2.1 Dielectric Polarization

The common feature of dielectric materials [1, 2] is their ability to store electric energy. This is accomplished by the displacement of positive and negative charges under the effect of the applied electric fields and against the force of atomic and molecular attraction. The mechanism of charge displacement (i.e. polarization) depends on the type of dielectric material and the frequency of the applied field. There are four main types of dielectric polarization. They have very similar qualitative effects but appear at very different frequencies. The microscopic elements that are involved in this are at the level of a complete zone of the material, the molecule, the ion and the atom, respectively. In all cases, the electric equilibrium is disturbed, because the applied field causes the spatial separation of charges opposite because the applied field causes the spatial separation of charges of opposite sign. With an alternating field, the frequency determines the dominant type of polarization.

Space charge polarization gives rise of low-frequency response. It occurs when the material contains free electrons whose displacements are restricted by obstacles, such as grain boundaries. When an electric field is applied, the electrons accumulate on the obstacle, and the resulting charge separation polarizes the material. Entire regions of the material become either
positive or negative. This type of polarization is fundamental in semiconductor electronics.

Polarization by dipole alignment occurs at higher frequencies (HF, Microwaves) and also at molecular level. It lies as the basic of dielectric heating. Ionic polarization takes place at infrared frequencies; it is due to the separation of the positive and negative ions in the molecule.

Electronic polarization occurs at very high frequencies close to the ultraviolet region. The atomic nucleus is positive and fixed in the matrix of the dielectric material. The negative electronic cloud surrounding it is displaced in the direction of the applied field.

In practice, these phenomena may overlap and it is not always easy to establish strict barriers between them. When a molecular system is placed in an electric field, there is always the tendency for the electrically charged species to move along the field in the appropriate direction, causing the atom to develop an induced dipole moment. This induced moment has all the characteristics of an assembly of dipoles produced by an elastic displacement of electrons. This polarization mechanism is known as electronic or optical polarization.

The structure of molecules has strong influence on polarization processes. Due to its asymmetrical structure when a polar molecule or dipole is put in an electromagnetic field, the two opposite charges in the molecule attempt to migrate in the field thus applying a couple to the molecule. This tends to align the dipole along the field. This is called orientation polarization and this leads to the phenomenon of dielectric relaxation. If the electric field strength varies very fast, the polarization will lag behind the changing field.
Therefore, the dielectric properties of materials in time dependent field will deviate characteristically from the corresponding equilibrium properties of steady fields.

Static dielectric constant ($\varepsilon_0$ or $\varepsilon_s$) is the dielectric constant at $\omega$ tends to zero, whereas $\varepsilon_\infty$ is the dielectric constant when $\omega$ tends to $\infty$, which is generally assumed to be square of the refractive index.

The complex permittivity is sufficient to describe behavior of the molecular system. Several method have been developed for the determination of $\varepsilon'$, $\varepsilon''$ and $\tan\delta$. Some employ transmission lines and others use resonant cavities into which the sample is introduced and the resulting perturbation is measured.

### 2.2 Area of dielectric study

#### 2.2.1 Agricultural

Knowledge of dielectric properties of grains and seeds becomes increasingly significant as agricultural technology becomes more sophisticated, new applications for electric energy are developed and as new methods, processes and devices come into being, which utilize or are influenced by the electrical nature of the materials.

The dielectric properties of grain and insect are key factors determining degree of differential heating that can be achieved in radio frequency dielectric heating for stored grain insect control [3]. Dielectric absorption properties are also important when microwave or dielectric heating applications are being considered for materials because the design of the equipment and power absorption by materials are dependent upon the
dielectric properties. The high correlation between dielectric constant and moisture content has made possible the development of electronic instruments for rapidly measuring moisture content [4]. The dielectric properties of grains have also been studied in order to determine usefulness of electronic moisture monitoring equipment for flowering grains, in drying of grain and in milling industries. Modern electrical moisture meters use either conductivity or dielectric properties depending upon their design. Many of them sense dielectric constant and use frequency of measurement in the range 1 MHz and 50 MHz. Holladay [5] detected successfully the heat damage in artificially dried corns through measurement of moisture distribution in corn kernel. Oil contents of soyabean can also be measured using dielectric measurement technique. Oil contents of sunflower seeds have also been successfully measured using similar technique. For designing equipments for all these applications, data on dielectric properties of these materials are necessary. Therefore investigations were undertaken to generate basic dielectric data on various kinds of seeds of Indian origin. A large number of grain species of different varieties e.g.- pulses (Lentil, Black gram, Green gram, Gram, Pigeon pea), Oil seeds (Groundnut Yellow sarson, Toria, Sesame, Linseed), Vegetable seeds (Tomato, Radish, Lady's finger, Spinach), seeds of aromatic and medicinal plants (Isabgol, Opium puppy, Ashwagandha, Pal marosa) were taken for investigating the dielectric behavior for varying moisture levels, over a wide range of frequencies (10 KHz-30 MHz and 10 GHz), and temperature range from 15˚C to 45˚C and for two bulk density levels.

In general, it was found that dielectric constant increased with increasing moisture content and decreased with increasing frequency. At high
Dielectric theory and description of experimental methods

moisture levels and low frequency range, the magnitudes of variations in dielectric constants were large.

