

## **CHAPTER 3**

### **DESIGN OF MICROSTRIP PATCH ARRAY ANTENNA**

#### **3.1 Introduction**

This chapter is discussed on the various factors that affect the design of microstrips patch array antenna. This chapter will covered the steps involved in designing the single patch and array antenna. In general, the construction of the microstrip patch array antenna is divided into four parts; the first part is on the design specification, the second part is on the single microstrip patch antenna design, the third part on the microstrip patch array antenna design and the last part on the design and simulation using Microwave office (MWO).

#### **3.2 Design Specifications**

Before designing the antenna, the first step is to consider the specification of the antenna base on it application. After performing some research, the various parameters are listed in the Table 3.0.

**Table 3.0:** Single Patch Antenna Design Specifications

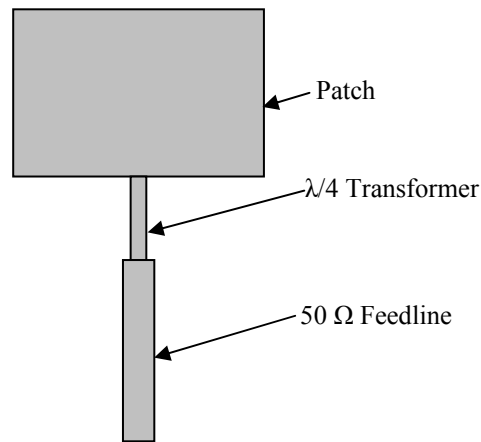
Frequency	2.45 GHz
Substrate	FR4
Dielectric Constant, $\epsilon_r$	4.7
Loss Tangent	0.019
Substrate Height	1.6 mm
Conductor Thickness	35.0 $\mu\text{m}$

The frequency 2.45 GHz is chosen because the frequency is suitable to test with the WATS equipment. The frequency also is widely used in a WI-FI application and the antenna can be used as a WI-FI antenna. As for the substrate selection, the major consideration will be the dielectric constant and loss tangent. A high dielectric constant will result in a smaller patch size but this will generally reduce bandwidth efficiency and might have difficulty in fabricating a very small patch size antenna. A high loss tangent will reduce the antenna efficiency.

RT Duroid 5870 was originally chosen as the substrate as it has a low loss tangent which will not reduce the antenna efficiency, and has a relatively low dielectric constant. It was replaced by FR4 as the cost of using RT Duroid 5870 exceeds this project's budget. FR4 in comparison has a higher dielectric constant which results in a smaller patch size but the high tangent loss will result in lower gain. This is not desirable but as the budget does not allow using RT Duroid 5870. One more point to note is the data sheet of FR4 obtained from the manufacturer does not show the value of the dielectric constant at GHz level. This is because FR4 does not have a very constant dielectric constant which limits usage to frequencies to 1 GHz or so. After analyzing the dielectric constant graph and some survey, it was decided that 4.7 was the value to use. This value might not be entirely true but nevertheless provide us with a start value to work with.

### 3.3 Single Microstrip Patch Antenna Design

The objective of this part is to design a single microstrip patch antenna which consists of patch, quarterwave transformer and feedline. For the patch antenna design, a rectangular patch antenna will be design. Since a 50  $\Omega$  surface mount adapter (SMA) connector is going to be used to connect the feedline to the coaxial cable, the feedline will be a 50  $\Omega$  feedline. The feedline will be feed to the patch through a matching network which is a quarter-wave transformer [1]. Refer to Figure 3.0.



**Figure 3.0:** Patch Antenna with Quarter-Wave Transformer.

The impedance of the quarter-wave transformer is given by the equation (3.1) [1].

$$Z_1 = \sqrt{R_{in} Z_0} \quad (3.1)$$

Where  $Z_1$  is the transformer characteristic impedance and  $Z_0$  is the characteristic impedance (real) of the input transmission line.  $R_{in}$  is the edge resistance at resonance.

### 3.3.1 Patch Calculations

The patch dimensions are calculated by using the equations (2.3) and (2.5). The following calculations are based on the transmission line model of Derneryd [2]. For the patch width equation (2.3) will be used. For the patch length, equations (2.5) and (2.7) are used. The edge resistance at resonance  $R_{in}$  can be calculated by using the equation (3.2) [5].

$$R_{in} = \frac{1}{(2G_e)} \quad (3.2)$$

$$\text{Where} \quad G_e = 0.00836 \frac{w}{\lambda_o} \quad (3.3)$$

$G_e$  is represent of edge conductance.

Details about the calculation for width,  $w$  and length,  $L$  for the patch are presented below. Calculation of  $R_{in}$  and  $Z_1$  also clearly visible.

#### 3.3.1.1 Calculation of Patch Dimension

Below is the calculation the width ( $w$ ), length, the improve length ( $L$ ), and fringe factor ( $\Delta L$ ) of microstrip patch antenna.

Calculation begin with the width,  $w$  of the radiating edge, using equation (2.3)

$$\begin{aligned} w &= \frac{c[(\epsilon_r + 1)/2]^{-\frac{1}{2}}}{2fo} \\ &= \frac{3 \times 10^8 [(4.7 + 1)/2]^{-\frac{1}{2}}}{2(2.45 \times 10^9)} \\ &= 36.266 \text{ mm} \end{aligned}$$

To obtain an initial value of  $L$ , calculation are based on equation (2.4)

$$\begin{aligned} L &= \frac{c}{2f_o\sqrt{\epsilon_r}} \\ &= \frac{3 \times 10^8}{2(2.45 \times 10^9)\sqrt{4.7}} \\ &= 28.241 \text{ mm} \end{aligned}$$

Using equation (2.5), to improved the value of  $L$ ,

$$L = \frac{c}{2f_o\sqrt{\epsilon_{eff}}} - 2\Delta L$$

Based on equation (2.6),

$$\begin{aligned} \epsilon_{eff} &= \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left( \frac{1}{\sqrt{1 + 12h/w}} \right) \\ \epsilon_{eff} &= \frac{4.7 + 1}{2} + \frac{4.7 - 1}{2} \left( \frac{1}{\sqrt{1 + 12(1.6 \times 10^{-3} / 36.266 \times 10^{-3})}} \right) \\ &= 4.3459 \end{aligned}$$

With this value of  $\epsilon_{eff}$ , the fringe factor  $\Delta L$  can be calculated using equation (2.7),

$$\begin{aligned} \Delta L &= 0.412h \frac{(\epsilon_{eff} + 0.300)(w/h + 0.264)}{(\epsilon_{eff} - 0.258)(w/h + 0.800)} \\ &= 0.412(1.6 \times 10^{-3}) \frac{(4.3459 + 0.300)(36.266 \times 10^{-3} / 1.6 \times 10^{-3} + 0.264)}{(4.3459 - 0.258)(36.266 \times 10^{-3} / 1.6 \times 10^{-3} + 0.800)} \\ &= 7.32069 \times 10^{-4} \end{aligned}$$

Therefore,

$$L = \frac{c}{2f_o\sqrt{\epsilon_{eff}}} - 2\Delta L$$

$$\begin{aligned}
&= \frac{3 \times 10^8}{2(2.45 \times 10^9)\sqrt{4.3459}} - 2(7.32069 \times 10^{-4}) \\
&= 27.9046 \text{ mm}
\end{aligned}$$

### 3.3.1.2 Calculation Of The Impedance For Quarter-Wave Transformer

Below is the calculation of the quarter-wave transformer impedance and the edge resistance at resonance.

Using equation (3.1) to compute the impedance for the quarter-wave transformer

$$Z_1 = \sqrt{R_{in} Z_0}$$

Where  $R_{in}$  is equal to edge resistance at resonance. By using the equation (3.2), the  $R_{in}$  can be calculate.

$$R_{in} = \frac{1}{(2G_e)}$$

Based on the equation (3.3)

$$\begin{aligned}
G_e &= 0.00836 \frac{w}{\lambda_o} \\
&= 0.00836 \frac{36.266 \times 10^{-3}}{0.12245} \\
&= 2.476 \times 10^{-3}
\end{aligned}$$

Therefore, using the value of the  $G_e$  above, the  $R_{in}$  can be calculating.

