Laboratory Manual

Microstrip Antenna Design Using Mstrip40

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Dedication

This manual is dedicated to the staff who have taught, encouraged and guided me throughout my course at the University of Canberra.

Foreword

There is a need for a microstrip antenna design program in a teaching environment that does not require large sums of money to purchase. Mstrip40 addresses these needs and is a free microstrip antenna design program, which free to download and does not require a licence to use. At the author's current institution only one antenna design package was available, while it had many benefits only one licence was obtained so it was limited for use in a learning laboratory environment.

Using approximate formulas in the analysis of microstrip antennas can lead to inaccuracies, therefore a full wave solution is required to model the antenna structure accurately. Mstip40 uses a method of moment so all effects such as coupling between layers, surface wave excitation and dielectric losses are taken into account. However students may find it difficult to use the software for microstrip antenna design. As a result, for an honours project, the author has designed a laboratory manual using Mstrip40 which can be used in a teaching environment. The aim of this manual is to promote student understanding and learning of microstrip antenna design.

Target Audience

The microstrip antenna design manual has been written for third year or four year students studying microwave communications to aid them in the basic learning and design of microstrip antennas. The author assumes that students already have a basic understanding of RF design and analysis methods such as interpreting smith charts, input reflection plots and basic antenna design theory.

Learning Outcomes

There are five experiments in this laboratory manual in addition to a introductory section on the use of Mstrip40. After completing the experiments thoroughly students will build on their knowledge of microstrip antennas and acquire the confidence to design microstrip antenna using various feed techniques.

Advantages

Mstrip40 is a free method of moments microstrip antenna design package which has a number of attractive features including:

- Free to download and use no dongle necessary
- Can analyse a microstrip antenna structure with up to 5 dielectric layers
- Structures placed on four layers

- Easy to use which will promote student interest and learning
- Slot coupled antennas can be modelled
- Can analyse Radiation pattern, input impedance and current distribution
- User controlled integration accuracy

Limitations

As Mstrip40 is not a commercially available students and users should not view Mstrip40 as a “perfect” piece of software. Some limitations of the program include:

- No probe or load modelling
- Limited multi-port analysis
- Rectangular basis functions only

Contents

Experiment 1 Introduction to Mstrip40

Students should attempt this experiment first then work through the rest of the experiments.

Before starting any experiments if Mstrip40 is not available in the laboratory, copy of Mstrip40 should be downloaded from Prof. Dr. Georg Splitt's website:

http://www.e-technik.fh-kiel.de/~splitt/html/mstrip.htm

Once the software is downloaded unzip all the files onto the hard drive of the computer that you wish to use. Print out a copy of the Mstrip40 user manual created by Prof. Dr. Georg Splitt's website.

Read through the early pages of the manual so you gain an understanding of how the program works and the full wave analysis that is used. The analysis that is use is a method of moments analysis which uses Maxwells equations and integral methods to solve for the various antenna parameters.

When the program has been successfully installed on the computer and the user has read through section 1 to 3 in the manual they should be ready to start using Mstrip40.

