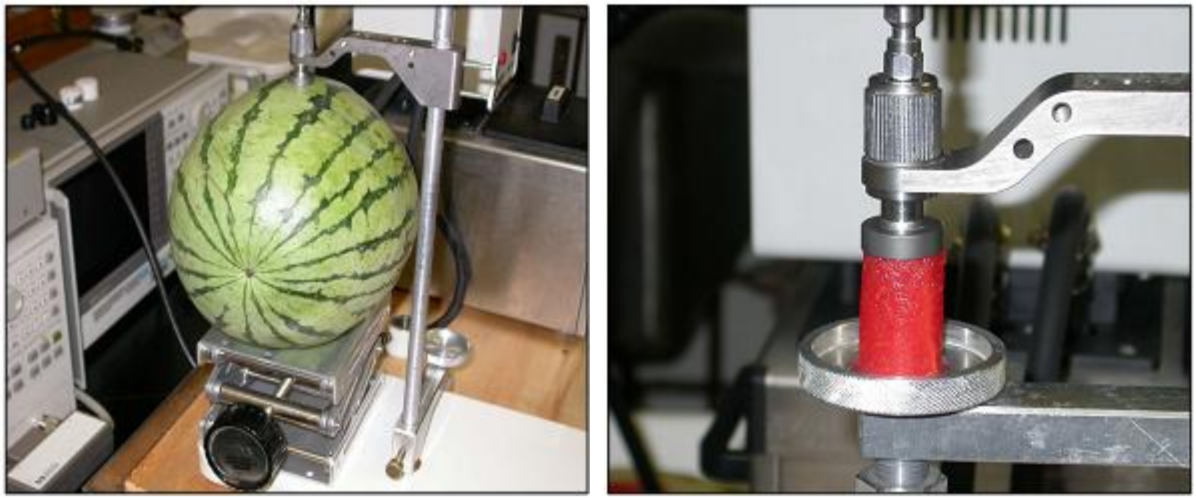
Fig.2.8 Frequency and temperature dependence of the permittivity of navel orange at indicated temperatures [94] ©ASABE 2003.

Nelson summarized values of permittivity at 25°C for all of the nine fruit and vegetable tissues [95] (2005) at frequencies of 10 and 100 MHz and 1 GHz as represented in table 2.2.

Table 2.2 Permittivities of fresh fruits and vegetables at indicated frequencies at 25 °C [95]

Fruit or vegetable	10 MHz		100 MHz		1 GHz	
	ε′	ε″	ε′	ε″	ε′	ε″
Apple	109	281	71	33	64	10
Avocado	245	759	66	89	56	14
Banana	166	834	76	91	65	18
Cantaloupe	260	629	70	72	63	14
Carrot	598	1291	87	157	72	23
Cucumber	123	361	80	39	77	9
Grape	122	570	78	60	73	13
Orange	197	617	78	69	72	14
Potato	183	679	73	77	62	16

In 2007, Guo W.C., Nelson S.O., Trabelsi S., and Kays S.J. measured the dielectric properties of fresh apples from three cultivations at 24°C over 10 weeks in storage at 4°C to determine whether these properties might be usable to determine factors such as soluble solids content (SSC), firmness, moisture content and pH [96]. Later that year, the same group continued their study for honeydew melon and watermelon measuring dielectric properties of both the surface and internal tissues [97, 98] using open ended coaxial probe technique as shown in figure 2.9.



(a) (b)

Fig.2.9 (a)Surface measurement (b) Internal tissue sample of watermelon dielectric properties with open-ended coaxial-line probe [98] ©ASABE

In the same year, Nelson S. O., Trabelsi S. and Zhuang H. worked on fresh chicken breast meat [99]. Nelson S. O. and Trabelsi S. summarized the dielectric properties of all kind of food materials with wide range of moisture content viz. fruits, vegetables, wheat, fresh chicken breast meat and apple juice and discussed the influence of water content on RF and microwave dielectric behavior of food [100] in 2009.

In 2014, Kundu A. and Gupta B. measured the dielectric properties of some fruits and vegetables at 16°C and 25°C using coaxial probe technique at Jadavpur University [101]. Later that year, the same group compared the SAR values of some Indian fruits viz. apple, guava and grape using CST Microwave Studio-2010 as per the revised Indian RF exposure guideline for public exposure zone and found high level of power absorption in the fruits[102].

2.5 Summary:

From the literature review, it is observed that lots of studies have been done on human phantom model for SAR measurement. Comparatively, very little amount of data is available in the context of plants, fruits and vegetables. From some research work, it was observed that quite high power is absorbed within the fruits which may cause possible hazards during their growth period which demands more research in this particular domain. Because, practical SAR measurement is required to support the simulated results.

Moreover, agricultural resources have a huge impact on Indian economy. Hence it is very urgent to incorporate SAR limits for plants, fruits and vegetables in the revised Indian RF exposure guidelines after performing rigorous studies in order to protect them before it is too late. As a first step, we need to perform the dielectric characterization of more number of fruits/vegetables in order to enlarge the data set for the purpose of SAR measurement.

On the other hand, the phantom liquids (very costly) are imported in India for performing SAR measurement for compliance testing as stated earlier. So from the economic point of view, it would be a great achievement if we can prepare the tissue equivalent phantom liquids in indigenous way.

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THEORETICAL BACKGROUND

3.1Introduction:

Mobile communication network has become an important infrastructure all over the world with the number of mobile phone users increasing by leaps and bounds. The health risks posed by the electromagnetic radiation (EMR) from mobile terminals as well as the cell phone towers have become a public concern. So initially it is important to know the types of radiation and how they affect the human being which is discussed hereafter.

The exposure of a person to Radio-Frequency (RF) electromagnetic energy from a nearby wireless transmitter, such as a mobile phone handset, is assessed by determining the Specific Absorption Rate (SAR) and standard measurement procedures are discussed by various international organizations such as International Commission on Non-Ionizing Radiation Protection (ICNIRP) and Federal Communications Commission (FCC). So their guidelines are illustrated in the next section. SAR is generally obtained by measuring the electric field in a 'phantom' that is made of a shell filled with tissue-equivalent liquid, whose dielectric properties almost match with the target values of the dielectric parameters of human head tissue. In the following section the relationship of SAR with the dielectric properties, the SAR measurement procedure and the stability of the tissue-equivalent phantom liquid are depicted.

Next section delves into a brief theory of complex relative permittivity of a material and its frequency dependence (Debye equation). Along with that, the procedure of dielectric properties measurement using open ended coaxial probe technique is also briefly discussed upon because this is the first step to prepare any phantom model.

The requirement of preparing phantom model for fruit has already been discussed in the 'Introduction' chapter. So the conclusion of this chapter gives the framework of the steps which are followed to achieve the target.

3.2 Radiation:

Radiation i.e. the emission or transmission of energy in the form of wave or particle through space or medium is of two types—

I. Ionizing Radiation:— High energy radiation such as X-rays and gamma rays in the higher frequency region of the electromagnetic spectrum can alter human DNA, can destroy tissues and are harmful.

II. Non-ionizing Radiation:—Low frequency radiation up to ultraviolet rays is low energy radiation, such as radio waves and microwave radiation from cell phone or the base station towers.

3.3 Effect of radiation on human being:

Radiation can affect us in two ways—

I. Thermal effects:—It is basically warming of body or surface exposed to low energy non-ionizing radiation such as radio and microwaves. High RF power density more than 100 mW/cm^2 is the cause of “thermal effect”. The radiated energy is absorbed in the body causing a thermal effect. The effect is generally evaluated by the value of the Specific Absorption Rate (SAR).

II. Biological effects:— This implies change in molecular structure of tissues exposed to extremely high energy radiation (ionizing radiation).

However, when microwave radiation from cell phones/towers impinges on the human body, it causes vibration in the water/blood/fluid molecules. Human body consists of 70% liquid and brain contains 90% liquid. When cell phone and cell tower radiation of GSM 900MHz band impinges on human body, the water (within blood, fluids, etc.) molecules inside the body vibrate at a speed of 900 Million times per second, which creates friction. This friction damages DNA and if damage to DNA is greater than DNA repair, then it initiates mutation and cancer.

In the context of this thesis we are mainly concerned about the thermal effect of EMR from cell phone as well as cell phone tower. Hence the term Specific Absorption Rate comes to focus which is discussed in the next section.

3.4 Specific Absorption Rate (SAR):

According to the safety guidelines of ICNIRP, FCC and IEEE standard, SAR is a measure of the rate at which RF energy is absorbed by an object when exposed to an electromagnetic field. It is usually averaged either over a small sample volume (typically a point, 1 g or 10 g of tissue) or over the whole body. Various national regulatory agencies limit the peak SAR (averaged over a 1- or 10-g mass of tissue) and require that wireless transmitters are assessed and comply with the limits prior to being sold in the marketplace. As a consequence, RF exposure guideline has been set for humans by International Commission on Non-Ionizing Radiation Protection [ICNIRP] along with some other international guidelines from FCC and IEEE[1-3].

3.5 ICNIRP and FCC Guidelines for Exposure to RF Field:

Federal Communications Commission (FCC) and The International Committee for Non-Ionizing Radiation Protection (ICNIRP) are the main two regulatory bodies for controlling RF electromagnetic exposure to human body in the whole world. It is relevant to point out that ICNIRP RF exposure guidelines were followed in India for a long time up to 31st August 2012, but then Indian government has lowered the RF exposure level to 1/10th of ICNIRP limits w. e. f. 1st September 2012.

1. ICNIRP Exposure Guidelines:

In 1974, the International Radiation Protection Association (IRPA) formed a working group on Non- Ionizing Radiation (NIR), which examined the problems arising in protection against the various types of NIR. At the IRPA Congress in Paris in 1977, this working group became the International Non-Ionizing Radiation Committee (INIRC). At the 8th international congress of the IRPA (Montreal, 18–22 May 1992), a new, independent scientific organization—the International Commission on Non-Ionizing Radiation Protection (ICNIRP) was established as a successor to the IRPA/INIRC. The functions of the commission are to investigate the hazards that may be associated with the different forms of NIR, develop international guidelines on NIR exposure limits, and deal with all aspects of NIR protection. Biological effects reported as resulting from exposure to static and Extremely-Low-Frequency (ELF) electric and magnetic fields have been reviewed by UNEP/ WHO/IRPA (1984, 1987). Those publications and a number of others, including UNEP/WHO/IRPA (1993) and Allen et al. (1991), provided the scientific rationale for these guidelines [1].

The main objective of this publication is to establish guidelines for limiting EMF exposure that will provide protection against known adverse health effects. An adverse health effect causes detectable impairment of the health of the exposed individual or of his or her offspring. A biological effect, on the other hand, may or may not result in an adverse health effect. Studies on both direct and indirect effects of EMF are described; direct effects result from direct interaction of fields with the body, indirect effects involve interactions with an object at a different electric potential from the body. Results of laboratory and epidemiological studies, basic exposure criteria, and reference levels for practical hazard assessment are discussed, and the guidelines presented apply to occupational and public exposure. Guidelines on high-frequency and 50/60 Hz electromagnetic fields were issued by IRPA/INIRC in 1988 and 1990, respectively, but are superseded by the present guidelines which cover the entire frequency range of time-varying EMF (up to 300 GHz). Static magnetic fields are covered too in the ICNIRP guidelines issued in 1994 (ICNIRP 1994) [1].

- **Guidelines for limiting EMF exposure**

- **Occupational and general public exposure limitations**:

  The occupationally exposed population consists of adults who are generally exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions. By contrast, the general public comprises individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals. In many cases, members of the public are unaware of their exposure to EMF. Moreover, individual members of the public cannot reasonably be expected to take precautions to minimize or avoid exposure. It is these considerations that underlie the adoption of more stringent exposure restrictions for the public than for the occupationally exposed population.

- **Basic restrictions and reference levels:**

Restrictions on the effects of exposure are based on established health effects and are termed basic restrictions. Depending on frequency, the physical quantities used to specify the basic restrictions on exposure to EMF are current density, SAR, and power density. Protection against adverse health effects requires that these basic restrictions are not violated. Reference levels of exposure are provided for comparison with measured values of physical quantities; compliance with all reference levels given in these guidelines will ensure compliance with basic restrictions. If measured values are higher than reference levels, it does not necessarily follow that the basic restrictions have been exceeded, but a more detailed analysis is necessary to assess compliance with the basic restrictions.

Table 3.1: ICNIRP Basic SAR restrictions for time varying electric and magnetic fields:

Exposure Zone	Frequency range	Current density(r.m.s) for head and trunk (mA/m²)	Whole body Average SAR (W/Kg)	Localized SAR (head & trunk) (W/Kg)	Localized SAR(limbs) (W/Kg)
Occupational / Controlled	Up to 1 Hz	40	-	-	-
	1Hz-4Hz	40/f	-	-	-
	4Hz-1KHz	10	-	-	-
	1KHz-100KHz	f/100	-	-	-
	100KHz-10MHz	f/100	0.4	10	20
	10 MHz-10GHz	-	0.4	10	20
Public / Uncontrolled	Up to 1 Hz	8	-	-	-
	1Hz-4Hz	8/f	-	-	-
	4Hz-1KHz	2	-	-	-
	1KHz-100KHz	f/500	-	-	-
	100KHz-10MHz	f/500	0.08	2	4
	10 MHz-10GHz	-	0.08	2	4

NOTE:

1. f is the frequency in hertz.
2. Because of electrical inhomogeneity of the body, current densities should be averaged over a cross-section of $1cm^2$ perpendicular to the current direction.
3. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ (=1.414). For pulses of duration tp the equivalent frequency to apply in the basic restrictions should be calculated as f =1/ (2tp).
4. For frequencies up to 10 KHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.
5. All SAR values are to be averaged over any 6-min period.
6. Localized SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure.
7. For pulses of duration tp the equivalent frequency to apply in the basic restrictions should be calculated as f =1/ (2tp). Additionally, for pulsed exposures in the frequency range 0.3 to 10 GHz and for localized exposure of the head, in order to limit or avoid auditory effects caused by thermo elastic expansion, an additional basic restriction is recommended. This is that the SA should not exceed 10 mJ/kg for workers and 2mJ/kg for the general public, averaged over 10 g tissues.

Table 3.2: ICNIRP Reference levels for occupational exposure to time-varying E and H fields (unperturbed r. m. s)

Frequency range	E field strength (V/m)	H field strength (A/m)	Equivalent plane wave power density (W/m²)
Up to 1 Hz	-	$1.63x10^5$	-
1 Hz-8Hz	20000	$1.63x10^5/f^2$	-
8Hz-25 Hz	20000	$2.5x10^4/f$	-
0.025 KHz-0.82 KHz	500/f	20/f	-
0.82 KHz-65KHz	610	24.4	-
0.065MHz-1MHz	610	1.6/f	-
1MHz-10MHz	610/f	1.6/f	-
10MHz-400MHz	61	0.16	10
400MHz-2000MHz	$3f^{1/2}$	$0.008f^{1/2}$	f/40
2GHz-300GHz	137	0.36	50

Table 3.3: ICNIRP Reference levels for public exposure to time-varying E and H fields (unperturbed r. m. s)

Frequency range	E field strength (V/m)	H field strength (A/m)	Equivalent plane wave power density (W/m²)
Up to 1 Hz	-	$3.2x10^4$	-
1 Hz-8Hz	10000	$3.2x10^4/f^2$	-
8Hz-25 Hz	10000	4000/f	-
0.025 KHz-0.82 KHz	250/f	4/f	-
0.8 KHz-3KHz	250/f	5	-
3KHz-150KHz	87	5	
0.15MHz-1MHz	87	0.73/f	-
1MHz-10MHz	$87/f^{1/2}$	0.73/f	-
10MHz-400MHz	28	0.073	2
400MHz-2000MHz	$1.375f^{1/2}$	$0.0037f^{1/2}$	f/200
2GHz-300GHz	61	0.16	10

NOTE:

1. f as indicated in the frequency range column.
2. Provided that basic restrictions are me t and adverse indirect effects can be excluded, field strength values can be exceeded.
3. For frequencies between 100 kHz and 10 GHz, Seq, E2and H2 are to averaged over any 6-min period.
4. Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width does not exceed 1,000 times the Seq restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.
5. For frequencies exceeding 10 GHz, Seq, E^2 and $H^2$are to be averaged over any $68/f^{1.05}$ -min period (f in GHz).
6. No E-field value is provided for frequencies, 1 Hz, which are effectively static electric fields. Perception of surface electric charges will not occur at field strengths less than 25 kV/m^2. Spark discharges causing stress or annoyance should be avoided.

2. FCC Exposure Guidelines:

The FCC guidelines are based on recommended exposure criteria issued by the NCRP and ANSI/IEEE [1, 3]. The NCRP exposure guidelines are similar to the ANSI/IEEE 1992 guidelines except for differences in recommended exposure levels for the lowest and highest frequencies of the RF spectrum. Both ANSI/IEEE and NCRP recommend two different tiers of exposure limits. The NCRP designates one tier for occupational exposure and the other for exposure of the general population while ANSI/IEEE designates exposure tiers in terms of "environment", one for "controlled" environment and the other for "uncontrolled" environment.

The NCRP and ANSI/IEEE exposure criteria identify the same threshold level at which harmful biological effects may occur and the values for Maximum Permissible Exposure (MPE) recommended for electric and magnetic field strength and power density in both documents are based on this threshold level. In addition, both the ANSI/IEEE and NCRP guidelines are frequency dependent i.e. the whole body human absorption of RF energy varies with the frequency of the RF signal. The most restrictive limits on exposure are in the frequency range of 30-300 MHz where the human body absorbs RF energy most efficiently when exposed to the far field of an RF transmitting source. Although the ANSI/IEEE and NCRP guidelines differ at higher and lower frequencies, at frequencies used by the majority of FCC licensees the MPE limits are essentially the same regardless of whether ANSI/IEEE or NCRP guidelines are used.

Most radiofrequency safety limits are defined in terms of the electric and magnetic field strengths as well as in terms of power density. For lower frequencies, limits are more meaningfully expressed in terms of electric and magnetic field strength values, and the indicated power densities are actually "far field equivalent" power density values. The latter are listed for comparison purposes and because some instrumentation used for measuring RF fields is calibrated in terms of far-field or plane-wave equivalent power density. In the far field of an RF transmitter power density and field strength are related by a closed form.

Table 3.4: FCC limits for controlled/occupational exposure zone

Frequency range (MHz)	Electric field (V/m)	Magnetic field (A/m)	Power density (mW/cm2)	Averaging time (minutes)
0.3-3.0	614	1.63	100*	6
3.0-30	1842/f	4.89/f	(900/f2)*	6
30-300	61.4	0.163	1	6
300-1,500	-	-	f/300	6
1,500-100,000	-	-	5	6
*plane wave equivalent power density		f = frequency in MHz		

Table 3.5: FCC limits for uncontrolled/public exposure zone

Frequency range (MHz)	Electric field (V/m)	Magnetic field (A/m)	Power density (mW/cm2)	Averaging time (minutes)
0.3-3.0	614	1.63	100*	30
3.0-30	824/f	2.19/f	(180/f2)*	30
30-300	27.5	0.073	0.2	30
300-1,500	-	-	f/1500	30
1,500-100,000	-	-	1	30
*plane wave equivalent power density		f = frequency in MHz		

NOTE 1: Occupational/controlled limits apply in situations in which persons are exposed as a consequence of their employment provided those persons are fully aware of the potential for and can exercise control over their exposure. Limits for occupational/controlled exposure also apply in situations when an individual is transient through a location where occupational/controlled limits apply provided he or she is made aware of the potential for exposure.

NOTE 2: General population/uncontrolled exposures apply in situations in which the general public may be exposed, or in which persons that are exposed as a consequence of their employment may not be fully aware of the potential for exposure or cannot exercise control over their exposure.

Table 3.6: FCC limits Localized (Partial body) and Whole body SAR:

Specific Absorption Rate (SAR)	
Controlled/occupational exposure (100KHz – 6 GHz)	Uncontrolled/public exposure (100KHz – 6 GHz)
< 0.4 W/Kg for whole body ≤ 8 W/Kg for partial body	< 0.08 W/Kg for whole body ≤ 1.6 W/Kg for partial body

3.6 Relationship of SAR with Dielectric Properties:

The SAR in a dielectric medium is related to the measured electric field (E) by—

$$\mathrm{SAR} = \frac{\sigma}{\rho}\,|\mathbf{E}|^2 \qquad \textbf{(3.1)}$$

where σ = electrical conductivity (in S/m) of the medium

ρ =density (in kg/m³) of the medium

| E | = root-mean-squared (rms) magnitude of the electric field strength (in V/m).

The electric field strength in a dielectric medium is affected by its permittivity, ε, for a given electric displacement field, **D**, from **D** = ε **E**, where **D** and **E** are complex vectors i.e. phasors for a time harmonic EM field, and ε is in general a complex 3 x 3 matrix which reduces to a scalar for an isotropic medium.

The complex permittivity of a dielectric medium reflects the extent to which that particular medium interacts with electric fields. Permittivity is a measure of how an electric field affects, and is affected by, a dielectric medium. It is determined by the ability of a medium to polarize in response to an electric field. Thus, permittivity relates to a medium's ability to permit the electrostatic lines of flux within that medium.

Permittivity from the theory of electromagnetic field can be written as—

$$\varepsilon=\varepsilon_o\varepsilon_c \qquad \textbf{(3.2)}$$

where ε_o is free space permittivity and ε_c is complex relative permittivity

Complex relative permittivity can be written as—

$$\varepsilon_c = \varepsilon_r{}' - j\,\varepsilon_r{}'' = \varepsilon_r{}' - j\,\varepsilon_r{}' \tan\delta \qquad \textbf{(3.3)}$$

where $\varepsilon_r{}'$ is the real part of complex relative permittivity

and $\varepsilon_r{}''$ is the imaginary part of complex relative permittivity

and tan δ is the loss tangent i.e. the ratio of the imaginary to the real part

The real part of the complex permittivity (ε') of a medium is associated with the RF energy storage capability within the medium in presence of an RF field whereas the imaginary part (ε") is associated with the energy dissipation (Ohmic losses) within the medium i.e. the conversion of RF energy to heat energy in the medium. Both permittivity (ε') and loss tangent (tan δ) are having importance in finding out SAR of an object.

Derivation of Complex Relative Permittivity:

• Following Maxwell's concept, Ampere's circuital law was modified by including a displacement current density term for sinusoidal electric field variations as given below—

$$\nabla \times \mathbf{H} = \mathbf{J} + j\omega\mathbf{D} \qquad \textbf{(3.4)}$$

where **H** is magnetic field strength, **J** is current density, **D** is electric flux density.

The conduction current density is a linear function of the electric field vector (Ohm's law)—

$$\mathbf{J} = \sigma\mathbf{E} \qquad \textbf{(3.5)}$$

where σ is medium conductivity.

Using material formula $\mathbf{D}=\varepsilon\mathbf{E}$ and $\varepsilon = \varepsilon_o\varepsilon_r$ we get—

$$\nabla \times \mathbf{H} = \sigma\mathbf{E} + j\omega\, \varepsilon_o\varepsilon_r \mathbf{E} = j\omega\varepsilon_o \mathbf{E}\, (\varepsilon_r + \sigma/ j\omega\varepsilon_o) = j\omega\varepsilon_o \mathbf{E}\, (\varepsilon_r - j\sigma/ \omega\varepsilon_o) \qquad \textbf{(3.6)}$$

Complex relative permittivity is finally expressed as—

$$\varepsilon_c = \varepsilon_r' - j\, \varepsilon_r'' = \varepsilon_r' - j\, (\sigma/ \omega\varepsilon_o) \qquad \textbf{(3.7)}$$

The procedure of complex permittivity measurement will be discussed in the later part of this chapter. Frequency dependence of dielectric constant and dielectric loss factor will also be discussed along with the Debye equations.

Few points on SAR:

- Unit of SAR is Watt/Kg as it is measured as power absorbed per unit mass of tissue.
- SAR is usually averaged either over a small sample volume or over the whole body.
- SAR measures exposure to fields from 100 KHz to 10 GHz.
- Value of SAR depends on the following factors—
    - the incident field parameters.
    - the characteristics of the exposed body viz. the dielectric parameters, conductivity, density of the material.
    - ground effects and reflector effects of nearby objects.

3.7 Procedure of SAR Measurement in case of human being:

According to ICNIRP standard the basic restriction on Whole Body Averaged SAR for human body is given by [1] :

—0.4W/kg for occupational/controlled exposure

—0.08 W/kg for public/uncontrolled exposure

To evaluate mobile telecommunication equipment, standard methods for measurement of the SAR, including recipes for tissue-equivalent dielectric liquids are presently under discussion by international standard organizations. In these standards, SAR is determined by measuring the electric field distribution in an artificial head (Phantom Model) made of a head-shaped shell filled with tissue-equivalent dielectric liquid i.e. the homogeneous phantom contains a liquid whose target complex permittivity results in a conservative SAR value as compared to the SAR in a heterogeneous tissue composition of a person [4]. Human tissues and the tissue equivalent liquids used for SAR measurement are linear, isotropic and lossy [5].

The maximum averaged SAR computed for a realistic head model reconstructed from magnetic resonance imaging is considered as the reference value. The phantom is obtained by covering the head model with plastic and by replacing all tissues by corresponding tissue equivalent liquids as shown in the figure below. Parametric studies are then performed on this phantom by varying the conductivity and the relative permittivity of the tissue equivalent liquids at the two Global System for Mobile Communications (GSM) frequencies(900 and 1800 MHz) [6].

Fig. 3.1 SAR measurement for human phantom model

To find suitable tissue equivalent liquids for IEEE 1528 and IEC 62209 standards, the committees adopted a two-step approach viz.

I. Target dielectric parameters (ε_r and σ) for a homogeneous phantom are derived that give a conservative estimate of SAR with respect to the heterogeneous tissue composition of a person [4].

II. Then liquid recipes are prepared that match the targets within a tolerance of ±5%.

Based on the values of dielectric characteristics of human body, such as the relative permittivities and conductivities of various tissues , various recipes for tissue-equivalent dielectric liquids have been proposed. Table 3.7 shows typical dielectric properties of the different tissues which constitute the head model [7].

Table 3.7 Dielectric properties of the tissues constituting the head model

Tissue type	900MHz		1800MHz	
	εr	σ (S/m)	εr	σ (S/m)
CRL *	68.60	2.41	67.20	2.92
Bone	16.60	0.24	15.56	0.43
Cartilage	42.65	0.78	40.22	1.29
Marrow	11.30	0.23	10.68	0.35
Grey matter	52.70	0.94	50.08	1.39
White matter	38.90	0.59	37.01	0.92
Eye	55.30	1.17	53.57	1.60
Inner ear	75.90	2.06	74.00	2.50
Ear(skin)	46.00	0.84	43.85	1.23
Skin	46.00	0.84	43.85	1.23

(*CRL = Cephalo Rachidian Liquid)

3.8 Phantom Liquid preparation:

The liquid recipes must also be non-toxic, non-corrosive to the electric field probe and phantom shell and weak enough in viscosity to allow for the movement of the electric field probe. Until recently, finding tissue equivalent liquids that match the target dielectric parameters has been challenging. One reason is that the frequency variation of the dielectric properties of many suitable liquids is different from those of the target parameters. Three recipes are shown that were adjusted to match the targets at 900 MHz i.e. ε_r=42.3, σ=0.99(EN 50361) and ε_r=41.5, σ=0.97(IEEE 1528-200x) [5]:

1.Sugar based recipe

Sugar(sucrose)	56.50%
Deionized water	40.92%
Hydroxyethyl Cellulose(HEC)	1.00% .
NaCl	1.48%
Bactericide($NaNO_3$)	0.10%

2. Glycol-based recipe

DGBE	48%
Deionized water	50.84%
NaCl	1.16%

3. Diacetin-based recipe

Diacetin	53%
Deionized water	45.88%
NaCl	1.02%
$NaNO_3$	0.10%

For higher frequencies, mixtures of de-ionized water and polyhydric alcohol, such as Diethylene Glycol Monobutyl Ether (DGBE), and polyethylene glycol mono phenyl ether (Triton X-100),or mixtures of de-ionized water and diacetin are recommended to reach the target value of ε_r=40.1, σ=1.38(EN 50361) and ε_r=40, σ=1.4(IEEE 1528-200x) [8]. The suitable proportion as mass percentage of the components is (1800MHz):

Deionized Water	65.30%
DGBE	16.33%
Triton X-100	17.96%
NaCl	0.41%

For higher frequencies mineral oil and water with TritonX-100 is used as surfactant to make an emulsion [9]. The suitable proportion as mass percentage of the components is (3000MHz):

Deionized water	61.3%
Mineral oil	12.6%
TritonX-100	25.4%
NaCl	0.7%

3.9 Changes in Dielectric Properties of the Tissue Equivalent Liquid:

The dielectric properties of the recommended tissue equivalent liquid change with time and temperature and accordingly affect the SAR measurement [8].

- The conductivity decreases with increasing temperature in all glycol-type specimens.
- The permittivity, on the other hand, remains almost constant.
- With the evaporation of water, the permittivity decreases, although the conductivities remain constant.

3.9.1 Increase in temperature of Tissue Equivalent Liquid by heat of mixing:

- When the ingredients are mixed, the heat of mixing increases the temperature of the mixture. Fig. 3.2 shows the increase in temperature of the mixtures. It becomes stable in about 20 minutes after mixing.
- The sugar-based liquid is not used, because it requires heating to mix the ingredients from the start.
- More than 5°C increase is shown in the mixture of de-ionized water, DGBE, and NaCl. The mixture with Triton shows slightly less of an increase in temperature than the others.

