1.1 Why microwaves?

Propagation of electromagnetic (EM) waves at radio and microwave frequencies, through vacuum and material medium is expressed mathematically by Maxwell’s equations with corresponding boundary conditions. Presence of lossless or lossy dielectric materials influence distribution of EM fields in space. The knowledge of their dielectric properties is necessary to understand the physical processes that take place when the materials interact with electromagnetic waves.

In food materials such interactions are prominent at microwave frequencies. This knowledge paved the way for invention of microwave oven, which operates at 2.45 GHz and in which cooking takes place most efficiently at this microwave frequency. The information about the dielectric properties of food material is vital in order to understand and predict the response of the material to the electromagnetic field, at desired frequencies. Knowledge of dielectric properties is used for research purposes to have better understanding of the structures and composition of foods, as well as in commercial applications, viz., for controlling manufacturing parameters in food processing. In the last few years, technological advances have speeded up and convenience of microwave instrumentation has provided the drive for the accelerated use of microwave techniques in the food industry. The increased interest in the microwave techniques has initiated the development of several innovative instruments for the control and monitoring of parameters in food manufacturing processes. The emergence of these techniques has created a need to develop fundamental knowledge of food and material structures and their electrical behaviour.

Microwaves are a part of the electromagnetic spectrum and have a frequency between 300 MHz and 300 GHz (Pozar, 1993; Sorrentino et al. 2010). This broad definition includes both Ultra High Frequency (UHF) band (300 MHz – 3 GHz) and Extremely High Frequency (EHF) band (30 GHz-300 GHz), but different sources define different boundaries for microwaves. In all cases, microwaves include the
entire Super High Frequency (SHF) band (3 GHz to 30 GHz, or 10cm to 1 cm), with RF engineering often considering the lower boundary at 1 GHz (30 cm), and the upper around 100 GHz (3 mm).

Microwave technology is extensively used for point-to-point communications. Microwaves are especially suitable for this purpose since they are more easily focused into narrow beams as compared to radio waves which allows the phenomenon of frequency reuse. The relatively higher frequencies of microwaves provide a greater bandwidth and high data transmission rates. The short wavelength of microwaves allows high gain antennas with narrow beam width to be constructed for use in radar applications. Microwave technologies have revolutionized the communication and transfer of information in the modern world. Microwaves are used in satellite communication for transmission of signals and information because they can penetrate the earth’s atmosphere with minimum losses.

The characteristic feature of microwave engineering is the short wavelength involved, these being of the same order of magnitude as the circuit elements or devices involved. At such low wavelengths or high frequencies, lumped circuit theory becomes inaccurate. As a consequence, practical microwave techniques tend to differ from the discrete resistors, capacitors, inductors which are used at lower-frequency radio waves. Distributed circuit elements and transmission-line theory are more useful methods for design and analysis of microwave circuits. Waveguides and striplines replace the open-wire and coaxial transmission lines used at lower frequencies and cavity resonators or resonant lines take place of lumped-element tuned circuits. Microwave techniques become unsuitable at higher frequencies, where the wavelength of the electromagnetic waves becomes small as compared to the size of the structures used to process them. At such frequencies, the methods of optics are used.

1.2 Principle of microwave heating

Microwave heating is based on the transformation of alternating electromagnetic field energy into thermal energy due to inertia of the polar molecules and the friction due to other molecules of the material which prohibits them from following the
variations of electromagnetic fields (Vadivambal and Jayas, 2007) The dipole
moment lags behind the electric field and a part of electrical energy is dissipated in
the material in the form of heat. The most important characteristic of microwave
heating is volumetric heat generation (Mullin, 1995). Conventional heating takes
place by convection followed by conduction where heat diffuses in from the surface
of the material. Volumetric heat generation means that the material absorbs
microwave energy in whole of its volume and converts it into heat (Vadivambal and
Jayas, 2010). In microwave heating, heat is generated throughout the material,
leading to faster heating rates (Gowen et al, 2006). Microwave and radio frequency
heating can also be called dielectric heating. When a dielectric material is brought
into a rapidly alternating electric field, heat is generated inside the material due to
dielectric absorption which is known as dielectric heating. Microwaves are reflected
by metals, transmitted by electrically neutral material, such as glass, plastic, paper
and ceramic and absorbed by electrically charged materials (Mullin, 1995). Microwave
heating has gained acceptance in domestic usage and industrial applications. The
changing attitude of consumers and their fast life style has resulted in “ready to eat”
meals for which microwave ovens are of great use. Some of the advantages related
with microwave heating are instant start-up; faster and homogeneous heating of the
bulk of food material; improved color, flavor, texture of cooked food and nutrient
retention. Microwave heating takes place more effectively on liquid water than on
frozen water because the movement of molecules is more restricted in case of frozen
water. Dielectric heating of liquid water varies with temperature. At 0°C, dielectric
loss (\(\varepsilon''\)) is found to be greatest at a field frequency of about 10 GHz, and for higher
water temperatures maximum loss occurs at higher field frequencies (Chaplin, 2012).

