Antenna Lab – Final Project

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1. Introduction to Microstrip Antennas (Summary of Lecture + Other References)

History and Motivation

These kinds of antennas are used since **1970's**. As the benefits of using microstrip antennas were revealed to the scientific society, and with the **development** of **PCBs**, and also due to **recent developments** of **communication systems**, the need of using a **small** and **simple** antenna with a **planar profile** that **obtains desired parameters**, especially in wireless systems, arose.

Main Structure

Microstrip antennas are considered as a **kind of internal antenna** usually used in **microwave frequencies** (1GHz – 1THz), which **are fabricated using photolithographic techniques on a PCB** (printed circuit board)

Microstrip antennas are somehow **similar** to **traditional plane capacitors** in **structure**:

Plane capacitors operated based in the electric field generated due to the potential difference between conductive planes which caused **electrostatic energy** to be **stored** in a **dielectric** placed between.

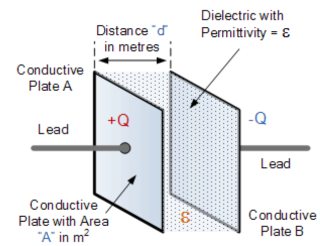


Figure 1.1 – Structure of a plane capacitor

Now, by **violating** the **exact alignment** of the **conductive planes**, the electric field is **no longer completely stored** within the planes and we some kind of **radiation**. This is quite interesting that what we prevent to do in capacitors for preserving energy, actually becomes a **motivation** to a **design** a **radiating structure**.

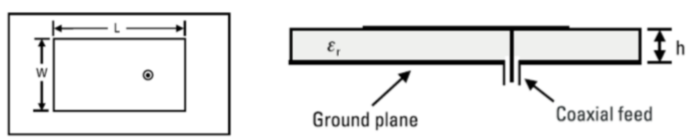


Figure 1.2 – Structure of a simple microstrip antenna

The **upper-plane** which causes radiation is called the **antenna patch**. The patch is **connected** to a **voltage source** via a **coaxial feed**. The **lower-plane** which **maintains** the **bounded radiation** is called the **ground plane**.

Due to low penetration depth in these conductive planes, we use a thin layer of them (low thickness):

$$t_{patch} \ll \lambda_0 \ (Eq\ 1.1)$$

Main radiation parameters are affected the **thickness** of the **dielectric layer** and the **length** and **width** of the **patch**. The **dielectric layer** should be **thick** enough, that the **radiated energy** is **much more** than the **stored energy** of the equivalent capacitor of this structure, resulting in **higher efficiency** and **lower inductive power**.

$$C = \frac{k\varepsilon_r\varepsilon_0 A}{h} \Rightarrow C \downarrow = \frac{k\varepsilon_r \downarrow \varepsilon_0 A}{h \uparrow}$$

$$0.003\lambda_0 \leq h_{dielectric} \leq 0.05\lambda_0 \ (Eq. 1.2)$$

$$\frac{\lambda_0}{3} \leq L_{patch\ (rect.)} \leq \frac{\lambda_0}{2} \ (Eq. 1.3) \rightarrow W_{patch\ (rect.)} = ? \rightarrow L, W_{ground} = ?$$

Not bad to mention that **most microstrip antennas** have an **array-based structure** consisting of **multiple patches placed beside one another** in a pre-defined topology and also a **common ground plane**.

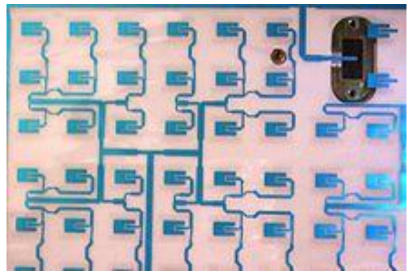


Figure 1.3 – Structure of a microstrip antenna array used in satellite television receivers

Patch Topology

Antenna patches can have different shapes based on the application and the radiation parameter values we want to obtain. Typical used shapes are shown in the figure below.

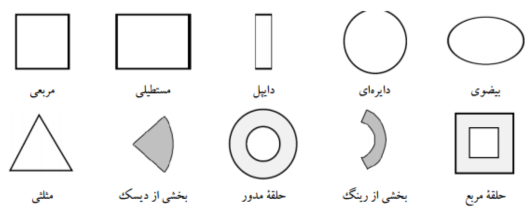


Figure 1.4 – Common patch topologies used in microstrip antennas

Choosing **square and rectangular shapes** for patches leads to **simple design** and **easier parameter tuning**.

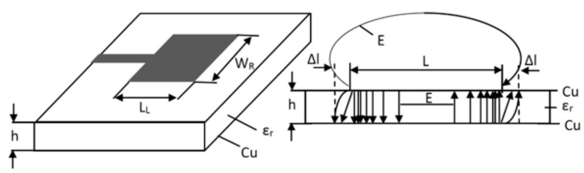


Figure 1.5 – Different views of a microstrip antenna

The **radiation** is occurred by means of the **front** and **back** side of the patch and not the **lateral sides.** The equivalent circuit of the patch is shown in the figure below:

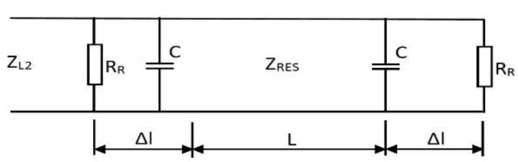


Figure 1.6 – Equivalent circuit for a radiating patch

The **Capacitors** and the **Resistors** in the **front** and **backside** of the antenna model the **fringing fields. (**It's ideal to choose as small capacitors as possible and large radiation resistors.) But first we should discuss "What is the fringing effect and how is it caused?"

