Design And Simulation Study of Microstrip Dipole Antennas Operating at 2.4GHz.

By

Ranvir Pal - 031102
Salaf Hayat-031109

MAY 2007

Submitted in partial fulfillment of the Degree of Bachelor of Technology

DEPARTMENT OF
ELECTRONICS & COMMUNICATION
JAYPEE UNIVERSITY OF INFORMATION
TECHNOLOGY - WAKNAGHAT, SOLAN, HP, INDIA

Declaration

We declare that this report is our own unaided work, and hereby certify that unless stated, all work contained within this report is our own to the best of our knowledge .This report is being submitted for the final year project of B.Tech degree in Electronics and Communication Engineering , at Jaypee University of Information Technology,Waknaghat.

Ranvir Pal - 031102
Salaf Hayat.-031109
May 10, 2007.

Acknowledgements

We would like to thank our Project incharge, **Professor Tapas Chakravarty** for his guidance and expertise throughout this project. We are also grateful to **Mr.Sunil Khah** for his helpful advices and assistance, especially for his guidance to use CST microwave software.

Salaf Hayat

Certificate

This is to certify that the work entitled, **"Design And Simulation Study of Microstrip Dipole Antennas Operating at 2.4GHz."** submitted by Ranvir Pal and Salaf Hayat in partial fulfillment for the award of degree of Bachelor of Technology in Electronics and communication engineering of Jaypee University of Information Technology has been carried out under my supervision. This work has not been submitted partially or wholly to any other University or Institute for the award of this or any other degree.

Professor Tapas Chakravarty

Deptt. Of Electronics and Communication engineering

JUIT, Waknaghat.

Synopsis

The two most widely used frequencies for WLAN and Wireless communication applications around the world in recent years are the 1.8 GHz and the 2.4 GHz bands due to the global rise in the industry of cellular networks. Most wireless communication devices manufactured today are using monopole antennas owing to it simple structure, omni directivity and its small size. However, these factors limit its signal strength because of the low gain. This is particularly apparent in the 2.4GHz band. A solution for this problem lies within the printed circuit technology, for its compact and cost effective nature. This document involves determining the most suitable printed circuit board antenna to use, designing it, simulating a suitable antenna array and testing it for the purpose of 2.4 GHz wireless application .The design project will include understanding the principle theories and properties of antenna, microstrip, balun (balanced to unbalanced transformer) .These important factors were acknowledged and understood before design procedures take place. After studying different types of antennas, designing of PCB dipole antennas were proposed due to its appropriate nature, these being omni directional, compact and cost effective. As a dipole antenna needs a balun to be compatible for connection to a co-axial cable, hence balun designs were also proposed. An important objective of this thesis was to provide a solution to the setback of having low antenna gain in mobile wireless devices. The proposed solution is to design a suitable antenna to increase antenna gain, and at the same time retaining the omni directivity desired.

The design procedure includes the following:

1. Study and understanding of the design, properties and radiation patterns of microstrip dipole antenna.

2. Understanding of microstrip synthesis line equations.

3. To obtain suitable dimensions for structure parameters.

4. To implement the design through software.

5. To make suitable modifications, by using recommended methods, so that the design obtained finally gives required result including the required gain and radiation pattern.

Conclusions were drawn from the test results, indicating that the antenna built is satisfactory and have achieved the objective set for this thesis, which is to design and build a high gain omni directional microstrip dipole antenna operating at 2.4 GHz. Recommendations are then made on the improvements, future testing methods. Further research and testing on the current antenna has also been proposed.

Contents

List of Figures

Chapter 1
Introduction

This document describes the design, construction and testing of microstrip dipole antennas operating at 2.4GHz.

1.1 Background

In recent years the two most widely used frequencies for radio communications around the world are the 1.8 GHz and the 2.4GHz bands due to the global rise in the industry of cellular networks. Yet as we progress through this rapidly growing market, one important factor that has immense potential to improve is the signal strength of the cellular devices that we carry. Most wireless communication devices that have been marketed today are using monopole antennas due to it simple structure, omni directivity and its small size. It is due to these factors that its signal strength is limited by the low gain of these antennas, this is especially apparent in the 2.4 GHz band. As these commercial devices evolve, the demands for better performance will rise, yet these products must still keep its limitations within the boundaries of being easy to implement, cost effective and physically small.

A solution for this problem lies within the microstrip technology, for its improved performance and cost effective nature. This thesis involves determining the most suitable microstrip dipole antenna to use, its design and simulation.

1.2 Micro strip dipole Antennas

Microstrip antennas dates back to the early 1950's, but due to the lack of good low cost microwave substrates the developments of these antennas were limited over the next 15 years. A rapid development in PCB antennas started in the 1970's as thin, low cost antennas were needed for missiles and spacecrafts. PCB or micro strip antennas are an extension of the microstrip transmission line. A basic microstrip structure contains a thin substrate between 2 metal sheets which are usually copper. Microstrip line is then formed by etching away the necessary metal on top surface in so forming a strip. As long as the physical dimension of the strip and the relative dielectric constant remains unchanged, virtually no radiation will occur. By shaping the microstrip line into a discontinuity, power will radiate off from an abrupt end in the strip line.

1.3 Antenna Array

A single antenna element is often limited to many applications because of its low gain and wide beam width. Where a higher gain, narrower beam width and increased range are required, an array of antenna is to be implemented. In physical terms, an antenna array would be multiple elements of antennas, in a linked configuration placed equal distances apart to achieve the desired higher gain.

1.4 Objectives

The objectives of this thesis are:

- To determine the best suited PCB antenna for cellular devices.
- To test and analyze the suitability of this antenna using the CST microwave software.
- To draw conclusions and make recommendations on how the PCB antenna built can be improved over the present design for the suitability of wireless communication devices at 2.4GHz.

1.5 Source of Information

The information and knowledge on which this report was based upon was acquired from **Prof. Tapas Chakravarty**, sites from the internet, Documents from the various Universities websites and some of the e-books.

1.6 Plan of Development

The report covers the following sections in the following order:

- Principles and concept involved in determining and constructing of a suitable PCB antenna.
- Proposed designs of the chosen antenna.
- Methods used in design and fabrication of antennas.
- Test performed and error analysis on the built antennas.
- Make conclusions and recommendation on the suitability of the antenna and suggestions of improvements.

Chapter 2
Literature Review

This chapter goes through the theories and properties of antenna, microstrip, and balun. These important factors were needed to be acknowledged, understood and practiced for this thesis.

2.1 Antenna Properties

This section describes the important properties of antennas, all of which crucial when determining and designing antennas for applications. Since this is a practical project, there was no attempt to present more fundamental antenna theory.

2.1.1 Impedance

The characteristic impedance of the transmission line that is connected to the antenna must equal input impedance of the antenna. Antenna resistance is also called radiation resistance. This factor is defined as the resistance that would dissipate as much power as the transmission line for which it is connected to. Antenna resistance is defined:

$$R = P / I^2$$

Where ***R*** is the antenna resistance

P is the power dissipated

I is the current drawn from the antenna.

2.1.2 Wavelength

The frequency at which the antenna operates at is dependant upon its wavelength. The following equation describes this relationship:

$$\lambda = c/f$$

Where λ is the wavelength

c is the speed of light (($3*10^8$) m/s)

f is the operating frequency of the antenna.

2.1.3 Gain

This antenna property is used to compare differences in antenna radiation characteristics, both directivity and efficiency needs to be taken into account when determining antenna gain. This comparison is done by using a reference antenna of known gain, generally either a monopole antenna or a dipole antenna. Therefore when we talk about a gain of an antenna, it is meant the gain for which the antenna improves beyond the reference antenna. The gain of an antenna can be expressed as a

Power ratio:

$$A(db) = 10 \log_{10}(P_2 / P_1)$$

Where A is the gain

P2 is the power of the reference antenna

P1 is the power of the actual antenna

The power received by an antenna through free space can be expressed as:

$$P_r = P_t \, G_t G_r \lambda^2/(16 \pi^2 d^2)$$

Where P_r is the power received

P_t is the power transmitted

G_t is the transmitting antenna gain

G_r is the receiving antenna gain

λ is the Wavelength in meters

d is the distance between the antennas, in metres

2.1.4 Effective Area

Effective area of an antenna can be said to be the measure of the effective transmitting or receiving area presented by an antenna. It is normally proportional, but less than, the physical area of the antenna. Effective are can be expressed as a relationship to gain by:

$$A_e = G\lambda^2/4\pi$$

Where A_e is the effective area

G is the gain of the antenna

λ is the wavelength in meters

2.1.5 Directivity

Directivity is the term used when measuring how focused an antenna radiation pattern is. Directivity can be divided into two classes, Omni-directional and directional ,Omni-directional antennas radiate and receive signals from all directions at the same time with the trade off of having a limited gain. Where directional antennas radiate and receive signals at a beam width that directed outwards from the antenna, either at one or opposite directions with a higher gain than omni-directional antennas. For any antenna, the directivity can be related to its effective area:

$$D = 4\pi A_e^2 / \lambda^2$$

Where D is the directivity, and

A_e is the effective area

λ is the wavelength in meters

For small Beam width radiation, directivity can be also approximated by:

$$D = 27000 / (\alpha_{0.5horizontal}\ \alpha_{0.5vertical})$$

Where $\alpha_{0.5horizontal}$ is the horizontal half-power beam width

$\alpha_{0.5vertical}$ is the vertical half-power beam width

2.1.6 Efficiency

This property is a measure of how much electrical power supplied to an antenna is transformed into electromagnet and due to losses (imperfect dielectrics, eddy current etc), not all energy transmitted to the antenna is radiated, with this the antenna efficiency is defined as :

$$\eta = P_{transmitted} / P_{input} = R_r / (R_r + R_l)$$

Where η is the antenna efficiency

$P_{transmitted}$ is the transmitted power

P_{input} is the input power

R_r is the antenna resistance

R_l is the resistance due to losses

2.1.7 Polarization

The electromagnetic wave that is radiated from an antenna is comprised of electric and magnetic field. These fields are orthogonal to each other and to the direction of propagation. The polarization of an antenna is described by the electric field propagated. In general, all electromagnetic fields are elliptically polarized.

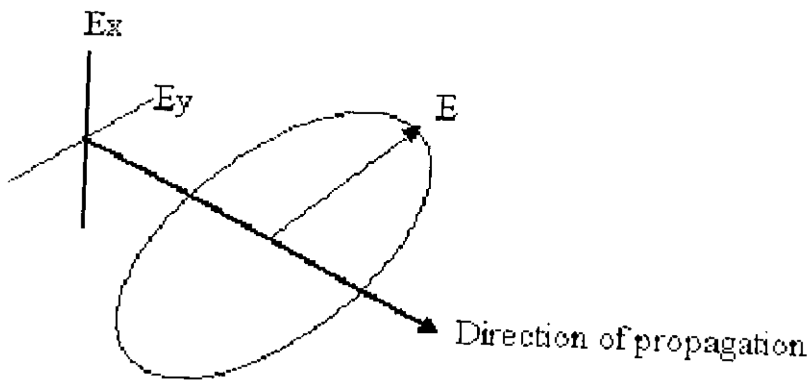

Figure 1: Elliptically polarized electromagnetic field

2.2 Printed Circuit Board Antenna

As mentioned before, PCB antennas are relatively simple structures where primary complicating factor are the relations between microstrip lines, dielectric substrates and the conducting ground plane .Although best accuracy can be achieved through rigorous mathematical and computational approaches, for this project, simpler and most widely used engineering methods will be used. This section will describe all the microstrip technology and techniques applied.

