CHAPTER 2
EXPERIMENTAL METHODS

The reported theory in Chapter 1 is used for the design of microstrip feed line and antenna. The present chapter deals with the details of experimentation including the design of two MPAs (CMPA & ETMPA), followed by the laboratory techniques used for fabrication of these samples viz. cleaning, vacuum deposition, Cu electroplating (up to the thickness of few skin-depth about 5-6 μm thick), thickness measurement techniques by Tolanski method (for Cr and Cu thickness measurements) and the mask preparation. This is followed by method of microwave measurement on the device under test (DUT) on HP Scalar Network Analyzer (HP8757C). The details of reflection measurements and radiation pattern (E and H-planes) measurements are given in this part. For the mathematical background of all the simulation methods by using computer software and detail of MStrip40 software (based on method of moment) is given in Appendix C.

The first experimental step involves the design of EMC MPAs i.e. the open-ended microstrip feed line for EMC and Microstrip patch antennas viz. CMPA, ETMPA.

2.1 The Design of Open-Ended Microstrip Line for EMC

In the present work the open-ended microstrip-line is used as the only feed line for EMC. The aim of the design and fabrication of such line is to get width \( w \) of microstrip line with better accuracy for proper \( Z_0 \) and low loss. Though the EMC demands the use of overlay (of alumina substrate in our case), it is not considered in the design procedure because the error introduced is less than the measurement errors (see art.3.1). The width of the 50Ω line is determined as the feedline for the bottom layer by using (i) *Formula for calculations* (art.1.3.3, Eqn.1.13 to 1.24) and (ii) *TX-line software* [145]. The following step by step procedure is used.
2.1.1 Calculations

The required formulae are given in article 1.3.3 (Eqn.(1.13) to (1.24)). The geometry of open-ended microstrip line of length \( l_f \) and width \( w_f \) is shown in Fig.2.1 and table 2.1 gives the values of parameters used.

Figure 2.1: Geometry for the design elements: Microstrip line for EMC

Table 2.1: Common parameters used for our design

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value/Units</th>
<th>Remark/Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t )</td>
<td>6( \mu )m</td>
<td>Thickness of the conductor (Cu)</td>
</tr>
<tr>
<td>( h )</td>
<td>0.635 mm</td>
<td>height of alumina substrate</td>
</tr>
<tr>
<td>( \sigma(Cu) )</td>
<td>5.88( \times )10(^{-4}) S/mm</td>
<td>specific electrical conductivity of Cu</td>
</tr>
<tr>
<td>( \tan\delta(\text{Al}_2\text{O}_3) )</td>
<td>0.0005</td>
<td>loss tangent for ( \text{Al}_2\text{O}_3 ) 99.5% at 10GHz</td>
</tr>
<tr>
<td>( c )</td>
<td>2.997925( \times )10(^{11}) mm/s</td>
<td>velocity of electromagnetic wave in free space[16]</td>
</tr>
<tr>
<td>( \varepsilon_r(\text{Al}_2\text{O}_3) )</td>
<td>9.8</td>
<td>dielectric constant of ( \text{Al}_2\text{O}_3 ) 99.5%(Table1.2)</td>
</tr>
<tr>
<td>( Z_0 )</td>
<td>50( \Omega )</td>
<td>Characteristic impedance</td>
</tr>
</tbody>
</table>

2.1.1.1 Narrow Strip Design: For narrow strip (i.e. when \( Z_0 > (44-2\varepsilon_r) \Omega \)): The width of the microstrip line \( w_f \) is given by

\[
\frac{w_f}{h} = \left( \frac{\exp H'}{8} - \frac{1}{4\exp H'} \right)^{-1} \quad (2.1)
\]
From table 2.1, Characteristic impedance \((Z_0) = 50\Omega\) and dielectric constant \((\varepsilon_r)\) of \(\text{Al}_2\text{O}_3\) (99.5%) is 9.8, substituting values of \(Z_0\) and \(\varepsilon_r\) in Eqn.(2.2)

\[ H' = 2.1321 \]  

(2.3)

Substituting the values of \(H'\) in the equation (2.1), where \(h = 0.635\) mm,

\[ w_f = 0.6198\) mm \]  

(2.4)

### 2.1.1.2 Guide Wavelength:

The guide wavelength of the frequency \(f\) of the microstrip line is given by [13]

\[ \lambda_g = \frac{c}{f \times \sqrt{\varepsilon_{\text{eff}}(f)}} \]  

(2.5)

Using expression by Edward and Owen [13, 146],

\[ \varepsilon_{\text{eff}}(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{\text{eff}}}{1 + \left( \frac{h}{Z_0} \right)^{133} \times (0.43 f^2 - 0.009 f^3)} \]  

(2.6)

where \(h\) in mm and \(f\) in GHz

When \(Z_0\) is known at first [13], \(\varepsilon_{\text{eff}}\) can be given by

\[ \varepsilon_{\text{eff}} = \frac{\varepsilon_r}{0.96 + \varepsilon_r \left( 0.109 - 0.004 \varepsilon_r \right) \log(10 + Z_0) - 1} \]  

\[ \varepsilon_{\text{eff}} = 6.5671 \]  

(2.7)