Fringing Effect

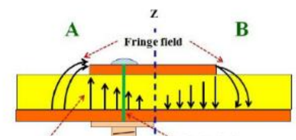


Figure 1.7 – Fringe fields in a rectangular patch

Fringing happens due to the airgap in a circuit. This makes the flux density of an airgap differ from the flux in the core.

Fringing fields have a great effect on the performance of a microstrip antenna. In **microstrip antennas** the **electric filed at the center of the patch is zero**.

The **radiation is due to the fringing field between the periphery of the patch and the ground plane**. For a rectangular patch, there **is no field variation along the width and thickness** [1]

E-plane, H-Plane & permittivity in microstrip antennas

The **E-plane** is **parallel** to the **direction** which **current** is fed to the antenna, and the **H-plane** is respectively **perpendicular** to it.

Radiated waves **travel both through the dielectric** and **air** so we should somehow find the **effective relative permittivity** ($\boldsymbol{\varepsilon_{eff}}$)according to the patch structure, which is smaller than the relative permittivity itself ($\boldsymbol{\varepsilon_r}$). Various models have been proposed but among all “Bahl & Trivedi” ‘s formula is more common. [2]

$$\text{when } \left(\frac{W}{H}\right) < 1$$

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\left(1 + 12\left(\frac{H}{W}\right)\right)^{-1/2} + 0.04\left(1 - \left(\frac{W}{H}\right)\right)^2\right]$$

$$\text{when } \left(\frac{W}{H}\right) \geq 1$$

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\left(\frac{H}{W}\right)\right)^{-1/2}$$

Eq. 1.4 – ‘Bahl-Trivedi’ formulation for ε_{eff}

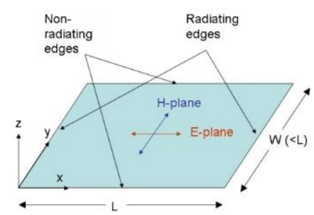


Figure 1.8 – E-plane & H-plane orientation

Length and Width Estimation and effective parameters

There’s a more precise formula for (Eq. 1.3) which suggests an upper bound for the length the microstrip according to the effective permittivity calculate by methods such as “Bahl-Trivedi” method.

$$L < \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} (Eq. 1.5)$$

To **increase** the **radiation power** of the patch we can:

1. **Increase** the **width** of the patch so more waves can fit more **current surfaces** within the patch structure.
2. **Increase** sublayer **thickness.**
3. **Decrease dielectric constant** (ε_{eff})

A set of equations to estimate proper the length and width are shown in the equations below. [3], [4]

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \text{ (Eq. 1.6)}$$

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}}\ ,\quad \Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \Rightarrow L = L_{eff} - 2\Delta L\ (Eq. 1.7)$$

Pros and Cons of Microstrip Antennas:

Pros (+):

- Light weight and small size make implementation easier
- Attachable on planar surfaces
- Using PCB technology, Cost efficiency
- Can be combined with microwave circuits
- Generating linear and circular polarizations
- Used in Mobile communication systems in an embedded fashion.
- Frequency Variability (Reconfigurability)
- Pattern and Radiation Variability

Cons (-):

- Low BW
- Low Gain
- Low quality Power Matching
- Polarization isn't completely linear or circular

Applications

- Missile communication (appropriate for planar surfaces)
- Height measurement devices use array based microstrips
- Satellite and telephone communication
- Aerial Imaging
- Marine Communication
- Intelligent Weapons
- Pagers, GSM system and GPS.

A variant of patch antennas known as Inverted F antennas, which are widely used in wireless communications due to better impedance matching and more compact structure. It consists of a monopole antenna parallel to a ground plane and grounded at one end.

The most common type of these antennas is known as PIFA (planar inverted F Antennas). In this kind of antenna one corner of the patch is grounded with the partially-attached ground plane.

Figure 1.9 – Inverted-F Antenna

2. Design Considerations

Step 1: Designing Patch and Ground Plane:

The main parameters which affect patch size:

- Operation Frequency
- BW
- Material

There are some papers which have worked on how to define the **dimensions of the corresponding ground plane** according to the dimension of a patch. **Antenna BW** and **Gain** peak at some point. **Researches** are mainly based on **optimizing** these **2 parameters** with respect to the dimensions and next trying to explain the results theoretically. [5]

$$L, W = argmax_{(L,W)}(BW, G) - (Eq. 2.1)$$

Step 2: Choosing substrate dielectric and its thickness:

Choosing **strong dielectrics** (large ε_r) make wave propagation **media loss larger**, but also **decrease effective wave length** which directly **decreases patch size** which is **desired for small devices**, so **choosing proper permittivity** is often considered as a **trade-off** according to our application.

$$1.2 \leq \varepsilon_r(usual) \leq 2.2 \quad (Eq. 2.2)$$

Another important issue is to choose a dielectric with low tangent loss.

Step 3: Designing the feed

We should choose a network which has the **best impedance matching** to our patch. **Coaxial lines** which feed current to the antenna, have a typical **impedance** of 50Ω**.** To obtain **ideal matching** and eventually high **VSWR** and **BW**, We, can attach a **feed line** to the antenna with such a **characteristic impedance**, that matches the total seen impedance equal to 50Ω.