The effect of microwave heating is less on fats and sugars (which have a
smaller molecular dipole moment) as compared to liquid water. Sugars and
triglycerides (fats and oils) absorb microwaves due to the presence of dipole
moments of their hydroxyl groups or ester groups. The temperature attained by fats
and oils inside microwave ovens is higher due to their lower specific heat capacity
and higher vaporization temperature (Chaplin, 2012). This can induce high
temperatures in oil or very fatty foods far above the boiling point of water. This
Temperature is high enough to cause some browning reactions similar to the case of conventional broiling or deep fat frying. Foods that have high water content and little oil rarely exceed the boiling temperature of water.

Microwave heating can cause localized thermal runaways in some materials which have low thermal conductivity and whose dielectric constants increases with temperature. Thermal runaway is a type of thermal instability that arises due to the interaction between electromagnetic waves and the material. When thermal runaway occurs, the temperature of the material increases uncontrollably. An example is glass, which shows thermal runaway to the point of melting, when it is exposed to a microwave heating. Similarly, microwaves can melt certain types of rocks, producing small quantities of synthetic lava. Some ceramics can also be melted by microwave heating. Thermal runaway is more common in liquids which are good electrical conductors, such as salty water.

A microwave oven operates by allowing non ionizing, microwave radiation to pass through the food. Water, fat and other substances present in the food absorb energy from the microwaves through a process called dielectric heating. Molecules such as water molecules are electric dipoles, having a partial positive charge at one end and a partial negative charge at the other. These dipoles rotate in order to align themselves with the applied alternating electric field of the microwaves. These rotating molecules strike with other molecules and set them into motion, thus dispersing energy. This energy, when disseminated as molecular vibration in solids and liquids (i.e., in the form of both potential energy and kinetic energy of the molecules or atoms), is converted into heat.

The energy of weak chemical bonds such as hydrogen bonds is several orders greater than the energy of microwave photons. The photons of radiation with frequency greater than $10^{16}$ hertz possess energy which is comparable to binding energy of electrons with atoms. Therefore, microwave photon can neither disrupt the electronic structure of atoms, nor can they disturb the chemical bonds (Rosenthal, 1992).

Microwave radiation has the capability to heat materials by penetrating and dissipating heat in them. This ability of microwaves is used in the polymer and
ceramic industries (for joining, sintering, combustion, synthesis, melting, epoxy curing, preheating rubber and thermosetting), in medicine (for thawing frozen tissues, warming blood, and tumor therapies), in textiles (for drying) and in agriculture (for estimating moisture level in crops). In food industry, micro waves have been used for several food processing operations, such as thawing, blanching, pasteurization, and sterilization, dehydration, baking, and roasting (Bengston and Ohlsson, 1974).

Interaction of microwaves with materials depends upon their dielectric properties, which determine the extent of heating of a material when subjected to electromagnetic fields. Therefore, knowledge of dielectric properties is important for the design of continuous flow microwave heating systems.

1.3 Dielectric Properties

Dielectric permittivity of a material at radio and microwave frequencies is a complex quantity, which can be expressed as \( \varepsilon^* = \varepsilon' - j\varepsilon'' \), where the real part (\( \varepsilon' \)) is called the dielectric constant and the imaginary part (\( \varepsilon'' \)) is called the dielectric loss factor (Saltiel and Datta, 1999). Dielectric constant is a measure of the ability of the material to store electromagnetic energy, whereas dielectric loss factor is the measure of the ability of a material to convert electromagnetic energy into heat (Metaxas and Meredith, 1983). The dielectric constant determines how much of the incident energy is reflected at the air–sample interface and how much enters the sample (for vacuum, \( \varepsilon' = 1 \)); the loss factor measures the efficiency of the absorbed microwave energy to be converted into heat. Mechanisms that contribute to the dielectric loss factor include dipole, electronic, ionic, and Maxwell-Wagner responses (Metaxas and Meredith, 1983). At RF and microwave frequencies (RF of 1-50 MHz and microwave frequencies of 915 and 2450 MHz), ionic conductivity and dipole rotation are considered to be the dominant loss mechanisms. (Ryynanen, 1995). The loss factor may therefore be expressed by the relation

\[
\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{\omega \varepsilon_0}
\]

where subscripts \( d \) and \( \sigma \) stand for contributions due to dipole rotation and ionic conduction, respectively; \( \sigma \) is the ionic conductivity expressed in Siemens/ meter (S m\(^{-1}\)) of the material, \( \omega \) is the angular frequency of the waves in Hz and \( \varepsilon_0 \) is the
permittivity of free space or vacuum. The conductivity of the dielectric $\sigma$ is related to the dielectric loss factor, and is given by

$$\sigma = \omega \varepsilon_0 \varepsilon''$$

Besides, Maxwell-Wagner polarization also arises from a charge build-up at the interface between components in heterogeneous systems. The Maxwell-Wagner polarization effect peaks at about 0.1 MHz (Metaxas and Meredith, 1983), but in general, its contribution is small as compared to that of ionic conductivity. For foods with low moisture content, bound water plays a major role in dielectric heating in the frequency range from 20 to 30,000 MHz (Wang et al, 2003). Dielectric materials, such as food products, convert electric energy at RF and microwave frequencies into heat. The rise in temperature is proportional to the loss factor of the material along with the electric field intensity, frequency and treatment time (Komarov et al, 2005).