Substituting the values of \(\varepsilon_{\text{eff}}\) in the equation (2.6), where \(f = 10\) GHz,

\[ \varepsilon_{\text{eff}}(f) = 6.8669 \]  

(2.8)

Substituting the values of \(\varepsilon_{\text{eff}}(f) = 6.8669\) in the Eqn. (2.5),
\[ \lambda_g = \frac{c}{f \times \sqrt{\varepsilon_{\text{eff}}(f)}} = \frac{300}{10 \times \sqrt{6.8669}} = 11.4483 \text{mm} \quad (2.9) \]

Since the physical length \( l \) of the microstrip line is required to be \( \lambda_g/4 \) we obtain

\[ l = \frac{\lambda_g}{4} = 2.8621 \text{mm} \quad (2.10) \]

Thus, final designed values of the microstrip line are:

- \( w_f = 0.6198 \text{ mm} \)
- \( \lambda_g = 11.4483 \text{ mm} \)
- \( l = 2.8621 \text{ mm} \)
- \( \varepsilon_{\text{eff}}(f) = 6.8669 \)

### 2.1.2 TX-line software [145]

The design procedure of microstrip line by using TXLINE 2003 software is as follow:

#### 2.1.2.1 Select the Material Parameters [Fig.2.2],

Dielectric: Alumina, the software window will automatically give Dielectric constant: \( 9.8 \) and Loss Tangent 0.0005.

Conductor: Copper, the software window will also automatically give Conductivity 58800S/mm.

#### 2.1.2.2 Give values for our present work of Electrical Characteristics:

Impedance 50Ω, Frequency: 10GHz, Conductor thickness 6\( \mu \) and Height of substrate 0.635 mm

#### 2.1.2.3 Click on the arrow, the final designed values of the microstrip line are given in Fig.2.2:

80
As stated above, the aim of the design and fabrication is to get the width \( w_f \) of the microstrip line with better accuracy for \( Z_0 \) and low loss. It can be seen that both, design method for (i) Formula calculation (art.1.3.3, Eqn.1.13 to 1.24) and (ii) TX-line software, [145] give accurate results (with 0.33% difference) for \( w_f \). The overall discussion will be presented in Chapter 3 (art.3.1, table 3.1). The value of \( w_f \) of the microstrip line is used for the mask preparation.

### 2.2 Design Procedure for Microstrip Patch Antennas

#### 2.2.1 The Design of CMPA

*Values for the present work are:*
\[
\varepsilon_r = 9.8, \quad f_r = 10 \text{ GHz}, \quad \text{and} \quad h = 0.0635\text{cm}
\]

*Determination of the actual radius \( a \) of the patch*

The dominant mode is the \( TM_{10} \), resonant frequency is

\[
(f_r)_{10} = \frac{1.8412c}{2\pi a \sqrt{\varepsilon_r}}
\] (2.11)
where \( c \) is the speed of light in free space. From Eqn.(2.11), a first-order approximation to the solution of \( a \) is given as [40, 67],

\[
a = \frac{F}{\left\{ 1 + \frac{2h}{\pi \varepsilon_r F} \left[ \ln \left( \frac{\pi F}{2h} \right) + 1.7726 \right] \right\}^{1/2}}  
\]

(2.12)

where

\[
F = \frac{8.791 \times 10^9}{f_0 \sqrt{\varepsilon_r}}  
\]

(2.13)

\( h \) is in cm and for our specific values (\( \varepsilon_r = 9.8 \), \( f_0 = 10 \text{ GHz} \), and \( h = 0.0635 \text{cm} \))

\[
F = \frac{8.791 \times 10^9}{10 \times 10^9 \sqrt{9.8}} = 0.280818  
\]

(2.14)

Substituting the value of \( F \) in the Eqn.(2.12), the actual radius \( a \) of the CMPA,

\[
a = 0.27346 \text{cm}(2.7346 \text{mm})  
\]

(2.15)

The resonant frequency of Eqn.(2.11) does not take into account fringing. The fringing makes the patch looks electrically larger. For CMPA a correction is introduced by using an effective radius \( a_e \), to replace the radius \( a \) in Eqn. (2.11), given by [67]

\[
a_e = a \left\{ 1 + \frac{2h}{\pi a \varepsilon_r} \left[ \ln \left( \frac{ma}{2h} \right) + 1.7726 \right] \right\}^{1/2}  
\]

(2.16)

Substituting the value of \( a \) in the Eqn.(2.16),

\[
a_e = 0.28096 \text{cm}(2.8096 \text{mm})  
\]

(2.17)

Thus, the final designed values of the CMPA are:

\[
a = 0.27346 \text{cm}(2.7346 \text{mm})  
\]

\[
a_e = 0.28096 \text{cm}(2.8096 \text{mm})  
\]

(2.18)

The value of the actual radius \( a \) of the CMPA is used for the mask preparation.
2.2.2 The Design of ETMPA

Values for the present work are:
\[ \varepsilon_r = 9.8, f_r = 10 \text{ GHz}, \text{ and } h = 0.0635\text{cm} \]

To Determination of the physical side-length \( a \) and effective \( a_e \) length of the dominant mode \( TM_{1,0,-1} \) of ETMPA is as follows:

As indicated in chapter 1 (art.1.8), the design procedure for ETMPA uses the relation between side-length \( a \) and the resonant frequency on the dielectric substrate. The resonant frequency of the ETMPA was given by [7, 79- 86]:

\[
f_{m,n,i} = \frac{2c}{3a\sqrt{\varepsilon_r}}(m^2 + mn + n^2)^{1/2}
\]

(2.19)

where \( c \) is the velocity of light \( (3 \times 10^{10} \text{ cm/s}) \), \( f_{m,n,i} = f_1,0,-1 = 10\text{GHz} \), \( \varepsilon_r = 9.8 \).