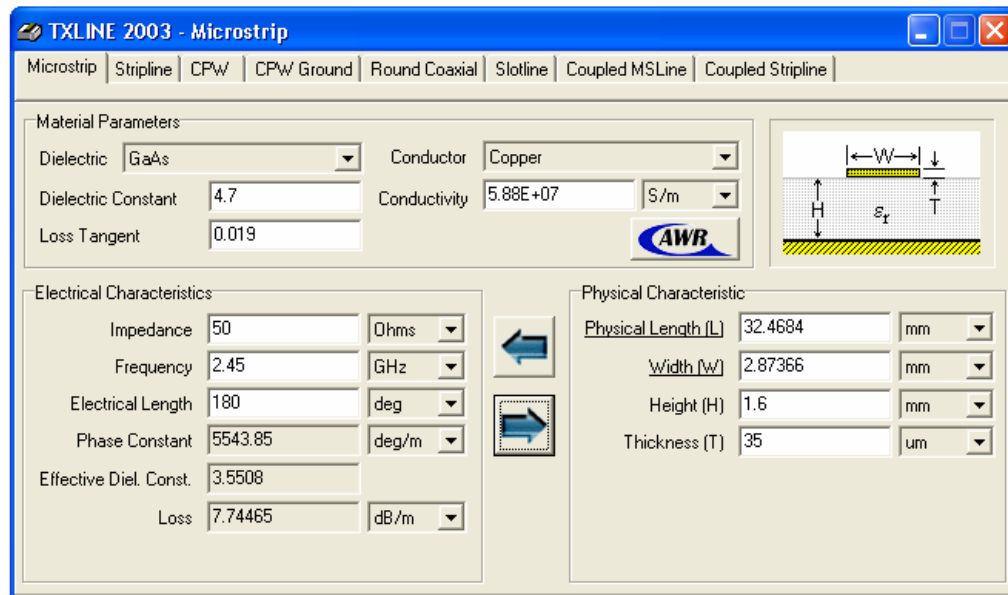
$$\begin{aligned}
R_{in} &= \frac{1}{(2(2.476 \times 10^{-3}))} \\
&= 201.94
\end{aligned}$$

Using the equation (3.1), where the  $Z_0 = 50 \Omega$  for the feedline.

$$\begin{aligned} Z_1 &= \sqrt{50(201.94)} \\ &= 100 \Omega \end{aligned}$$

### 3.3.2 Quarter-Wave Transformer and 50 $\Omega$ Feedline Calculations.

For the width and length of the quarter-wave transformer and 50  $\Omega$  feedline in this project are determined by the *Txline Calculator* in MWO software. Figure 3.1 show the screenshot of the *Txline Calculator*. However the value that obtained from *Txline Calculator* will be modified to suitable value suite with the fabrication technology that will be use to fabricate the antenna.

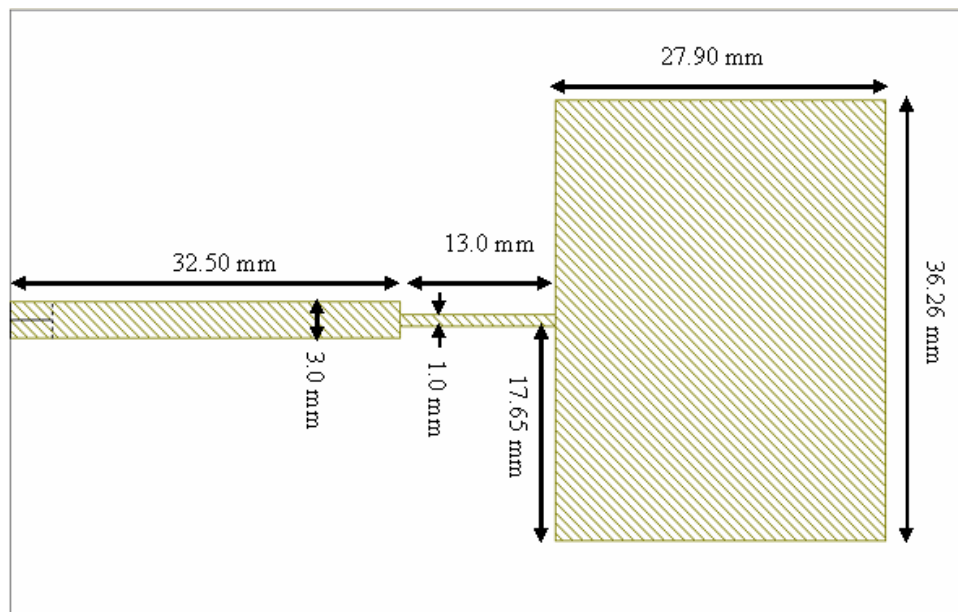


**Figure 3.1:** Screenshot of the *Txline Calculator*

The obtained values for the parameter are illustrated in the Table 3.1 and Figure 3.2 below.

**Table 3.1:** Dimension of Rectangular Patch Antenna

Patch	
Width, $w$	36.26 mm
Length, $L$	27.90 mm
$\lambda/4$ Transformer	
Width	1.0 mm
Length	13.0 mm
50 $\Omega$ Feedline	
Width	3.0 mm
Length	32.5 mm



**Figure 3.2:** Single Patch Antenna Design Layout



### 3.3.3 Radiation Pattern Calculation

The radiation pattern of the patch antenna can be calculated by using the equation 3.4 and 3.5 [13].

$$\text{E plane: } F(\theta) = \frac{\sin\left(\frac{K_o h}{2} \cos \theta\right)}{\frac{K_o h}{2} \cos \theta} \cos\left(\frac{K_o L}{2} \cos \theta\right) \quad (3.4)$$

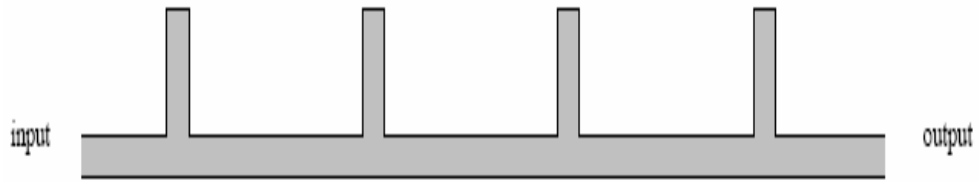
$$\text{H plane: } F(\phi) = \frac{\sin\left(\frac{K_o w}{2} \cos \phi\right) \sin \phi}{\frac{K_o w}{2} \cos \phi} \quad (3.5)$$

Where  $K_o = 2\pi / \lambda_o$

After all the important parameter has calculated, then the design procedure is proceeding to simulation stage using MWO software. The simulation process and result will be discussed at next chapter.

### 3.4 Microstrip Patch Array Antenna Design

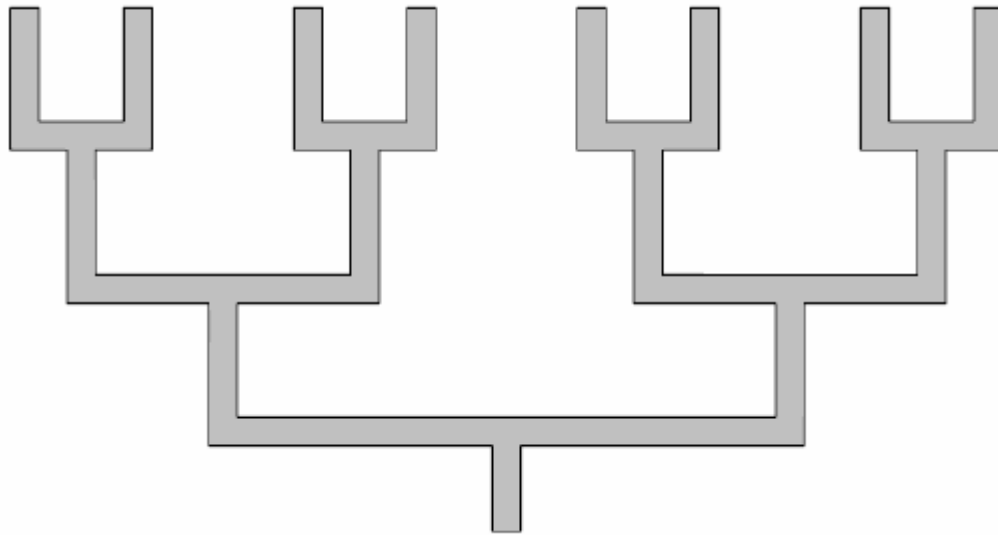
The existing feed methods for microstrip array can be categorized into series and corporate (parallel) feeds. Series feed normally consist of a continuous transmission line connected with a series of patch element as shown in Figure 3.3. Small portions of energy are coupled into the next element by various means which include proximity coupling, probe coupling or aperture coupling.



**Figure 3.3:** Example of Series Feed

There are two typical configurations for series feed arrays, transposed and untransposed. Figure 3.3 shows the untransposed configuration. As compared to parallel feed, series feed will normally have better overall antenna efficiency. This is because the number feed lines are fewer for the series feed which reduces the insertion loss. However series feed array have narrow bandwidth and inherent beam shift with frequencies due to the insertion phase shift of the patches.

