Microstrip Antennas

I. Introduction

a. Motivation

In this document, I mainly focus on design; however, other important parameters or ideas can go along as it proceeds.

b. Advantages

These antennas open up many possibilities in terms of polarization, resonant frequency, pattern and impedance. In addition, they can be compatible with MMIC (Monolithic Microwave Integrated Circuit) designs.

Adding loads, such as pins and varactor diodes, between the patch and the ground plane allows variable resonant frequency, impedance, pattern, and polarization.

c. Disadvantages

Low efficiency, low power, high Q, poor polarization purity, poor scan performance, spurious feed radiation and very narrow bandwidth.

However, by manipulating design, some of these parameters can be overcome and improved.

d. Shapes of Microstrip

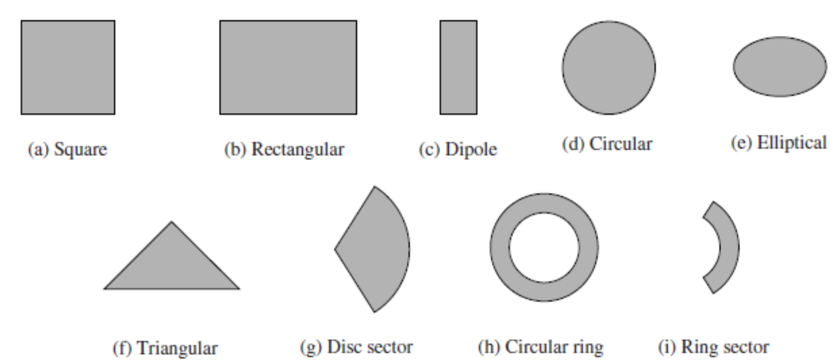

Figure 14.2 Representative shapes of microstrip patch elements.

e. Mode of Excitation

Design the patch so that the maximum pattern occurs normal to the patch. This can be done by setting an appropriate mode of excitation (field configuration).

II. Substrate Candidates

TABLE 14.1 Typical Substrates and Their Parameters

Company	Substrate	Thickness (mm)	Frequency (GHz)	ε_r	$\tan\delta$
Rogers Corporation	Duroid® 5880	0.127	0 – 40	2.20	0.0009
	RO 3003	1.575	0 – 40	3.00	0.0010
	RO 3010	3.175	0 – 10	10.2	0.0022
	RO 4350	0.168	0 – 10	3.48	0.0037
		0.508			
		1.524			
—	FR4	0.05 – 100	0.001	4.70	—
DuPont	HK 04J	0.025	0.001	3.50	0.005
Isola	IS 410	0.05 – 3.2	0.1	5.40	0.035
Arlon	DiClad 870	0.091	0 – 10	2.33	0.0013
Polyflon	Polyguide	0.102	0 – 10	2.32	0.0005
Neltec	NH 9320	3.175	0 – 10	3.20	0.0024
Taconic	RF-60A	0.102	0 – 10	6.15	0.0038

Substrates are dielectric materials that separate the patch and the ground plane. Usually thicker substrates reveal better antenna performance because they provide lower dielectric constant, which in turn shows better efficiency and larger bandwidth. Thin substrates with higher dielectric constants are desirable for microwave circuitry to minimize undesirable radiation and coupling.

FR4 is one popular substrate among other candidates.

