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Patch Antenna for 1420MHz Radio Telescope

Master's Thesis in Electrical Engineering

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Preface

This project was performed during the autumn of 2006 with Emil Nilsson and Arne Sikö as supervisors. I would like to sincerely thank them for their great help both in theoretical guidance and practical works. Hopefully this project can give some helpful experience in future work on this project.

Yan Zhang
Halmstad University, May 2007

Abstract

Patch antenna is one of the most rapidly popular topics in the antenna field in the past twenty years. In high-performance aircraft, spacecraft, satellite and missile applications, where size, weight, cost, performance, ease of installation, and aerodynamic profile are constraints, low profile antennas may be required. [7].

The project is to develop a single patch antenna operating on a specific frequency 1420MHz. The frequencies near to 1420MHz are worth to observe because the hydrogen in throughout of the space can be mapped by the observation of the 21 – cm wavelength line which is corresponding to 1420 MHz radiation. The final product antenna will be used in a radio telescope as a part of the signal receiving system.

The work within the project contains simulation, fabrication and test of final antenna. The simulation work was carried out in advanced design system which is developed by Agilent technologies, USA. The most different feature of the project is that, comparing to normal patch antenna, usually 50 ohms is selected as the matching impedance, while in this project we made it conjugate to the input impedance of the LNA. In this way we can save extra components, as well as energy consuming.

1 Introduction

1.1 Background

The hydrogen gas is one of the main materials that can be found in throughout of the space. The 1420 MHz radiation comes from the transition between the two levels of the hydrogen 1s ground state, slightly split by the interaction between the electron spin and the nuclear spin. In this procedure hydrogen in its lower state will absorb 1420 MHz.

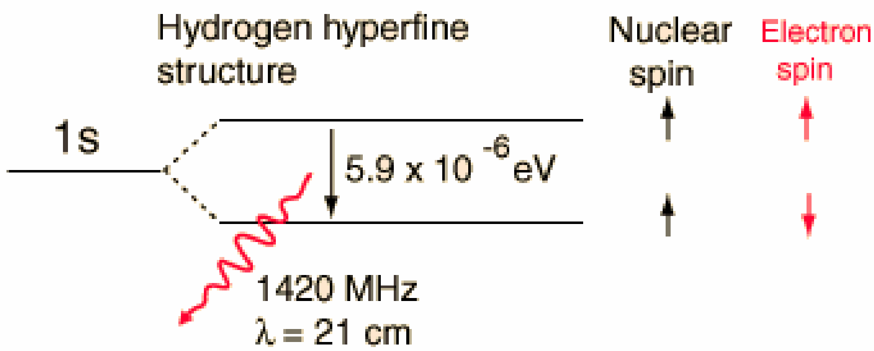


Figure 1.1 1420 MHz radiation principle

A radio telescope is powerful piece of equipment, which can "see" radio waves emitted by radio sources in throughout the space. Generally, the simplest radio telescope has the following essential parts: an antenna, a LNA, Spectrum Analysis Module (an oscillator, a mixer, an IF amplifier, a square law detector, an AD converter), control computer and mechanical control unit. *Figure 1.2* shows the basic structure of the radio telescope .The antenna and LNA are contained within the design work of this project.

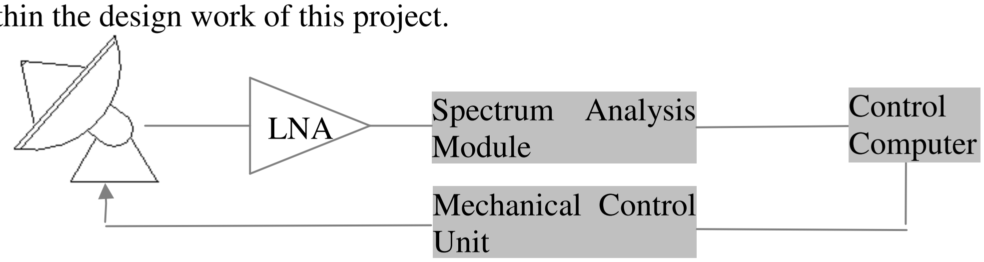


Figure 1.2 Basic structure of a radio telescope

In order to receive weak radio wave signals, the antenna is often shown as a parabolic dish. In this project we will design a patch antenna and a low noise amplifier, which are compacted together and put at the focus point of the dish. *Figure* 1.3 shows the parabolic dish and the box with patch antenna and LNA inside.

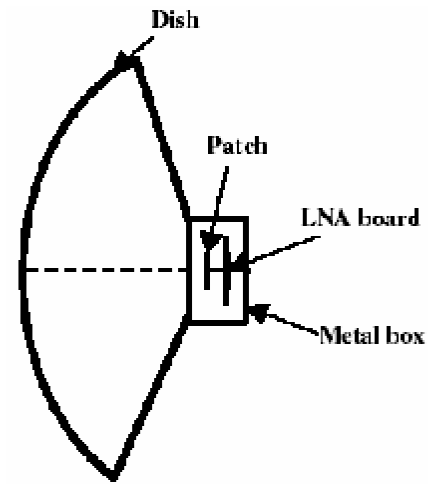


Figure 1.3 Dish, patch antenna and LNA

1.2 Assignment

The main work is divided into two parts, which are the simulating a rectangular patch antenna in ADS system and fabricate/test it respectively. For the final product there should be a 10 dB illumination fall from the centre of the dish to the rim. The angle between the two rims is 130 degree. In the design we need try to reduce the power radiate outside the range of the dish and minimize the noise that come from the ground.

The detailed works are:

1) Theoretical calculation
    a. Choose material and feeding technical
    b. Calculate the dimension of the antenna
    c. Choose feeding technical and feeding point
    d. Other calculations
2) Simulation in ADS: momentum, equivalent circuit simulation, optimization, etc.
3) Fabrication
4) Measurement
5) Thesis writing

1.3 Method

1.3.1 Theory study

Theory that is needed in doing this project consists of:

1) General understanding of astronomy, especially the knowledge about 1420MHz radio wave
2) Radio telescope technology
3) Radio wave design technology
4) ADS system

1.3.2 Simulation, fabrication and final product test

After simulation, a final product will be tested with the network analyzer, signal generator and network analyser.

1.3.3 Thesis writing and dissertation

2 Theoretical Background

2.1 Basic knowledge for antenna

2.1.1 Basic antenna parameters

In wireless transmission and receiving system, antenna is the critical device/equipment that is used to efficiently transmit wireless signal to the free space and/or receive wireless signal. When evaluating the performance of an antenna, there are several parameters need to be taken into account and some concepts should be known.