Loss tangent (tan $\delta$), is a parameter used to describe the extent of absorption of microwave energy by a material. It is defined is the ratio of dielectric loss factor ($\varepsilon''$) to the dielectric constant ($\varepsilon'$). A material with a higher loss tangent will heat faster under the influence of microwave field as compared to a material with a lower loss tangent (Nelson and Datta, 2001).

The skin depth $\delta$ provides a more convenient measure of how far the field will penetrate. It is defined as the depth at which the magnitude of the field has been attenuated to 1/e of its value at the surface of the material. For very lossy materials, which have a small value of $\delta$, the field will decay very rapidly so that the heating will be confined to the surface of the material. For low loss materials, such as frozen foods, skin depth ($\delta$) is much larger, therefore, the field is able to penetrate much further.

1.4 Mechanism of microwave heating

Food materials, in general, can be considered as poor electric insulators. They have the ability to store and dissipate electrical energy when placed in an electromagnetic field. Dielectric properties play an important role in determining the interaction between the electromagnetic field and the foods (Buffler, 1993).
For dielectric heating, the power dissipated per unit volume (W/m$^3$) in the dielectric material is expressed as

$$ P = \sigma E^2 = 55.63 \times 10^{-12} f \varepsilon'' E^2 $$

(1.1)

where $P$ is the power absorbed in Watt m$^3$; $E$ is the root mean square value of the electric field intensity in Volts / m inside given volume; $f$ is the frequency in Hz; and $\varepsilon''$ is the dielectric loss factor of the food or other product. The power absorbed and the heat generated is directly related to $\varepsilon''$ (lossiness) of the material, and can be calculated by using the relation given by equation (1.1) (Venkatesh and Raghavan, 2004). From this equation, it is seen that the amount of heating is dependent on the electric field intensity. The electric field inside the load is determined by the dielectric properties and the geometry of the load, and by the oven configuration. Therefore, this equation for determination of $P$ is generally impractical since the electric field distribution inside the oven is very complex and cannot be determined easily (Buffler, 1993).

The rate of increase in temperature in °C / second due to this dielectric heating is given by

$$ \frac{dT}{dt} = \frac{P}{C_p \rho} $$

(1.2)

where, $C_p$ denotes specific heat of material in J / Kg / °C; $\rho$ is the density of the material in kg / m$^3$; $P$ is the power absorbed in Watt / m$^3$. It is apparent from Eq. (1.2) that the rise in temperature is proportional to the material’s dielectric loss factor, in addition to electric field intensity squared, frequency, and treatment time, as $\rho$ and $C_p$ remain almost constant for small variation of temperature.

The penetration depth $d_p$ is usually defined as the depth into a sample where the microwave power is dropped to $1/e$ or 36.8% of its value at the surface of the sample. Sometimes, $d_p$ is defined as the distance at which the microwave power is attenuated by 50% of its value at incidence. The penetration depth is a function of $\varepsilon'$ and $\varepsilon''$ and is given by

$$ d_p = \frac{(\lambda_0 \sqrt{\varepsilon'})}{(2\pi \varepsilon'')} $$

(1.3)
where $\lambda_o$ is the free space microwave wavelength given by $\lambda_o = c / f$, $c$ being velocity of light in free space and $f$ is the frequency of electromagnetic radiation (viz., for $f = 2.45$ GHz, $\lambda_o = 12.24$ cm). As the wave passes through a material that has significant dielectric loss, its energy gets attenuated. If the attenuation is high in the material, the dielectric heating will taper off quickly as the wave penetrates the material (Venkatesh and Raghavan, 2004). Attenuation is often expressed in decibels per unit length in metres ($\text{dbm}^{-1}$).

In dielectric materials, the electric field strength decreases with distance $z$ from the surface and is written as

$$E = E_0 e^{-\alpha z} \quad (1.4)$$

The attenuation factor $\alpha$ depends on the dielectric properties of the material (Hippel, 1954) and is given by

$$\alpha = \frac{2\pi\varepsilon'_0}{\lambda_o z^2} \left[ \varepsilon' \left( \sqrt{1 + \left( \frac{\varepsilon''}{\varepsilon'} \right)^2} - 1 \right) \right] \quad (1.5)$$

where $\lambda_o$ is the free-space wavelength.

In terms of power densities, attenuation in a medium can be expressed as:

$$P = P_0 e^{-2\alpha z} \quad (1.6)$$

where: $P_0$ is the power level at a point of reference; $P$ is the power level at distance $z$ from the reference point; and $\alpha$ is the attenuation in nepers per metre ($\text{Npm}^{-1}$).