III. Design

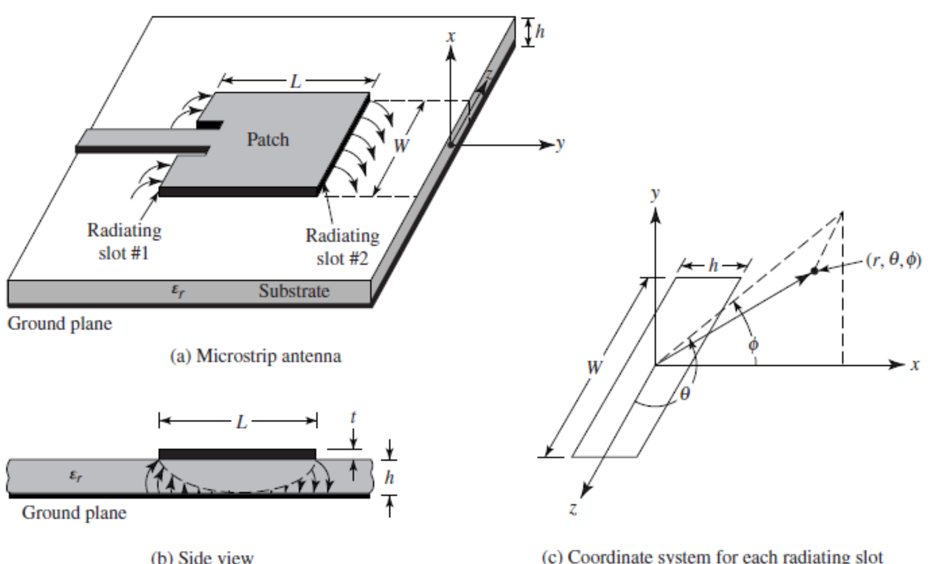

Figure 14.1 Microstrip antenna and coordinate system.

The patch is usually very thin:

$$t \ll \lambda_0$$

The thickness of substrate is also thin and it usually falls into the following region:

$$h \ll \lambda_0$$

$$0.003\lambda_0 \leq h \leq 0.005\lambda_0$$

The length of the element is usually:

$$\frac{\lambda_0}{3} < L < \frac{\lambda_0}{2}$$

a. Feeding Methods

The four most popular feeding elements are the microstrip line, coaxial probe, aperture coupling, and proximity coupling. Equivalent circuit models are shown:

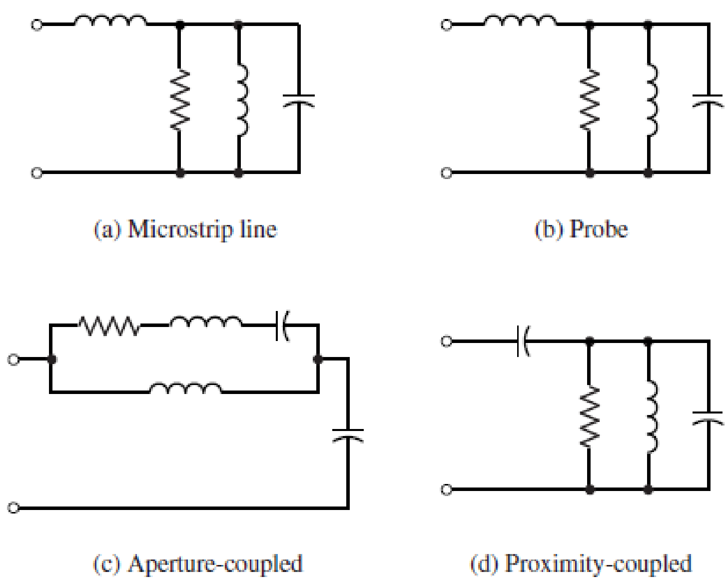

Figure 14.4 Equivalent circuits for typical feeds of Figure 14.3.

The microstrip line is one of the easy ways to match and fabricate.

IV. Method of Analysis

There are many ways to analyze microstrip antennas. The most popular models are the transmission-line, cavity, and full-wave (integral equations and Moment Method). The following table is for pro/con for each model.

	Physical Insight	Difficulty	Accuracy
Transmission-line	Good	Easy	Poor accuracy

Cavity	Good	Complex	More accurate
Full-wave	Poor	Most complex	Very accurate

The full-wave analysis can be used for analyzing complex structure (complex geometry), array, stacked, etc. In other words, for example, the transmission-line model can analyze only simple models.