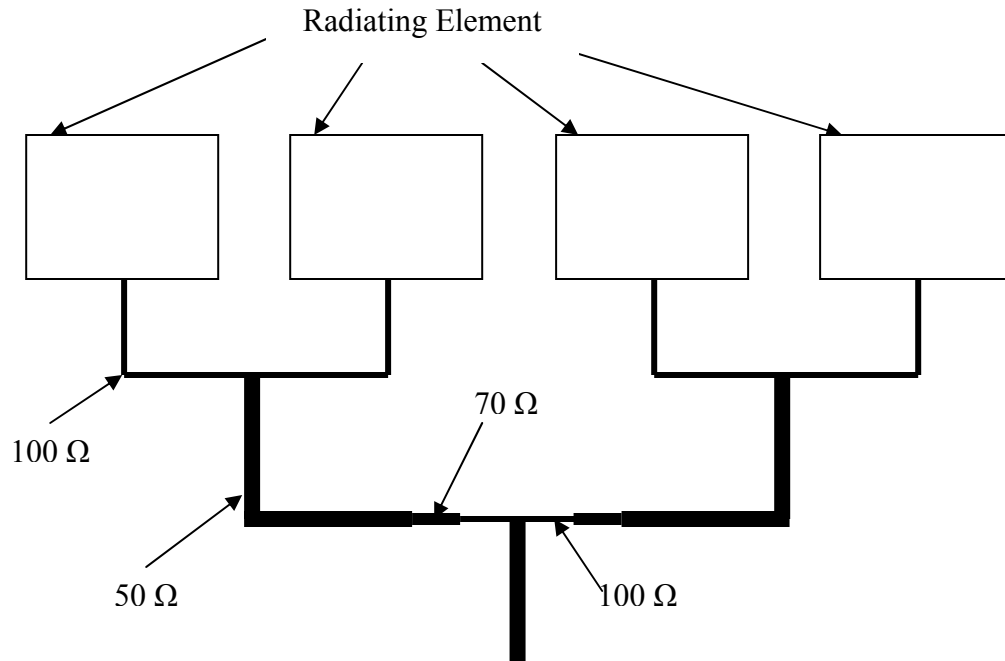
Corporate feed has a single input port and multiple feed lines in parallel which is terminated at an individual radiating element which could be a patch. One basic corporate feed is a one-dimensional network which consists of a two way power divider. This configuration is shown in Figure 3.4. This configuration is known as corporate feed and is the most widely used configuration.



**Figure 3.4:** One Dimension Parallel Feed Network

In this configuration, antenna elements are fed by 1:n power divider network. The power is equally divided at each junction if the lines distributions are symmetric. If the distance of from each radiating element to the input port is identical, the beam position is independent of the frequency. So by varying the position of the input with method such as line extension, the beam direction can be controlled. This is one of the advantages of this configuration. Others include design simplicity, flexible choice of element spacing and boarder bandwidth. The disadvantage of this feed is that since long transmission lines are used, insertion loss is also larger, reducing the efficiency of the array.

In this project, the corporate feed network is chosen for designing four element array networks. The array antenna consists of a branching network of two-way power dividers. Quarter-wave transformers ( $70 \Omega$ ) are used to match the  $100 \Omega$  lines to the  $50 \Omega$  lines. Figure 3.5 shows the impedance for individual lines in the four element array antenna.



**Figure 3.5:** Four Elements Array Line Impedance Design Layout

### 3.4.1 Array Calculation

The array calculation consists of two parts. The first is the patch calculation and the second is for 50 Ω, 70 Ω and 100 Ω transmission lines.

#### 3.4.1.1 Patch Calculation

Similarly the patch dimensions are obtained through equations (2.3) and (2.5) same as a single patch.

### 3.4.1.2 Calculation Of The Impedance For Quarter-Wave Transformer

Calculation for impedance is also similar as a single patch by using equations (3.1) to (3.3). However to matching the 100  $\Omega$  to 50  $\Omega$  transmission lines, the calculation step is shown below.

Using the equation (3.1), where by replacing  $Z_0 = 50 \Omega$  and  $R_{in} = 100 \Omega$ , the transformer characteristic impedance:

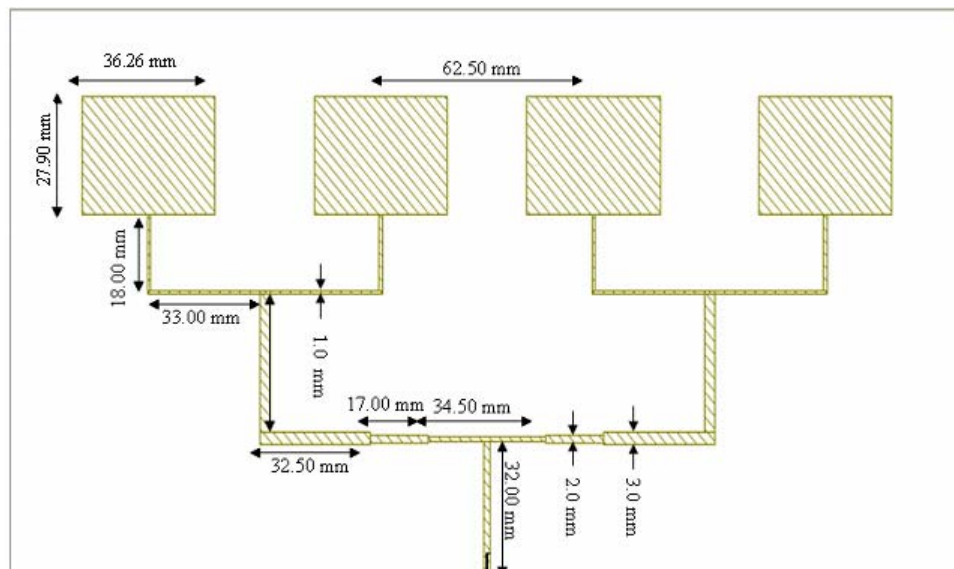
$$\begin{aligned} Z_1 &= \sqrt{50(100)} \\ &= 70 \Omega \end{aligned}$$

### 3.4.2 50 $\Omega$ , 70 $\Omega$ and 100 $\Omega$ Transmission Line Calculation

As a single patch, the different impedance dimensions are obtained by using the same *Txline Calculator* that is existing in MWO software. The dimensions of the array are shown in the table and figure at the next page.

**Table 3.2:** Dimension of Rectangular Patch Array Antenna

Patch	
Width, $w$	36.26 mm
Length, $L$	27.90 mm
100Ω Feedline	
Width	1.00 mm
Length	34.50 mm
70 Ω Feedline ( $\lambda/4$ Transformer)	
Width	2.00 mm
Length	17.00 mm
50 Ω Feedline	
Width	3.00 mm
Length	32.50 mm



**Figure 3.6:** Design Layout of Array Antenna

### 3.4.3 Radiation Pattern Calculation

For the radiation pattern of the array antenna, equations (3.4) and (3.5) are also will be used as an approximation calculation. The width,  $w$  and length,  $L$  to substitute into the equation will be the total length and width of the patches. This gives a brief insight into the radiation pattern of the array antenna. Then the design will be simulate using MWO.

### 3.5 Introduction to Microwave Office

In providing a general platform for simulation, software which is able to simulate the circuit as well as the layout based design is chosen. This software is called Microwave Office as it is shown in Figure 3.7. It is produced by Applied Wave Research Inc., El Segundo, California.

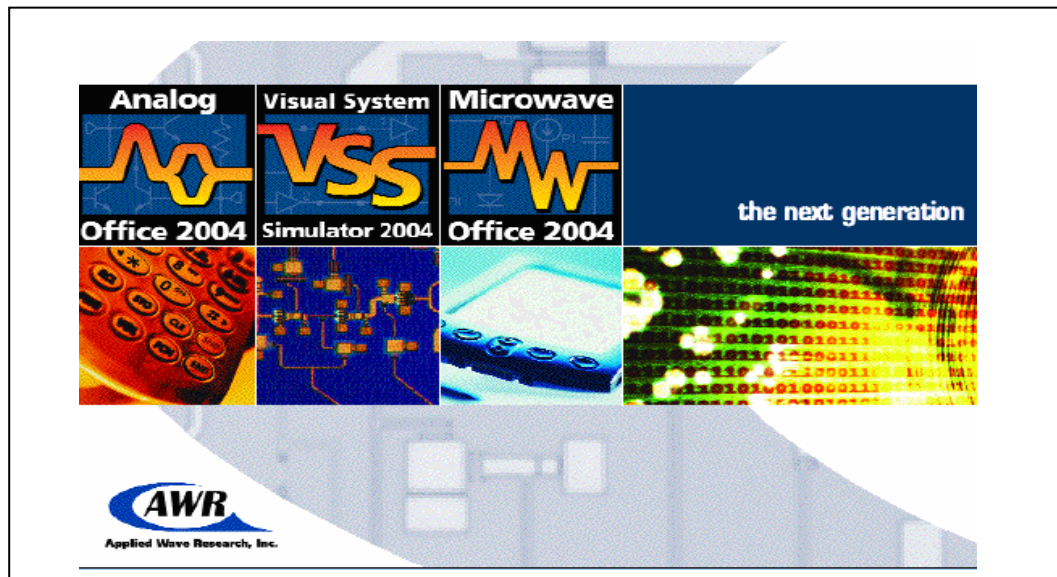
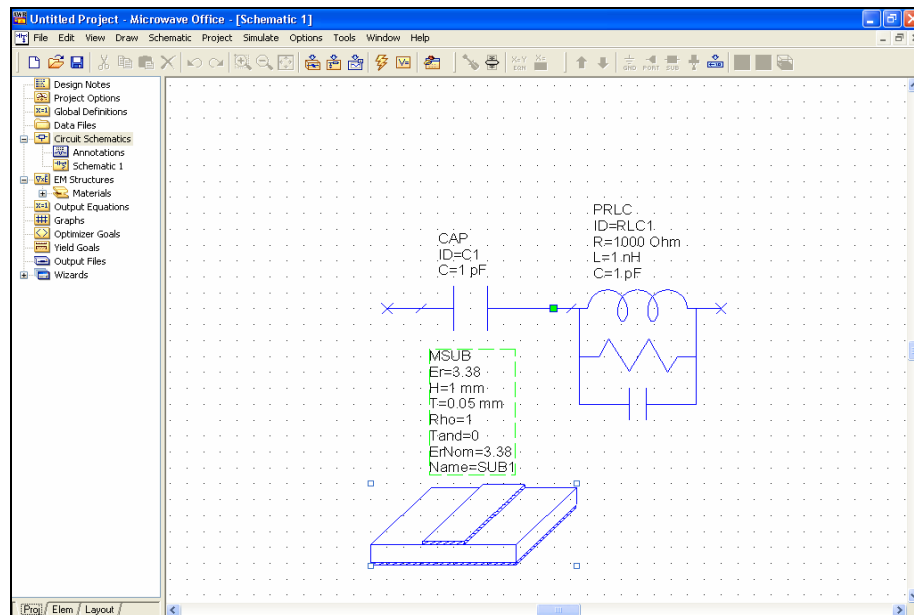