The dielectric study has variety of applications, which are listed below

1) Display devices
2) Electronics
3) Ceramic industries
4) Polymer industry
5) Medical

2.3 The slotted line

The slotted line is the one of the important measuring instrument at microwave frequencies. It is designed to measure the standing wave pattern of the electric field intensity, which is a function of longitudinal position in the guiding structure. A probe is mounted on a carriage, which slides along the outside section of the coaxial section of the line or wave-guide, which has a longitudinal slot. The probe extends into the slot and is provided with an adjustment for varying the probe penetration into the slot and with a tuning adjustment used to cancel the reactive component of the probe impedance. The probe is connected to a barrater or crystal detector, which detects the r. f. voltage. This voltage is amplified and applied to the appropriate indicating meter. A slotted section used over a frequency range from about 300 to 5000 MHz and the modified form is used over the frequency range in GHz is shown in figure (2.3.1). The standing wave ratio is measured by sliding the probe along the line for a maximum to minimum indication on the output meter.
The wavelength of the signal frequency can be measured by obtaining the distance between the minima since the distance between the successive maxima or minima is equal to half the wavelength. Slotted section model is shown in figure 2.3.1

Figure 2.3.1 Slotted section model
2.3.1 Errors in slotted line technique

The possible sources of errors associated with slotted line measurements must be carefully evaluated and proper operating technique must be applied in order to minimize these errors. The connectors on the coaxial slotted section limit the accuracy of standing wave ratio measurements since the slotted section probe responds to the combined reflections from the connector and the load beyond the connector. The uncertainty in the standing wave ratio measurements can be evaluated when the inherent S.W.R. of the slotted section is known.

Variation of maxima and minima at different points on the line is referred to as the slope error. It can be caused by the variation of the probe depth as the probe carriage is varied and also by energy leakage through the slot. This error can be adjusted to a minimum value in some slotted sections [6].

2.3.2 Probe tuning error

One of the major sources of error in standing wave measurements is excessive probe penetration. The presence of probe affects the voltage standing wave ratio (V.S.W.R.) because it is essential an admittance shunting the line. Excessive coupling to the line causes a shift in maxima and minima and also cause the measured V.S. W. R. to be lower than the true (V.S.W.R.) In addition to the distortion of the field pattern, reflections from the probe vary when the probe is moved. Errors in measurement of low V.S.W.R. arise when these reflections are reflected from a mismatched source. Therefore, the probe coupling should be kept as small as possible expect in case where it is only
desired to examine the minimum point on the standing wave pattern. Using can minimize excessive probe penetration high sensitive detector, assuming that there is adequate signal source power available [6].

2.4 Review of experimental methods

The method is divided into four groups

1) Resonance method

2) Non-resonance method

3) Von-Hipple or shorted waveguide method

4) Two-point methods

2.4.1 Resonance method

Let us consider a cylindrical resonator of volume \( V \), natural frequency \( f_0 \) and quality factor \( Q_0 \). Upon introducing the dielectric into the cavity, the resonance frequency will change to \( f_1 \). Similarly, the quality factor will also change to \( Q_1 \), depending on the shape, size and dielectric constant the sample introduce into the cavity. Under idealized conditions of very small coupling, cavity shape of high symmetry, high conductivity and low dielectric loss, the power \( p \) at the detector as the input frequency \( f \), is given by,

\[
\frac{P}{P_{\text{max}}} = \left[ 1 + 4Q^2 (f - f_{\text{max}})^2 / f_{\text{max}}^2 \right]^{-1} \quad (2.4.1)
\]

Where \( P_{\text{max}} \) is the maximum power that reaches the detector. The expression for dielectric permittivity can be obtained as follows,
Dielectric theory and description of experimental methods

\[ \varepsilon' = \left( \frac{f_0}{f_1} \right)^2 \]
\[ \varepsilon'' = \left( \frac{1}{Q_1} - \frac{1}{Q_0} \right) \]

(2.4.2)

Different groups have been used different types of cavities for this experimental technique, depending upon the frequency range and the type of material used. Works, Dakin and Boggs have used a double re-entrant cavity of high \( Q > (2000) \) made from a length of coaxial line short circulated at both ends, with a small cylindrical section removed from central conductor near one end of cavity. The sample, the cylinder of the same dimension as the removed section is placed near the cut. The accuracy of this found to be \( \pm 1 \) percent in \( \varepsilon \) and \( \pm 5 \times 10^{-5} \) percent in \( \tan \varepsilon \). A microwave resonance technique studied for high loss material has been developed by Birnbaum, Kryder and Lyons, with the accuracy of \( \pm 4 \) percent in \( \varepsilon \) and \( \pm 2 \) percent \( \varepsilon'' \). The method can be used from 3 GHz to 24 GHz. Pitt and Smyth has developed a short circular coaxial line of adjustable length to which the generator and detector are connected loosely. The cavity can be used over the range of 0.5 to 3 GHz with an accuracy of 0.5 \( \pm \) percent in \( \varepsilon' \) and 3 percent in \( \varepsilon'' \).

### 2.4.2 Non-resonance method

The classical methods of Durbe for the centimeter wave have been employed for this technique. The method can be described as follows,

Consider a wave-guide shorted at one end shown in figure (2.4.1) with wave propagating along it. As a result of the interference between the incident and
reflected waves a standing wave will form in the wave-guide; its distribution is shown in Figure (2.4.1).