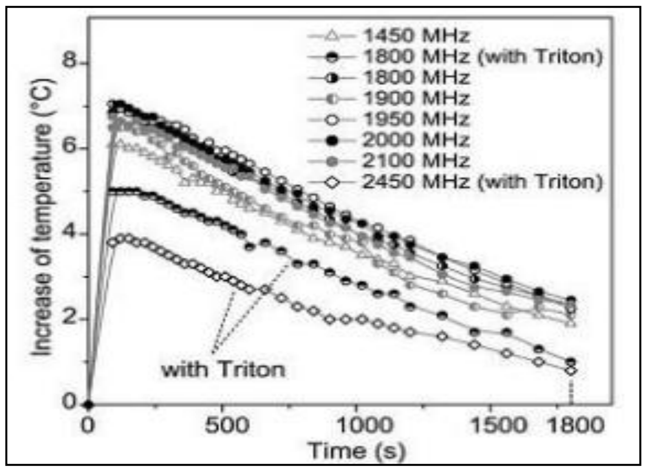


Fig.3.2 Increase in temperature by heat of mixing [11]

3.9.2 Effect of temperature increase in dielectric properties of Tissue Equivalent Liquid:

- The temperature dependence of permittivities and conductivities of specimens are shown in the following figure. The values are described in terms of deviation from the target value for each specimen.
- The permittivities are almost constant within the tolerance of ±5% at the outset against changes in temperature.

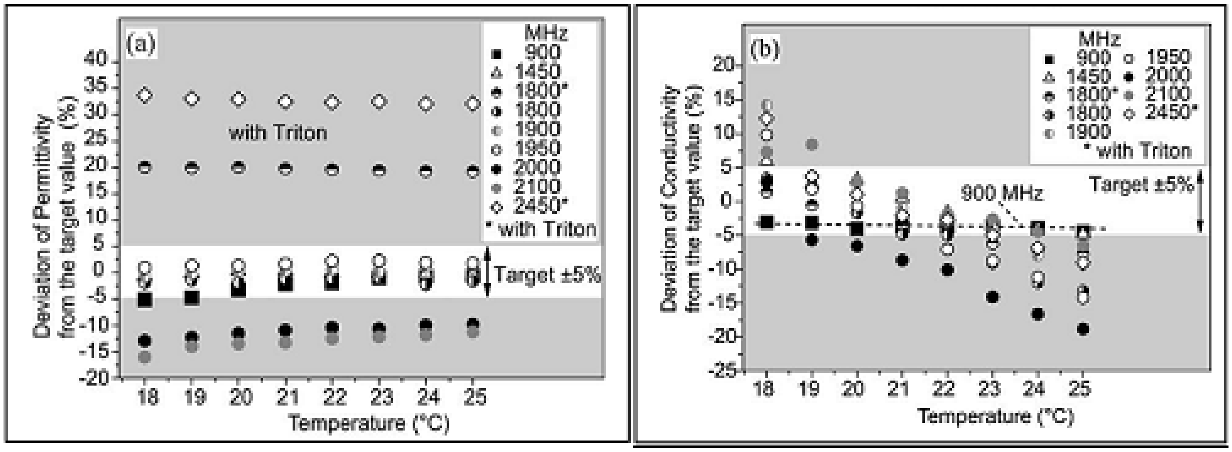


Fig.3.3 Temperature dependence of dielectric properties (a) Permittivity (b) Conductivity [8].

- On the other hand, conductivity decreases with increasing temperature at the rate of about 2% per degree. In order to maintain the conductivity variation within ± 5%, it would make sense to comply with temperature tolerance during testing; that is, ±2°C.
- For glycol type liquids the stability of dielectric properties against temperature is low. So further research developed non-toxic tissue-equivalent liquids which are stable against the temperature change for various frequencies from 50 MHz to 2450 MHz .

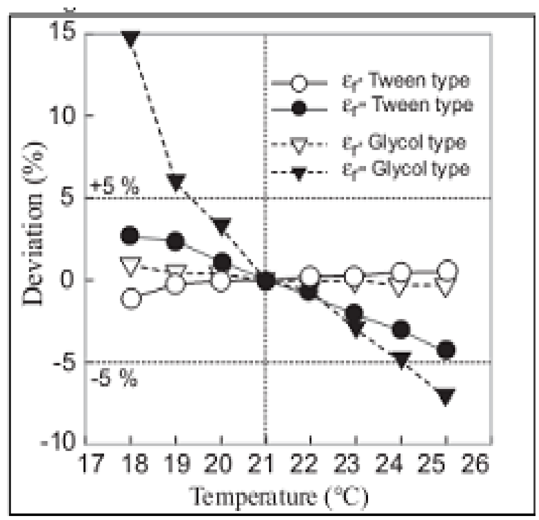
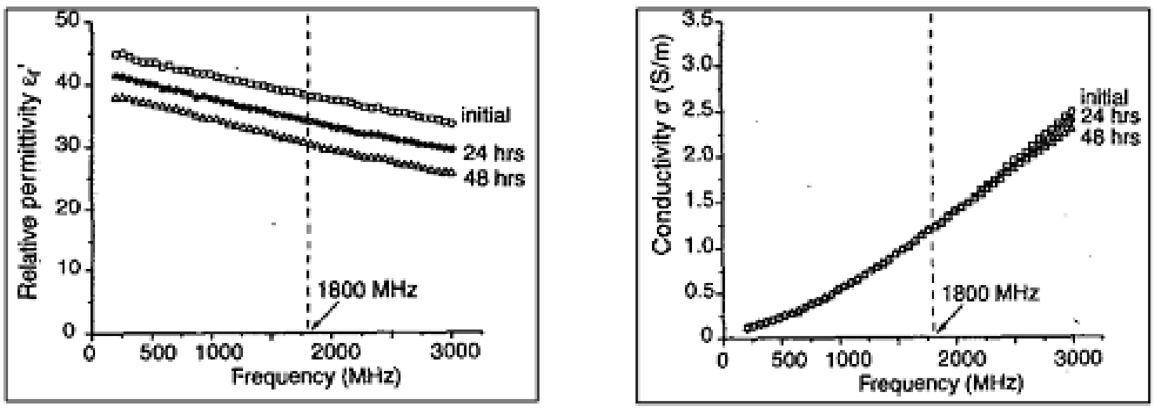


Fig.3.4 Temperature dependence of tissue-equivalent liquids [10]

- The materials used in recipes are basically de-ionised water and a nonion surfactant polyoxyethylene sorbitan monolaurate. This surfactant is well known as Tween, and is used in foods, cosmetics, etc. The use of this material was originally proposed by Alan Preece of Bristol University [10]. The effect of temperature variation is shown in figure 3.4.

3.9.3 Time dependence of dielectric properties of Tissue Equivalent Liquid:

- Relative permittivity decreases with time for glycol type liquid without Titron X-100. It becomes about 10% less after 24hours and about 20% less after 48 hours at the frequency of 1800MHz due to evaporation of water under a low humidity (20%) experimental condition [11].
- The conductivity remains almost constant throughout the whole time duration. The changes are depicted in figure 3.5 (a) and (b). Although a small amount of preservative should be added to avoid growth of fungi for long time use, it should improve working condition of SAR measurements [10].



(a) (b)

Fig 3.5 Time dependence of dielectric properties of dielectric liquid at 1800MHz: (a) Permittivity, (b) Conductivity [11]

In a similar way, if we want to make a phantom model for the fruits for the purpose of SAR measurement, initially we have to prepare the customized tissue equivalent phantom liquid for those particular fruits and then we need to study the stability of the liquid with respect to frequency, temperature and time also. But to prepare the phantom liquids, first and foremost step is to characterize the dielectric properties of the fruits. Because the values of the dielectric parameters viz. dielectric constant and loss tangent of the fruit tissue will be set as the target values while preparing the tissue equivalent phantom liquids. So in the following section, a brief theory of dielectric properties of a material is discussed and the procedure to measure the dielectric parameters is also elaborated.

3.10 Theory of Complex Permittivity:

3.10.1 Polarization in the context of Relative Permittivity:

The complex permittivity is a quantity which describes the electrical properties of materials. In case of dielectrics, the complex permittivity describes the interaction between the dielectric and the applied external electric field. The interaction of an electric field with a biological tissue has its origin in the response of the charged particles to the applied field; the displacement of these charged particles from their equilibrium positions gives rise to induced dipoles which respond to the applied field. The phenomenon is described in detail in the following section.

Electric dipole moment (**p**) is a vector which is nothing but the separation between a positive and negative charge of equal magnitude Q given by the expression— **p** = Q **a**

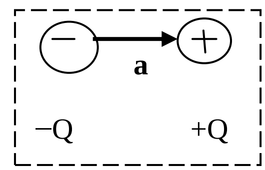


Fig.3.6 Electric dipole moment

where **a** is the vector from negative to positive charge as shown in the adjacent figure.

The net charge within a neutral atom is zero. In general, the center of negative charge of the electrons coincides with the positive nuclear charge, which means that the atom has no net dipole moment in absence of any external field as depicted in figure 3.7 (a). However, when this atom is placed in an external electric field (**E**), it will develop an induced dipole moment. The electrons, being much lighter than the positive nucleus, become easily displaced by the field, which results in the separation of the negative charge center from the positive charge center, as shown in figure 3.7 (b). This separation of charge and resulting induced dipole moment is called **polarization**.

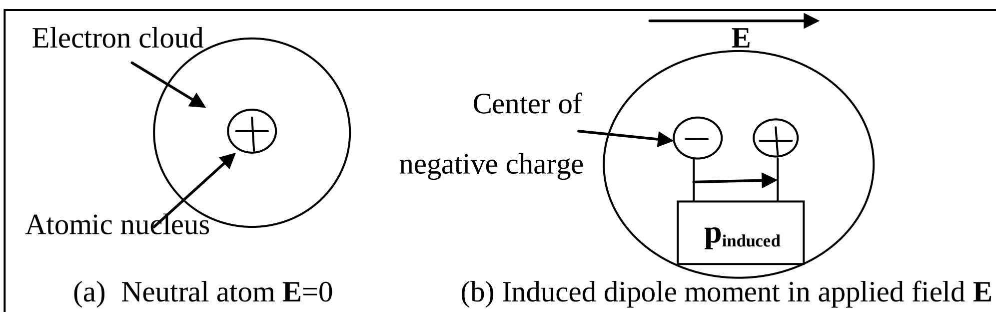


Fig.3.7 Origin of polarization

An atom is said to be polarized if it possesses an effective dipole moment i.e. if there is a separation between the centers of negative and positive charge distributions. To relate induced dipole moment to its cause i.e. the applied electric field (**E**), a coefficient called polarizability (α) is introduced given by—

$$\mathbf{p}_{\text{induced}} = \alpha \mathbf{E} \qquad \textbf{(3.8)}$$

The term polarizability of atom depends on the polarization mechanism shown by various materials as discussed below—

- **Electronic or Atomic Polarization**

This involves the separation of the centre of the electron cloud around an atom with respect to the centre of its nucleus under the application of electric field as discussed above.

- **Ionic Polarization**

This happens in solids with ionic bonding which automatically have dipoles but which get cancelled due to symmetry of the crystals. Here, external field leads to small displacement of ions from their equilibrium positions and hence induces a net dipole moment.

- **Dipolar or Orientation Polarization**

Polar dielectrics (such as water) contain permanent dipoles due to the asymmetric charge distribution of unlike charge partners in a molecule which tend to reorient under the influence of a changing electric field, thus giving rise to orientation polarization. The orientation polarization is temperature and frequency dependent which will be discussed in detail in the next section. Orientation polarization due to an alternating electric field is dominant at microwave frequency region.

- **Interface or Space Charge Polarization**

This involves limited movement of charges resulting in alignment of charge dipoles under applied field. This usually happens at the grain boundaries or any other interface such as electrode-material interface.

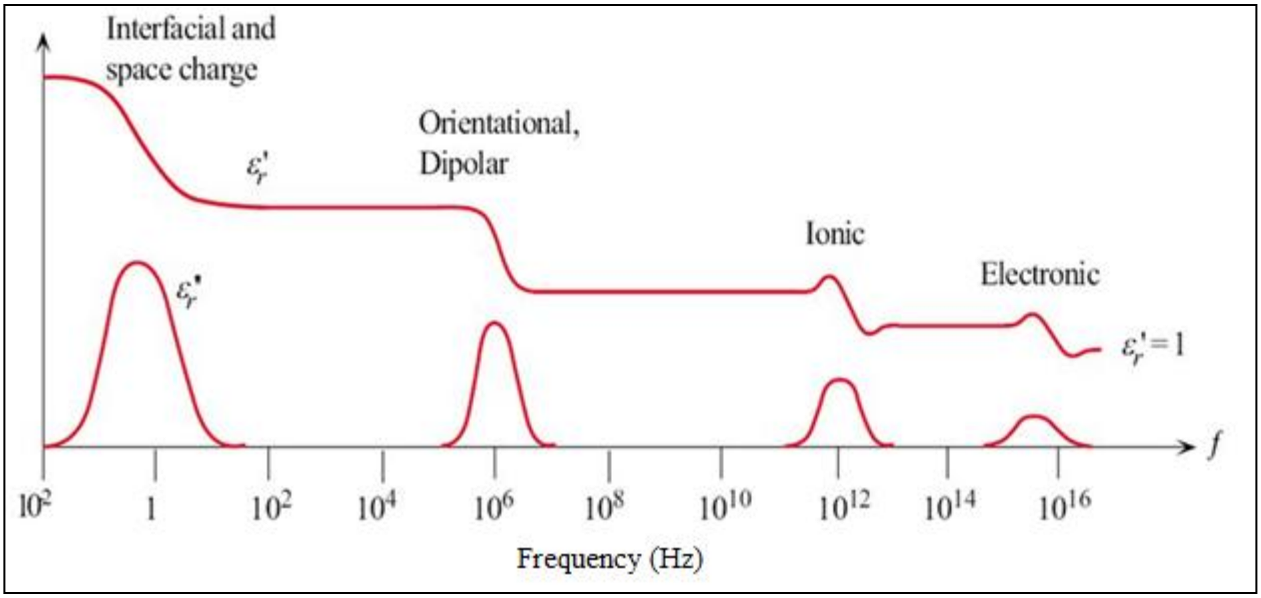


Fig.3.8 Polarization effects at broad frequency range [12]

3.10.2 Frequency dependence of dielectric properties for a dipolar molecule:

The static dielectric constant is an effect of polarization under dc conditions. When the applied field is sinusoidal then the polarization of the medium under these conditions leads to an ac dielectric constant that is generally different from the static case. For dipolar molecule we have to consider orientation polarization. The sinusoidally varying field changes magnitude and direction continuously, and it tries to line up the dipoles in one direction and then in the other direction and so on. If the instantaneous induced dipole moment **p** per molecule can instantaneously follow the field variations, then at any instant

$$\mathbf{p} = \alpha_d \mathbf{E} \qquad \textbf{(3.9)}$$

and the polarzability has its maximum value from Boltzman statistics given by

$$\alpha_d = \frac{p_o^2}{3kT} \qquad \textbf{(3.10)}$$

where p_o is the induced dipole moment at dc condition.

k is the Boltzman's constant

and T is the absolute temperature in Kelvin.

Two factors opposing the immediate alignment of the dipoles with the field are—

- Thermal agitation tries to randomize the dipole orientations. Random jolting from lattice vibrations in the liquid, aid the randomization of the dipole orientations.
- The molecules rotate in a viscous medium by virtue of their interactions with neighbors, which does not allow the dipoles to respond immediately with the change in the applied field.

If the field changes too fast then the dipoles cannot follow the field and remain randomly oriented. At high frequencies, α_d will be zero as the field cannot induce a dipole moment. But at low frequencies, the dipoles can respond rapidly to follow the field and α_d has its maximum value. So basically α_d changes it value from the maximum given in equation 3.10 to zero as the frequency of the field is increased. We need to find the behavior of α_d as a function of frequency ω so that we can determine the dielectric constant ε_r.

Let us assume that after a prolonged application, corresponding to dc conditions, the applied field across the dipolar medium is suddenly decreased from $\mathbf{E}_o$ to $\mathbf{E}$ at a time we define as zero, as shown in the figure below. So the induced dipole moment per molecule should be smaller and given by $\alpha_d(0)\mathbf{E}$ where $\alpha_d(0)$ is α_d at $\omega = 0$ i.e. dc conditions. So the induced dipole moment has to decrease or relax as shown in figure 3.9.

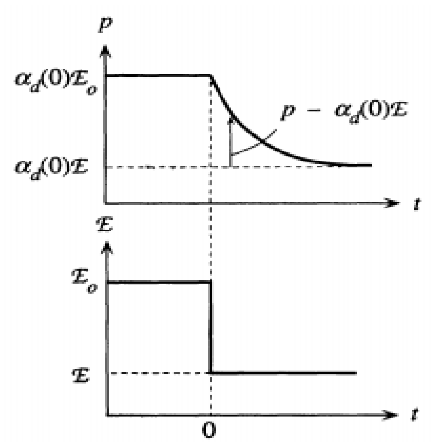


Fig.3.9 The decrease in induced dipole moment as a result of decrease in the applied field [12]

So the **dipolar relaxation** occurs due to random jolting of the molecules in the dipolar medium and their collisions with the wall of the container. The mean period associated with the time for the dipoles to revert to random orientation when the electric field is reduced is called the **relaxation time** (τ). We expect a smooth change over from polarization to zero within this relaxation time.

If $\mathbf{p}$ is the instantaneous induced dipole moment, then $\mathbf{p}-\alpha_d(0)\mathbf{E}$ is the excess dipole moment, which must eventually disappear to zero through random collisions as $t\to\infty$. It would take an average of τ seconds to eliminate the excess dipole moment. We have to assume that the rate at which induced dipole moment decreases from oriented to random state is proportional to the number of oriented dipoles i.e. the excess dipoles as given below—

$$\frac{d\mathbf{p}}{dt} = -\frac{\mathbf{p}-\alpha_d(0)\mathbf{E}}{\tau} \qquad \textbf{(3.11)}$$

Let the applied sinusoidal field be $\mathbf{E}=\mathbf{E}_o \sin \omega t$ which can be expressed in exponential form as—

$$\mathbf{E}=\mathbf{E}_o \exp(j\omega t) \qquad \textbf{(3.12)}$$

Putting the expression of $\mathbf{E}$ in equation (3.11) —

$$\frac{d\mathbf{p}}{dt} = -\frac{\mathbf{p}}{\tau} + \frac{\alpha_d(0)}{\tau}\mathbf{E}_o \exp(j\omega t) \qquad \textbf{(3.13)}$$

Solving above equation induced dipole moment is—

$$\mathbf{p}= \alpha_d(\omega)\, \mathbf{E}_o \exp(j\omega t)$$

$$\text{where } \alpha_d(\omega) = \frac{\alpha_d(0)}{1+j\omega\tau} \qquad \textbf{(3.14)}$$

$\alpha_d(\omega)$ is the orientational polarizability which depends on the frequency of the applied ac electric field and it is a complex number indicating that $\mathbf{p}$ and $\mathbf{E}$ are out of phase.

- At low frequencies, $\omega\tau>>1$, $\alpha_d(\omega)$ is nearly equal to $\alpha_d(0)$ and $\mathbf{p}$ is in phase with $\mathbf{E}$. The rate of relaxation $1/\tau$ is much faster than the frequency of the field or the rate at which the polarization is being changed; $\mathbf{p}$ then closely follows $\mathbf{E}$.
- At very high frequencies, $\omega\tau<<1$, the rate of relaxation $1/\tau$ is much slower than the frequency of the field and $\mathbf{p}$ can no longer follow the variations in the field.

Although we considered only orientational polarization, in general a dielectric medium will also exhibit other polarization mechanisms and certainly electronic polarization since there will always be electron clouds around individual atoms, or electrons in covalent bonds.

Let us consider a dipolar dielectric in which there are both orientational and electronic polarizations, α_d and α_e, respectively, contributing to the overall polarizability. Electronic polarization α_e will be independent of frequency over the typical frequency range of operation of a dipolar dielectric (i.e. RF and microwave). At high frequencies, orientational polarization will be too sluggish too respond, $\alpha_d = 0$, and the ε_c will be $\varepsilon_{r\infty}$ (The subscript 'infinity' implies high frequencies where orientational polarization is negligible.) The relative permittivity and polarizabilities are generally related as—

$$\varepsilon_c = 1 + \frac{N}{\varepsilon o}\alpha_e + \frac{N}{\varepsilon o}\alpha_d(\omega) = \varepsilon_{r\infty} + \frac{N}{\varepsilon o}\alpha_d(\omega) = \varepsilon_{r\infty} + \frac{N}{\varepsilon o}\frac{\alpha_d(0)}{1+j\omega\tau} \quad \textbf{(3.15)}$$

where 1 and α_e are combined to represent high frequency ε_c as $\varepsilon_{r\infty}$ and the second term of the above sum determines the contribution of orientational polarization to the static relative permittivity ε_{rdc}, so $\frac{N}{\varepsilon o}\alpha_d(0)$ is simply $(\varepsilon_{rdc} - \varepsilon_{r\infty})$. Hence the above equation becomes—

$$\varepsilon_c = \varepsilon_r' - j\,\varepsilon_r'' = \varepsilon_{r\infty} + \frac{(\varepsilon_{rdc} - \varepsilon_{r\infty})}{1+j\omega\tau} \quad \textbf{(3.16)}$$

Rationalizing the above equation we get the **Debye equation**—

$$\varepsilon_r' = \varepsilon_{r\infty} + \frac{(\varepsilon_{rdc} - \varepsilon_{r\infty})}{1+(\omega\tau)^2} \quad \textbf{(3.17a)}$$

$$\varepsilon_r'' = \frac{(\varepsilon_{rdc} - \varepsilon_{r\infty})\omega\tau}{1+(\omega\tau)^2} \quad \textbf{(3.17b)}$$

Equations 3.17a and 3.17b depicts the behavior of ε_r' and ε_r'' as a function of frequency shown in the adjacent figure. The real part ε_r'(dielectric constant), decreases from its maximum value $\varepsilon_r'(0)$ corresponding to $\alpha_d(0)$ to 1 at high frequencies when $\alpha_d= 0$ as $\omega\rightarrow\infty$. The imaginary part ε_r''(dielectric loss factor) is zero at low and high frequencies but peaks for $\omega\tau = 1$ or at $\omega= 1/\tau$ which is called a **Debye loss peak**. The significance of the term 'loss' is discussed in the following section.

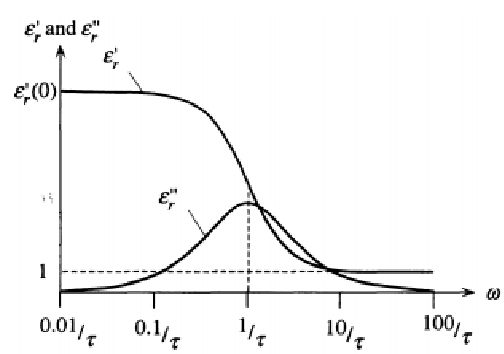


Fig. 3.10 Real and imaginary part of relative permittivity as a function of frequency [12]

The dielectric medium behaves like an ideal (lossless) capacitor of capacitance C, which is in parallel with a conductance Gp. Then the admittance of the capacitor which is filled with a dielectric medium of relative permittivity ε_c can be written as —

$$Y = \frac{j\omega A\varepsilon_o\varepsilon_c(\omega)}{d} = \frac{j\omega A\varepsilon_o\varepsilon_r'(\omega)}{d} + \frac{\omega A\varepsilon_o\varepsilon_r''(\omega)}{d} = j\omega C + G_p \quad \textbf{(3.18)}$$

$$\text{where } C = \frac{A\varepsilon_o\varepsilon_r'(\omega)}{d} \quad \text{and} \quad G_p = \frac{\omega A\varepsilon_o\varepsilon_r''(\omega)}{d}$$

We know that capacitance (C) is used as an energy storing device and conductance (G_p) i.e. the inverse of resistance (R_p) is associated with energy dissipation. Thus dielectric constant i.e. the real part of permittivity (ε_r') of a medium is associated with the RF energy storage capability within the medium in presence of an RF field whereas the imaginary part (ε_r'') is associated with the energy dissipation (loss) within the medium i.e. the conversion of RF energy to heat energy in the medium.

The rate of energy storage in the field is determined by ω whereas the rate of energy transfer to molecular collisions is determined by 1/τ. When ω= 1/τ, the two processes, energy storage by the field and energy transfer to random collisions, are then occurring at the same rate, and hence energy is being transferred to heat most efficiently. The peak in ε_r'' versus ω is called a **relaxation peak** (Debye loss peak), which is at a frequency when the dipole relaxations are at the right rate for maximum power dissipation. This process is known as **dielectric resonance.**

In figure 3.8 the frequency dependence of real and imaginary part was already shown mentioning different polarization mechanism. Although the figure shows distinctive peaks in ε_r'' and transition features in ε_r', in reality these peaks and various features are broader. There is no single well defined lattice vibration frequency but instead an allowed range of frequencies [12].

Now, the issue is how to measure this dielectric constant and dielectric loss factor. There are different methods available for the measurement. However, each of these techniques is useful for certain kinds of materials and certain frequency range. In microwave frequency range, we have to measure the dielectric parameters of both the tissue of the fruits and their tissue equivalent phantom liquids. So, open ended coaxial probe technique has been chosen as the most suitable technique for the measurement purpose as illustrated below.

3.11 Complex permittivity determination by open ended coaxial probe technique:

Open ended coaxial probe technique is being used for several years as a non-destructive dielectric properties evaluation method especially for biological specimens and agricultural products. This technique was pioneered by Stuchly and Stuchly in 1980 [13]. This method allows the sample to be placed in close contact with the probe without causing any disturbance to the material characteristics. More care should be taken for materials having low value of permittivity and low loss factor because errors are introduced in the measured data especially for those types of materials. This technique is accurate enough for dielectric characterization of different fruits as they are having high permittivity along with high loss factor. In this technique, permittivity and loss tangent of a **m**aterial **u**nder **t**est (MUT) are evaluated from the phase and amplitude of reflected signal at the open end of a coaxial probe inserted or immersed into solid, semi-solid or liquid MUT [14].

3.11.1 Principle of reflection method:

Reflection method means the measurement of reflection coefficient on the interface between two materials viz. coaxial probe (and **V**ector **N**etwork **A**nalyzer VNA) and MUT from the view point of theory of electromagnetic fields and propagation of electromagnetic waves on the interface between two materials with different impedances as shown in figure below [15]—

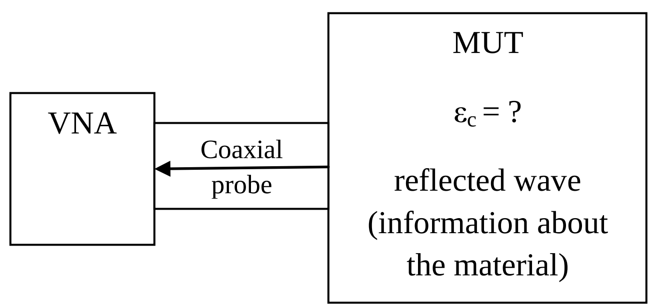


Fig.3.11 Principle of reflection method

Reflection coefficient relates the tangential components of the incident and the reflected electric fields and is a frequency dependent and complex quantity given by— $\Gamma = \frac{\mathbf{E}r}{\mathbf{E}i}$

where **E**r and **E**i are reflected and incident wave respectively.

, In case of interface between two materials with different impedances the reflection coefficient is defined as—

$$\Gamma = \frac{Z_1 - Z_0}{Z_1 + Z_0} \tag{3.19}$$

where Z_0 is the impedance of coaxial line (50Ω) and Z_1 is the impedance of a MUT sample.

3.11.2 Relation between reflection coefficient and permittivity:

The probe translates changes in the permittivity of a MUT into changes of the input reflection coefficient of the probe. The interface between the measurement probe and the sample of biological tissue is represented by an impedance jump. Biological tissues have extremely high permittivity values. At low frequencies its permittivity is more than 100 and the value of the loss factor more than 0.1 as shown in the figure below. An accurate evaluation is very difficult because the reflection coefficient is close to 1. This means that only a very small part of the incident energy penetrates into the sample [16].