V. Transmission-Line Model

Fringing Effects
Effective Length, Resonant Frequency, and Effective Width
Design Procedure

a. Design of Rectangular Patch

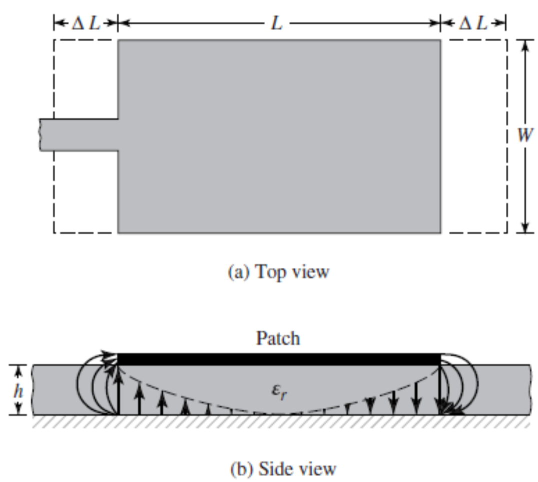

Figure 14.7 Physical and effective lengths of rectangular microstrip patch.

What do we have to specify first?

$\varepsilon_r, f_r, and\ h$

As before, $h = height\ of\ substrate$, and $f_r = resonant\ frequency$

The width of rectangular patch is given:

$$W = \frac{1}{2f_r\sqrt{\varepsilon_0\mu_0}}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

From [2], the speed of light in free-space is given as $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 299{,}792{,}458 \left[\frac{m}{s}\right] \approx 3 \times 10^8$

Now, we need to calculate the effective dielectric constant. Assume that

$$\frac{W}{h} > 1$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{W}\right)^{-0.5}$$

Note this value falls into: $1 < \varepsilon_{eff} < \varepsilon_r$

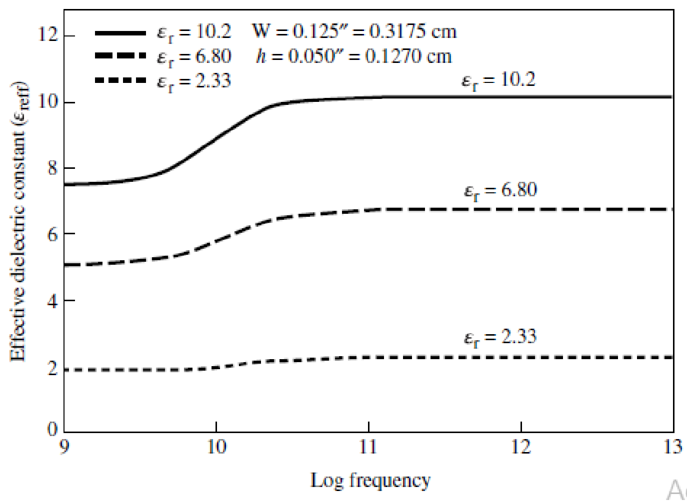

Figure 14.6 Effective dielectric constant versus frequency for typical substrates.

Then, we need to calculate the extended length of patch as shown in Figure 14.7. It can be determined from:

$$\frac{\Delta L}{h} = 0.412 \frac{\left(\varepsilon_{eff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{eff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)}$$

What is this ΔL?   Because of the fringing effect, the patch "looks" greater than the physical dimension (the actual size).

After accounting the extension, the effective length now becomes:

$$L_{eff} = L + 2\Delta L$$

The actual size L should be $L = L_{eff} - 2\Delta L$. Please do not get confused this part.

For dominant TM_{010}, <<Yet, I don't know how can we determine which mode is dominant. Maybe I should go over this later.>> the resonant frequency of patch antenna is a function of its length.

$$(f_r)_{010} = \frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\varepsilon_0 \mu_0}}$$

Note that this frequency doesn't account for the fringing effect.

After accounting the fringing effect (with scaled quantities, ε_{eff} and L_{eff}):

$$(f_{rc})_{010} = \frac{1}{2L_{eff}\sqrt{\varepsilon_{eff}}\sqrt{\varepsilon_0 \mu_0}} = q\frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\varepsilon_0 \mu_0}}$$

Where

$$q = \frac{(f_{rc})_{010}}{(f_r)_{010}}$$

This factor is called the fringing factor (***Length reduction*** factor).

