CHAPTER III

RECTANGULAR PATCH ANTENNA ON SINGLE LAYER AND GRADED COMPOSITE SUBSTRATE

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Adaptation of different patch geometries to achieve broadband operation of microstrip antenna on customized composite substrate in X-band
3.1 INTRODUCTION

This chapter describes studies on the developed composite materials for their applicability as substrates for microstrip antennas. Rectangular patch is the simplest geometry to design [1-5] and hence, a rectangular radiator is designed and analyzed on the composite material. The performance is analyzed by varying the material properties of the composite.

Complex permittivity of substrate material plays a critical role in antenna operation. By varying the substrate permittivity, one can control the size of the radiator and radiation performance of microstrip antennas [13-18]. Substrate material with low permittivity may be used to increase the bandwidth of operation, but very low permittivity material increases the dimensions of the microstrip patch antenna (MPA), which poses difficulty for use in handheld devices. Increase in permittivity of the substrate material increases the Q of the antenna and hence its impedance bandwidth is reduced [3, 10]. With a view to increase the bandwidth and directivity of operation of rectangular patch antenna without increasing the complexity in design and patch dimensions, substrate grading is investigated. This may also suppress the surface wave propagation.

3.2 DESIGN AND FABRICATION OF RECTANGULAR PATCH MICROSTRIP ANTENNA

Rectangular patch antennas are designed using transmission line model (TLM) [7-9]. The dimensions of the radiating patch can be estimated using this technique.

3.2.1 Design formulation of rectangular patch

TLM represents the microstrip antenna as two slots of width \( W \) and height \( h \), separated by a transmission line of length \( L \) [7-9] as shown in figure 3.1 (a). The dielectric constant, \( \varepsilon_r \) (real part of complex permittivity) is an important parameter in calculating these two dimensions.
The value of effective dielectric constant \( \varepsilon_{\text{reff}} \) can be expressed as [10]:

\[
\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \left( \frac{h}{W} \right)^2 \right]^{\frac{1}{2}}
\]  

(3.1)

where, \( \varepsilon_r \) stands for dielectric constant of substrate, \( h \) represents height of dielectric substrate, and \( W \) is the width of the patch.

![Diagram of microstrip antenna](image)

Figure 3.1  
(a) Coaxially fed microstrip antenna  
(b) Top view of the antenna  
(c) Cross sectional view of the antenna

The edges along the width are the two radiating slots, which are ‘L’ distance apart and excited in phase and radiating in the space above the ground plane. The fringing fields along the width can be modeled as radiating slots and electrically the patch of the microstrip antenna looks greater than its physical dimensions (figure 3.1 (b–c)). The dimensions of the patch along its length have now been extended on each end by a distance \( \Delta L \), which is given empirically by Hammerstad [8] as,
The effective length of the patch $L_{eff}$ now becomes,

$$L_{eff} = L + \Delta L$$

(3.3)

For a given resonance frequency $f_0$, the effective length is given in [7] as

$$L_{eff} = \frac{c}{2f_0 \sqrt{\varepsilon_{reff}}}$$

(3.4)

For efficient radiation, the width $W$ can be represented as [9]

$$W = \frac{c}{2f_0 \sqrt{\frac{\varepsilon_r + 1}{2}}}$$

(3.5)

The patch dimension is calculated using equations 3.1-3.5. The dimensions are further optimized using numerical simulations to obtain the desired antenna performance.

### 3.2.2 Determination of feed point

The rectangular patch antenna is fed coaxially at the point where the input impedance is 50 $\Omega$. The location of the feed point can be found out using the two slot model for microstrip antenna [7-12].

The resonant radiation conductance $G_r$ for a patch fed at an edge can be determined from the radiated power as

$$P_r = \frac{1}{2} G_r (E_0 h)^2 = \frac{1}{2} G_r V_0^2$$

(3.6)

$$R_r = \frac{1}{G_r}$$

(3.7)

Where, $R_r$ is the radiation resistance.

