Chapter VI
Discussion of the results of the studies of Soybean, Sunflower and
Groundnut using overlay on microstrip components
and waveguide techniques

6.1 Introduction

The results elaborated in chapter III, IV and V are discussed in this chapter. Seeds such as soybean, sunflower and groundnuts provide a variety of food products for humanity. Apart from extraction of oil, the soybean and groundnut are sources of protein. Compositional analysis of seeds plays an important role for the quality control and assurance of seeds in both agriculture and food industries. The protein, oil, fiber content and moisture contents in these seeds affect their usefulness and self life of these seeds. A small change in the seed moisture content has a large effect on the storage life of the seeds. Grain permittivity and moisture measurements have become a necessity because of highly automated industrial processes and the growing need for real time decision making. As already discussed in chapter I, the radio frequency range (which includes microwaves) of the electromagnetic spectrum is most suited for moisture measurement purposes.

The radio frequency dielectric method measures moisture content in the seed by sensing the dielectric constant of the seed. The dielectric constant being a measure of a materials ability to store electrical energy when placed in an electric field, the water (H₂O) because of its molecular structure has very high dielectric constant (~ 60) in the microwave region. The other constituents of the seed is protein, oil, starch etc has a dielectric constant between ~ 2-5 [1]. This wide difference in the dielectric constants between water and seed constituents makes the RF dielectric moisture measurement quite insensitive to the seed composition. The moisture distribution within the seed influences the microwave measurements significantly.

Amongst the three seeds studied soybean and groundnut has ~ 40% protein, ~ 22% oil and ~ 24% starch [2]. Each grain displays a characteristic
water vapor pressure at a certain temperature and moisture content. The grains with high oil content are in equilibrium at lower moisture content than are seeds with high protein content. This is the reason why after 24 hours of soaking the equilibrium moisture content of sunflower was ~ 34.78% whereas of soybean was ~ 60.40% and groundnut was ~ 61.73% (Table 2.2).

As already mentioned in this work the microwave region especially the frequency range 13-18 GHz has been used to study the moisture laden seeds. There are very few reports on the properties of the seeds in this frequency range. Use of a non-resonant Ag thick film microstripline to measure moisture dependant permittivity and to predict moisture content in soybean, sunflower and groundnut seeds has been reported for the first time. The Ag thick film equilateral triangular microstrip patch antenna has also been studied for the first time and used to predict moisture content. The permittivities of the moisture laden seeds have been compared with those obtained by waveguide reflectometer method and VSWR technique also. The microstrip components being miniaturized version of the microwave components compare very well with the other methods as far as sensitivity to moisture content is concerned.

6.2 Microstrip Components without overlay:

For the fabrication of MIC, the metallization is a very important aspect to be taken into consideration. The function of the circuit depends on the extent of power loss, adhesion, and geometry and line definition of the metallic conductors. Our previous work [3] has proved the efficiency of Ag thick film paste up to 18 GHz frequency. The microstripline is a non-resonant circuit and the simplest of all the microstrip passive elements, so this circuit was chosen for the overlay studies. By using microstripline evaluation of dielectric properties and prediction of moisture content have been done. The transmitted output of the microstripline was ~ 65% with a slight notch between 16-16.5GHz. The rough and porous surface morphology along with the ragged edges and hemispherical shape of thick film fired conductors may contribute to the losses [4].
The circuit loss in all forms of planar components tends to be an order of magnitude higher than losses in conventional circuits, due to the great reduction in conductor surface area. The bonding agents which are basically inorganic oxides, since Ag paste used is fritless also increase the sheet resistance of the metallization. As the frequency increases beyond 15GHz the transmission loss tend to be larger for thick film microstripline. At higher frequency the current density distribution concentrates on the area close to be the conductor surface and the effective cross-section area for the conduction current is smaller than the effective cross section area at lower frequencies.

Miniature 50Ω OSM series connectors and launchers have been used. The launchers at the input and output ends are basically coaxial centre pin which has shape of a wedge of width ~25mil. If the width of the microstripline does not match these dimensions the capacitive discontinuity with a capacity of ~ 0.01 pf can exit [5].

The launchers tab increases its thickness and reduces the characteristic impedance [6]. These types of discontinuities may produce associated frequency dependent standing wave current existing along the line. The characteristics of the component may be distorted due to this in the reflection mode.

It has been reported [7-9] that leaky surface waves exist in the open structures like microstrip. These leaky modes often resemble the bound modes of the microstrip and travel along with it. This increases the attenuation. These waves when it encounters the edge of substrates produce reflection [10].

The triangular patch has been found to provide radiation characteristics similar to those of rectangular patches, but with smaller size [11]. The designing has been done so that the dominant mode was TM_{11} mode. The field pattern is shown in figure 6.1.

From the figure, it is seen that at the three edges and at the center there is a concentration of electric field on the patch. The various position of the seeds where chosen because of this field configuration, since the electric field interacts with the water in the seed to produce the observed change.
Fig. 6.1 Field pattern in equilateral triangular microstrip patch antenna with magnetic walls.

As already indicated the thick film equilateral triangular microstrip patch antenna showed a single resonance peak characteristic. In the antenna the metallization of the patch and feed line is an important aspect in the power efficiency of the antenna.

Basically, microstrip patch antennas are radiating structures and the microstriplines are transmitting structures. The dimensions of the antenna were according to design for frequencies corresponding to the dominant TM_{11} mode. Radiation from a microstrip patch antenna occurs mainly from the fringing fields between the edges of the patch conductor and ground plane. The field at the edges can be resolved into the normal and tangential components with respect to the ground planes. The tangential component gives radiated field normal to the ground plane.

For the thick film equilateral triangular microstrip patch antenna the dimension of the triangular structure and feed line both are important aspects in the efficiency of the antenna. In this work a peak amplitude of \( \sim 37.44\% \) for the designed antenna indicates good delineation of the component. All the
arguments mentioned earlier for thick film components are valid for the antenna structure also. The accurate measurement of E plane and H plane radiation patterns depends on the factors like the physical and effective dimensions of the antenna elements, its feed point location, operation frequency and the environment.