Substituting these values in Eqn.(2.19), we obtain,

\[
a = 0.63888\text{cm}(6.3888\text{mm})
\]

(2.20)

The resonant frequency of Eqn.(2.19) does not take into account fringing. The fringing field makes the patch look electrically larger. The formula for resonant frequency in (2.19) is modified to account for the extension of edges defined by

\[
f_{m,n,i} = \frac{2c}{3a_e\sqrt{\varepsilon_r}}(m^2 + mn + n^2)^{1/2}
\]

(2.21)

The next step is to find effective \( a_e \) length of the ETMPA for the corrected side-length due to the effect of the fringing fields by using [86],

\[
a_e = a\left[1 + \frac{2h}{\pi \varepsilon, a}\left\{\ln\left(\frac{a}{2h}\right) + (1.41\varepsilon, +1.77) + \frac{h}{a}(0.268\varepsilon, +1.65)\right\}\right]^{1/2}
\]

(2.22)

Substituting \( a \) in the Eqn.(2.22), we obtain,

\[
a_e = 0.67426\text{cm}(6.7426\text{mm})
\]

(2.23)
The final values for our design side-length of ETMPA are:

\[ a = 0.63888 \text{cm}(6.3888 \text{mm}) \]
\[ a_c = 0.67426 \text{cm}(6.7426 \text{mm}) \] (2.24)

The value of the physical side length \(a\) of the ETMPA is used for the mask preparation.

2.3 Metallization

Open-ended microstrip feed line and microstrip antennas (CMPA, ETMPA) are the main configurations used throughout the present work. The fabrication involves, formation of conductor (Cu) films i.e. metallization on the substrate (physical vapor deposition and electroplating) and pattern delineation (mask preparation and lithography).

Most commercially available microstrip substrates are metallized on both faces. The circuit pattern is realized by the photolithographic process. A mask of the circuit to be realized is drawn at a suitable scale; cut, and then reduced and placed on the top of a photo resistive layer, which was previously deposited on the top of the microstrip. The structure is then exposed to ultraviolet radiation [see Fig.2.3], which reaches the photosensitive layer through the mask openings (negative mask). The exposed parts are removed by the photographic development, and the metal cover is etched away selectively. It is also possible to deposit metal by evaporation or sputtering upon a bare dielectric substrate which is done in our laboratory. Metal layer deposited on the dielectric substrate must exhibit characteristics like low resistivity, good resolution, adaptation to different contact-making processes etc. The five main steps of processes and details are given below.

2.3.1: Laboratory Cleanliness:

For the thin film work in general, and MICs in particular, care has to be taken in the organization of the laboratory. The laboratory must be dust-free or should be kept as clean as possible. For the present work, to achieve a reasonably clean working area, the following precautions are taken [3, 5, 100, 101, 110-115]. The deposition and
electroplating are carried out in the air conditioned room having a clean bench (Kirloskar Engineering model Surgico 100, India) facility. After electroplating, the substrates were wrapped in lint-less tissue paper and were kept in a dessicator. A clean dark room was arranged for photolithography. After pattern delineation, the substrates were wrapped in lint-less tissue paper and were stored in a closed plastic container.

2.3.2 Substrate Cleaning Procedure:

Cleaning of the substrate used for the fabrication of Open-ended microstrip feed line and microstrip antennas (CMPA, ETMPA) have been carried out using the standard procedure. The process of substrate cleaning requires that the bond between contaminant molecules as well as that between contaminant and substrate should be broken. This may be accomplished either by chemical means as in solvent cleaning or by supplying sufficient energy to vaporize the impurity. In the present work chemical cleaning procedure is used.

Chemical method is used to clean the substrates. Chromic acid is prepared by dissolving potassium dichromate in the distilled water plus a few drops of sulphuric acid. Alumina substrates (Kyocera, purity 99%, $\varepsilon_r = 9.8$, thickness (h) =0.635mm, size 25.4mm×25.4mm) are used for experimentation. They are kept in Chromic acid for 15-20 minutes and washed under tap water. They are then kept in a soap solution for 10-15 minutes. After this they are washed with distilled water. To remove the fine impurities (like dust particle) on the surface, they are kept in an Ultrasonic cleaner (Ralsonsics) for 3 minutes after which they are dried under an IR lamp. The substrates, thus cleaned are then wrapped in lint-less tissue paper before transferring them to the vacuum chamber.
Figure 2.3: Series of fabrication processes for the required pattern
2.3.3 Physical Vapor Deposition:

The metallization is done first by vacuum depositing a thin conductor film (Cr, Cu) (see Fig.2.3 and Fig.2.4). The vacuum deposition system used in the present work is shown in Fig.2.4. It has a ED-12 double stage rotary pump and diffusion pump with 100 ml of Silicon oil, (both made by M/s Hind Hi-Vacuum co. Pvt.Ltd., Bangalore) and a 12” diameter Borosilicate glass dome (bell-jar). Substrates to be metallized are kept on a substrate holder, whose height is optimized to 15 cm from the source. The substrate holder is aligned centrally over the evaporation source.