Bahl and Trivedi, [2] have also suggested formulas to obtain characteristic impedance according to the dimensions and the material. Which we will not use due to the fact that PCAAD will calculate it for us.

$$when \left(\frac{W}{H}\right) < 1$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}} \ln\left(8\frac{H}{W} + 0.25\frac{W}{H}\right) \; (ohms)$$

$$when \left(\frac{W}{H}\right) \geq 1$$

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}} \times \left[\frac{W}{H} + 1.393 + \frac{2}{3}\ln\left(\frac{W}{H} + 1.444\right)\right]} \; (ohms)$$

(Eq. 2.3)

3. Parameter Calculation of Rectangular Patch Microstrip Antenna

Desired parameters for my microstrip design are shown in the table below:

Radiation Frequency	$7Ghz$
Patch Topology	Rectangular
BW $(\frac{\Delta f}{f})$	$5\% = 350MHz$
Gain	$\geq 3dB$
VSWR	$2:1$
Substrate	$FR-4$
Polarization	Linear

Table 3.1 – Radiation Characteristics of my patch

Step 1-Finding ε_r and $tg(\delta)$, proper thickness for FR-4 sublayer

$$\lambda_0 = \frac{3 \times 10^8}{7 \times 10^9} = 4.285(cm)$$

I found a paper published on the variability of **relative permittivity of FR-4** along **frequency**. The fact is that **sublayer** change **behaviour** according to the wave **frequency** they are reacting to. FR-4 is known to have $\varepsilon_r = 4.4$, but experiments show a **decrease** in **permitivitty** in **higher freqencies**. [6] This can be due to the fact that **a material's net polarization drops** as each polarization mechanism ceases to contribute, and hence its **dielectric constant drops.**

$$\varepsilon_{r(FR-4, f=7Ghz)} = 4.2$$

According to another paper that used the same frequency as I did and the same material (FR-4). The **loss tangent** is about 0.021. This paper has also used a **thickness** of 1.6mm. [7]

$$tg(\delta)_{(FR-4, f=7Ghz)} = 0.021$$

$$h_{(FR-4, f=7Ghz)} = 1.6\ (mm)$$

Step 2- Initializing Length, Width & Thickness of the patch

- *Based on 'Bahl-Trivedi 'Equations [2]*

I have used equations (1.6), (1.7) introduced in the first chapter to initialize length and width of the patch.

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{3\times10^8}{2\times7\times10^9}\sqrt{\frac{2}{5.2}} = \frac{3}{140}\sqrt{0.385} = 0.01329\ (m) \quad \boxed{\Rightarrow W = \mathbf{1.329}\ (cm)}$$

According to the fact that $\frac{W}{h}(initial) \geq 1$, using 'Bahl-Trivedi' formula [2](Eq. 1.4):

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+\frac{12h}{W}}}\right] = \frac{5.2}{2}+\frac{3.2}{2}\left[\frac{1}{\sqrt{1+\frac{12(0.16)}{1.329}}}\right] = \mathbf{3.6233} \quad \boxed{\rightarrow \lambda_{eff} = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} = 2.252(cm)}$$

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} = \frac{3\times10^8}{2\times7\times10^9\times1.9035} = 1.1257(cm) \quad \boxed{\Rightarrow L = L_{eff} - 2\Delta L = \mathbf{0.981}(cm)}$$

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} = 0.412(0.16)\frac{33.6237}{(3.3653)(9.10625)} = 0.0723$$

$$\boxed{\Rightarrow Aspect\ Ratio = \frac{L}{W} = \mathbf{0.738}}$$

- *Based on simple approximation:*

$$\boxed{L = 0.49\,\lambda_{eff} = 1.103(cm)}$$

Using the same aspect ratio derived from the previous method we obtain the width:

$$\boxed{W = 1.495(cm)}$$

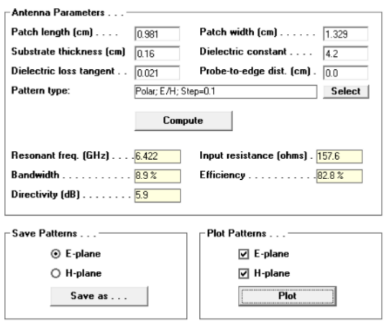
Thickness of the patch

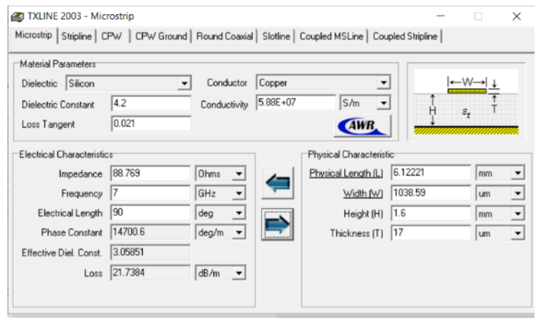
- According to the video #1, the thickness of usual metals in microstrips are:

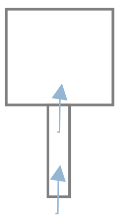
$$\boxed{t_{patch} = 17(\mu m)}$$

Step 3– Calculating characteristic impedance of the patch, load matching and feed design

By giving PCAAD the dimensions, $\varepsilon_r, tg(\delta)$ and plugging in the results in TX-line:







$$Z_{feed} = \sqrt{Z_{line} \times Z_{patch}} = \mathbf{88.769}\ (\Omega)$$

$$L_{feed} = \mathbf{6.1221} (mm)$$

$$W_{feed} = \mathbf{1038.59} (\mu m)$$

Step 4–Calculating Substrate Length and Width:

According to the video, the **substrate** should **be at least 2 times larger** than the patch, I assume a **guard band around** this **size** to and make **the length about 2.5 times larger and the width about 1.5 times larger than the current patch** to make further configurations.

$$\boxed{\Rightarrow W_{substrate} = \mathbf{2}\ (cm)}$$

$$\boxed{\Rightarrow L_{substrate} = \mathbf{2.5}\ (cm)}$$

4. Design procedure in HFSS

Step 1- Substrate:

The first step of design is to draw the substrate box of the antenna, according to the dimensions we chose for the substrate in the previous page.