Dipolar rotation and ionic conduction are the two major mechanism which are responsible for the heating effect produced in agri-food materials when they are subjected to electromagnetic radiation at microwave frequency. Water molecule, which is the major constituent of most agri-food materials is the dipole most responsible for heating of food materials. When dipoles are placed in an oscillating field, there is an increase in rotational and vibrational energies, depending on the degrees of freedom of the molecule, along with generation of heat due to the friction generated. Non polar molecules that have asymmetrical charge distribution also
behave as dipoles in an electrical field; however, their response to microwave energy is lesser in magnitude as compared to that of water. Ionic conduction is the other heating mechanism. The electrical field causes dissolved ions of positive and negative charge to migrate towards oppositely charged regions. This results in multiple billiard-ball-like collisions and disruption of hydrogen bonds in water and food materials which results in the generation of heat. Ionic conduction has a larger influence on \( \varepsilon' \) than on \( \varepsilon'' \), and therefore causes the penetration depth to decrease. This behaviour of ionic conduction was predicted by the Hasted–Debye relations for aqueous electrolytic solutions (Hasted et al., 1948). In this work, the static dielectric constant of a solution was observed to decrease with the salt concentration, a phenomena called dielectric decrement (Venkatesh and Raghavan, 2004).

A decrement in the value of \( \varepsilon' \) is observed due to depletion of free water by dissolved ions and an increase in the value of \( \varepsilon'' \) is observed due to an increase in the free charge density (Kudra et al., 1992). Magnetic field interactions are negligible, since foods contain only trace amounts of magnetic minerals such as nickel, cobalt, and iron. The temperature profile and heating rate of foods developed during exposure to electromagnetic radiation depends on the distribution and nature of susceptors, the relationships between the dielectric properties and moisture, temperature and frequency, as well as on the thermo-physical properties (thermal conductivity, thermal diffusivity, specific heat, etc.) of the constituents (Venkatesh and Raghavan, 2004). It is therefore difficult to obtain a detailed description of the temperature profile of a complex agri-food material. The dielectric properties of a given material are not unique and are specific only for a given frequency and state of the material. Thus, during processing, the dielectric properties are not constant but transient since the state of the material is changing with time. Therefore, it is necessary to establish the relationships for \( \varepsilon' \) and \( \varepsilon'' \) for their dependence on state variables at the processing frequency(ies). The principal state variables that influence the dielectric properties at a given frequency are temperature and moisture content (Venkatesh and Raghavan, 2005).
1.5 Nature of Variation of the Dielectric Properties of Foods

Dielectric properties of food materials are influenced by several factors, including frequency of the microwaves, temperature, moisture content, salt content and other constituents present in the materials. In granular and particulate materials, the bulk density of the air-particle mixture is an important factor that affects the permittivity (Krazewski and Nelson, 2004). The variation in bulk density is dependent on the shape, dimensions, and surface character of the particles. In the presence of an externally applied field, charged particles in the material (polar molecules, ions, atomic nuclei and electrons) migrate and build up charges of opposite polarity on the boundaries in the direction of field and need some definite time to set up an equilibrium polarization. If the electric field strength changes rapidly, the polarization will lag behind the varying field. The dielectric properties of the material in time-dependent fields, therefore differ characteristically from the corresponding equilibrium properties in steady fields. The study of these characteristic properties helps to know about the structure and composition of the material.

The frequency-dependent tendency of dielectric properties provides an important information about the material characteristics. In theory, electric conduction and various polarization mechanisms (including dipole, electronic, ionic, and Maxwell–Wagner) contribute to the dielectric loss factor (Fig. 1.1). For moist dielectric materials, ionic conductivity plays a major role at lower frequencies (e.g. < 200 MHz), whereas both ionic conductivity and dipole rotation of free water play a combined role at microwave frequencies. For pure liquids with polar molecules, like alcohols or water, frequency characteristics of dielectric properties are dependent on polarization arising from the orientation of molecules with the imposed electric field. Dielectric heating in materials containing low amount of water is governed by bound water in the frequency range between 20 and 30 GHz (Harvey and Hoekstra, 1972; Wang et al, 2003) at room temperature (20°C). Frequency and the dielectric relaxation processes operating under the particular conditions determine the dependence of dielectric properties on temperature.
1.6 Debye Relaxation

Debye relaxation is the dielectric relaxation response of an ideal, noninteracting group of dipoles to an alternating external electric field. It is usually expressed in the complex permittivity ($\varepsilon^*$) of a medium as a function of the field's frequency $\omega$. Materials that exhibit a single relaxation time constant can be modelled by the Debye relation (Debye, 1929) in which permittivity is represented as a function of frequency as shown in Fig. (1.2).