If the ends of the wave-guide are filled with dielectric layer of thickness d then as the result absorption, the amplitude of the reflected wave will differ from the amplitude of incoming wave, and the distribution of amplitude in standing waves changes as shown in figure (2.4.1). The amplitude of the electric field at nodes is no longer zero, and the maxima minima of wave shift. First of all, the shift is related to the changes of the wavelength in the dielectric as compared with its length in air Roberts and Von Hipple worked out a method determining the complex permittivity form measurements of the parameters of the standing wave, which arises in the air filled part of the wave guide.
Dielectric theory and description of experimental methods

Figure 2.4.1 Standing waves in a wave guide

(a) Without dielectric

(b) Loaded with dielectric of any length

(c) Loaded with dielectric of length $\lambda d/2$
The principle equation relating the parameter, which described the standing in the wave-guide

\[
\frac{\tan h \gamma_2 d}{\gamma_2 d} = j \left( \frac{\lambda}{2\pi d} \right) \frac{\kappa s - j\tan \theta}{1 - j \kappa s \tan \theta} = c e^{j \xi} \quad (2.4.3)
\]

where,

\[
\gamma_2 = j\omega \sqrt{\varepsilon \mu} = \alpha_2 + j\beta_2 \quad (2.4.4)
\]

\(\gamma_2\) is characteristics propagation coefficient for the dielectric layer, \(\alpha_2\) is the attenuation coefficient and \(\beta_2 = 2\pi / \lambda_2\) is the phase shift for the dielectric layer. \(\lambda\) is the wavelength in the air filled part of the wave guide,

\[Q = \frac{2\pi \varepsilon_0}{\lambda_0}\]

where \(\varepsilon_0 = (\lambda / 2) - d - 1\) is the distance between the first minima of the wave from the surface of the dielectric and 1 is the shift of minima brought about by the introduction of the dielectric into the wave guide figure (2.4.2) on the other hand is the reciprocal of the voltage coefficient of the standing wave.

Figure 2.4.2. Determination of standing wave coefficient
Dielectric theory and description of experimental methods

\[ K_s = \frac{E_{\text{min}}}{E_{\text{max}}} \]  \hspace{1cm} (2.4.5)

\( E_{\text{min}} \) and \( E_{\text{max}} \) respectively, are the minimum and maximum amplitudes of the standing wave electric field in the wave-guide figure (2.4.2). For low loss material (\( k_s < 0.1 \))

\[ K_s = \frac{\pi \delta x}{\lambda} \]  \hspace{1cm} (2.4.6)

Where \( \delta x \) is the distance between the points of the standing wave where the intensity of the current flowing into the detector is twice as high as the minimum value. Figure (2.4.1) and \( d \) is the thickness of the dielectric layer.

From measurements parameters \( \lambda, d, k, \) and \( X_0 \) we can find the functions \( C \) \( \exp^{j\xi} \) and the function

\[ \gamma_d = \tau \exp^{j\tau} \]  \hspace{1cm} (2.4.7)

can be found from the plot of equation

\[ \frac{\tan hT e^{j\tau}}{T e^{j\tau}} = c e^{j\xi} \]  \hspace{1cm} (2.4.8)

In the plot \( \tau \) is on \( Y \)-axis, and the absolute magnitude of \( T \) is on \( X \)-axis. \( C \) and \( \xi \) are the parameters of the intersection curves. From equation (2.4.5) we get

\[ C = \frac{\lambda}{2\pi d} \sqrt{\frac{(ks + \tan^2\theta)}{(1+k^2s \tan^2\theta)}} \]

and

\[ \tan\xi = \frac{k (1+ \tan^2\theta)}{(1-k^2s) \tan\theta} \]  \hspace{1cm} (2.4.9)

The complex electric permittivity of the dielectric is given by the equation.

\[ \varepsilon^* = \frac{(\gamma_d / 2\pi)^2 + (1 / \lambda)^2}{(1+\lambda c)^2 + (1+\lambda)^2} \]  \hspace{1cm} (2.4.10)
where $\lambda_c$ is the limiting length of the wave-guide for rectangular wave-guide 
$\lambda_c = 2 \times$ the width, i.e. $\lambda_c = 2 \times a \ [9]$.

### 2.4.3 Von-Hipple or shorted waveguide method

There are many ways in which dielectric measurements may be made. We shall study the shorted waveguide or Von-Hipple method. The method consists of reflecting microwaves at normal incidence in TE mode from a dielectric sample placed against a perfectly reflecting surface. The reflection set up standing waves in space in front of the sample. The separation of the first minimum from the face of the sample will depend upon wavelength of the EM wave in the sample and on sample dimensions (thickness) and hence on dielectric constant. Further, the change in wavelength shall cause shift in the minima and in turn a change in half power width of the standing wave pattern. Also, losses in the dielectric shall decrease to VSWR ($E_{\text{max}}/E_{\text{min}}$) and so $\tan \delta$ may be related to this decrease in VSWR.

To proceed, consider that an EM wave traveling through medium 1 (air) strikes normally to the medium 2 (dielectric), a part of it is reflected and the rest gets transmitted (figure 2.4.1). A standing wave pattern is thus produced in medium 1. The transverse electric field component in this partial reflection case is given by

$$E_y = [E_0 e^{j\omega t-y_1 x}] [1 + \Gamma_0 e^{2 y_1 x}]$$

(2.4.11)

Where $\gamma_1$ is the propagation constant in medium 1 and is the sum of attenuation constant $\alpha_1$ and phase shift constant $\beta_1$.

$$\gamma_1 = \alpha_1 + j \beta_1$$

(2.4.12)

The reflection coefficient $\Gamma_0$ is given by
Dielectric theory and description of experimental methods

\[ \Gamma_0 = |\Gamma_0|e^{-2j\Psi} \quad (2.4.13) \]

\( \Psi \) is the phase of the reflection coefficient

The input impedance \( Z(0) \) at the boundary (x=0) is given by

\[ \frac{1+\Gamma_0}{1-\Gamma_0} \]

\[ Z(0) = Z_1 \quad (2.4.14) \]

\( Z_1 \) being the impedance of medium 1. Further, if attenuation in medium 1 were negligible, then the inverse voltage standing wave ratio in medium 1,

\[ \rho = (E_{\text{max}}/E_{\text{min}})^{-1} \]

is written as

\[ \rho = \frac{E_{\text{min}}}{E_{\text{max}}} \]

\[ \rho = \frac{1 - \Gamma_0}{1 + \Gamma_0} \quad (2.4.15) \]