Due to triangular structure of the radiator and straight structure of feed line discontinuities can cause asymmetry in both the radiation patterns. Beam width of H-plane radiation pattern is quite larger than E-plane. The E-plane beam width decreases due to increase in substrate thickness has been reported by Kara [12]. In the present work the radiation patterns obtained are coplanar.

6.3. Model of the moisture laden seeds:

The seeds are porous bodies with capillaries consisting of natural, small diameter necks with large diameter tubes. During absorption and desorption of water, the small radii of the necks controls the filling and emptying of the capillaries. All the experiments reported in this thesis are when the moisture content desorbs from the seed. Due to molecular shrinkage of the seed the availability of the water binding polar sites on the grain surface reduces following desorption [13]. This might make the various portions of the seeds have slightly different moisture content. This process might result in orientation dependent effects in the microwave measurement using microstripline.

Dielectric properties of a biomaterial are intrinsic electrical properties that describe its polarization status when subjected to an electric field. At microwave frequencies, this polarization is orientational dipolar polarization resulting from rotation of water-molecule dipoles with the electric filed. Microwaves interact with the seeds mainly due to the presence of water in almost all of them. The dielectric properties of the seeds due to presence of water varying quantities can be detected using microwave methods [14-16]. Therefore, water dominates the dielectric response of water containing seeds. The dielectric properties of the seeds are represented by the relative complex
permittivity, $\varepsilon^* = \varepsilon' - j\varepsilon''$ where the real part, $\varepsilon'$ - dielectric constant characterizes the ability of material to store the electric field energy and the imaginary part, $\varepsilon''$ - dielectric loss factor reflects the ability of the material to dissipate the electric energy in the form of heat. At microwave frequencies, the effect of ionic conductivity is negligible therefore; all losses are attributed to the water molecule rotation, better correlation between permittivity and moisture content can be expected.

For pure polar substances like liquid water $\varepsilon'$ and $\varepsilon''$ are frequency and temperature dependent. Its frequency behaviour is well known and well described by the single relaxation Debye model and its temperature behaviour is well-documented [17]. Very little is known about the dielectric properties of organic substances containing water. As already explained the seeds used in this work are porous materials with capillaries. When immersed in moisture these capillaries fill with water of high dielectric constant ($\varepsilon_r \approx 60$ at 10 GHz). These moisture filled capillaries are embedded in a low $\varepsilon_r$ matrix made up of proteins, oil, starch and fats etc in the seed. The moisture may be present in two forms-

(1) Bound moisture attached to the porous capillary walls or cavities or chemically bound

(2) Comparatively free moisture in the capillaries [18].

Since the water molecule possesses permanent dipole moments, these will be randomly oriented before the application of electromagnetic field. After the application of electromagnetic field all the dipoles tend to align in the direction of the applied field. This may produce two effects-

(i) The water molecules chemisorbed in the porous capillary walls are not easily oriented in the direction of applied field.

(ii) The free moisture in the capillaries and cavities will oriented more freely and so it will be easily polarized.

Due to these effects, there is a possibility of existence of several relaxations resulting from different modes of binding, ranging from tightly to loosely bound, depending on the level of hydration, composition and structure
of the seed. Due to the sensitivity in the moisture content measurement varying with moist biomaterials like moisture-laden seeds, the density is another factor, which affects their permittivity; such media are considered ‘chaotic’ or ‘statistical’ mixtures involving components with different dielectric behaviours (air, dry matter and water). Mixture equation has to be used to correlate the permittivity of the mixture to those of its components. No specific theories are available for such systems. An empirical approach has to be used to study the variations of permittivity of most organic substances with factors such as frequency, temperature density and moisture content [19].

In this work the response of the microstrip components to the moisture laden seed overlay has been used to establish a direct relationship between seed moisture content and density independent permittivity for obtaining the moisture calibration equation. In the case of microstripline, the transmittance and reflectance have been used and in the case of equilateral triangular microstrip patch antenna the change in resonance frequency, quality factor and bandwidth has been used. The other studies using waveguide method also uses the transmittance and reflectance when tightly packed seeds are kept in the path of microwaves in the waveguide. In the VSWR method the reflectance data has been used to predict the permittivity and moisture content.

6.4 Effect of seed overlay on the thick film microstrip components:

By assuming the medium on the top of microstripline component as air with dielectric constant ($\varepsilon' = 1$), the design parameters of the components have been obtained. When overlay is used above these components the dielectric constant of the medium changes. The fringing fields of the microstrip components interact with the dielectric material resulting in an increase in the effective dielectric constant of the system. Due to the change in the effective dielectric constant, the characteristics of microstrip component changes. The changes observed are in the transmittance, reflectance and resonance frequency, phase, bandwidth and Q of the circuit. As already indicated in chapter I, the use of overlay technique to study biomaterials has been done by
group at Pune University [20-24] and in our lab only. The Pune University group mainly used thin film MRR in X-band whereas in this work thick film resonant and non-resonant microstrip components have been used. To the authors' knowledge there are no reports on the use of Ag thick film microstripline and equilateral triangular microstrip patch antenna for moisture laden studies in the Ku band.

Since the moisture laden seed is used as overlay over microstrip line components, the changes in effective dielectric constant of microstrip line with overlay has been studied. If the experimental value of change in phase ($\Delta\phi$) and amplitude change ($\Delta A$) are calculated, the dielectric constant of overlay material can be found out. The dielectric constant $\varepsilon'$ was calculated by using phase change ($\Delta\phi$) and dielectric loss factor ($\varepsilon''$) by amplitude change ($\Delta A$). In order to obtain the change in dielectric constant of seeds the formula of effective dielectric constant $\varepsilon_{\text{eff}}$ as suggested by Gouker et al [25] was used to calculate the amount of phase change due to overlaid seed. The following equations were used for calculations. All these equations have been explained in the previous chapters. In this chapter a typical calculation has been explained.