2.3 Types of Microstrip Antenna

Two main types of PCB antennas will be considered. Mainly the patch and dipole the following table shows the characteristics of these antennas at 2.4GHz:

PCB Antennas	Efficiency	Directivity	Physical Dimensions
Patch	High	Directional	Compact
Dipole	Medium	Omni directional	Compact

2.4 Microstrip Line

The following figure shows the physical properties of a microstrip line:

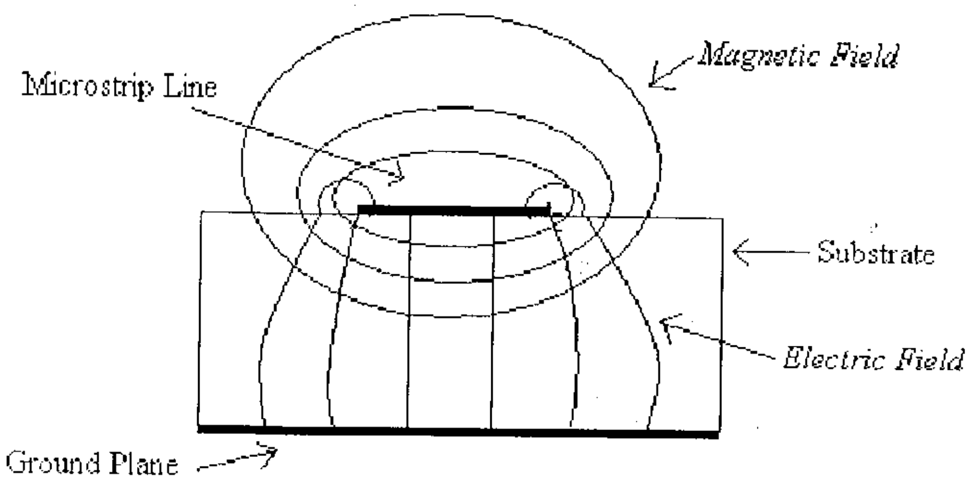

Figure 2: Microstrip line

The electric field lines are perpendicular to the microstrip line to the ground plane. Most of the lines are concentrated below the strip where some lines partially extend into the air space above. These lines are parallel to the conducting surfaces of the microstrip lines. The magnetic field circles the microstrip line and doing so also extends into the air space above the strip. Both fields that exist in the air space above the strip reduce the effective dielectric constant seen by waves propagating along the line. If the fields above the strip did not exist, then the dielectric constant would the same as the substrate. The width and height of the microstrip line controls how much the dielectric constant depends on the substrate, this in term affects crucial microstrip parameters such as characteristics impedance and phase velocity, making them frequency dependent. These factors provides us with analysis techniques in calculating and designing microstrip lines, and hence PCB antennas. The following synthesis formula helps approximate the width of microstrip lines:

$A=119.9/\sqrt{2(\xi r+1)}$

$B=1/2(\xi r-1)/(\xi r+1)\left(\ln(\pi/2)+\ln(4/\pi)/\xi r\right)$

$C=\ln\left(4h/\omega+\sqrt{(4/h)^2+2}\right)$

$D=59.95\pi/\sqrt{\xi_r}$

A, B, C, D parameter defined for convenience in applying the design formula

$$Z_0=A(C - B)$$

$$W/h=2/\pi\left(\left(\pi D/Z_0\right)-1-\ln\left(\left(2\pi D/Z_0\right)-1\right)\right)+$$

$$(\xi_r-1)/(\pi\xi_r)\left[\ln\left(\left(\pi D/Z\right)-1\right)+0.293-\left(0.517/\xi_r\right)\right]$$

where *w* is the desired width of the microstrip line

h is the height of the microstrip line above the ground plane

Z_0 is the characteristic impedance

εr is the relative dielectric constant

Due to difference in impedance with changing line width, impedance matching is between two different impedance elements is necessary. This can be done by placing a matching strip between the elements to be matched. The impedance of this matching strip can be expressed by:

$$Z_0=\sqrt{Z_1 Z_2}$$

where Z_0 is the matched impedance

2.5 Discontinuity

Discontinuity is a term for a geometric change in the microstrip line referring to a gap, notch or a bend in the strip. This physical change alters the electric and magnetic field distributions of the strip resulting in energy storage and often radiation at the discontinuity. Due to these factors showing similar characteristics as elements such as capacitors and inductors, discontinuities can be expressed as the following equivalent circuits:

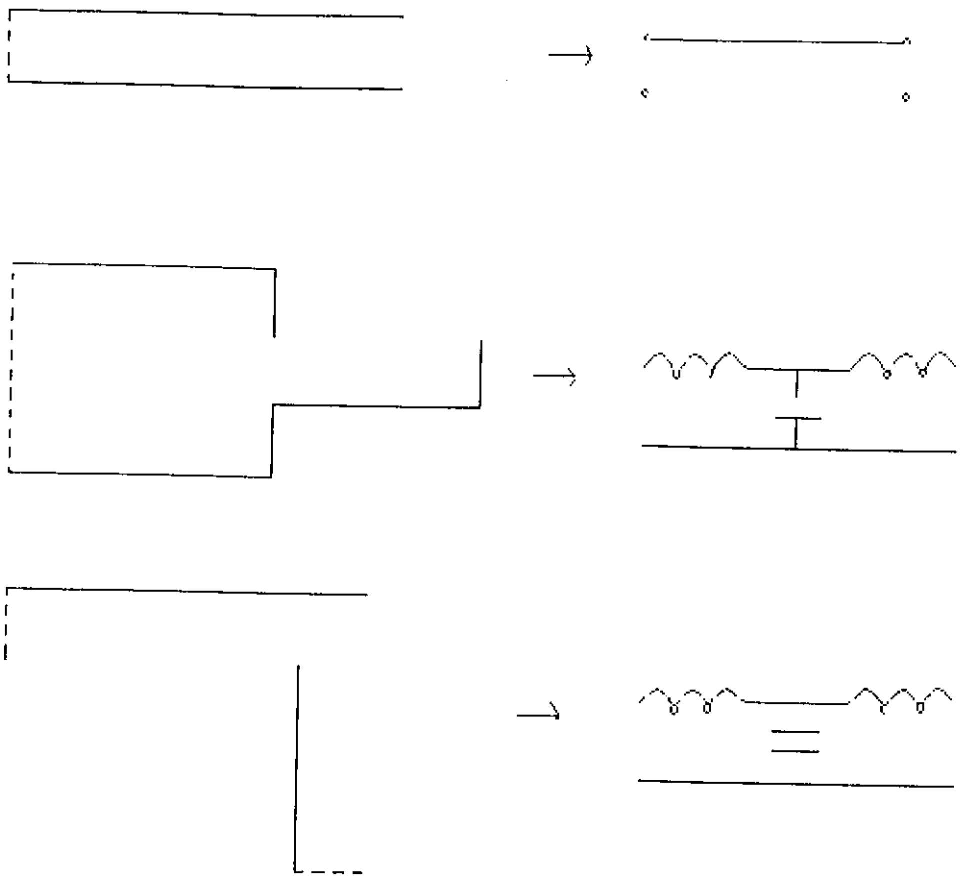

Figure 3: Discontinuity Equivalent Circuit

2.6 Balun

The word balun is a contraction for "balanced to unbalanced", where balanced means that both terminals of the feed must be of the same voltage level with respect to ground, if not then it is said to be unbalanced. This device is designed for systems where a centre-fed antenna (dipole for example) which is a balanced device, is fed to a coaxial line, which is unbalanced. The balance of the system is then upset as one side of the antenna is connected to the outer shield while the other is connected to the inner conductor. On the side connected to the shield, a current can flow across over the outer of the coaxial line. The fields that exist outside cannot be cancelled by the fields from the inner conductor as the fields within can not escape, and hence the current flowing outside of the coaxial line will cause unwanted radiation. This is called line radiation. Baluns manipulate the voltages at the antenna terminals equal in amplitude with respect ground but opposite in phase, these voltages causes equal amount of current to flow on the outside of the coaxial line. Since the current are equal and out of phase with each other, they cancel out and hence reducing the effect of line current .

2.7 Antenna Array

In some antenna applications, higher gain and narrower beam width is required to increase range and to reject interference. Antennas can be arrayed to produce these characters. In this section, array theory and architecture is discussed.

2.8 Design Consideration

As our aim in this project is to determine and design a suitable antenna for the mobile cellular technology, the following important factors are considered:

- Antenna designed needs to be omnidirectional for effective reception on a mobile device.
- Array design and configuration needs to have the potential for simple implementation and installation.
- The antenna needs to be compact in physical dimension for compatibility in the mobile cellular industry.

Chapter 3

Proposed Design

As the antenna design needed to perform the requirements of the design consideration mentioned in the last chapter, we chose to design PCB dipole antennas due to its appropriate characteristics, these been omnidirectional, compact. cost effective. Mentioned in the last chapter, a dipole antenna needs a balun to be compatible for connection to a co-axial cable, hence balun designs were also proposed.

3.1 Proposed PCB Dipole Radiator Design

The following **radiator design** was proposed:

The half-wave PCB dipole design, as to all half-wave dipole, has two quarter-wavelength radiating elements. The radiating elements are connected to a ground patch by two quarter-wavelength strips, these strips provide the ground plane for the balun element on the other side of the substrate.

This radiator design is the "ground sheet" of the whole dipole antenna, where it is connected to the ground/outer conductors of the co-axial cable. The copper sheet on the other side of the substrate will be the balun, where it is connected to the feed/inner conductor of the coaxial cable. These two sheets including the substrate in the middle will form the whole PCB dipole antenna design.

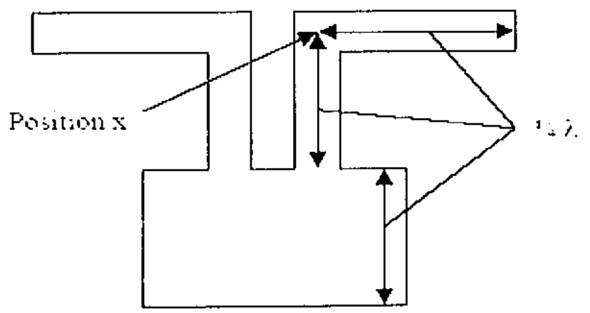

Figure 4: Groundsheet design

3.2 Proposed Balun Design

There are two balun designs implemented. One is the short circuit design and the other is the physically connected design. The following illustration describes the two designs:

In design "a", the quarter-wavelength strips leading to the ground patch on the radiating sheet mentioned acts as a ground plane for the balun microstrip line. This microstrip line effectively has a gap in the ground plane between the two radiating element, this gap is terminated by an open circuit a quarter wavelength away at position y. The combination of these elements provides the balanced to unbalanced transition and the necessary impedance needed.

In design "b", position z is physically connected to position x. This design is fundamentally similar to design "a", except in this case it does not need to provide an open circuit quarter-wavelength away to terminate the gap, it is already physically terminated.

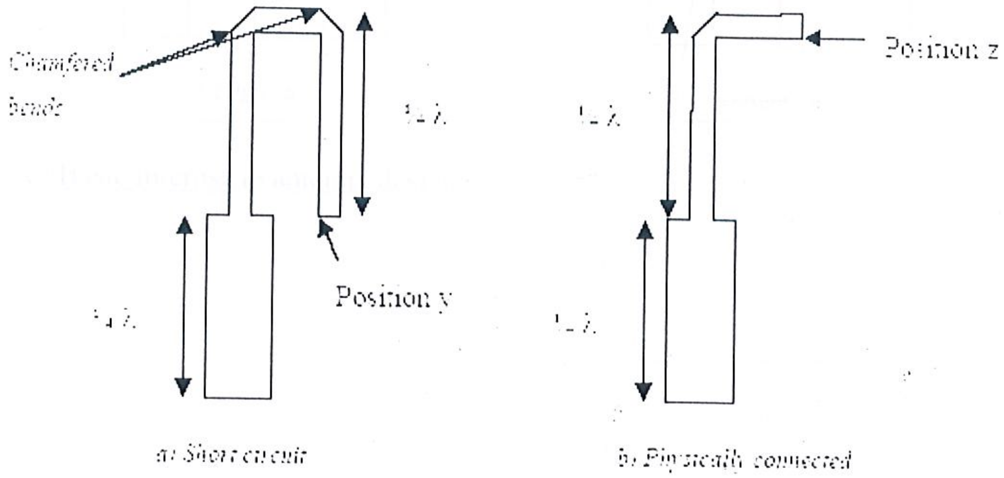

Figure 5: Balun design

The 45^0 diagonal chamfered (or metered) bends on the microstrip lines shown in the figure above greatly minimizes the discontinuity reactance that would normally occur on a bend, as these chamfered bend are electrically shorter than the physical distance of the bend path. In an even more understanding perspective, a chamfered bend seems though if it is guiding the signal traveling through the path.