Putting \( \Gamma_0 = e^{-2j\phi} \) and \( \phi = \rho_1 + j\Psi \)

(Equ.2.4.13)

We have,

\[ \frac{1 + \Gamma_0}{1 - \Gamma_0} \]

\[ Z_0 = Z_1 \quad (2.4.14) \]

and

\[ \frac{E_{\text{min}}}{E_{\text{max}}} = \frac{1 - e^{-2\rho_1}}{1 + e^{-2\rho_1}} = \tanh \rho_1 \quad (2.4.16) \]

If xo be the position of the first minimum where incident and reflected waves combine out of \( \pi \) phase then,
\[
\begin{align*}
\frac{2\pi x_0}{\lambda_g} - \frac{2\pi x_0}{\lambda_g} &= -2\psi - \frac{\pi}{\lambda_g} \\
\frac{1}{x_0} &= 2\pi \left(\frac{\pi}{\lambda_g} - \frac{\pi}{\lambda_g}\right) \quad (2.4.17)
\end{align*}
\]

where \(\lambda_g\) is guide wavelength.

Now using Equations (2.4.14) and (2.4.17) we have

\[
Z_0 = Z_1 \frac{\tanh \rho_1 - j \cot \psi}{1 - j \tanh \rho_1 \cot \psi} \quad (2.4.18)
\]

Further, using Eqs. (2.4.16) and (2.4.18),

\[
Z_0 = Z_1 \frac{E_{\text{min}}}{E_{\text{max}}} \left\{ \frac{2\pi x_0}{\lambda_g} - j \frac{2\pi x_0}{\lambda_g} \right\} \quad (2.4.19)
\]

If medium 2 is terminated in a short-circuit, the input impedance at the interface,
\[ Z_{(0)se} = Z_2 \tanh \gamma_2 d \quad (2.4.20) \]

where \( Z_2 \), \( \gamma_2 \), and \( d \) are respectively the characteristic impedance, propagation constant and the length of the medium 2. Equating the two impedances at the interface \((x = 0)\), we find,

\[
Z_0 = \left\{ \begin{array}{c}
\frac{2\pi x_0}{\rho - j \tan \frac{\lambda_g}{2}} \\
1 - j \rho \tan \frac{\lambda_g}{2}
\end{array} \right\} = Z_2 \tanh \gamma_2 d
\]

Since \( \frac{Z_1}{Z_2} = \frac{\gamma_2}{\gamma_1} \) so, we have,

\[
\tanh \gamma_2 d = \frac{1}{\gamma_2 d} \left\{ \begin{array}{c}
\frac{2\pi x_0}{\rho - j \tan \frac{\lambda_g}{2}} \\
1 - j \rho \tan \frac{\lambda_g}{2}
\end{array} \right\} \]

or

\[
\tanh \gamma_2 d = \frac{j\lambda_g}{2\pi d} \left\{ \begin{array}{c}
\frac{2\pi x_0}{\rho - j \tan \frac{\lambda_g}{2}} \\
1 - j \rho \tan \frac{\lambda_g}{2}
\end{array} \right\} \quad (2.4.21)
\]

Now characteristic propagation constant \( \gamma_2 \) of the EM wave in the dielectric is related to the intrinsic propagation constant of the waves in vacuum (or air) is
\[
\gamma_2^2 = \gamma_1^2 + \left\{ \frac{m\pi^2}{a} \right\} + \left\{ \frac{n\pi^2}{b} \right\} \tag{2.4.22}
\]

For TE_{mn} mode, for TE_{10} it, however, reduces to
\[
\gamma_2^2 = \gamma_1^2 + (\pi/a)^2 \tag{2.4.23}
\]
a and b broad and narrow dimensions of the waveguide. The complex dielectric constant of the medium 2 is given by.

\[
\varepsilon_2^* = \frac{-\gamma_1^2}{\omega^2\mu_0} = \varepsilon_0 \left\{ \frac{1}{\lambda_c} \right\}^2 + \left\{ \frac{\gamma_2}{2\pi} \right\}^2 + \left\{ \frac{1}{\lambda_g} \right\}^2 \tag{2.4.24}
\]

Where \( \lambda_c = 2a \) is cut-off wavelength, \( \gamma_2 \) is propagation constant in the dielectric and \( \lambda_g \) is guide wavelength (air-filled). Knowing \( \lambda_c, \varepsilon_0, \gamma_2 \) and \( \gamma_g \), \( \varepsilon_2^* \) can be calculated. Separating \( \varepsilon_2^* \) into real and imaginary parts one may obtain the value of \( \varepsilon' \) and \( \varepsilon'' \) or the loss tangent, \( \tan \delta \). The measurement of \( \gamma_2 \) is effected by using Eq. (2.4.21). The values of \( \rho = 1/VSWR, \lambda_0 \) and \( \lambda_g \) can be experimentally measured to give a complex value of

\[
\frac{\tanh \gamma_2 d}{\gamma_2}
\]

To find \( \gamma_2 \) from this value, put \( \gamma_2 d = Te^{ij\tau} \), then

\[
\frac{\tanh Te^{ij\tau}}{Te^{ij\tau}} = ce^{ij\xi}
\]  \tag{2.4.25}
Dielectric theory and description of experimental methods

Knowing $c$ and $\xi$, values of $T$ and $\tau$ are seen from the standard tables* and hence $\gamma_2$ is determined.