The metals used for deposition are Cr (Fluka, purity 99.99%); this is required for good adhesion, and Cu (Balzar, purity 99.99%). The evaporation source has a transformer of 8V, 200A. Cr is evaporated using Molybdenum boat (Balzar, thickness 100 μm) to a thickness of about 500 Å. This is followed by Cu deposition using a filament of Tungsten wire (500 μm thick). Both depositions are carried out between $10^{-5}$ to $10^{-6}$ Torr of pressure. Some half-covered glass substrates are also placed along with alumina substrates for metallization, which are further used for thickness measurement (art.2.3.5). After copper deposition is completed the substrates are kept in vacuum for few hours. Both side of Alumina substrate are deposited using the same procedure.
2.3.4 Electroplating:

The copper film for microstrip line circuits need to be about 5-6 times the skin-depth at the centre frequency of interest i.e. 10 GHz, in order to reduce the surface resistance, which can be achieved by electroplating. The required thickness at 10 GHz comes out to be about 5-6 μm. The experimental setup used for electroplating is shown in Fig.2.5. This setup is easily available and gives good results.

The electroplating set up consists of two Cu plates used as anodes, held parallel to each other at a distance of 20 cm. The substrate to be electroplated is suspended at the center of two anodes and is held parallel to them, which forms a cathode. Analytical grade copper sulphate (99.5% pure) is dissolved in double distilled water in proportion of 150 gm/lit. The function of complex additive compound EDTA (Ethylene Dinitrilo Tetra Acetate Disodium Na₂C₁₀H₁₄O₆N₂.2H₂O) is added in proportion of 3 gm/lit to give the smoother surface [129]. Though the exact function of complex additive is not known, it is expected that, if at any point on substrate growth is faster, the complex compound
molecules will sit at such point, and reduce the growth rate. Few drops of nitric acid (HNO₃) are added to the solution to give much smoother and more adherent deposition. The function of acid is to depolarize the cathode for constant current method. The calculation of time and current for the deposition of 5-6 μm thickness are shown below:

Volume of copper required for thickness ‘t’ is given by

\[ V = a \times b \times t \]  (2.25)

Where \( a \) = length, \( b \) = breadth and \( t \) = thickness of the electroplated copper film.

\[ V = 2.54 \times 2.54 \times 5 \times 10^{-4} \text{ cm}^3 \]
\[ = 32.258 \times 10^{-4} \text{ cm}^3 \]

Mass of the copper; \( m = V \times d \), where \( d \) is the density of copper 8.9 gm/cm³.

Therefore, mass of the copper deposited in the form of film (electroplated) is

\[ m = 32.258 \times 10^{-4} \times 8.9 \text{ gm} = 2.87 \times 10^{-2} \text{ gm.} \]

To deposit the mass \( m \) of copper, the quantity of electric charge required is given by

\[ Q = \frac{m}{\text{electrochemical equivalent of copper}} \]  (2.26)

Electrochemical equivalent of copper = Molecular weight / (valency x Faraday constant)

Molecular weight of copper 63.6, valency = 2

Therefore electrochemical equivalent of copper = \( \frac{63.6}{(2 \times 96500)} \)
\[ = 3.295 \times 10^{-4} \text{ gm/ C} \]

So that from (2.26) charge required is \( Q = 2.87 \times 10^{-2} \text{ gm} / 3.295 \times 10^{-4} \text{ gm/ C} \)
\[ = 87.10 \text{ C} \]

The optimum current is reported to be 80 mA per square inch, with dc potential of 8 – 12 V [129]. Therefore the time required can be calculated as

\[ t = \frac{Q}{I} \text{ where, } I \text{ is the current} \]  (2.27)

\[ t = 87.10 \text{ C} / 80 \text{ mA} \]
\[ t = 1088 \text{ sec (≈18 min.)} \]
As the metallization has to be done on both sides of the substrate, the time of plating has to be doubled. The current is optimized at 80 mA/ sq. inch is passed for the time of about 30–35 minutes with a dc potential of 8 – 12 V. It is observed that the higher and lower rates of deposition increase the surface roughness and turn the metallization blackish in color. After electroplating, the sample has to be well washed with distilled water, cleaned ultrasonically in distilled water and dried with tissue paper. The same procedure is repeated for different substrates. The electroplated substrates are observed under a traveling microscope, of magnification 30, to check for any pin holes and/or granules. The substrates free from these defects are then used for photolithography which will be discussed next.