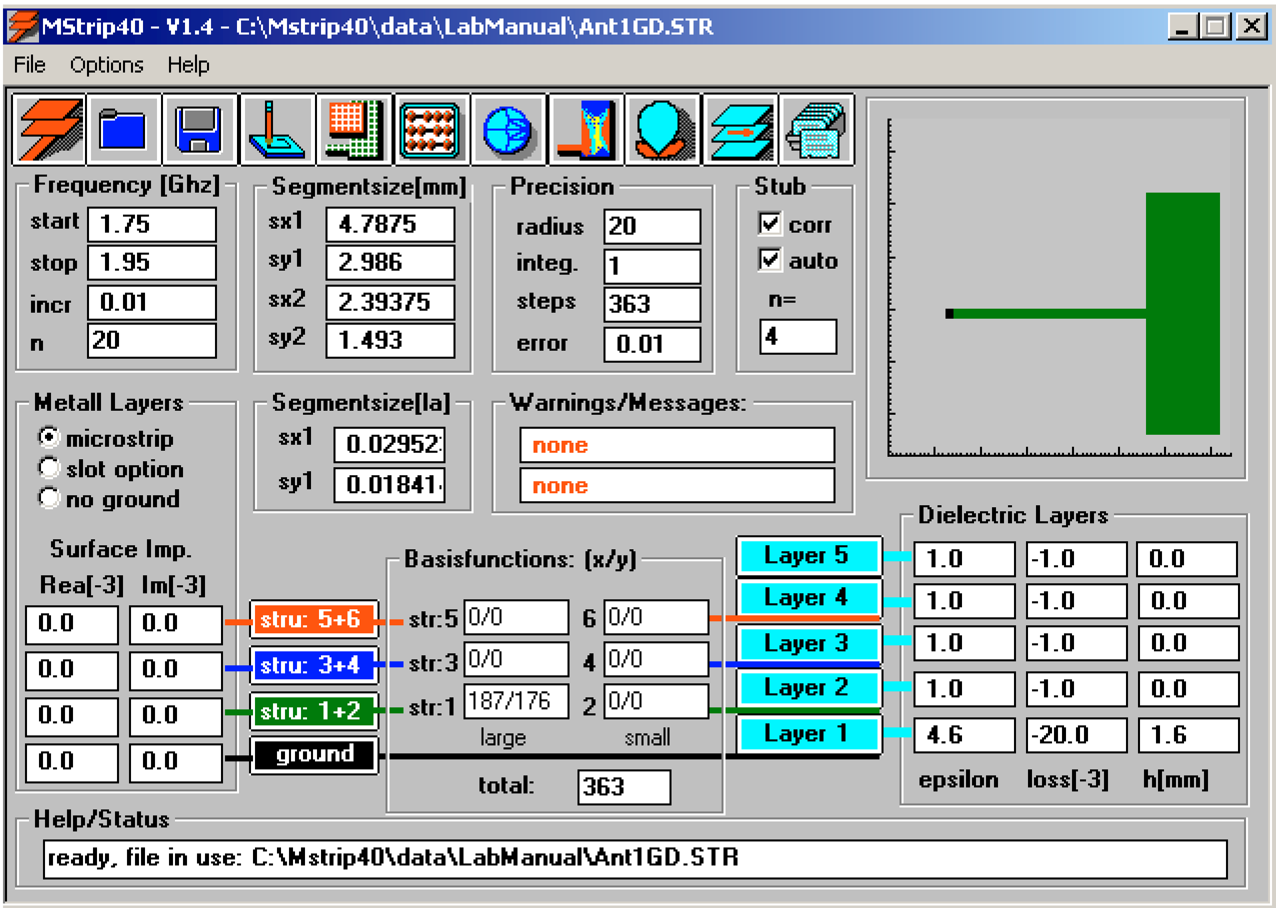
Mstrip40 Run through

Open the Mstrip40 interface by going to the installed Mstrip40 selecting the Mstrip40.exe command.

Select file open then double click on the DEMO1.STR file.

Become familiar with the various menus on the screen Frequency, Segment Size, Precision, Stub, Dielectric Layers and Basis functions sub windows by moving your mouse over the text boxes and observing Help/Status window at the bottom of the interface.

Once the user has a good understanding of each section in the interface and where to input the frequency sweep, segment sizes and dielectric layers, they should become familiar with the various output windows. The output windows appear by clicking the icons below the top of the screen. A screen dump of Mstrip40 is provided on the next page.



The main icons that we will be using for design in this lab manual are:

- The edit structure file command, invoking this menu opens a STR file in which users can impalement their antenna designs.
- Simulation command which has an abacus as an icon which is pressed to simulate the current STR file.

Students should become familiar with the simulation windows and how to interpret the data. Here are the main analytical windows which will be used in the design:

- Smith chart icon, this shows all the input impedance information such as the various s-parameters in magnitude and degree, input impedance and VSWR for varying frequency.
- The icon to the right of the smith chart icon shows the current distribution on each layer of the antenna, which also has a 3D command for better visual interpretation.
- The radiation pattern icon brings up a window of the radiation pattern of the current antenna. By selecting the info and control window, users can observe the gain and efficiency of the antenna at different frequencies.

The best way to learn how to use Mstrip40 is to spend more time using it and experimenting with different commands.

This section is only a basic guide to get started a lot more detail is contained in the Mstrip40 user manual, which will be refereed to later on in the laboratory manual. There are also 21 demo files that students are encouraged to open and simulate to get an idea of how different antennas behave.

Experiment 2 End Fed Microstrip Antenna Design

Aim

Students should gain a good understanding of how an end fed microstrip antenna is modelled using the transmission line method. In addition students will learn how to design an antenna to operate at a particular design frequency and analyse its characteristics.

Introduction

A microstrip antenna is basically a conductor printed on top of a layer of substrate with a backing ground plane as shown in figure 1.

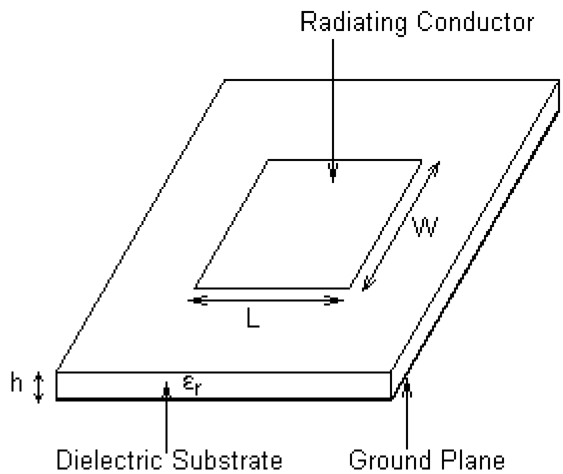


Figure 1 A typical microstrip antenna.

The length of the radiating conductor or patch is made approximately $\lambda_g/2$, so the patch starts to radiate. In this experiment the patch will be fed by a microstrip transmission line, which usually has a 50Ω impedance. The antenna is usually fed at the radiating edge along the width (W) as it gives good polarisation, however the disadvantages are the spurious radiation and the need for impedance matching [1]. This is because the typical edge resistance of a microstrip antenna ranges from 150Ω to 300Ω [2].