Figure 3.7: The Microwave Office Welcome Page

The AWR Design Environment comprises two powerful tools that can be used together to create an integrated system and RF design environment: Visual System

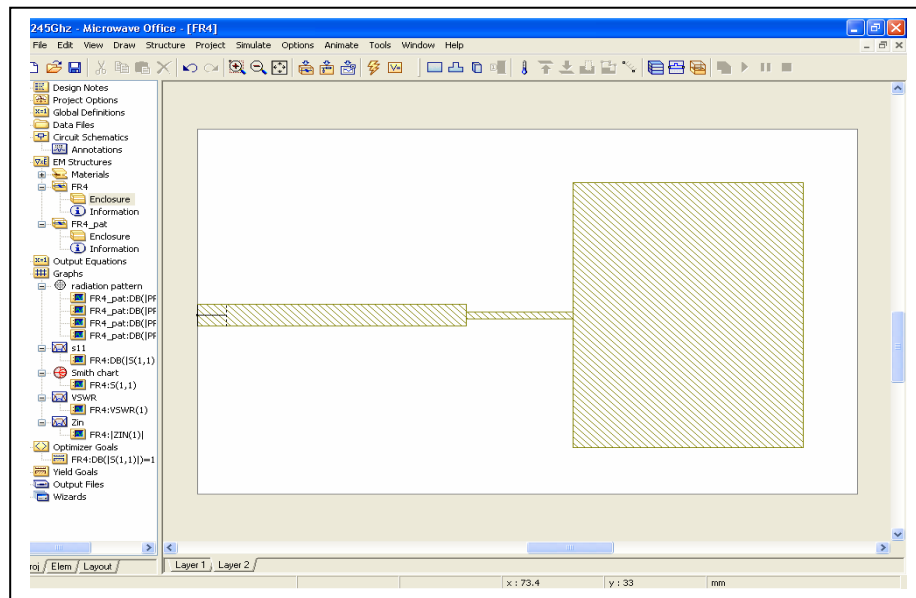
Simulator (VSS) and Microwave Office (MWO). These powerful tools are fully integrated in the AWR Design Environment and allow the user to incorporate circuit designs into system designs without leaving the AWR Design Environment.

Microwave Office enables the user to use either schematic based simulation (Figure 3.8) or layout based simulation (Figure 3.9). Schematic based simulation design circuits composed of schematics and electromagnetic (EM) structures from an extensive electrical model database, and then generate layout representations of these designs. Users can perform simulations using one of Microwave Office's simulation engines – a linear simulator, an advanced harmonic balance simulator, a 3D-planar EM simulator (EMSiht), or an optional HSPICE simulator, and display the output in a wide variety of graphical forms based on analysis needs. Users can then tune or optimize the designs and changes are automatically and immediately reflected in the layout. However in this project the layout based simulation is used to design the single patch and array antenna. The step will be show at the next page.



**Figure 3.8:** The Circuit Schematic Based Environment





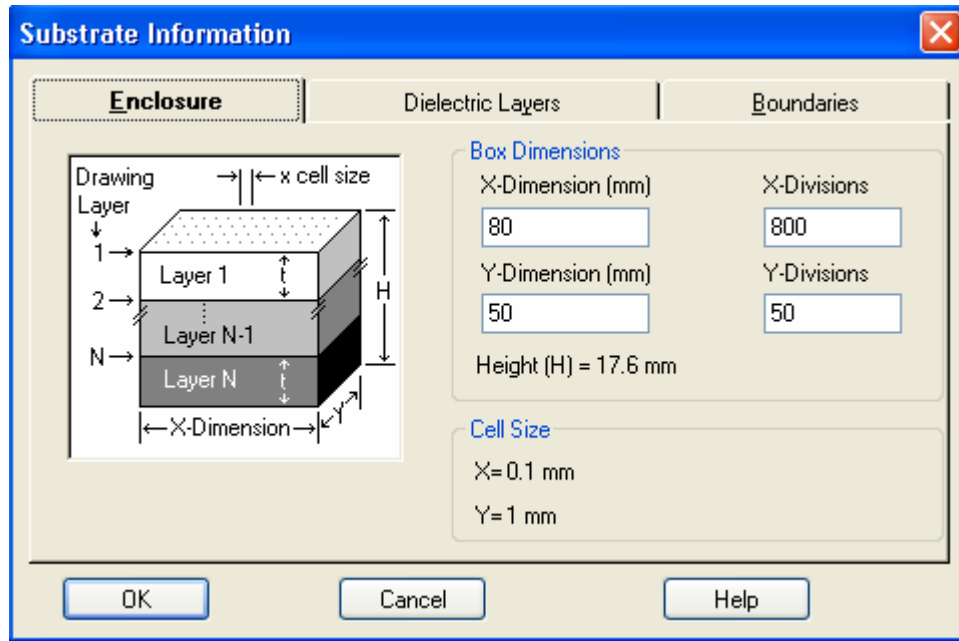
**Figure 3.9:** The Layout Schematic Based Environment

### 3.5.1 Layout Based Simulation

First step before designing the layouts, the dimensions of the desired antenna and feeds should be calculated first. The layout design environment is brought out by referring back to Figure 3.9. The *EM Structure* on the *PROJ* tab is right clicked. *New EM Structure* option is selected. An empty design layout will appear in the main design window on the right.

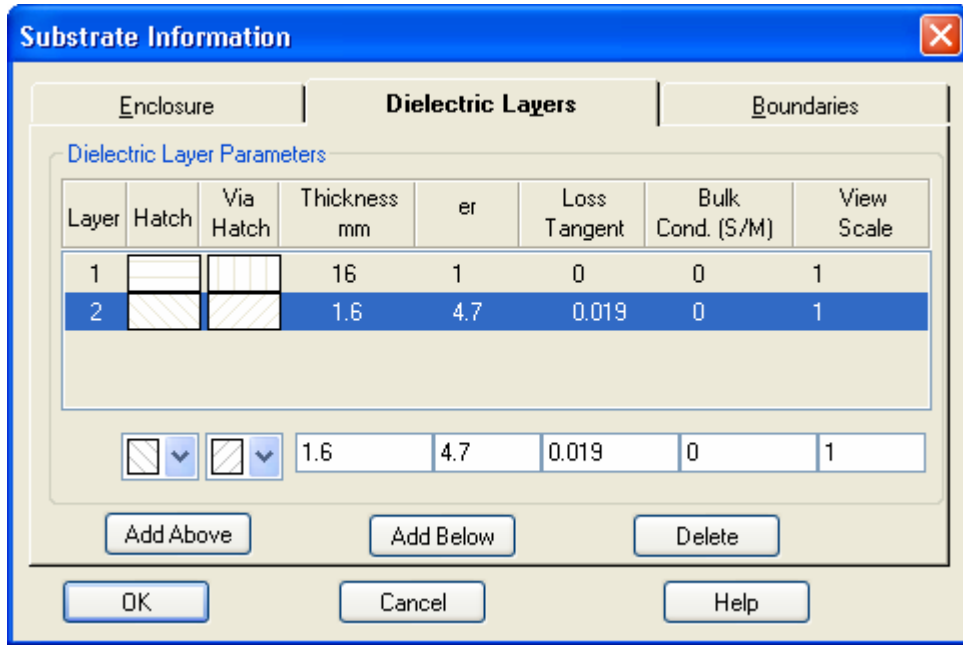
Before starting to draw the conductors on the enclosure, the correct size and dimensions should be defined for the enclosure. This can be done by clicking on the *Enclosure* button. A substrate information option window will appear before the user, as shown in Figure 3.10. The desired size on  $x$  and  $y$  position (length and width) enough for the antenna and feed to be printed on is entered. Cell size is the distance of a point to the next point in the layout. It will be determined by the value of the  $x$ - and  $y$ -divisions. Once

again, a refined cell size will give a greater accuracy, however, at the expense of simulation resources.