1-2: Copper Anode, 3: Cathode lead-in, 4: Insulated cover, 5: Substrate for electroplating, 6: Ammeter, 7: Rheostat, 8: Power supply, 9: Electroplating vessel tank, 10: Electrolyte (CuSO₄)

Figure 2.5: Electroplating setup
2.3.5 Thickness Measurement:

The two methods are used for thickness measurement. The thickness of the adhesion layer (Cr) is measured with the Tolanski method [3, 5, 147, 148] and the thickness of electroplated Cu is measured using a Light Section Microscope [3, 5, 147, 149, 150]. These two methods are described in brief in this article.

2.3.5.1 Tolanski Method

Half-coated glass substrates are used for this method. The thickness of Cr films is measured using this method, which uses the principle of fringes, generated by monochromatic light. The fringes represent contours of equal thickness arising from an area of varying thickness formed due to the cover slip kept on the abrupt step in thickness of the vacuum deposited Cr–Cu. A monochromatic light is obtained with the help of Mercury lamp and a green filter (λ = 0.546 μm wavelength), which is made to fall on the cover slip by a slide arranged at an angle of 45° to the incident rays. Fringe width (D) and fringe shift (d) are measured using the micrometer eyepiece (LC = 10 μm). The two prerequisites for an accurate thickness measurement are extremely flat, smooth film surface and a monochromatic light. Film thickness is calculated using the standard formula: \((d/D) \times (\lambda/2)\).

This method is useful for film thickness 30 Å to 20000 Å with an accuracy of ±30 Å. The average thickness of the Cr films on all the substrates is found to be about 600 Å.

2.3.5.2 Light Section Microscope

This method is used for measuring the thickness of Cr + Cu films after electroplating and is directly used with metallized alumina substrates. Use of the technique is limited to the films of thickness greater than 1μm. It consists of two optical systems: one which projects light on the sample at an angle of 45° with the sample and an observing microscope, forming an angle of 90° with the illuminating microscope and of 45° with the sample. The image of the slit is observed by means of an eye-piece with a
reticle and a micrometer. In the case of opaque films, the slit is projected across the step in the film. For transparent films, a step is not necessary, as the two images are obtained due to the reflection from both interfaces. Accuracy of measurement is from few tens of a micron to a micron for film thickness from 3 to 25 μm, and for thicker films the accuracy approaches 2%. The Cu electroplated films have thickness in the range of 4-7 μm in our case.

2.4 Pattern Delineation:

The pattern of the microstrip circuits (microstrip feedline, CMPA, ETMPA) is to be realized on the metallization substrates. For this, a mask of the pattern has to be prepared accurate artwork, in which following three steps are involved.

2.4.1: Artwork and Mask Preparation:

As discussed in above articles (art 2.1 and art.2.2), the design values of the microstrip circuits are in millimeters. If an artwork of the same dimension is prepared, it may involve error. Moreover, the dimensions have to be rounded off due to the accuracy of the measuring scale, which may affect the desired electrical characteristics of the samples. In order to avoid these problems a 10–times enlarged artwork is prepared by using available computer software (Microsoft word XP and Corel draw 9). Then it is reduced 10–times to retrieve the design parameters. Two negative masks (N₁, N₂) were prepared using the same artwork (Fig.2.6). Dimensions of the negative were measured using traveling microscope (LC = 10 μm). The errors in the mask dimensions and the designed dimensions are given in next chapter (art 3.2). These negatives are further used in photolithography (art 2.4.2) to transfer the microstrip patch antennas (CMPA and ETMPA) and feed system pattern on the metallized alumina substrates.
2.4.2 Photolithography:

To transfer the desired microstrip patch antenna and feed system, the vacuum pump-chuck with the spinner is used, both sides of metallized Al₂O₃ substrates are spin coated with a thin layer (≈50 μm) of a negative photoresist (Lunar, E-1020). The substrate is spinned to get a uniform resist coating, for about 5 minutes [3, 5, 151], which is also sufficient to dry the photoresist completely. One of the two sides is exposed to UV light (100 W), without any mask, at an optimized distance of 15 cm. and for the optimized time of 13-14 minutes, to ensure a pinhole-free ground plane. On the second side of substrate, a negative mask (either of N₁ or N₂) of the microstrip circuits (open-ended microstrip line) is kept in a firm contact with the other side of the substrates, and is exposed to UV light as stated above. These UV exposed substrates are then developed (Lunar Photo Developer) for 30-35 seconds and then washed out the unexposed photoresist on the substrate.
2.4.3 Chemical Etching:

The last step in pattern delineation is the chemical etching. The photo-developed substrates are then subjected to chemical etching. Firstly, the Cu layer where there is no photoresist (washed in the developer) is etched out using FeCl$_3$ solution (300g/lit) in about 10 minutes. The samples are then thoroughly washed under tap water. Secondly, Cr is etched by Cr etchant [3, 5, 151] which is prepared by dissolving K$_3$Fe(CN)$_6$ in distilled water (34 g/lit), to which NaOH is added (5 g/lit.). The etchant is highly toxic and proper handling is necessary. After etching out Cr (for about 3-4 min.), the pattern delineation process is completed.

Typical microstrip patch antennas and open-ended microstrip line designed and fabricated with the above procedure are shown in the photograph below (Fig.2.7).