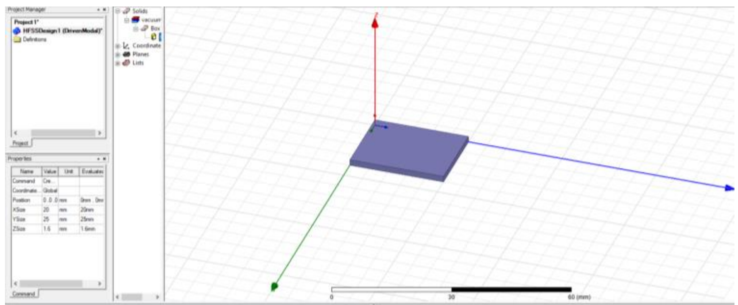


Figure 4.1 – Substrate Box

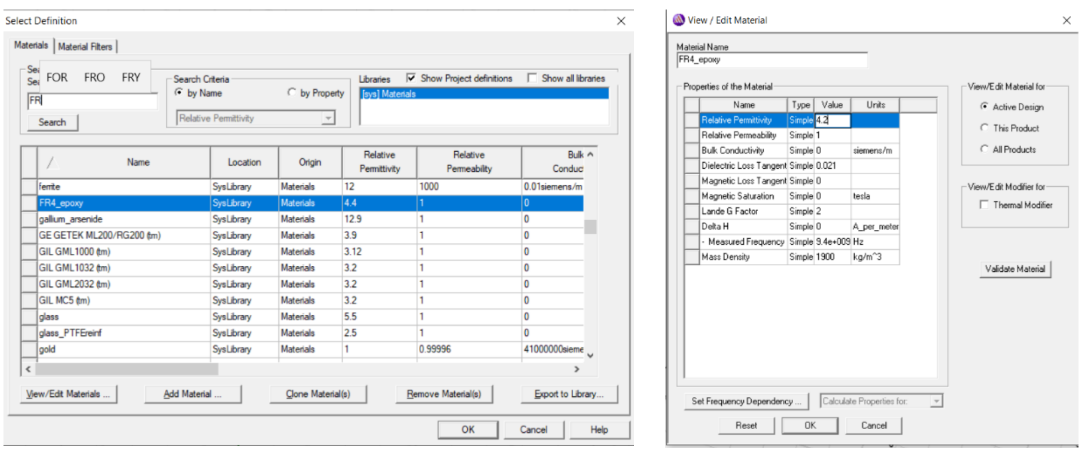


Figure 4.2 – Substrate Material Assignment

Step 2– Ground Plane:

The ground plane should completely cover the substrate. For easy simulation we can use zero-thickness ground planes. We should also move the ground layer beneath the substrate.

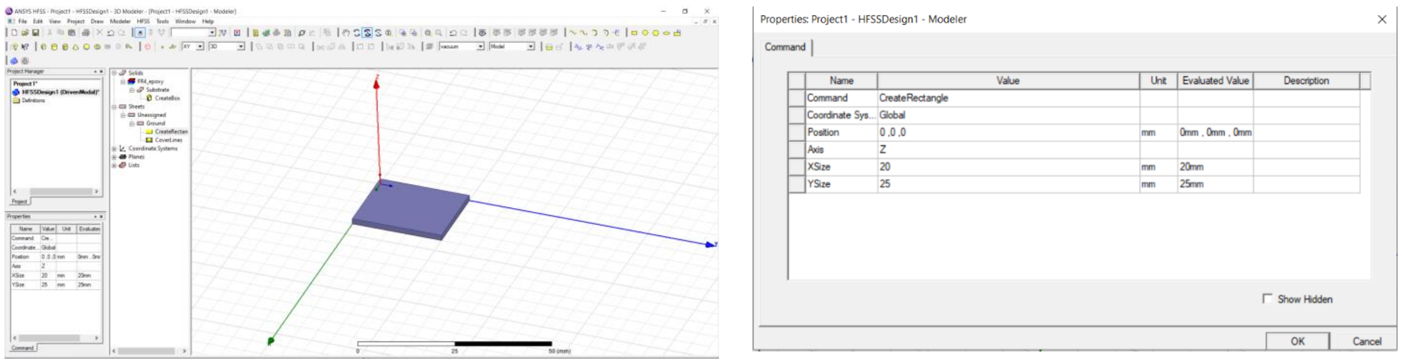


Figure 4.3 – Ground Box

Next, we choose a PEC material for the ground layer. We can assume the ground plane is infinite to make the simulation faster.

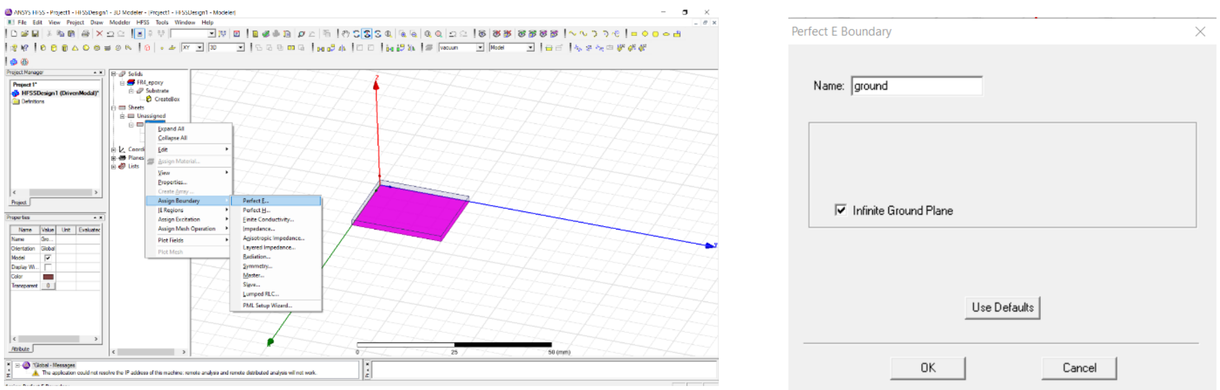


Figure 4.4 – Ground Material Assignment

Step 3– Antenna Patch:

We select a rectangular plane (without thickness) again and enter the dimensions we've calculated in the previous part.