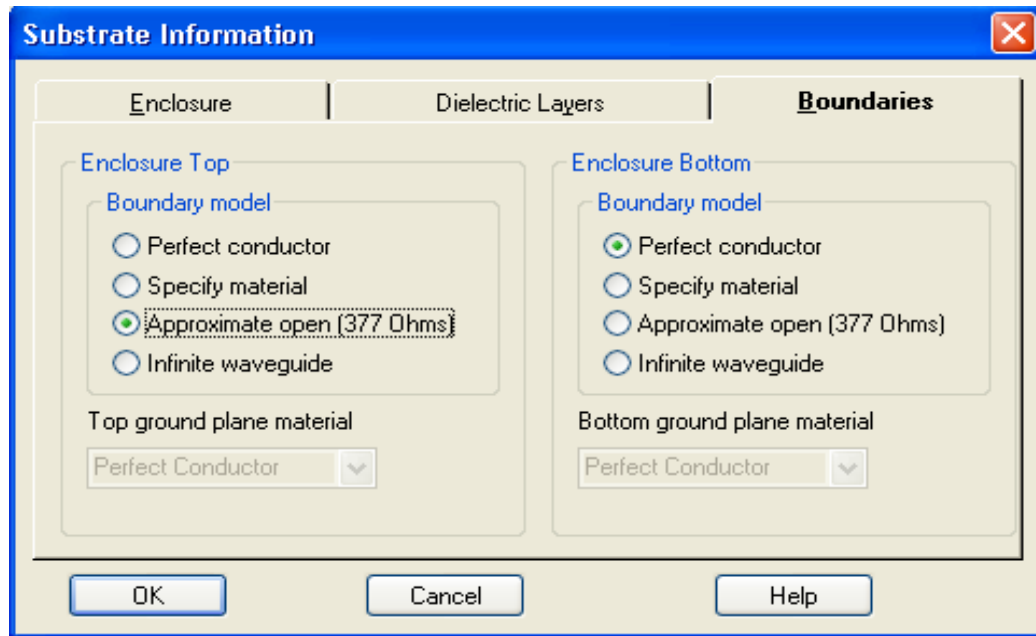
**Figure 3.10:** The *Substrate Information* Option Window (*Enclosure* Tab)

The dielectric layer properties are defined in the next tab which is the *Dielectric Layers* tab (Figure 3.11). On the top layer, a layer filled with air must be defined first. The air layer should be ten times the thickness of the dielectric substrate. For the air layer, the loss tangent is defined as 0 and relative dielectric constant as 1. As was explained earlier about the substrate used in this work, the thickness used is 1.6 mm, with relative dielectric constant 4.7 and dielectric loss tangent of 0.019. For non-contacting feeds, the substrate is two times higher than the contacting feeds, which is 3.2 mm. This makes the air layer also twice as thick compared to the air layer defined for a contacting feed.



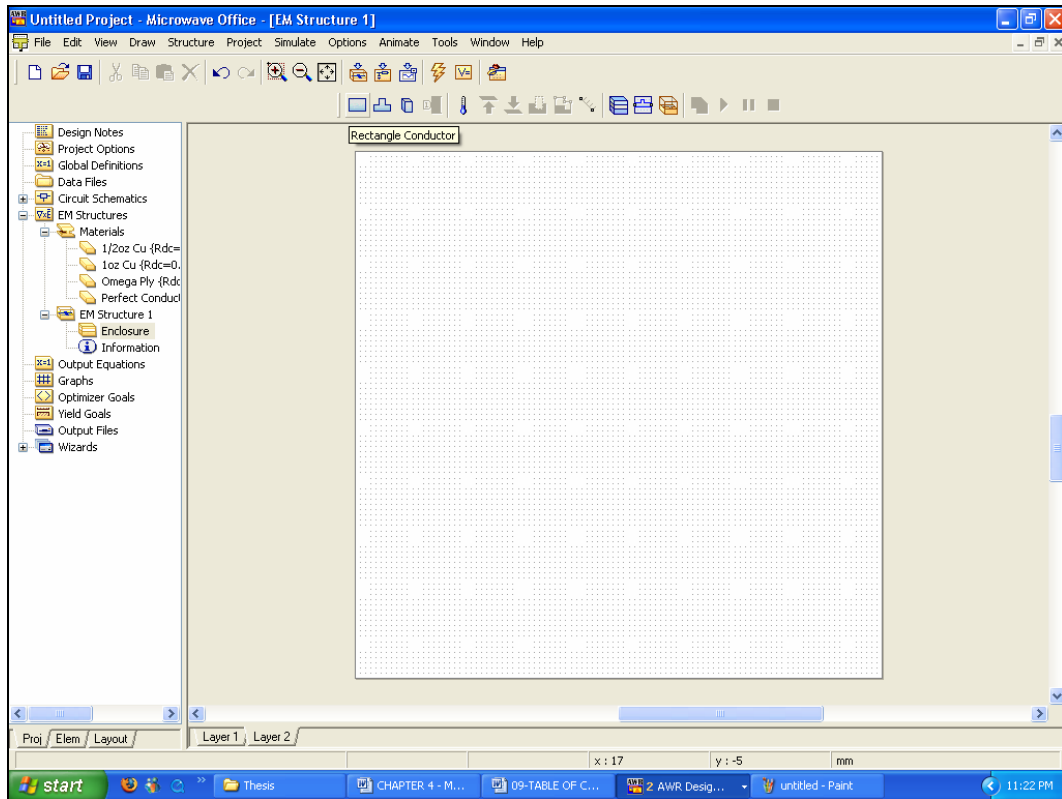
**Figure 3.11:** The *Substrate Information* Option Window (*Dielectric* Tab)

The enclosure top and bottom properties are defined in the next tab which is the *Boundaries* tab. It is a definition of whether the top and bottom of the enclosure need to be assumed as a ground plane or open. In this work, all antennas except for aperture coupled feed have a ground plane at bottom enclosure. Thus definition for the other three feeding method will have similar characteristics as it is shown in Figure 3.12.



**Figure 3.12:** The *Substrate Information* Option Window (*Boundaries* Tab)

After all attributes in the enclosure and substrate information option window have been filled up, drawing and plotting of the calculated dimensions can be done. This is done by selecting and clicking the *Rectangular Conductor* button (Figure 3.13). Users can proceed to drag the whole dimension on the enclosure, while referring to the *X* and *Y* values as indication of its width and length.



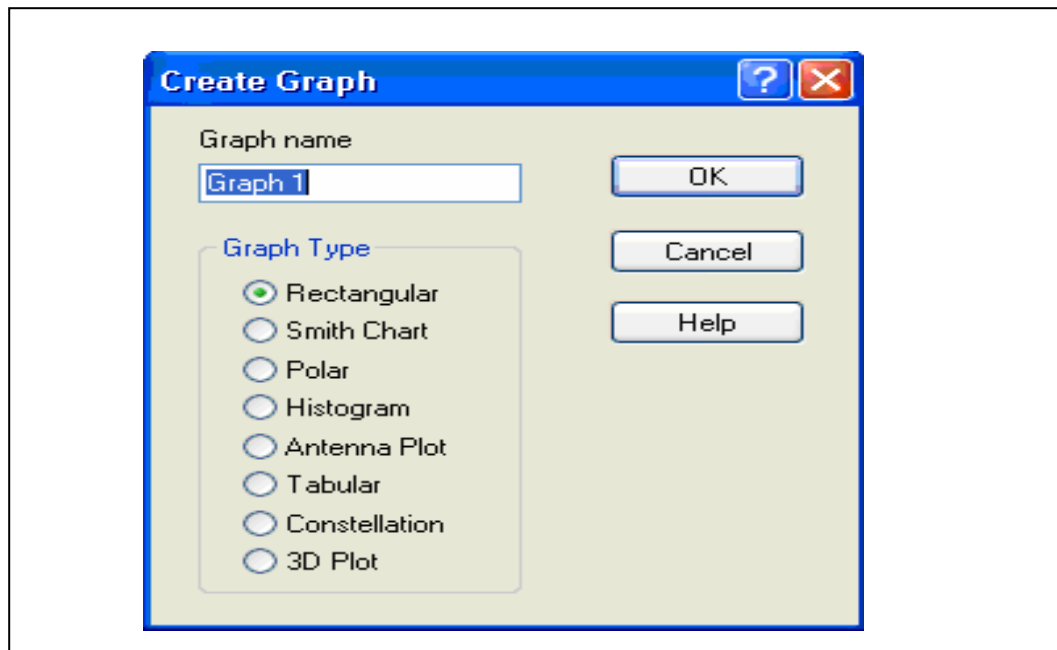
**Figure 3.13:** The *Rectangular Conductor* Button Located At the Top Toolbar Used For Initial Drawing and Sizing

Users need not worry if an initial element drawn onto the enclosure surface does not meet desired shapes and sizes. Additional tweaking and adjustments could be done further using the *Notch Conductor* or *Stretch Area* buttons, located at the top toolbars. A ruler is also provided to measure an exact amount of dimensions, activated using the *Measure* button. Multiple components also could be drawn and simulated as a single unit. As long as the different components contact each other at the edges, the simulator will be simulating the whole structure as a single component. Grounding of a certain intermediate layer is also made easy using this software. Users only need to connect the conductor to any of the enclosure's boundary and the simulator will assume the whole layer is grounded.