The actual length of the patch can be calculated from:

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{eff}}\sqrt{\varepsilon_0 \mu_0}} - 2\Delta L$$

Typically, the length of the patch varies between

$$L \approx (0.47 - 0.49)\frac{\lambda_0}{\sqrt{\varepsilon_r}}$$

Note the wavelength in the dielectric can be calculated from:

$$\lambda_d = \frac{\lambda_0}{\sqrt{\varepsilon_r}}$$

i. Example – Design Patch Antenna

RT/duroid 5880 whose dielectric constant is:

$$\varepsilon_r = 2.2$$

$$h = 1.588\ mm$$

$$f_r = 10GHz$$

Calculated results:

$$\varepsilon_{eff} = 1.9715$$

$$L = 9.053\ mm$$

$$W = 11.85\ mm$$

$$\Delta L = 0.811\ mm$$

$$L_{eff} = 10.675\ mm$$

b.Conductance

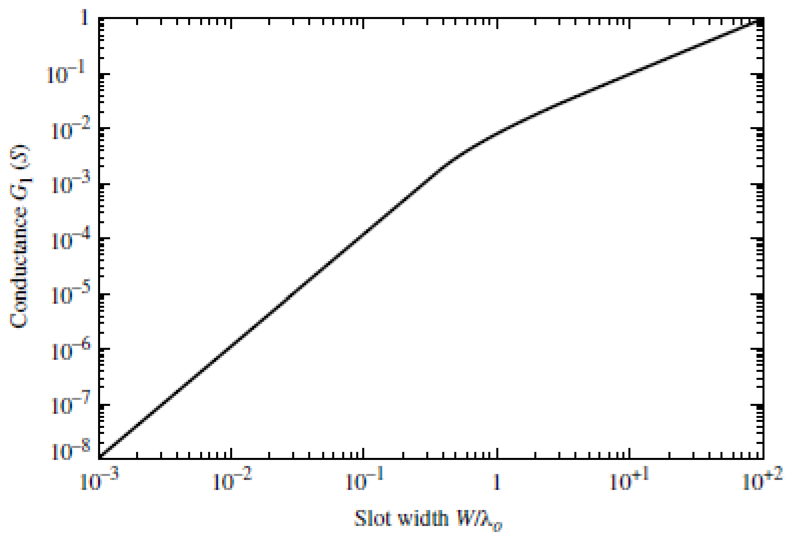

Figure 14.10 Slot conductance as a function of slot width.

c. Matching Techniques

Once the input resistance has been calculated by:

$$R_{in} = \frac{1}{2(G_1 \pm G_{12})}$$

Where the positive sign is for modes with odd (antisymmetric) resonant voltage distribution beneath the patch and the negative sign for modes with even (symmetric) resonant voltage distribution.

$$G_{12} = mutual\ conductance$$

Mutual conductance is defined in terms of far-zone field.

i. Example – Coupling Matching

In the previous example, we got the dimension of a rectangular patch antenna. Here, we try to match the antenna with 50-ohm transmission line feed.

Calculated results:

$$G_{12} = 6.167 \times 10^{-4}\ mho$$

$$G_1 = 1.736 \times 10^{-3}\ mho$$

$$R_{in}^{+} = 244.56\ ohm$$

$$R_{in}^{-} = 350.21\ ohm$$

The textbook claims that we need to the positive one since there is odd field distribution between radiating slots for the dominant TM_{010} mode.

$$R_{in}(y = y_0) = R_{in}(y = 0) \times \cos^2\left(\frac{\pi}{L} y_0\right)$$

$y = y_0 = {}^{L}/_{2}$	Voltage zero and current maximum
$y = 0$	Voltage maximum and current minimum

In this case,

$$R_{in}(y = y_0) = 50\ ohm$$

$$R_{in}(y = 0) = 244.56\ ohm$$

Hence,

$$y_0 = 3.175\ mm$$

From reference [3],

$$W_0 = 3.898\ mm$$

Where the thickness of copper was assumed as (from reference [4]):