The expressions for $R_r$ with an estimated accuracy of 10 % average for $h \leq 0.03\lambda_0$ and $\varepsilon_r \leq 5$ can be expressed as,

$$R_r = \frac{V_0^2}{2P_r} = \varepsilon_{reff} \frac{Z_0^2}{120I^2}$$

(3.8)
Where, \( Z_0 \) is the characteristic impedance of the microstrip line of which the patch is a segment and

\[
I_2 = (k_0 h)^2 \left[ 0.53 - 0.03795 \left( k_0 \frac{W}{2} \right)^2 - 0.03553 \frac{1}{\varepsilon_{\text{eff}}} \right]
\]

(3.9)

where, \( k_0 = \frac{2\pi}{\lambda_0} \) is the wave number.

If the patch is fed at a distance \( x_f \) from one of the radiating edges, the input resistance can be expressed as,

\[
R_{\text{in}} = R_r \cos^2 \left( \frac{\pi x_f}{L} \right)
\]

(3.10)

The distance, \( x_f \), is selected such that the value of \( R_{\text{in}} \) is equal to the feed line impedance, usually taken to be 50 Ω. The y position of the feed can be taken at any point along the width of the patch which is usually taken to be \( W/2 \).

The approximate dimensions calculated using TLM technique are further optimized using numerical modeling software CST Microwave Studio.

3.2.3 Software for numerical simulation

Computer-aided design (CAD) is emerging as a norm in microstrip antenna design. This is because the use of such softwares helps to reduce development time by serving as a tool in the design process. Another reason is the increase in complexity in designs where accurate prediction of system performance can only be made with the help of CAD software packages.

In this work, CST Microwave Studio is used to model microstrip antenna structures. CST Microwave Studio is a full-featured software package for electromagnetic analysis and design in the high frequency range. It simplifies the process of analyzing the structure by providing a powerful solid 3D modeling. After the component has been modeled, a fully automatic meshing procedure is applied before the simulation process is started. CST Microwave Studio is part of the CST Design Studio Suite.

Since no method works equally well in all the application domains, the software contains four different simulation techniques (transient solver,
frequency domain solver, integral equation solver, eigenmode solver) to best fit the particular application. The most flexible tool is the transient solver, which can obtain the entire broadband frequency behavior of the simulated structure from only one computation run (in contrast to the frequency step approach of many other simulators). It is based on the Finite Integration Technique (FIT). All the simulations in this work are done in transient solver mode to cover the entire X-band.

3.3 ANTENNA PERFORMANCE MEASUREMENT SET UP

To analyze the performance of an antenna, $S_{11}$ and radiation pattern measurements are to be carried out on the fabricated antennas. The set ups for measurement are described below.

3.3.1 $S_{11}$ measurement set up

$S_{11}$ measurements are carried out over the X-band using Agilent PNA series vector network analyzer (VNA) E8362C.

Calibration of the VNA is done using Agilent 85052 D calibration kit. The actual reflection coefficient is found from the measured value using equation [13].

$$S_{11M} = E + E_{RT} \left[ \frac{S_{11A}}{1 - E_S S_{11A}} \right]$$

(3.11)

Schematic for the measurement is shown in figure 3.2.

![Schematic of S11 measurement scheme](image)

**Figure 3.2** Schematic of $S_{11}$ measurement scheme

There are three systematic errors. In order to solve the individual error terms, measurement of three known calibration standards is carried out: a
short, an open, and a broad band load ($Z_0$). Calibrated value is stored in the system and used to solve the equations 3.11 yielding the systematic error terms and this allows deriving the actual $S_{11}$ parameter of the antenna from measurements.

All the antennas for measurement are fed coaxially. The photograph of the measurement system is shown in figure 3.3.