When microstrip line is used for calculating the permittivity, reflection coefficient changes are observed due to overlays. From the reflection coefficient, the characteristic impedance of microstrip line at various frequencies can be calculated. Though these calculations and final results have been given in previous chapter, in this article a typical calculation has been explained.

$$Z_0 = \frac{1-|\Gamma|}{1+|\Gamma|} \quad \text{-------------------- 6.1}$$

For frequency 13GHz, Reflection coefficient $|r| = 0.06$

$$Z_0 = \frac{1-0.06}{1+0.06} = 0.8867 \quad \text{-------------------- 6.2}$$

The equation related with $\varepsilon_{\text{eff}}$ with characteristic impedance $Z_0$ is,
The formula suggested by Gouker et al was used to calculate the phase change ($\Delta \phi$). For overlay, $\varepsilon_{\text{eff}}$ of the microstripline with overlay was calculated by using equation 3.7 (chapter III).

For stripline effective dielectric constant is given by,

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r}{0.96 + \varepsilon_r(0.109 - 0.004 \varepsilon_r)\left\{\log(10 + Z_\circ) - 1\right\}}, \quad \text{(6.4)}$$

Here, $\varepsilon_r = 9.8$ and $Z_\circ = 50 \Omega$,

$$\varepsilon_{\text{eff}} = \frac{9.8}{0.96 + 9.8(0.109 - 0.004 \times 9.8)\left\{\log(10 + 50) - 1\right\}} = 6.5672$$

By using $\varepsilon_{\text{eff}}$ with overlay $\varepsilon_{\text{over}}$ can be calculated,

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_{r,\text{sub}} + e^{-\frac{1.4 H_{\text{over}}}{H_{\text{sub}}}} + \left(\frac{\varepsilon_{r,\text{sub}}}{\varepsilon_{r,\text{over}}}\right)^{0.1} x e^{\varepsilon_{r,\text{over}}} \left[1 - e^{-\frac{1.4 H_{\text{over}}}{H_{\text{sub}}}}\right]}{2}$$

$$\varepsilon_{r,\text{sub}} + e^{-\frac{1.4 H_{\text{over}}}{H_{\text{sub}}}} = \left(\frac{\varepsilon_{r,\text{sub}}}{\varepsilon_{r,\text{over}}}\right)^{0.1} x e^{\varepsilon_{r,\text{over}}} \left[1 - e^{-\frac{1.4 H_{\text{over}}}{H_{\text{sub}}}}\right]$$

$$X \left(\frac{W}{H}\right) + A e^{-\beta \frac{H_{\text{over}}}{H_{\text{sub}}}} \left[1 - e^{-\beta \frac{H_{\text{over}}}{H_{\text{sub}}}}\right] \quad \text{(6.5)}$$

where,
\[ F \left( \frac{W}{H} \right) = \begin{cases} \left[ 1 + 12 \frac{H_{sub}}{W_{line}} \right]^{-0.5} + 0.04 \left( 1 - \frac{W_{line}}{H_{sub}} \right), & \frac{W_{line}}{H_{sub}} < 1 \\ \left[ 1 + 12 \frac{H_{sub}}{W_{line}} \right], & \frac{W_{line}}{H_{sub}} \geq 1 \end{cases} \] 

And,
\[ A = \begin{cases} - \left( \frac{\varepsilon_{\text{eff,over}}}{\varepsilon_{\text{eff,sub}}} - 1 \right) \ln \left( \frac{W_{line}}{H_{sub}} \right), & \frac{\varepsilon_{\text{eff,over}}}{\varepsilon_{\text{eff,sub}}} \leq 1 \\ 0, & \frac{\varepsilon_{\text{eff,over}}}{\varepsilon_{\text{eff,sub}}} > 1 \end{cases} \]

Phase change \( \Delta \phi \) is given by,
\[ \Delta \phi = (360 \left( \sqrt{\varepsilon_{\text{eff,over}}} - \sqrt{\varepsilon_{\text{eff,covered}}} \right) ) L_{\text{over}} \]

\[ L_{\text{over}} = \frac{\lambda_0}{2 \sqrt{\varepsilon_{\text{eff,over}}}} = 0.4210 \text{cm} \]

\[ \lambda_0 = \frac{c}{f_r} = \frac{3 \times 10^8}{13 \times 10^6} = 2.3076 \]

\[ \Delta \phi = (360 \left( 7.5088 - 6.5672 \right) ) 0.4210 \]

\[ \Delta \phi = 61.84 \]

\[ L_{\text{over}} = \text{Length of the overlaid seed} \]
\[ d = \text{Thickness of sample} = 0.40 \text{ cm} \]

The dielectric constant \( \varepsilon' \) and \( \varepsilon'' \) are calculated as,
\[ \varepsilon' = \left( 1 + \frac{\Delta \phi \lambda_0}{360 \times d} \right)^2 \]

\[ \varepsilon' = 3.9642 \]
Using the dielectric loss factor $\varepsilon''$, microwave conductivity was also calculated.

6.4.1 Seed overlay effect on Ag thick film microstripline:

The size of the seed is smaller than the dimensions of the microstripline; therefore, at any position of the seed, the seed will act like partial overlay. Since the seed is kept as overlay the microwaves in the form of fringing field on microstripline interacts with only part of seed and not with the absolute water content of the seed.

When the seed is used as a overlay there is possibility of air gaps present below the overlay. The overlay material does not conform to the conductor contour the seed being oval in shape with rounded contour where as the microstripline has flat contour. The size of the overlay is also smaller than the length of circuit.

Since the seed is placed at the center, the electromagnetic waves suddenly meet a partially perturbed situation with a low dielectric constant. The perturbation seems to be highly frequency dependent. The unevenness of the lower surface of the seed seems to increase the air gaps more causing the fringing field to interact less in the thick film microstripline. The thick film circuits due to its rougher surface may be enhancing these effects. As the moisture content decreases (drying of seed) as expected transmittance increases while as reflectance decreases.