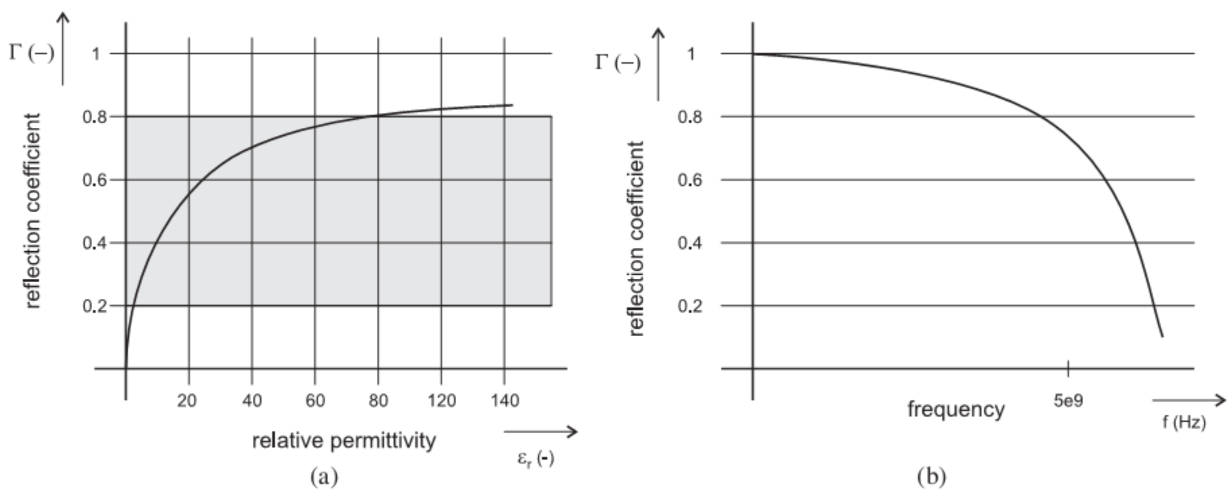


Fig.3.12 Reflection coefficient versus (a) relative permittivity and (b) frequency [16]

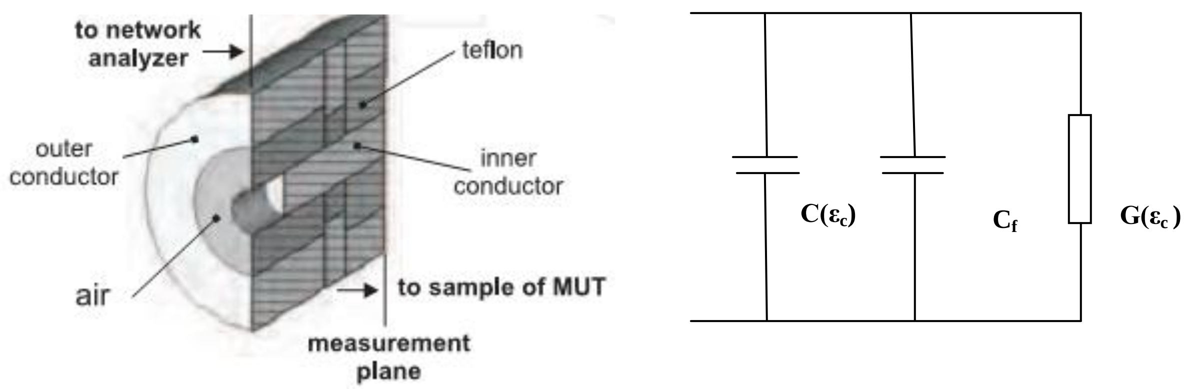
The surface of the sample of MUT must be in the perfect contact with the probe. The thickness of a measured sample must be at least twice an equivalent penetration depth of the electromagnetic wave *d*. This assures that the waves reflected from the far MUT interface are attenuated approximately by –35 dB, which assures that their effect on the measured reflection coefficient is insignificant [16].

$$d = \sqrt{\frac{2}{\omega\mu\sigma}} = \frac{1}{\omega}\sqrt{\frac{2}{\mu\varepsilon_o\varepsilon_r \tan\delta}} \tag{3.20}$$

Equation 3.20 depicts the dependence of equivalent penetration depth *d* on dielectric parameters ε_r and tan δ and also frequency ω.

3.11.3 N and SMA connector type coaxial probe:

€ N type coaxial connectors are medium size units which have constant 50Ω impedance and provide radio frequency performance up to 11GHz. SMA (SubMiniature, version A) connectors are coaxial connectors developed as a minimal connector interface for coaxial cable with a screw type coupling mechanism. The connector has 50Ω impedance. It offers excellent electrical performance from DC to 18GHz. The cross sectional view of the probe is shown in figure 3.13.



(a) **(b)**

Fig.3.13 Coaxial probe (a) cross sectional view [17] (b) equivalent circuit [18]

The equivalent circuit of the measurement probe consists of fringing capacitance ($C\varepsilon_c$) due to the fringing field concentration in the dielectric, capacitance (C_f) due to field concentration inside Teflon filled part of the coaxial line and conductance ($G\varepsilon_c$) due to radiation into dielectric surrounding sensor representing propagation losses. The fringing capacitance and the radiating conductance are frequency and permittivity dependent and are also dependent on the dimensions (inner and outer diameters viz. 2b and 2a respectively) of the probe.

A measurement probe can be described as an antenna with the input admittance expressed as—

$$Y_o = G_o(\varepsilon_c, \omega) + j\omega C_o(\varepsilon_c, \omega) \qquad (3.21)$$

where G_o and C_o are constants if the antenna radiates in

free space (ε_c=1) at angular frequency ω.

When the medium is free space, capacitance Co can be considered to be constant. The radiation into the dielectric surrounding the antenna can be calculated when the dielectric is air [19].

$$G_o = \frac{Yo}{\ln\frac{a}{b}} \int_0^{\frac{\pi}{2}} [\, J_o(ka \sin\theta) - J_o(kb \sin\theta)]^2 \frac{d\theta}{\sin\theta} \qquad (3.22)$$

where $J_o(x)$ is Bessel function of order 0 and k= $2\pi/\lambda_o$. Expanding the Bessel function into a Maclaurin series and substituting it into equation 3.22 yields—

$$G_o \approx \frac{Y_o}{\ln\frac{a}{b}} [G_1(f^4) + G_2(f^6) + \ldots.] \qquad (3.23)$$

where G_i are parameters dependent on the antenna dimensions (radii a and b) and wavelength. An investigation into coefficients G_i showed that $G \approx G_1$ for the N and SMA connector type probes. Therefore the radiation effect of coaxial probe, which is represented as radiation conductance in the probe's equivalent circuit, can be approximated as varying with frequency as f^4 as shown below—

$$G_1(f^4) = \frac{2}{3}(a^2 - b^2)\frac{\pi^4}{\lambda^4} = \frac{2}{3}(a^2 - b^2)\frac{\pi^4}{c^4} f^4 \approx f^4 \qquad (3.24)$$

Now, if we change the free space surrounding the medium for a lossy biological tissue medium, the dependence of the antenna admittance on the properties of surrounding medium can be derived using Deschamps' theorem [20] which tells that the admittance of medium of permittivity ε_c at angular frequency ω is the same as the admittance measured in the free space at frequency $\sqrt{\varepsilon_c}$ times higher and further multiplied by $\sqrt{\varepsilon_c}$ as shown below—

$$Y(\varepsilon_c, \omega) = \sqrt{\varepsilon_c}\, Y_o(1, \omega\sqrt{\varepsilon_c})$$

$$= \sqrt{\varepsilon_c}\, [G_o(\varepsilon_c, \omega) + j\omega C_o(\varepsilon_c, \omega)]$$

$$= \sqrt{\varepsilon_c}\, G_o(\sqrt{\varepsilon_c})^4 + \sqrt{\varepsilon_c}\, (j\omega\sqrt{\varepsilon_c}\, C_o)$$

$$= \varepsilon_c^{\frac{5}{2}} G_o + j\omega\varepsilon_c C_o$$

Hence the overall admittance is— $Y = \varepsilon_c^{\frac{5}{2}} G_o + j\omega\varepsilon_c C_o + j\omega C_f$ (3.25)

3.11.4 Evaluation of real and imaginary part of complex relative permittivity:

Equation 3.25 can be split into real and imaginary parts, obtaining a set of two nonlinear equations for the two real unknowns which are C_o and G_o or the real and imaginary parts of the complex permittivity ε_c of the MUT.

- To obtain C_o and G_o, admittance Y for a material with a known complex permittivity ε_c (e.g. distilled water) is measured and the set of two equations is solved for the unknowns.
- To measure complex permittivity, the admittance Y of an MUT is measured and the set of the two equations is solved for the unknown real and imaginary parts of the $\varepsilon_{c.}$

And this admittance Y of an MUT is related to measured reflection coefficient Γ as— •

$$Y = Y_o \frac{1-\Gamma}{1+\Gamma} \tag{3.26}$$

where $Y_o = 1/Z_o = 1/50\ \Omega = 0.02$ S is the characteristic admittance of the probe.

The amplitude and phase of the reflected signal (at open end of the coaxial probe) is measured with a VNA. The VNA with open ended probe is initially calibrated to measure the reflection coefficient at the probe aperture plane. The method uses distilled water (at 25ºC) for direct calibration at the open end of the probe. In the method, all measurements are performed by placing the standards (short, open and distilled water) at the open end of Agilent 85070E coaxial probe. Next, the measured amplitude and phase of the reflection coefficient are post-processed to obtain the dielectric parameters using Agilent 85070E software.

3.12 Conclusion:

The framework of the project follows similar procedure as the human phantom model preparation to study the equivalent phantom models for some fruits. Initially, the dielectric parameters of some fruits are measured using the aforesaid technique and the characterization of some other common fruits are already done as stated in the literature review. These values of the dielectric parameters are set as the target value to prepare the tissue equivalent phantom liquids for those fruits and the characteristics of those liquids are studied with respect to frequency, temperature and time to comment on their stability.

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DIELECTRIC CHARACTERIZATION OF SOME FRUITS

4.1 Introduction:

Dielectric characterization of a material implies formation of an idea about the dielectric properties i.e. the permittivity of the material. As discussed in theory, complex relative permittivity is expressed as $\varepsilon = \varepsilon' - j\,\varepsilon''$ where ε' and ε'' are real and imaginary part of complex relative permittivity and loss tangent ($\tan\delta$) is the ratio of its imaginary part to the real one. This chapter onwards the term "permittivity" is used in general to indicate the real part (ε').

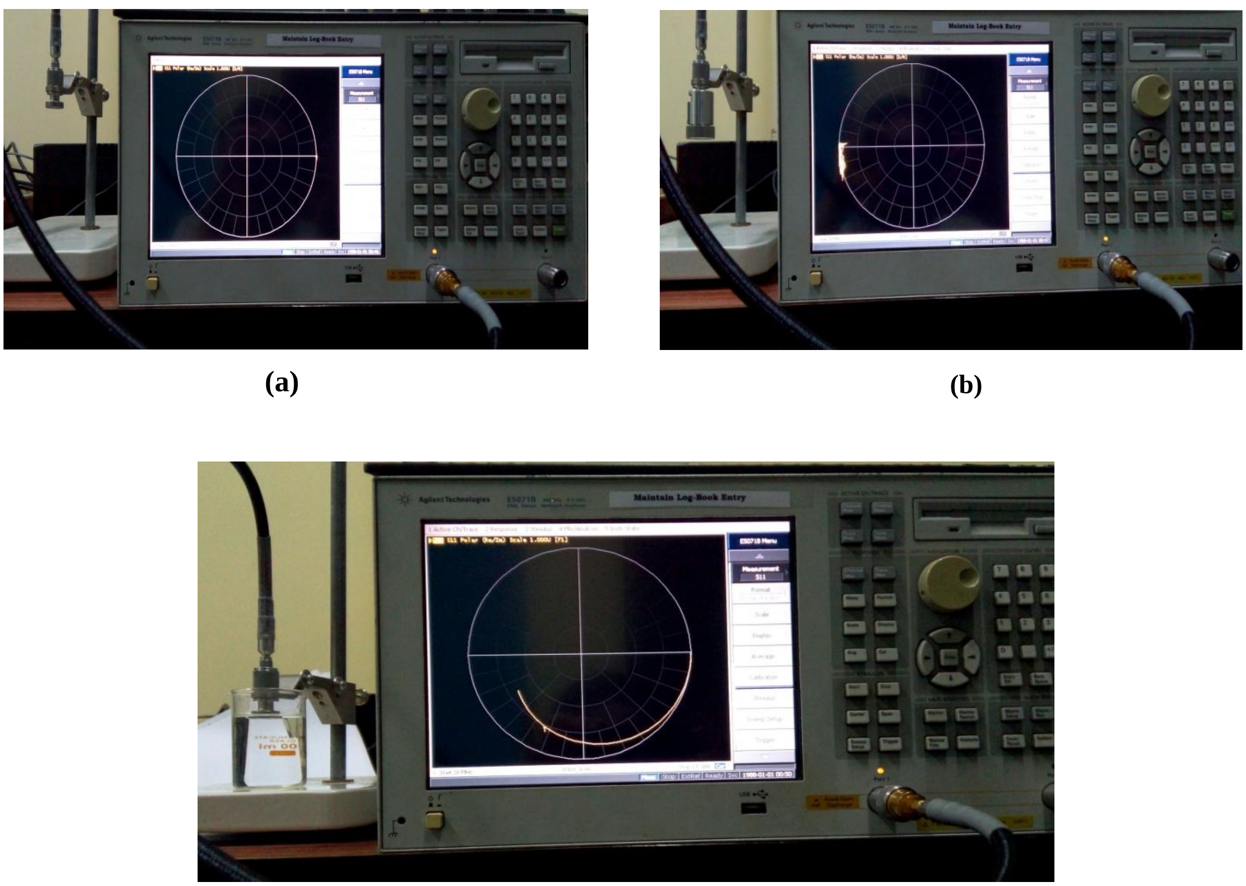
In the Literature Review chapter, it is mentioned that dielectric characterization of many fruits and vegetables are already done by Nelson S.O. and his group in the context of studying the maturity level/processing of the fruits/vegetables in terms of moisture content and soluble solid content etc. Among those specimens, some have very high permittivity and conductivity, even more than that of the human brain tissue due to high water content and ionic concentration of those specimens; this initiates further scope of research in this particular field so as to propose some safety guidelines for the fruits/vegetables to protect them from the adverse effect of electromagnetic exposure.

Moreover, Indian climate has a huge variety of vegetation which includes large variety of fruits growing throughout the whole year. In comparison to that variety, dielectric properties of a small number of Indian fruits have been characterized in the context of SAR measurement. Characterizations of some relevant fruits are still left e.g. the fruits which grow at certain height (because of the normal tree height); they may get affected by the RF exposure from cell phone towers. Three such Indian fruits (viz. water apple, chiku and black grape) are chosen whose dielectric properties are reported in this chapter in terms of their permittivity and loss tangent. Because dielectric characterization is the first step for SAR measurement of the already mentioned fruits as the values of dielectric parameters of those fruits will be chosen as the target values for preparing corresponding tissue equivalent phantom liquids of those fruits.

4.2 Measurement procedure:

Dielectric parameters of the fruits were measured using the high temperature dielectric constant measuring open-ended coaxial probe (Agilent 85070E Dielectric Probe

Kit) and the Agilent E5071B Vector Network Analyzer (VNA) in the Microwave Engineering Laboratory of Jadavpur University. Initially the probe kit connected with the VNA was calibrated with an open load i.e. the probe was left open in the air, then with a shorting block (provided with the instrument kit) and finally with distilled water at 25°C as shown in figure 4.1. After proper calibration, the dielectric properties of three fruits (viz. water apple, chiku and black grape) were measured using this probe kit as discussed later. The data for reflection coefficient within the frequency range of 200MHz and 8.5 GHz (from the active tip of the probe through VNA), was transformed into the dielectric parameters using Agilent 85070E software installed in a personal computer connected with the VNA. The data were recorded from which the plot of real part of permittivity (ε′) and loss tangent (tan δ) for those particular fruits were obtained using MATLAB to observe the variation of the dielectric parameters with frequency.



(a) (b)

(c)

Fig. 4.1 Calibration of the open ended coaxial probe kit connected with the VNA with (a) open load, (b) shorting block and (c) distilled water at 25°C

4.3.1 Dielectric characterization of Water Apple:

Water apple is a common Indian fruit and the trees are tall (average height 30ft) enough to reach vicinity of cell phone towers. Also the moisture content of this particular fruit is quite high. So, it is highly expected that it absorbs the radiated energy from those towers and gets affected due to RF exposure. Hence dielectric characterization of this fruit is necessary in the context of SAR measurement. Measurements were done using Agilent 85070E Dielectric Probe Kit and VNA as shown earlier. The open ended coaxial probe was pressed on the internal tissue of the fruit without keeping any air gap and also avoiding extraction of the juice as shown in figure 4.2.

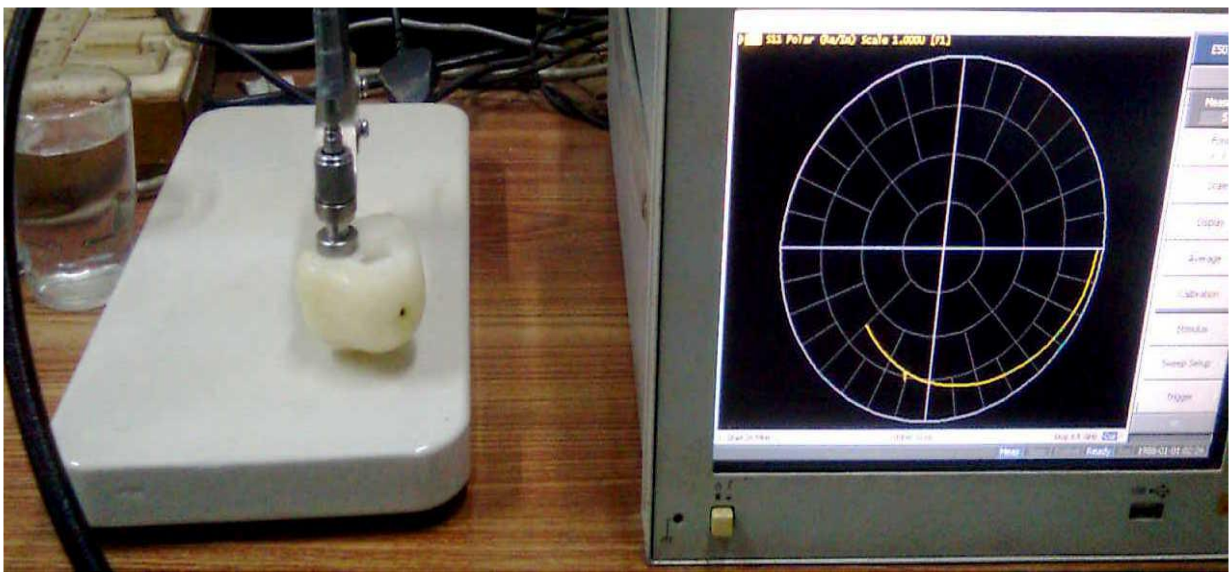


Fig. 4.2 Dielectric parameter measurement of water apple with Agilent 85070E Dielectric Probe Kit and VNA

From the measured data, the real part of permittivity (ε′) and loss tangent (tan δ) of water apple are plotted using MATLAB in figures 4.3 and 4.4. From the plot it can be observed that ε′ decreases from a value of 70 at 200MHz to almost 50 at 8.5GHz which implies energy storage capacity of the fruit reduces with frequency. So the value of the measured SAR will be less at higher frequencies than that at lower frequencies with the same level of electric field exposure. The loss tangent initially decreases reaching a minimum at 1GHz and then increases. The values of the real part of permittivity and loss tangent at 900MHz are marked in the corresponding plots as shown in figures 4.4 and 4.5.

For GSM frequency of 900MHz, ε′= 65.52 and tan δ = 0.149 for water apple.

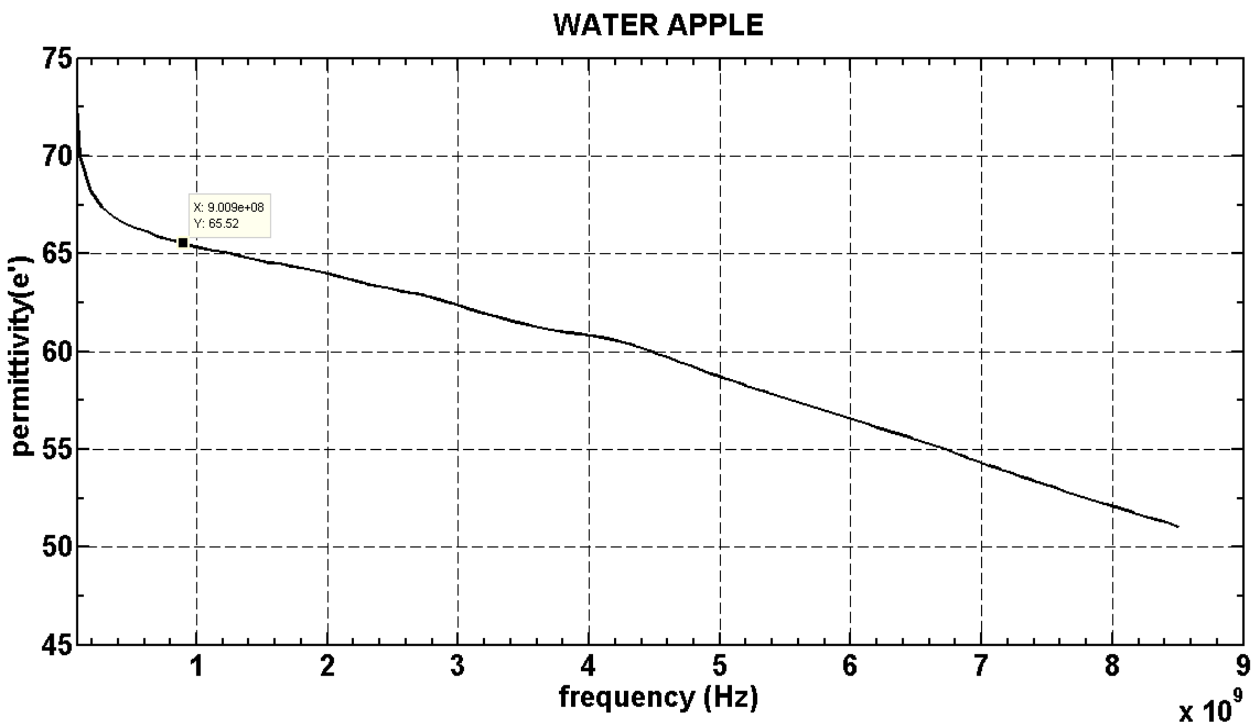


Fig.4.3 Real part of permittivity (ε′) of water apple vs. frequency

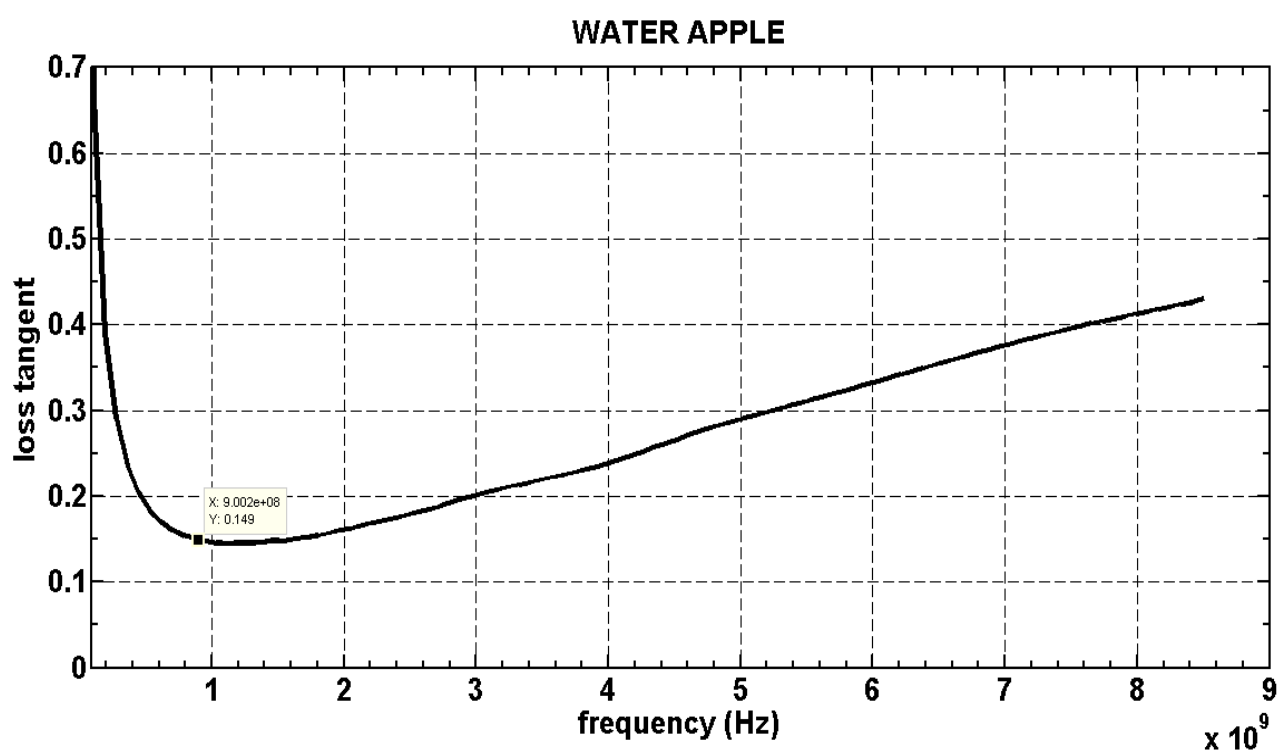


Fig.4.4 Loss tangent (tan δ) of water apple vs. frequency

4.3.2 Dielectric characterization of Chiku:

Chiku is also a common Indian fruit and these trees are normally 20ft high on an average. The fruits in the growing stage may come under the effect of the cell phone towers. It is expected that it absorbs the radiated EMF from such towers due to high moisture content of the fruit. Hence it is necessary to perform dielectric characterization of this fruit for SAR measurement. The spherical surface of a fresh chiku was cut with a sharp knife to get a flat surface of the internal tissue and the open end of the probe was pressed on that surface (without keeping any airgap) as shown in figure 4.5. While taking measurement, extraction of juice from the internal tissue of the fruit should be avoided.

Fig. 4.5 Dielectric parameter measurement of chiku with Agilent 85070E Dielectric Probe Kit and VNA

The real part of permittivity (ε') and loss tangent ($\tan\delta$) of chiku are plotted with frequency using MATLAB from the recorded data. From the plots of figures 4.6 and 4.7, it can be observed that ε' decreases from a value of 70 at 200MHz to almost 45 at 8.5GHz which implies reduction in energy storage capacity of the fruit with frequency. So the value of the measured SAR will be less at higher frequencies than at lower frequencies with the same level of electric field exposure. The loss tangent initially decreases reaching a minima at 1GHz and then increases. The values of the real part of permittivity and loss tangent at 900MHz are marked in the corresponding plots as shown in figures 4.6 and 4.7.

At GSM 900MHz frequency band, ε'= 65.48 and $\tan\delta$ = 0.189 for chiku.

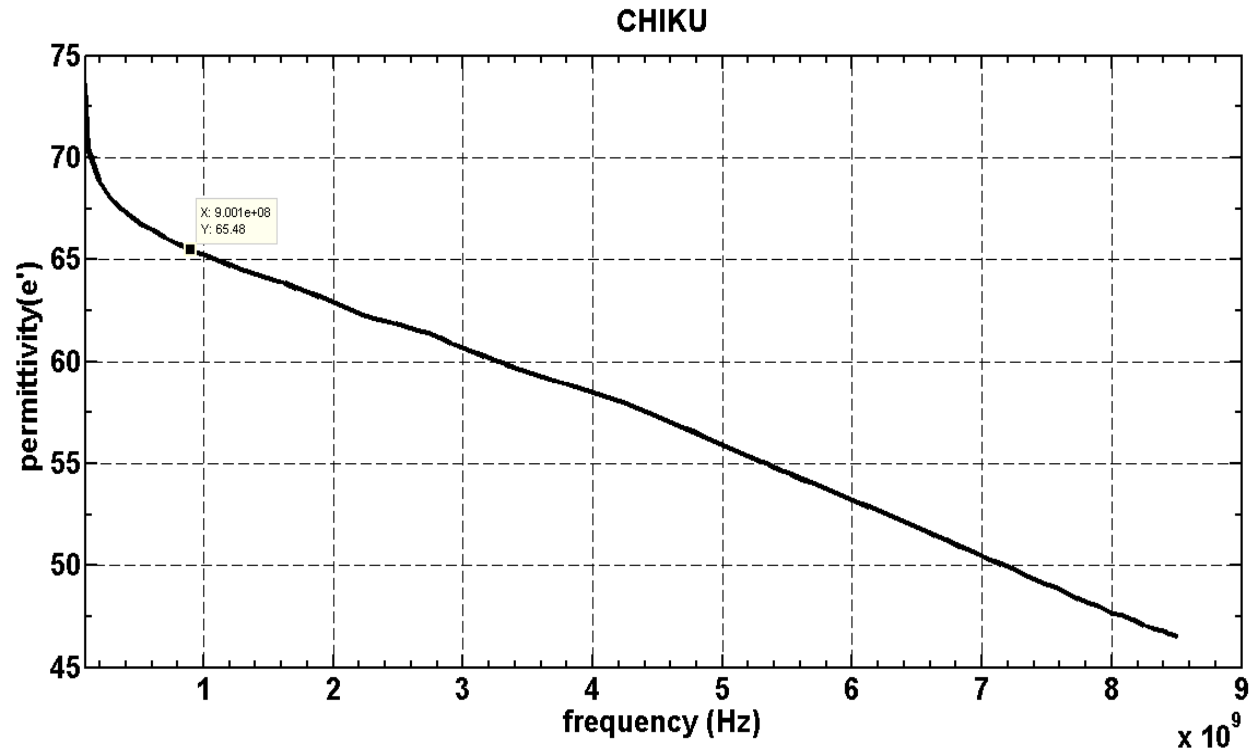


Fig.4.6 Real part of permittivity (ε′) of chiku vs. frequency

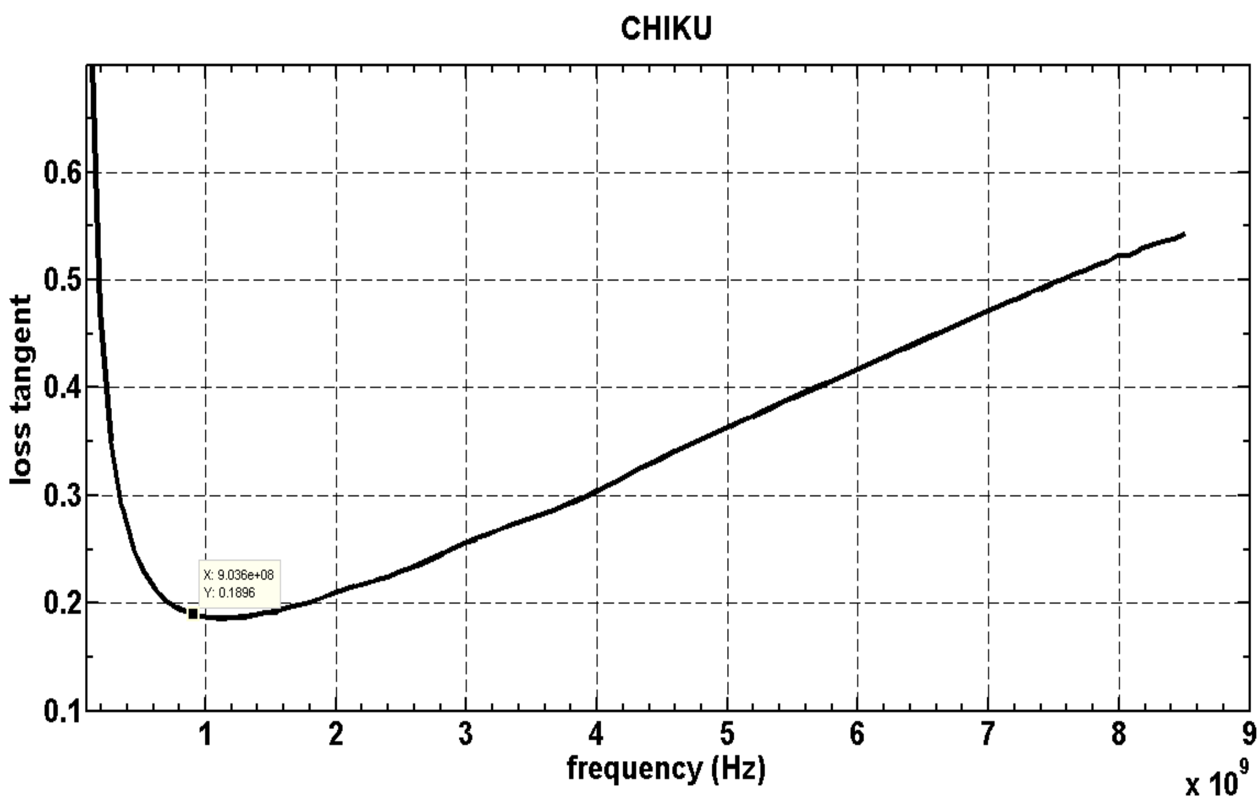


Fig.4.7 Loss tangent (tan δ) of chiku vs. frequency

4.3.3 Dielectric characterization of Black grape:

Grape is also a common Indian fruit and they are grown normally on grape vines of 10ft height (average). Dielectric characterization of green grape has been already done as mentioned in the literature review. SAR simulation performed in bunch of green grapes at general public exposure zone was quite alarming. Hence dielectric characterization of another variety of grape (black grape) is necessary in the context of SAR measurement. Measurements for it were done in a similar way. The open end of coaxial probe was pressed on the flat surface of the internal tissue of black grape (which was cut using a sharp knife) without keeping any air gap and also avoiding extraction of the juice as shown in figure 4.8.