The design of a microstrip antenna begins by determining the substrate used for the antenna and then the dimensions of the patch. Due to the fringing fields along the radiating edges of the antenna there is a line extension associated with the patch, which is given by the formula [3]:

$$\frac{\Delta L}{h} = 0.412\left[\frac{\varepsilon_{eff} + 0.3}{\varepsilon_{eff} - 0.258}\right]\left[\frac{W/h + 0.264}{W/h + 0.813}\right] \qquad (1)$$

The effective dielectric constant (ε_{eff}) due to the air dielectric boundary is given by [3]:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10h}{W}\right)^{-\frac{1}{2}} \quad (2)$$

The resonant frequency can be estimated by using the formula [2]:

$$f_r = \frac{1}{2\sqrt{\mu_o \varepsilon_o}\,(L + 2\Delta L)\sqrt{\varepsilon_{eff}}} \quad (3)$$

Where: μ_o = permeability of free space
ε_o = permittivity of free space
ΔL = line extension
ε_{eff} = effective dielectric constant

Estimation of width and length

By choosing the substrate, the width and length of the patch can be estimated. An initial approximation for the length can be made for a half wave microstrip antenna radiated by the formula:

$$L = 0.48\lambda_g \sim 0.49\lambda_g \quad (4)$$

Where: $\lambda_g = \dfrac{c}{f_r\sqrt{\varepsilon_r}}$

The width (W) is usually chosen such that it lies in the ratio, L < W < 2L for good radiation characteristics, if W is too large then higher order modes will move closer to the design frequency.

Radiation characteristics: A microstrip antenna is basically a broadside radiator, which has a relatively large beamwidth and low, gain characteristics. The formulas for the E and H plane radiation patterns are given by [3]:

E-plane:

$$F(\theta) = \frac{\sin\left(\frac{k_o h}{2}\cos\theta\right)}{\frac{k_o h}{2}\cos\theta}\cos\left(\frac{k_o L}{2}\cos\theta\right) \quad (5)$$

H-Plane:

$$F(\phi) = \frac{\sin\left(\frac{k_o W}{2}\cos\phi\right)\sin\phi}{\frac{k_o W}{2}\cos\phi} \quad (6)$$

Where: $k_o = 2\pi/\lambda_o$ (free space wavenumber)

*Note: Equations (1) to (4) are only approximate formulas and numerical analysis using a full wave analysis package such as Mstrip40 is necessary.

Experiment

1. Design a microstrip antenna to operate at 1.8GHz given the substrate used in the design is FR4 PCB material with the following parameter:
   $\varepsilon_r = 4.6$
   $\tan\delta = 0.022$
   h = 1.6mm
   copper thickness = 35μm

   A program, using equations 1 to 3, can be written which calculates the resonant frequency of an antenna using estimates for W, L and for a given h, ε_r.

2. After determining the patch dimensions L and W, the feed line can be estimated using closed form equations in microstrip transmission line text books or using a commercially free program found on the website [4].

3. Draw the design on the Mstrip40 structure file, the file Demo1 can used as a template for the design. Remember to change the dielectric properties, segment sizes and frequency simulation range to suit your design. The file must be saved each time alterations are made or else it will not simulate the any of the changed parameters.

4. Observe the smith chart what kind of bandwidth characteristics does the end fed antenna possess?

5. Plot the theoretical E-plane microstrip antenna radiation pattern given in equation 5 and compare it with the simulated Mstrip40 radiation plot.

6. If the student is satisfied with the design then if there are materials available in the laboratory then students can build their own antenna (see the section in the manual about antenna design)

Further Investigation

Try and redesign the antenna by using low loss substrates such as Rogers RT/Duriod material, Taconic TLX substrates etc.

Vary the height of the antenna substrate and observe the effects on the impedance plot and the bandwidth, are there any improvements?

A stacked configuration can be designed by invoking the STRUKTU command and adding another dielectric layer, see the Mstrip40 user manual for details.

Experiment 3 Inset Fed Microstrip Antenna Design

Aim

To design a matched microstrip antenna by using an inset feed configuration.

Introduction

In most microstrip end fed antennas the feed line impedance (50Ω) is always the same as the radiation resistance at the edge of the patch, which is usually a few hundred ohms depending on the patch dimensions and the substrate used. As a result this input mismatch will affect the antenna performance because maximum power is not being transferred. When a matching network is implemented on the feed network this improves the performance of the antenna as there are less reflections.

A typical method used to match the antenna is the use of an inset feed, because the resistance varies as a cosine squared function along the length of the patch a 50Ω can be found which is a distance from the edge of the patch [5]. This distance is called the inset distance. A diagram of an inset fed patch is shown in figure 1, where x_o represents the inset length:

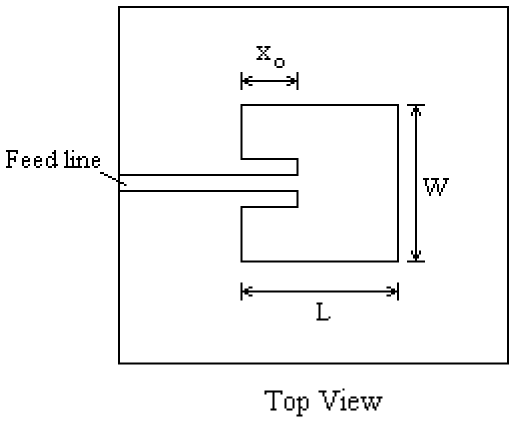


Figure 1 Inset fed patch.