The calculation part is greatly simplified if we take the length of the dielectric sample in a multiple of quarter-or-half wavelength of the EM waves in the dielectric (possible in case of liquids and solutions only). Thus if the short-circuiting plunger is placed at a distance of $\lambda_g /4$ from medium 2, it corresponds to an open circuit (Figure 2.4.3) termination and consequently the input impedance is given by.

$$Z_{(0)oc} = Z_2 \coth \gamma_2 d \quad (2.4.26)$$

Figure 2.4.3 Standing waves in which short circuiting plunges is placed at a distance $\lambda_g/4$ for medium 2

The propagation constant along the axis of a hollow waveguide of uniform cross-section an highly conducting walls, is given by

$$\gamma_2 = \frac{2\pi j}{\lambda_0} \left\{ \varepsilon' - \left( \frac{\lambda_0}{\lambda_c} \right)^2 - \omega j \right\}^{\frac{1}{2}} \quad (2.4.27)$$

$\lambda_0$ is free-space wavelength and $\lambda_c = 2a$ is the cut-off wavelength.
Equation (2.4.27) can be written as

\[ \gamma_2 = \alpha_d + j \left( \frac{2\pi}{\lambda_d} \right) \]

\( \alpha_d \) is the attention in the dielectric while \( \lambda_d \) is the wavelength of EM waves in the dielectric. Hence, separating Eq. (2.4.27) into real and imaginary parts, we have

\[ \varepsilon' = \left( \frac{\lambda_0}{\lambda_c} \right)^2 + \left( \frac{\lambda_0}{\lambda_d} \right)^2 \left( 1 + \frac{\alpha_d\lambda_d}{2\pi} \right) \] (2.4.28)

and

\[ \varepsilon'' = \frac{1}{\pi} \left( \frac{\lambda_0}{\lambda_d} \right)^2 \frac{\lambda_0}{\lambda_d \alpha_d} \] (2.4.29)

\( \lambda_0, \lambda_c \) and \( \lambda_d \) are known \( \alpha_d, \varepsilon', \varepsilon'' \) and \( \tan \delta \) can be computed. The method depends upon the dielectric under test.

### 2.4.4 Two-point methods

(a) **Loss-less dielectric**

Consider a solid sample of length \( l_e \) loaded in a rectangular wavelength against short circuit that touches it well. In Figure 2.4.1 (b) and (c) \( D \) and \( D_R \) are respectively the positions of first voltage minimum of the standing wave pattern when waveguide is unloaded and loaded with the dielectric. The respective distances from the short circuit will be \( (1 + l_e) \) and \( (l_R + l_e) \). Now looking from \( A \) towards right and left, the impedances are equal, so

\[ Z_0 \tan \beta l = - Z_e \tan \beta_e l_e \] (2.4.30)
where \( Z_0 \) and \( Z_\varepsilon \) are respectively the characteristic impedance of empty and dielectric-filled wave guides and \( \beta \) and \( \beta_\varepsilon \) are respective propagation constants.

Similarly from Figure 2.4.1 (b) one has

\[
Z_0 \tan \beta (l_R + l_\varepsilon) = 0 \tag{2.4.31}
\]

Now, consider the expression.

\[
\tan \beta (D_R - D + l_\varepsilon) = \tan \beta \{(l_R + l_\varepsilon) - (1 + l_\varepsilon) + l_\varepsilon\} \\
= \tan \beta \{(l_R + l_\varepsilon) - 1\}
\]

Expanding the tangent sum angle and making use of Equation (2.4.31), one obtains.

\[
Z_0 \tan \beta (D_R - D + l_\varepsilon) = Z_\varepsilon \tan \beta_\varepsilon l_\varepsilon \tag{2.4.32}
\]

Again recalling the relation

\[
\frac{\tan \beta (D_R - D + l_\varepsilon) \tan \beta_\varepsilon l_\varepsilon}{\beta l_\varepsilon} = \frac{\beta_\varepsilon l_\varepsilon}{\beta l_\varepsilon} \tag{2.4.33}
\]

Equation (2.4.33) suggests a method for measuring dielectric constant. Quantities on the LHS are all experimentally measurable (\( \beta = 2\pi/\lambda_\varepsilon \)). Thus value of \( \tan \beta_\varepsilon l_\varepsilon / \beta l_\varepsilon \) is known and so value of \( \beta_\varepsilon l_\varepsilon \) can be known from the standard tables. Since \( \tan \beta_\varepsilon l_\varepsilon / \beta l_\varepsilon \) is a multivalued function, so correct value has to be selected. This is done in two ways (i) when approximate value of dielectric constant is known, select that value, say \( \beta_\varepsilon \) and compute dielectric constant from the relation.
Dielectric theory and description of experimental methods

\[ \beta_e = \frac{2\pi}{\lambda_0} \left\{ \varepsilon_r \mu_r - \left( \frac{\lambda_0}{\lambda_c} \right)^2 \right\}^{1/2} = \frac{2\pi}{\lambda_d} \]

Where \( \lambda_c = 2a \) is cut-off wavelength, \( \lambda_0 \) is free-space wavelength, \( \lambda_d \) is guide wavelength when it is filled with the dielectric. \( \varepsilon_r \) is relative dielectric constant and \( \mu_r \) is the relative permeability.

or

\[ \varepsilon_r = \frac{\frac{a}{\pi} \left( \frac{\beta_e l_e}{l_e} \right)^2 + 1}{\left( \frac{2a}{\lambda_d} \right)^2 + 1} \quad (2.4.34) \]

If this value is close to the approximately known value, then the value obtained is true value, otherwise try another solution and so on.