From the results obtained for the permittivity using the microstripline it is seen that the permittivity obtained are in the range expected of these types of moisture laden biomaterials as seeds. Even a non resonant simple microstripline can be used to predict the moisture dependent dielectric constant of seeds.
6.4.2 Seed overlay effect on Ag thick film Equilateral Triangular Microstrip Patch Antenna:

As already mentioned in chapter-IV the Ku band studies were undertaken for the Ag thick film equilateral triangular microstrip patch antenna. When overlay is kept in touch with the antenna it is the radiated field which interacts with the overlay and not the fringing fields as in the microstripline. The electromagnetic field passes through the entire material, so the entire moisture content and other components in the seed are expected to interact. The seeds kept at the different positions on the triangular patch meet concentrated electric field patterns. When an overlay of high permittivity is used, more field lines tend to move towards the overlay [26].

When the overlay is in-touch with the antenna, in the close proximity, the antenna radiation fields exhibits complex characteristics because of reactive component due to the electrostatic zone in the radiated field of the antenna. The high permittivity of water-laden seeds can also increase the magnetic field intensity on the surface of the patch antenna [27]. This increases the possibility of electromagnetic induction which influences the radiated fields. The seeds when they are loaded with water, the size changes from larger than patch to smaller than patch as the seed dries. Since most of the patch is covered by the seed, not much variation in the response of the antenna is observed due to the various position of the seed overlay.

The radiation from the patch passes directly through the seed and also some might pass through the sides. The soybean and groundnut seeds being larger in size show larger dimensional variations during drying. When radiation passes directly through the seed, power is transmitted by multiple internal reflections, the electromagnetic field meeting various dielectric inclusions. When wave passes through the sides they can be diffracted or reflected at the edges of seed. The overlay behaves as a secondary parasitic radiator fed by the patch. At the resonance frequency of the antenna, the changes seem to be more sensitive to moisture content of seed.
The E-plane and H-plane radiation patterns due to the seed overlay generally follow that of without overlay antenna. The beam width of both E-plane and H-plane radiation pattern increases due to the seed overlay (both wet and oven dried) for the thick film patch antenna.

6.5 Prediction of moisture content

6.5.1 Prediction of moisture content using microstripline:

Though the moisture content is a major component in the wave material interaction at micro frequencies, the densities also play a definite role. It is often used as a quality indicator. For moisture content prediction, compensation has to be done for the density effects. The two components of the relative complex permittivity, \( \varepsilon^* = \varepsilon' - j\varepsilon'' \) were determined from measurement of their corresponding scattering coefficients, \( S_{21 \%} \) and \( S_{11 \%} \). Measurements were conducted at the room where the relative humidity and temperature were controlled.

By plotting the graph of dielectric loss (\( \varepsilon'' \)) as a function of the dielectric constant (\( \varepsilon' \)) for three different seeds, soybean, sunflower and groundnuts at a particular frequency for different moisture contents, a cluster of data points is obtained in the complex plane. This gives the distribution of the electric field energy between dissipated and stored energy within the oil seed. It is observed that both dielectric constant and dielectric loss show a slight decrease with increase in frequency while as moisture content increases \( \varepsilon' \) and \( \varepsilon'' \) also increases. The vertical spread of data points is due to the variation of moisture contents.

For higher moisture contents, both \( \varepsilon' \) and \( \varepsilon'' \) decreases more as already mentioned in chapter-III and V. This is to be expected, because when more water is added, it takes longer for water molecule to reach a final stage of binding in the seeds. In fact the time interval reveals the changes of activation energy as the binding modes of water molecules change. At microwave frequencies, water in its liquid form has activation energy of 4.5 Kcal/mol. The single ice crystal has activation energy of 13 Kcal/mol [18]. In each material,
bound water is characterized by a spectrum of activation energies, that lie somewhere between liquid water and that of ice. This uncertainty constitutes a major obstacle in the modeling of the dielectric response of bound water.

When the complex permittivity is normalized to the bulk density and plotted, the slope of straight line is the coefficient $a_f$ which is dependent on the frequency alone [28] and moisture effects are interchangeable. It was also revealed that the frequency change translates into a rotation of the line about the intercept on the $\varepsilon'/\rho$ axis, where, $f$ is the frequency in GHz, $r^2$ is the coefficient of determination for linear regression [Fig. 3.12]

For $a_f$ determination, measurements at one frequency and one moisture content are sufficient. As the frequency increases, the slope decreases. The X-axis intercept is the characteristic of the material and represents the normalized dielectric constant of dry sample. As moisture content increases, the mobility of the water molecules increases, making their contribution to the polarization of the medium higher and increasing the losses at the same time.

After obtaining $\varepsilon'$ and $\varepsilon''$, the calibration permittivity function $\psi$ is computed for each sample at different frequencies and moisture content. The equation governing the various parameters is [29],

$$\psi = \sqrt{\frac{\varepsilon''}{\varepsilon'(a_f\varepsilon'-\varepsilon'')}}$$

6.11

The variation of $\psi$ as a function of moisture content was plotted, the data points for each material lie in the same plane, forming a network of nearly parallel straight lines. The value of $\psi$ increases linearly with moisture content therefore a linear regression of the form $\psi=AM+B$ (here $A$ represents slope of the graph and $B$ represents intercept) can be used to correlate $\psi$ with the moisture content. The value of $(r^2)$ nearer to 1 indicates the higher coefficient of determination.

Linear fitting provides the frequency dependant coefficient ($a_f$), intercept (K) and coefficient of determination ($r^2$). Consequently, a single
calibration equation can be established and used for moisture content determination for all those seeds from the measurement of their dielectric properties at microwave frequencies. The following linear fitting is used to correlate \( \psi \) with moisture content.