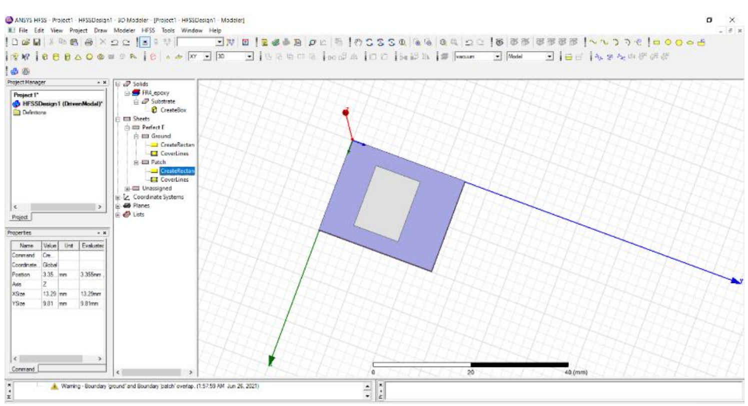


Figure 4.5 – Patch Design

Step 4- Antenna Feed:

According to the values obtained from TX-line, we design the feed, attached to the patch:

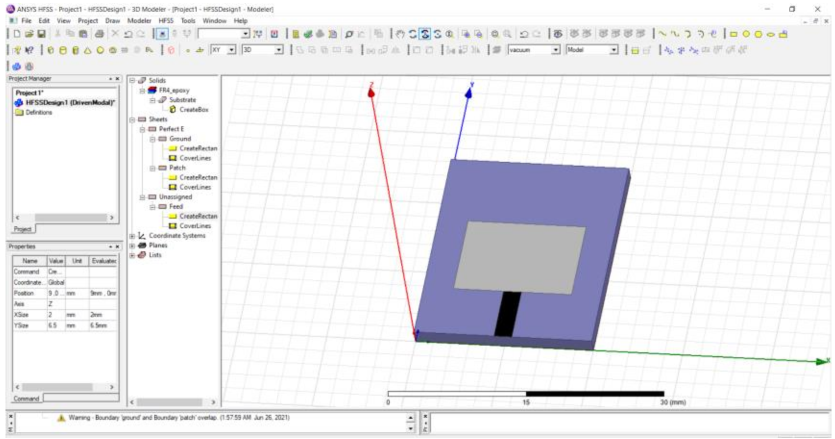


Figure 4.6 – Feed Design

Step 5- Antenna Port:

The port is parallel to the XZ plane so first we have to change the plane construction direction.

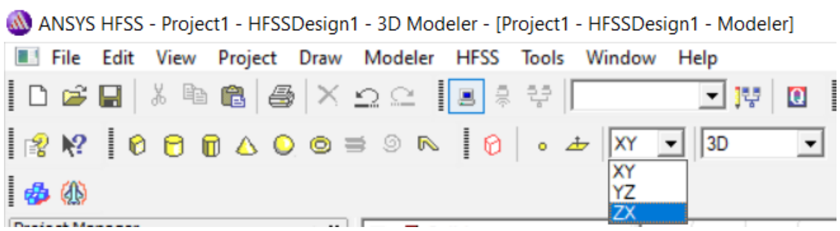


Figure 4.7 – Changing reference plane

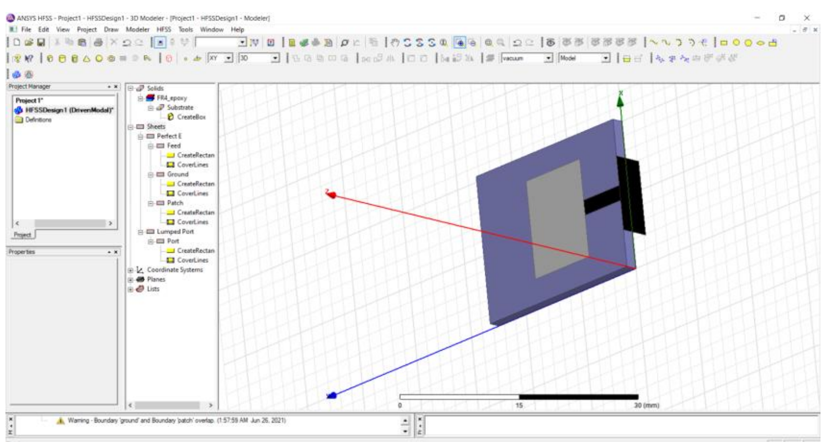


Figure 4.8 – Lumped port design

Step 6- Far-Field Box design:

The box should at least have dimensions of $\frac{\lambda_0}{4} = 1.052(cm)$, but for the patch to completely be inside I've decided to use a much bigger cube box of 60mm dimensions.