Figure: 2.7 Photograph: Typical patterns on alumina substrate after etching
2.5 Microwave Measurements on Device Under Test (DUT):

2.5.1 Scalar Network Analyzer (HP 8757C) (SNA) and other related system

There are several steps to measure DUT for transmission, reflection or transmission and reflection. The HP-systems used in this experiment work, are given below:

1) HP-83592B RF PLUG-IN 0.01-20 GHz Power Source [152]
2) HP-8350B Sweep Oscillator [153]
3) HP-8757C Scalar Network Analyzer (SNA) [154]
4) HP-9122C Computer [155]
5) HP-437B Power meter [156]
6) HP8481A Power Sensor [157]
7) HP-11667A Power Splitter [158]
8) HP-85027A Directional Bridge [159]
9) HP-85025A A/B/E Detector [160]
10) HP-85023A APC-7 System [161]
11) HP-color Pro. (Plotter) [162]

i) HP-83592B RF PLUG-IN (including options 002 and 004) with serial number prefix 2718A printed July 1987 is used. The power variation is 0.0 to 23 dBm/dB and frequency range 0.01 to 20 GHz.

ii) HP-8350B Sweep Oscillator (including option 400) with serial number prefix 3116A [153] is used to control the source (RF).

iii) HP-8757C Scalar Network Analyzer (SNA) with serial number prefix 3026A [154] is used to study the transmission and reflection measurements. The detail to operate this system is given in [154].

iv) HP-9122C Disc Drive uses the new high-density, 2-megabyte (unformatted) flexible disk [155]. A disk drive is an electromechanical device that stores computer data disk and retrieves computer data from a disk [155].
v) **HP-437B Power meter** is a single channel programmable, average-responding power meter [156]. It measures power in the range of -70 to +44 dBm (0.1 mW to 25 W) over the frequency range of 100 KHz to 50 GHz using the existing HP-8480 series power sensor [156]. The HP-8481 power sensor is compatible and used here [157].

vi) **HP-Color Graphic Plotter** is employed to avoid use of "computer jargon" [162], and gives direct output plot.

vii) **HP-11667A Power Splitter** is a two-resistor type power splitter for use in a network measurement where one arm of the power splitter is used for leveling or to supply a reference signal for a ratio measurement [158].

viii) **HP-85027A Directional Bridge** is a microwave directional bridge that has a frequency range of 0.01 to 18 GHz [159]. The bridge is equipped with a type-N(f) input connector and a precision 7mm test port connector. The bridge makes modulated (AC) or unmodulated (DC) scalar reflection measurements with the HP-8757C Scalar Network Analyzer. A signal zero-biased schottky diode detector in the bridge performs reflection measurements by sampling the return loss of DUT. A detector can be added for simultaneous transmission measurements. A power splitter can be used with the bridge or detector (or both) for ratio measurements. The RF input signal is typically supplied by a sweep oscillator or a synthesized sweeper [159] (Fig.2.8).

ix) **HP-85025A Detector**: This detector is specifically designed for use with the HP-8757 SNA. The detector enables the SNA to measure either modulated (AC) or unmodulated (DC) test signals. This detector can measure RF signal levels (dependent on AC or DC mode) from -55 to +16 dBm [160]. The HP85025A standard (or option 001) both can measure frequencies from 0.01 to 18 GHz [160].

x) **HP-85023A APC-7 System verification kit** [161]: The HP-85023A APC-7 50 ohms system verification kit is a set of precision components used to perform a system verification procedure for SNA system and for verification of directional bridge [161]. The system verification kit can also be used for normal measurement calibration of a scalar network analyzer. The measurement calibration procedure is in art.2.5.2.1. The kit
consists of a combination open/short, a 50 Ω termination, the 10 dB fixed attenuator, and a type-N(m) to type-N(m) adapter [161]. Photograph 2.9 shows this kit and other adapters used for this experimental work (Fig.2.9).

The HP-system is used to measure the power of reflection is shown in Fig.2.8. The detail of reflection measurement is given in details in [163] and will be discussed in brief in the next article.

The detail of reflection measurement is given in details in [163] and will be discussed in brief in the next article.

![Block diagram of the test set-up, in reflection mode used for measurement](image)

**Figure 2.8:** Block diagram of the test set-up, in reflection mode used for measurement

### 2.5.2 Measurements on SNA

As is indicted in the previous article, the present work is mainly related with reflection parameters measurement method. This method is described in brief in this article.

#### 2.5.2.1 Reflection Measurement Method for MPAs

Measuring the return loss (RL), impedance bandwidth (BW) and SWR completes the device characterization. Procedure below demonstrates how to perform reflection measurements with SNA system.