(ii) If approximately value of the dielectric constant is not known, a second identical experiment is to be performed with the sample of a different length. The proper solution of the transcendental Eq. (2.4.33) is common to the two sets of samples and is thus the point of intersection of the two curves drawn for each sample between dielectric constant \( \varepsilon \) and the solutions for \( \beta_e l_e \) as shown in Figure 2.4.4.
2.5 Basic equation for low loss dielectric materials

Consider an Em wave at the surface separating air and dielectric specimen by a thin mica foil at $Z = 0$. It is represented by $E_0 \exp j\omega t$ where $E_0$ is the maximum amplitude and $\omega$ is the angular frequency of the microwave electric field. The wave is transmitted through the sample of length $d$ and reflected at the shorting plunger. The reflected wave at $Z = 0$ is given by

$$E_0 \exp (j\omega t - 2\gamma_1 d + j\delta) \quad (2.5.1)$$

Where $\gamma_1$ is the propagation constant in the medium is given by

$$\gamma_1 = \alpha_1 + j\beta_1$$

here $\alpha_1$ is propagation constant and $\beta_1$ is phase constant, and $\delta$ is the phase change by reflection due to plunger. The total amplitude of the resulting wave in the air medium is given by

$$E = E_0 \exp(j\omega t) + E_0 \exp(j\omega t - 2\gamma_1 d + j\delta) \quad (2.5.2)$$
The power $P$ at $Z = 0$ is given by

$$P = EE^* = |P|^2$$

$$P = P_0 \left[ 1 + e^{-4\alpha_1 d} + 2e^{-2\alpha_1 d} \cos(2\beta_1 - \delta) \right] \quad (2.5.3)$$

Keeping the plunger at $Z = 0$ (mica sheet) the slotted line probe is moved, till the digital power meter (DPM) connected to the crystal detector resisters zero current. Now keeping the slotted line probe at this position, the shorting plunger is moved back and the standing wave power i.e. current at that location is recorded for different sample thickness.

Equation 2.5.3 is used to determine the different parameters via; attenuation constant ($\alpha_1$), phase constant ($\beta_1$), power at infinite thickness $P_0 = \{E_0\}^2$ and the phase change $\delta$.

### 2.5.1 Basic equation for high loss materials

For high loss materials, one has to consider multiple reflections in the material. Using boundary conditions at each interface and solving the resulting simultaneous equations can find total reflection coefficient. The condition at the plunger yields.

$$E_{10} \exp(-\gamma_1 d) + R E_{30} \exp(\gamma_1 d) = 0 \quad (2.5.4)$$

Where $E_{10}$ is the transmitted electric field from dielectric media to air, $E_{30}$ is the amplitude of the wave traveling in negative X – direction in the dielectric and $R$ is the reflection coefficient due to plunger, other boundary conditions for the transmitted ($E_{00}$) and reflected ($E_{20}$) waves are

"Dielectric theory and description of experimental methods"
Dielectric theory and description of experimental methods

\[ E_{00} + E_{20} = E_{10} + E_{30} \]  
\[ (2.5.5) \]

\[ \gamma_2 (E_{00} - E_{20}) = \gamma_1 (E_{10} - E_{20}) \]  
\[ (2.5.6) \]

The above three equation to get the value of \( E_{20}/E_{00} \) as

\[ \frac{E_{20}}{E_{00}} = \frac{(\gamma_2/\gamma_1) \tan \gamma_1 d + R}{(\gamma_2/\gamma_1) \tan \gamma_1 d + Ro} \]  
\[ (2.5.7) \]

&

\[ \frac{E_{20}}{E_{00}} = \frac{(\gamma_2 \cdot \gamma_1) \exp (2\gamma_1 d) + (\gamma_2 + \gamma_1) R}{(\gamma_2 + \gamma_1) \exp (2\gamma_1 d) + (\gamma_2 \cdot \gamma_1) Ro} \]  
\[ (2.5.8) \]

The standing wave in the wave guide can be describe as

\[ E = E_o (\exp -\gamma_2 x) + \left(\frac{E_{20}}{E_{00}}\right) (\exp +\gamma_2 x) \]  
\[ (2.5.9) \]

The power \( P \) at the position is given by:

\[ P = P_0 \left| \left(\exp -\gamma_2 x\right) + \left(\frac{E_{20}}{E_{00}}\right) (\exp +\gamma_2 x) \right|^2 \]  
\[ (2.5.10) \]

In our experiment, the probe position was kept at minima (\( X = 0 \)) when the plunger was shorted. The above equation 2.5.10 becomes \( P = P_0 \left| 1+Q \right|^2 \), where \( Q = (E_{20}/E_{00}) \) as given in equation 2.5.1.

\[ P = P_0 \left| \exp -\gamma_2 x + \frac{(\gamma_2 \cdot \gamma_1) \exp (2\gamma_1 d) + (\gamma_2 + \gamma_1) R \exp +\gamma_1 x}{(\gamma_2 + \gamma_1) \exp (2\gamma_1 d) + (\gamma_2 \cdot \gamma_1) Ro} \right| \]  
\[ (2.5.11) \]

Where \( \gamma_2 = \alpha_2 + j\beta_2 \) is the propagation constant in the wave guide section preceding the dielectric cell, \( \gamma_1 = \alpha_1 + j\beta_1 \) is the propagation constant in the
Dielectric theory and description of experimental methods

dielectric cell. $R = R_0 \exp(j\phi)$ is the complex reflection coefficient of the plunger in contact with the dielectric. This equation (2.5.11) was fitted in experimental data using $\alpha_1, \beta_1, \phi$ and $P_0$ as fitting parameters. The value of $\beta_z(2\pi/\lambda_g)$ was measured experimentally and $R_0, \alpha_x$ are assumed to be one and zero for ideal plunger respectively.