Fig. 4.8 Dielectric parameter measurement of black grape with Agilent 85070E Dielectric Probe Kit and VNA

From the measured data, the real part of permittivity (ε') and loss tangent ($\tan \delta$) of black grape are plotted using MATLAB in figures 4.9 and 4.10. From the plots it can be observed that ε' decreases from a value of 75 at 200MHz to almost 50 at 8.5GHz which implies energy storage capacity of the fruit reduces with frequency. So the value of the measured SAR will be less at higher frequencies than that at lower frequencies with the same level of electric field exposure. The loss tangent initially decreases steeply reaching a minimum at 1GHz and then increases. The values of the real part of permittivity and loss tangent at 900MHz are marked in the corresponding plots as shown in figures 4.9 and 4.10.

At GSM 900MHz frequency band, ε'= 71.43 and $\tan \delta$ = 0.177 for black grape.

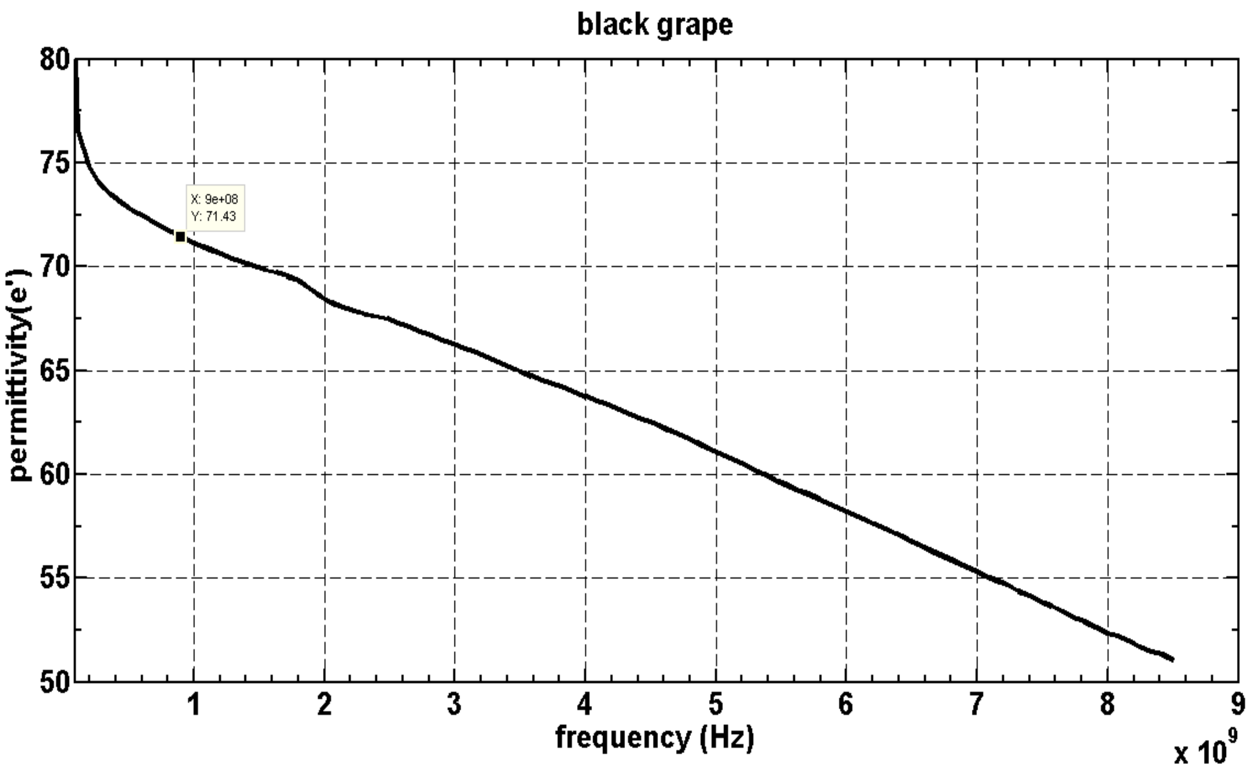


Fig.4.9 Real part of permittivity (ε′) of black grape vs. frequency

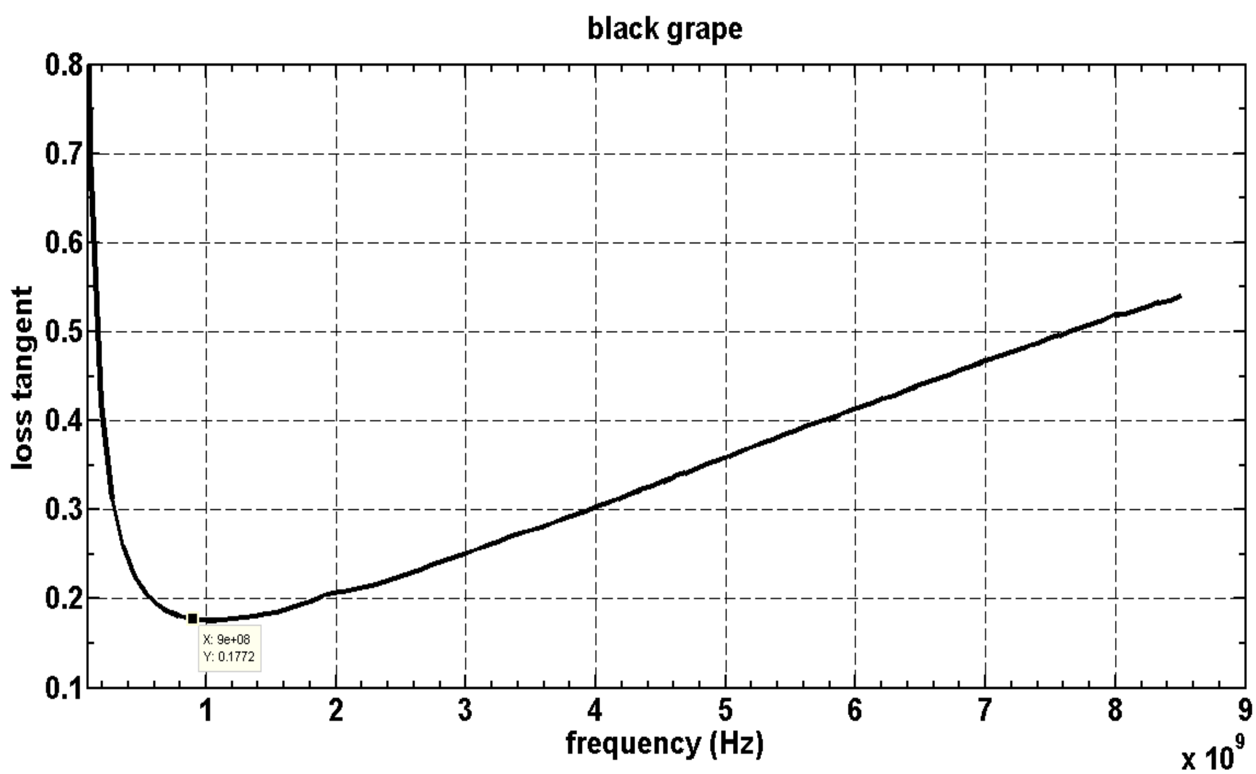


Fig.4.10 Loss tangent (tan δ) of black grape vs. frequency

4.4 Conclusion:

In this chapter the dielectric properties of three fruits (viz. water apple, chiku and grape) are reported for the first time. However, the characteristics of the dielectric parameters are similar to the already reported data for some other fruits. Apart from the context of SAR measurement, this dielectric characterization is also useful to have an idea about moisture content or soluble solid content which helps to determine the ripeness of the fruit. Also during storage time quality of the fruit is an essential factor and dielectric characterization is an important way to assess that quality.

PREPARATION OF PHANTOM LIQUID FOR SOME FRUITS

5.1 Introduction:

In this chapter, different recipes for the preparation of phantom liquids of five different fruits (viz. apple, banana, guava, grape and orange) have been presented. In the first stage, dielectric characterization of those fruits at 900MHz is discussed to set the target values of dielectric parameters for preparing the liquids. Then customized phantom liquids are prepared and dielectric properties of the liquids are studied in a frequency range varying from 200MHz to 8.5GHz. In the concluding portion, generalized recipe of the phantom liquids are proposed for two different categories of fruits based on the values of their dielectric constant.

5.2 Dielectric parameters of the fruits chosen:

To study the SAR analysis of the fruit tissues, we must have an idea of dielectric parameters of the fruits at GSM 900MHz frequency band. Based on these dielectric characteristics of the specimens, various recipes for tissue-equivalent dielectric liquids have to be proposed. The permittivity (ε') and loss tangent ($\tan \delta$) values of five common fruits viz. apple ,banana, guava, grape, orange (in GSM 900MHz band) are presented in Table 5.1.The data for banana and orange are taken from [1] and for apple, guava and grape the same has been taken from [2].

Table 5.1 Dielectric parameters of the fruits at GSM 900MHz

Name of fruit	ε'	$\tan \delta$
Apple	65.03	0.135
Banana	65.00	0.280
Guava	72.08	0.154
Grape	69.11	0.167
Orange	72.00	0.194

Now, finding the tissue equivalent liquids that match the above target dielectric parameters is really challenging; because the frequency variation in the dielectric properties of many suitable liquids are different from that of the fruit-tissues.

5.3 Customized Phantom Liquid Preparation:

Recipes of customized tissue equivalent phantom liquid for five different fruits are proposed in the following section with various concentrations of sugar and salt in water. The weights of commercially available sugar and salt were measured using a physical balance (along with a standard weight box) and the volume of de-ionized water was measured in a measuring cylinder (shown in Figure 5.1) at the Microwave Engineering Laboratory of Jadavpur University.

<u>Specification of the physical balance:</u>

- Precision of the balance is 1mg.
- Maximum weight available in the weight box is 100g.

<u>Specification of the measuring cylinder:</u>

- Precision of the measuring cylinder is 1ml.
- It can measure up to 100ml.

(a)

(b)

Fig 5.1 Measuring (a) weight of salt in physical balance (b) volume of de-ionized water in measuring cylinder

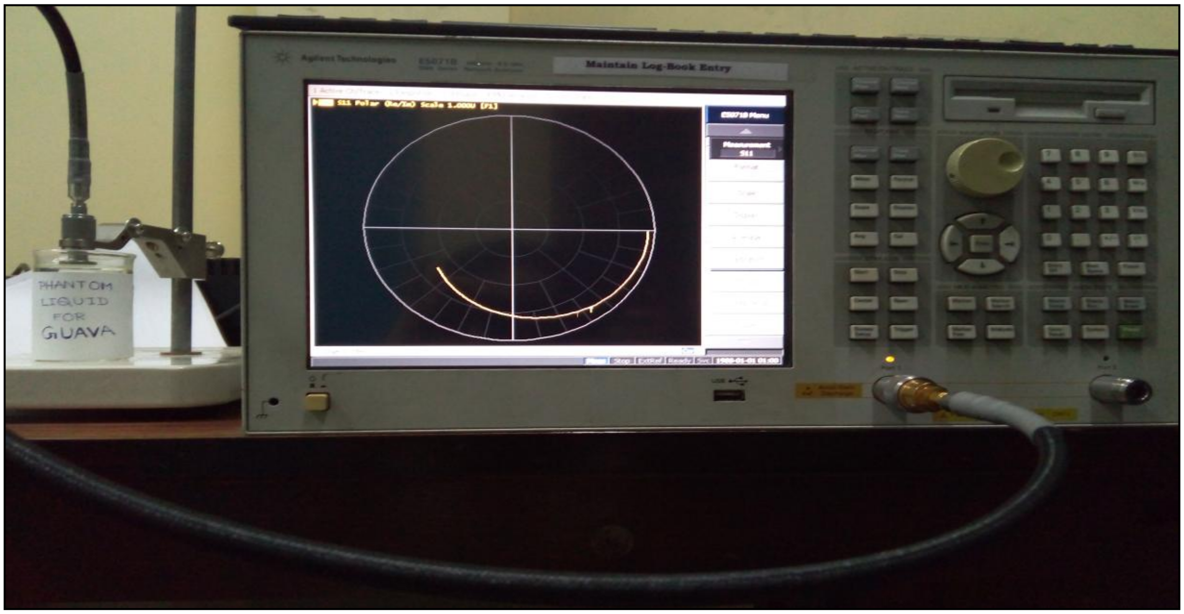


Fig 5.2 Measuring dielectric constant of phantom liquid with Agilent 85070E Dielectric Probe Kit and VNA

Then the dielectric parameters of the liquids were measured using the high temperature dielectric constant measuring open-ended coaxial probe (Agilent 85070E Dielectric Probe Kit) and the Agilent E5071B Vector Network Analyzer (VNA) as shown in Figure 5.2 in the Microwave Engineering Laboratory of Jadavpur University.

Initially the probe kit connected with the VNA was calibrated with an open load i.e. the probe was left open in the air, then with a shorting block (provided with the instrument kit) and finally with the distilled water at 25°C. After proper calibration, the open-ended probe was inserted into the customized liquid without any air bubble for accuracy. The data of the reflection coefficient within the frequency range of 200MHz and 8.5 GHz (from the active tip of the probe through VNA), was transformed into the dielectric parameters using Agilent 85070E software installed in a personal computer connected with the VNA. And the data were recorded from which the plot of real part of permittivity (ε′) and loss tangent (tan δ) for those particular liquids were obtained using MATLAB and then curve fitting was applied to observe the variation of the dielectric parameters with frequency.

The whole experiment was repeated thrice (for all the phantom liquids) with 3 different volume of de-ionized water viz. 320ml, 640ml and 800ml and accordingly the other constituents of the corresponding phantom liquids.

5.3.1 Phantom Liquid for Apple:

To prepare the tissue equivalent liquid of apple the target values of the dielectric parameters (i.e. the dielectric parameters of apple tissue) are presented in table 5.2. To prepare a sugar based aqueous solution, first we need to know the dielectric parameter of de-ionized water which is given in table 5.3.

Table 5.2 Target dielectric parameters for phantom liquid of apple at 900MHz [2]

Permittivity(ε′)	Loss factor(tan δ)
65.03	0.135

Table 5.3 Dielectric parameters of de-ionized (DI) water at 900MHz

Permittivity(ε′)	Loss factor(tan δ)
78	0.043

To reduce permittivity of DI water, initially the experiment was started with mixing sugar gradually with de-ionized water and it was repeated for higher proportion. To work with more refined sugar, another solution was prepared mixing brown sugar (but more costly) with de-ionized water. While mixing sugar or brown sugar, loss factor also increased but very slowly. Thus, two recipes of phantom liquid for apple were obtained as shown in table 5.4.

Table 5.4 Phantom liquid for apple (Recipe 1and 2) at 900MHz:

Recipe	Concentration of sugar in the solution		Permittivity(ε′)	Loss factor(tan δ)
1	Sugar	0.5625g/ml	65.27	0.139
2	Brown sugar	0.5g/ml	65.09	0.129

Considering the cost effectiveness of the phantom liquid, an alternative way to achieve the target values was suggested where at first, lesser amount of sugar was added to get the target permittivity value and then common salt (NaCl) was added gradually to obtain the target value of loss factor. Finally a 3rd recipe was prepared for phantom liquid of apple as shown in table 5.5. In this recipe, the amount of sugar required is less compared to recipe 1 and 2. So, recipe 3 is cost efficient in comparison to recipe 1 and 2.

Table 5.5 Phantom liquid for apple (Recipe 3) at 900MHz:

Concentration of sugar and common salt in the solution		Permittivity(ε′)	Loss factor(tan δ)
Sugar	0.375g/ml	67.99	0.137
Common Salt	1.25mg/ml		

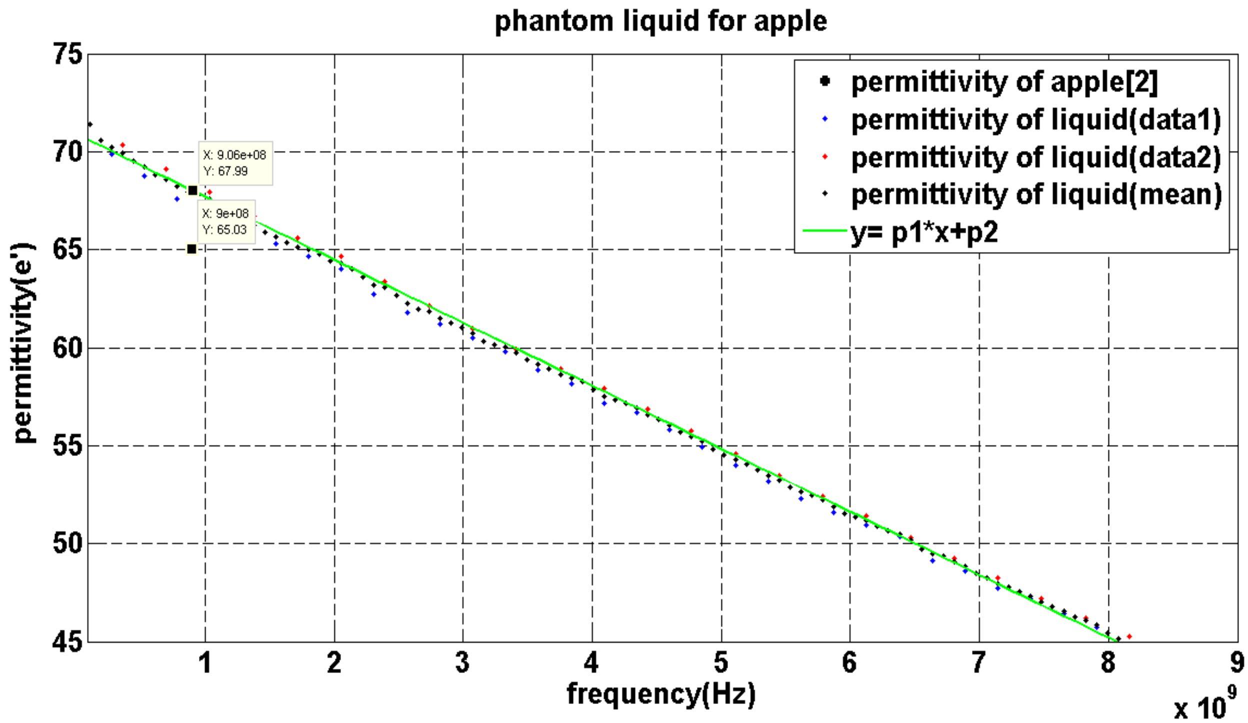


Fig.5.3 Real part of permittivity of phantom liquid (recipe 3) for apple with frequency

The dielectric parameter measurement was done for the phantom liquid in the aforesaid way. From the plot (Figure5.3) of the real part of permittivity (ε′) along with frequency for phantom liquid of apple, it can be shown that ε′ varies linearly from 70.9 at 200MHz to 45 at 8GHz following the equation: $Y=P_1*F+ P_2$…………………………………...(5.3.1.1)

where P_1 = -3.215e-009, P_2=70.9, F= frequency in Hz

The difference between the target value and the achieved value of permittivity (ε′) for the phantom liquid at 900MHz and 1800MHz is presented in the table below:

Table 5.6 Difference between the target value and the achieved value of ε′ for phantom liquid of apple

Frequency	Target value of ε′	Achieved value of ε′	Deviation
900MHz	65.03	67.99	+4.55%
1800MHz	63.72	65.11	+2.18%

For permittivity, the permissible limit of deviation is considered to be ±10%. At 900MHz and 1800MHz, the deviation in ε′ is within the limit. So, from the point of view of permittivity, the liquid can be used as tissue equivalent phantom liquid for apple.

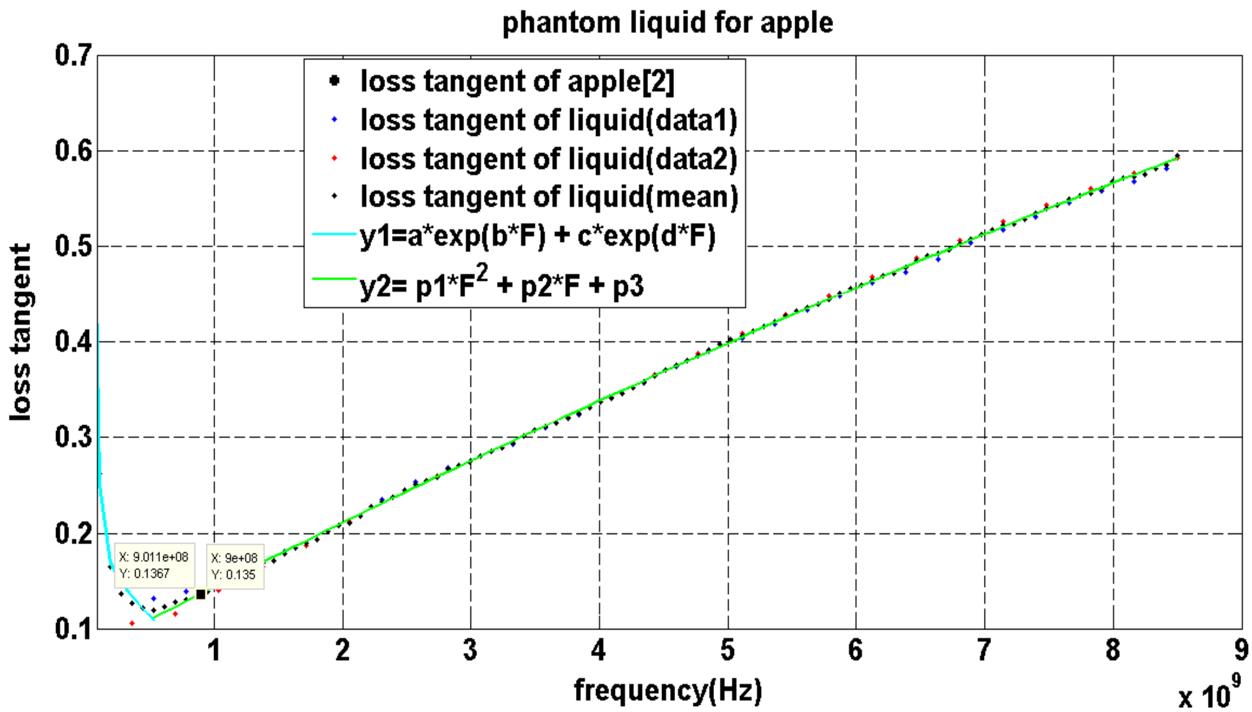


Fig.5.4 Loss tangent of phantom liquid (recipe 3) for apple with frequency

From Figure5.4, it is observed that in the lower frequency range (up to 528MHz) the loss tangent (tan δ) of the liquid decreases exponentially (according to equation 5.3.1.2) and then it increases following a quadratic equation in terms of frequency as given in equation 5.3.1.3.

$$Y_1=a*\exp(b*F) + c*\exp(d*F) \qquad \text{.......5.3.1.2}$$

where a = 1.776; b = -3.078e-008 ; c =0.2057 ; d = -1.209e-009; F= frequency in Hz

$$Y_2= P_1*F^2 + P_2*F + P_3 \qquad \text{.......5.3.1.3}$$

where P_1 =-1.128e-021 ; P_2 =7.067e-011 ; P_3 =0.07394; F= frequency in Hz

Here also a little deviation is observed in the value of loss tangent at 900MHz which increases quite a lot at 1800MHz as depicted in the table below:

Table 5.7 Difference between the target value and the achieved value of tan δ for phantom liquid of apple

Frequency	Target value of tan δ	Achieved value of tan δ	Deviation
900MHz	0.135	0.137	+1.48%
1800MHz	0.156	0.198	+26.92%

The permissible limit of deviation for loss tangent is considered to be ±5%.So, the phantom liquid for apple is apt for 900MHz but not for 1800MHz.

5.3.2 Phantom Liquid for Banana:

To propose the recipe of the tissue equivalent liquid of banana the target value i.e. the values of the dielectric parameter of banana tissue are presented in the table below:

Table 5.8 Target dielectric parameters for phantom liquid of banana at 900MHz [1]

Permittivity(ε′)	Loss factor(tan δ)
65	0.28

In case of banana, the experiment was not tried with only adding sugar to DI water as the loss tangent value is too high, and it would have required a huge amount of sugar to be added which is not convenient. It was not even tried with adding brown sugar, as it was not cost efficient. Henceforth, the approach was first adding the sugar to reach the permittivity range and then adding common salt to attain the prescribed value of loss tangent.

As the permittivity of banana is almost same as that of the apple, the experiment was started in a similar way, with mixing sugar gradually with DI water to lower the permittivity of water and then common salt (NaCl) was added step by step to obtain the target value of loss factor e.g. at first 200mg common salt was added to the solution of sugar (120g) and DI water (320ml), loss tangent was increased but did not reach the target value. So, again 200mg common salt was added to that solution but the target value was not achieved. Thus the addition of same amount of salt was repeated several times to reach the target value as the value (0.28) is quite higher than that of the apple (0.135), as a consequence the requirement of addition of are more. The similar steps were repeated with 640ml as well as 800ml of DI water to reach a conclusion. Finally a recipe was prepared for phantom liquid of banana as shown in table 5.9.