1) Radiation pattern.
Radiation pattern is the schematic description of antenna transmitting or receiving relative field-strength.

2) Directivity and Gain
Directivity is the ability that antennas transmit and receive wireless signal in some specific direction. It is the power in the main beam of an antenna compared to an isotropic [1].

$$D = \frac{p(\theta,\phi)_{\max}}{p(\theta,\phi)_{average}} \tag{2-1}$$

Because of ohmic losses, gain G is always partial of directivity in value.

$G = K_g D$, where k_g is efficiency factor. (0< k_g <1)

3) Beam width
Beam width is the angle that the main beam falls to its 3 dB points. It is often measured in degrees.

4) VSWR
VSWR stands for voltage standing waves ratio. It is the ratio of reflected power to the input power. From the value of VSWR we can determine how the antenna is matched to the transmission line. The maximum output power may be possible only when the standing waves are at maximum. 1:1 is the ideal ratio for VSWR which is nearly impossible to achieve. 1.5:1 is a typical value at which 96 percent is transferred.

5) Polarization
Polarization is the orientation of the electric field of the electromagnetic wave as it travels through the space [1]. Linear polarization refers to the power in some specific plane (horizontally, vertically or 45 degrees to the ground plane). In order to minimize the losses that come from mismatch in polarization aspect, the receiving antenna must have the same polarization orientation to the radio wave signal.

6) Main lobe, Side lobes and back lobes
Main lobe is the dominant lobe of a directional antenna where the majority of the output power radiates. Side/back lobes are the other lobes besides the main lobe. The side/back lobes have three bad influences:

a. Consume power
b. Interfere on other elements in side/back of the antenna
c. The interference signals from other equipment may enter the system through the radiation of side/back lobes.
d. Noise from the ground

2.1.2 Antenna Types

Antenna can be categorized according to different consideration. In appearance consideration, there are wire antennas, aperture antennas and arrays antennas. Wire antennas can be dipole, loop, folded dipoles, helical antenna, Yagi (array of dipoles), corner reflector and many other types. Aperture antenna types include reflector antennas, horn antennas, and lens.

2.2 Microstrip

2.2.1 Introduction

At microwave frequency, microstrip is often used as a transmission line because of its very good performance in transfering energy and microwave signals. One of microstrip line's significant advantages is that it does not generate as much parasitic capacitances and inductances as lumped elements do. Furthermore, compared with another kind of transmission line - stripline, microstrip is much easier and cheaper to fabricate and easy to connect surface mounted components. As regards to our project, the operating frequency of the signal receiving system is about 1420 MHz, microstrip is the preferable transmission line components. *Figure 2.1* shows the typical structure of a microstrip .

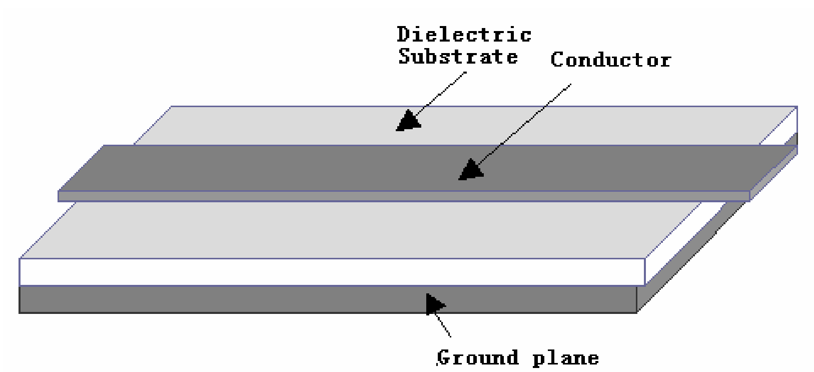


Figure 2.1 Microstrip, three layers structure

Microstrip line is constructed with three layers with different material separately: a thin metal layer is printed on a substrate layer which is usually made of materials like Fiberglas, polystyrene or Teflon, and the dielectric constant varies from 1.2 to 25. While on the downwards side of the substrate is the ground plane which is also a layer of metal which is a good conductor. The characteristic impedance of a microstrip is closely associated with the width of the conductor, the thickness and the material of the substrate; lower-impedance microstrip lines are comparably wider and vice-versa. As well as 75 ohms for a coax cable line, 50 ohms is most often used for the transmission line. For a fixed width microstrip line, the transmission line impedance does not change with the length.

2.2.2 Application of microstrip in microwave design

In Microwave circuit designing, microstrip can act as two useful function elements, one of which is transmission line, and the other is an equivalent components used in impedance matching network, performing similar function as capacitor and inductor in low frequency circuit.

1) Microstrip as transmission line

With changing the width of the conductor, we can get a microstrip line with a different impedance value, combined with its other advantageous virtues, which makes microstrip a perfect transmission line in microwave circuit. With the impedance matching network connecting between the output of front circuit and the input of lateral circuit, reflection and mismatch loss can be efficiently reduced to a value as low as possible. The only power dissipation is copper losses as the performance of heat. Thus the standing wave and reflected wave, compared to the transferred wave power, is quite low. When designing a transmission line with desired impedance, the following equation can be used to calculate the width of the line:

$$Z = \frac{377}{(W/h+1)\sqrt{\varepsilon_r + \sqrt{\varepsilon_r}}} \qquad (2\text{-}2)$$

Where

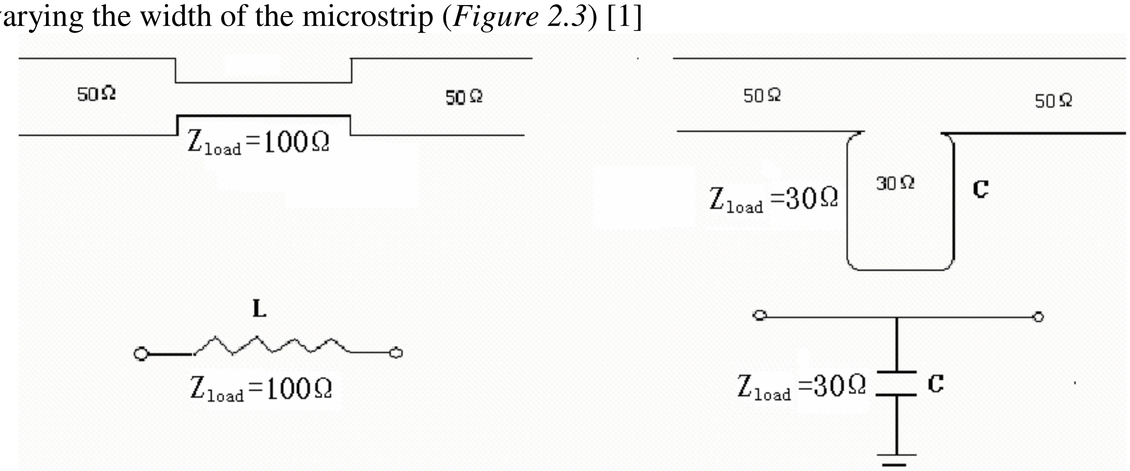
Z = the characteristic impedance of the microstrip, ohms