**Using microstripline:**

**For Soybean,**

For 13 GHz, \( \Psi = 0.001M_a + 0.173 \) \( r^2 = 0.934 \) 6.12

For 18 GHz, \( \Psi = 0.003M_a + 0.179 \) \( r^2 = 0.891 \) 6.13

**For Sunflower,**

For 13 GHz, \( \Psi = 0.003M_a + 0.331 \) \( r^2 = 0.807 \) 6.14

For 18 GHz, \( \Psi = 0.003M_a + 0.387 \) \( r^2 = 0.656 \) 6.15

**For Groundnut,**

For 13 GHz, \( \Psi = 0.001M_a + 0.106 \) \( r^2 = 0.969 \) 6.16

For 18 GHz, \( \Psi = 0.001M_a + 0.109 \) \( r^2 = 0.966 \) 6.17

Although soybean, sunflower and groundnuts have pronounced differences in shape, dimensions and composition, the coefficients of the fitting equations (6.12 to 6.17) are nearly the same.

(Here, \( M_a \) represents actual moisture content and \( M_p \) represents predicted moisture content).

From equations 6.12 to 6.17 the universal moisture calibration equation is determined as:

**For Soybean,**

For 13 GHz, \( M_p = 490.0 \psi - 83.96 \) \( r^2 = 0.934 \) 6.18

For 18 GHz, \( M_p = 278.3 \psi - 48.13 \) \( r^2 = 0.891 \) 6.19

**For Sunflower,**

For 13 GHz, \( M_p = 219.2 \psi - 68.68 \) \( r^2 = 0.807 \) 6.20

For 18 GHz, \( M_p = 210.3 \psi - 75.48 \) \( r^2 = 0.656 \) 6.21

**For Groundnut,**

For 13 GHz, \( M_p = 734.4 \psi - 75.83 \) \( r^2 = 0.969 \) 6.22

For 18 GHz, \( M_p = 528.7 \psi - 56.67 \) \( r^2 = 0.966 \) 6.23
6.5.2 Prediction of moisture content using waveguide technique i.e. reflectometer and VSWR methods:

The formulations elaborated in the previous article are valid for these two methods also, since the transmittance and reflectance are measured in the reflectometer from which the $\varepsilon'$ and $\varepsilon''$ are obtained. In the VSWR method, the reflectance and position of minima along with the use of Smith chart gives the $\varepsilon'$ and $\varepsilon''$.

In the case of overlay studies one seed was used at a time as overlay, whereas in the waveguide studies a container was filled with seeds. The seeds were assumed to be randomly oriented so that no particular direction for the electric field and material interaction was privileged. The moisture content, bulk density and temperature were assumed uniform throughout the entire volume.

The linear fitting obtained is as given below for soybean seed,

**By waveguide reflectometer method:**

For Soybean,

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Equation</th>
<th>$r^2$</th>
<th>$M_p$</th>
<th>$r^2$</th>
<th>$M_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 GHz</td>
<td>$\Psi = 0.001M_d + 0.087$</td>
<td>0.842</td>
<td>512.8$\Psi - 39.8$</td>
<td>0.842</td>
<td>6.26</td>
</tr>
<tr>
<td>18 GHz</td>
<td>$\Psi = 0.003M_d + 0.075$</td>
<td>0.926</td>
<td>258.3$\Psi - 18.79$</td>
<td>0.926</td>
<td>6.27</td>
</tr>
</tbody>
</table>

**By VSWR slotted section method:**

For Soybean,

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Equation</th>
<th>$r^2$</th>
<th>$M_p$</th>
<th>$r^2$</th>
<th>$M_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 GHz</td>
<td>$\Psi = 0.002M_d + 0.707$</td>
<td>0.407</td>
<td>190.1$\Psi - 116.4$</td>
<td>0.407</td>
<td>6.30</td>
</tr>
<tr>
<td>18 GHz</td>
<td>$\Psi = 0.004M_d + 0.973$</td>
<td>0.721</td>
<td>151.1$\Psi - 138.3$</td>
<td>0.721</td>
<td>6.31</td>
</tr>
</tbody>
</table>
From the graph of predicted moisture content % vs. actual moisture content, it is observed that the data points lie along the straight line that corresponds to the ideal relationship [Fig. 5.13].

6.5.3 Prediction of moisture content using equilateral triangular microstrip patch antenna:

Similar to microstripline, equilateral triangular microstrip patch antenna a resonant component was used to predict moisture content. The resonant frequency \( f_r \), bandwidth \( B \) and quality factor \( Q \) of the triangular patch antenna were used for calibration. The patch antenna in the multilayer (overlay) configuration as a moisture sensor for biomaterials as the seeds has been used. This technique is mainly based on that, when circuit is covered (overlaid) with a dielectric material, its electrical properties are subject to change in accordance with the dielectric constant and thickness of the overlaid material. In the patch antenna, the change is reflected as change in resonating frequency, bandwidth, and quality factor and insertion loss.

Besides being fast and nondestructive like resonant cavity technique, it is miniaturized and loading/unloading of the samples is facilitated by its open structure. For without overlay, the resonant frequency was 17.5 GHz with the bandwidth 130 MHz and quality factor \( Q \) is 134.61.

When the variations of resonant frequency \( f_r \), bandwidth \( B \) and quality factor \( Q \) Vs moisture content increases resonant frequency linearly decreases. Related to bandwidth \( B \), bandwidth increases as moisture content increases, similar to resonant frequency effects are observed for quality factor \( Q \).

Linear fitting equations are obtained. The slope of the linear fit gives the sensitivity of the sensor. The resonance frequency variations give better sensitivity and also better moisture content prediction. The seed is overlaid at the center of microstrip patch antenna. The sensitivity of patch antenna is higher because there is better coupling to the seeds at center. [Fig. 4.17]
The resonant frequency of the patch antenna decreases with the moisture content because as moisture content increases there is an increase in the permittivity (dielectric constant $\varepsilon'$ and dielectric loss factor $\varepsilon''$) of the seeds. The increase in permittivity of the seeds will result in an increase in the effective dielectric constant sensed by the patch antenna, thereby decreasing its resonant frequency. The increase in bandwidth of the patch antenna with moisture content can be attributed to the lossy nature of water in the seeds.