An alternating field causes a reorientation of the dipoles which causes thermal agitation and molecular interactions as opposing effects. This behaviour is captured by the Debye Equation. The mathematical formulation developed by Debye (1929) to describe the permittivity for pure polar materials can be expressed as

$$\varepsilon^* = \varepsilon + \frac{\varepsilon_\infty - \varepsilon}{1 + j\omega\tau}$$

where $\omega = 2\pi f$ is the angular frequency of electromagnetic field, $\varepsilon_\infty$ represents the dielectric constant at frequencies so high that molecules do not have time to orient
and contribute to the polarization, \( \varepsilon_s \) represents the static dielectric constant, i.e., the value at zero frequency or dc value of the permittivity, and \( \tau \) is the relaxation time in seconds and represents the time period required for the dipoles to revert to random orientation when the electric field is removed (Nelson, 1994). Separation of Equation (1.8) into its real and imaginary parts yields

\[
\varepsilon' = \varepsilon_s + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (\omega \tau)^2} \quad (1.9)
\]

\[
\varepsilon'' = \varepsilon_s + \frac{(\varepsilon_s - \varepsilon_\infty) \omega \tau}{1 + (\omega \tau)^2} \quad (1.10)
\]

The variation of \( \varepsilon' \) and \( \varepsilon'' \) with frequency are illustrated in Fig. 1.2. \( \varepsilon' \) is constant above and below the relaxation with the transition occurring near the relaxation frequency. Further, \( \varepsilon'' \) is small above and below relaxation and peaks in the transition region at the relaxation frequency. At frequencies very low and very high with respect to the molecular relaxation frequency, the dielectric constant (\( \varepsilon' \)) possesses constant values, \( \varepsilon_s \) and \( \varepsilon_\infty \), respectively, while the value of loss factor (\( \varepsilon'' \)) is zero at these frequencies. At intermediate frequencies, the dielectric constant (\( \varepsilon' \)) undergoes a dispersion whereas dielectric loss factor (\( \varepsilon'' \)) shows a maxima with the peak loss at the relaxation frequency, \( \omega_0 = 1/ \tau \). The Debye equation can be represented graphically in the complex \( \varepsilon'' \) vs. \( \varepsilon' \) plane as a semicircle with locus of points ranging from \( (\varepsilon' = \varepsilon_s, \varepsilon'' = 0) \) at the low-frequency limit to \( (\varepsilon' = \varepsilon_\infty, \varepsilon'' = 0) \) at the high-frequency limit and centre of semicircle at \( (\varepsilon_\infty + \varepsilon_s)/2 \) as shown in Fig. 1.3. Such a representation is known as a Cole-Cole diagram (Cole and Cole, 1941). Since few materials of interest consist of pure polar materials with a single relaxation time, many other equations have been developed to better describe the frequency-dependent behaviour of materials with more relaxation times or a distribution of relaxation times (Nigmatullin et al., 2006; Nigmatullin and Nelson, 2006).
1.7 Dielectric Mechanisms

A material has several dielectric mechanisms or polarization effects which contribute to its overall permittivity as shown in Fig. 1.4. A dielectric material consists of an arrangement of electric charge carriers that are bound and cannot freely move but can be displaced in presence of an electric field. Polarization of
chances takes place in order to neutralize the electric field by developing equal and opposite induced field, such that the positive and negative charges continue to move in opposite directions till the net field becomes zero and an equilibrium state is reached.

![Fig. 1.4: Frequency response of dielectric mechanisms (Agilent,2005)](image)

Dielectric behaviour of a material is governed by several dielectric mechanisms at the microscopic level. Dipole orientation and ionic conduction are the major contributors at microwave frequencies. Water molecules, for example, are permanent dipoles, which rotate themselves in order to align with the applied alternating electric field. These mechanisms involve losses which explains why foods heat up when placed in a microwave oven. Atomic and electronic mechanisms are relatively weak, and usually their contribution remains almost constant over the frequencies in the microwave region. Each dielectric mechanism has a characteristic “cutoff frequency.” The contribution from each mechanism changes with the increase in frequency. The loss factor (\(\varepsilon''\)) shows corresponding peak at each critical frequency. The magnitude of interaction and “cutoff frequency” of each mechanism is unique for different materials. A resonant effect is usually associated with electronic or atomic polarization and a relaxation effect is usually associated with orientation polarization.
1.7.1 Orientation (Dipolar) Polarization

This type of polarization occurs due to the effect of applied field on the orientation of molecules with permanent electric moments. Atoms combine to form a molecule by sharing one or more of theirs electrons. This rearrangement of electrons gives rise to an asymmetry in charge - distribution causing a permanent dipole moment. These moments are randomly oriented in the absence of an electric field and hence, no polarization of charges exists. The electric field (E) applied to the material exercises a torque on the electric dipole, and under its influence the dipole rotates to align with the electric field, causing orientation polarization to occur. If the field changes the direction, the direction of torque also changes. The friction accompanying the orientation of the dipole contributes to the dielectric losses. The dipole rotation causes a variation in both $\varepsilon'$ and $\varepsilon''$ at the relaxation frequency which usually occurs in the microwave region for some organic liquids. Water is an example of a substance that exhibits a strong orientation polarization.

1.7.2 Electronic Polarization

Electronic polarization occurs in neutral atoms when an electric field applied to it displaces the electrons with respect to nuclei within the atom and induced dipole moments result. Electronic polarizability per unit volume is proportional to the number of bound electrons in a unit volume and inversely proportional to forces binding them to the nuclei of the atoms.