After all the elements have been added into the simulator, graphs should be added into the circuit. This depends on the types of analysis parameters that needed to be analyzed. To add a graph, the *Graph* icon on the right of the *PROJ* tab is right-clicked. Another window

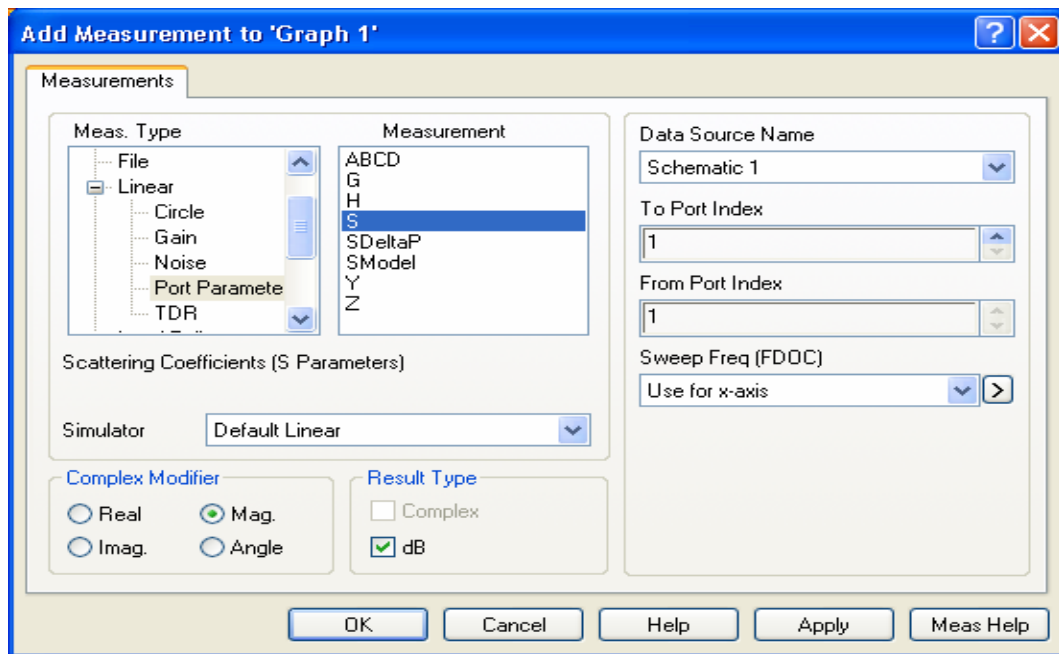
will appear, as shown in Figure 3.14, as to determine which type of graph that should be added onto it. After the type of graph has been determined, desired measurements which need to be plotted on the graph are added under the graph (Figure 3.15). The graphs and measurements need to be added, as follow;

- i. Return loss – to add this graph, *Rectangular* option is selected on the pop-up window. The  $S_{11}$  (dB) parameter is added in the add measurement option window
- ii. Matching Smith Chart – to add this graph, *Smith* option is selected on the pop-up window. The  $S_{11}$  parameter is added in the add measurement option window
- iii. Radiation Patterns – to add this graph, *Antenna Plot* should be selected in the option window. Four *Principal Plane Cut* measurements must be added into this graph. These are  $PPC\_E\theta$  at  $0^\circ$  and  $90^\circ$ , and  $PPC\_E\phi$  at  $0^\circ$  and  $90^\circ$ . All the measurements are in dB.

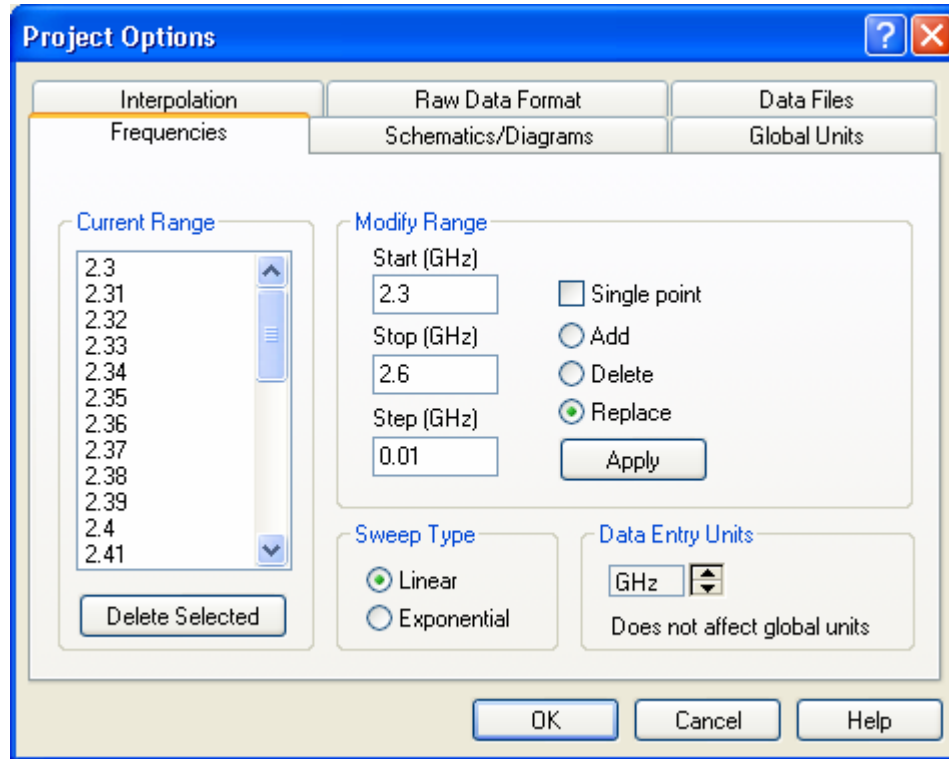


**Figure 3.14:** The *Create Graph* Pop-Up Window Option Indicating Types of Graphs

Project frequency for the simulator is then set within a specified range. This range should include the desired design frequency, and is determined by the user. Normally a larger range should be used during initial design stage, and refined into a smaller range as the circuit is fine tuned and optimized. To set the simulation project frequency, the *Project Option* icon on the left side of design window must be double-clicked on. An additional window will appear with several tabs on the top (Figure 3.16.). In this study, the frequency range for simulation is set from 2.3 GHz to 2.6 GHz, in 0.01 GHz steps. More refined steps will generate a smoother graph, at the expense of more resources that would be needed for the simulation.