**a) Signal Separation:** The reflection measurements require the separation of the signal incident upon the input of the device from the device’s reflected power. A signal separator such as a directional bridge or coupler provides a sample of the power traveling
in only one direction; when it is connected as shown in the Fig.2.8-Fig.2.10, the reflected power is separated and measured independently of the incident power. Many types of directional bridges and couplers are available. They are differentiated by frequency range, directivity and connector type [163, chap.3].

b) Device Termination: The reflection measurements involve only one port of a test device. When a device has more than one port, it is critical that all of the unused ports are properly terminated in their characteristic impedance (e.g. 50 or 75 ohms). High quality loads or detectors with excellent return loss (such as the HP-80525D/E) should be used whenever possible, particularly with low loss devices. Otherwise, reflections of the unused ports will cause measurements errors [163, chap.3].

c) Measurement Accuracy: In reflection measurements, the accuracy of the final results is highly dependent on the signal separation devices, adapters, and the DUT terminations. Systematic errors such as the frequency response of the test setup, directivity, and mismatch degrade overall measurement accuracy [163, chap.2]. The HP 8757 C/E’s calibration routines can significantly reduce these measurement errors.

d) Measurement Setup for Return loss, SWR and BW (-3dB): As stated above, the signal reflected from the DUT is most often measured as a ratio with the incident signal and can be expressed as return loss or SWR (standing wave ratio) or BW in MHz. These measurements are mathematically defined as:

\[
\text{reflection loss} = \frac{\text{reflected}}{\text{incident}} = \rho \\
\text{Return loss (RL; dB)} = -20\log_{10}\rho \\
\text{SWR} = \frac{(1 + \rho)}{(1 - \rho)}
\]

**Procedure of measurement setup**

**Preset**

**Connections:** Connect DUT as shown in Fig.2.8-Fig.2.10

**Controls**

setup instrument.

**Measurement**
CHANNEL [1]: Actives channel 1.

CHANNEL 2 OFF

[MEAS][A/R]: Sets up reflection measurement.

[MEAS][A/R]: Sets up reflection measurement.

Source parameters

[CF][10.0][GHz]

[ΔF][2][GHz]

[POWER LEVEL][10][dBm/dB]

Calibrate: Perform reflection calibration.

[CAL]: Accesses calibration menu

[SHORT/OPEN] Set up calibration; connect short.

[STORE SHORT] Connect open.

[STORE OPEN] Stores calibration in memory of active channel.

[DISPLAY] Accesses display menu.

[MEAS-MEM] Normalizes measurement trace.

Save [2]: Save instrument state and calibration in register 2.

Measurement: Reconnect DUT and adjust parameters to enhance useability of measurement data.

e) Return loss (dB): The following figure (Fig.2.9 and Fig.2.10) displays the return loss of BW of MPAs. Since the return loss is low in the BW of the MPAs. The return loss in the microstrip patch antenna is approximately 30dB (the best match between feed system and MPAs, VSWR≈1, no reflection). Conversion between some values of reflection coefficient, SWR and return loss are shown in Table 2.2.
Figure 2.9: Experimental set up for reflection measurement

Figure 2.10: Measurement of in-set and off-set variation of open ended feed line w.r.t MPA.
Table 2.2: Conversion between some values of reflection coefficient ($\rho$), SWR and return loss (RL) [164]

| $|\rho|$ | 0.024 | 0.032 | 0.048 | 0.050 | 0.056 | 0.10 | 0.178 | 0.200 | 0.316 | 0.33 |
| SWR   | 1.05  | 1.07  | 1.10  | 1.11  | 1.12  | 1.22 | 1.43  | 1.50  | 1.92  | 2.00 |
| RL(dB) | 32.3  | 30.0  | 26.4  | 26.0  | 25.0  | 20.0 | 15.0  | 14.0  | 10.0  | 9.6  |

f) VSWR: To study reflection data in terms of SWR, select [DISPLAY] then the [TRC FMT SWR dB] soft key. SWR is a unitless value, a SWR =1 corresponds to no reflection (perfect match) (see table 2.2), while an infinite SWR corresponds to 100% reflection (poor match). SWR is only available for Channel 1 and 2, and for ratios or normalized measurement with 401 points of [163, chap.3]. This is the one for present geometry to find the best match point of the patches [101, 110-115].

2.5.2.2 Reflection Measurement Method for CMPA with dielectric overlay

The effect of dielectric strip overlay for CMPA is studied, which is an extension of work on sensors in this laboratory [129-133]. Our present system (with flexible rotational position overlay and flexible coupling) becomes the most general one. We have studied the effect of dielectric strip overlay for CMPA (as in [5 for MRA with EMC]) for reflection (though not transmission as in [129-133]) parameters i.e. resonance frequency ($f_r$), return loss (RL), VSWR and bandwidth (BW), and also radiation pattern. The CMPA is perturbed by keeping crossed partial overlays of alumina strip ($\varepsilon_r = 9.8$, length = 22 cm, height = 0.635 mm, and width of the strips = 1.0, 1.3, 1.5, 1.8, 2.0, 2.5, 3, 3.5, 4.0, 4.5 mm) at various azimuth angles $\phi$. The thickness (height) of the overlay is increased by keeping alumina strips of the same width, one over the other (with vacuum grease in between, to avoid air gap). The azimuth angle $\phi$ is varied from 0° to 360° in the step of 22.5° in the four quadrants (Fig.2.11). For each position of overlay the CMPA reflection parameters are noted.
Figure 2.11: The two layered CMPA with separate EMC feed (a) Flared out view, (b) Cross-section and (c) Overlay orientation and overlay of Alumina strip on the CMPA at azimuthal angle $\phi = 45^\circ$ or $225^\circ$
2.5.3 Radiation Measurement Method for MPAs

(Radiation Pattern, Half-power lobe-width, Directivity and Gain)

The field (far-field) pattern of an antenna is one of its most important characteristics. The setup for radiation pattern for microstrip patch antenna is shown in Fig.2.12. In this part of experiment, the radiation pattern, half power lobe-width, amplitude of the main lobe (antenna beam), directivity and gain are studied. The radiation pattern studied can be divided in two parts (i) Radiation Measurement for MPAs (CMPA and ETMPA) and (ii) Radiation Measurement for CMPA with dielectric sheet ($\text{Al}_2\text{O}_3$) overlay.