The sensitivity of patch antenna is higher than microstripline and waveguide technique. This is because; size of the seed is comparable small. The fact that there is a more scatter in sensitivity curves with patch antenna. In this work using patch antenna, the uncertainty in the moisture content determination is ~2.53%.

6.5.4 Cole- Cole Plots:

Another way to analyze the data that is of Cole- Cole plot. Cole- Cole plot is used to elucidate the dielectric response of materials with changing physical conditions over a wide frequency range. Fig 6.2 shows Cole-Cole plot corresponding to the various moisture levels of soybean, sunflower and groundnut between 13GHz and 18GHz. From the figure it is shown that, for each moisture content, the data of the six frequencies form an arc in the complex plane, which is the characteristic of the binding state of the water molecules. As frequency increases $\varepsilon'$ and $\varepsilon''$ also slightly decreases.

For each seed although moisture content in the sample the dielectric property responses is higher which reflects the effect of the different stages of water binding and can be interpreted as an apparent higher moisture content. It is observed that water molecules are loosely bound to the constituents of oilseeds in the beginning and then reach a higher level of binding when they reach the equilibrium stages.
**Fig. 6.2** Cole-Cole plots corresponding to the various moisture levels of soybean, sunflower and groundnut between 13 and 18GHz.

### 6.5.5 Comparison of predicted moisture content from the various methods:

The plots of predicted moisture content of the seed obtained from overlay method (microstripline), waveguide method and VSWR method are plotted in Fig. 6.3.

From the figure it is seen that, VSWR slotted section technique is more sensitive than the simple microstripline and waveguide reflectometer. For higher moisture content, large variations in scatters (seeds) are obtained while...
for lower moisture content it is less. The difference between actual moisture content and predicted moisture content is higher for higher moisture content.

**Fig. 6.3** Predicted moisture content versus actual moisture content for soybean, sunflower and groundnut by various methods at 13 GHz frequency.

**Fig.6.4** shows predicted moisture content versus actual moisture content for soybean, sunflower and groundnut at resonance frequency (GHz) using patch antenna. From the figure, it is seen that the slope of linear fit gives the sensitivity of equilateral triangular microstrip patch antenna as a moisture sensor for soybean, sunflower and groundnut. The resonance frequency of the
Fig. 6.4 Predicted moisture content versus actual moisture content for soybean, sunflower and groundnut at resonance frequency (GHz).

The equilateral triangular microstrip patch antenna decreases with moisture content. This is because as moisture content increases there is an increase in the $\varepsilon_r$ of the seeds. This increase in $\varepsilon_r$ of the seed will result in an increase in effective $\varepsilon_r$ sensed by the patch antenna, thereby decreasing its $f_r$.

The errors in the moisture content measurements are tabulated in table 6.1. From the table it is seen that, equilateral triangular microstrip patch antenna shows the higher sensitivity than other techniques. This is because, the size of the seed is comparable to the size of the patch antenna, whereas in microstripline, waveguide and VSWR sensor, it is relatively quite small. The
accuracy of the patch antenna can be improved by taking better account of the effects of the seed shape and size.

**Table 6.1: Error in % moisture content**

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Type of technique</th>
<th>Error in % moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ag thick film Microstripline</td>
<td>~ 2.26</td>
</tr>
<tr>
<td>2</td>
<td>Ag thick film Equilateral Triangular Microstrip patch antenna</td>
<td>~ 1.04</td>
</tr>
<tr>
<td>3</td>
<td>Waveguide reflectometer</td>
<td>~ 2.43</td>
</tr>
<tr>
<td>4</td>
<td>VSWR slotted section</td>
<td>~ 1.08</td>
</tr>
</tbody>
</table>

**6.6 Error Analysis:**

Errors in overlay and waveguide technique measurements for prediction of moisture content are caused by imperfection in the measuring system, mismatches, diffraction at the edges of sample and multiple reflections. For particulate, materials depending on the size and geometry of the particles scattering can be an additional factor. Some of these errors can be minimized by using calibration, selection of the best matching conditions between the different parts of the measuring system (connectors, adaptors, cables, antennas, and resonators) and selection of the transverse dimensions and the thickness of the samples. However, some of them have random character and therefore they are unpredictable.

Accuracies of determinations of moisture content from microwave permittivity measurements critically depends upon the accuracy with which the dielectric constant ($\varepsilon'$) and dielectric loss factor ($\varepsilon''$) are determined and thus the accuracy with which the phase change ($\Delta\phi$) and attenuation ($\Delta A$) can be measured. Errors in the transmission measurements have various natures and sources. Error analysis is focused on errors mainly related to phase change ($\Delta\phi$) and attenuation ($\Delta A$) measurements.
Attenuation measurements are affected by diffraction at the edges of the sample, multiple reflections and scattering by the particles. Diffraction at the edges can be minimized by making the sample in large quantity that it ‘appears’ laterally infinite to the incident and diffused waves. Usually a transverse dimension of the sample of about three times the E - plane 3dB beam width of antenna is enough [30].

This works well if free space measurements are done. In the case of overlay method the size of sample (seed) in most cases is smaller than the component. Multiple reflections occur inside the sample, between the sample interfaces and the antenna and the antenna through the sample.

At a given thickness, the apparent nonlinearities of the attenuation and phase change with moisture content are mainly related to difference in bulk density of the seed at different moisture contents. The oscillations in the attenuation due multiple reflections are drastically reduced. Effects of multiple reflections between the sample interfaces and the antennas through the sample are reduced by selecting the best conditions for matching of various components of the measuring system.