W= width of the microstrip conductor (same units as h)

h = thickness of the substrate between the ground plane and the microstrip conductor (same units as W)

ε_r =dielectric constant of the board material

2) Another important application of microstrip is in microwave frequency, it can be used as equivalent components; performing similar functions as inductor, capacitor and transformer at low frequency. A series or shunt thin trace forms a distributed inductor (*Figure 2.2a*), while a shunt capacitor can be formed by a wide trace (*Figure 2.2b*), and a transformer can be formed by varying the width of the microstrip (*Figure 2.3*) [1]



(a) **(b)**

Figure 2.2 (a) A series distributed inductor and its equivalent lumped circuit (Z_{load} =100Ω) (b) A shunt capacitor and its equivalent lumped circuit (Z_{load} =30 Ω).

a.) Suppose an equivalent distributed inductance XL is required in a circuit using a 100 Ω (the impedance of the load) microstrip line. Firstly, calculating the width of required for 100 ohms microstrip line, this can be done through many transmission line calculator (i.e. ADS linecalc function); secondly, calculating how long microstrip line gives the required capacitance can be carried out using the following equation [1]:

$$Length = \frac{\arctan(\frac{X_l}{100})}{360} \tag{2-3}$$

b) For an equivalent distributed capacitor with a reactance Xc using a shunt transmission line with characteristic impedance 30 Ω, we can calculate the length of the 30 Ω transmission lines by [1]:

$$Length = \frac{\arctan(\frac{30}{X_c})}{360} \tag{2-4}$$

c) A quarter wavelength transformer is a connection used in between two transmission lines that have different characteristic impedance or matching a load with a normalized transmission line. The length of a quarter wavelength transformer is one fourth of the wavelength in dielectric material. If the impedance difference between two parts is extremely high, several transformers in series can be employed. We can calculate the impedance needed of a transformer by [1]:

$$Z = \sqrt{Z_1 * Z_2} \tag{2-5}$$

Thus the width of the transformer can be achieved by some transmission line calculator or calculate with equations.

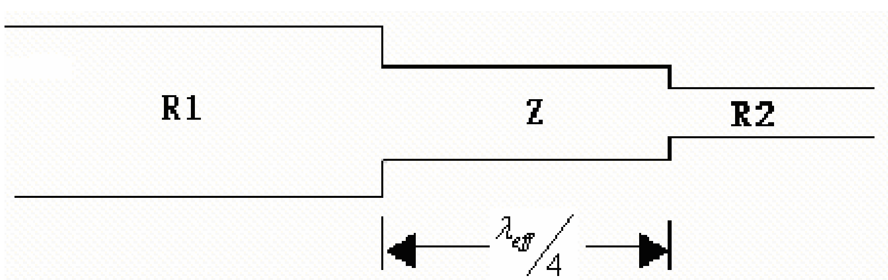


Figure 2.3 A quarter wavelength transformer between two transmission lines

There are two things that should always be remembered:
Firstly, the length of the equivalent distributed elements should always be kept less than 12 percent of a complete effective wavelength, or they will lose the equivalent effect of lumped elements.
Secondly, both the distributed conductor or capacitor and the transformer are all dielectric and frequency dependent elements. The calculation is only valid for the particular situation. The wavelength λ is not that in air or in vacuum, because the signal propagates partly in the substrate and partly in the air above the microstrip. For a substrate material with the dielectric constant ε_r, we can calculate the effective dielectric constant ε_{eff} of the microstrip with the following equation [3]:

$$\varepsilon_{eff} = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2} * \frac{1}{\sqrt{1 + 12\,h/W}} \qquad (2\text{-}6)$$

Where ε_{eff} = effective dielectric constant, $\lambda_{eff}/4$

ε_r , h and W have the same definition as those in Z_0

We know the wavelength in vacuum can be calculated by:

$$\lambda = \frac{c}{f} \qquad (2\text{-}7)$$

Where *c* is the velocity of light in vacuum and f is the frequency of the signal.
Combining the above three functions, we derive the equation to calculate the effective wavelength in microstrip:

$$\lambda_{eff} = \lambda / \sqrt{\varepsilon_{eff}} \qquad (2\text{-}8)$$

2.3 Microstrip Patch Antenna

2.3.1 Introduction

It is not very easy to give an exact definition of a microstrip antenna because of its flexibility in construction. While the most commonly used microstrip patch antenna has similar structure as a microstrip line. On one side of a thin dielectric substrate layer, is an extremely thin layer of conductor, which forms the radiating element, and on the downwards side is the ground plane, which is also made of metal material. Square, rectangles, triangles and circles are general shapes of the conductor for easy analysis or fabrication consideration.
The operating frequency of microstrip antennas usually ranges from 1GHz to 50GHz.
Compare to other kinds of antenna, microstrip antennas have the following advantages:
a. Lower profile, light in weight, easily compacted with circuit and conformability to mounting hosts, lower the cost of fabrication
b. Easily to get different polarization
c. Can work in dual frequency or multi-frequency

The main disadvantages are:
a. Narrow bandwidth, (5% to 10% [2:1 VSWR])
b. Higher losses in conductor and dielectric material results in lower efficiency
c. Lower transmitting power for single patch antenna

2.3.2 Rectangular patch antenna

The rectangle is one of the most frequently used patch shapes. *Figure* 2.4 shows a three-layer geometry antenna. Similar to the structure of microstrip line, the top layer rectangular metal is separated from the ground plane by a dielectric substrate. The rectangular patch antenna can be a half wave or a quarter wave in length. Similarly microstrip can also be analyzed with transmission line module. If the signal is fed along the length dimension *b*, then the two edges of dimension *a* can be treated as two radiating slot elements. The edge radiating is called the fringing effect which contributes to a slight reduction in the electrical length of the patch. The feeding point can be chosen at the radiating edge as well as some point on the patch depending on the polarization and impedance matching requirement. There are numbers of choices for the substrate material, such as Teflon, ceramics and alumina. The higher dielectric constant, the lower thickness of substrate can be achieved. Loss tangent is another key parameter regarding to the heat loss and the efficiency of the antenna. If the volume is not strictly limited, like in our project, air is a good choice. Higher efficiency, lower surface loss, maximum gain is its main merits.