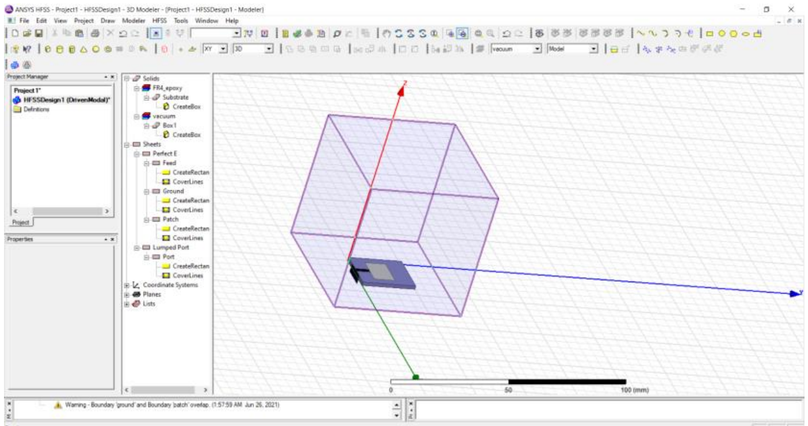


Figure 4.9 – Far-field box design

5. Analysis Simulation

First, we go to the analysis tab on the upper-left menu and click on add solution setup. We can change the number of passes according to the sweeping accuracy we want. Next, we can go to the setup we have configured and click on frequency sweep. Issue the frequency interval we want to examine and click OK. I used 6-8 GHz sweep with step size of 0.1 GHz.

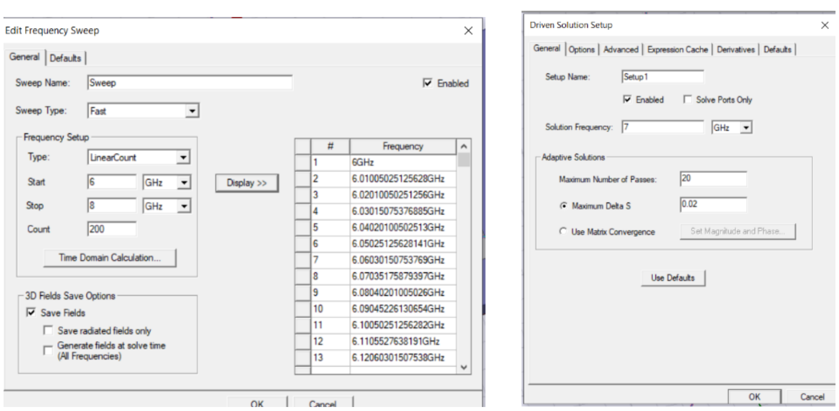


Figure 5.1 – Sweep and solution setup

At the end we check for validity of our simulation which I realized that some boundary conditions overlay and the app issues this problem as a warning

Next, we just start our analysis and let it run

6. Results and Parameter Tuning

Step 1- Plotting results

Next, we define our far field resolution. Then we set our plotting settings in the result tab. Sadly we observe a peak instead of a dive in our goal frequency.

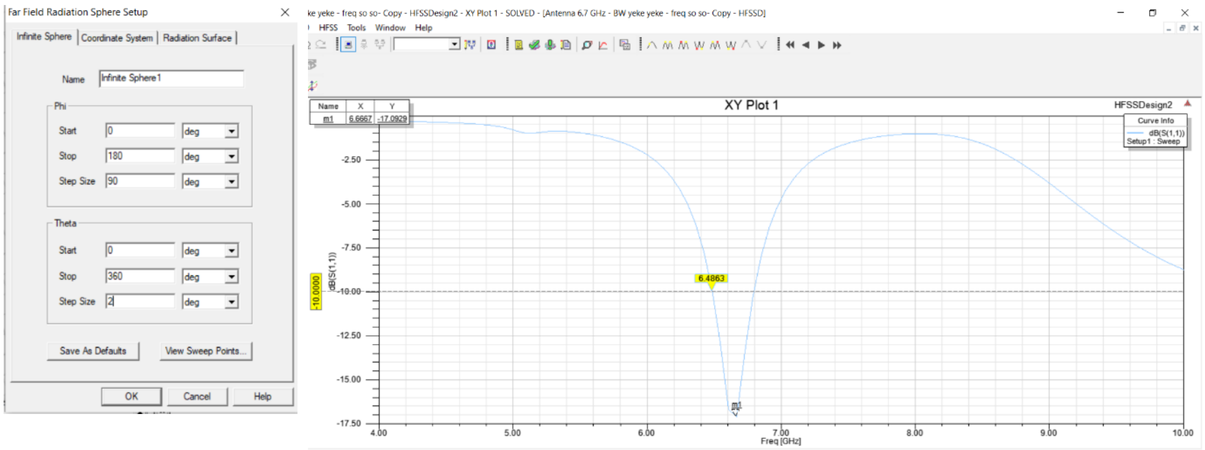


Figure 6.1 – Far field setup and initial results (S11)

Bandwidth is about **350MHz** which we wanted and **radiation frequency** has a **330MHz offset** which **isn't quite bad**. But by observing the gain and VSWR plots we see quite **unfortunate** results. A **gain** near **0.3** dB and **VSWR** of **1.3** around the radiation frequency.

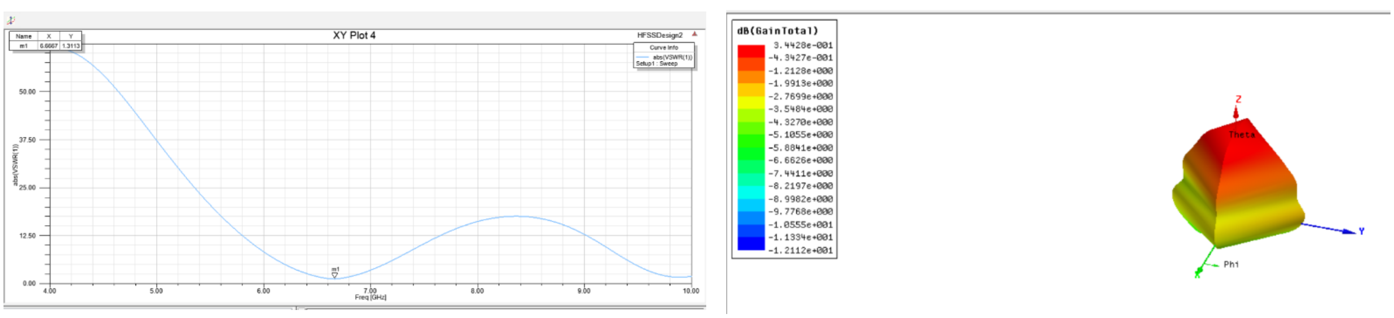


Figure 6.2 – VSWR and Gain plots for initial setup

Step 2- Improving results:

So, we have to improve the matching. The **first way is to increase the thickness** of the **sublayer**, we **will move it to 3.2(cm)** from 1.6(cm). but as it has effect on the desired dimensions of the feed which causes a warning on the width of the feed becoming dangerously large. So instead of this way w**e perform an optimization on patch dimensions** in the frequency range of 6-8.