Table 5.9 Phantom liquid for banana at 900MHz:

<table>
<tr><th colspan="2">Concentration of sugar and common salt in the solution</th><th>Permittivity(ε′)</th><th>Loss factor(tan δ)</th></tr>
<tr><td>Sugar</td><td>0.375g/ml</td><td rowspan="2">65.4</td><td rowspan="2">0.285</td></tr>
<tr><td>Common Salt</td><td>6.25mg/ml</td></tr>
</table>

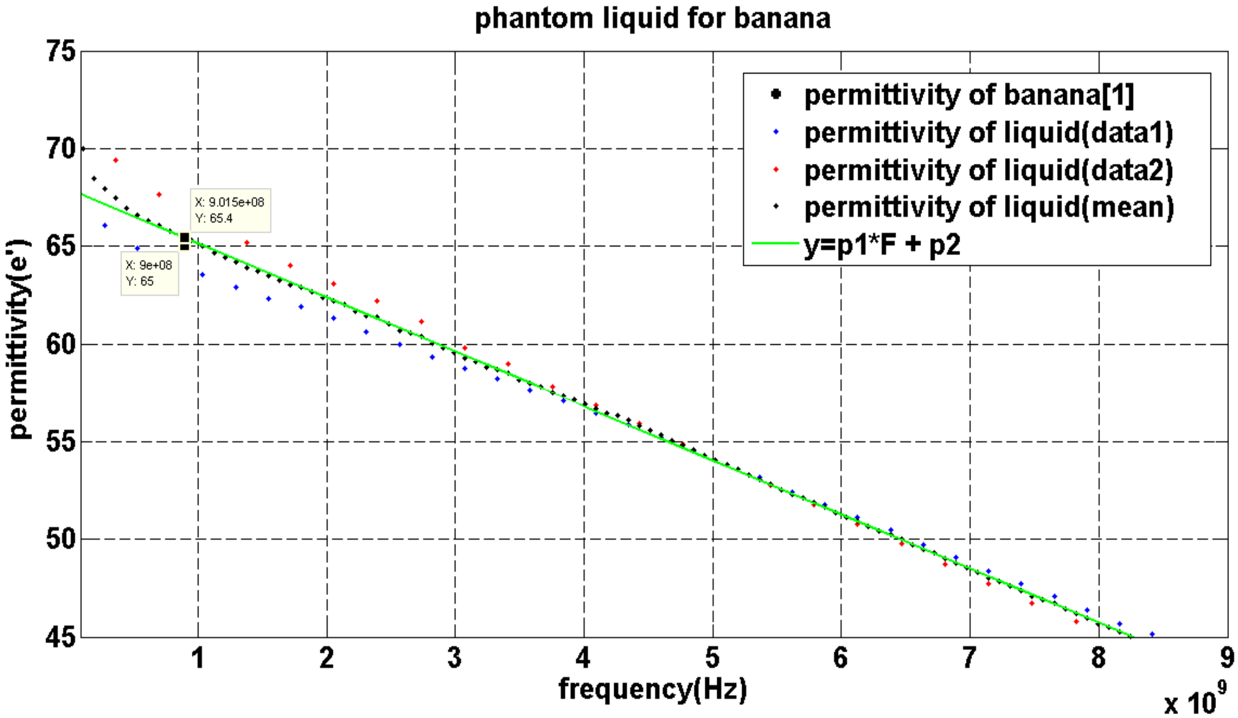


Fig.5.5 Real part of permittivity of phantom liquid for banana with frequency

The dielectric parameter measurement was done for the phantom liquid as stated before. From the plot (Figure5.5) of the real part of permittivity (ε′) along with frequency for phantom liquid of banana, it can be shown that ε′ varies linearly from 67.9 at 200MHz to 45 at 8GHz following the equation: $Y=P_1*F+P_2$…………………………………...(5.3.2.1)

where $P_1 = -2.77e\text{-}009$, $P_2=67.9$; F= frequency in Hz

The difference between the target value and the achieved value of permittivity (ε′) for the phantom liquid at 900MHz and 1800MHz is presented in table 5.10:

Table 5.10 Difference between the target value and the achieved value of ε′ for phantom liquid of banana

Frequency	Target value of ε′	Achieved value of ε′	Deviation
900MHz	65.00	65.40	+0.62%
1800MHz	64.39	62.91	-2.30%

For permittivity the permissible limit of deviation is considered to be ±10%. At 900MHz and 1800MHz, the deviation in ε′ is within the limit. So, from the point of view of permittivity, the liquid can be used as tissue equivalent phantom liquid for banana.

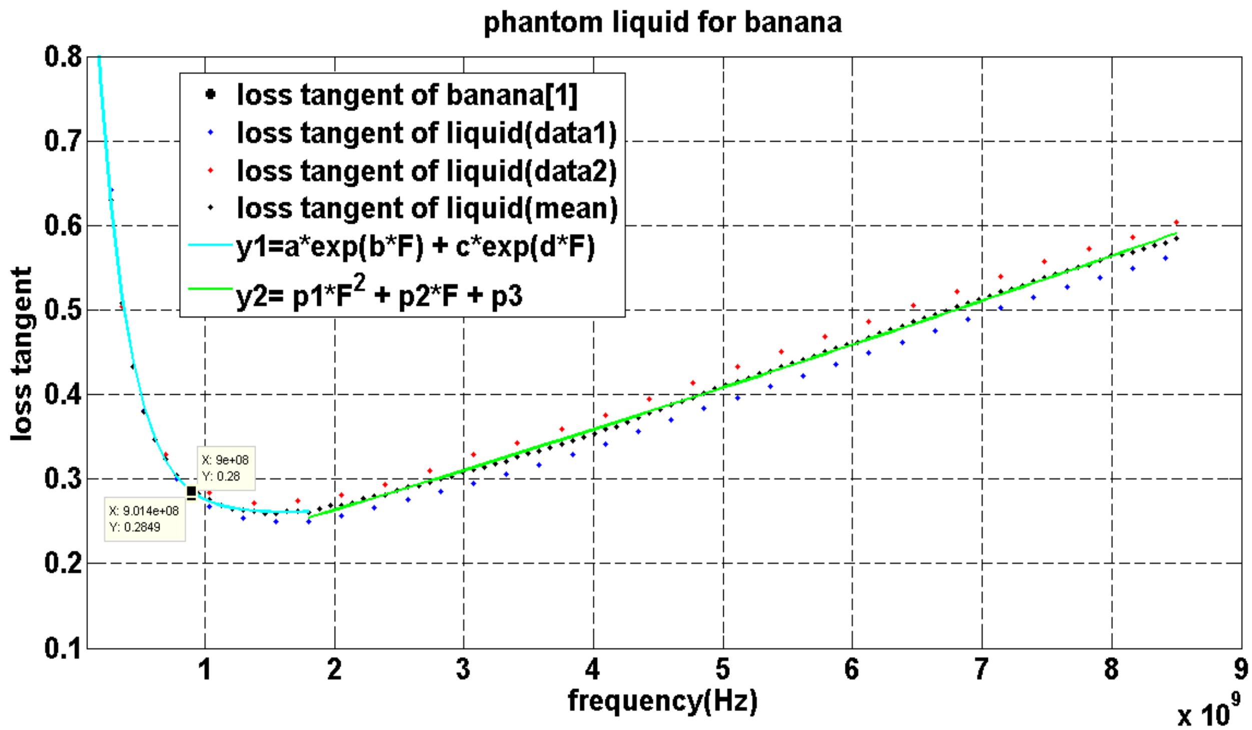


Fig.5.6 Loss tangent of phantom liquid for banana with frequency

From Figure5.6, it is observed that in the lower frequency range (up to 1.8GHz higher than that of the apple) the loss tangent (tan δ) of the liquid decreases exponentially (according to equation 5.3.2.2) and then it increases following a quadratic equation in terms of frequency as given in equation 5.3.2.3.

$$Y_1=a*\exp(b*F) + c*\exp(d*F) \quad \ldots\ldots\ldots 5.3.2.2$$

where a = 1.132; b = -4.076e-009; c = 0.251 ; d = 2.089e-011 ;F= frequency in Hz

$$Y_2= P_1*F^2 + P_2*F + P_3 \quad \ldots\ldots\ldots 5.3.2.3$$

where P_1 =-6.124e-022 ; P_2 =4.397e-011 ; P_3 =0.1728; F= frequency in Hz

Here also a little deviation is observed in the value of loss tangent at 900MHz which increases a bit at 1800MHz as depicted in the table below:

Table 5.11 Deviation of the target value from the achieved value of tan δ for phantom liquid of banana

Frequency	Target value of tan δ	Achieved value of tan δ	Deviation
900MHz	0.280	0.285	+1.78%
1800MHz	0.240	0.261	+8.75%

The permissible limit of deviation for loss tangent is considered to be ±5%.So, the liquid is appropriate for 900MHz but not for 1800MHz.

5.3.3 Phantom Liquid for Guava:

To propose the recipe of the tissue equivalent liquid of guava the target value i.e. the values of the dielectric parameter of guava tissue are presented in the table below:

Table 5.12 Target dielectric parameters for phantom liquid of guava at 900MHz [2]

Permittivity(ε′)	Loss factor(tan δ)
72.08	0.154

Similar approach of adding sugar and common salt to DI water was applied in case of preparing the phantom liquid of guava. While preparing the phantom liquid, the amount of added sugar to DI water was less than that of the apple or banana. As the target value of permittivity of guava (72.08) is in the higher range i.e. closer to that of the DI water (78), so after adding little amount of sugar e.g. 40g sugar to 320ml DI water, the range of target value of permittivity (74.3) was attained. But the value of loss tangent of that solution was 0.07. In order to increase it to a target value of 0.154, common salt was added gradually step by step. After adding 600mg salt to that particular solution finally the target value was achieved. Then similar steps were repeated with 640ml as well as 800ml of DI water to reach an acceptable conclusion. Finally a recipe was proposed for phantom liquid of guava as shown in table 5.13.

Table 5.13 Phantom liquid for guava at 900MHz:

<table>
<tr><th colspan="2">Concentration of sugar and common salt in the solution</th><th>Permittivity(ε′)</th><th>Loss factor(tan δ)</th></tr>
<tr><td>Sugar</td><td>0.125g/ml</td><td rowspan="2">73.58</td><td rowspan="2">0.152</td></tr>
<tr><td>Common salt</td><td>1.875mg/ml</td></tr>
</table>

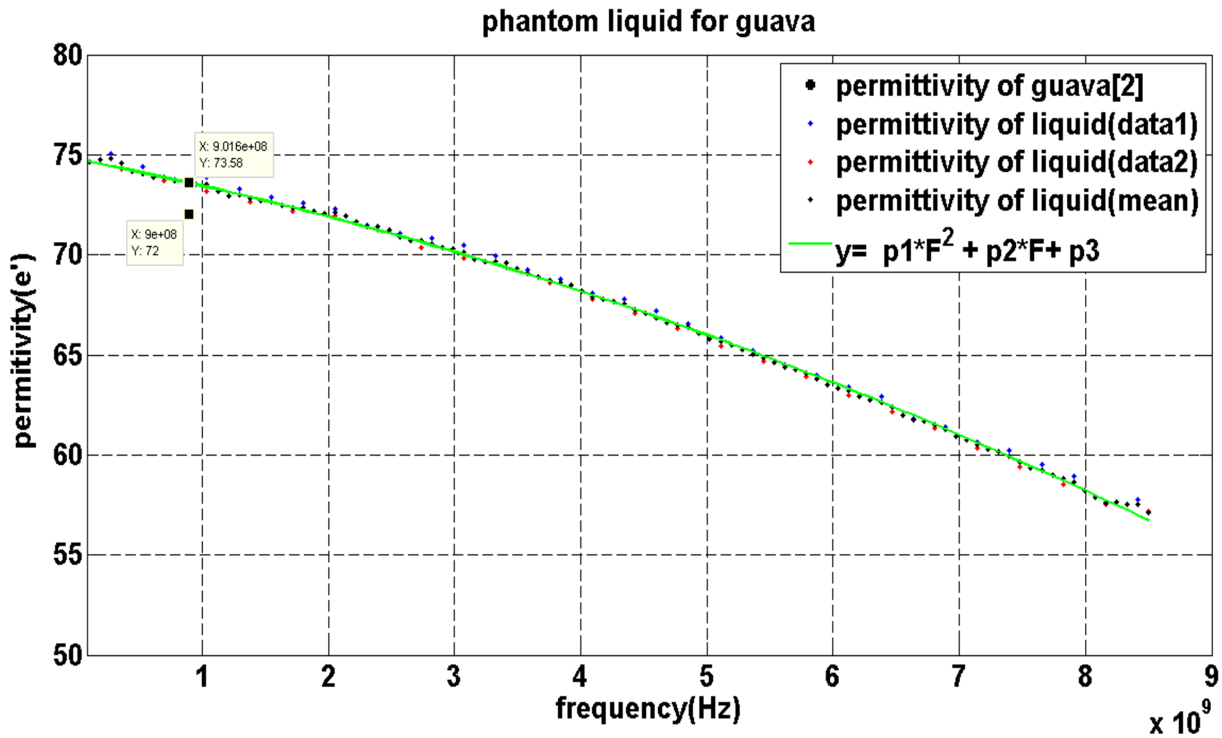


Fig.5.7 Real part of permittivity of phantom liquid for guava with frequency

The dielectric parameter measurement was done for the phantom liquid as stated earlier. From the plot (Figure5.7) of the real part of permittivity (ε′) along with frequency for phantom liquid of guava, it can be shown that ε′ varies in a quadratic manner from 75 at 200MHz to 57 at 8.5GHz following the equation: $Y=P_1*F^2+ P_2*F+ P_3$……………………………...(5.3.3.1)

where P_1 = -1.047e-019, P_2= -1.233e-009; P_3= 74.78; F= frequency in Hz

The difference between the target value and the achieved value of permittivity (ε′) for the phantom liquid at 900MHz and 1800MHz is presented in the table below:

Table 5.14 Difference between the target value and the achieved value of ε′ for phantom liquid of guava

Frequency	Target value of ε′	Achieved value of ε′	Deviation
900MHz	72.08	73.58	+2.08%
1800MHz	71.05	72.22	+1.65%

For permittivity the permissible limit of deviation is considered to be ±10%. At 900MHz and 1800MHz, the deviation in ε′ is within the limit. So, from the point of view of permittivity, the liquid can be used as tissue equivalent phantom liquid for guava.

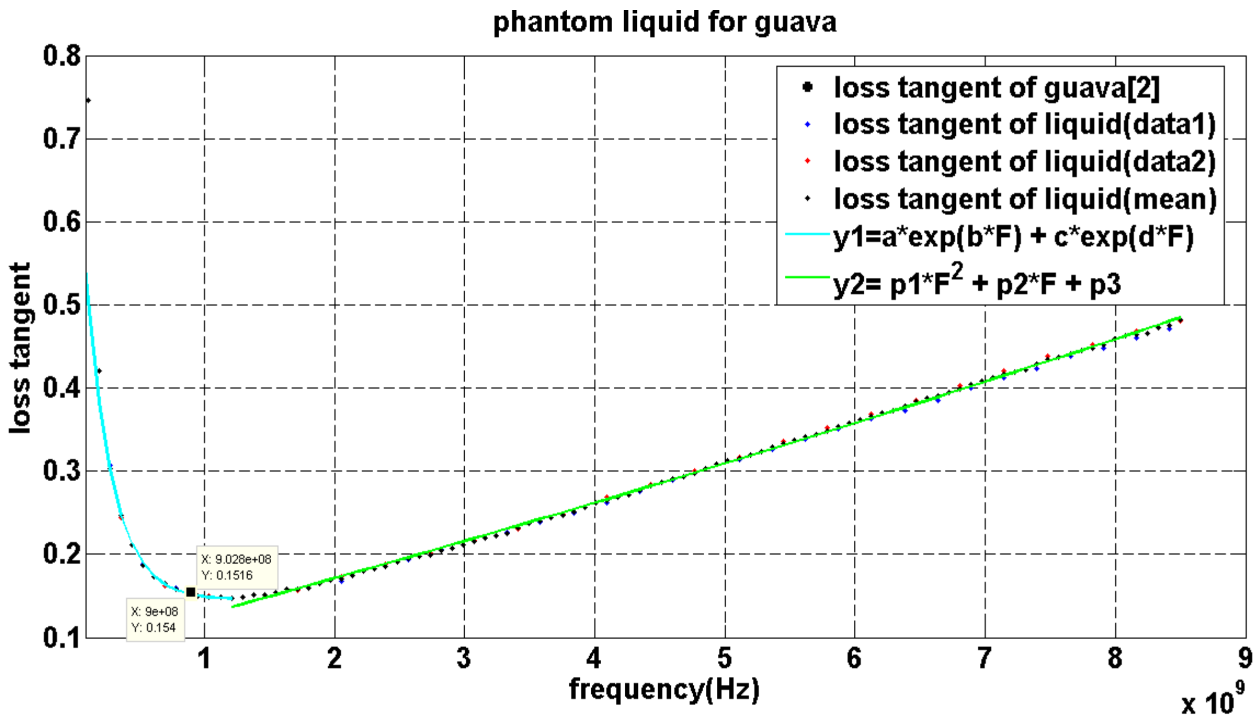


Fig.5.8 Loss tangent of phantom liquid for guava with frequency

From Figure5.8, it is observed that in the lower frequency range (up to 1.2GHz) the loss tangent (tan δ) of the liquid decreases exponentially (according to equation 5.3.3.2) and then it increases following a quadratic equation in terms of frequency as given in equation 5.3.3.3.

$$Y_1=a*\exp(b*F) + c*\exp(d*F) \qquad 5.3.3.2$$

where a = 0.6065 ; b = -4.808e-009 ; c = 0.1383 ; d = 4.086e-011 ; F= frequency in Hz

$$Y_2= P_1*F^2 + P_2*F + P_3 \qquad 5.3.3.3$$

where P_1 = 6.431e-022 ;P_2 = 4.149e-011 ; P_3 = 0.08554 ; F= frequency in Hz

Here also a little deviation is observed in the value of loss tangent at 900MHz which decreases a bit at 1800MHz as depicted in the table below:

Table 5.15 Deviation of the target value from the achieved value of tan δ for phantom liquid of guava

Frequency	Target value of tan δ	Achieved value of tan δ	Deviation
900MHz	0.154	0.152	+1.30%
1800MHz	0.159	0.160	+0.63%

The permissible limit of deviation for loss tangent is considered to be ±5%. So, exceptionally this phantom liquid for guava is appropriate for 900MHz as well as for 1800MHz.

5.3.4 Phantom Liquid for Grape:

To prepare the tissue equivalent phantom liquid of grape the target values i.e. the values of the dielectric parameter of grape tissue are presented in the table below:

Table 5.16 Target dielectric parameters for phantom liquid of grape at 900MHz [2]

Permittivity(ε′)	Loss factor(tan δ)
69.11	0.167

In a similar way as before, sugar and common salt were added to DI water for preparing the tissue equivalent liquid of grape. The amount of added sugar to DI water was similar as it was done for preparing the phantom liquid for guava. As the target value of permittivity (69.11) is in the higher range, similar to guava i.e. closer to that of the DI water (78), so after adding little amount of sugar e.g. 40g sugar to 320ml DI water (same as that of the phantom liquid for guava), the range of target value of permittivity (74.3) was attained. But the value of loss tangent of that solution was 0.07. In order to increase it to a target value of 0.167 and to decrease the permittivity value to almost 70, common salt was added gradually step by step. After adding 800mg salt to that particular solution finally the target was reached. In this case the concentration of salt in the solution was more than that of the phantom liquid for guava as the loss tangent value is more for grape. Then similar steps were repeated with 640ml as well as 800ml of DI water to reach an acceptable conclusion. Finally a recipe was proposed for phantom liquid of grape as shown in the table 5.17.

Table 5.17 Phantom liquid for grape at 900MHz:

Concentration of sugar and common salt in the solution		Permittivity(ε′)	Loss factor(tan δ)
Sugar	0.125g/ml	73.68	0.168
Common salt	2.5mg/ml		

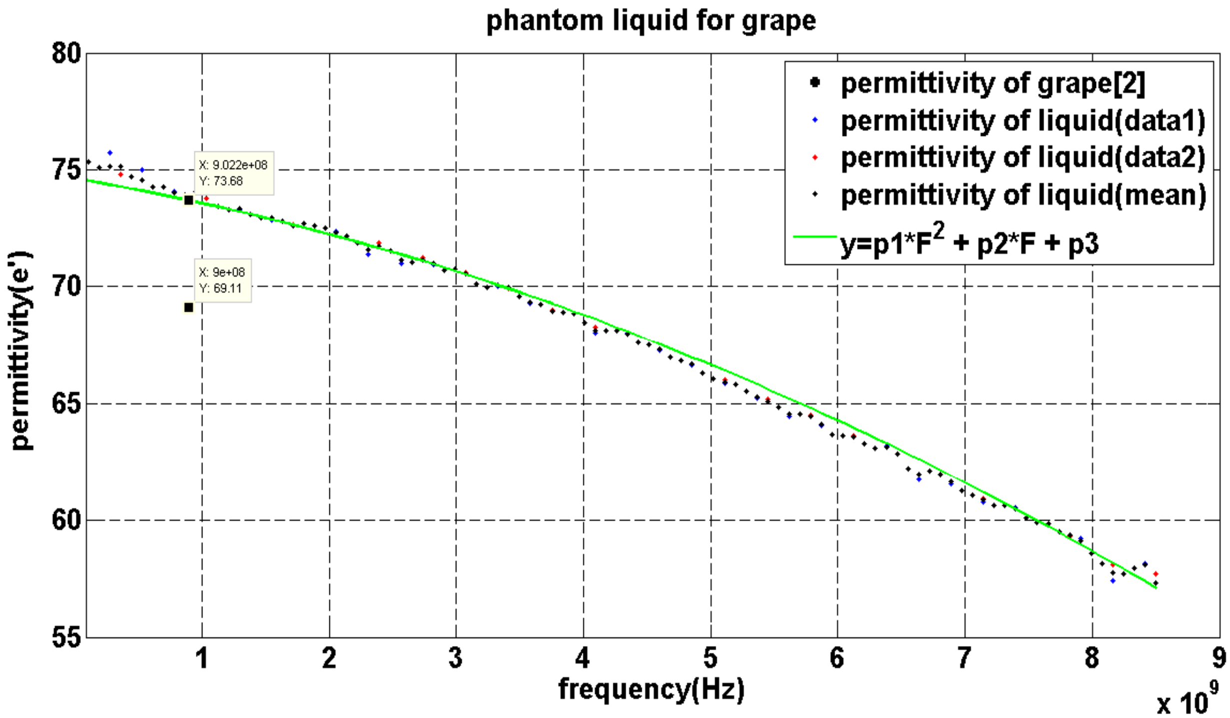


Fig.5.9 Real part of permittivity of phantom liquid for grape with frequency

The dielectric parameter measurement was done for the phantom liquid as stated before. From the plot (Figure5.9) of the real part of permittivity (ε′) along with frequency for phantom liquid of grape, it can be shown that ε′ varies in a quadratic manner from 75 at 200MHz to 57 at 8.5GHz following the equation: $Y=P_1*F^2+ P_2*F+ P_3$……………………………...(5.3.4.1)

where $P_1 =$ -1.334e-19, P_2=-9.263e-10; P_3=74.62; F= frequency in Hz

The difference between the target value and the achieved value of permittivity (ε′) for the phantom liquid at 900MHz and 1800MHz is presented in the table below:

Table 5.18 Difference between the target value and the achieved value of ε′ for phantom liquid of grape

Frequency	Target value of ε′	Achieved value of ε′	Deviation
900MHz	69.11	73.68	+6.61%
1800MHz	66.81	72.34	+8.28%

For permittivity, the permissible limit of deviation is considered to be ±10%. At 900MHz and 1800MHz, the deviation in ε′ is within the limit. So, from the point of view of permittivity, the liquid can be used as tissue equivalent phantom liquid for grape.

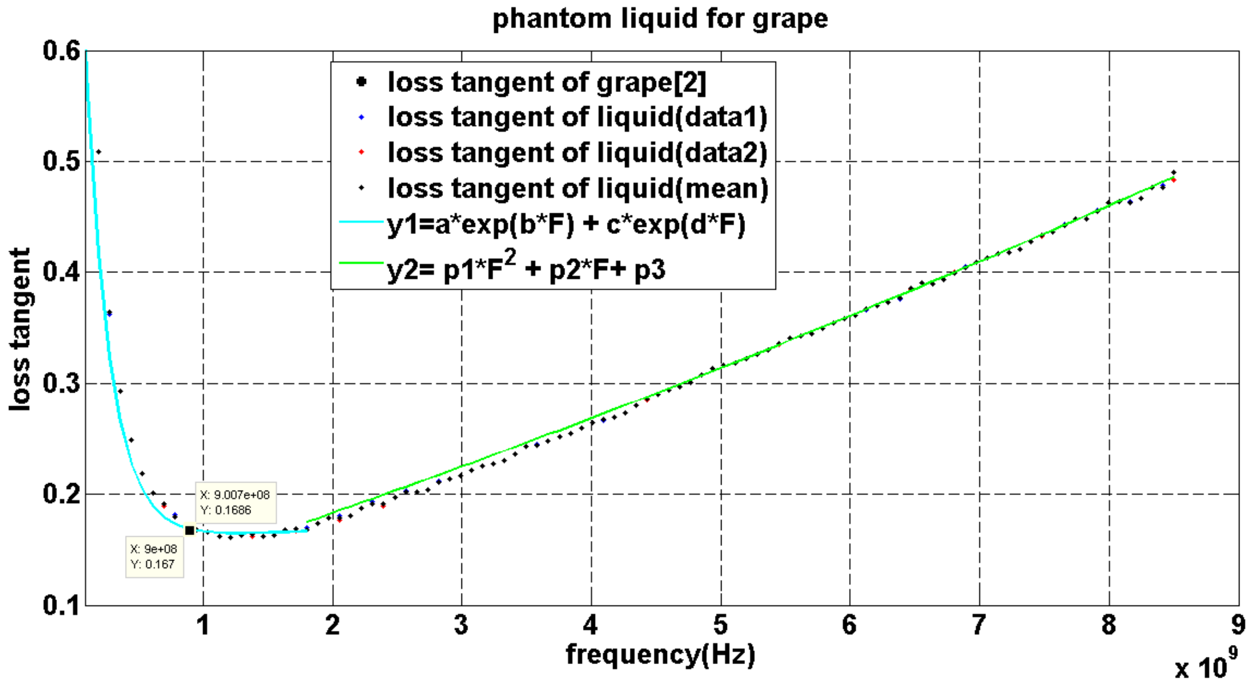


Fig.5.10 Loss tangent of phantom liquid for grape with frequency

From Figure5.10, it is observed that in the lower frequency range (up to 1.8GHz) the loss tangent (tan δ) of the liquid decreases exponentially (according to equation 5.3.4.2) and then it increases following a quadratic equation in terms of frequency as given in equation 5.3.4.3.

Y_1=a*exp(b*F) + c*exp(d*F)……………………………5.3.4.2

where a = 0.7002 ; b = -5.276e-009 ; c = 0.1585 ; d = 2.691e-011 ; F= frequency in Hz

Y_2= P_1*F^2 + P_2*F + P_3………………………….........5.3.4.3

where P_1 = 8.62e-022 ;P_2 = 3.754e-01 ; P_3 = 0.1047; F= frequency in Hz

Here also a little deviation is observed in the value of loss tangent at 900MHz which increases quite a lot at 1800MHz as depicted in the table below:

Table 5.19 Deviation of the target value from the achieved value of tan δ for phantom liquid of grape

Frequency	Target value of tan δ	Achieved value of tan δ	Deviation
900MHz	0.167	0.169	+1.19%
1800MHz	0.185	0.166	+10.27%

The permissible limit of deviation for loss tangent is considered to be ±5%. So, the phantom liquid for grape is appropriate for 900MHz but not for 1800MHz.

5.3.5 Phantom Liquid for Orange:

To prepare the recipe of the tissue equivalent liquid of orange the target value i.e. the values of the dielectric parameter of orange tissue are presented in the table below:

Table 5.20 Target dielectric parameters for phantom liquid of orange at 900MHz [1]

Permittivity(ε′)	Loss factor(tan δ)
72.00	0.194

From the above table, we can see that orange has its permittivity value in the same range of guava and grape, whereas its loss tangent value is quite high. So, similar approach of adding sugar first and then common salt to DI water was applied in case of orange also. For preparing the tissue equivalent liquid of orange, the amount of adding sugar to DI water was less than that of the apple or banana. As the target value of permittivity (72) is more close to that of the DI water (78), so after adding little amount of sugar e.g. 40g sugar to 320ml DI water, the range of target value of permittivity (74.3) was attained. But the value of loss tangent of that solution was 0.07. In order to increase it to a target value of 0.194 and to decrease the permittivity value to almost 72, common salt was added gradually step by step. After adding 1000mg salt to that particular solution finally the target was reached. In this case the concentration of common salt in the solution was considerably more than that of the phantom liquid for grape as the loss tangent value is more for orange. The similar steps were repeated with 640ml as well as 800ml of DI water to reach an acceptable conclusion. Finally a recipe was proposed for phantom liquid of orange as shown in the table below.

Table 5.21 Phantom liquid for orange at 900MHz:

Concentration of sugar and common salt in the solution		Permittivity(ε′)	Loss factor(tan δ)
Sugar	0.125g/ml	73.94	0.193
Common salt	3.125mg/ml		

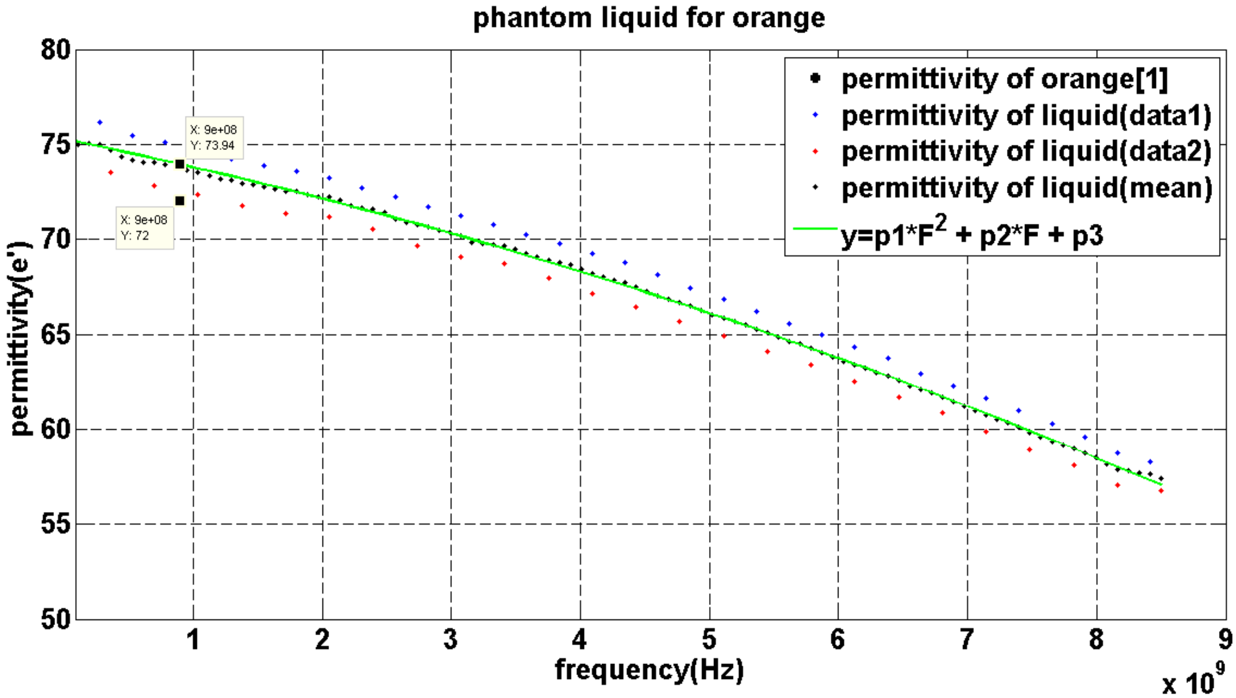


Fig.5.11 Real part of permittivity of phantom liquid for orange with frequency

The dielectric parameter measurement was done for the phantom liquid as stated before. From the plot (Figure5.11) of the real part of permittivity (ε′) along with frequency for phantom liquid of orange, it can be shown that ε′ varies in a quadratic manner from 75 at 200MHz to 57 at 8.5GHz following the equation: $Y=P_1*F^2+ P_2*F+ P_3$……………………………...(5.3.5.1)

where P_1 = -8.796e-020, P_2= -1.393e-009; P_3= 75.27; F= frequency in Hz

The difference between the target value and the achieved value of permittivity (ε′) for the phantom liquid at 900MHz and 1800MHz is presented in the table below:

Table 5.22 Difference between the target value and the achieved value of ε′ for phantom liquid of orange

Frequency	Target value of ε′	Achieved value of ε′	Deviation
900MHz	72.00	73.94	+2.69%
1800MHz	71.34	72.76	+1.99%

For permittivity the permissible limit of deviation is considered to be ±10%. At 900MHz and 1800MHz, the deviation in ε′ is within the limit. So, from the point of view of permittivity, the liquid can be used as tissue equivalent phantom liquid for orange.