Figure 2.5.1 Multiple reflection in a material with high loss dielectric permittivity

2.6 Method of experimental analysis for seeds

The experimental technique used to measure the dielectric permittivity and water content is that of Roberts and Von Hipple and Gopal Krishna. A least squares fit programme of Sobhanadri is used to calculate the dielectric permittivity. An X-band microwave transmission line waveguide setup is used for this purpose. The dielectric permittivity and loss of seeds have been
measured for two different frequencies i.e. at 8-GHz and 11-GHz and at room temperature. The seed samples were collected from Aurangabad market. The seed samples under measurement of known volume was placed in the empty solid dielectric cell, and well pressed by a laboratory developed mechanical system (Figure 2.8.2) to remove the air and discontinuities in the sample. The solid cell with sample was connected to the opposite end of the source of microwave bench set up. The signal generated from the microwave source was allowed to incident on the seed sample. The seed sample reflects part of the incident signal through the seed from its front surface. The values of power at different points of standing waves have been measured as a function of probe position. About (80 – 100) points were recorded for a single standing wave pattern. The least squares fit has been used to determine the values of $\lambda_0$, $\lambda_c$, $\alpha$ and $\beta$ for the sample.

Firstly, emerging the microwave transmission line the standing wave pattern was recorded for empty cell. The seeds under measurement were placed in the cell pressed it, and connecting it to the other end of the microwave bench setup. The measurements were conducted for three different lengths of the collected seeds. The same procedure is applied for other seed samples. Fitting these standing wave patterns of dry seed samples along with empty standing wave pattern into least squares fit programme, the dielectric permittivity and loss were determined.

The free space wavelength was determine from following equation

$$\frac{1}{\lambda_0^2} = \frac{1}{\lambda_g^2} + \frac{1}{\lambda_c^2}$$  \hspace{1cm} (2.6.1)

Where $\lambda_c$ is the cutoff wavelength determine by
\[ \lambda c = 2 \times a \]

\[ = 2 a \]

where ‘a’ is the border side of the rectangular waveguide. The real and imaginary parts of the permittivity is

\[ \varepsilon^* = (\varepsilon' - j\varepsilon'') \quad (2.6.2) \]

have been determined from the following equations

\[ \varepsilon' = \lambda_o^2 \left[ \frac{1}{\lambda_c^2} + \frac{(\beta_1^2 - \alpha_1^2)}{4\pi^2} \right] \quad (2.6.3) \]

\[ \varepsilon'' = \frac{\lambda_o^2 \beta_1 \alpha_1}{2\pi^2} \quad (2.6.4) \]

### 2.7 X-Band microwave bench setup

The necessary components are as follows for X-band Set-up.

1) Sweep Oscillator  
2) Coaxial connector  
3) Isolator  
4) Attenuator  
5) Slot line  
6) Solid dielectric cell  
7) Power Meter

Experimental set-up of Microwave X-Band is given in figure 2.7.1.
Figure 2.7.1 Block diagram of experimental setup of microwave X-band
2.8 Special component used in the experiment

2.8.1 Agilent 53147A/148A/149 microwave frequency counter/power meter/DVM

a) Measuring frequency

Connect the instrument to a power source when the instrument is connected to an AC power source, the Standby indicator on the front panel lights. The standby indicator also lights if the instrument is connected to an external DC power source or is operated from internal batteries and the battery power switch is on (with the Battery option only).

Press the POWER button on the front panel. The standby indicator goes off, and all segments of the front-panel display are temporarily activated.
TESTING is displayed while the instrument performs its power-on self-test. If the instrument passes all of the tests, SELF TEST OK is displayed, and the instrument displays its model number, firmware version number, GPIB address, and CH2 NO SIGNAL. The Counter is now ready to measure the frequency of a signal applied to the Channel 2 input. Note that the Ch 2 Freq annunciators are activated.

Connect an input signal to Channel 2. The Channel 2 input path circuits contain sensitive GaAs semiconductors. To prevent damage to these components, always adhere to standard ESD (Electro Static Discharge) prevention procedures, and ensure that the maximum power specification for this channel (+27 dBm) is not exceeded.

To measure the frequency of a signal applied to the Channel 1 input, press the Chan Select key. CHANNEL 1 is displayed momentarily, and the Ch 1 and Freq annunciators are activated. If a signal is presently applied to the Channel 1 input, the measured frequency is then displayed. If no signal is applied, CH1 NO SIGNAL is displayed until an input signal is connected to the Channel 1 input connector.

b) Measuring power

The Agilent 53147A/53148A/53149A can measure signal power in the power and frequency ranges. The power measurement, which is shown in a dedicated area of the display, includes a digital readout and an analog representation. The display, which can be configured to shows power in units of dBm or Watts, is auto-ranging when set to measure in watts.
Selecting a Power Head (Sensor)

There are a number of Agilent power heads that can be used with the Power Meter in this instrument. Choosing the appropriate power head is a matter of matching the head’s characteristics to the signal to be measured.

Before one can make any power measurement, one must determine which power head (sensor) to use for the measurement, select the power head in the instrument’s menu and configure the power meter to use the appropriate calibration factor for the frequency of the signal. The five power head models that have recorded calibration-factor tables in the instrument’s non-volatile memory are listed. One can also modify the data points (frequency/calibration-factor data pairs) in the preconfigured calibration-factor tables, add data points to these tables, and add up to three custom tables for power heads that are not included in the instrument’s menu. Instructions for modifying and adding data points in calibration-factor tables are in “Modifying and Adding Calibration Factor Tables”.

MAKING A POWER MEASUREMENT

When you turn the power Meter on, you must always zero and calibrate it with the power head connected before making any measurements. If you are using a different model power head than the one used the last time the Power Meter was used, you must also set the power head model in the instrument’s menu.