![Antenna S11 measurement setup using VNA](image)

**Figure 3.3** Antenna $S_{11}$ measurement setup using VNA

### 3.3.2 Radiation pattern measurement setup

The E-plane and H-plane radiation pattern measurements are carried out using an automated measurement setup with a PC controlled turn table figure 3.4. An Agilent MXG-N5183A signal generator is used as the source to feed the transmitting X-band horn antenna while the received power from the test antenna mounted on the PC controlled turn table is measured by Anritsu spectrum analyzer. The system is calibrated using two standard horn antenna in receiving and transmitting ends.
Radiation pattern measurements are taken in open space so that the effect of reflection of microwave signals from the walls can be avoided.

![Antenna radiation pattern measurement set up](image)

**Figure 3.4** Antenna radiation pattern measurement set up

### 3.3.3 Calculation of Directivity

The directivity ($D$) is calculated from the radiation pattern as [15],

$$D \approx \frac{32400}{\Theta_{1d} \Theta_{2d}}$$

(3.12)

Where, $\Theta_{1d}$ is the half power beamwidth in E-plane and $\Theta_{2d}$ is the half power beamwidth in H-plane. $D$ is a unitless quantity and is expressed in dBi as [16],

$$D_{dBi} = 10 \cdot \log_{10} [D]$$

(3.13)

### 3.4 Fabrication and Measurements of Rectangular Patch Microstrip Antenna on Single Layer Composite Substrate

#### 3.4.1 Preparation of substrate for microstrip antenna

The synthesis process of polymer composite material, described in Chapter II, in the final stage, the material with different VF is casted on a
square mold of dimension 4 cm × 4 cm × 2 mm. Rectangular patch antenna is fabricated on 2 % VF of alumina in LDPE and 2 % VF of titania in LDPE composite substrates. The samples are chosen, as the permittivity value of these composites lies almost midway to the values of pure LDPE and composites with 6 % VF of the inclusions in the matrix. Dielectric parameters of the composites and the optimized antenna dimensions are given in table 3.1.

The antennas are fed coaxially at 50 Ω impedance matching point, which is at 2.1 mm from the radiating edge for the microstrip antenna with dimension as given in the table 3.1. Figure 3.5 (b) shows the fabricated antenna on composite substrate. Performance studies of the fabricated antennas are carried out in the X-band of microwave frequencies.

**Table 3.1** Optimized Design parameters of rectangular microstrip antenna on LDPE/alumina and LDPE/titania composite substrate at 10 GHz

<table>
<thead>
<tr>
<th>Substrate</th>
<th>$\varepsilon'$</th>
<th>$\varepsilon''$</th>
<th>$f_0$(GHz)</th>
<th>$h$ (mm)</th>
<th>$W$ (mm)</th>
<th>$L$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2% VF of alumina in LDPE</td>
<td>2.14</td>
<td>0.0011</td>
<td>10</td>
<td>2</td>
<td>11.9</td>
<td>8.6</td>
</tr>
<tr>
<td>2% VF of titania in LDPE</td>
<td>2.23</td>
<td>0.0036</td>
<td>10</td>
<td>2</td>
<td>11.4</td>
<td>8.3</td>
</tr>
</tbody>
</table>

**Figure 3.5**

(a) Layout of a coaxially fed microstrip antenna
(b) Coaxially fed microstrip antenna fabricated on composite substrate.
3.4.2 Fabrication of microstrip patch antenna

Radiating patches of dimensions given in table 3.1 is fabricated on the composite substrates. The fabrication of copper patch on the dielectric composite substrate is performed in two steps by rolling technique [14], as described in the following paragraphs.

In the first step of the process, the substrate is thoroughly cleaned with acetone to remove oil and grime from the surface. Subsequently, the substrate is dried at 30 °C in a vacuum oven. A thin layer of cyanoacrylate epoxy resin (CER), of thickness less than 20 micron (99.95% less than the probing wavelength), is used on both sides of the substrate as an adhesive. It is observed with the cavity resonator method that the loaded frequency of the substrate does not shift its position on brushing thin layer of CER adhesive on both sides of the substrate. Copper sheet of thickness 0.4 mm is placed on both sides of the substrate, and rolled at pressure 6 torr for one hour, to obtain the metalized substrate.