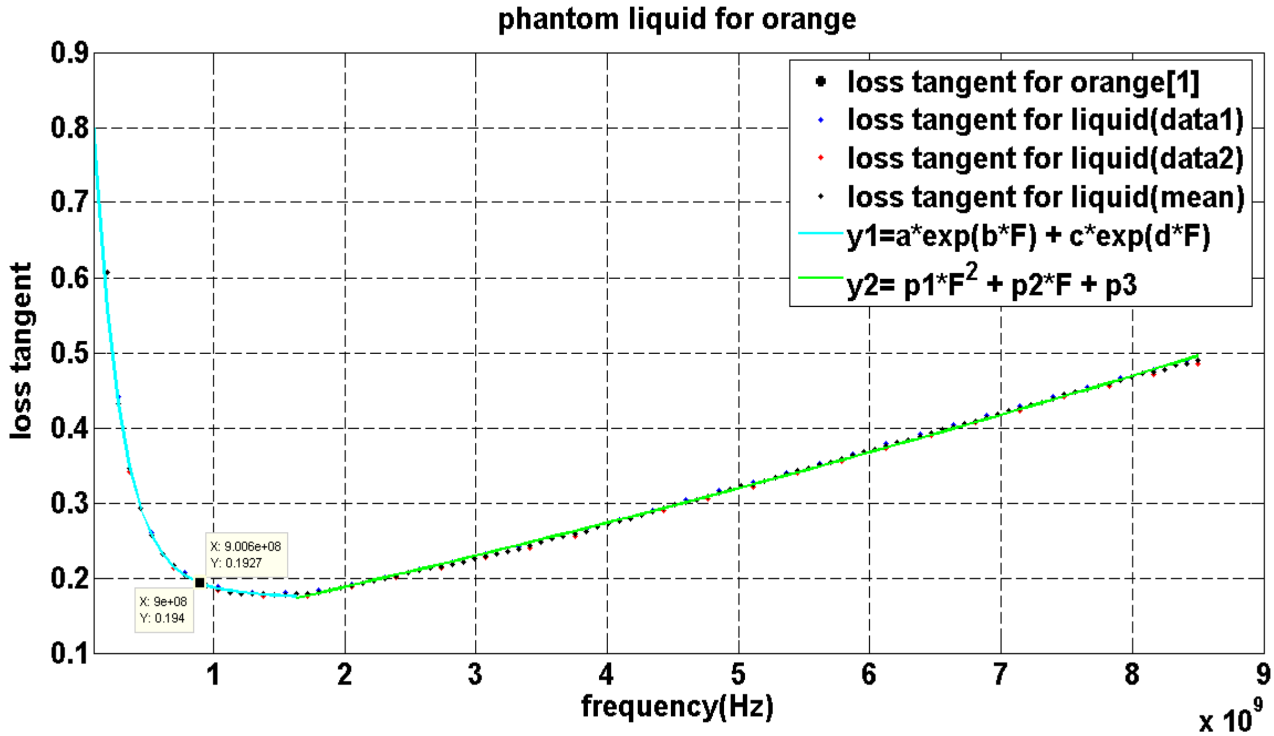


Fig.5.12 Loss tangent of phantom liquid for orange with frequency

From Figure5.12, it is observed that in the lower frequency range (up to 1.63GHz) the loss tangent (tan δ) of the liquid decreases exponentially (according to equation 5.3.5.2) and then it increases following a quadratic equation in terms of frequency as given in equation 5.3.5.3.

$$Y_1=a*exp(b*F) + c*exp(d*F) \qquad \ldots\ldots 5.3.5.2$$

where a = 0.9289 ; b =-4.83e-009 ; c = 0.1878 ; d = -4.393e-01;F= frequency in Hz

$$Y_2= P_1*F^2 + P_2*F + P_3 \qquad \ldots\ldots 5.3.5.3$$

where P_1 =1.023e-021 ;P_2 = 3.664e-011 ; P_3 = 0.1104 ; F= frequency in Hz

Here also a little deviation is observed in the value of loss tangent at 900MHz which increases a bit at 1800MHz as depicted in the table below:

Table 5.23 Deviation of the target value from the achieved value of tan δ for phantom liquid of orange

Frequency	Target value of tan δ	Achieved value of tan δ	Deviation
900MHz	0.194	0.193	+0.52%
1800MHz	0.179	0.176	+1.68%

The permissible limit of deviation for loss tangent is considered to be ±5%. So, the phantom liquid for orange is also appropriate for 900MHz as well as for 1800MHz like that of guava.

5.4 Generalization of the recipe for phantom liquid preparation:

The recipes of the already mentioned phantom liquids can be generalized in order to make the liquids more convenient for the purpose of SAR measurement of the corresponding fruits. If we can prepare a common solution for a group of fruits which have permittivity values in the same range at 900MHz, then by adding different amount of common salt their loss tangent values can be attained. Then the process of preparing customized phantom liquids for different fruits would be more general. In this work the fruits can be classified in two groups depending on the values of their permittivity and accordingly two general recipes are proposed for them.

Group 1: Till now, it were observed that in case of phantom liquids for apple and banana the concentration of sugar in both the solutions were same as their permittivity values are 65. But the salt concentrations of those liquids were different as the target values of that parameter were different. So a general aqueous solution with sugar concentration of 0.375g/ml was prepared and then common salt was added gradually up to a concentration of 6.875mg/ml so that a target value up to 0.3 (in terms of loss tangent) may be reached.

The recorded data of permittivity and loss tangent for corresponding salt concentration were plotted using MATLAB and then curve fitting technique was applied to yield a general formula for ε' as well as $\tan\delta$ for a given common salt concentration in an aqueous solution of known sugar concentration (0.375g/ml). From the plot of figure 5.13, it can be observed that the permittivity values always remain within the permissible limit though the salt concentration changes.

The target values of the permittivity and loss tangent of some fruits (mentioned in the last chapter) along with apple and banana at 900MHZ are tabulated in the table below whose loss tangent values are marked in figure 5.14. From those marked values, corresponding salt concentrations can be known and on adding that amount of common salt to a sugar solution of 0.375g/ml concentration customized phantom liquids of those fruits (grouped below) can be achieved.

Table 5.24 Dielectric parameters of group 1 fruits at GSM 900MHz frequency band

Name of the fruit	Permittivity (ε')	Loss tangent ($\tan\delta$)
Apple	65.03	0.135
Water Apple	65.52	0.149
Chiku	65.48	0.188
Banana	65.00	0.280

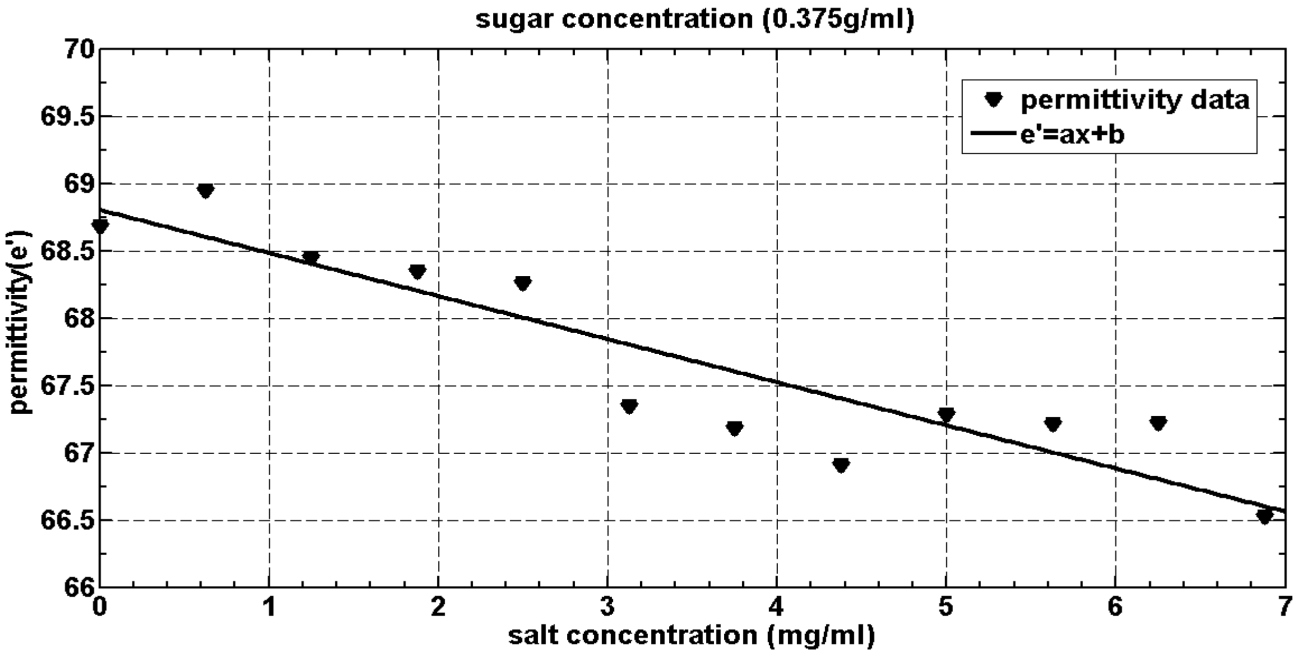


Fig5.13 Permittivity of aqueous sugar solution (0.375g/ml) with varying salt concentration

(a = –0.3202, b = 68.8)

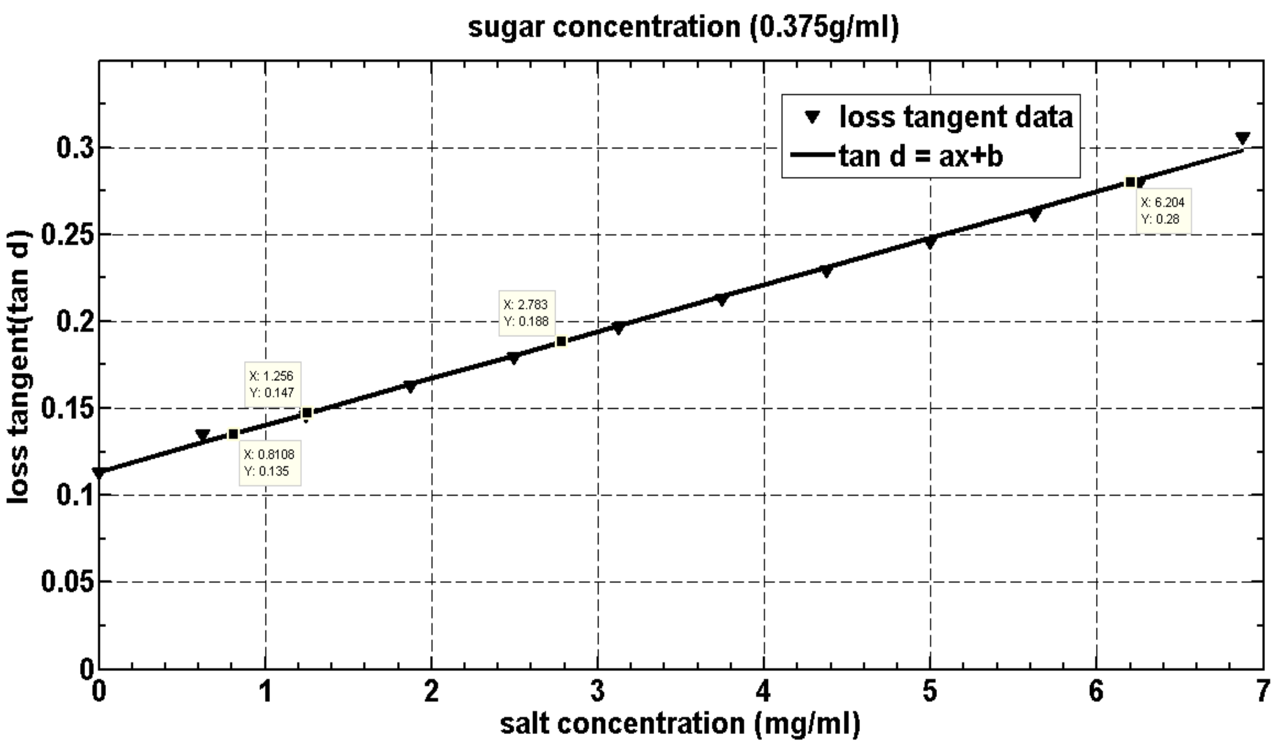


Fig5.14 Loss tangent of aqueous sugar solution (0.375g/ml) with varying salt concentration

(a = 0.02689, b = 0.1132)

Group 2:

This group comprises of the fruits having their permittivity in the range of 70. From the initial recipes of the proposed phantom liquids, another observation is that the phantom liquids for guava, grape and orange contained same sugar concentration in the aqueous solution. But the salt concentrations of those liquids were different as the target values of that parameter were different. So a general aqueous solution with sugar concentration of 0.125g/ml was prepared and then common salt was added gradually up to a concentration of 4.5mg/ml so that a target value up to 0.24 in terms of loss tangent can be reached.

Similarly, the recorded data of permittivity and loss tangent for corresponding salt concentration were plotted using MATLAB and then curve fitting was applied to yield a general formula for ε′ as well as tanδ for a given salt concentration in an aqueous solution of known sugar concentration (0.125g/ml). From the plot of figure 5.15, it can be observed that here also the permittivity value always remain within the permissible limit though the salt concentration changes.

The target values of the permittivity and loss tangent of a new fruit (black grape, mentioned in the last chapter) is added along with guava, grape and orange at 900MHZ which are tabulated in the table below and the loss tangent values of these fruits are marked in figure 5.16. From those marked values, corresponding salt concentrations can be known and on adding that amount of salt to a sugar solution of 0.125g/ml concentration customized phantom liquids of the fruits in group 2 can be achieved.

Table 5.25 Dielectric parameters of group 2 fruits at GSM 900MHz frequency band

Name of the fruit	Permittivity (ε′)	Loss tangent (tanδ)
Guava	72.08	0.154
Grape	69.11	0.167
Black Grape	71.43	0.177
Orange	72.00	0.194

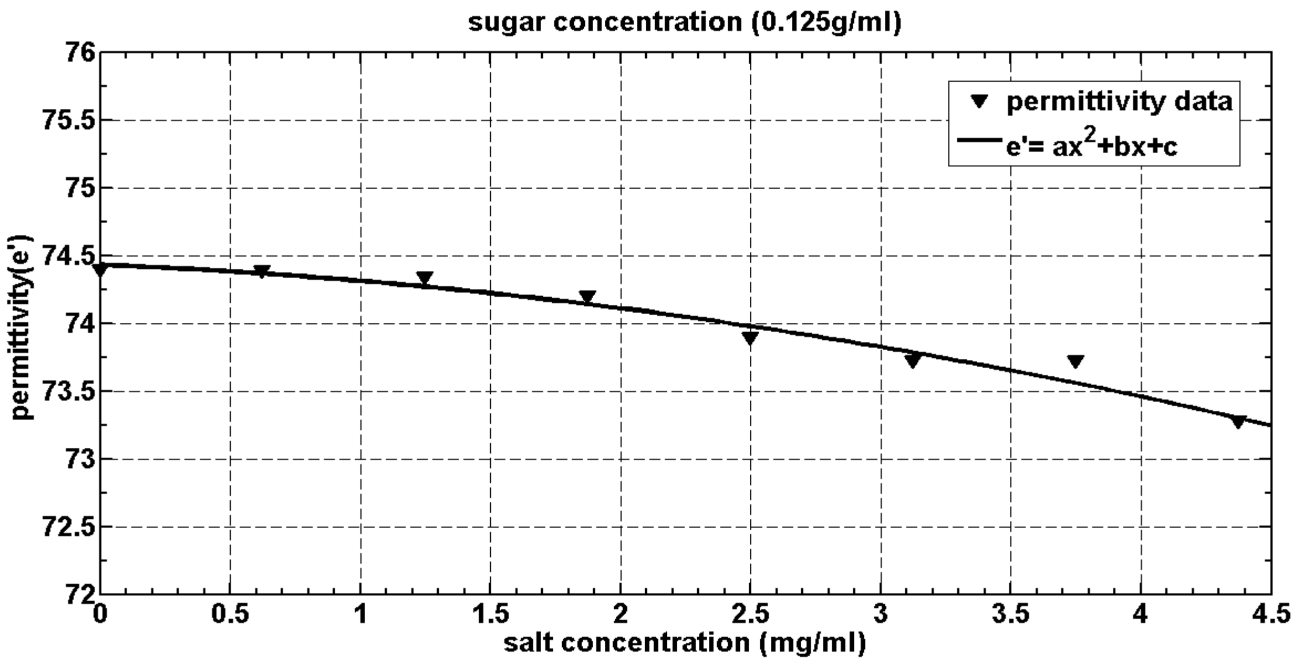


Fig5.15 Permittivity of aqueous sugar solution (0.125g/ml) with varying salt concentration

(a = –0.04144; b = −0.07744 ; c = 74.43)

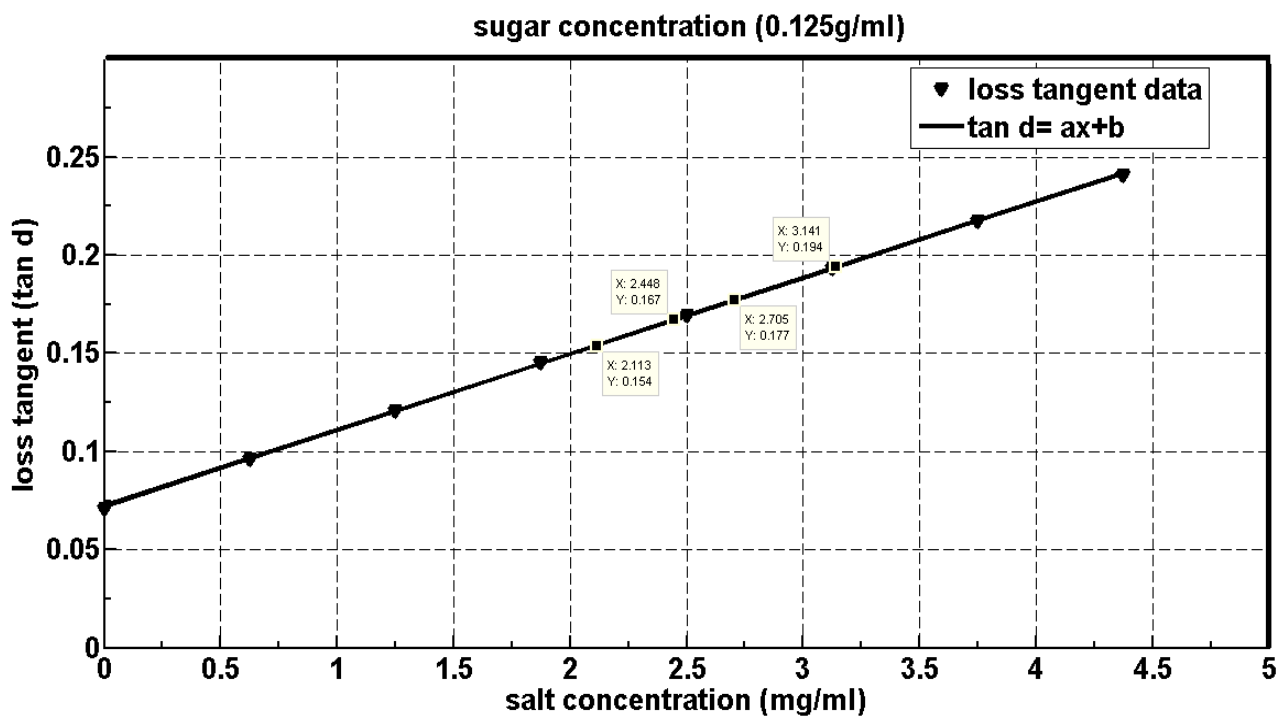


Fig5.16 Loss tangent of aqueous sugar solution (0.125g/ml) with varying salt concentration

(a = 0.03884, b = 0.07195)

5.5 Conclusion:

The recipes for the preparation of customized phantom liquids of five fruits (viz. apple, banana, guava, grape and orange) are presented in this chapter. Their behavior in the frequency range varying from 200MHz to 8.5GHz is studied and from that observation we can say that the liquids are perfect for GSM 900MHz frequency band but not for 1800MHz frequency band with some exception (for guava and orange). So, further study needs to be done in order to achieve the target values of the dielectric parameters for these particular fruits at the other frequency band of interest also.

In the last part, we have suggested the generalized recipes of the phantom liquids for GSM frequency of 900MHz. Target values of more number of fruits and vegetables can be obtained from that generalized formula of the phantom liquid which is an important step for performing practical SAR measurement for the corresponding fruits and vegetables. From the plot of the variation in permittivity and loss tangent versus salt concentration (as shown in figure 5.15 and figure 5.16), it is also observed that permittivity decreases and loss tangent increases with addition of salt to a particular sugar solution.

References:

[1] Nelson, S. O. "Dielectric spectroscopy of Fresh Fruits and Vegetables". *Instrumentation and Measurement Technology Conference*, Ottawa, Canada, 17-19 May 2005.

[2] A. Kundu, B. Gupta; "Comparative SAR Analysis of Some Indian Fruits as per the Revised RF Exposure Guideline", *IETE Journal of Research*, Published online: 01 Oct 2014.

FREQUENCY AND TEMPERATURE DEPENDENCE OF THE PREPARED PHANTOM LIQUIDS

6.1 Introduction:

This chapter deals with the variation of dielectric properties for the prepared tissue equivalent phantom liquids (for the five fruits described in the previous chapter) with the variation in temperature along with frequency. The variation depends on the concentration of the liquid as the ionic conductivity change due to dissolved salt and sugar. In the microwave frequency range, dipolar relaxation dominates the behavior of polar liquid which is water in this case. Depending on all these factors, the change in dielectric constant (ε′) and loss factor (tanδ) of those phantom liquids are analyzed in the frequency range of 200MHz to 8.5GHz.

6.2 Measurement procedure:

The phantom liquids were initially kept into refrigerator to reduce the temperature. After taking it out, the coaxial probe was immersed into it after proper calibration and a bromine thermometer was placed inside the beaker to observe the change in temperature. As the temperature of the liquid kept on increasing from 10°C up to room temperature (25°C), the triggering of the probe kit was done at 1°C interval to record the data of the dielectric parameters at each instant. To increase the temperature of the liquid even more, hot water was added externally to the container where the beaker containing the liquid was placed as shown in figure 6.1. Again the same procedure was repeated at 1°C interval and the data were recorded up to 40°C. Later, the recorded data were imported in MATLAB to plot the dielectric parameters with temperature along with the frequency as presented in the following section. The whole process was repeated for all five different phantom liquids which were prepared for apple, banana, guava, grape and orange.

Fig.6.1 Measuring temperature of the phantom liquid using thermometer when the beaker is placed in hot water

6.3.1 Frequency and Temperature dependence of Phantom liquid for Apple and Banana:

6.3.1.1 Dielectric constant (ε′):

From the plots of figure 6.2 and 6.3, it can be observed that in the lower frequency range from 200MHz to 3GHz the dielectric constant (ε′) of both the phantom liquids for apple and banana decreases with increase in temperature from 10°C to 40°C whereas the behavior reverses from 3GHz to 8.5GHz frequency. At 3GHz, the dependence of dielectric constant on temperature is zero. So, the temperature coefficient for the dielectric constant of phantom liquid for apple as well as banana changes from negative to positive, revealing a zero-temperature dependence at that particular frequency (3GHz). But the value of the dielectric constant monotonically decreases for a particular temperature over the frequency range of 200MHz to 8.5GHz.

The nature of temperature dependence of the dielectric properties is a function of the dielectric relaxation processes operating under the particular conditions existing and the frequency being used. With the increase in temperature, the relaxation time, τ (the mean time it takes per molecule to randomize the induced dipole moment) reduces and the Debye loss peak shifts to higher frequency (ω=1/ τ).

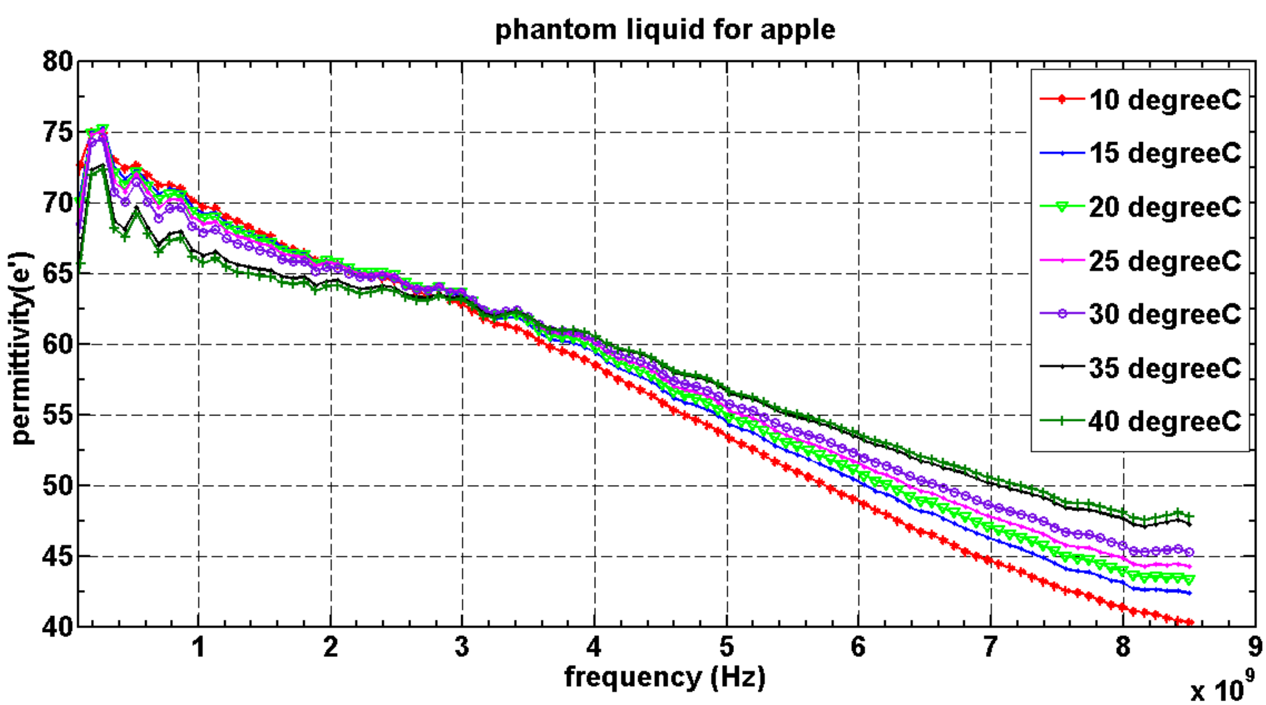


Fig.6.2 Frequency and temperature dependence of permittivity of phantom liquid for Apple

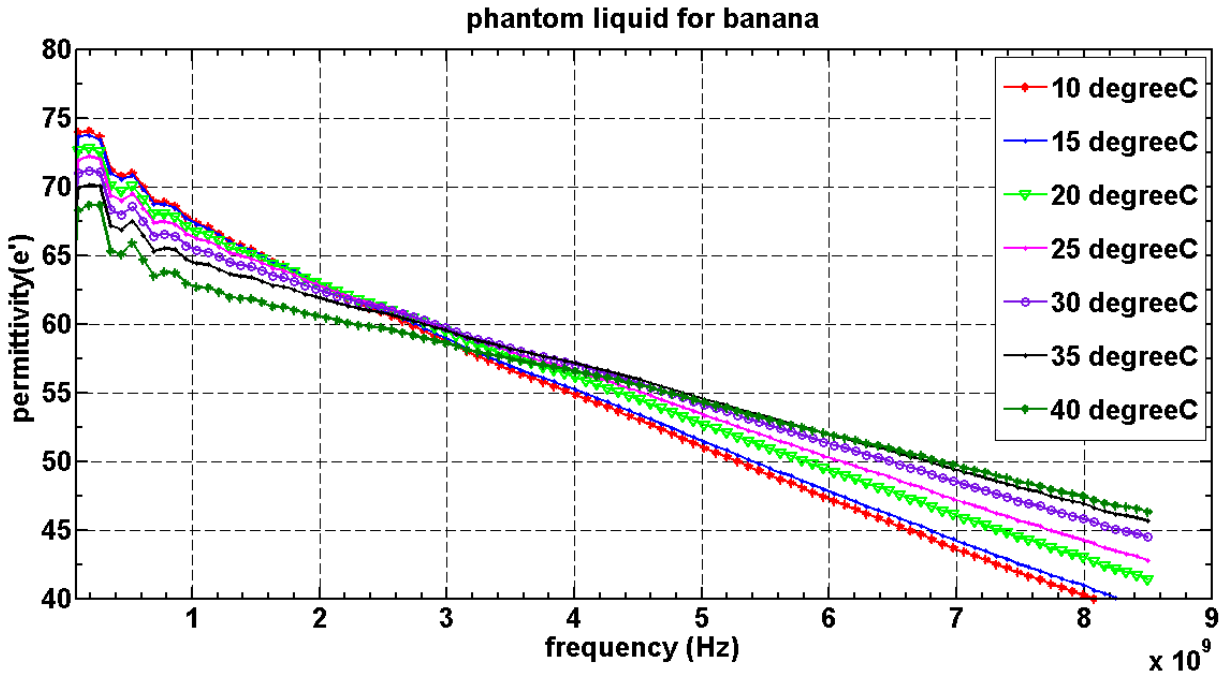


Fig.6.3 Frequency and temperature dependence of permittivity of phantom liquid for Banana

6.3.1.2 Loss tangent (tanδ):

The loss tangent for phantom liquid of apple increases monotonically with increase in frequency from 200MHz to 8.5GHZ. No inversion of temperature dependence is observed. tanδ decreases with increase in temperature throughout the entire frequency range.