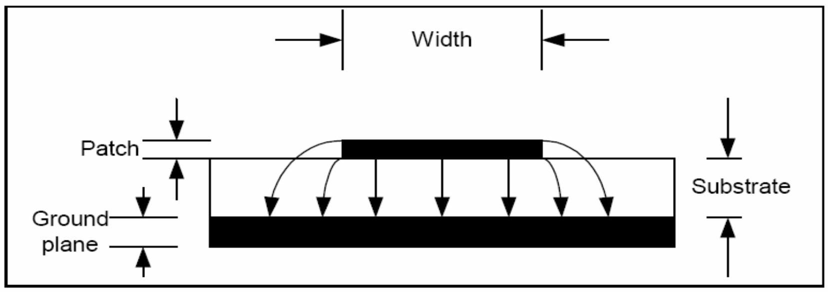


Figure 2.4 Side view of a rectangular patch

2.3.3 Feeding technical and impedance matching network

Microstrip antenna can be fed in many ways. The feeding point can be either at the edge or somewhere inside the patch. The feeding point can be either single point or multiple points. It can be fed directly or non-connecting feeding (coupled feeding). Feeding methods should be selected flexibly according to the polarization ways, the shape and structure of antenna. *Figure* 2.5 gives three kinds of simple directly feed methods.

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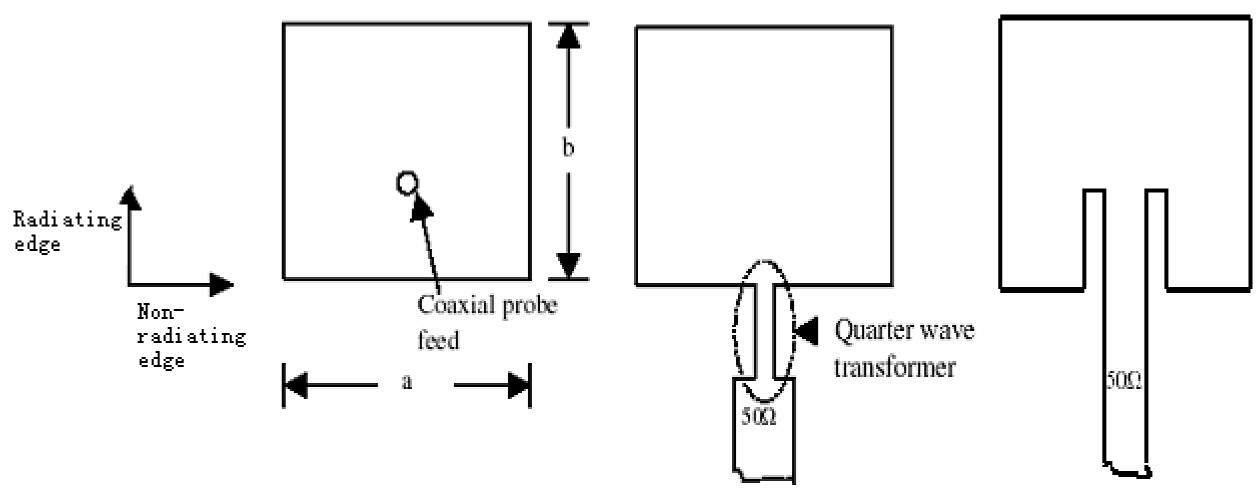

(a) (b) (c)

Figure 2.5 Three typical methods to feed a rectangular patch antenna along the length dimension: (a) Coaxial probe feed (b) A quarter wave transformer feed (c) In-set microstrip line feed

a) The first one is coaxial probe feeding. The patch is fed by a coaxial probe, which is object to the patch and passes the substrate and ground plane. The outer shield of the probe is connected with the ground plane. The input impedance of the patch antenna exhibits some dependence on the substrate thickness and permittivity, but it is strongly dependent on the location of the connection between the feed line and the patch [4]. The feeding point is often selected between the centre of the patch and the radiating edge which can give 50 ohms impedance. From above figure we can see that coaxial probe feed need the least space compares to the other two methods

The next figure shows the side view of a coaxial probe feed antenna and its equivalent circuit.

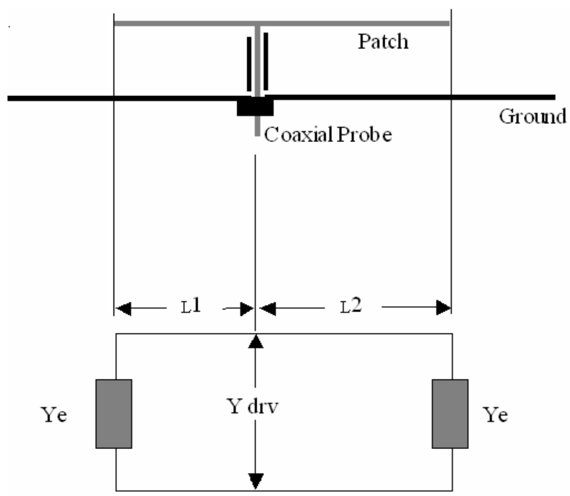

Figure 2.6 Equivalent circuit of coaxial probe feed antenna

Y_e is the complex admittance at each radiating edge which consists of an edge conductance G_e and edge susceptance B_e as related in equation

$$Y_e = G_e + \mathrm{j} B_e \tag{2-9}$$

G_e and B_e can be calculated with equation [3]

$$G_e = 0.00836 \frac{W}{\lambda_0} \tag{2-10}$$

Here 0.00836 is calculated from $\frac{\pi}{376\lambda}$, represents the conductance per unit length in the microstrip. [3]

$$B_e = 0.01668 \frac{\Delta l}{h} \frac{W}{\lambda} \varepsilon_{eff} \tag{2-11}$$

b) The patch can also be fed with the transmission line at one side of the radiating edge as shown in *Figure* 2.5 (b) shows. A quarter wave transformer must be used in between the patch and 50 ohms transmission line. The width of the transmission line can be calculated in the way what is illustrated in last chapter about designing transmission line. Y_e is same as above.