Figure 6.3 – Warning on high width

Step 2.1 – Defining parameterized values and decreasing width with fixed AR

To perform an optimization, we should define our values as parametrized values. To do so we go do design properties and select add variable.

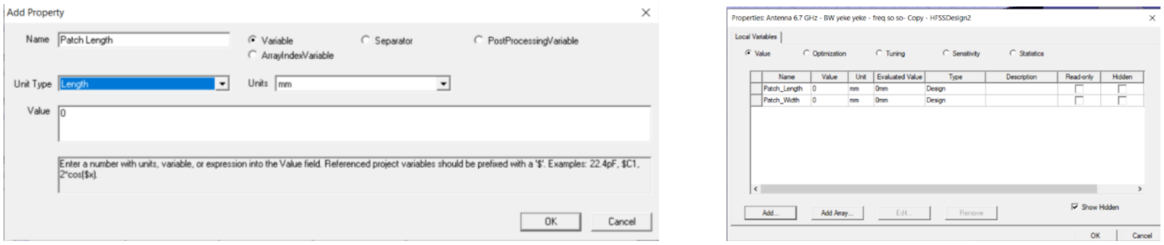


Figure 6.4 – Variable definition

Next, we should assign parameterized values to our patch, I also decreased the width a little bit, holding the aspect ration fixed (L = 0.738w), to just change the radiation frequency.

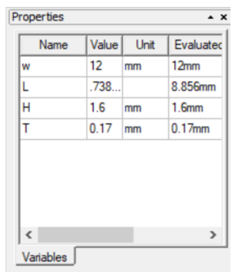


Figure 6.5 – Assigning parameterized values to patch

By plotting the results, we see that the radiation frequency has come very close to 7GHz

$(W = 12.5mm, L = 0.739W = 9.24mm)$

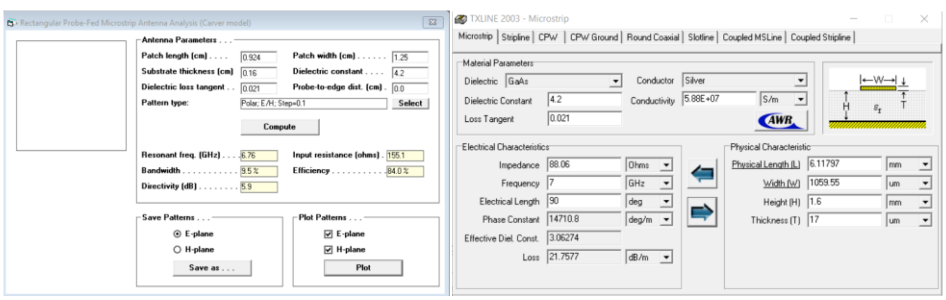


Figure 6.6 – Finding feed dimensions for W = 12.5mm, AR = 0.738

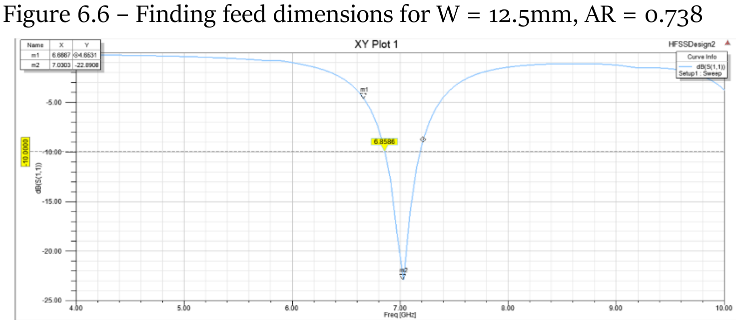


Figure 6.7 – S11 plot for W = 12.5mm, AR = 0.738

We obtain a much better gain (about 5dB), a fair BW (about 5%), an accurate frequency, but a pretty low VSWR, showing low impedance matching.

Figure 6.8 – Gain(db) for W = 12.5mm, AR = 0.738

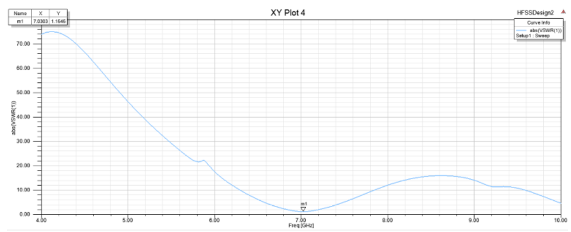


Figure 6.9 – VSWR(abs) for W = 12.5mm, AR = 0.738

Step 2.2 – Unifying Patch and Feed to ensure connection:

To ensure patch and feed connection I unified them as an object.

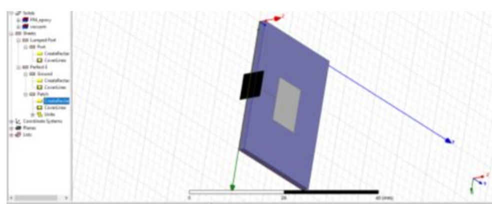


Figure 6.10 – Unifying patch and feed

Step 2.3 – Performing Optimization:

We can go the "Optimetrics" tab and select parametric. Select the range of variability for the patch length and width. To **check other AR's**. I personally didn't get quite better results but I wanted to test optimization too.