The scattering by the particle is mainly dependent on the size geometry and moisture content of the individual seeds and increases with the frequency. The shape of the seeds ranged from nearly spherical to ellipsoidal with dimensions corresponding to $\lambda_d/4$ and $\lambda_d/2$ at some frequencies. For higher moisture content of seeds, the permittivity is higher and the difference between the scatter (seeds) is also greater and the host background material (air, $\varepsilon=1$). On the bulk material scale, the scattering is also dependent on the layer thickness (in waveguide) and bulk density of the seed. All these factors combined together influence the scattering and thus make it difficult to quantify or predict how it will affect the attenuation measurements. The imaginary part of effective permittivity is composed of two terms, absorption and scattering. Due to reflection and scattering, frequency increases.

For phase shift measurements, the effect of multiple reflections is not evident. The changes in the seed thickness as the sample is compacted or in the
angle of incident when sample is placed may produce errors that are not negligible.

6.7 Summary
Oilseeds form a major constituent of agricultural and food sector. Biogranular material is a complex random dense medium consisting of mixtures of components with various dielectric behaviour. Moisture content of seed is the most important characteristic used for quality assessment and process control. In agriculture, determination of moisture content of seed is needed for decision making during harvest handling, safe storage and in trade. At microwave frequencies, water in moist substances play a major role in the polarization phenomenon.

In this work, an effort has been made towards a evaluation of dielectric properties of moisture laden seeds and prediction of moisture content. The basic aim was to find a suitable microwave circuit most sensitive to predict moisture content of seeds using the microwave response of Ag thick film microstrip components, waveguide reflectometer and VSWR slotted section. The overlay technique has been used in this lab previously to study dielectric materials in thin film, thick film and bulk forms. By using Ag thick film microstrip components, waveguide reflectometer and VSWR slotted section method the dielectric characterization and prediction of moisture content of seed is being reported for the first time in the Ku band.

Extensive experimental work in the Ku band frequency range 13-18 GHz on the effects of position, type and moisture content of the seeds on two types of Ag thick film microstrip components, waveguide reflectometer and VSWR slotted section method is reported in this work. Dielectric characterization, microwave conductivity and impedance using waveguide methods are also reported. The three types of the seeds have been used. In the present work two types of microstrip components -Ag thick film simple microstripline and Ag thick film equilateral triangular microstrip patch antenna have been used.
The designing and fabrication work was done in the thick and thin film device laboratory, Department of physics, Shivaji University, Kolhapur itself. All these circuits were delineated using thick film technology.

Three types of seeds were studied. The seeds were –

1. Soybean (Glycine Max)
2. Sunflower (Helianthus Annuus)
3. Groundnut (Archies Hypogaea)

The dielectric properties of the oilseeds are intrinsic properties that describe the wave-matter interaction and also dependent on internal properties of the material including its moisture content, salt content, density and temperature. The permittivity is the effective permittivity of a mixture of components with different dielectric behaviours.

Chapter-I includes the relevant literature survey and theoretical consideration of microstrip components. The range of microwave frequency also useful for agricultural purposes is explained. The techniques for microwave measurements of materials such as transmission and reflection parameter, rectangular waveguide, cavity resonant technique, slotted line, overlay technique and impedance bridge method are explained and a brief review of microstrip components with overlay is done.

On reviewing the literature, it is found that there are only few reports especially in the Ku band on the use of microstrip components for study of seeds. Use of Ag thick film microstrip component for biomaterial study has not been reported. Prediction of moisture content by using thick film microstripline components, waveguide reflectometer and VSWR slotted section method has been studied for the first time.

Chapter-II explains the experimental details of microstripline overlay studies on seeds. The brief description of the seeds used in the study is given. Sample preparation, characteristics of the seeds and data of different seed conditions in % of moisture content is also given. The actual fabrication of Ag thick film equilateral triangular microstrip patch antenna is described. The design equation of triangular patch antenna and design parameters are given.
The experimental set up for microwave measurement of the waveguide reflectometer method and VSWR slotted section technique is also explained here. The following characterization techniques were used.

1. Infrared Spectroscopy
2. Morphology using SEM

Dielectric characterization and prediction of moisture content using permittivity data is described.

Chapter-III describes the use of overlay method on the simple microstripline to predict permittivity, conductivity and moisture content of oilseeds, when used as overlay. The seeds studied were obtained from the fields of Krishna Valley at Sangli district in Maharashtra state of India (June-Sept.2006). The experiment was carried out at least 7-8 times using three identical microstripline. Following six types of measurements were done.

(1) **P1**: seed at odd mode (\( \phi = 90^\circ \)) means the length of seed is perpendicular to the microstripline.

(2) **P2**: seed at even mode (\( \phi = 0^\circ \)) means the length of seed is parallel to the direction of propagation in the microstripline.

(3) **P3**: seed making angle 45\(^\circ\) with the strip towards input direction.

(4) **P4**: seed making angle 45\(^\circ\) with the strip towards output direction.

(5) **P5**: seed at odd mode position (\( \phi = 90^\circ \)) and nearer to the input direction.

(6) **P6**: seed at odd mode position (\( \phi = 90^\circ \)) and nearer to the output direction.

The seed was held in place with pressure block of thermocol on it to ensure better contact between circuit and seed and to avoid air gap. The thermocol block did not change the characteristics of microstripline when placed over them. Initially for the thick film microstripline, the characteristics in the Ku band were studied without overlay.

From the results it is seen that the microstripline designed give the average transmittance is between 0.6 and 0.7 and reflectance is between 0.03-0.05. In general, the transmittance of the microstripline decreases and reflectance increases due to moisture laden soybean, sunflower and groundnut seed overlay. The microstripline response becomes oscillatory due to the seed...
overlay. The transmittance and reflectance characteristics of the Ag thick film microstripline due to soybean, sunflower and groundnut seed overlay shows similar response which change in the values. Due to different positions of the seed, the reflectance of the microstripline is almost same for each seed.

The perturbation in transmission and reflection due to seed overlay with error bar indicates that groundnut seeds shows more error while a sunflower shows less.

The dielectric characterization of the seeds due to phase change and attenuation is also reported. As moisture content increases dielectric constant ($\varepsilon'$) and dielectric loss factor ($\varepsilon''$) also increases. All these seeds exhibits low dielectric constant and are in the range reported using other techniques. The values of microwave conductivity lie between $\sim$0.04-1.4S/cm. Prediction of moisture and standard error of performance (SEP) is also given here. As moisture content increases SEP increases and also it increases with frequency.