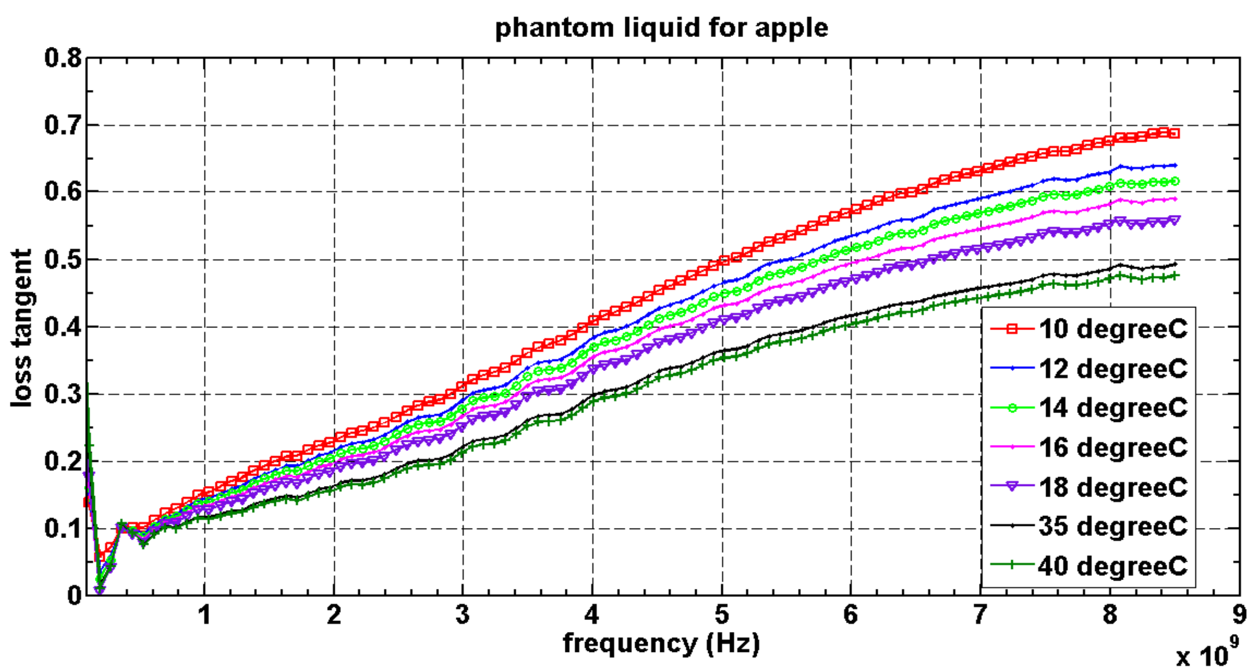


Fig.6.4 Frequency and temperature dependence of loss tangent of phantom liquid for Apple

Exceptionally, from the plot of the loss tangent of phantom liquid for banana with temperature variation along with frequency ranging from 200MHz to 8.5GHz as shown in figure 6.5, it can be observed that the inversion of temperature coefficient of loss tangent for phantom liquid of banana occurs at about 1.2GHz. Below this frequency of zero temperature dependence, loss tangent increases with increasing temperature and then it decreases with increasing temperature. So here the inversion occurs from positive temperature coefficient of loss tangent to negative which was opposite in case of dielectric constant where the temperature coefficient of dielectric constant changes from negative to positive.

The loss tangent of phantom liquid for banana at 900MHz is 0.28. So, the salt concentration in the solution was considerably more. It may so happen that due to higher concentration of salt in the phantom liquid for banana the inversion of temperature coefficient of loss tangent occurs which was absent in case of phantom liquid for apple although both the solutions had same sugar concentration.

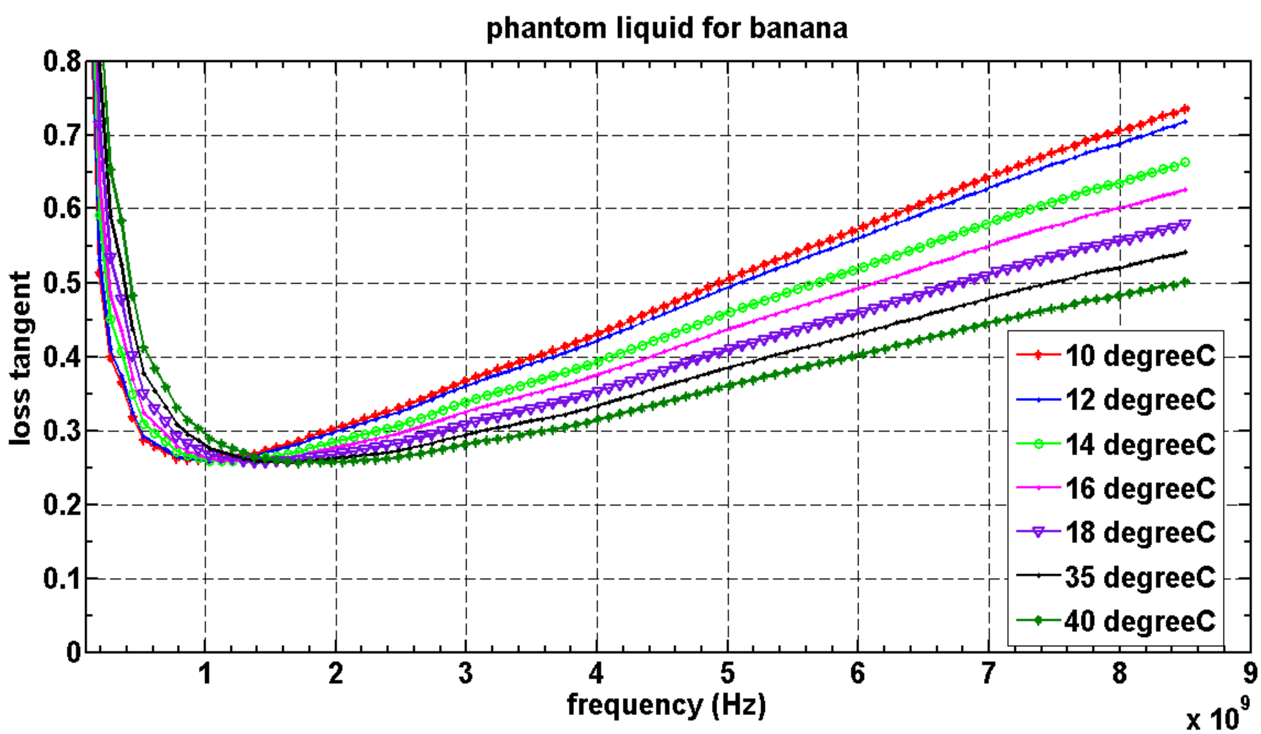


Fig.6.5 Frequency and temperature dependence of loss tangent of phantom liquid for Banana

6.3.2 Frequency and Temperature dependence of Phantom liquid for Guava, Grape and Orange:

6.3.2.1 Dielectric constant (ε′):

The dielectric constant of phantom liquid for guava, grape and orange are plotted with varying temperature along with frequency in the following figures. In all the cases, the point of zero dependence of temperature coefficient of dielectric constant shifts to higher frequency at about 5GHz in comparison to that of the apple or banana. However the temperature coefficient changes from negative to positive, similar to that of the phantom liquid for apple and banana.

Due to higher concentration of water in these phantom liquids in comparison to that of the apple or banana, the dipolar relaxation is more dominant in these cases. As a result the Debye loss peak shifts to higher frequency. Consequently, the behavior of dielectric constant of all the phantom liquids changes with temperature.

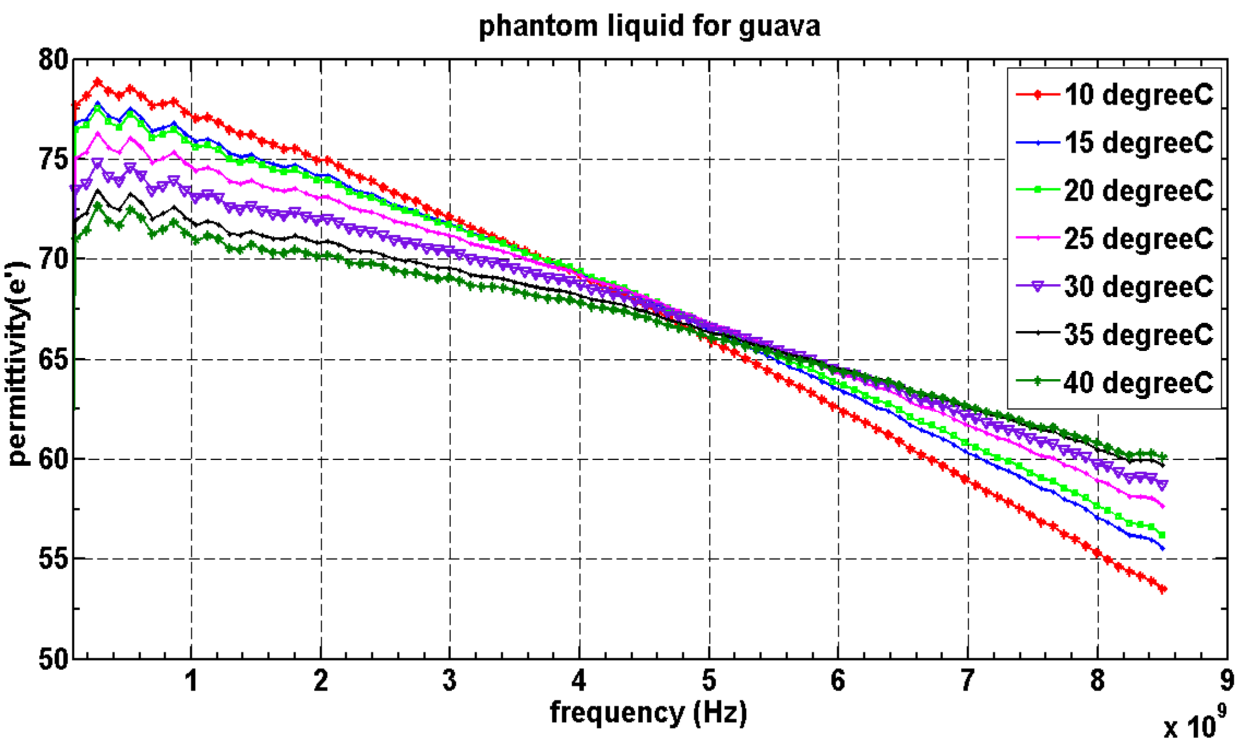


Fig.6.6 Frequency and temperature dependence of permittivity of phantom liquid for Guava

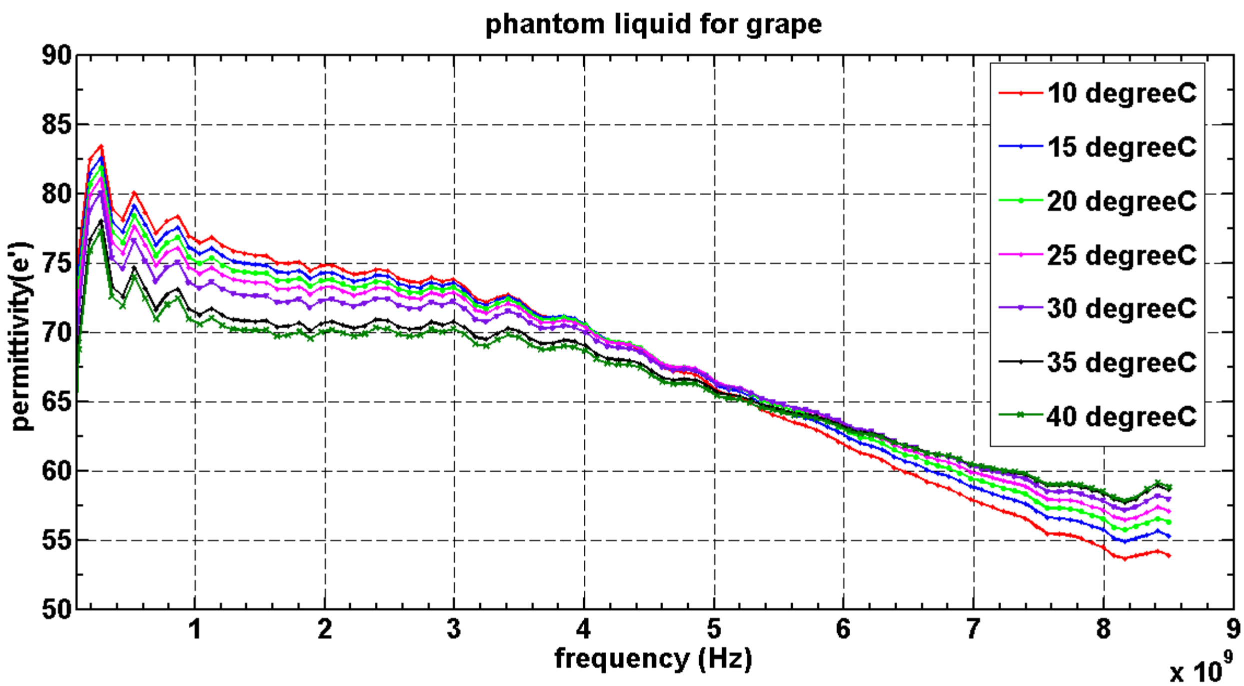


Fig.6.7 Frequency and temperature dependence of permittivity of phantom liquid for Grape

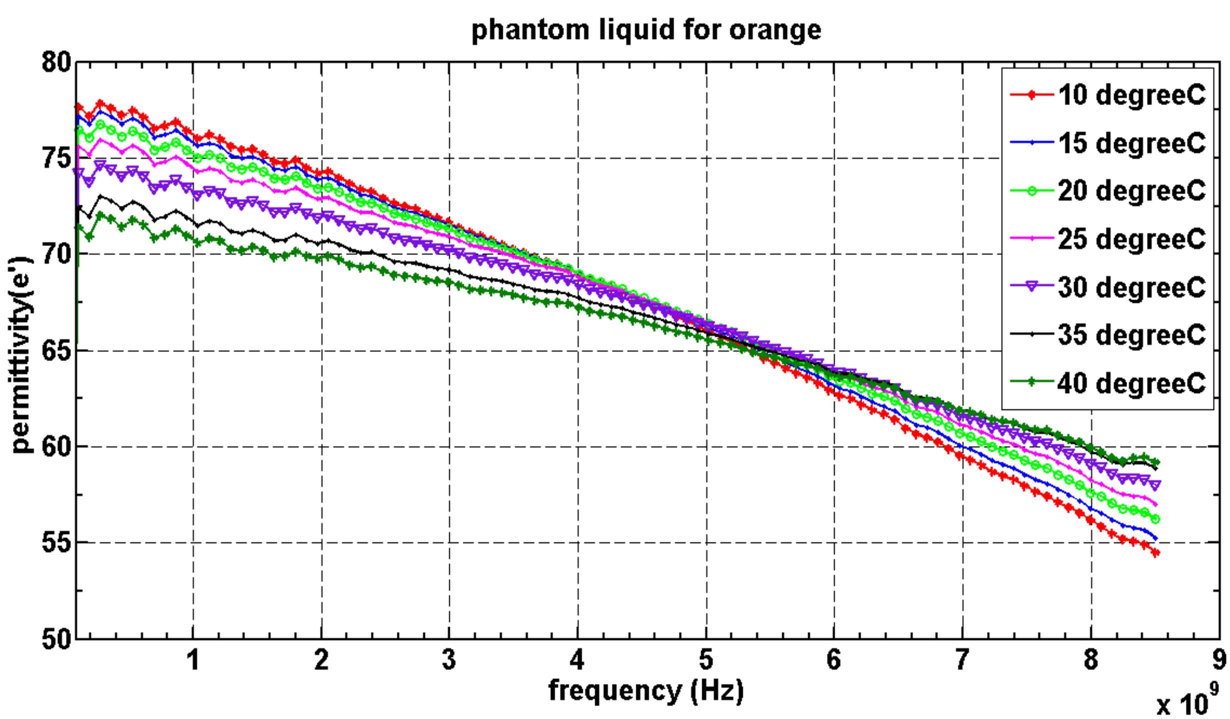


Fig.6.8 Frequency and temperature dependence of permittivity of phantom liquid for Orange

6.3.2.2 Loss tangent (tanδ):

The temperature coefficient of loss tangent for phantom liquid of guava, grape and orange changes from positive to negative at 1.1GHz, 1.3GHz and 1.5GHz respectively as depicted in the following figures e.g. in case of phantom liquid for guava, loss tangent increases with temperature from 200MHz to 1.1GHz and beyond 1.1GHz it decreases with increasing temperature. So, basically at 1.1GHz the temperature dependence of loss tangent of phantom liquid for guava disappears.

It may be inferred that the shift in the frequency of zero dependence of temperature coefficient of loss tangent for the three fruits mentioned above, occurs due to different concentration of salt in the corresponding phantom liquids e.g. the loss tangent of phantom liquid for grape at 900MHz was more than that of the guava, consequently the concentration of salt in the phantom liquid for grape was more. It may so happen that due to higher concentration of salt the frequency of zero temperature dependence of loss tangent shifts toward higher frequency in case of phantom liquid for grape.

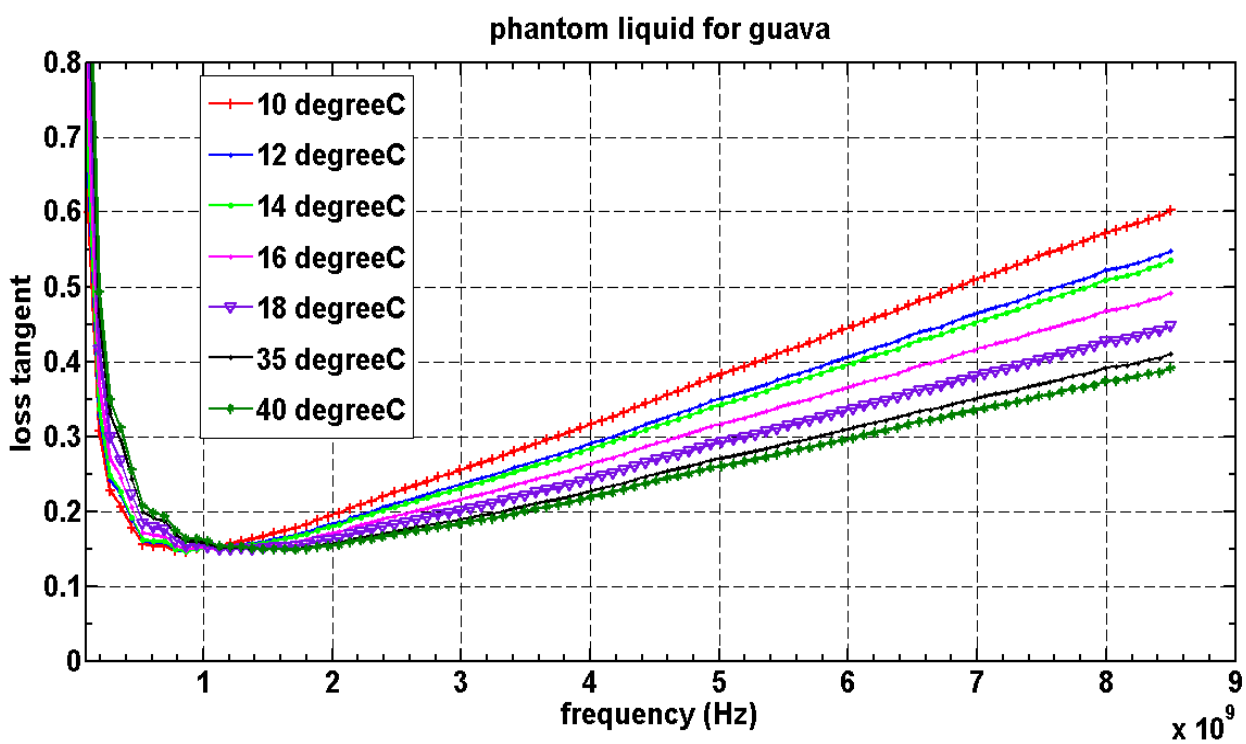


Fig.6.9 Frequency and temperature dependence of loss tangent of phantom liquid for Guava

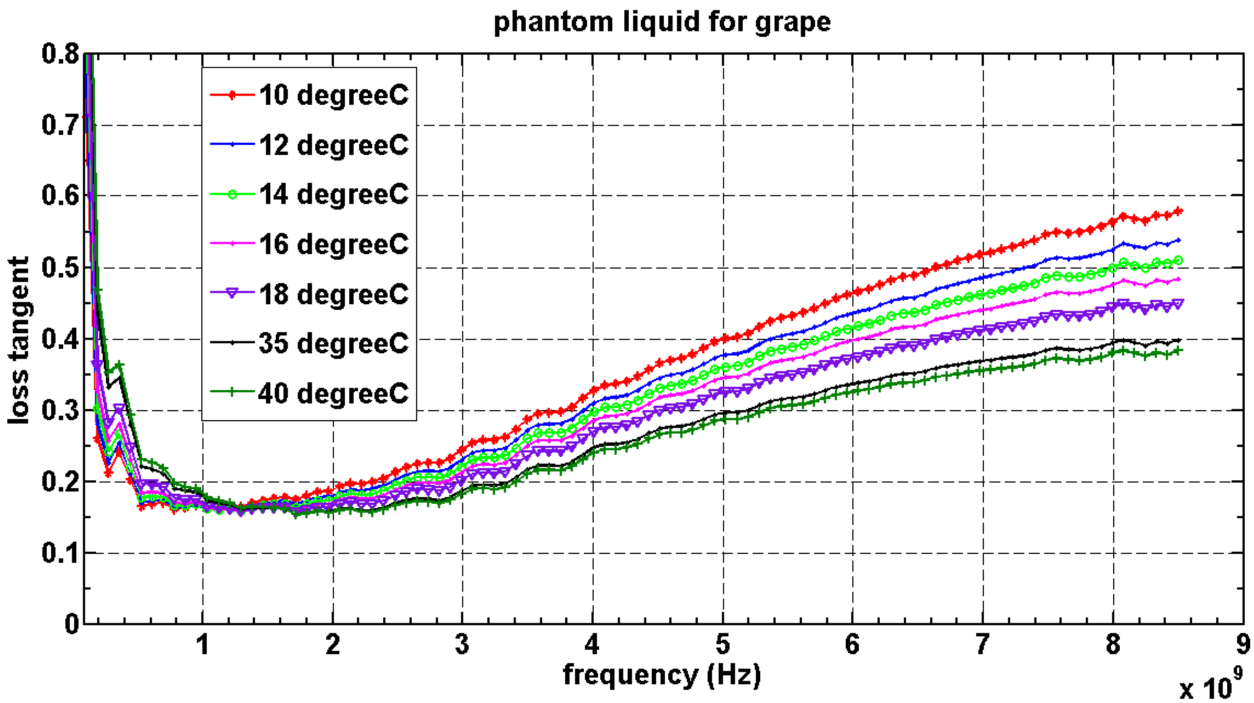


Fig.6.10 Frequency and temperature dependence of loss tangent of phantom liquid for Grape

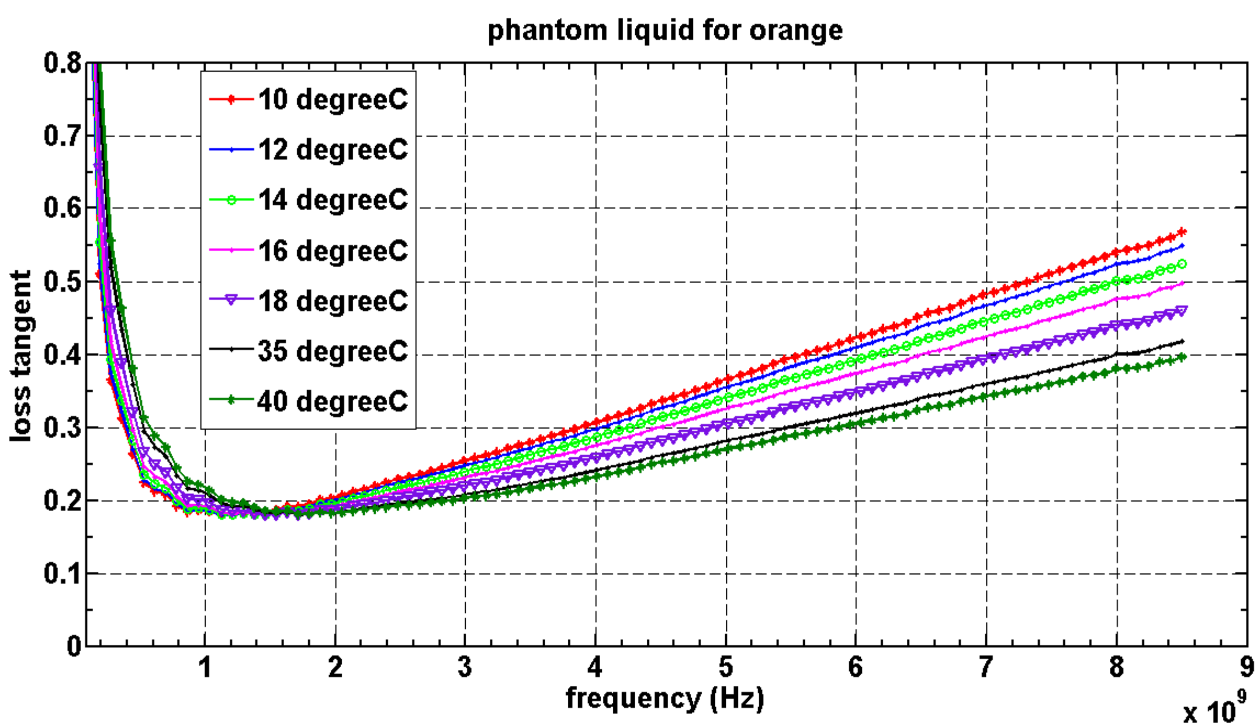


Fig.6.11 Frequency and temperature dependence of loss tangent of phantom liquid for Orange

6.4 Conclusion:

The temperature dependence of the phantom liquids prepared for apple, banana, guava, grape and orange has been discussed over the frequency range of 200MHz to 8.5GHz. But the main concern was at GSM 900MHz band as the phantom liquids were prepared to meet the target values at that particular frequency. For all the phantom liquids, the dielectric constant decreases with increasing temperature at 900MHz. So the temperature coefficient of dielectric constant is negative at 900MHz.

In case of loss tangent, at 900MHz it decreases with increase in temperature for phantom liquid of apple only. But for other phantom liquids, it increases with increasing temperature at 900MHz. So the temperature coefficient of loss tangent for phantom liquid of apple at 900MHz is negative where as it is positive for the other phantom liquids.

STABILITY OF PHANTOM LIQUIDS WITH RESPECT TO TIME IN TERMS OF DIELECTRIC PARAMETERS

7.1 Introduction:

The stability of phantom liquid is an important factor in studying the phantom model for SAR measurement. The stability is to be studied in terms of variation in permittivity and loss tangent with respect to time. If the dielectric parameters of the phantom liquids vary with time exceeding the permissible limit, then the constituents of the phantom liquids has not been chosen in a proper way. So, a time study of 7days duration has been performed to observe if there is any variation in the dielectric parameters of the prepared phantom liquids.

7.2 Measurement procedure:

The customized phantom liquids were prepared in day1 and the dielectric parameters were measured. And then they were preserved in air tight bottles in the refrigerator for 7 days. On the 7^{th} day, they were taken out and brought to room temperature (25°C) and again their dielectric properties were measured using the same coaxial probe technique.

7.3.1 Stability of phantom liquids in terms of permittivity:

The permittivities of phantom liquid for apple and guava remain almost constant as depicted in the following plots in figure 7.1 and 7.2 whereas in case of other phantom liquids it decreased a bit. For example, on the 7^{th} day, for phantom liquid of banana it decreased by 8.57% on the 7^{th} day, for that of the grape it was reduced by 2.03% and for phantom liquid of orange it was 3.33% less. Surprisingly, all these three liquids mentioned in this last group contained higher salt concentration in comparison to that of the apple or guava and it was already observed that permittivity decreases with increased salt concentration. And also due to evaporation of water permittivity value of those liquids change. All these decrements are presented from figure 7.3 to figure 7.5. So in all the cases, the permittivities remain within permissible limit (±10%) and the phantom liquids can be used for SAR measurement.