1.7.3 Atomic Polarization

Atomic polarization occurs when adjacent positive and negative ions “stretch” under an applied electric field. When a molecule is formed by atoms of different kinds, the electrons are not shared symmetrically, as the electron clouds are displaced eccentrically towards the stronger binding atoms. Thus, atoms acquire charges of opposite polarity and an externally applied field perturbs the equilibrium positions of the atoms. Due to this displacement, induced dipole moments are formed giving rise to atomic polarization. For many dry solids, these are the dominant polarization mechanisms at microwave frequencies, although the actual resonance occurs at a much higher frequency.
The contribution from atomic polarization starts at frequency in the infrared region wherein the inertia of the orbiting electrons is also taken into account. Atoms can be considered as oscillators with a damping effect similar to a mechanical spring and mass system as depicted in Fig. 1.4. The amplitude of the oscillations is small for any frequency other than the resonant frequency. Contribution from the electronic and atomic mechanisms towards dielectric constant (ε') and dielectric loss (ε'″) is very small at frequency much below the resonant frequency. The resonant frequency is recognized by a resonant response in ε' and a peak of maximum absorption in ε'″. Above the resonance, the contribution from these mechanisms is again negligible.

1.7.4 Interfacial or Space Charge Polarization

Electronic, atomic, and orientation polarizations occur when charges are locally bound in atoms, molecules, or structures of solids or liquids. This type of polarization results from heterogeneous nature of material. When a low frequency electric field is applied, charge carriers that exist travel through the dielectric material. Interfacial or space charge polarization occurs when the motion of these migrating charges is obstructed either because the charges become trapped within the interfaces of a material or because charges cannot be freely discharged or replaced at the electrodes. The field deformation caused by the accumulation of these charges increases the overall capacitance of a material which appears as an increase in the value of dielectric constant (ε').

Mixtures of materials with electrically conducting regions that are not in contact with each other (separated by non-conducting regions) exhibit the Maxwell-Wagner effect at low frequencies. If the charge layers are thin and much smaller than the particle dimensions, the response of the charge is independent of the charge on nearby particles. This effect is more common at low frequencies where the charges find time to accumulate at the borders of the conducting regions and thus cause dielectric constant (ε') to increase. At higher frequencies the charges do not have enough time to accumulate and polarization does not happen since the charge displacement is small compared to the dimensions of the conducting region. As the frequency increases, the value of dielectric constant (ε') decreases and the loss factor (ε'″) exhibits the same 1/f slope as normal ionic conductivity.
1.7.5 Frequency Response of Dielectric Mechanisms

Each of the different types of polarization is a function of the frequency of the applied field. When the frequency of the applied field is sufficiently low, all types of polarization attain the value that they would have reached at steady field equal to the instantaneous value of alternating field. But as the frequency increases, the polarization no longer has time to reach its steady peak value. First, the orientation polarization is affected, since the time taken by this type of polarization to reach equilibrium value in liquid and solids with moderately small molecules, is of the order of $10^{-12}$ to $10^{-10}$ sec. Therefore, at the normal temperature when the applied field has a frequency of $10^{10}$ to $10^{12}$ Hz, orientation polarization fails to reach its equilibrium value and contributes less and less to the total polarization as frequency increases further. In Fig. 1.4, the orientational polarization for a particular molecule is shown to decrease after $10^9$ Hz and has minimum value at about $10^{11}$ Hz.

1.7.6 Relaxation Time ($\tau$)

Relaxation time $\tau$ is a measure of the mobility of the molecules (dipoles) that are present in a material. The total polarizability of the dielectric is the sum of contributions due to all different types of displacement of charges produced in the material due to the applied field. The magnitude of polarizability in a material and the time required for it to form or disappear is determined by the constitutive forces which are characteristic of that material. The quantitative measure of the time required to form or disappear polarization is called relaxation time. It is the time required by a displaced system aligned in an electric field to return to its random equilibrium position or the time required for dipoles to become oriented in an electric field. Liquid and solid materials have molecules that are in a condensed state and hence have limited freedom to move when an electric field is applied. Continuous collisions with other molecules cause internal friction so that the molecules rotate slowly and exponentially approach the final state of orientation polarization with relaxation time constant $\tau$. When the field is switched off, the sequence is reversed and random distribution is restored with the same time constant. The relaxation frequency $f_c$ is inversely related to relaxation time $\tau$. At frequencies below the relaxation frequency, the variation in the alternating electric
field is slow enough so that the dipoles are able to keep pace with the field variations. Because the polarization is able to develop fully, the loss factor \( (\varepsilon'') \) is directly proportional to the frequency. As the frequency increases, \( \varepsilon'' \) continues to increase but the energy storage capacity, dielectric constant \( (\varepsilon') \) begins to decrease due to the phase lag between the dipole alignment and the electric field. Above the relaxation frequency both \( \varepsilon'' \) and \( \varepsilon' \) drop off as the electric field is too fast to influence the dipole rotation and the orientation polarization disappears.