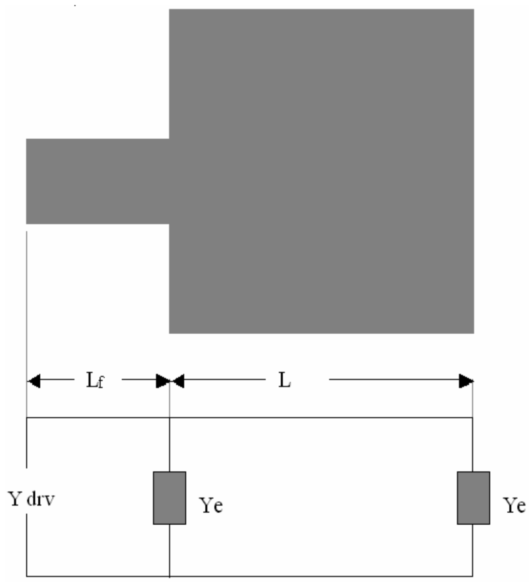

Figure 2.7 Equivalent circuit of microstrip feed rectangular patch antenna.

c. The third method is called in-set feeding. The feed line extends into a narrow notch at one of the radiating edges. The distance of the feeding point gives 50 ohms impedance.

There is also another directly feed method witch uses microstrip line feed at the non-radiating edge where a 50 ohms impedance is introduced.

2.3.4 Operating modes of rectangular patch antenna

When the rectangular antenna is driven along the centreline of the wider dimension (as *Figure* 2.8 shows), the main mode will be T10; while if it is fed along the shorter dimension T01 is the first order mode. The horizontal arrows in T10 mode indicate the copolar edge field, while the horizontal arrows in T01 mode indicate the cross-polar edge field. Notice that in mode T01 mode the horizontal arrows point to different directions which causes the cross polar field offsets at the broadside direction.

If $L > W >> h$, T10 is the dominant mode with the resonant frequency [7]:

$$(f_r)_{T10} = \frac{c}{2L\sqrt{\varepsilon_{eff}}}; \qquad (2\text{-}12)$$

If $L/2 > W >> h$, the second order mode is T20 with the resonant frequency [7]:

$$(f_r)_{T20} = \frac{c}{L\sqrt{\varepsilon_{eff}}} \qquad (2\text{-}13)$$

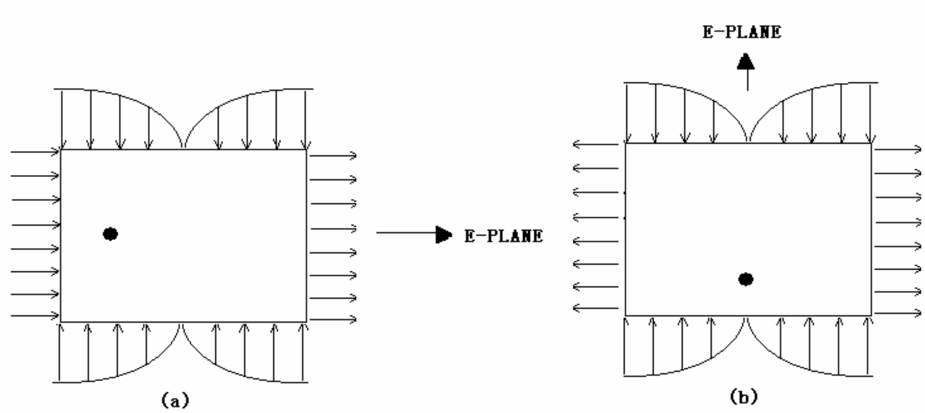

Figure 2.8 Perimeter fields of a rectangular patch for (a) T10 mode and (b) T01 mode

2.3.5 Design procedures

a) Specifications of the design

Firstly, we should make sure some design specifications such as operating frequency, directivity, gain, VSWR, polarization, mechanical requirement, etc. The environment situation should also be considered. In this project the antenna will work on 1420 MHz, and it will be located inside a metal box that will be put at the focus point of a parabolic dish. The dimension is limited within 200*200 mm

b) Choose the material of the substrate and metal

Secondly, the substrate material needs to be chosen prior to calculation. Usually after the material is decided, the thickness of the substrate can then be decided. Thicker substrate means wider bandwidth and increasing driven point impedance, while the dimension increases as well. [3] There should be a trade-off between the bandwidth and impedance match. In our project we let the substrate to be air (18 mm thickness) whose dielectric constant is nearly 1 and loss tangent approximates zero.

c) Calculating the dimension of the patch and ground plane

Thirdly, we start the calculation of the key parameters of the antenna; including length, width of the patch and the ground plane and also the driving point.

Width and length of the patch

When ε_r and *h* are confirmed, ε_r is decided by *W*, while *L* is decided by ε_r. *W* has influence both on directivity and input impedance. Smaller value of *W* results in lower antenna efficiency while larger *W* leads to high order modes. It is beneficial to have a relatively wider *W*, but usually not more than a half wave length (relative). The length of the patch decides the centre frequency of the patch antenna. Longer length gives lower resonant frequency and narrower width gives higher impedance.

There are following equations that can be used directly:

$$W = \frac{c}{f}\frac{1}{\sqrt{2\varepsilon_r + 2}} \qquad (2\text{-}14)$$

$$L = \frac{\lambda_{\mathrm{eff}}}{2} - 2\Delta l \qquad (2\text{-}15)$$

$$\Delta l = \quad 0.412h \frac{(\varepsilon_{\mathrm{eff}} + 0.3)(W/h + 0.264)}{(\varepsilon_{\mathrm{eff}} - 0.258)(W/h + 0.8)} \qquad (2\text{-}16)$$

Where λ_{eff} and ε_{eff} have the same definitions as above.

After calculation, we arrived at the length of our patch as 82 mm and width 105 mm.
For a rectangular patch antenna working in T01 mode the length of the patch is a little bit less than a half wavelength because of the fringing effect, which is where Δl is derived from. In our case Δl=11.94 mm. In equation (2.15), $2\Delta l$ represent 2 fringing field lengths which can be derived from equation (2-16). When fabricating the patch antenna, we made the length as 90 mm initially thinking of tuning the frequency later.

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- The dimension of ground plane

There is no specific equation to calculate the ground dimensions, while considering the weight and dimension of the antenna, the substrate and ground metal should be as small as possible. Most of the field is confined within a small area around the patch; consequently it is not much sense to extend the ground plane and substrate too greatly. The dimension of a side feed antenna is larger than a back feed one because of the feeding transmission line. In this project we choose a ground metal with the dimensions of 200*200 mm².

- Feeding point calculation

For a coaxial probe feed antenna, it is quite important to find a exact feeding point where 50 ohms (if 50 ohms coaxial probe is used) input impedance and minimum return loss is achieved. For a rectangular patch, the input impedance at resonant frequency varies along the feeding dimension according to the equation [7]:

$$R_{in} = (R_{in})_0 \ \cos^2(\pi \ Y / L) \qquad (2\text{-}17)$$

Where $(R_{in})_0$ =the impedance at the radiating edge and

Y = the distance from the feeding point to the radiating edge.