The analysis of the inset fed patch is summarised from the references [6] and [7] which uses a transmission line model network to analyse the antenna.

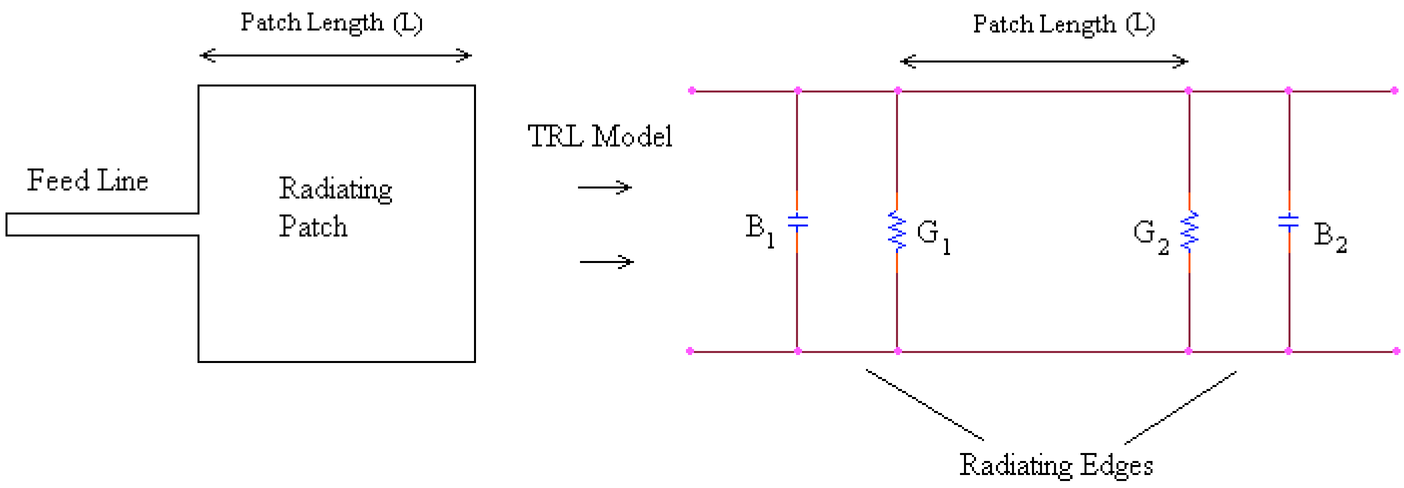


Figure 2 Transmission line network model of a rectangular patch antenna.

When the antenna resonates ($L \sim \lambda_g/2$), the total admittance becomes real and is calculated using the formula:

$$Y_{in} = Y_1 + Y_2 = 2G_1 \qquad (1)$$

The input impedance is calculated using the formula:

$$Z_{in} = \frac{1}{Y_{in}} = \frac{1}{2G_1} \qquad (2)$$

However the above equation for input impedance does not take into consideration the mutual coupling between the radiating slots, so we can redefine the input resistance:

$$R_{in} = \frac{1}{2\left(G_1 \pm G_{12}\right)} \qquad (3)$$

Where: G_{12} = mutual conductance
G_1 = self conductance.
$+$ = odd resonant modes
$-$ = even resonant modes

The self conductance can be calculated using the following expressions [9]:

$$G_1 = \frac{I_1}{120\pi^2} \qquad (4)$$

Where I_1 is the integral defined by:

$$I_1 = \int_0^{\pi} \left[\frac{\sin\left(\frac{k_o W}{2} \cos\theta \right)}{\cos\theta} \right]^2 \sin^3 \theta d\theta$$

$$= -2 + \cos(X) + XS_i(X) + \frac{\sin(X)}{X} \qquad (5)$$

Where: $X = k_oW$

$k_o = 2\pi/\lambda_o$

S_i = sin integral

The mutual conductance G_{12} is calculated using the following expression [10]:

$$G_{12} = \frac{1}{120\pi^2} \int_0^{\pi} \left[\frac{\sin\left(\frac{k_o W}{2} \cos\theta \right)}{\cos\theta} \right]^2 J_o\left(k_o L \sin\theta\right) \sin^3 \theta d\theta \qquad (6)$$

Were: J_o = Bessel function of the first kind

The input resistance for an inset fed patch is given by the simplified expression [11]:

$$R_{in}(x = x_o) = \frac{1}{2(G_1 + G_{12})} \cos^2\left(\frac{\pi x_o}{L} \right) \qquad (7)$$

Where: x_o = the inset feed distance

When xo = 0, then the resistance at the edge of the patch can be found:

$$R_{in}(x_o = 0) = \frac{1}{2(G_1 + G_{12})} \qquad (8)$$

The optimum value of x_o, (Rin = 50 Ω), can be found using equations 4 to 7. The resistance at the edge of the patch can be used to design a matching network for the antenna.