3.3 PCB Dipole Antenna

The figure below explains illustratively how the previously mentioned designs in this chapter are associated:

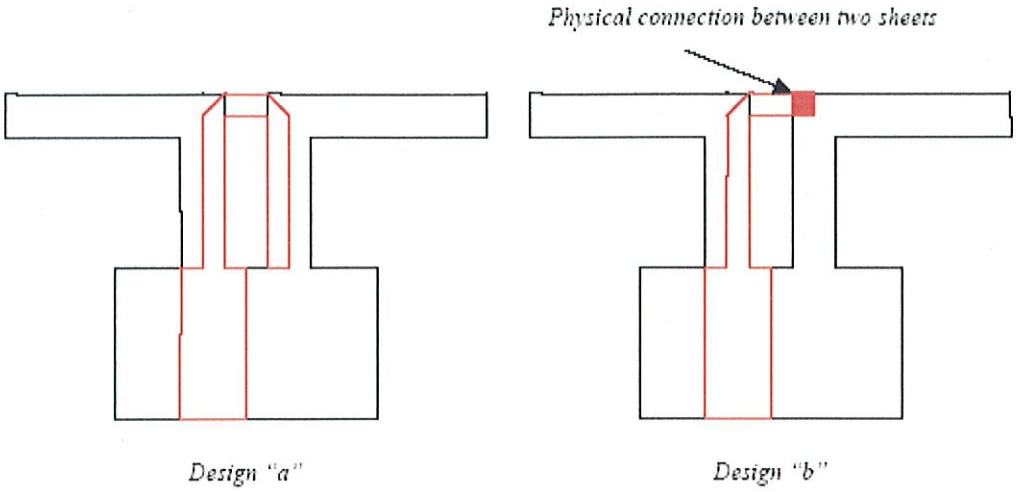

Figure 6: Basic microstrip antenna design

Chapter4

Design and Fabrication Methods

This chapter describes the design procedures taken in assisting linking knowledge between the theoretical understandings, and the practical fabrication of antennas.

4.1 Design Procedures

The following design procedures were implemented, taking into consideration the time and cost constraints:

- Design and building of prototype microstrip dipole antennas.
- Analyzing the performance of prototype antennas in helping designing the etched PCB dipole antennas.
- Design and fabrication of required PCB dipole antennas.

4.2 Building and Testing of Prototype Microstrip Antennas

The reason for building these initial antennas are so that the relationship between antenna theory and practical antenna building could be more understood before going ahead in designing the final PCB antennas. Further, it is possible to "tune" these antennas by trimming the copper strip conductors and adjusting the dimensions. Three prototype antennas were built using different dimensions and methods, this assists in determining which type would be more feasible for further design. All three antennas were fabricated using 0.5mm copper plate as conductive sheet and 1.66mm FR-4 substrate.

4.3 Prototype Designs

The width the microstrip lines to be used in these antennas will be calculated using the microstrip line synthesis equation with the known dimensions and the lengths of the dipole- arm strip and the micro strip balun are all approximately a quarter wavelength.

The specifications for the design of the prototype antennas are as follows:

- Operating Frequency: 2.4 GHz.
- For all the designs we have used a dielectric of thickness 1.6 mm and relative permittivity of 2.2 and the height of copper strip on both sides of dielectric is 0.5 mm.
- Now by assuming impedance for quarter wavelength strips and balun we can obtain their respective width.

In our designs we have used following notations:

Ground plane:

a) Length = L_g

b) Width = W_g

Micro strip balun

a) Length = L_f

b) Width = Wf

Quarter wavelength strips

a) Length = L_b

b) Width =W_b

c) Gap between two strips =g_1

Dipole arm (radiating element)

a) Length = L_d

b) Width = W_d

c) Gap between two strips =g_2

Design A: Short Circuit Design

The dimensions for this prototype design are as follows:

L_g = 39.5mm

W_g = 50 mm

L_b = 40mm

W_b = 1mm

L_f = 40mm

W_f = 1mm

L_d = 6mm

W_d =39.5mm

g_2 = 5mm

The above dimension when plotted in software results in following structure

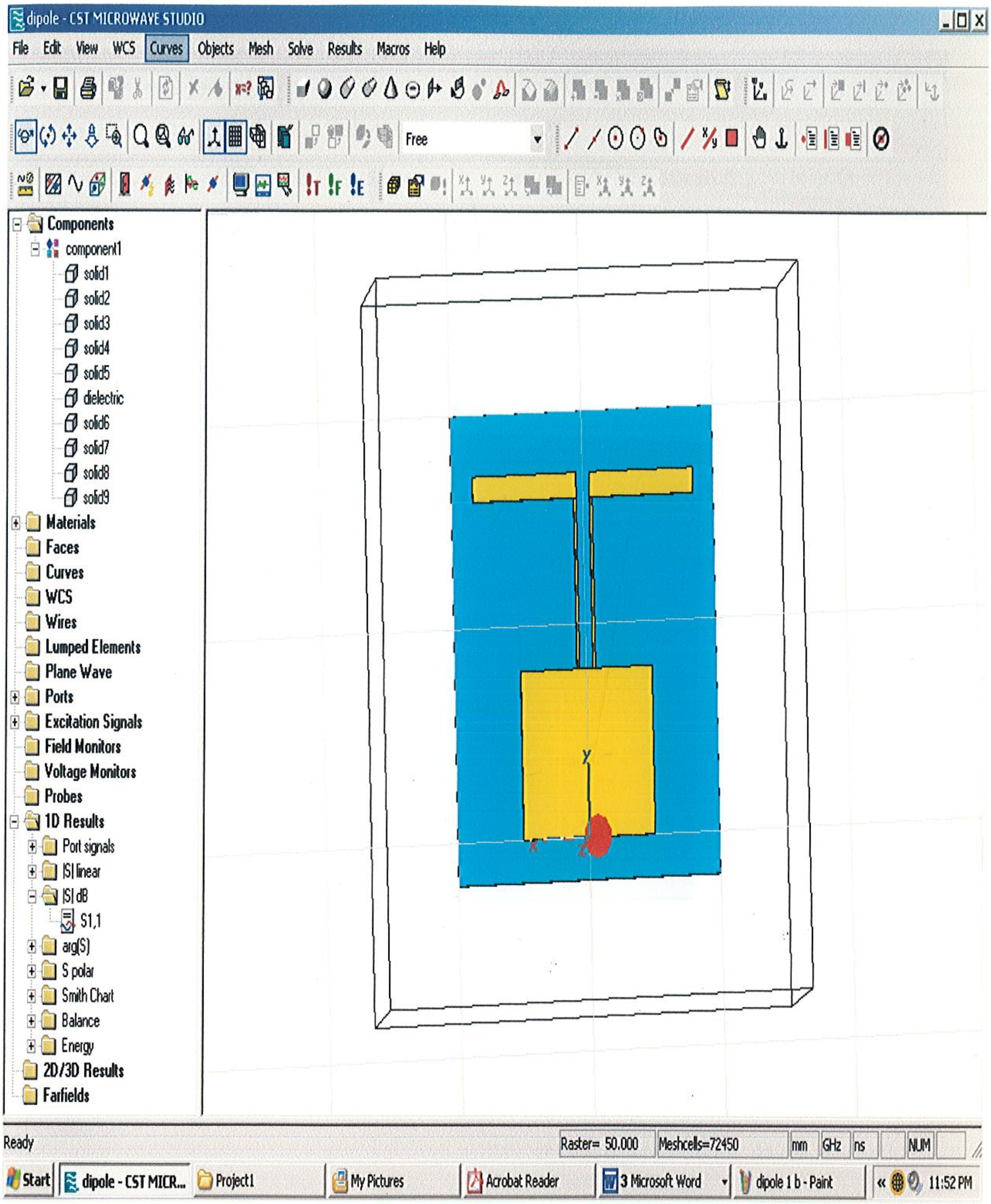

Figure 7: Groundsheet of prototype design A

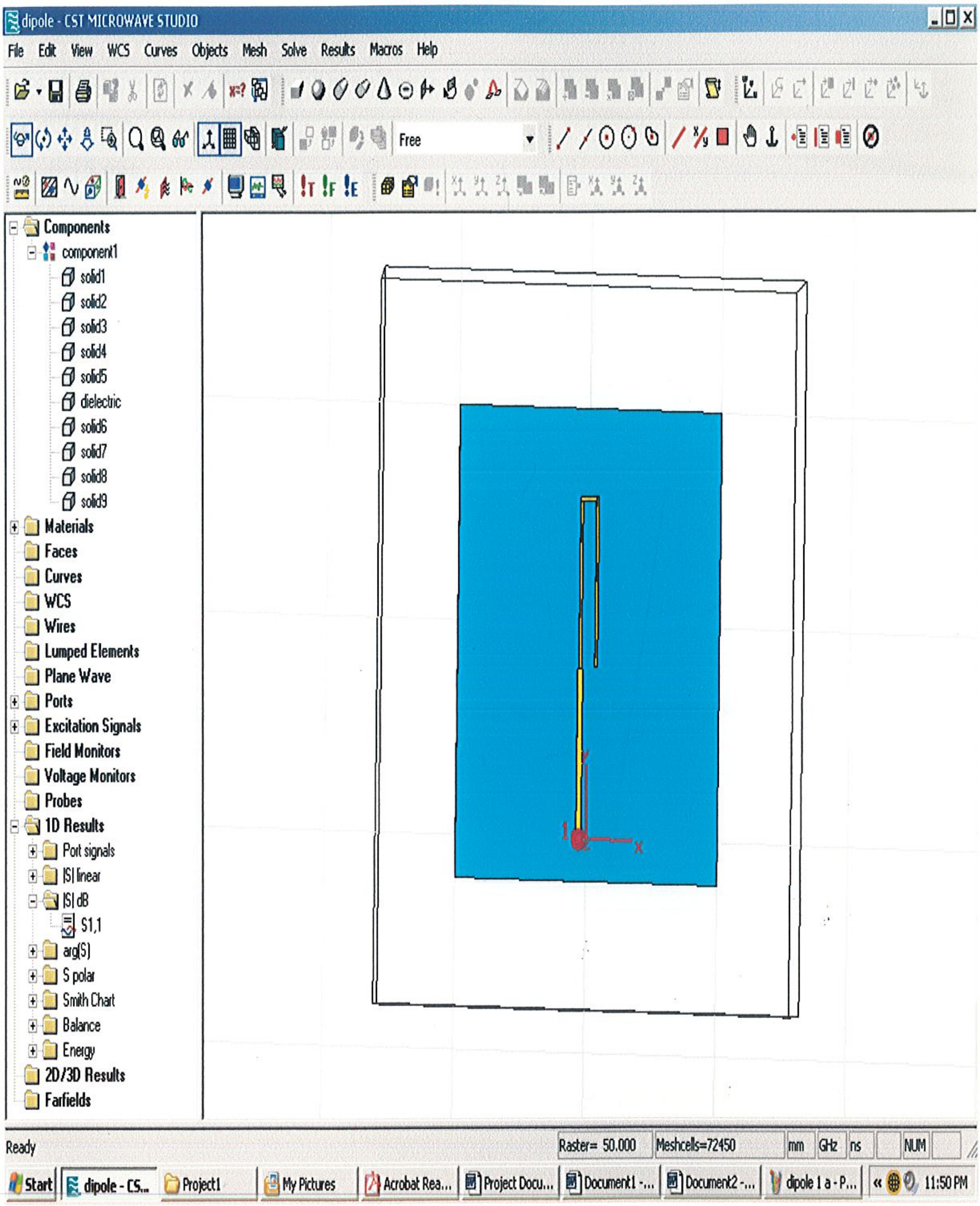

Figure 8: Balun of prototype design A

Design B: <u>Short Circuit Design</u>

The dimensions for this prototype design are as follows:

L_g = 10 mm

W_g = 15 mm

L_b = 19 mm

W_b = 5 mm

L_f = 34 mm

W_f = 3 mm

L_d = 6 mm

W_d =19 mm

g_2 = 3mm

The above dimension when plotted in software results in following structure:

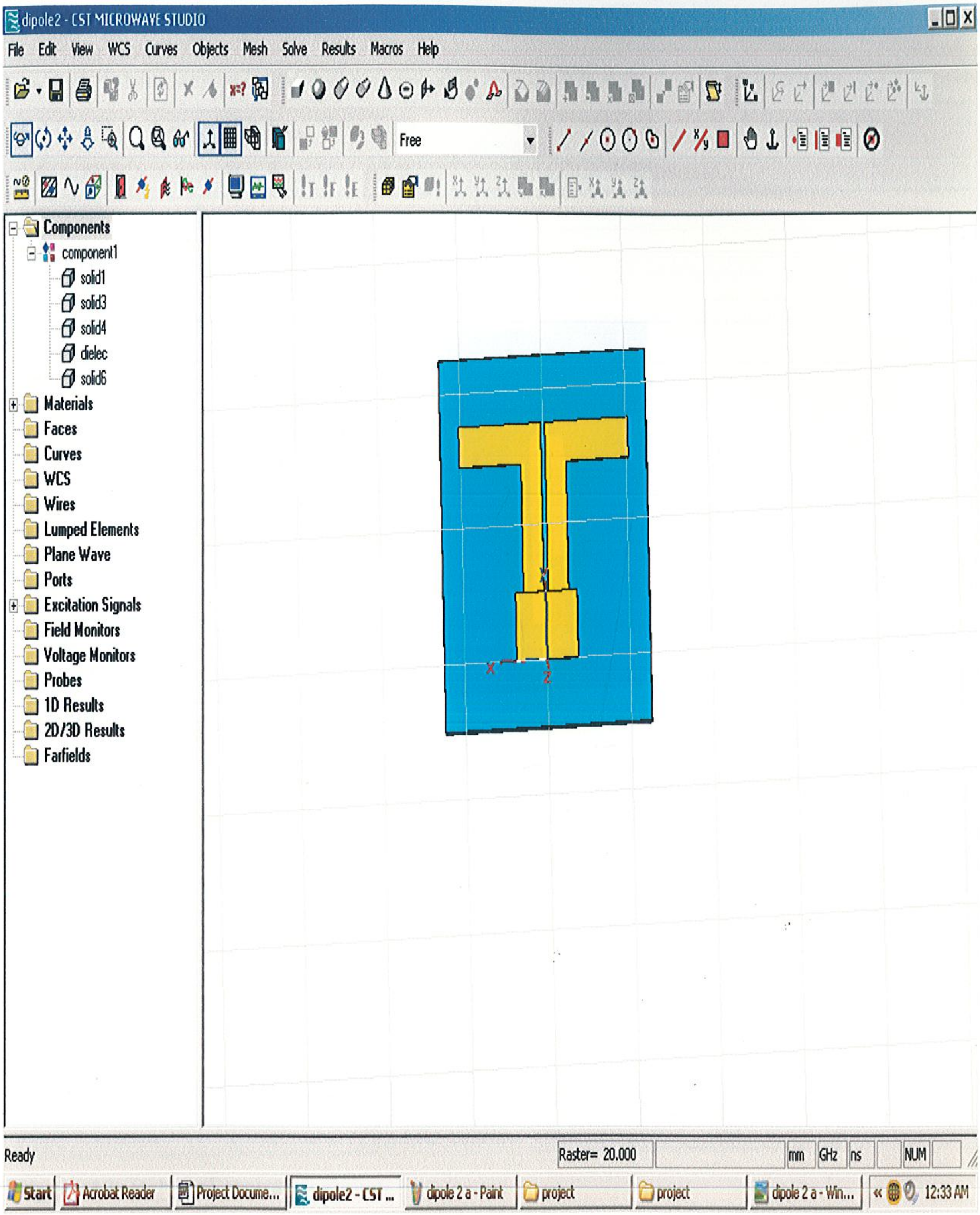

Figure 9: Groundsheet of prototype design B

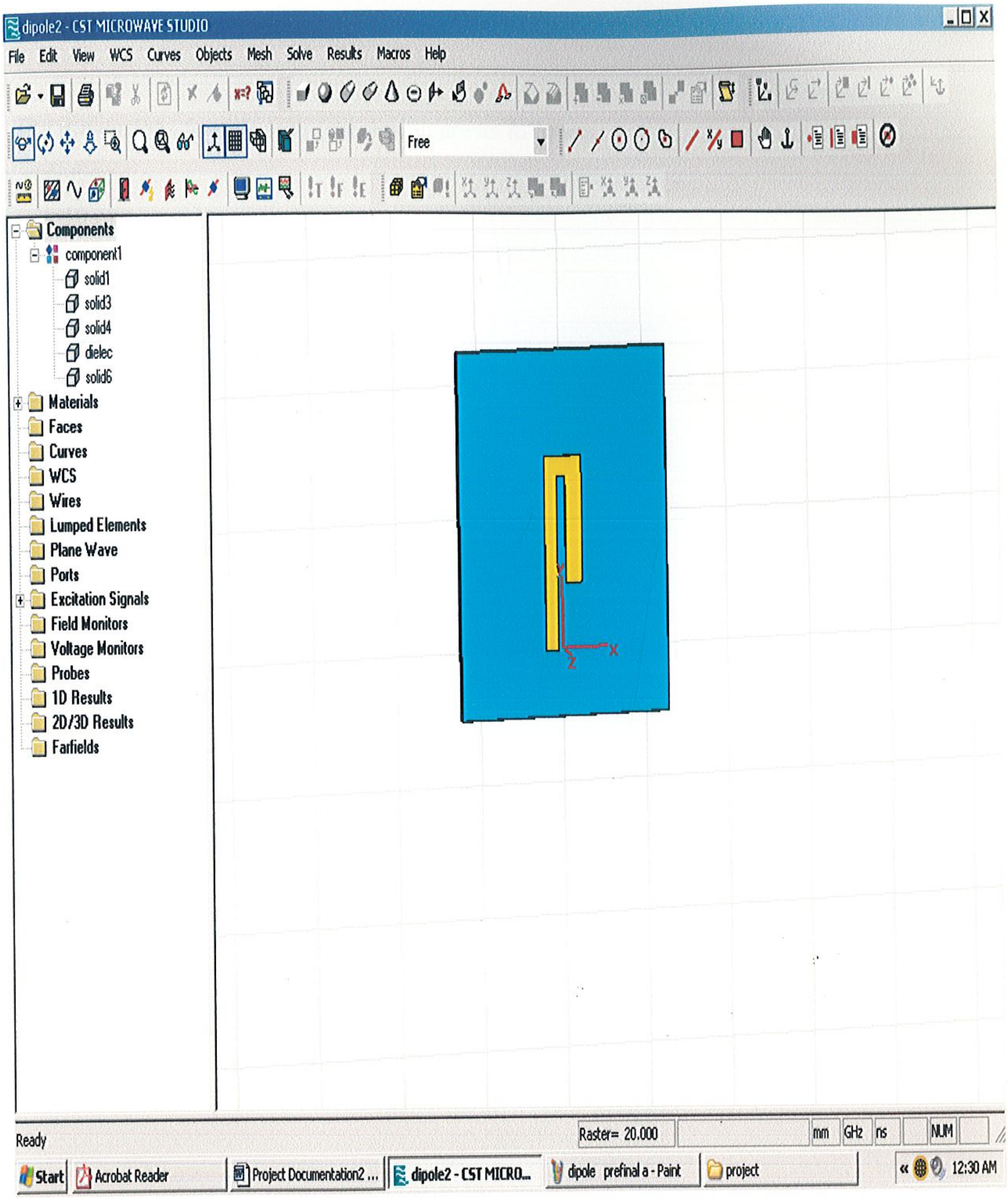

Figure 10: Balun of prototype design B

Design C: Physically connected

The dimensions for this prototype design are as follows:

L_g = 10 mm

W_g = 15 mm

L_b = 19 mm

W_b = 5 mm

L_f = 34 mm

W_f = 3 mm

L_d = 6 mm

W_d =19 mm

g_2 = 3mm

In this design there is a physical connection between ground sheet and balun via hole, of radius r = 0.375 mm (taken from theory of micro strip antenna)