From this equation we can find that at the centre point of the patch (Y =0), the resonant impedance falls to zero.
With the Advanced Design System, we can easily find the matching point within several trials.

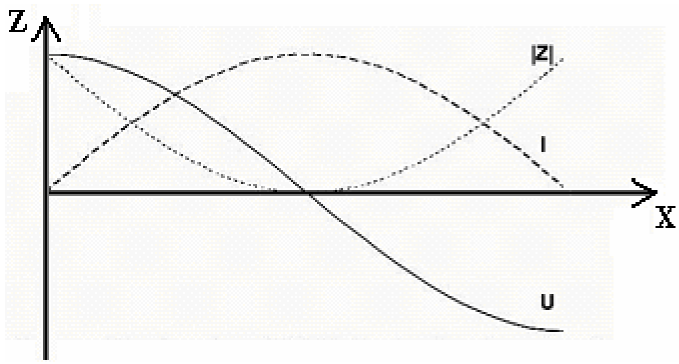


Figure 2.9 Voltage, current and impedance along the patch's resonant length(x axis)

According to transmission line model, the edge resistance at resonant frequency is:

$$(R_{in})_0 = \frac{1}{2}\frac{120\lambda_{eff}}{W} \approx \frac{1}{2}\frac{120*211}{105} \approx 120\Omega$$

Then we can decide *Y* at whatever input impedance that is needed.
The *Y* value for 50 Ω input impedance is calculated as 22.69 mm(Equation 2-14）.

4) The complex admittance at each radiating edge
Edge conductance:

$$G_e \approx 0.00836*\frac{105}{211} = 0.00416 \quad \text{（Equation 2-10）}$$

Edge susceptance:

$$B_e \approx 0.01668*\frac{11.94}{18}*\frac{105}{211}*1 = 0.0055 \quad \text{（Equation 2-11）}$$

$$Y_e = G_e + jB_e = 0.00416 + j0.0055 \quad \text{（Equation 2-9）}$$

Impedance:

$$Z_e = \frac{1}{Y_e} = \frac{1}{0.00416 + j0.0055} = 87.48 - j115.65\Omega$$

3 Results

3.1 Simulation result

3.1.1 Initial simulations

Having calculated the parameters, we initially set up a basic structure of the rectangular patch antenna in "layout" window, which has only a patch and a ground plane and fed through an internal port. A simple three-layer structure was employed, which are a metal layer (it can be supposed as a perfect thin conductor), a substrate layer with 18 mm thickness of air and the ground layer. Here we choose h=18 mm as the thickness of the substrate thinking of that it is a proper dimension comparing to the length and width of the patch.

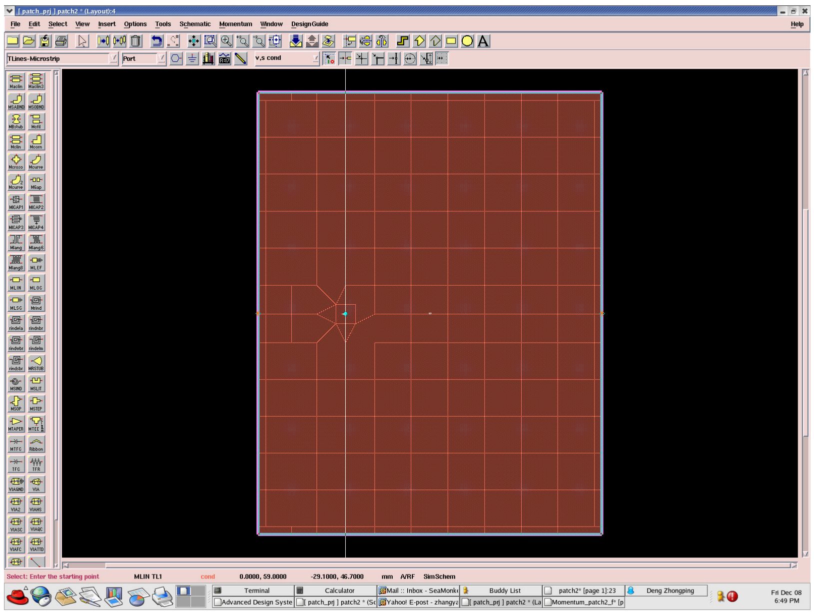


Figure 3.1 Rectangular patch antenna with coaxial probe fed

After several trials, we found the feed point where the smallest return loss achieved is on the centreline of the length, with a distance 20.9 mm to the centre of the patch and the length of the patch is turned to 81.9 mm as well. It can be seen that the simulated patch's dimension has some changes to that what is calculated with equations (we got the calculated feeding point at 22.69 mm to the edge, see last page). Generally speaking, the return loss of a patch antenna with a calculated dimension is still large, and the matching result also unacceptable. The tolerance is most probably the result of the approximation of the equations; thus the impedance matching is an essential procedure in simulations.

The result of S-parameter simulation is shown in following figure.