Preliminary

Students should attempt experiment 2 before they start experiment 3, so they do not need to recalculate the dimensions of the patch.

Experiment

1. Use a mathematical package such as Maple of Matlab to design a program that estimates the required inset feed distance for a R_{in} = 50Ω. Run the program to find the optimum inset distance.

2. Use the STR file from experiment 2 and modify it so the inset is implemented similar to figure 1. The size of the segment sizes in the x-direction my need to be adjusted to draw the inset distance accurately. The width of the inset, either side of the feed line, is usually made the same as the feed line.

3. Once the STR has been finished then simulate the file in Mstrip40.

4. Observe the outputs such as the smith chart, feed current and radiation pattern, how do the compare to the end fed design in experiment 2. Plot the VSWR by using the data in the SNP file.

5. The last step is the construction of the antenna when the student is satisfied with the design.

Further Investigation

Design a single stub matching circuit using a smith chart instead of using an inset feed and compare the results. The 50Ω feed line impedance should be matched to the resistance at the edge of the patch using equation 8. Remember to use open-circuited stubs in the design as Mstrip40 does not model loads.

Students should be familiar with the single stub matching technique if not they should read up on the literature [12] and [13].

Other matching techniques employing microstrip lines taught in class or in the literature can be designed and implemented simulated in Mstrip40 to compare the bandwidth.

Experiment 4 Proximity Fed Microstrip Antenna Design

Aim

To analyse and design a proximity coupled microstrip antenna.

Introduction

Electromagnetically coupled (EMC) designs such as proximity coupled and aperture fed antennas have many advantages over end fed and coaxial fed antennas. Some advantages include:

- No physical contact between feed line and radiating element.
- No drilling required.
- Less spurious radiation.
- Better for array configurations.
- Good suppression of higher order modes.
- Better high frequency performance.

A proximity-coupled antenna consists of two layers: it has a feed layer which is just a 50Ω microstrip line with a backing ground plane and the upper layer is the main radiating patch. Here is a diagram of the proximity coupled antenna:

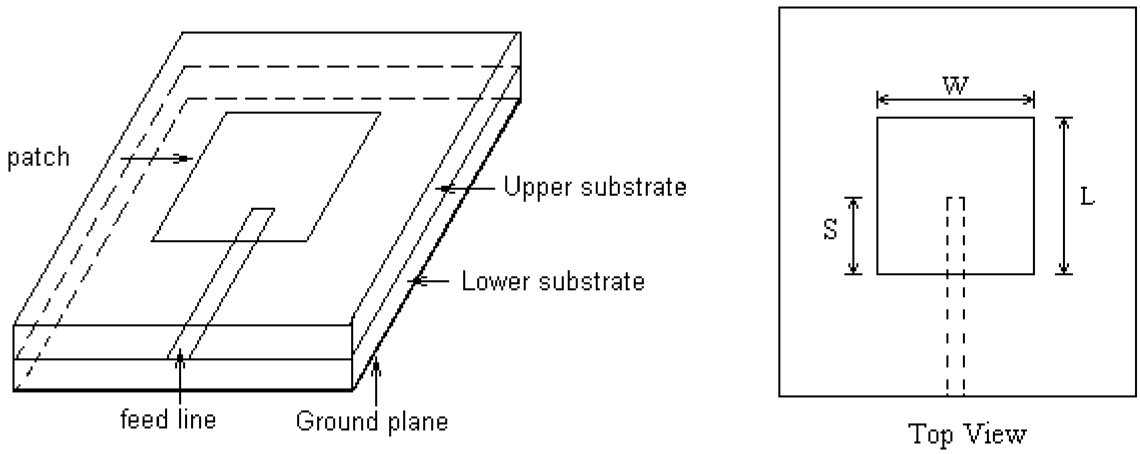


Figure 1 Proximity coupled antenna

The equivalent circuit diagram of the structure is shown on the next page [14]:

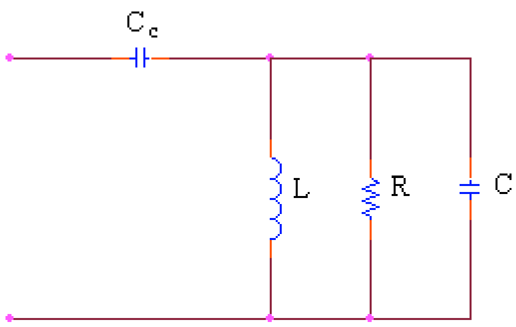


Figure 2 Equivalent circuit of a proximity coupled antenna at the patch edge.

The main radiating patch is represented by a parallel resonant (RLC) circuit, with the feed line represented by the coupling capacitance Cc. The level of coupling can be adjusted by varying the length of the overlap distance S in figure 1. Maximum coupling occurs when the overlap distance is approximately half of the patch length.