Both sides of the metalized substrate are masked with an adhesive tape. The artwork of microstrip patch in accordance with the design formulae (table 3.1) is drawn on one surface of the masked substrate by specially designed sharp tool with precision of 0.02 mm attached to milling machine whose least count is 0.002 mm. The adhesive tape from all the side of the microstrip patch drawn is peeled off and is dipped in a slightly acidic ferric chloride (FeCl₃ + HCl) bath. Ferric chloride solution is continuously stirred for uniform etching of the copper. To prevent the sample from over etching, which may cause corroded edge of the microstrip patch, the concentration of ferric chloride solution is gradually reduced with time. The whole system is then taken out from the solution and washed with distilled water to remove any traces of ferric chloride solution. The tape on the bottom side is lifted carefully to release ground plane side. To determine any discrepancies in the
line pattern, the microstrip patch is observed under a microscope of least count 0.01 mm. This process of transferring artwork on the substrate, avoids the underneath etching of copper, thus keeping the dimension of the patch accurate and hence the frequency of operation remains same as designed.

Antenna performance measurements are carried out on the rectangular patch antennas fabricated on LDPE/alumina and LDPE/titania composites in X-band.

3.4.3 $S_{11}$ parameter and radiation pattern studies for rectangular patch antenna

Figure 3.6 – 3.7 gives the measured and simulated $S_{11}$ results for rectangular patch antennas on the 2 % VF of alumina in LDPE and 2 % VF of titania in LDPE composite substrates.

![Figure 3.6](image)

**Figure 3.6** Measured and simulated $S_{11}$ results for rectangular patch antenna on 2 % VF of alumina in LDPE composite substrate
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Rectangular patch antenna on single layer and graded composite substrate

Adaptation of different patch geometries to achieve broadband operation of microstrip antenna on customized composite substrate in X-band

Figure 3.7  Measured and simulated $S_{11}$ results for rectangular patch antenna on 2 % VF of titania in LDPE composite substrate

Figure 3.8 - 3.9 show radiation pattern in E and H plane of microstrip antenna fabricated on LDPE/alumina and LDPE/titania composites.

Figure 3.8  Measured (a) E-plane and (b) H-plane radiation pattern of rectangular patch antenna on 2 % VF of alumina in LDPE composite substrate

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Figure 3.9  Measured (a) E-plane and (b) H-plane radiation pattern of rectangular patch antenna on 2% VF of titania in LDPE composite substrate

Comparison of $S_{11}$ parameter of microstrip antennas on LDPE/Titania and LDPE/alumina substrates are shown in figure 3.10.

Figure 3.10  Measured $S_{11}$ results for rectangular patch antenna on LDPE/alumina and LDPE/titania composite substrates
The performance parameters determined from the $S_{11}$ measurement and radiation pattern studies are tabulated in table 3.2.

**Table 3.2** Antenna performance parameters

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Patch dimension (mm²)</th>
<th>Ground plane dimension (mm²)</th>
<th>Resonating frequency (GHz)</th>
<th>$S_{11}$ at center frequency (dB)</th>
<th>-10 dB operational bandwidth</th>
<th>Directivity (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 % VF of alumina in LDPE</td>
<td>Expt 11.9 × 8.6</td>
<td>35 × 30</td>
<td>10.06</td>
<td>-24.52</td>
<td>5.6 %</td>
<td>5.91</td>
</tr>
<tr>
<td></td>
<td>Sim 11.9 × 8.6</td>
<td>35 × 30</td>
<td>10.00</td>
<td>-22.5</td>
<td>5.8%</td>
<td>-</td>
</tr>
<tr>
<td>2 % VF of titania in LDPE</td>
<td>Expt 11.4 × 8.3</td>
<td>35 × 30</td>
<td>10.04</td>
<td>-29.1</td>
<td>6 %</td>
<td>6.29</td>
</tr>
<tr>
<td></td>
<td>Sim 11.4 × 8.3</td>
<td>35 × 30</td>
<td>10.00</td>
<td>-22.5</td>
<td>6.1%</td>
<td>-</td>
</tr>
</tbody>
</table>