$$t = 70\ \mu m$$

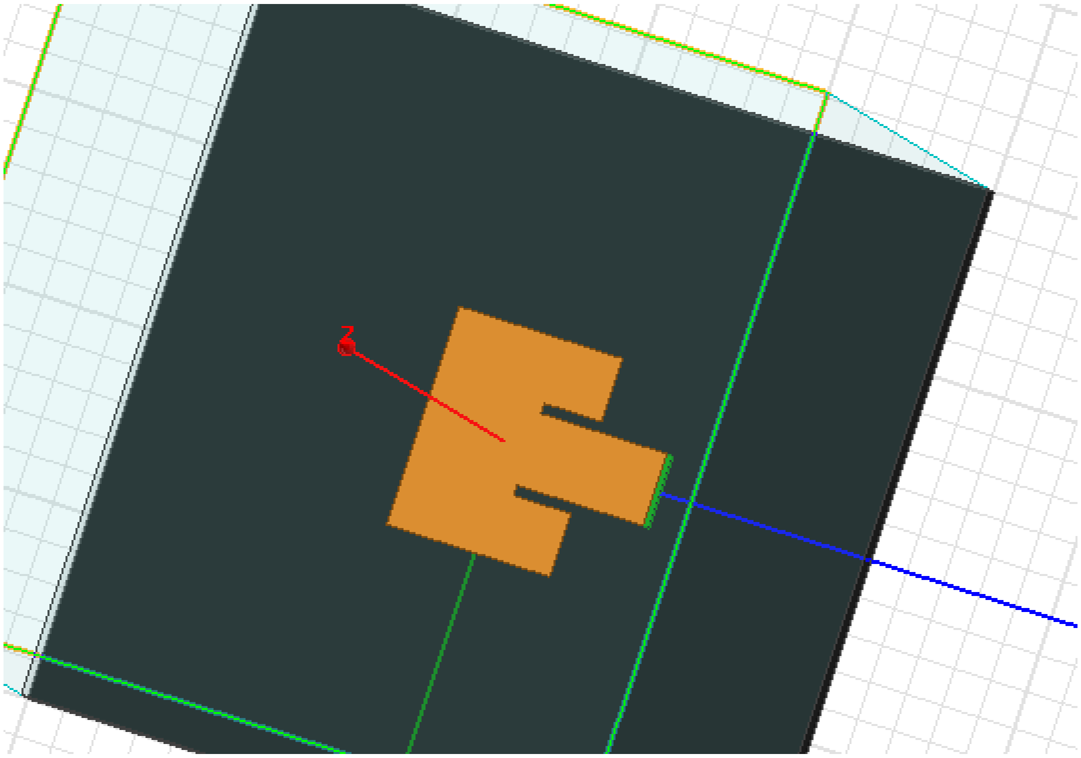

Figure. Rectangular Patch Antenna operating at 10GHz

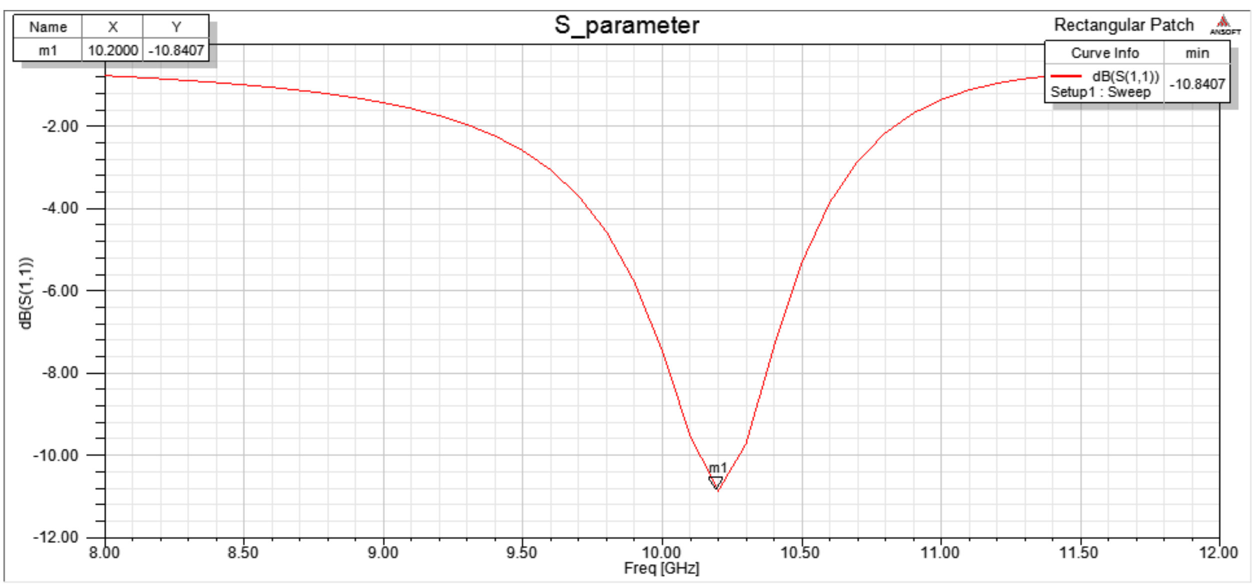

Figure. S parameter

As shown in the Figure, the patch antenna is matched at

$$f_{mathced} = 10.2GHz$$
$$S_{11}|_{10GHz} = -7.511dB = 0.421$$
$$S_{11}|_{10.2GHz} = -10.84dB = 0.287$$

The textbook pointed out the frequency shift (usually 10%) would occur if the patch is analyzed with transmission line method, which is the least accurate method for analysis.