In a typical design the resonant frequency usually shifts up by 1 to 2% for an overlap of L/2 so the dimensions of the radiating patch should be designed at a lower frequency [14].

The theory behind EMC patches is quite complex and only design guidelines will be presented in this experiment for interested students they can refer to the literature [15].

Experiment

1. Calculate the dimensions for the upper layer by using the methods in experiment to determine the patch dimensions for a square patch (L = W) to resonate at 1.8GHz using FR4 PCB substrate:
   $\varepsilon_r = 4.6$
   $\tan\delta = 0.022$
   h = 1.6mm
   copper thickness = 35µm

2. Determine the width of the 50Ω line for the feed line for the bottom layer.
3. Draw the geometry of the proximity coupled patch in the STR file in Mstrip40. The files DEMO6 and DEMO7 can be used as templates for the design. Remember to choose the appropriate segment sizes, excitation frequency and substrate parameters.

4. Simulate the design.

5. How does the impedance locus change on the smith chart?

6. Try and increase the precision of the program by setting the radius to 30 and integration accuracy to 4. Is there any difference compared with previous results?

Further Investigation

Vary the inset feed distance by making the offset larger what is the effect on the coupling? Now try and decrease the offset simulate the design and note the results.

Experiment 5 Aperture Fed Microstrip Antenna Design

Aim

To design an aperture fed microstrip antenna.

Introduction

In an aperture coupled feed, which is another type of EMC feed, the RF energy from the feed line is coupled to the radiating element through a common aperture in the form of a rectangular slot. This type of feed was first proposed by Pozar in 1985 [16]. The aperture coupled feeding mechanism is shown in figure 1:

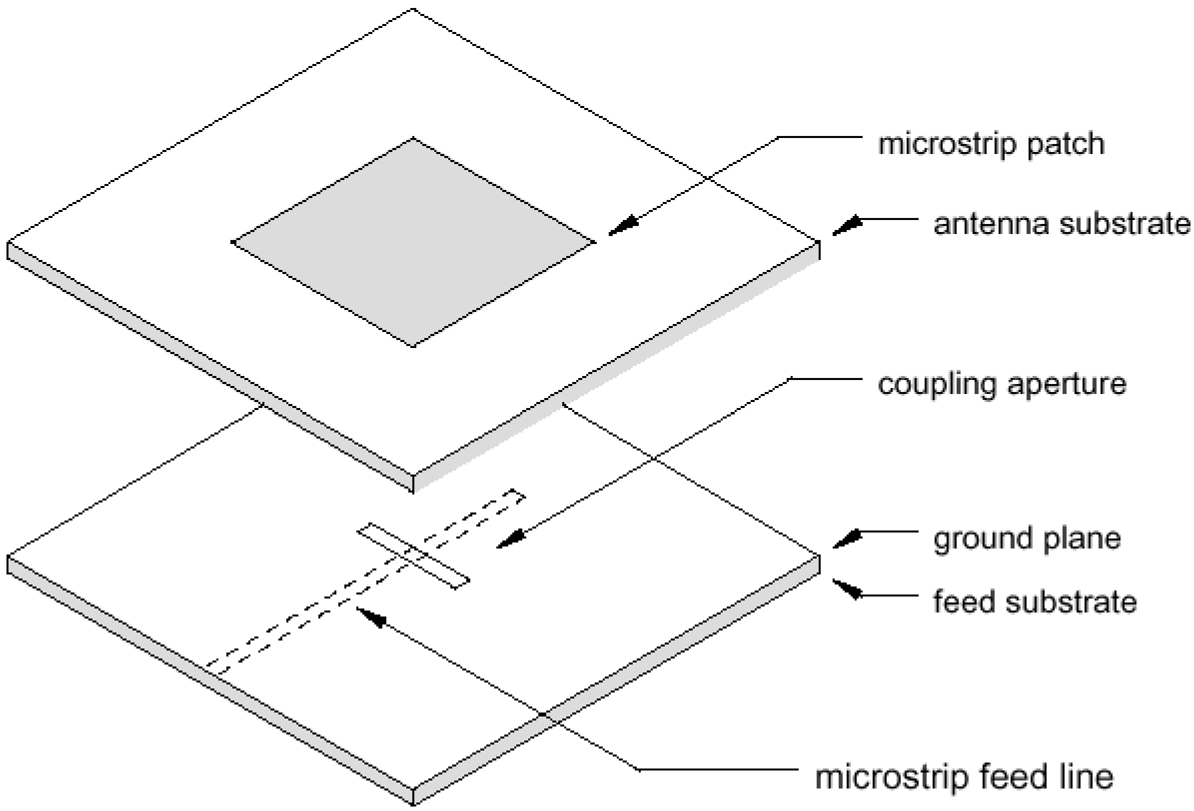


Figure 1 Aperture coupled feed [17].

In this design we will concentrate on the design of this antenna rather than the theory, for students interested in finding more about aperture fed antenna they should consult the references: [18] and [19].