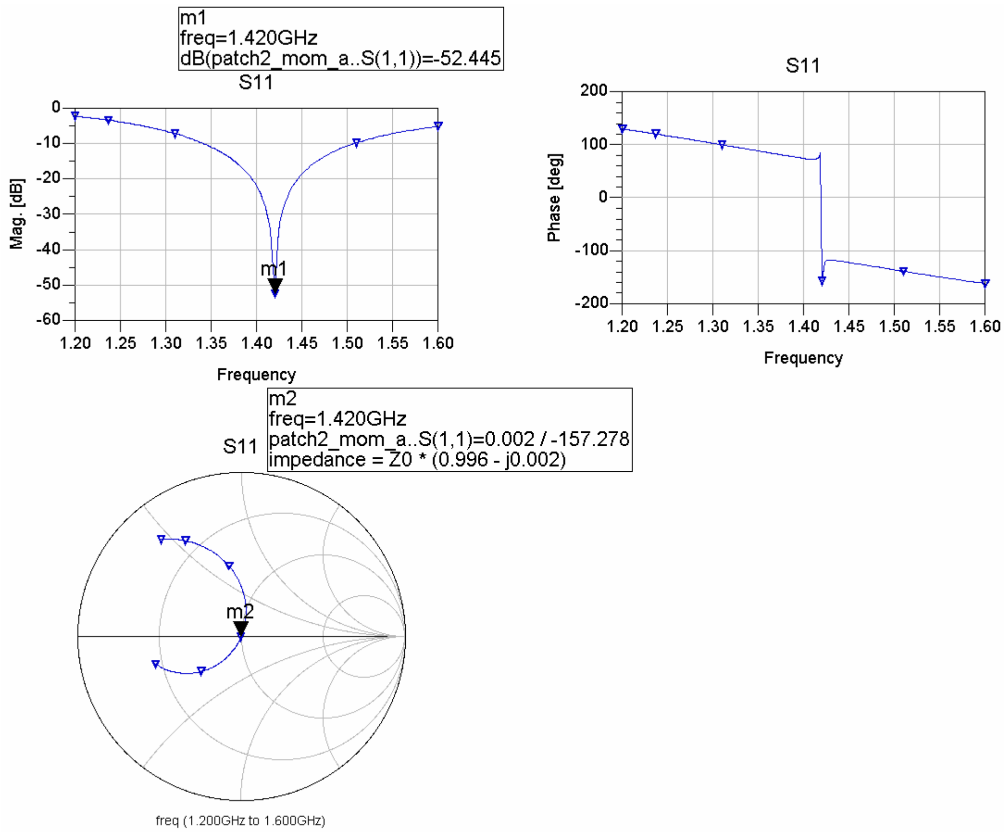


Figure 3.2 Simulation result of the patch antenna shown in *Figure*.3.1

The Power radiation pattern is shown below.

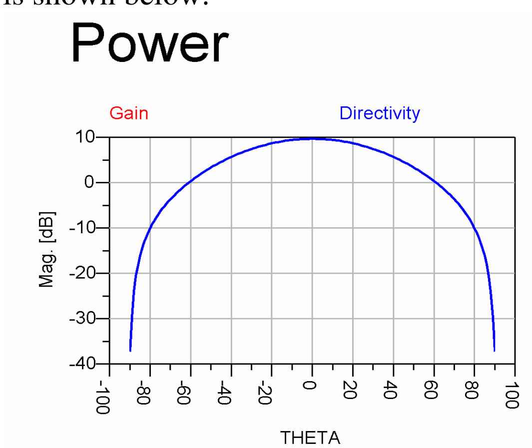


Figure 3.3 radiation pattern of Power

In the power radiation pattern figure, we found that the Gain and the Directivity of the patch is nearly coincided. This is because we supposed the permittivity of the air is 1, which means we “inform” the system that there is no loss in the substrate. Actually the permittivity should always more or less large than 1 and the gain is usually less than the directivity.

At the same time we also tried an equivalent circuit in the schematic window using the calculated parameters in chapter 2, as next figure shows:

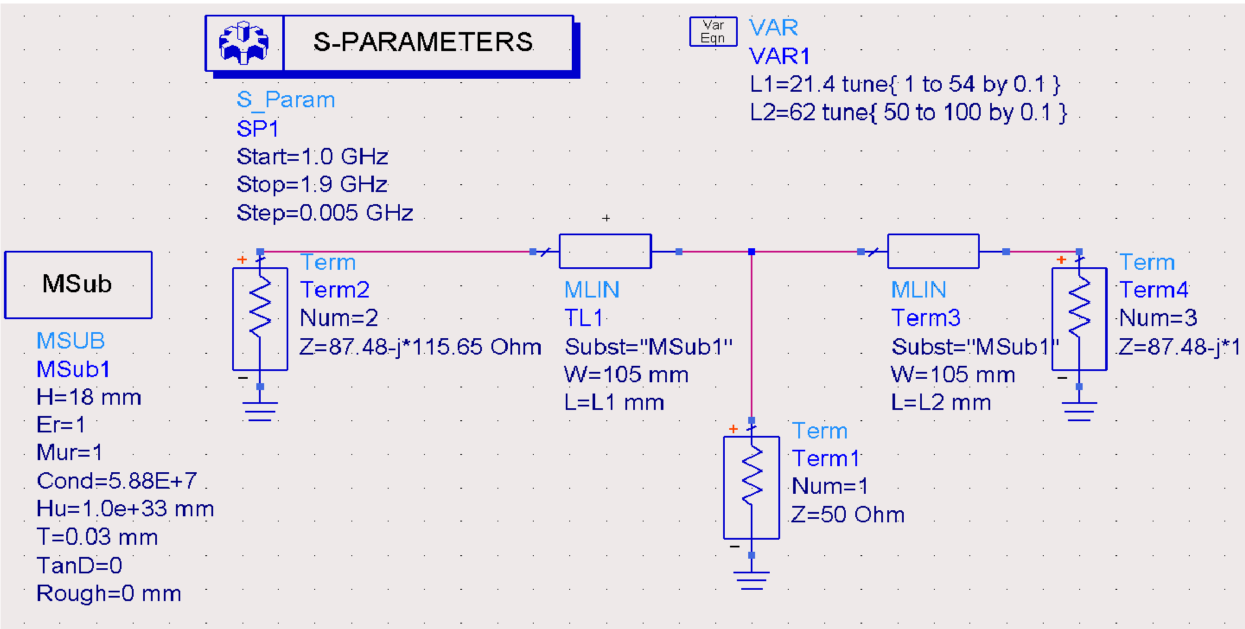


Figure 3.4 The equivalent circuit of the patch antenna in *Figure* 3.1

"Term 1" and "Term 3" are equivalent elements of the two fringing radiating slots with a calculated equivalent resonant impedance 87.48-j115.65 ohm (chapter 2.3.5 Design procedures in page13). "TL 1" and "TL 2" represent the microstrip patch. "Term 2" is the equivalent element of the impedance matching network. In this case we set the port impedance value as 50 ohms which is the impedance of the normalized transmission line. Here we also set two variables *L1* and *L2,* which are the distance to the two radiating edges. With changing the two distances in the "tune" function in the ADS system the process of finding the proper feed point can be very efficient. In the end we arrived at the result as: the length is 89.07 mm and the driven point is 22.57 mm to the radiation edge. The width was not changed.

3.1.2 Matching between patch antenna and LNA

Impedance matching network should be designed flexibly according to the real situation. In this project, the patch antenna and the LNA should be put in a small box. In order to save space and material in the box and minimize the signal power loss in the impedance matching network, the input of LNA and the output port of patch antenna will be directly matched to each other. That means both the two parts will not be matched to a 50 ohms characteristic impedance network. The ground metal plane can be exactly the metal side of the PCB board. This is achieved by choosing a point on the patch at which the impedance is exactly the input impedance of the LNA. This idea can be implied in the next figure.