My understanding is that a fairly good design would require around -20dB (10% reduction) for the reflection coefficient.

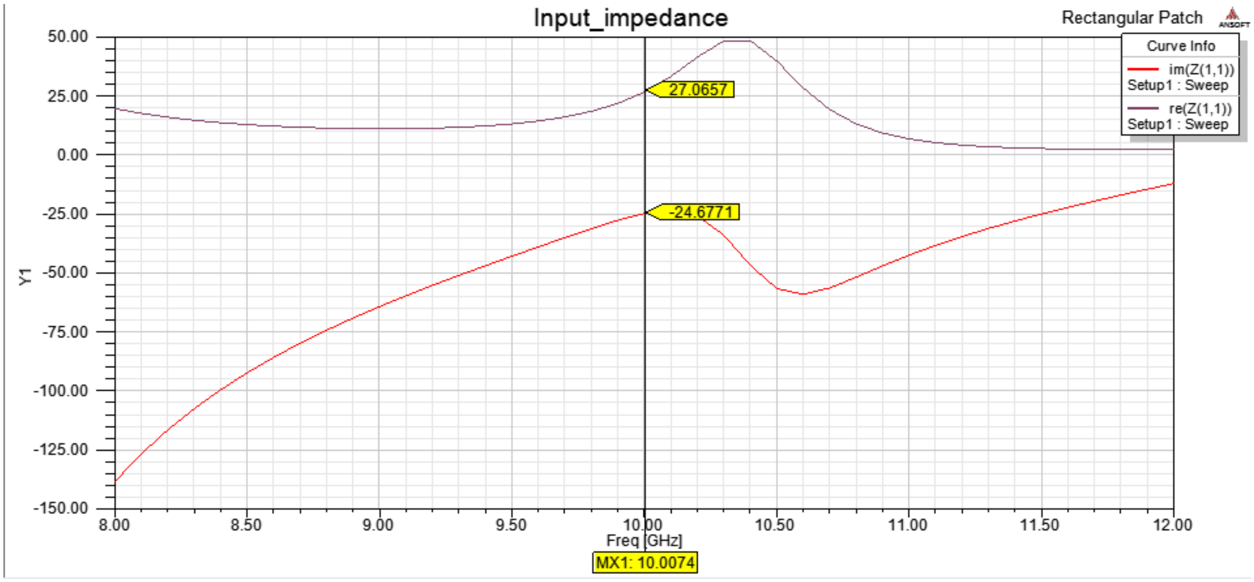

Figure. Input Impedance Plot

The input impedance is:

$$Z_{in}|_{10GHz} \approx 27.1 - j24.67\ ohm$$

$$Z_{in}|_{10.2GHz} \approx 41.6 - j26.2\ ohm$$

This reactance is another obstacle to be taken down in order to enhance the performance of the patch antenna.