The above dimension when plotted in software results in following structure

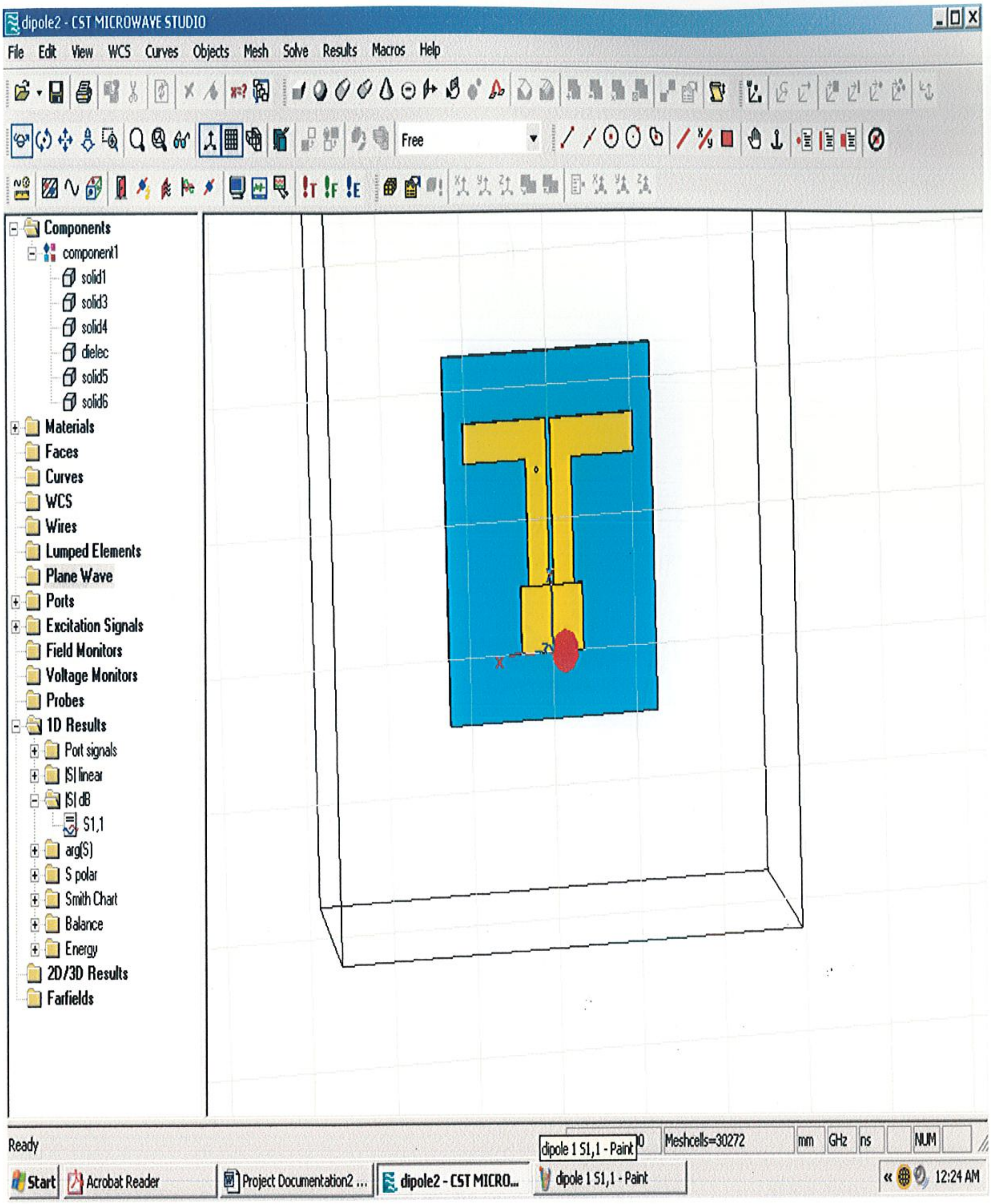

Figure 11: Groundsheet of prototype design C

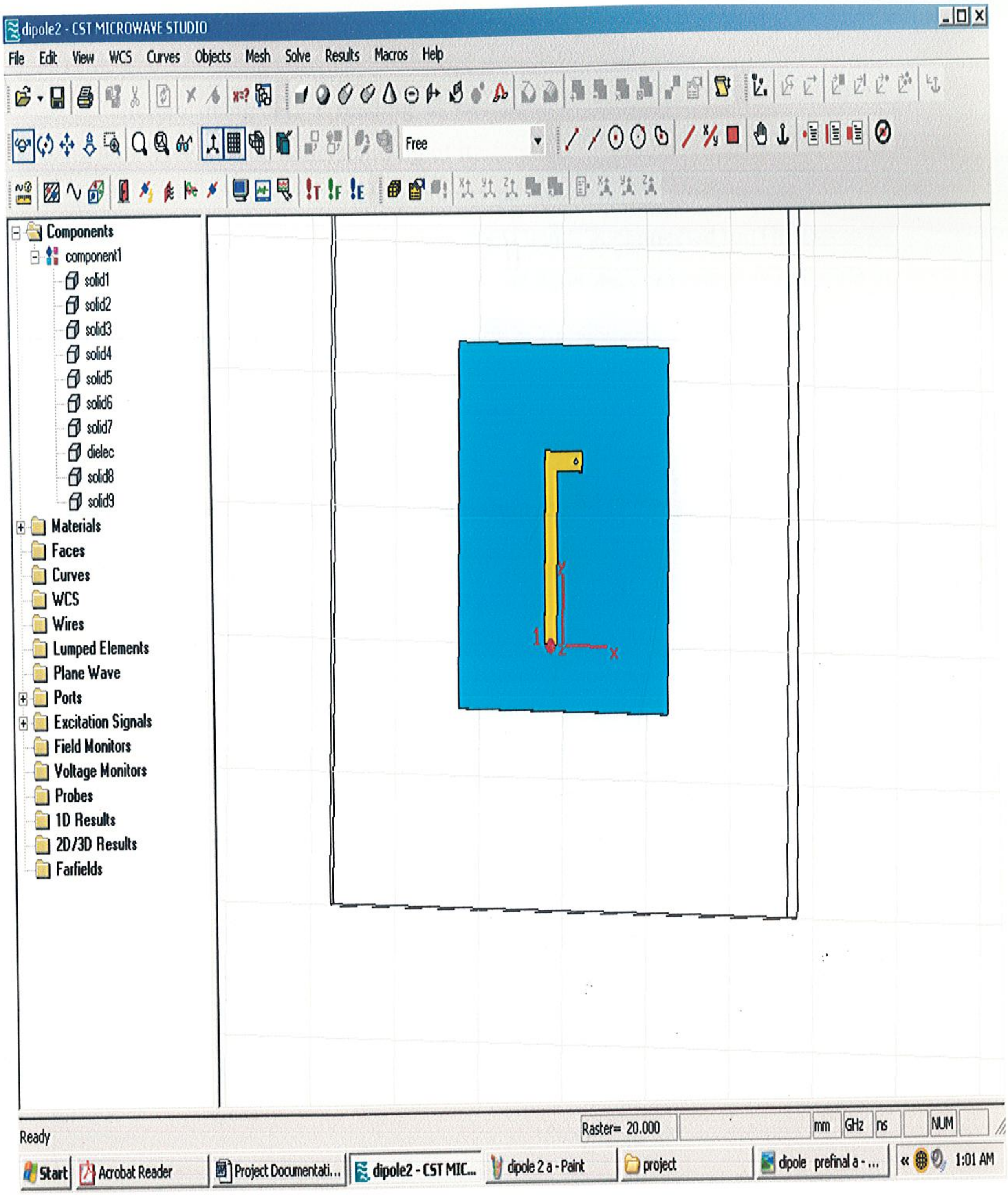

Figure 12: Balun of prototype design C

4.4 What is S1,1 Reading ?

Before using S1, 1 reading as our basis to determine the most appropriate antenna let's have a basic understanding of it.

The |S11| reading shown on the network analyzer determines how well the impedance is matched on the component that it is connected to. The test is an indicator of the reflected power which analyzes whether the component is radiating at the correct frequency and its radiating bandwidth.

4.5 Prototype Performance

The antenna performances below were taken from the S1,1 readings on the CST microwave software.