Similar to studies on microstriplines, Ag thick film equilateral triangular microstrip patch antenna in the frequency range 13-18 GHz was investigated and is given in chapter IV. The microstrip patch antenna was used a transmitting antenna and horn antenna fixed in a rotating stand was used as receiving antenna. The following characteristics of the patch antenna were studied.

(a) % power efficiency as a function of frequency
(b) Reflected output as a function of frequency
(c) Dielectric characterization
(d) E-plane and H-plane radiation pattern, and
(e) Prediction of moisture content using resonance frequency ($f_r$), bandwidth (B) and quality factor (Q)

The equilateral triangular microstrip patch antenna without overlay showed a single peak at 17.5 GHz with the peak amplitude of $\sim$37.44%. The reflectance was low at the resonance frequency though between 15.5 to 16.5 GHz split resonance peaks were obtained with % power efficiency $\sim$12%. The E plane radiation pattern of thick film antenna is symmetric whereas for the H
plane pattern is asymmetric. The radiated power is almost zero at -90° and +90°.

Due to moisture laden seed overlay and also oven dried overlay of all types of seeds and all positions there is shift in resonance frequency of antenna. When fully soaked seed is used as overlay, % of power efficiency decreases. As the seed dried the amplitude of resonance peak increases. This effect is observed for all the positions.

For patch antenna five types of measurements were conducted for each case-

(1) **P1**: Seed overlay on the center of patch
(2) **P2**: Seed overlay on the right side vertex of the patch
(3) **P3**: Seed overlay on the top side vertex of the patch
(4) **P4**: Seed overlay on the left side vertex of the patch
(5) **P5**: Seed overlay on the microstrip feed line

Due to higher moisture content of all those seeds, antenna shifts to 17.2 GHz with peak amplitude ~24% and band width becomes larger. Due to the dried seed overlay the resonance peak shifts towards higher frequency side and bandwidth becomes smaller. The E-plane and H-plane radiation patterns were investigated at the resonance frequency. The radiation pattern showed split in maxima. E-plane radiation pattern showed less amplitude than H-plane. Due to seed overlay amplitude increases in both planes. For the groundnut overlay, peak transmittance of antenna showed higher value while lesser for sunflower.

The dielectric characterization was done by overlay method. As moisture content decreases $\varepsilon'$ and $\varepsilon''$ also decreases and penetration depth increases. For groundnut seed penetration depth is higher while less for sunflower. By using linear fitting for resonance frequency ($f_r$), band width (B) and quality factor (Q), moisture prediction was done.

The results obtained by using the waveguide reflectometer technique and VSWR technique are elaborated in chapter V. From the changes in the transmission and reflection coefficients using the equation relating characteristic impedance and reflection coefficient, the phase of the reflected
waves was found and the dielectric constant ($\varepsilon'$) and dielectric loss factor ($\varepsilon''$) were calculated. The microwave conductivity was obtained using Nelson’s formula. Using double minima method also the permittivity of the seeds was calculated.

Similar to microstripline, moisture content was predicted using waveguide reflectometer and VSWR slotted section technique. The dielectric constant ($\varepsilon'$) and dielectric loss factor ($\varepsilon''$) is smaller than obtained from waveguide reflectometer method. All the components showed moisture dependant effects.

The consolidated discussion of all the results of chapter III, IV and V is given in chapter VI along with summary and conclusion. Comparing all these methods, equilateral triangular microstrip patch antenna showed higher moisture sensitivity while waveguide reflectometer showed the least. The dielectric constant and loss factor of moisture laden seeds are generally dependant on frequency, density, moisture content, temperature and other factors such as the composition of seed, and binding modes of water molecules. Bound water is major in the range of low moisture content and free water is major in a high water range. The complex permittivity is a measure of the ability of material to polarize when subject to an electric field. The real part is dependent on phase change ($\Delta\Phi$) and imaginary part on the change in amplitude ($\Delta A$). The value of $\varepsilon'$ oven dried seeds are quite low ~ 2.

### 6.8 Conclusions

Our results have shown that the overlay technique for studying the moisture laden seeds compare very well with other techniques like free space technique, waveguide reflectometer, VSWR and cavity perturbation etc. Microstrip offers an open structure, the easy loading and unloading of sample is possible. The dielectric characterization of the seeds has been done using overlay technique, waveguide reflectometer and VSWR slotted section method. The result shows that all the microstrip components are sensitive to the presence of overlay on it. The sensitivity of the Ag thick film equilateral
triangular microstrip patch antenna is more than the microstripline, waveguide and VSWR method.

A non resonant Ag thick film microstripline and resonant Ag thick film equilateral triangular microstrip patch antenna has been used for the first time to study the permittivity of the overlaid material. \( \varepsilon' \) and \( \varepsilon'' \) shows different values. This indicates that the circuits show different reactions to the variation in the moisture content in the seed overlay.

The rapid nondestructive and reliable sensing of moisture content in seeds and other agricultural crops is essential in modern agriculture for prevention of losses and improvements in efficiency of production of these sources of food. Measurement of the dielectric properties at microwave frequencies offers advantages that the density independent sensing of the moisture content and the reduction of variations which arise from ionic conductivity of high moisture laden seeds. Results shown for soybean, sunflower and groundnuts at 13GHz and 18GHz indicate that moisture content can be predicted in all materials from a single calibration equation.

**6.9 Scope for future work**

1. Theoretical analysis of overlaid microstrip circuits especially the equilateral triangular microstrip patch antenna should be undertaken.
2. A universal moisture calibration should encourage the development of microwave measurement systems for on-line moisture sensing for oilseeds and other granular materials.
3. Efforts have to be made using the miniaturize microstrip components to fabricate a hand held moisture sensor for insitu moisture and dielectric measurement during storage of the seeds.
REFERENCES