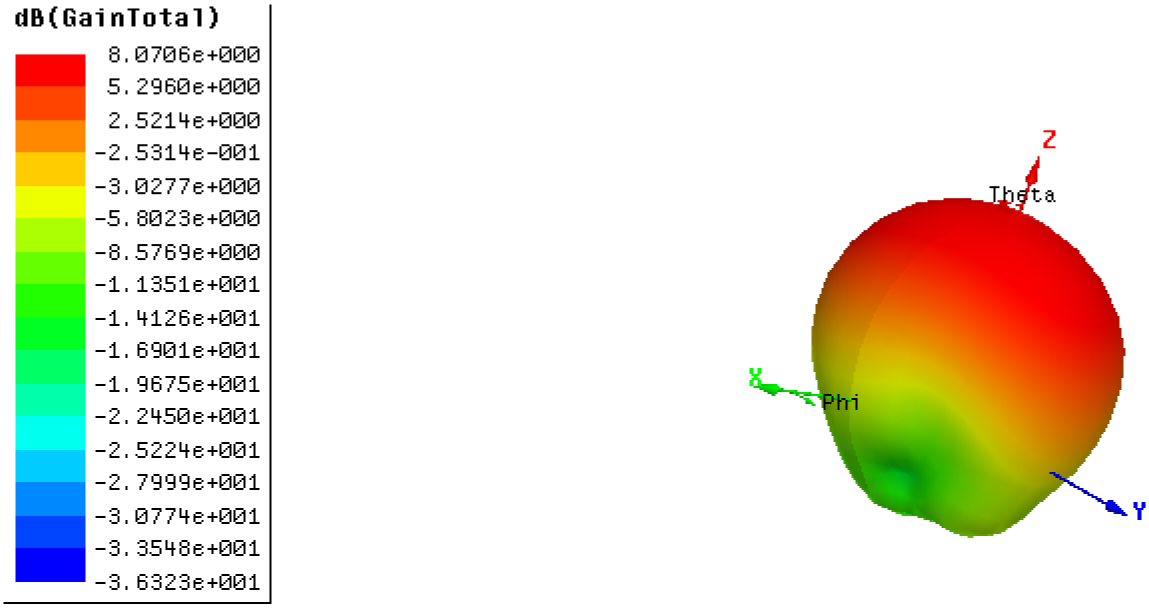

Figure. Gain in 3D plot

ii. Fabrication Tips

For printed antennas designed using HFSS following are the steps for antenna fabrication:-

* Click Modeler in the Menu bar of HFSS and then click Export.

* Select the file type to be .dxf and provide name to the file and location.

* Keep in mind that HFSS will export 2D design of the antenna which means whatever is at z = 0 mm. If you want to the top patch design also then you have to shift that to z = 0 mm and export it as a separate file.

* Then the dxf file can be opened using some CAD software or Corel Draw.

* Fill the region where you want conductor and rest to be white. So that it can be etched.

* Follow the conventional PCB fabrication process i.e. screen printing, masking, etching etc.

Figure. [5]

d.Conclusion of Rectangular Patch

The fringing effect will increase as the dielectric constant of substrate reduces. This will lead to a smaller patch length. Let’s think of it in the following way: substrate is like ***a sponge*** that it ***absorbs*** the electric field lines (or, concentrate them in the center of patch). As the dielectric constant of substrate increases, the more intense electric field would be concentrated in the dielectric; thus, reducing the fringing effect, lowing the microstrip patch length.

Another variation can be made with the height of a substrate. As the height of substrate increases, the more fringing effect would occur because of the larger separation between the patch and the ground plane.

VI. References

[1] Antenna Theory Analysis and Design, Constantine Balanis, 4th Edition

[2] https://en.wikipedia.org/wiki/Speed_of_light

[3] https://www.everythingrf.com/rf-calculators/microstrip-width-calculator

[4] https://www.seeed.cc/How-to-use-the-relationship-of-copper-foil%27s-thickness%2C-width-and-current-to-calculate-the-accurate-value-of-PCB-t-5957.html

[5] https://www.researchgate.net/post/Fabrication_of_Microstrip_antenna