Design A

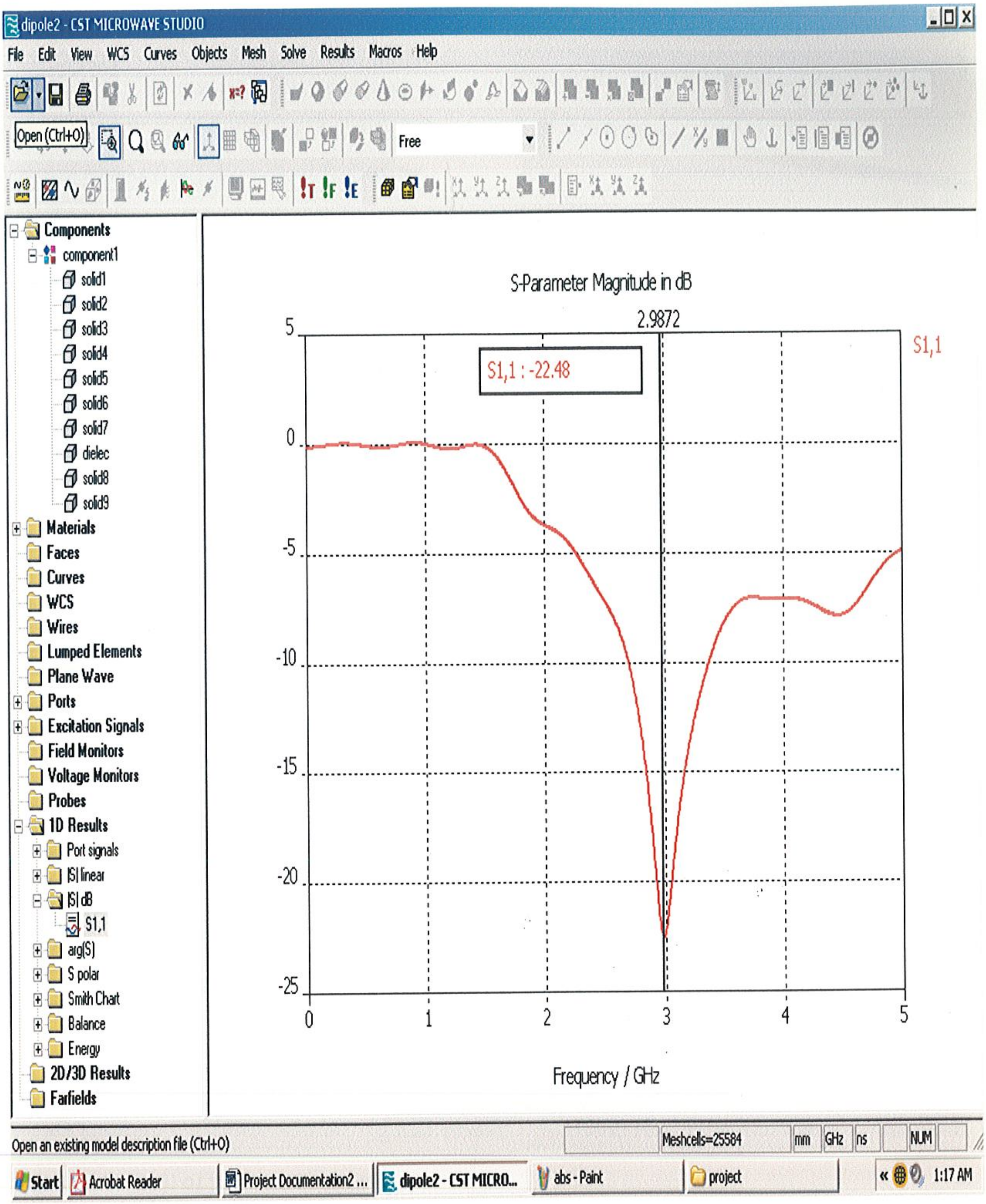

Figure 13: |S11| of prototype design A

Design B

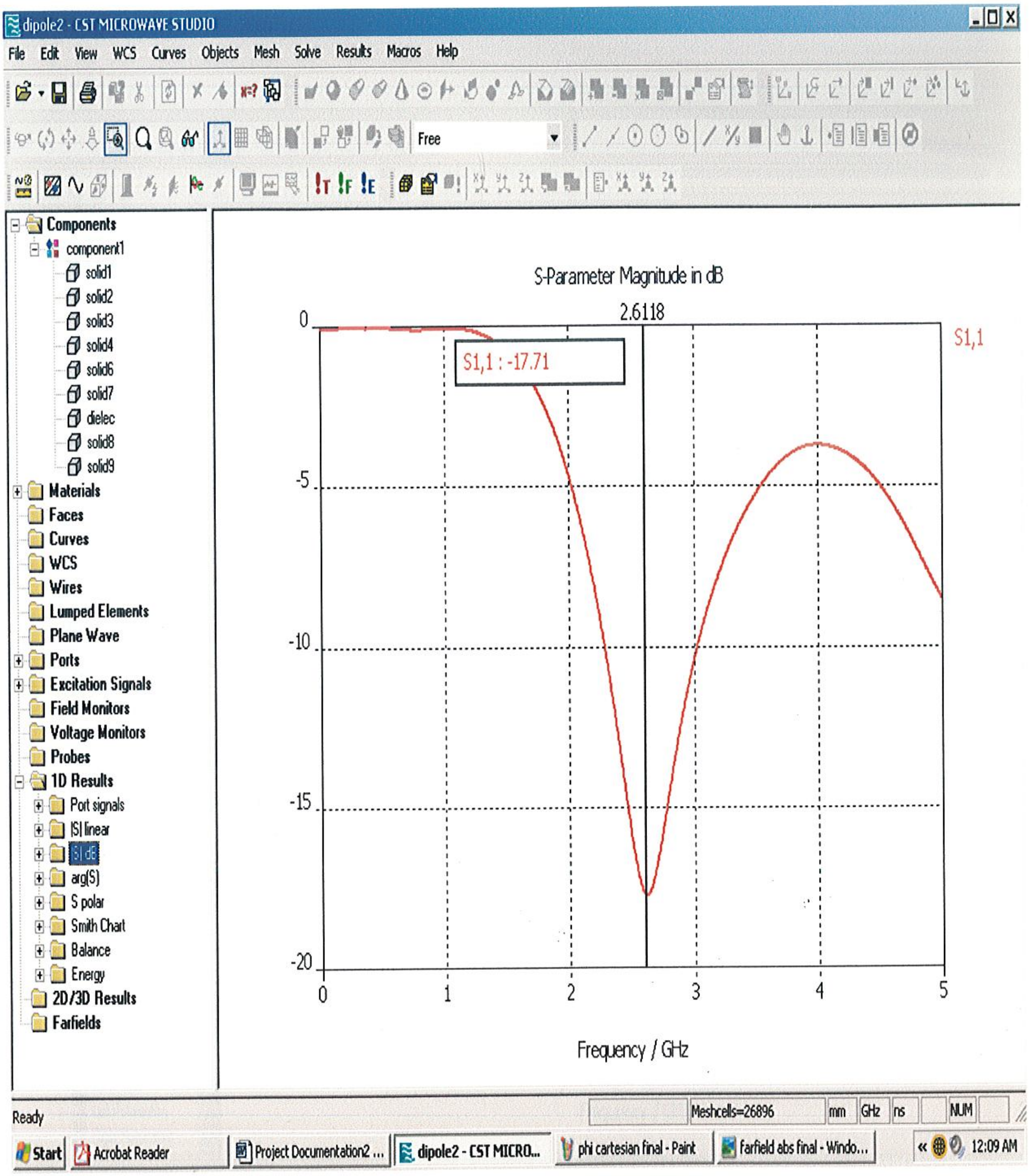

Figure 14: |S11| of prototype design B

Design C

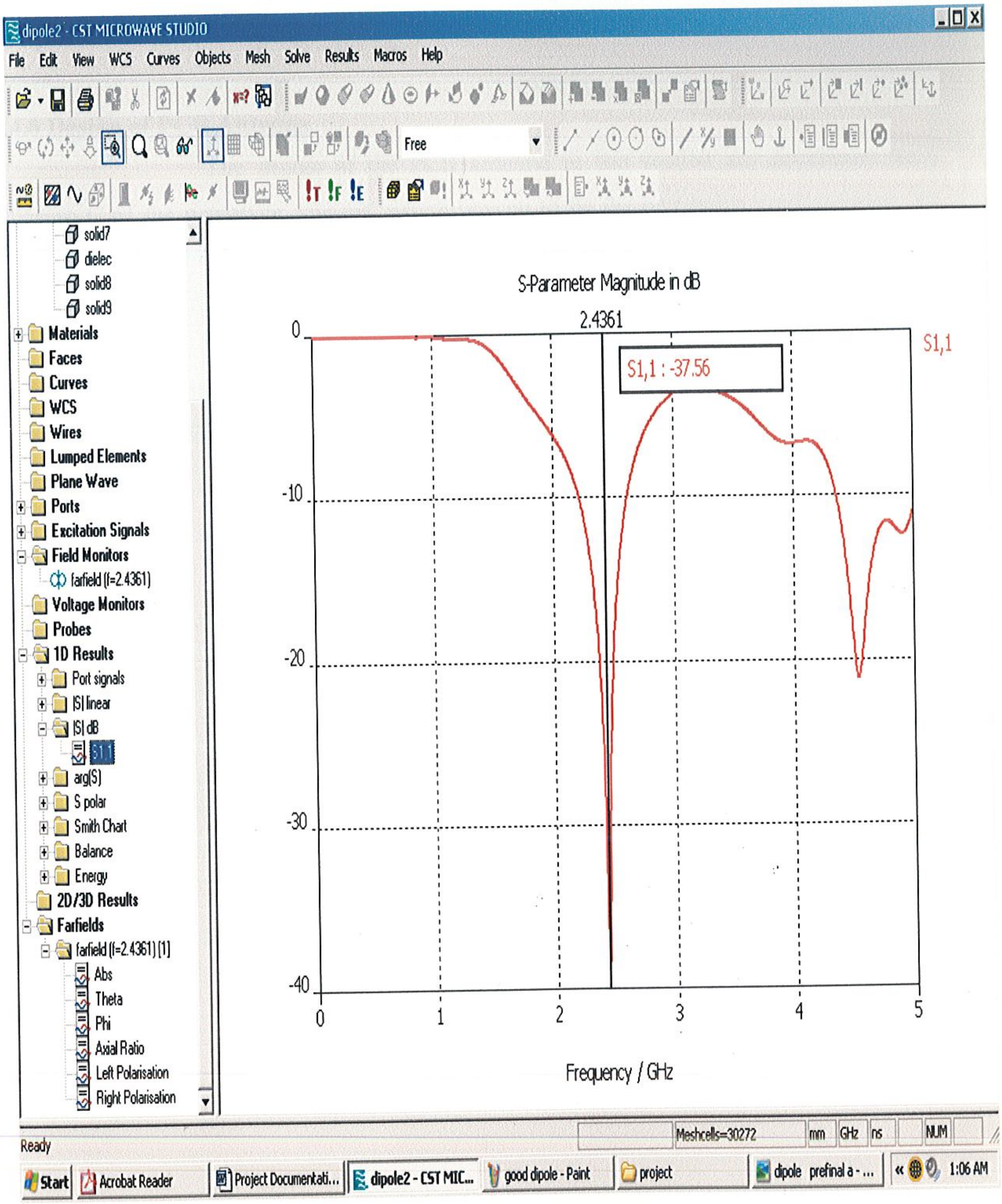

Figure 15: |S11| of prototype design C

From the result shown above, we can see that neither the design A nor design B had the satisfactory result; hence the designs for etched PCB antennas will be implemented using design C.

4.6 Design of PCB Antenna

The design of the PCB antenna in this section are developed from design C of the prototype antenna, which proven to be the best balun configuration. At this stage, the aim is to design the best suited antenna which fulfills the condition of required pattern, directivity and resonating frequency as close as possible to 2.4 GHz.

From the S1,1 reading above and far field pattern shown below (see the gain of 2.2 dBi) it is clear that the Design C prototype is giving result very much closer to the required result.

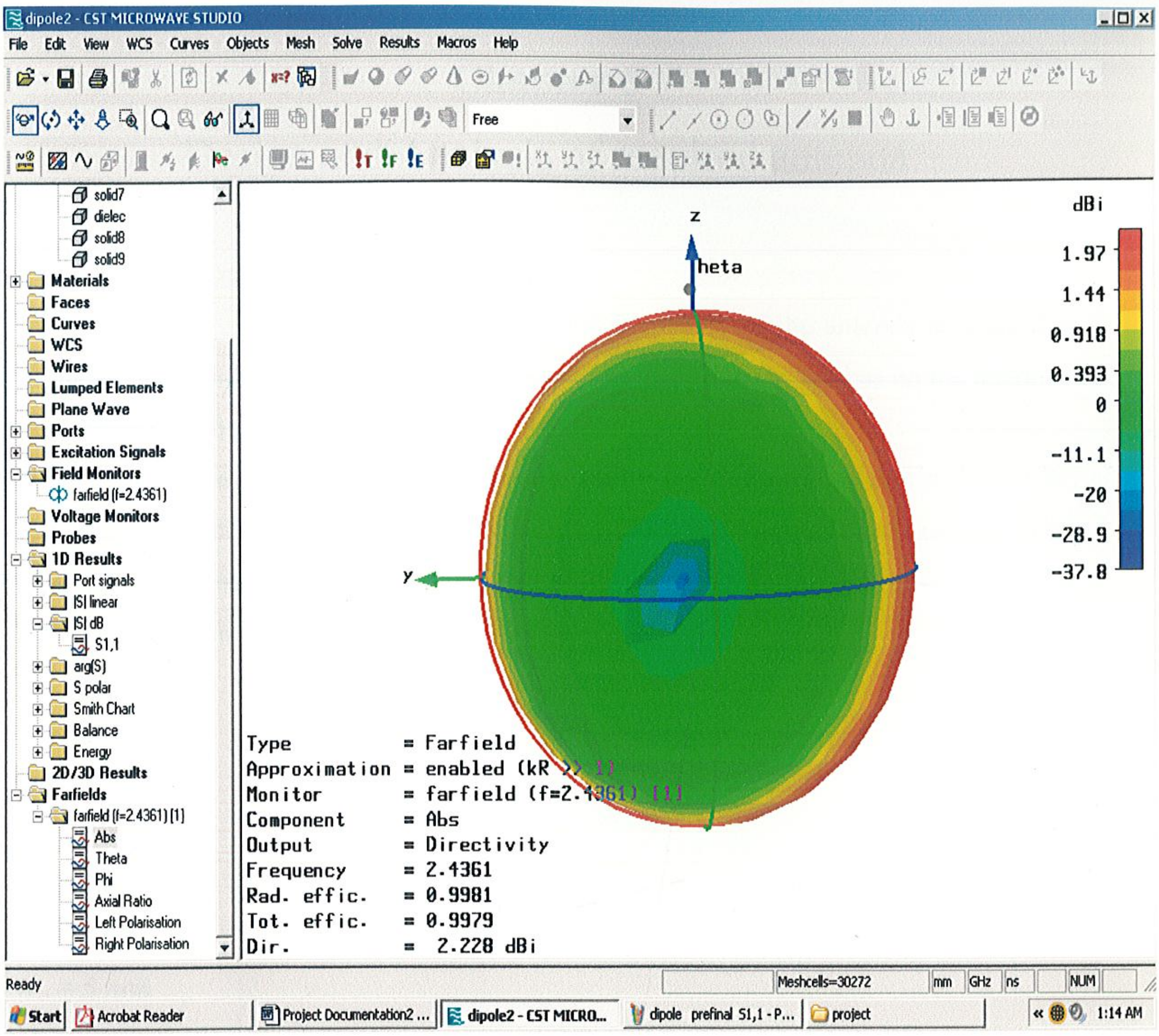

Figure 16: Abs component farfield

So in the next chapter we will be using Design C prototype antenna and frequency correction techniques to implement our final, required antenna.

Chapter 5

Design and Analysis of required antenna

5.1 Frequency Correction on Design C

We know that the operating frequency of the antenna is dependent on the length and the width of the quarter-wave matching strip as well as on the length of the radiating element.

In our case we have decreased the width of the quarter-wave matching strip. Hence by, trial and error, decreasing the width of these two matching strip near the radiating strip, we obtain following dimension.

The dimensions for this design are as follows:

L_g = 10 mm

W_g = 15 mm

L_b = 16 mm

L_h = 3mm

W_b = 5 mm

where L_h is the length of decreased width of the quarter-wave matching strip.

L_f = 34 mm

W_f = 3 mm

L_d = 6 mm

W_d =19 mm

g_2 = 3mm

Via – hole radius r = 0.375 mm

g_1=1mm.