Aperture fed antenna design parameters

There are various parameters, which may be varied in an aperture fed design, which can be used to tune the antenna [17]:

- Slot length (L_a): this parameter determines the coupling level to the upper patch as well as the back radiation level, and should be optimised for impedance matching. Typical lengths for the slot length are $0.082\lambda_o$ for low dielectric constants ($\varepsilon_r = 2.54$) and $0.074\lambda_o$ for high dielectric constants ($\varepsilon_r = 10.2$) [20].

- Slot width (W_a): the width of the slot affects the coupling level however does not have a very large effect, the slot width is usually made 1/10×slot length.

- Feed line width (W_f): determines the characteristic impedance of the feed line, which is usually 50Ω.

- Position of the patch relative to the slot: for maximum coupling the patch should be centred over the slot. Moving the patch relative to the slot in the H-plane (y-direction) has little effect on the input impedance, whereas moving the patch patch relative to the slot in the E-plane (x-direction) decreases the coupling.

- Length of open circuited stub (L_s): used to tune out the reactance of the slot and is usually made slightly less than $\lambda_g/4$

The parameters that are usually optimised in aperture fed designs are the slot length and open circuited stub length. The size of the impedance locus is determined by the slot length, when the slot length is increased the diameter of the locus becomes larger due to the increase in coupling. The length of the stub rotates the input impedance locus and is used to compensate for the inductance of the slot and patch and helps create a real impedance for the patch.

Experiment

1. Design an aperture fed antenna for the following antenna properties:
   Substrate = RO4003
   $\varepsilon_r = 3.38$
   $\tan\delta = 0.0021$ (tested at 2.5GHz)
   h = 1.524mm
   copper thickness = 17.5µm
   Design Frequency = 1.8GHz
   From this data the dimensions of the radiating patch (square) and feed line width (50Ω) can be calculated.

   The design guidelines to estimate the antenna parameters such as:
   - Slot length
   - Slot width

- Length of the open circuited stub

2. Draw up the structure with the parameters calculated in part 1 in Mstrip40 using DEMO11 as a template, make sure the slot option is chosen.

3. Simulate the design, the precision of the integration needs to be increased due to the coupling from the slot. The simulation may take a long time due to the increased precision.

4. Look at the smith chart and radiation pattern output how do the results compare with the proximity fed design.

5. Try vary the slot dimensions and observe the effect of the smith chart.

6. Now vary the length of the open circuited stub (end of the feed line) and note the results.

Further Investigation

Redesign the antenna using different substrates and observe the difference on the radiation plot. Foam (ε_r = 1.0) can be used in the upper substrate, layer 3 to try and improve the bandwidth.

A dielectric layer can be added on the main radiating patch (randome) to observe the change in the resonant frequency.

Experiment 6 Microstrip Antenna Array Design

Aim

In this experiment a log periodic antenna array will be analysed and designed.

Introduction

Microstrip antennas that operate as a single element usually have a relatively large half power beamwidth, low gain and low radiation efficiency. In order to improve on these parameters, microstrip antennas are used in array configurations to improve the gain and range of the radiating structure.

There are many effects such as mutual coupling between elements which must be taken into consideration when analysing array structure. As a result full wave analyses are usually used to model arrays.

The log periodic antenna structure consists is similar to a proximity coupled antenna, however the elements are designed such that they are a log size and spacing apart. These structures have relatively broad bandwidth, some in the order of 40% [21]. The following section will present a series of design guidelines summarised from the reference [21]:

The basic configuration of the log periodic antenna array is shown below:

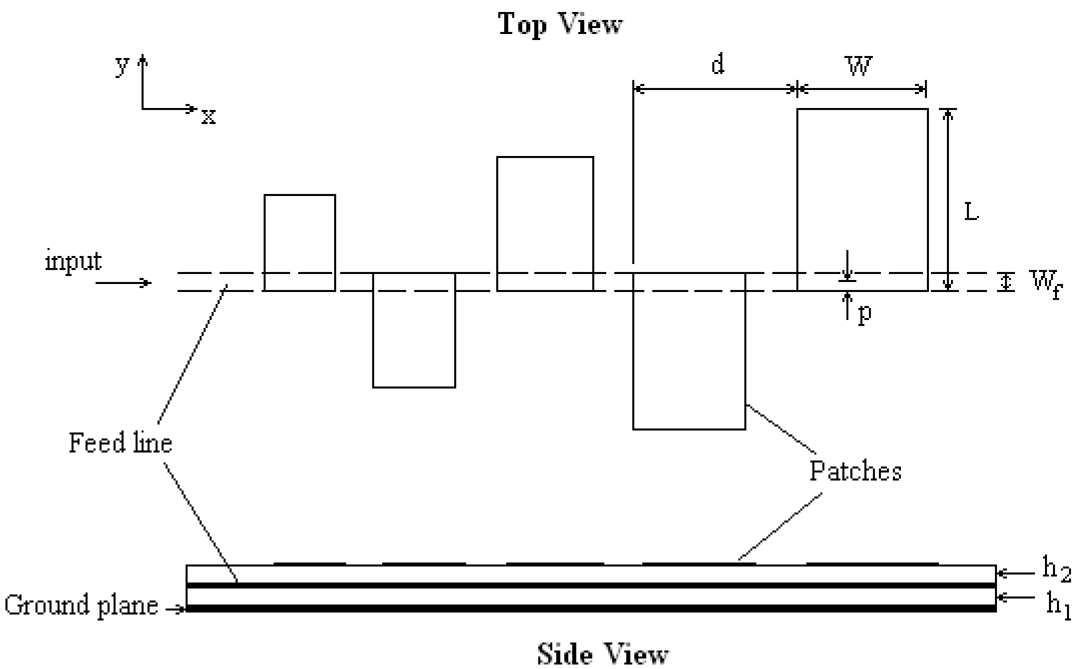


Figure 1 Log periodic antenna array configuration [21].