**Figure 3.15:** The *Add Measurement* Option Window



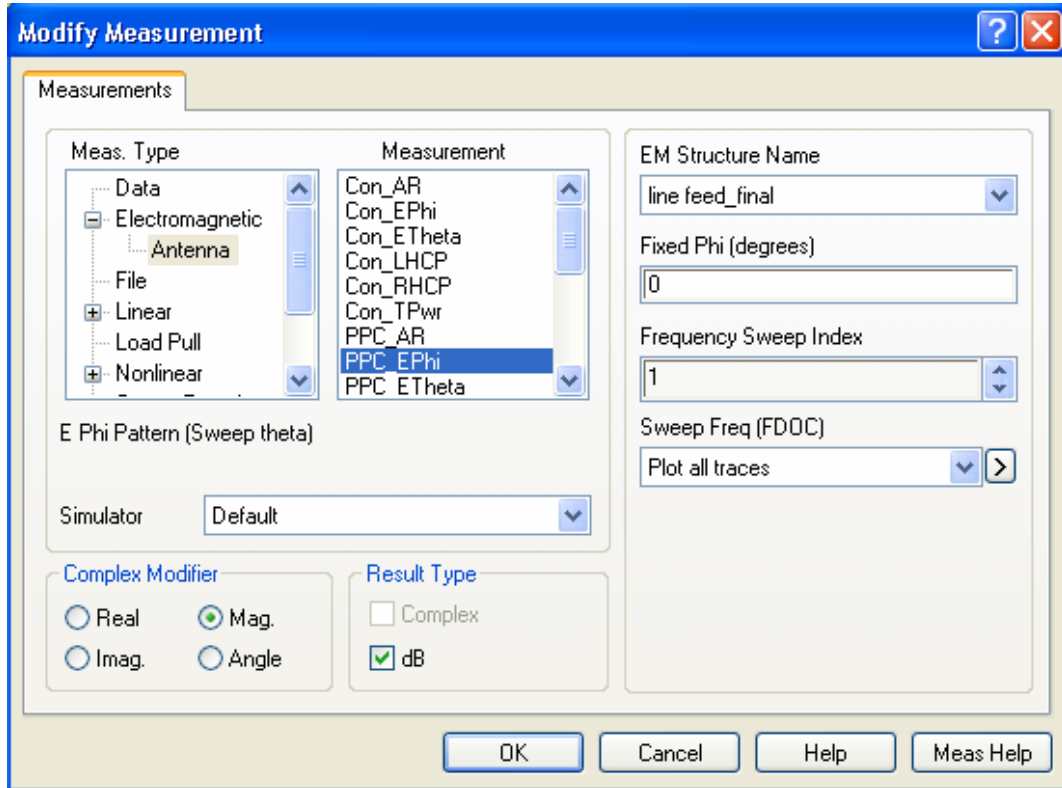
**Figure 3.16:** The *Project Options* Option Window

### 3.5.2 Radiation Pattern Generation

$PPC_{E\theta}$  is also known as a Principle Plane Cut or Theta Sweep polarized along  $E_\theta$ , this measurement fixes the values of Frequency and Phi while sweeping Theta from  $-90^\circ$  to  $90^\circ$  or  $-\pi/2$  to  $\pi/2$  radians.  $PPC_{E\theta}$  at  $0^\circ$  is equivalent to co polarization pattern for H plane, while  $PPC_{E\theta}$  at  $90^\circ$  is equivalent to cross polarization pattern for H plane.  $PPC_{E\phi}$  is also known as a Principle Plane Cut or Theta Sweep polarized along  $E_\phi$ , this measurement fixes the values of Frequency and Phi while sweeping Theta from  $-90^\circ$  to  $90^\circ$  or  $-\pi/2$  to  $\pi/2$  radians.  $PPC_{E\phi}$  at  $0^\circ$  is equivalent to the far field cross polarization pattern for E plane, while  $PPC_{E\phi}$  at  $90^\circ$  is equivalent to the far field co polarization of E plane.

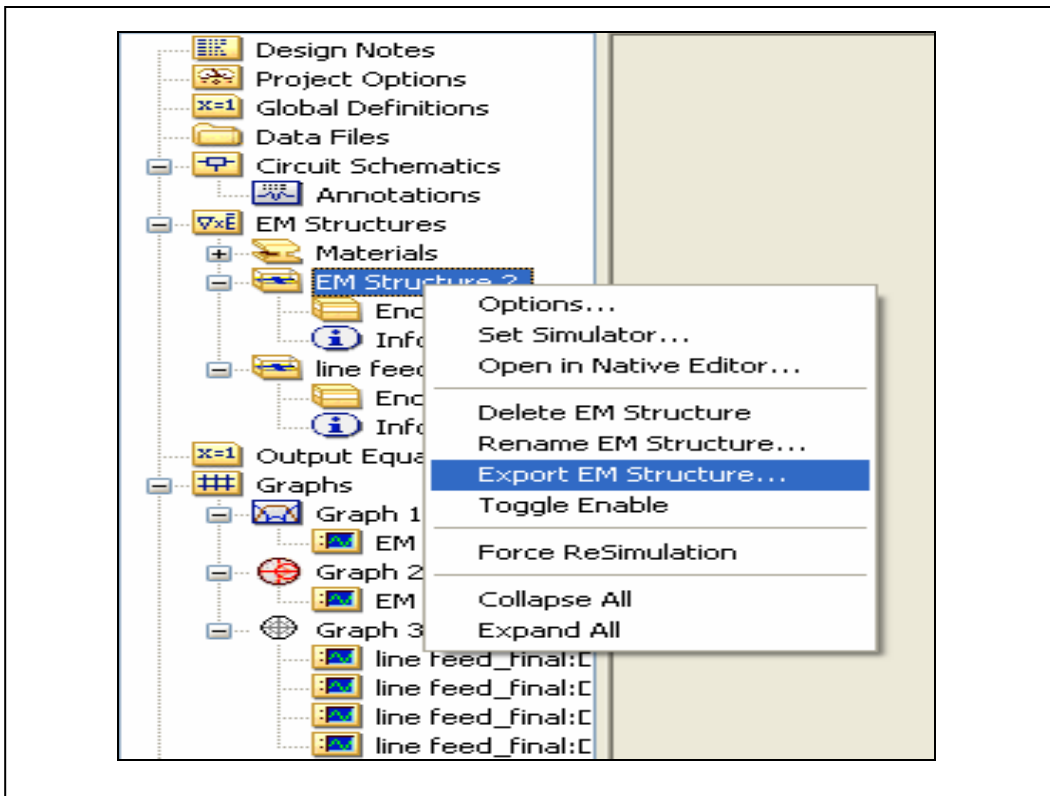


Since an antenna radiation pattern is plotted using a fixed frequency, in contrast to the project frequency that sweeps the frequency for  $S_{11}$  values, a need to separate the two arises. Before proceeding to add those measurements as it is explained above, an identical designed layout must be exported out and re-imported back into the simulation so that it is duplicated.

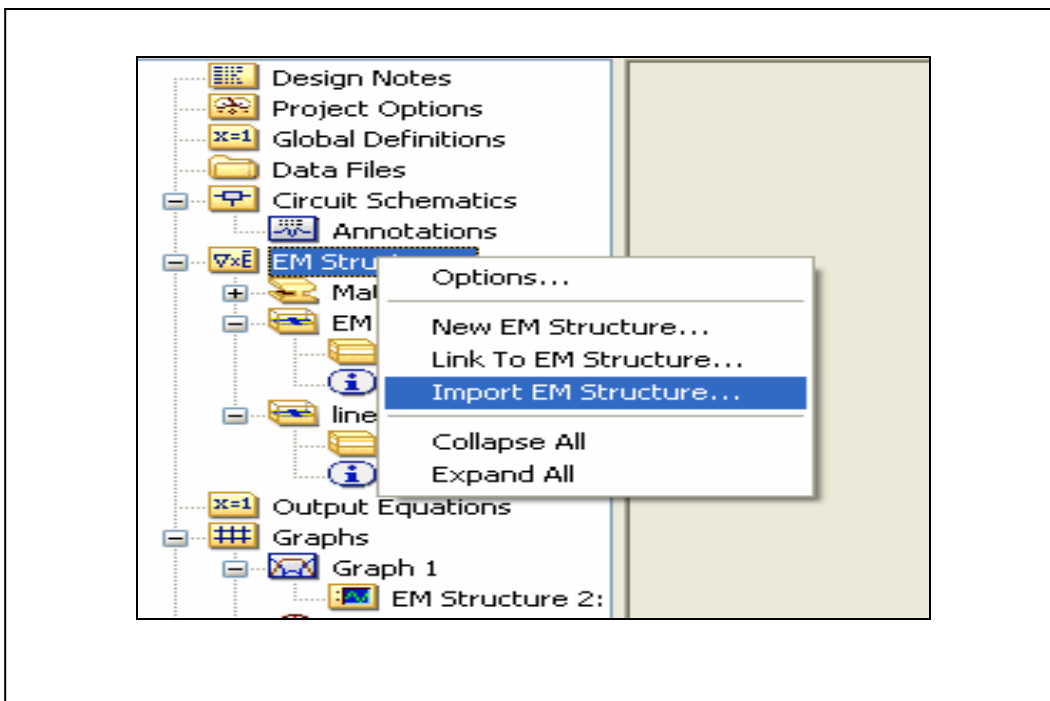


**Figure 3.17:** Add Measurement Option Windows When Adding *PPC\_EPhi* and *PPC\_Etheta*

This can be done by right clicking the EM Structure’s name and selecting the *Export EM Structure* option (Figure 3.18). The exported layout is saved at a designated place before re-imported back into simulation. To create a duplicate, right click *EM Structures* icon and select *Import EM Structure* (Figure 3.19). The exported file then selected and duplication process is completed.