(I used 5 counts for width covering 8-16 mm's along 7 counts for length covering 5-11 mm's, resulting in a total of 35 runs which took about an hour and a half to simulate)

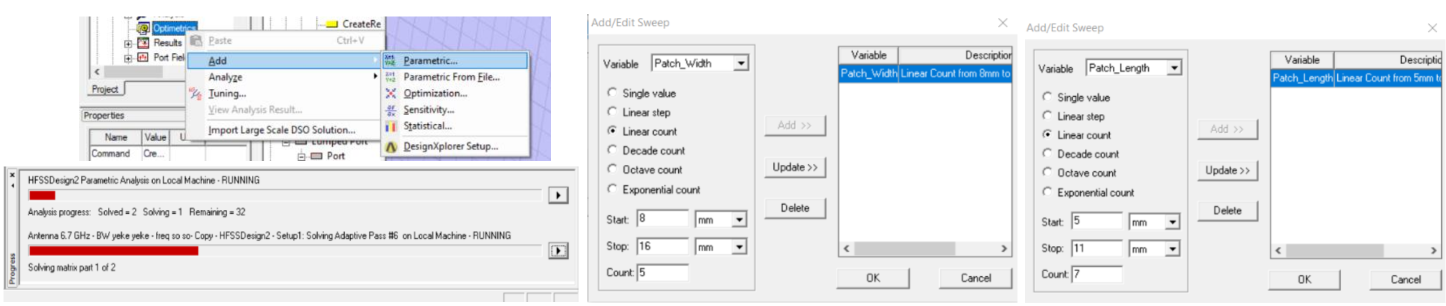


Figure 6.11 – Patch length and width optimization

7. Final Results

After multiple runs **everything except VSWR was optimized,** Unfortunately, I couldn't achieve better VSWR for the optimized design with respect to gain, frequency accuracy and BW. But I have reached VSWR of about 1.6 in previous runs which is shown among the figures below. $(\boldsymbol{f} = 7.03GHz, \boldsymbol{BW} \approx 360MHz, \boldsymbol{Gain} = 4.85dB, \ldots)$

(The file corresponding to this design is also available in the zip folder of the project. It is named "VSWR_better")

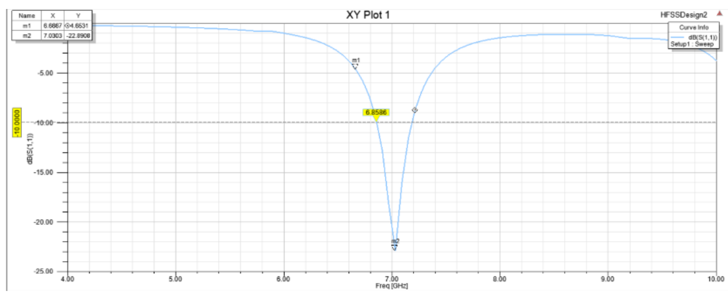


Figure 7.1 – S11 plot for main file

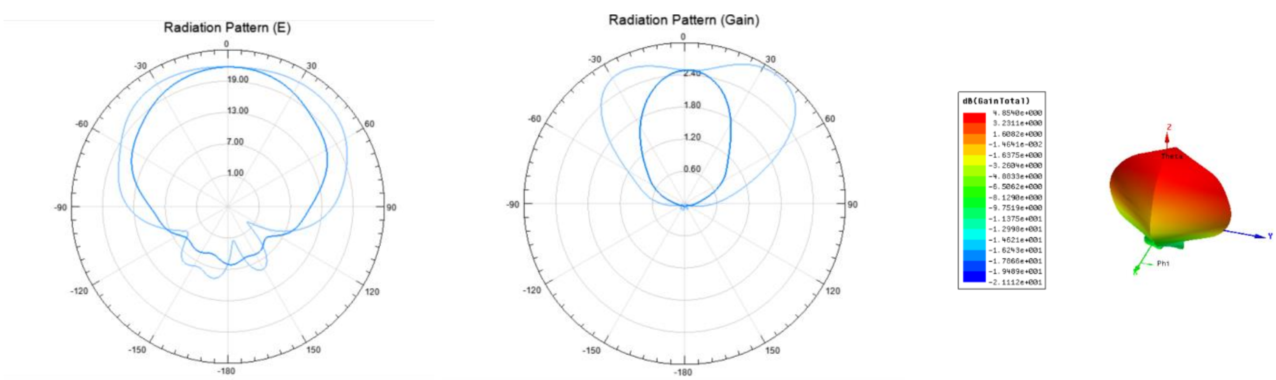


Figure 7.2 – Gain and Directivity Patterns for main file

$(L = 9.24(mm), W = 12.5(mm), AR = 0.739, h = 1.6(mm), t = 17(\mu m), \varepsilon_r = 4.2\ (FR - 4\ @\ \&GHz)$

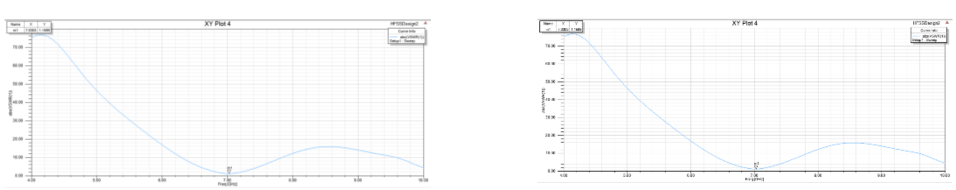


Figure 7.3 – VSWR for main file (right figure) and second file (left figure)

8. References

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