The length, width and spacing between patches (d) is given by the expression

$$\tau = \frac{L_{m+1}}{L_m} + \frac{W_{m+1}}{W_m} + \frac{d_{m+1}}{d_m} \qquad (1)$$

Where: τ = scale factor.

The height of both the substrate layers and feed line width should be kept constant.

Here are the basic guidelines for the design:

- Select the substrate layers.
- Determine the upper or lower patch length then using equation 1 to find all the corresponding patch widths and element distances.
- For the initial patch the width is chosen such that W=0.8×L, to prevent higher order modes.
- Find the number of patches (M) required which is the ratio of the desired bandwidth:

$$M = \frac{BW\left(Desired\right)}{BW\left(Single\ Patch\right)} \qquad (2)$$

- The input return loss or bandwidth can be improved by changing the patch spacing, d.
- The value for d is usually very close to the length L so for the initial design a “d” of around d = 1.05×L can be used as an initial estimate then varied in the simulation to determine the optimum spacing.

The above design steps should only be used as a guide to log periodic antenna array design, and are simplified for learning purposes, for a very thorough analysis of the log periodic microstrip antenna array refer to the literature [21].

Experiment

1. Design a log periodic antenna array using the following parameters:
   Layer 1 and 2 are FR4 with the following properties.
   ε_r = 4.6
   tanδ = 0.022
   h = 1.6mm
   copper thickness = 35μm
   Design the array to have a centre frequency of 1.8GHz.
   Use a scale factor of τ = 1.05.

2. Find the number of patches (M) given you want an 8% desired bandwidth.

3. Find the dimensions of the patch for upper frequency or lower frequency then use equation 1 to determine the size of the other elements.

4. Once the dimensions are found draw the design up in the STR file a proximity coupled design used in experiment 4 can be used as template. Choose the segment size to give you the best accuracy. Initially try a spacing between patches of one x-directed segment size.

5. Simulate the design.

6. Look at the input impedance plot on the smith chart is the antenna matched?

7. Open the radiation pattern window compare the pattern and gain with the previous antenna designs. Is the radiation pattern symmetrical?

Further Investigation

Try and design other array structures using coplanar feeds rather than a proximity coupled feed.

Include matching elements on the feed line to try and improve the input return loss of the array.

Design a log periodic array with more elements to try and improve the bandwidth and gain.

Future Experiments

Additional experiments that students can undertake are the following:

- Design of antennas employing foam substrates to improve the bandwidth.
- Design of slot antennas
- Further array investigation
- Circularly polarised antennas

Many of the demo files contained in Mstrip40 such as Demo17 and Demo20 can be further researched.

The design of novel antenna designs are only limited by a student's creativity so there are many other arbitrary patch shapes which can be analysed and designed using Mstrip40.

Practical Antenna Design

Over the course of my project I have gained skills in microstrip patch antenna manufacture using basic printed circuit manufacturing techniques. Here are the basic guidelines for producing your own rectangular microstrip antenna:

1. Choose your antenna substrate, normal PCB material will be fine for frequencies below 1 GHz.
2. Design the antenna using experiment 2 or some other method.
3. Once you are happy draw up the artwork of the antenna on Protel or another program, which will print out the design in a 1:1 scale.
4. Print the design on transparent film (ask lab technicians and lecturers for details.)
5. Expose the design under UV light with the design on the film covering the substrate area you want the design to appear on.
6. Create a developer solution to remove the photoresist.
7. Place the antenna in the etching tank to remove the unwanted copper.
8. Once the antenna is finished then you can solder a connector on the feed line and then test it.

Antenna Testing

Here is a description of some basic methods, which are used to test the various microstrip antenna parameters.

Impedance measurements

Network Analyser
Input Impedance characteristics
    Smith Chart plot analysis
    SWR analysis
s_{12}, s_{21} transmission characteristics

Radiation measurements

Preferably done in an anechoic chamber
Can use a simple set up with the following equipment:
Signal generator (transmitter)
Spectrum analyser (receiver)
Set up which will rotate the antenna 360^o.

Alternatively use a network analyser and connect the transmitting antenna to one port (s_{11}) and receiving antenna to the output port (s_{22}).

By moving the antenna at different angles and taking power measurements using the receiver (spectrum analyser or network analyser), a plot of the radiation pattern can be obtained. Cross-polarisation measurements can be made by changing the field plane of the receiving antenna. The gain of the antenna can be measured using various methods described in the literature [22] and [23].

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