### 1.7.7 Ionic Conductivity

The measured loss of energy in a material can actually be expressed as a function of both the dielectric loss \( (\varepsilon''_d) \) and ionic conductance \( (\varepsilon''_\sigma) \).

\[
\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma
\]

with \( \varepsilon''_\sigma = \sigma/\omega\varepsilon_0 \) \hspace{1cm} (1.8)

where subscripts \( d \) and \( \sigma \) stand for contributions due to dipole rotation and ionic conduction, respectively; \( \sigma \) is the ionic conductivity \( (\text{S m}^{-1}) \) of a material, \( \omega \) is the frequency \( (\text{Hz}) \), and \( \varepsilon_0 \) is the permittivity of free space or vacuum \( \left( 8.854 \times 10^{-12} \text{ F m}^{-1} \right) \).

### 1.8 Applications of Dielectric Measuring Microwave Techniques

Measurement of dielectric properties provides important information about material characterization, design specifications for many electronic applications and remote sensing applications. The measurement of dielectric properties has gained importance because it can be used for non destructive and non invasive testing of specific properties of materials undergoing physical or chemical changes. Microwave techniques have found general and commercial applications in many areas. These include food processing, analytical chemistry, heating and vulcanization of rubber, molecular structure determination, soil testing etc. Microwave techniques play a crucial role in analytical chemistry applications which cover a range of applications and involve high-volume, repetitive, batch processing, often with long intermediate drying and reaction steps that can be reduced using microwave heating.
1.8.1 Industrial Applications

Application of materials in microwave and communication industries requires the exact knowledge of material parameters such as permittivity. For examples, the dielectric materials used for manufacturing microstrip antenna substrates and the plastics and rubbers which are used in manufacturing of antenna sleeves are those which are used on the band sets of personal communication systems (Deshpande and Reddy, 1995). Another application of complex permittivity measurement is for evaluation of material deterioration. This microwave measurement technique has been used for evaluation of both the combustion engine oil-fill and electrical transformer oil deterioration (Al-Mously et al., 2001).

1.8.2 Biological Applications

Biological applications of dielectric measuring techniques include imaging of soft tissues as they have substantial difference in their dielectric properties. It has been established that dielectric properties of cancerous or malign tissues are quite different from the healthy tissues. Since the energy of a microwave photon is less than that of X-rays, it is considered to be relatively safe. Since 1970s, with the advent of microwave oven as a domestic kitchen appliance, the major concern of scientists was to evaluate the effect of microwave devices radiation, such as microwave ovens, on human body. As such, the measurement of complex permittivity of biological substances became important in microwave research. Nowadays, measurement of complex permittivity of biological substances takes a lot of attention to mitigate the mobile telephone radiation hazard (Stuchly et al., 1982).

1.8.3 Agricultural Applications

The dielectric properties measurements are used for the exploitation of rapid and nondestructive sensing of moisture in materials. Moisture content is an important characteristic of agricultural products, because it determines their suitability for harvest and for subsequent storage or processing. The information about moisture content of the crops often helps in determining the selling price of the products for intended purposes. Dielectric properties can be utilized with properly designed electronic sensors with reasonable accuracy. Such moisture testing
instruments, operating in the 1-50 MHz range, have been developed and used for rapid determination of moisture in grains for many years.

Knowledge of the relationship between frequency and dielectric properties is helpful in determining the optimum frequency range in which the material has the desired dielectric characteristics for intended applications. This relationship is also useful in studying and developing heating processes or grading techniques based on electromagnetic energy (Nelson and Payne 1982; Nelson 2005; Wang et al. 2001). This knowledge also helps in the selection of proper packaging materials and cooking utensils and in the design of microwave and radio frequency heating equipment (Ohlsson 1989). The moisture-dependent dielectric properties in specific frequency ranges can be used to develop online moisture meters (Nelson 1992), which may be applied not only in drying processes but also in other unit operations in the food industry (Berbert et al., 2002; Nelson, 1984). The possible selective dielectric heating for control of insects that infest stored grain (Nelson and Whitney, 1960; Nelson, 1996). Nelson (1965) suggested that dielectric properties data are also important in the investigation of seed treatment to improve germination. Engelder and Buffler (1991) reported that dielectric measurements can also be used to measure density and water activity.

1.8.4 In Food Industry

Dielectric properties can be used to predict the behaviour of food materials in radio frequency bands and during microwave processing, heating and cooling (Ryynanen, 1995). These properties determines the interaction between food and high frequency electromagnetic energy. Therefore, they play an important role in the design of radio frequency and microwave processing equipment and in the development of foods and meals intended for microwave preparation (Mudgett, 1985). These properties are very important in evaluating the penetration depth of energy that can be achieved in a certain food and characterizing physical properties of biomaterials. Berbert et al. (2002) observed that the online moisture meters can be used for drying purpose as well as for other operations in food industry. With a good understanding of the dielectric properties of various food components and their
interaction during microwave heating, it is possible to develop successful microwaveable foods (Shukla and Anantheswaran, 2001).