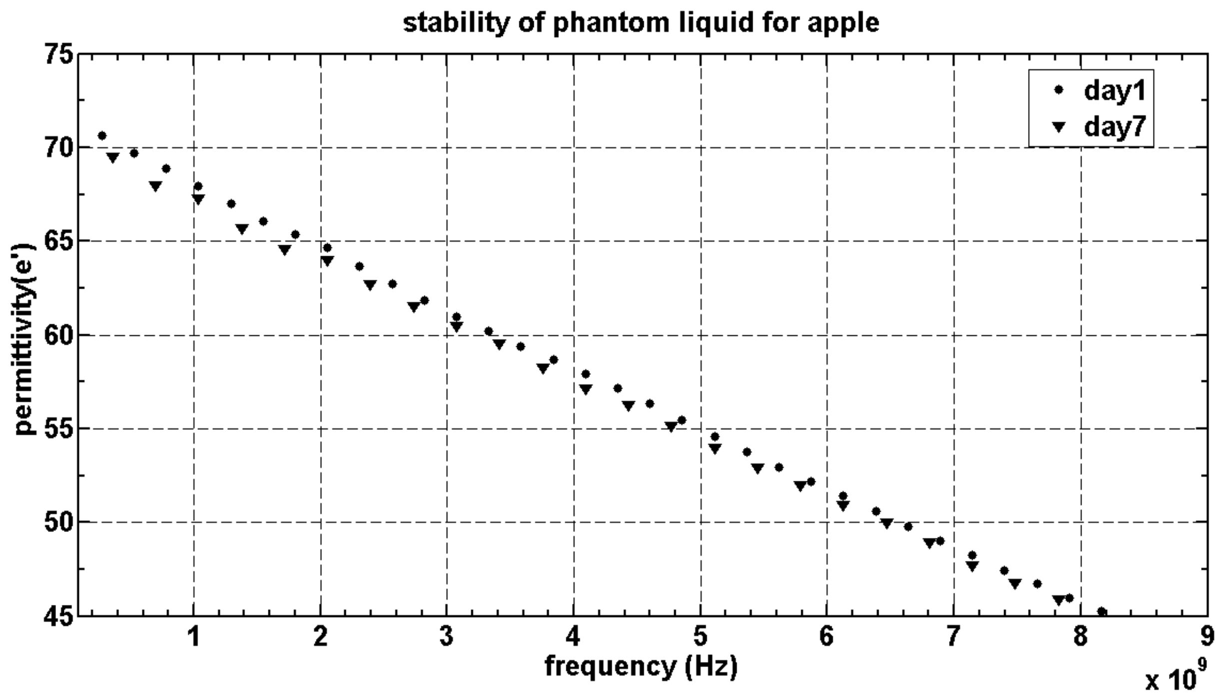


Fig.7.1 Time dependence of permittivity of phantom liquid for apple

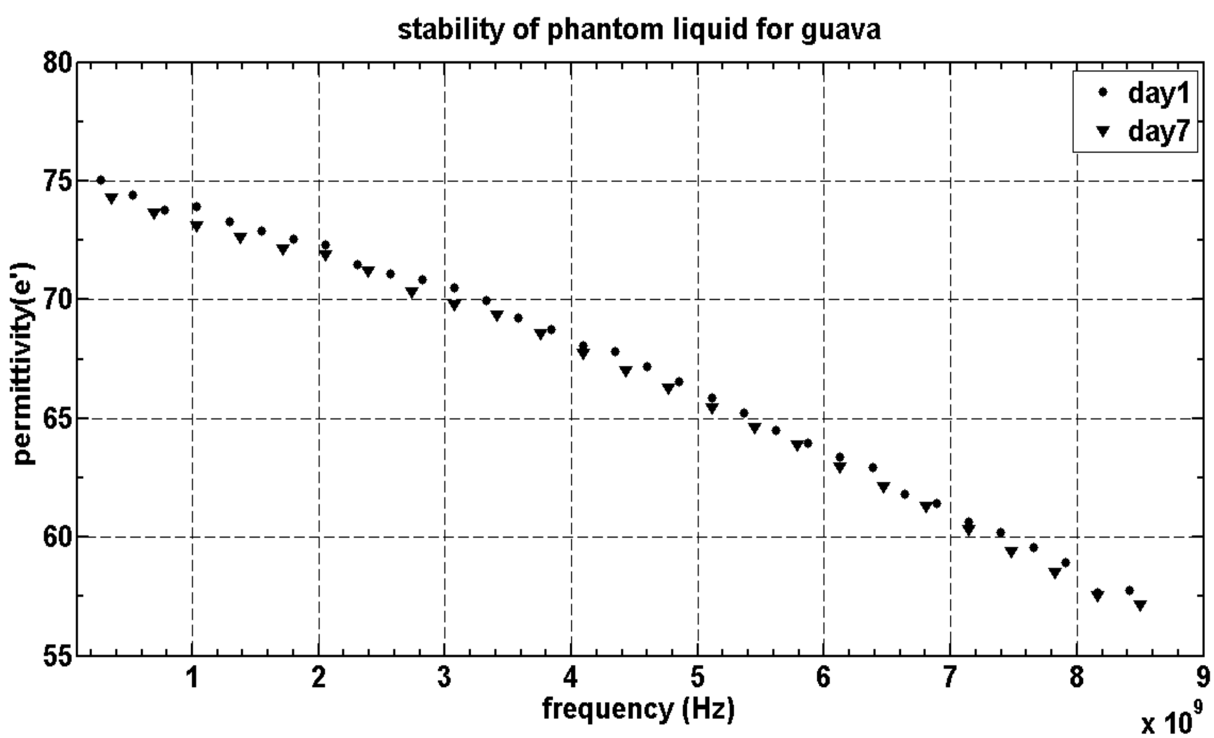


Fig.7.2 Time dependence of permittivity of phantom liquid for guava

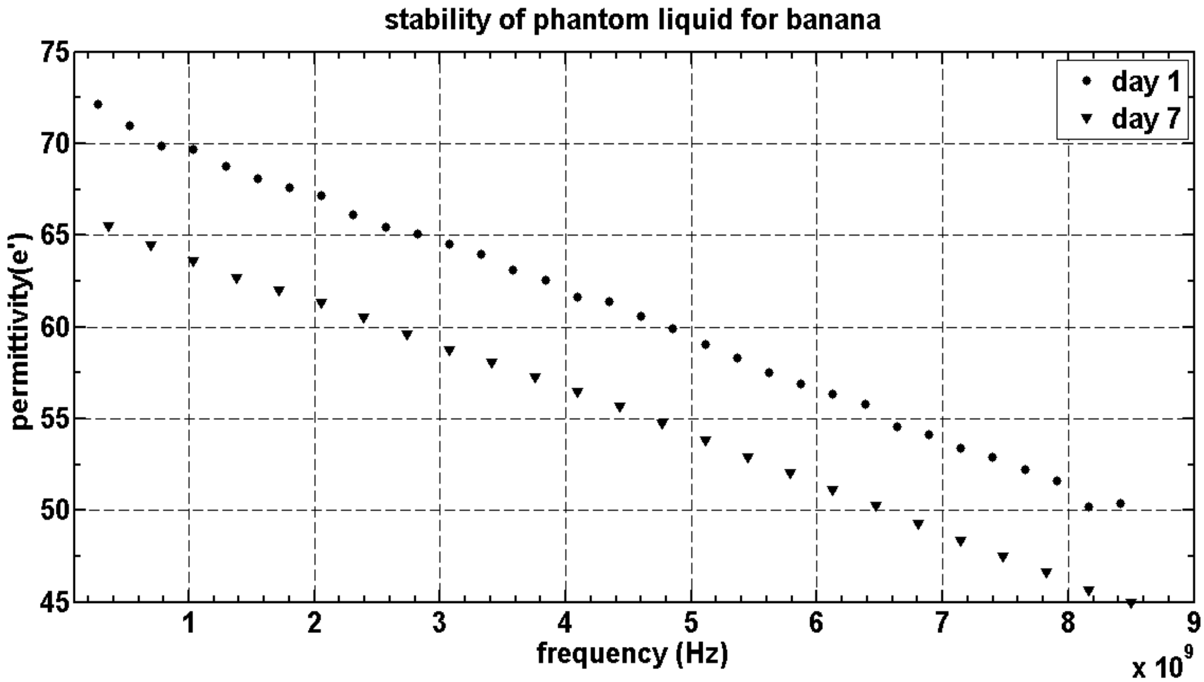


Fig.7.3 Time dependence of permittivity of phantom liquid for banana

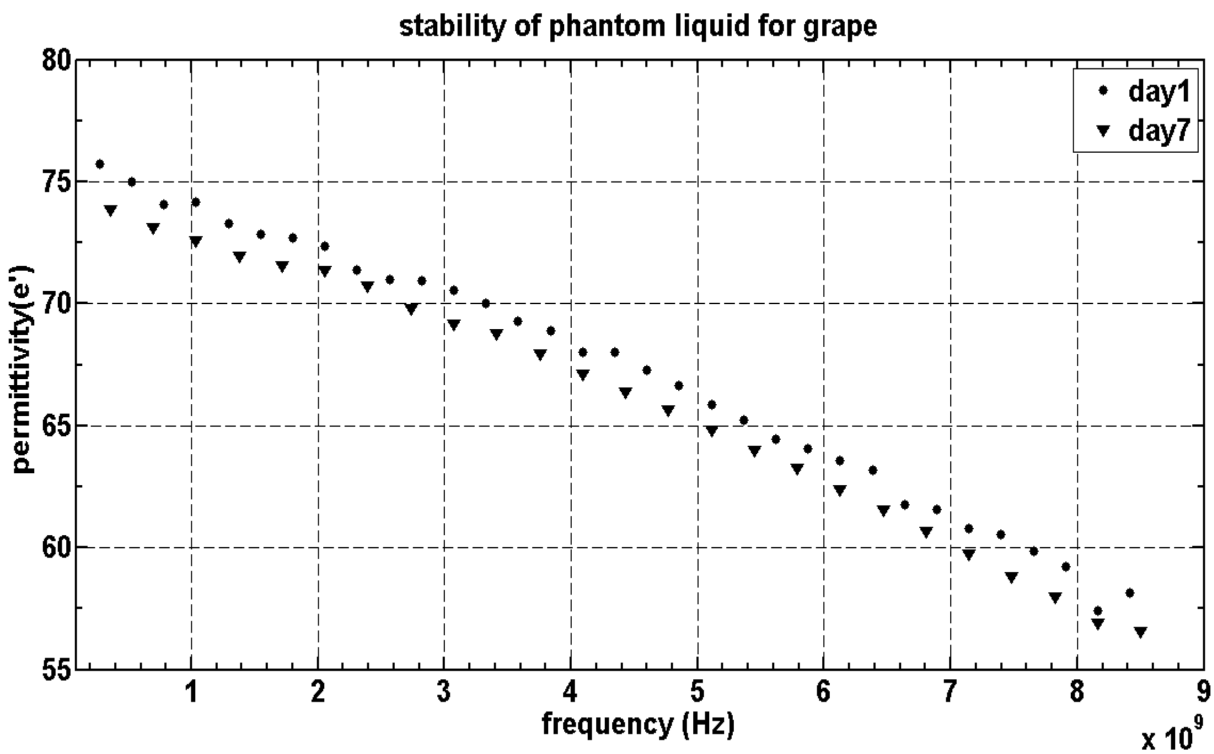


Fig.7.4 Time dependence of permittivity of phantom liquid for grape

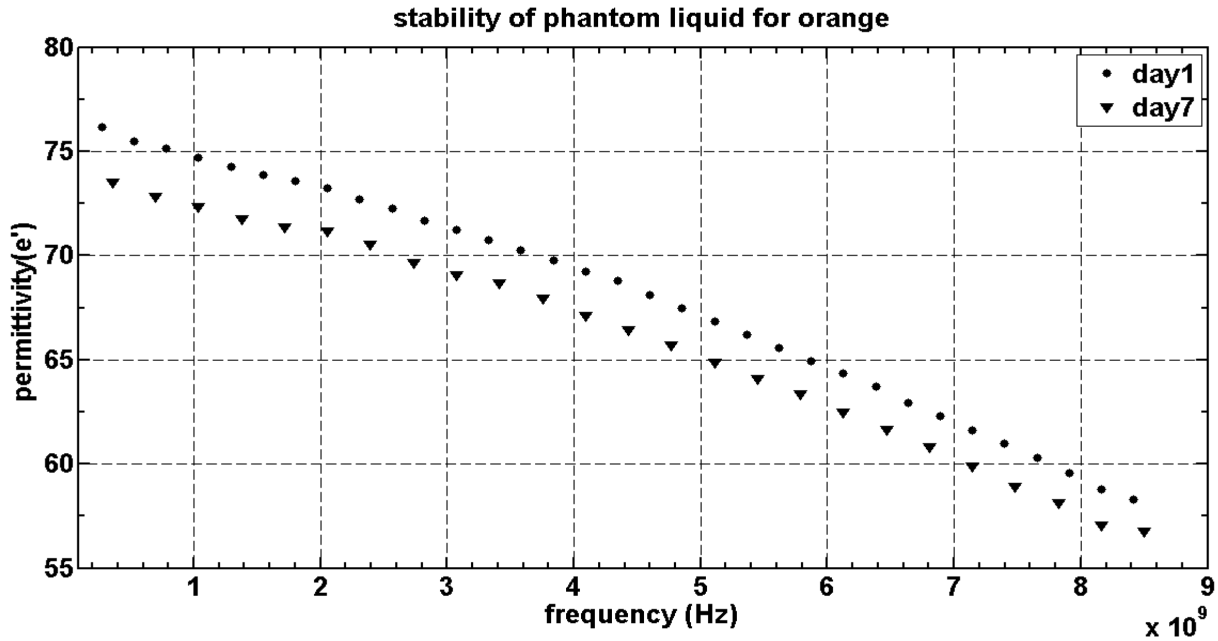


Fig.7.5 Time dependence of permittivity of phantom liquid for orange

7.3.2 Stability of phantom liquids in terms of loss tangent:

Interestingly, the loss tangent of the phantom liquids for all the fruits remained almost constant after the duration of 7 days as shown in the following figures.

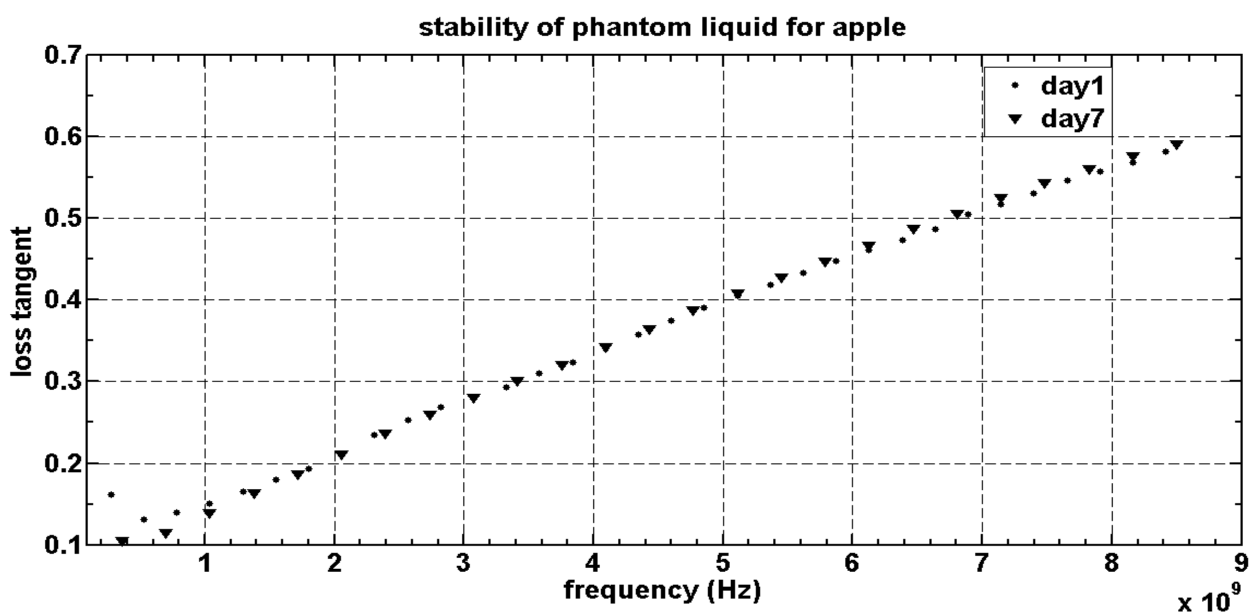


Fig.7.6 Time dependence of permittivity of phantom liquid for apple

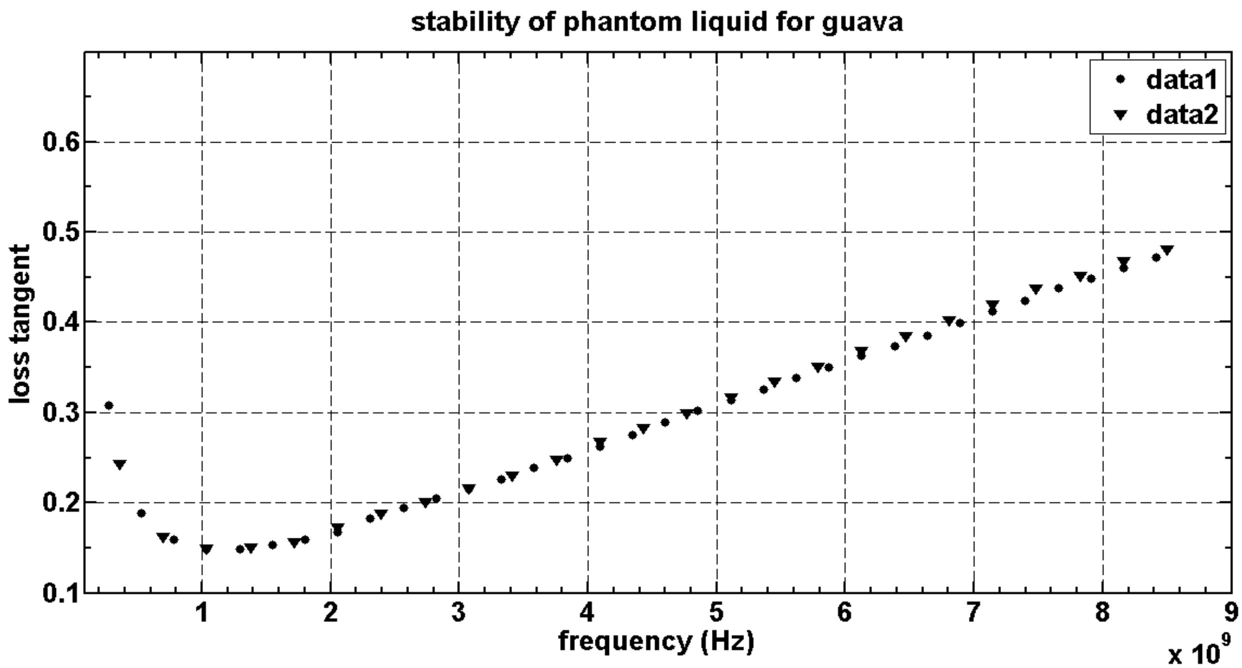


Fig.7.7 Time dependence of permittivity of phantom liquid for guava

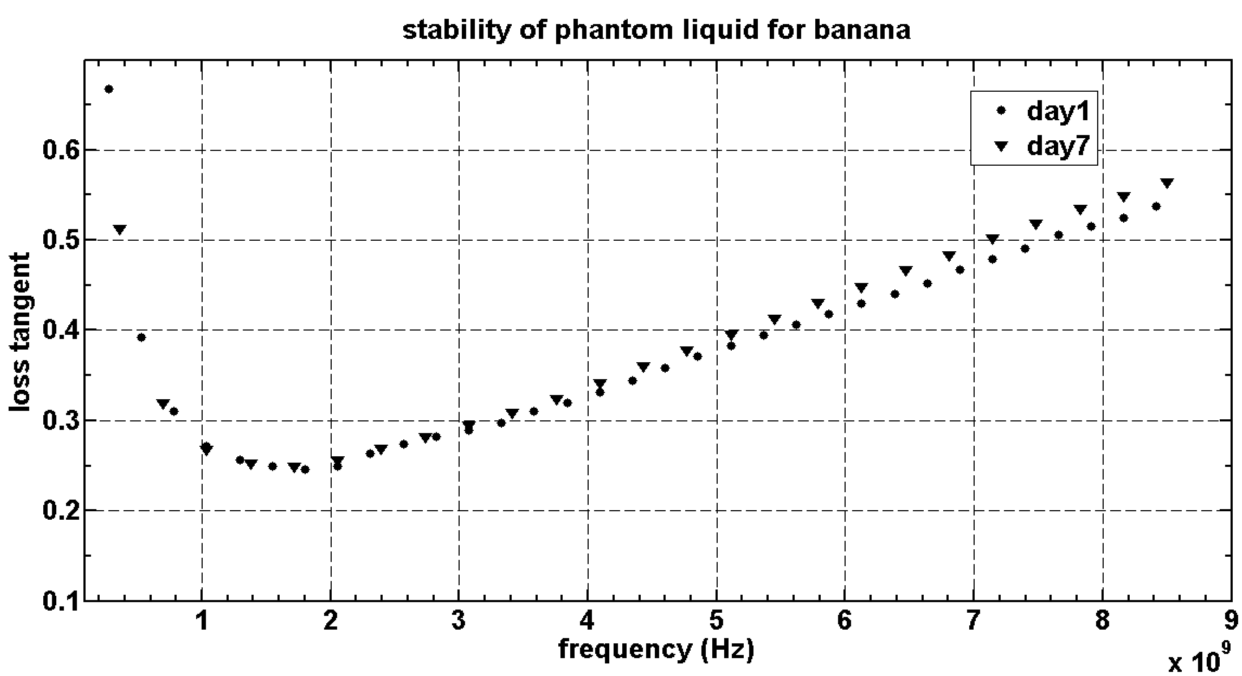


Fig.7.8 Time dependence of permittivity of phantom liquid for banana

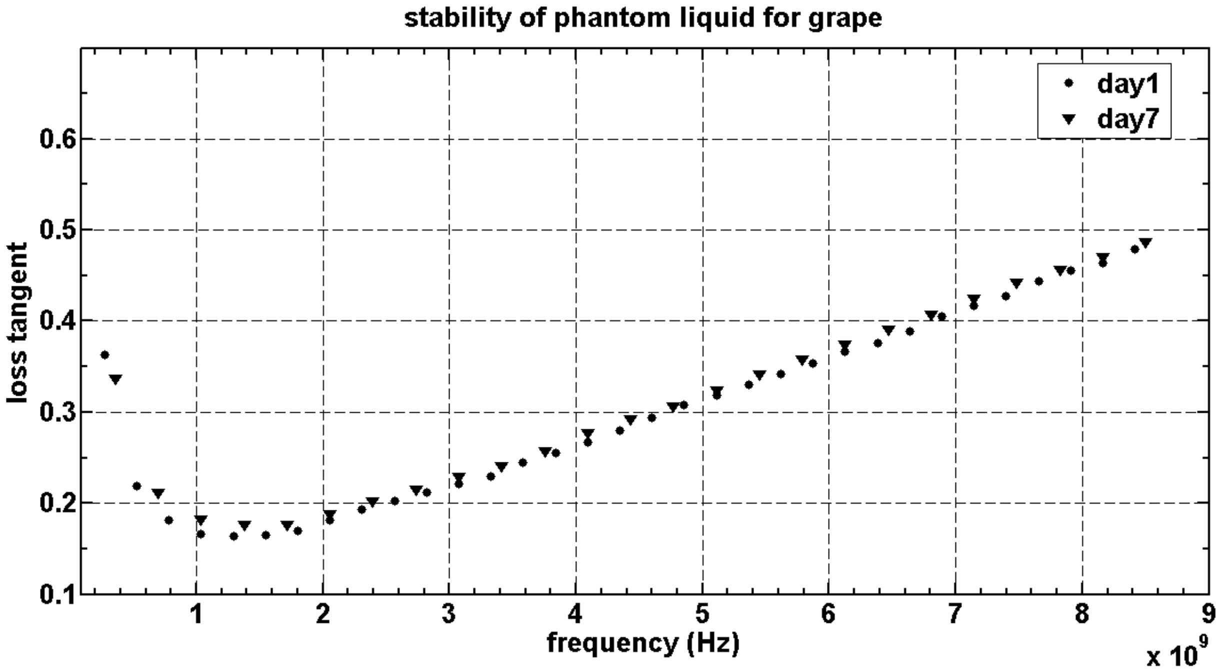


Fig.7.9 Time dependence of permittivity of phantom liquid for grape

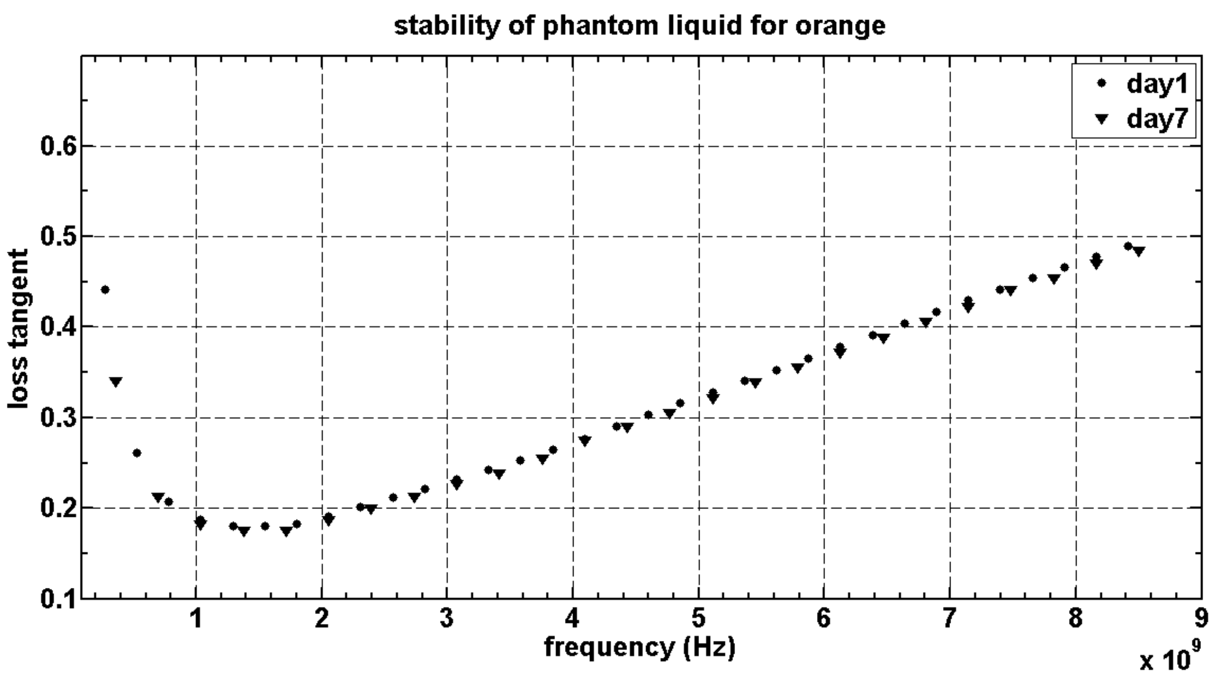


Fig.7.10 Time dependence of permittivity of phantom liquid for orange

7.4 Conclusion:

All the phantom liquids are stable both in terms of permittivity and loss tangent over the duration of 7 days. But on increasing the duration, some fungal growth was observed in all the containers. To get rid of that problem, a small amount of preservatives like toluene (one drop) or sodium azide (one crystal) or Triton-X100 should be added to avoid fungi, for long term use and this should improve working condition of SAR measurements.

CONCLUSIONS AND FUTURE SCOPE

8.1 Conclusion:

Adverse impact of cell phone towers on environment is depicted in the introductory part of the thesis. From literature review, the requirement for study on plants, fruits, vegetables etc. has been originated. Some specific fruits (viz. apple, banana, guava, grape and orange) have been taken into consideration for performing practical SAR measurement as simulated results for SAR for some of them (viz. apple, guava and grape) have been already performed. In the preliminary section, the study of human phantom model for SAR measurement has been briefed as a reference for preparing the phantom model of the mentioned fruits. As a first step, dielectric characterization of some common Indian fruits apart from the aforesaid fruits (viz. water apple, chiku and black grape) have been performed initially. Then dielectric properties of the mentioned fruits are discussed at GSM 900MHz frequency band to set the target values of dielectric parameters for the tissue equivalent phantom liquids to be prepared.

In the second phase, some recipes of sugar based aqueous solution have been presented to prepare customized phantom liquids which match the target values of dielectric parameters at GSM 900MHz and their characterization have been done in the frequency range from 200MHz to 8.5GHz. In the next section, temperature dependence of the prepared phantom liquids has been discussed over the same frequency range in terms of dielectric constant and loss tangent. Finally, the observation regarding their stability with respect to time has been reported in the last section.

8.2 Future scope:

- Dielectric characterization of more number of fruits needs to be done and temperature profile of dielectric properties for the fruits are required in order to study their behavior in different climatic condition.
- The prepared phantom liquids are apt for GSM 900MHz but not in the other frequencies, so some other recipes need to be proposed for GSM 1800MHz and WiFi 2.45GHz as well.

- Phantom shells could not be procured within the stipulated duration of course of the study. So, they are required to be prepared in order to perform practical SAR measurement.
- Further, morphological analysis of the mentioned fruits tissues is required to comment on adverse effects of RF energy absorption in those fruits to ensure their food values w. r. t non-exposed fruits growing far away from cell phone towers.