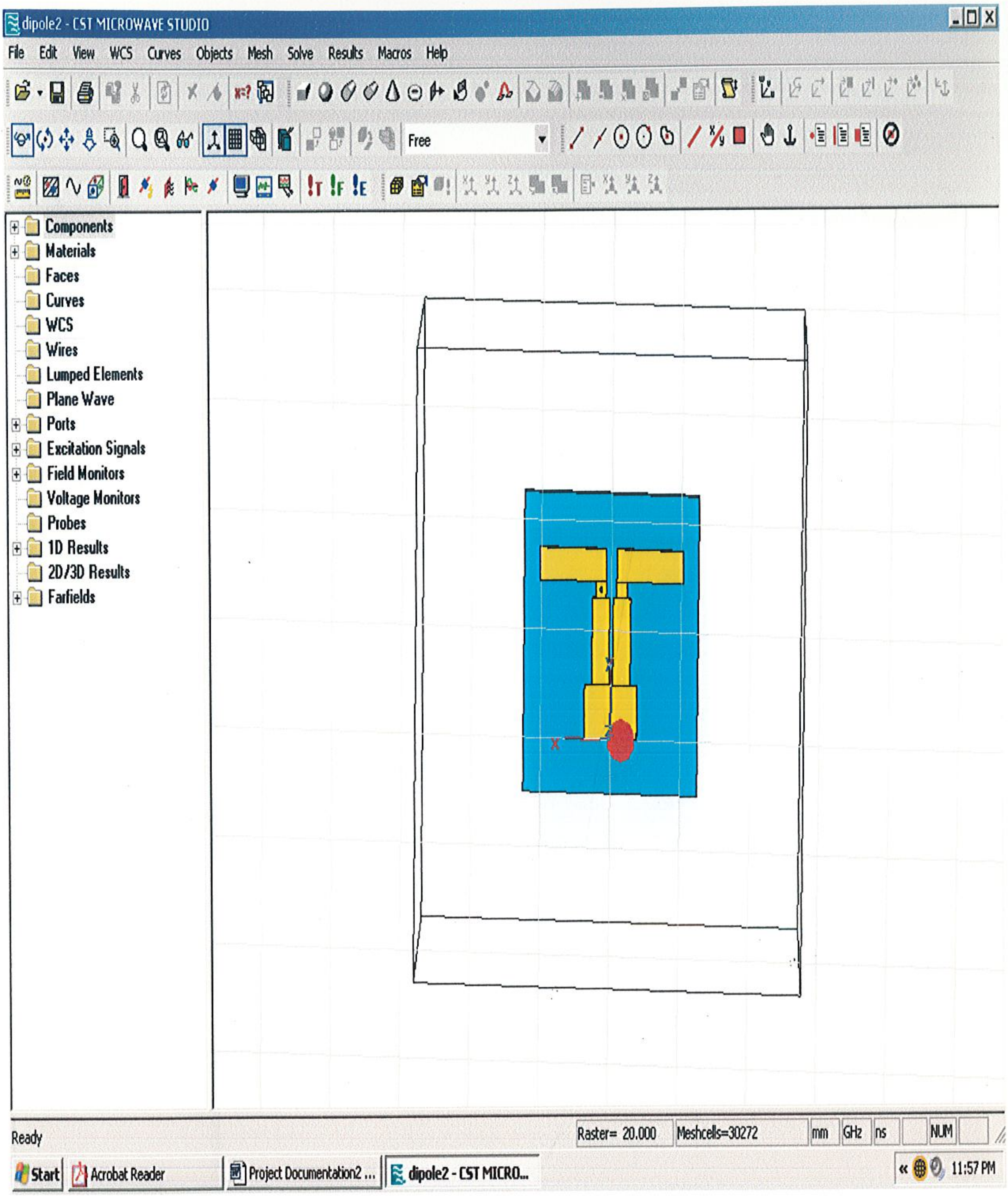

Figure 17: Groundsheet for desired antenna

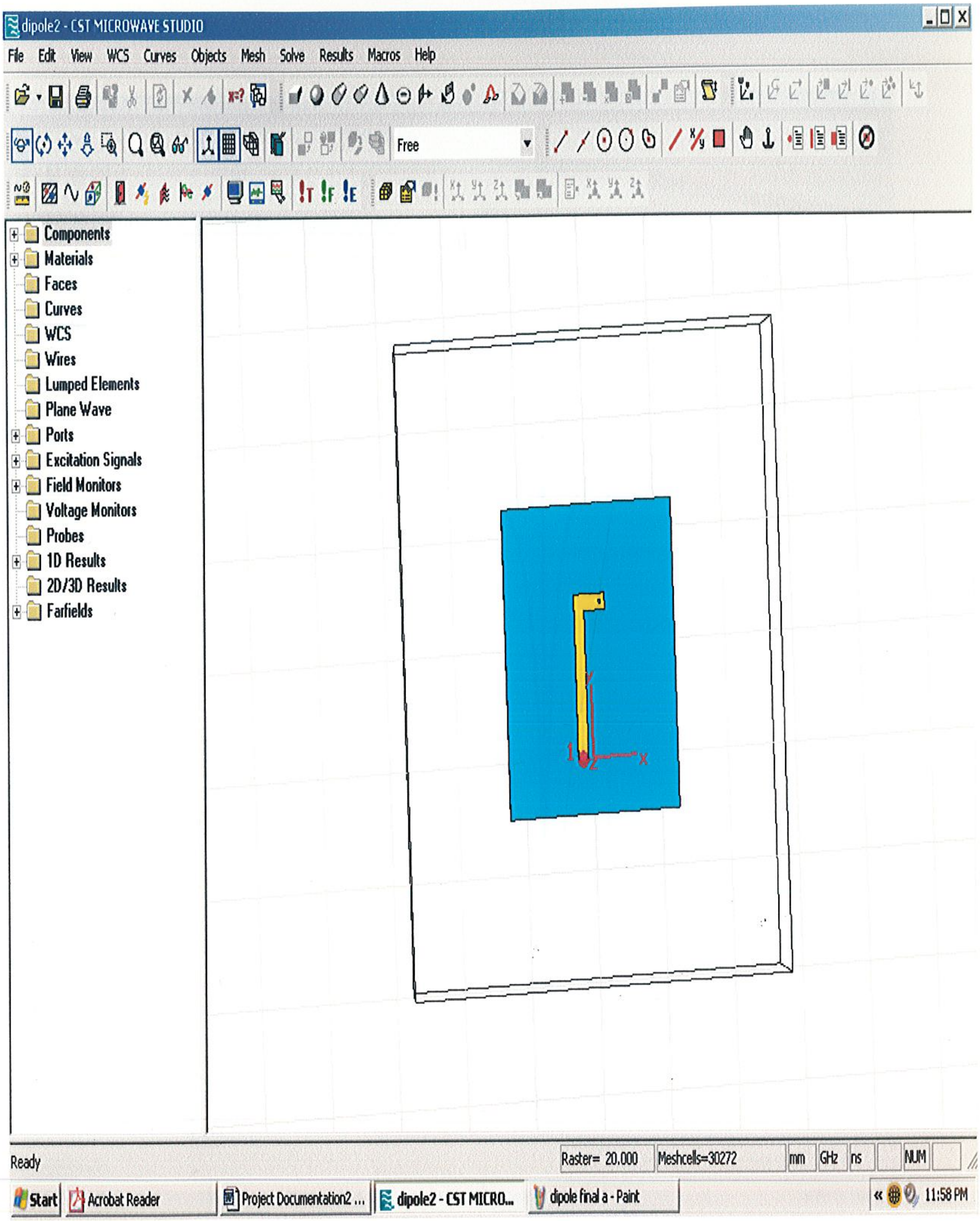

Figure 18: Balun for desired antenna

The S1,1 reading obtained for above design as obtained on software is shown below:

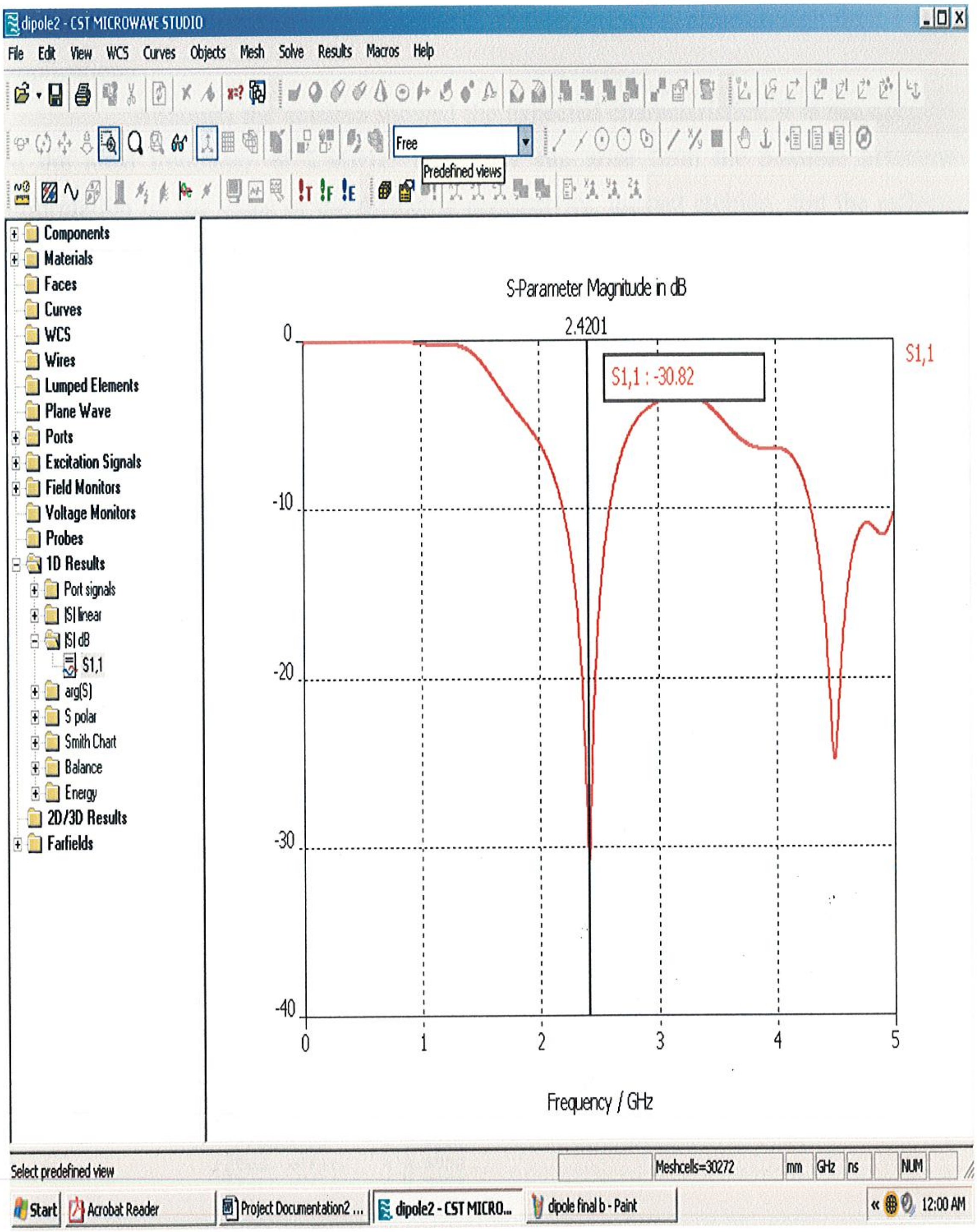

Figure 19: |S11| reading obtained for desired antenna

In the figure above, although the reflected power is lower than the original, the center frequency has been corrected to 2. 42 GHz, which is close enough for 2.4 GHz applications.

Although the antenna showed the expected characteristics, it is not operating at the ideal frequency of 2.4GHz. This error can arise from the possible inaccurate information on the value of the dielectric permittivity, inexact etching, and the reflected loss at the connectors.

The polar radiation test result shown below indicates that the antenna designed omni directional and due to the ground plane located behind the radiating element, it has a lot less back radiation as expected:

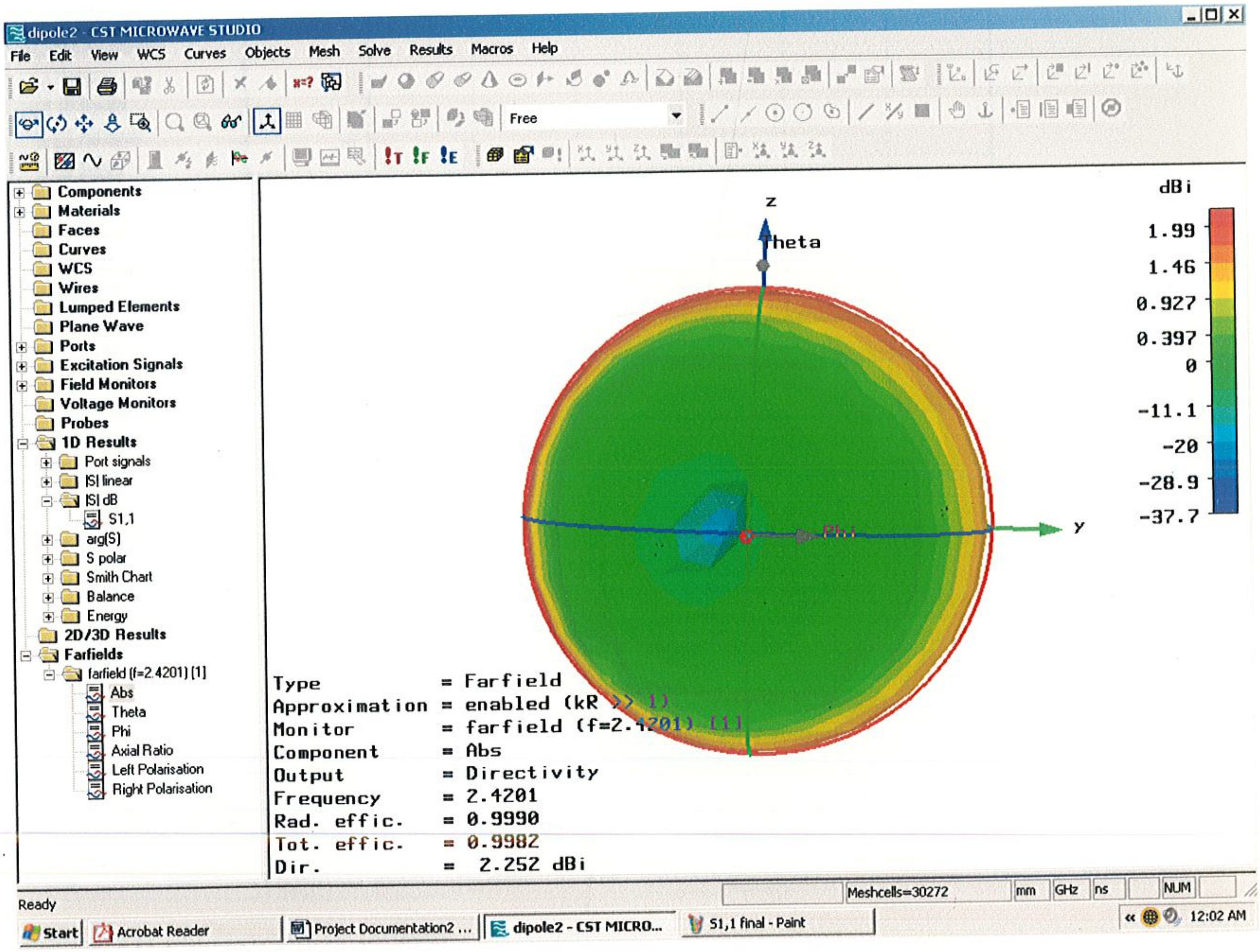

Figure 20: Abs component farfield

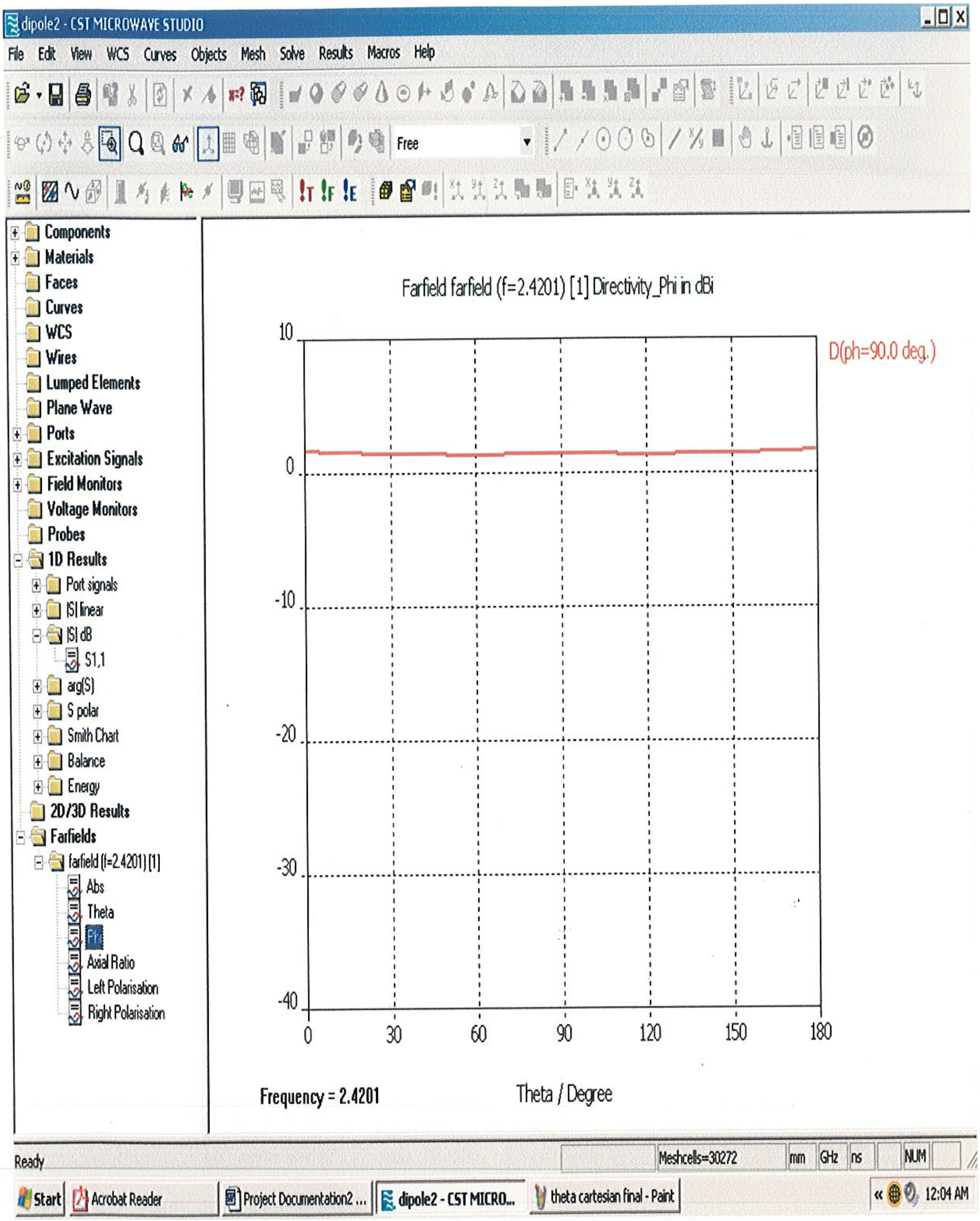

Figure 21: Phi component farfield

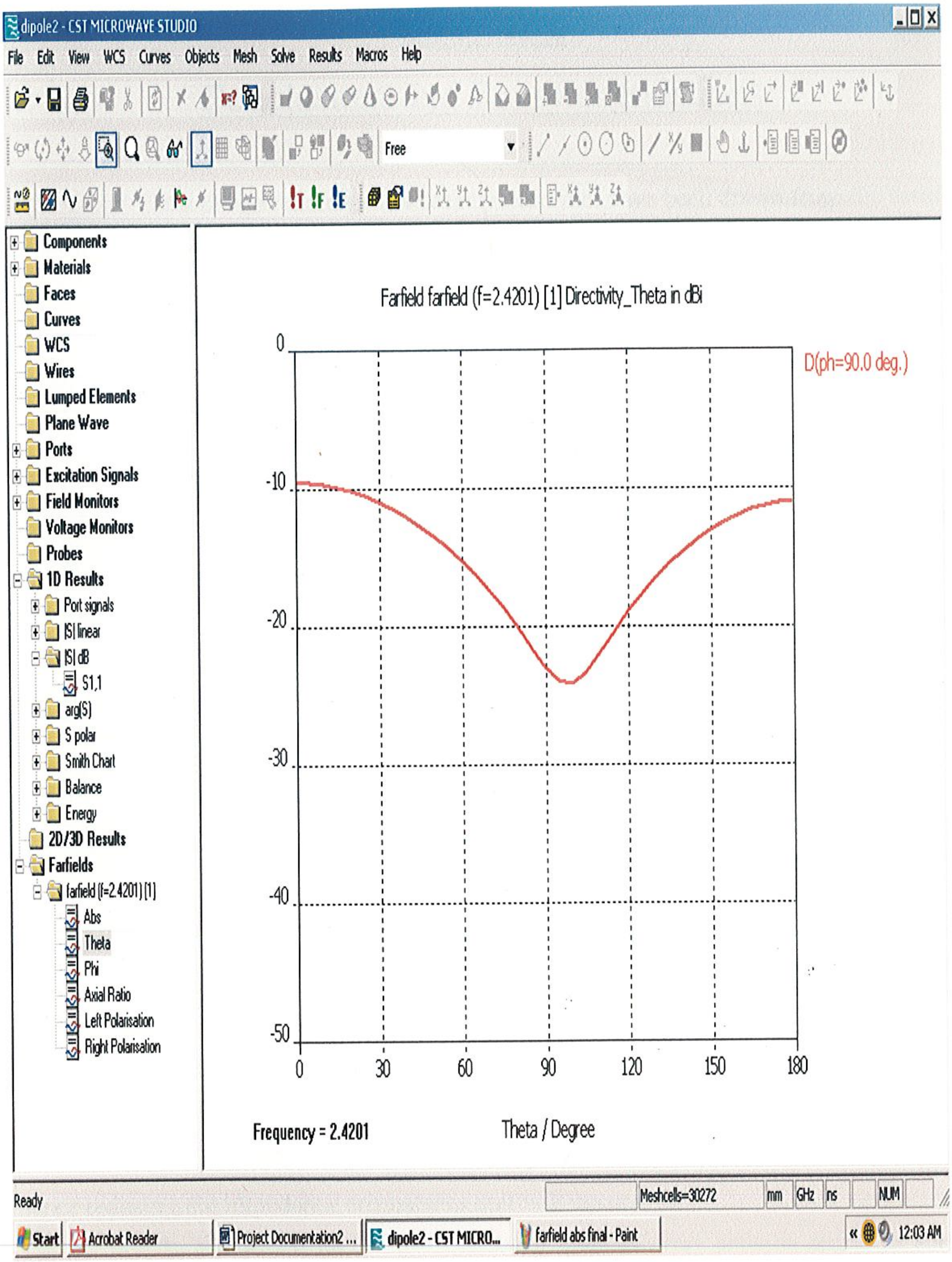

Figure 22: Theta component farfield

Chapter 6

Conclusions and Recommendations

This chapter discusses the conclusions that have been drawn from the results of tests conducted on the antenna array. Recommendations are then made with regard to the conclusions.

6.1 Conclusions

The results from the tested antenna are satisfactory and have achieved the objective set for this thesis, which is to design and build a high gain omnidirectional printed circuit board dipole antenna array operating at 2.4 GHz. The S1, 1 test indicates that the tested antenna is closely matched to 2.4 GHz at 2.42 GHz, with an excellent radiated power.

6.2 Recommendations

The following recommendations on the improvements, testing and possible applications of the antenna have been made from the drawn conclusions. Further testing on the current antenna array has also been proposed.

6.2.1 Improvements on the Antenna Array

The following recommendations are made to improve the performance of the antenna array:

Instead of printing designs on CST microwave software, rather implement the software form of the design on more advanced and improved software which are capable of more accurate designing. This will greatly improve the precision of etching, hence reducing the impedance mismatches that will occur.

Improvement on the gain by using antenna array antenna array. In some antenna applications, higher gain and narrower beam width is required to increase range and to reject interference. Antennas can be arrayed to produce these characters. In this section, array theory and architecture is discussed.

6.2.2 Antenna Testing Recommendations (for hardware testing)

The following should be implemented to improve accuracy of the test results:

- An anechoic chamber will greatly improve the accuracy of radiation tests conducted on antennas, as reflections are reduced.
- An automated stepping turn table would help with taking polar radiation readings, as each reading taken will be stepped at an accurate angle.

6.2.3 Possible Antenna Array Application

As the antenna array built is omnidirectional with high gain in the vertical region, it could be implemented in the case where ground to air communications were needed at 2.4 GHz.

Bibliography

- Sainati, Robert A. CAD of Microstrip Antennas for Wireless Applications.(e-book)
- Antenna theory analysis and design,Balanis,2nd Edition
- Antenna Theory,Krauss
- Transactions and publications available on ieee.org
- Chang, Kai. *RF* and Microwave Wireless Devices. Texas A&M University: John Wiley & Sons, Inc, 2000.
- Prof. M. Reineck, university of Cape Town. Lecture notes from course EEE497C. *RF* Components and Satellite Systems.