Antenna designed on titania in LDPE substrate shows better $S_{11}$ characteristics and directivity (table 3.2) than alumina in LDPE substrate. For further investigations, LDPE/titania is used as substrates for microstrip antennas. Moreover addition of a small amount of titania in the matrix can sufficiently alter the dielectric properties of the composite as compared to the addition of same amount of alumina in the matrix.

**3.5 DESIGN AND FABRICATION OF RECTANGULAR PATCH MICROSTRIP ANTENNA ON GRADED COMPOSITE SUBSTRATE**

MPA with graded layer substrate is investigated for enhancement of return loss and band width of operation. Unlike other multilayer structure reported in [17-21], the permittivity of the substrate immediately below the radiator is kept lowest, increasing towards the ground plane (figure 3.10). To obtain the variation in permittivity in the layers, percentage volume fraction of titania is changed for the different layers in the substrate. Percentage volume fraction of titania is increased in the subsequent layers below, to give a graded permittivity substrate structure.
3.5.1 Fabrication of graded composite substrate

The graded composite substrate is synthesized using different layers of composite material with different VF of filler. Figure 3.11 shows the schematic of the microstrip antenna on graded substrate. Layer 1 (0.5 mm thick) is of 4 % VF of TiO$_2$ in LDPE, layer 2 (0.5 mm thick) is of 3 % VF of TiO$_2$ in LDPE and layer 3 is of 2 % VF of TiO$_2$ in LDPE (1 mm thick). Individual layers of required thickness are fabricated separately using the process described in the chapter II. The three layers are compressed under pressure of up to 0.3 kg/cm$^2$ in a compression mould and temperature is slowly increased till 90 °C, just enough for the layer to coalesce into a uniform structure without losing its form. The temperature is immediately reduced thereafter so that a smooth transition of grading is obtained without affecting the concentration of inclusions across the boundaries and hence the permittivity of individual layers.

To verify that the thickness of the layers does not change during the graded substrate formation, the relative dielectric permittivity of the graded substrate structure ($\varepsilon_{rc}$) is calculated using the multilayer formulation as used in [22, 23] and compared with experimental results. The theoretical relative dielectric permittivity for three layer substrate is expressed as,

$$\varepsilon_{rc} = \frac{\sum_{i=1}^{3} h_i}{\sum_{i=1}^{3} \frac{h_i}{\varepsilon_{ri}}}$$

(3.14)
where $h_i$ is the height of the $i^{th}$ layer and $\varepsilon_{ri}$ is the dielectric permittivity of the $i^{th}$ layer. Using the permittivity values for different composites as determined in chapter II (section 2.5.2) $\varepsilon_{rc}$ is calculated using equation 3.14. The experimental results for permittivity determined for graded substrate using Nicolson-Ross method is almost same (99.9 % accurate) as that calculated for three layer geometry using equation 3.14. The measured and calculated relative permittivity is plotted in figure 3.12. The result indicates that during graded substrate formation the thickness of individual layer remains the same, as expected.

![Figure 3.12](image.png)

**Figure 3.12** Calculated and measured permittivity for the graded substrate

### 3.5.2 Design of rectangular patch antenna on graded composite substrate

A rectangular microstrip patch antenna on the developed substrate is designed at 10 GHz using the equations 3.1-3.7 and then optimized using CST Microwave studio. The geometry of the radiator is determined using permittivity value, $\varepsilon_{ro}$ of the graded substrate in transmission line model. The
dimension of the radiator patch is found to be 11.2 mm × 8.1 mm. The antennas are fed coaxially at 50 Ω impedance matched point.