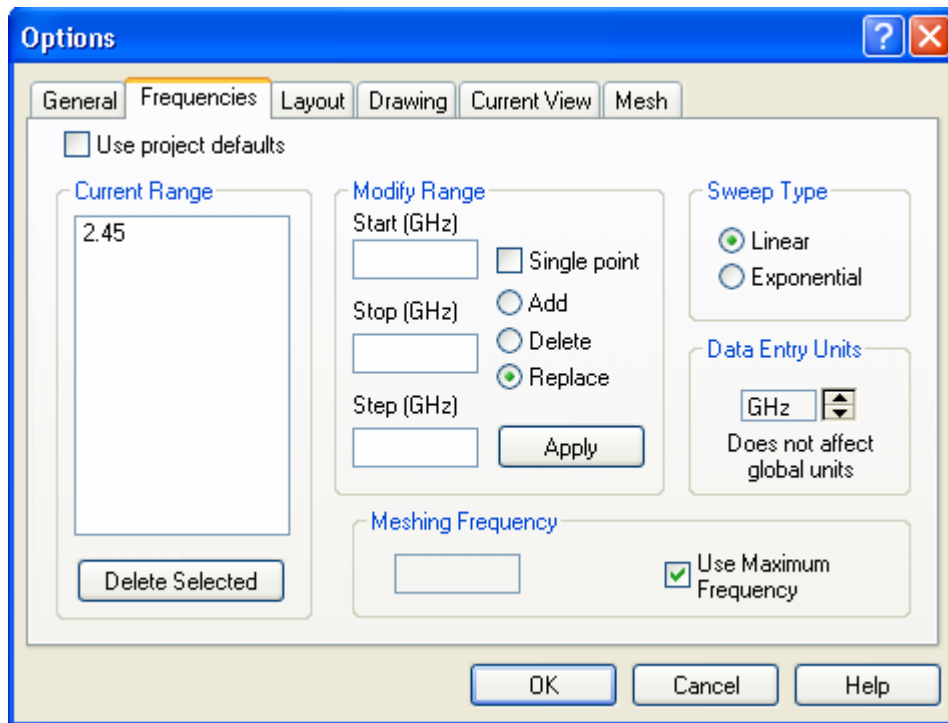


**Figure 3.18:** Exporting the Existing EM Structure



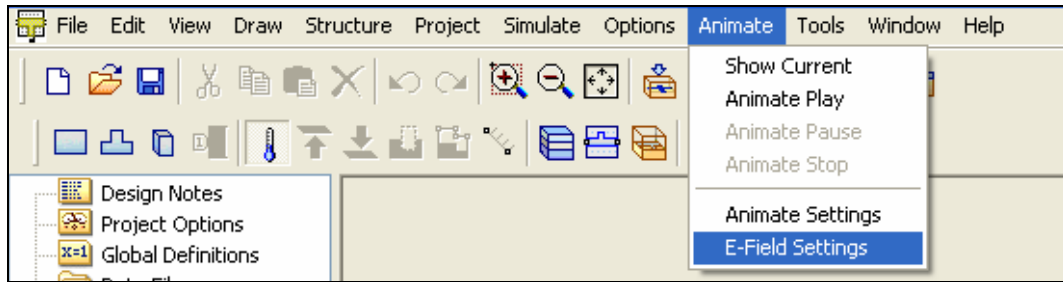
**Figure 3.19:** Re-Importing the Existing EM Structure

The newly duplicated layout is then altered to be the source of the non frequency sweeping, source for radiation pattern plot. Normally the frequency with the best return loss value is chosen as the single point frequency which radiation patterns shall be extracted from. To set the duplicated layout to be non frequency sweeping, the EM structure's name is right clicked on, and *Options* is selected. The *Options* window with several tabs will appear as shown in Figure 3.20. The *Use Project Defaults* check box must be un-checked and the desired, single frequency point should be entered.

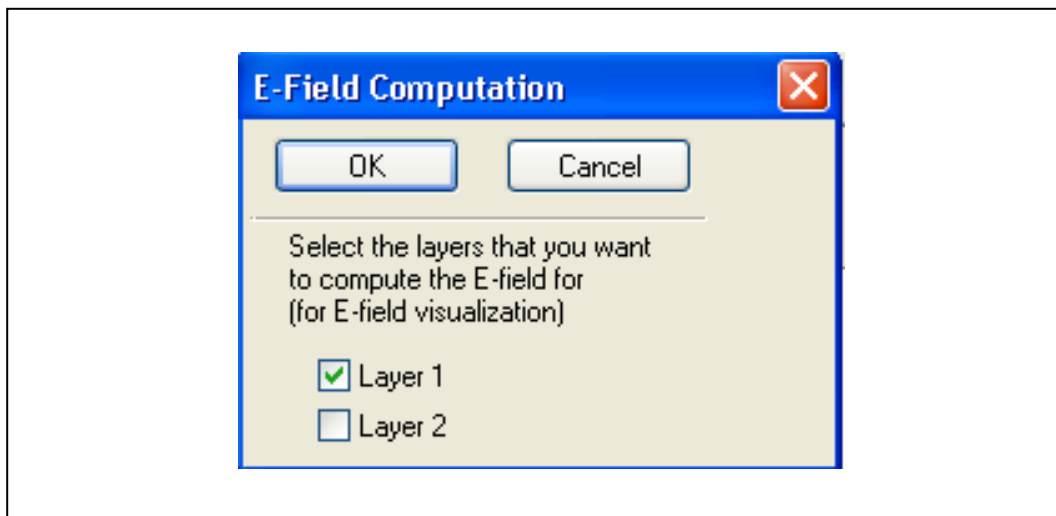


**Figure 3.20:** The *Options* Window (*Frequencies* Tab)

After this is done, the E field computation should be activated for the top layer, so as to enable the far field radiation patterns to be plotted. This is done by double clicking on the duplicated layout and selecting the *Animate* option at the top tool bar. *E-Field Settings* is then selected (Figure 3.21), and when the E-Field Computation window appears, *Layer 1* check box is ticked (Figure 3.22).



**Figure 3.21:** Selecting the *E-Field Settings* Option



**Figure 3.22:** Checking the *Layer 1* Check Box So That E-Field Is Computed For That Layer

The next step is to simulate the whole structure. To do this the *Analyze* button is pressed. Before pressing the button, all frequency settings, graphs and measurements needed to be ensured to be included in the simulation or else an error prompt will appear. The simulation process window and the *Analyze* button are shown in Figure 3.23.

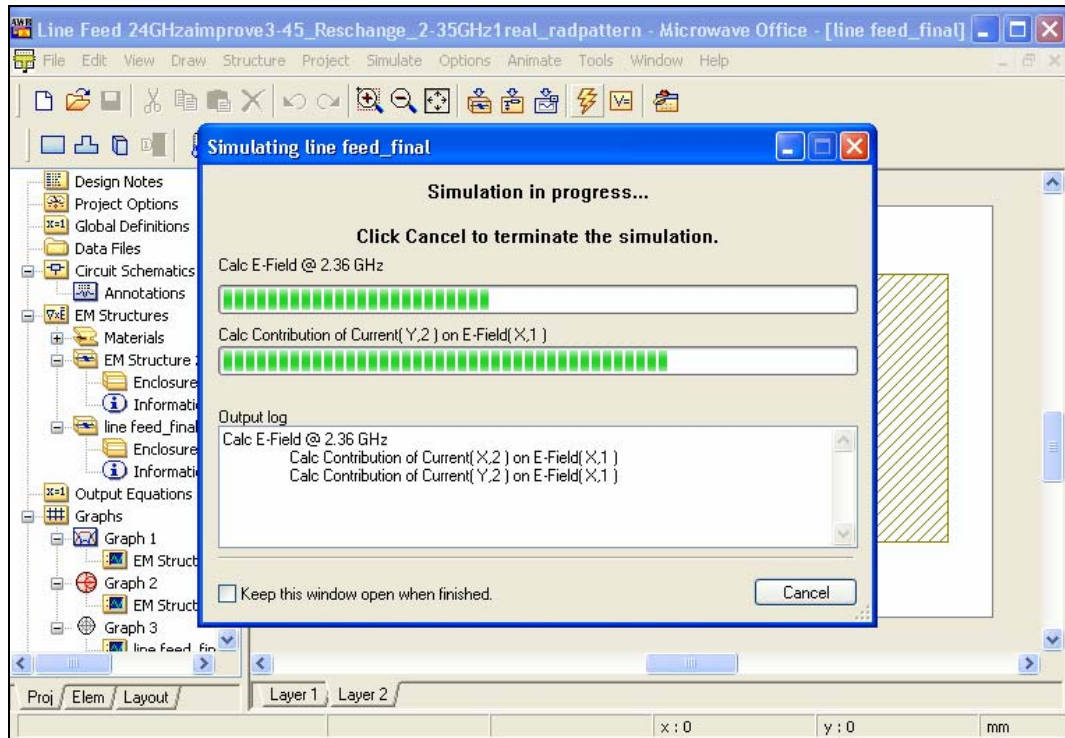


Figure 3.23: The *Analyze* Button and Simulation Process Window