1.8.5 Water Quality Detection

Microwave technology is used to study and assess water quality aspects. Raveendranath and Mathew (1995) suggested that the dielectric behaviour of artificially polluted water and polluted water collected from various industrial locations could be related for detecting the pollutants in water at 2.685 GHz microwave frequencies, based on the measurement of complex permittivity of polluted water at 27°C. This technique could also be used to evaluate adulteration in edible oils or oil-water mixtures for food applications.

1.8.6 Application in Textiles

The dielectric properties are exploited in a variety of applications involving fibers, yarns and fabrics. Some applications are meant for quality checking, some for quality control, some for processing and some for functional performance. The major areas where dielectric properties are used are Moisture content measurement in textiles, Evenness measurement in textiles, Dielectric heating and Sensor type application in textiles. Dielectric properties have been used to detect the continuity of a textile strand for certain application. Capacitive type measurement technique of dielectric properties provides an accurate and sensitive method to measure several important properties of textile material. Dielectric properties determine the level of static generation in textiles (Bal and Kothari, 2009).

1.8.7 Application in Civil

Microwave technology is widely used in civil and industrial engineering, such as for material characterization and crack detection. However, these technologies are related to concepts based on transmission and reflection of microwaves. In material characterization, microwaves are used to derive the information about the main properties of the materials under test, such as determination of constituents, evaluation of porosity and assessment of the curing state (Pastorino, 2010). It is clear that this goal can be achieved by microwave techniques if there is a precise correlation between the properties of inspected materials and the values of the
Introduction

Macroscopic dielectric parameters that can be detected by microwave inspection technique, working under both classical transmission and reflection condition. According to Zoughi (2000), microwave techniques can be used for inspection of composites, in particular for the accurate thickness measurement of dielectric layers such as coatings or layered composites; for the detection of voids, rust and corrosion under paint (Quddoumi et al, 1997) and stratified coatings for the inspection of thick plastic and glass reinforced composites and for several other diagnostic objectives that can be performed both during the material production and during the service or use.

1.9 Microwave Hazards

The human organs and organ systems are susceptible to microwave energy in terms of functional disturbance and structural changes. High power density of microwave energy can result in patho-physiological manifestations of thermal nature and low power density leads to non thermal biological effects in humans and animals. Some of the serious side effects of exposure to electromagnetic radiation are Blurry Vision, Headaches, Nausea, Fatigue, Neck Pain, Memory Loss, Leukemia, Rare Brain Cancers, Enzyme changes that affect DNA, birth defects, changes in metabolism, increased risk for Alzheimer’s disease, increased risk for heart conditions, neurological hormone changes linked impaired brain function etc. The cell phone radiation causes side effects which range range from occasional headaches and fatigue to enzyme changes that affect DNA and cell growth and can result in cancer. The electromagnetic radiation emitted from the antenna, circuitry and the battery of a cellphone causes harmful biological effects.

Several studies have shown that the use of microwave oven for cooking purpose has adverse effects on human health. This is because the person cooking food in the microwave oven may get exposed to the microwaves and secondly, the food cooked in the microwave oven may loose its nutrients.

Additional studies have shown that people who sleep with a cellphone by the bed have poor REM (Rapid eye movement) sleep, leading to impaired learning and memory. This is related to melatonin production that is impaired by the ELF
(Extremely low frequency) radiation emitted from the nearby cell phones or wireless devices. Thus, the exposure to electromagnetic radiation of microwave frequency poses several health issues, both physical and mental.

1.10 Interdisciplinary Relevance

As apparent from the title, the proposed research is of interdisciplinary character. The tools and techniques to be used in the research are based on the principles, theories and applications based on Physics in general and microwaves in particular. As the specimen chosen for study are food grains, the findings of research will be more relevant to areas like Food science and Agriculture.

The investigation of dielectric properties of food grains and agriculture products at microwave frequencies is important because it provides information about the moisture content of the products. A great deal of food science and food technology can be described in terms of the manipulation of the water content of foods, its removal, its freezing, its emulsification and its addition in case of dissolving or reconstituting dehydrated foods. The management of moisture content in foods acts as a major controlling parameter during preparation of microwaveable food. Close control of final water content is essential in the production of numerous foods; as little as 1-2% excess of water can result in such common defects as molding of wheat, bread crust becoming tough or rubbery, soggy potato chips and caking of salt and sugar. Thus, the dielectric measurements help in food product development.

It also implies the principles of marketing, especially in agriculture and food science. The crop and food variety containing different amount of water and food components are ranked depending on the water content. Detection of exact moisture level is necessary in fixing market price of all foods. The dielectric measurements therefore help in determination of water content and quality assessment of food. The information about the dielectric properties of food grains may also help in design of microwave processing equipments and improving technique for processing of food.

Since the dielectric studies throw light on molecular behavior of the species, the results of this research are also relevant to the chemists. As such, research in this
field may further be taken up by scholars of Physics, Electronics, Food Science, Home Science, Agriculture and Chemistry etc.

The present studies will certainly enhance the existing knowledge stock of major practices related to moisture monitoring in crops, storage of food grains, fruits and vegetables, food cultivation, food storage, food processing and simultaneously to the allied industries dealing with food packaging and marketing.