Figure 2.12: Experimental set up for radiation pattern measurement.

The same SNA source is used for radiation measurements with a standard horn antenna as a receiver on a stand with adjustable X-Y-Z positions (mechanical adjustment) (see Fig.2.12) and MPAs (ETMPA, CMPA) as a transmitter. The MPAs have a
mechanical system to convert horizontal rotation of a low speed (2RP, 240V, AC, Mahendra Eng.-Pune) electric motor to vertical rotation (in ratio 2:1) though 360° [3-chap.3, 5-chap.3]. MPA is fixed on a metallic substrate holder (see Fig.2.12 and Fig.2.13) and holder is fixed on a piece of Perspex on the rotating rod. The patch is fed with OSM connector as a transmitting antenna and standard horn antenna is connected to OSM or HP bend with diode detector and is then connected to the plotter or power meter as a receiving antenna. The power fed to the patch or horn antenna is fixed, through-out the 360° rotation of the antenna due to flexible coaxial cable even if MPA is used for receiving or transmitting. The fixed position horn antenna is used as horn antenna (for transmitting or receiving). Both MPA and horn antenna are aligned and kept at maximum height to avoid the interference due to ground reflection in the radiation pattern. Further, the spacing between patch and horn is kept of about 600 to 800 to carry the measurements in far field zone. The far field zone is taken to be the distance of
\[
S \geq 2d_1D_2/\lambda_0
\]  
(2.31)

where d_1 and D_2 are aperture size of receiving and transmitting antenna [3, 5, 165]. The power fed to patch is CW (by HP-83529B RF with HP-8359B sweep oscillator) at its resonance frequency (f_0). This frequency is found by reflection procedure (art.2.5.2.1). The frequency of the MPA is adjusted by HP-8350B sweep oscillator at the designed frequency of the patch to get maximum power by receiver antenna.

The power received by fixed horn or movable patch antenna is converted to DC by the square law diode detector and is fed to recorder for recording. The radiation pattern measurement for each antenna is repeated 3 to 10 times for accuracy and repeatability (some of them at different time for different parameters).
$S_f$: Substrate with feed line and ground plane

$S_p$: Substrate with patch antenna

Figure 2.13 Schematic arrangement of radiator (on $S_p$), feed line (on $S_f$), metallic substrate holder (for $S_p$ and $S_f$) and launcher (for RF connect to radiator). The E and H-plane are also shown in this figure.
2.5.4 Polarization Measurement

The microstrip antenna normally gives a linear polarization, but circular polarization can also be achieved by (i) single feed line with SMPA and RMPA [47-p.220, 104, 108, 109] and more easily with disk and ring antenna (ii) with two feed lines [47-p.220, 108, 109].

For polarization studies we have used the fact that the horn antenna, radiates/receives one polarization field by its excitation in TE\textsubscript{10} (dominant mode). Hence, while studying the simple antenna viz. SMPA, RMPA, CMPA and ETMPA, we have always kept the horn antenna with E-plane of both parallel to each other (see Fig.2.14), hence, the electric field. This gives the co-polar pattern [47-art.23.2.1, 5-art.3.6]. When we rotate the microstrip antenna around X-axis (hence, the feed direction or electric field direction) we get the H-plane pattern (in YZ-plane), we get E-plane pattern in XZ-plane. In practice we have to rotate both microstrip antenna and horn antenna through 90° because of the available facility (see Fig.2.12, Fig.2.13 and Fig.2.14).

For cross polarization study to get cross polar RPs, the arrangement in Fig.2.14b can be used. The microstrip patch antenna is kept for H-plane RP, in this figure, but rotates the horn through 90° and rotate patch about X-axis. For E-plane RP, we have to rotate microstrip patch about Y-axis.

In present work, the focus is on co-polarization only and the concentration is on the studies at dominant mode as MPAs designed.
Figure 2.14: The normally used position and electric fields for Horn and experimental antenna (here for RMPA) for H-plane radiation pattern (a) Co-polar, (b) Cross-polar.
To conclude,

1. MPAs (CMPA, RMPA, SMPA, and ETMPA) and the open-ended microstrip-line are designed at x-band frequency and they are fabricated using vacuum evaporation, photolithography technique and electroplating.

2. Reflection parameters (VSWR, BW, RL and \( f_l \)) and radiation patterns (E and H planes, co and cross polarizations) are experimentally studied for EMC CMPA and ETMPA.

3. For EMC CMPA is also studied by angular position overlay for reflection parameters (VSWR, BW and \( f_l \)) and radiation patterns (E and H planes, co-polarization).

4. Simulation studied is also carried out (by MStrip40). The method required for simulation is given in Appendix C.