3.5.3 $S_{11}$ and radiation pattern measurement for the rectangular patch antenna on graded substrate

Figure 3.13 shows the simulated and measured $S_{11}$ characteristics of the rectangular patch antenna fabricated on graded composite substrate. The measured resonant frequency is shifted by 0.1 GHz from the simulated value.

![Graph](image.png)

**Figure 3.13** Simulated and measured $S_{11}$ results for rectangular patch antenna on graded substrate

The performance of the antenna fabricated on graded substrate is compared with MPAs designed at same frequency but fabricated on single composition viz. 2 %, 3 % and 4 % VF of TiO$_2$ in LDPE substrate (figure 3.14). The height of substrate is kept same for all the four MPAs i.e. 2 mm. Comparison of performance of all the antennas is given in table 3.3.
Figure 3.14  Comparison of measured \( S_{11} \) results for rectangular patch antenna on different substrate.

Radiation patterns are measured at 10 GHz. Co polar and cross polar E-plane and H-plane patterns are shown in figure 3.15 (a-b).

Figure 3.15  Measured (a) E-plane and (b) H-plane radiation pattern of rectangular patch antenna on graded composite substrate.
From the E-plane and H-plane measured patterns, the directivity of the rectangular patch antenna on grade substrate at 10 GHz is found out to be 9.91 dBi. Table 3.3 compares the performance of rectangular patch antenna designed at 10 GHz on different substrates.

**Table 3.3** $S_{11}$ parameter result comparison

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Permittivity at 10 GHz</th>
<th>Patch dimension (mm$^2$)</th>
<th>Resonating frequency (GHz)</th>
<th>$S_{11}$ at the resonating frequency (dB)</th>
<th>-10dB bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2% VF of titania in LDPE</td>
<td>2.23</td>
<td>11.4 x 8.3</td>
<td>10.06</td>
<td>-29</td>
<td>6.06 %</td>
</tr>
<tr>
<td>3% VF of titania in LDPE</td>
<td>2.28</td>
<td>11.2 x 8.1</td>
<td>10.04</td>
<td>-26.8</td>
<td>5.87 %</td>
</tr>
<tr>
<td>4% VF of titania in LDPE</td>
<td>2.39</td>
<td>10.9 x 7.8</td>
<td>10.02</td>
<td>-22.4</td>
<td>5.78 %</td>
</tr>
<tr>
<td>Graded Expt</td>
<td>2.27</td>
<td>11.2 x 8.1</td>
<td>10.1</td>
<td>-38.6</td>
<td>6.73 %</td>
</tr>
<tr>
<td>Graded Sim</td>
<td>-</td>
<td>11.2 x 8.1</td>
<td>10.0</td>
<td>-23</td>
<td>6.75%</td>
</tr>
</tbody>
</table>

### 3.6 CONCLUSIONS

Studies carried out, indicate that, alumina in LDPE and titania in LDPE composites are suitable substrates for microstrip antennas. The microstrip antenna designed on the graded substrate resonates at the design frequency confirming the formation of the individual layers of the graded substrate with the desired thickness. Graded composite material developed as substrate for microstrip antenna shows an enhanced $S_{11}$ performance and bandwidth as compared to single composition substrate. The directivity values are also high for antenna on graded substrate. All these are achieved with the antenna size being reduced marginally in comparison to the antenna on 2% VF of titania in LDPE substrate (4% reduction in area) (Table 3.1). Instead of using commercially available substrates, where the material properties cannot be altered, graded particulate composite substrates may form a new technological alternative, where the substrate properties can be tailored easily by altering the filler content in the matrix. In all the future investigations of this work, graded composite material is used as substrate for antenna designs.
References