As part of the measurement sequence, you must input either the frequency of the signal you intend to measure or the power factor for that frequency.
POWER MEASUREMENT EXAMPLE

The instrument must be powered on and must remain at the same ambient temperature for 15 minutes before beginning this procedure. If the temperature changes by 5 °C or more, wait another 15 minutes.

Connect the output cable from the power-meter head to the Power Meter connector. This example assumes that you have a power head available that is appropriate for the measurement to be taken.

Press the Display Power key to enable power measurement. The Power annunciator at the left side of the display is activated, and the Power Meter’s digital and analog power displays show the power measurement in Db or dBm (the default units of power measurement).

Press the shift key, and then press the menu (Reset / Local) key. One of the items in the instrument’s menu is displayed (if the menu has not been used since the instrument was turned on, the initial menu display is “REF OSC>INT”).

Use the up and/or down arrow keys to cycle through the menu until

“HEAD > OFF” is shown.

Press the right arrow key. The flashing indicator after HEAD changes from to, and “OFF” (or the currently selected power head model number) begins to flash.

Select the model number of the power head you intend to use by pressing the up- and/or down- arrow key repeatedly until the correct model number is displayed, and then press Enter.
Press the Zero key. The Power Meter displays ZEROING and then returns to the display shown in step 2.

Connect the power-head input connector to the Power Meter Output Connector.

Press the Call key. During calibration, the Power Meter displays CALIBRATING. It then returns to the display shown in step 2.

If you know the frequency of the signal you intend to measure, press the Freq. key, enter the frequency value, and press Enter. The Power Meter uses the frequency to set the power-factor per the values in the stored calibration tables. If you prefer, you can use the Cal Factor key to enter the calibration factor value directly.

Disconnect the power-head input connector from the Power Meter output Connector and connect it to the signal to be measured.

To measure the signal power in Watts, press the Shift key, and then press the dBm/W (Display power) key. When you press the Shift key, the Shift annunciator is activated. When you press the dBm/W (Display power) key, the Shift annunciator goes off, and the units of measurement annunciator group to the right of the digital power measurement changes from dB or dBm to Watts, mw, microwatt or nanowatt.

Photograph of the Agilent microwave power/frequency meter is shown in Figure 2.8.1.
Dielectric theory and description of experimental methods

Figure 2.8.1 Photograph of the Agilent microwave Power/Frequency meter
Modifying and adding calibration factor tables

The Head menu option provides access to reconfigure, editable calibration-factor tables for vive models of Agilent power sensor heads (models 8481A, 8481D, 8482A, 8485A and 8487A) and three custom tables. You can modify the frequency/calibration-factor values in any of the data points for any power head, and you can input data to build new calibration Tables.

<table>
<thead>
<tr>
<th>Calibration table data points</th>
<th>modify</th>
<th>Delete</th>
<th>reset</th>
<th>add</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factory defined data points (for 8481A, 8481D,8482A,8485A and 8487A)</td>
<td>all</td>
<td>None</td>
<td>All</td>
<td>yes</td>
</tr>
<tr>
<td>Data points added to factory-defined tables</td>
<td>all</td>
<td>All</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>By user</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Custom calibration-factor tables</td>
<td>all</td>
<td>All</td>
<td>N/A</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Calibration table modification example

This example demonstrates how to view and modify the values in any of the Preconfigured calibration tables or in one of the three custom calibration tables

Press the shift key and then press the menu (reset/local) key.
Use the up and/or down arrow keys to cycle through the menu until “HEAD>OFF” is shown Press the right arrow key. Select the model no. of the power head you intend jto modify the data points for by pressing the up-and/or
down-arrow key repeatedly until the correct model no. is displayed, and then press Enter.

Press the right arrow key. Press the right arrow key again

When you move the focus to the last digit of the frequency value, an additional flashing indicator appears at the right end of the display and indicator to the left of the frequency value stops flashing.

Press the right arrow key until focus moves from the last digit of the frequency value to the first digit of the calibration factor value. The flashing indicator at the right of the frequency value changes direction, which indicates that you can use the left arrow to return to frequency value, if you need to.

If you want to change values in additional data points, res. the right arrow key to save your changes and move to the next data point. If you are done changing data point values, press the Enter key to save your changes exit the menu.

2.8.2 Instrument used for removing the discontinuities in the seeds

In order to remove the discontinuities in the seed sample the laboratory developed mechanical system was used in the present research work. This system is as shown in Figure 2.8.2.
Figure 2.8.2 Mechanical system for removing discontinuities in the seed sample in dielectric cell
Figure 2.8.3 The dielectric cell specially prepared for the temperature variation

It is a rectangular dielectric cell. Its one end is shorted and the other end is open for allowing the microwaves to enter through it. The leakage of water is avoided by sealing the shorted end with the sealing material.
Figure 2.8.4 Seed samples used for the measurement

1) Pigeon pea,
2) Lentil,
3) Black gram,
4) Cowpea,
5) Bengal gram
Figure 2.8.5 Seed samples used for the measurement

1) Cluster bean,

2) Bhedi,

3) Brinjal,

4) Fenugreek
Figure 2.8.6 Seed samples used for the measurement

1) Soyabeans,
2) Safflower,
3) Bajra,
4) Corn
Figure 2.8.7 seed samples used for the measurement

1) Groundnut,  
2) Sesame,  
3) Niger,  
4) Sunflower
Figure 2.8.8 Seed samples used for the measurement

1) Spinach,
2) Tomato,
3) Mustard,
4) Linseed
Figure 2.8.9 Experimental setup for temperature variation while taking preliminary tests with two thermometers and temperature heater
Figure 2.8.10 Experimental setup for temperature variation
Figure 2.8.11 Temperature heater used for the temperature variation
References

[8] Principles of microwave circuits: vol.8 of MIT Radiation Laboratory series Lexington, mass (1964)