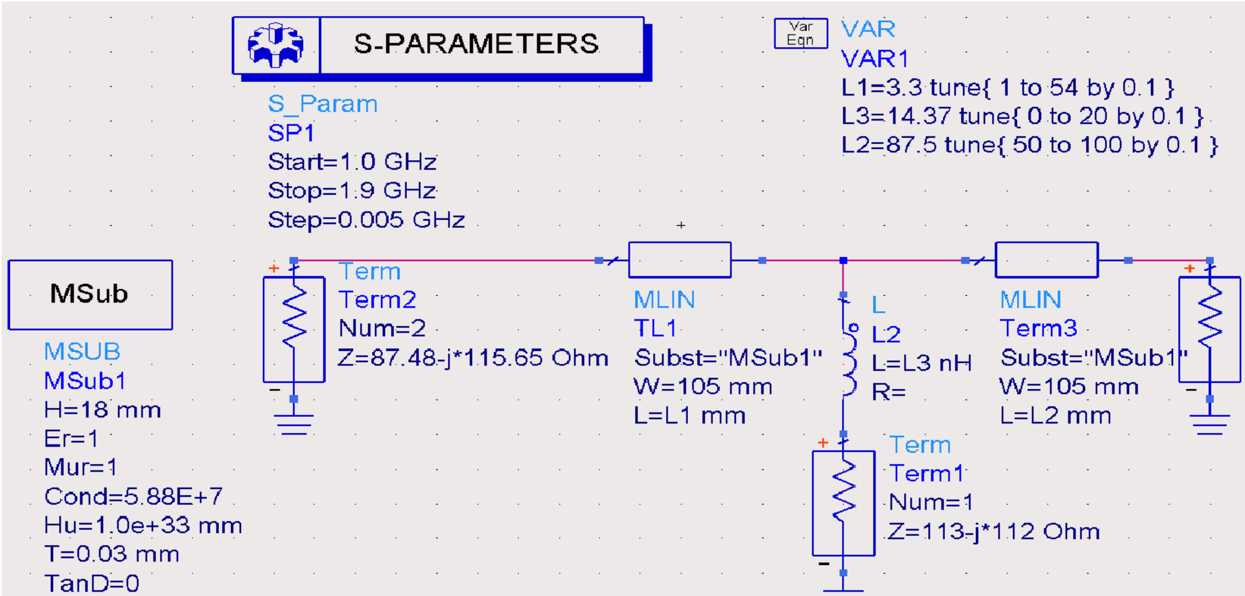


Figure 3.5 Match the patch antenna with the LNA which has input impedance as 113-j112 Ω.

In accordance with the idea described above, we want to find a point that can give impedance as 113+j112 Ω which is the conjugate of the input impedance of the LNA. While after many trials we found it is impossible to fix a position that has such large inductive impedance, which is why we lead an equivalent inductive element into the impedance matching network. The equivalent inductor can be designed with 50 ohms transmission line in the LNA circuit easily. The finally result is: the antenna is 90.8mm in length; the driven point is 3.3 mm to the radiation edge and the equivalent inductor is 14.37 nH which gives 128.15Ω reactance.

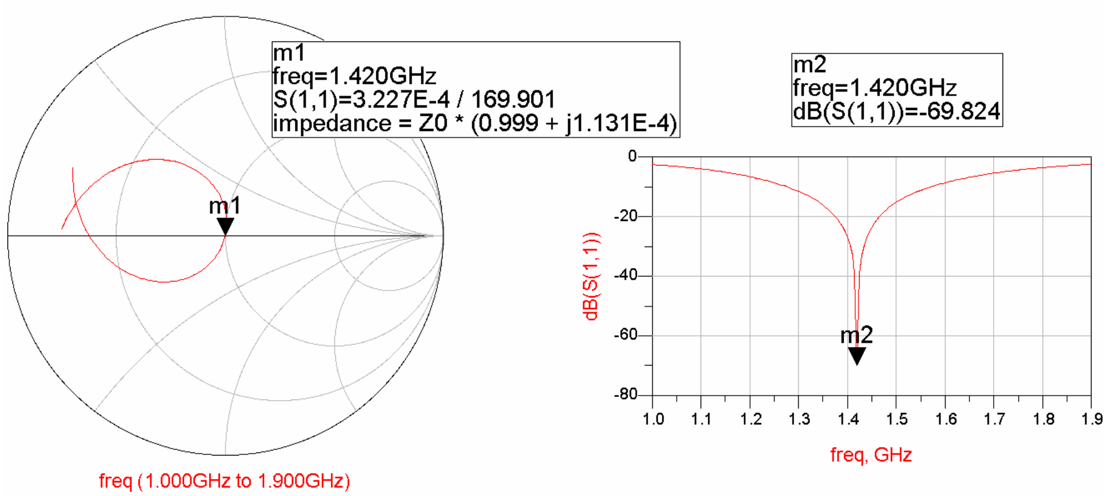


*Figure 3.6*Impedance matching and return loss plot

The calculated bandwidth is about 300 MHz if the return loss -9.5 dB (VSWR≤2) is chosen.

Finally in the momentum simulation (the layout window), we changed the port impedance to 113+j16 (the input impedance of the LNA plus the reactance of the equivalent element). The result is: the length is 83.1mm; the driven point is 7.5 mm to the edge of the radiation edge.

3.1.3 Patch antenna with a box

In the real situation, patch antennas are often required to work outside the rooms, so a protective box is needed. In ADS momentum simulation this is possible to be simulated as well, while the only material available for the box is metal which has a very large influence on the resonant frequency of the patch, In order to minimize the influence from the box, we only use a metal box with a plastic cover 5 mm above the plane of the patch. For between the patch and the cover we can choose a foam ($\varepsilon_r \approx 1, \sigma \approx 0$) which may have little influence on the frequency and radiation of the patch. Finally a thin layer of plastic cover is added to the surface of the foam and the box.

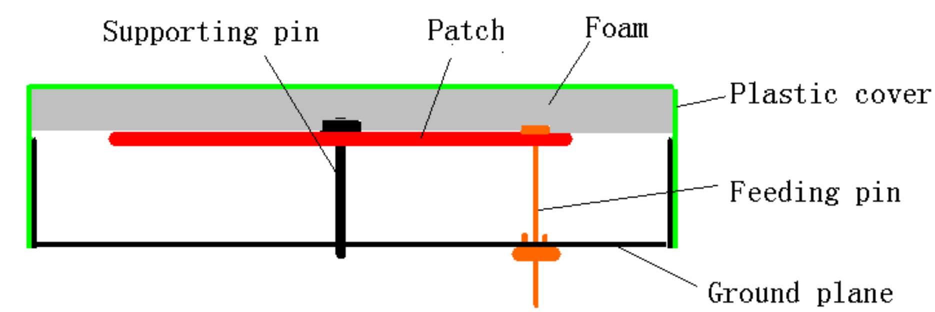


Figure 3.7 Side view of the patch antenna with plastic cover and foam between the patch and the cover

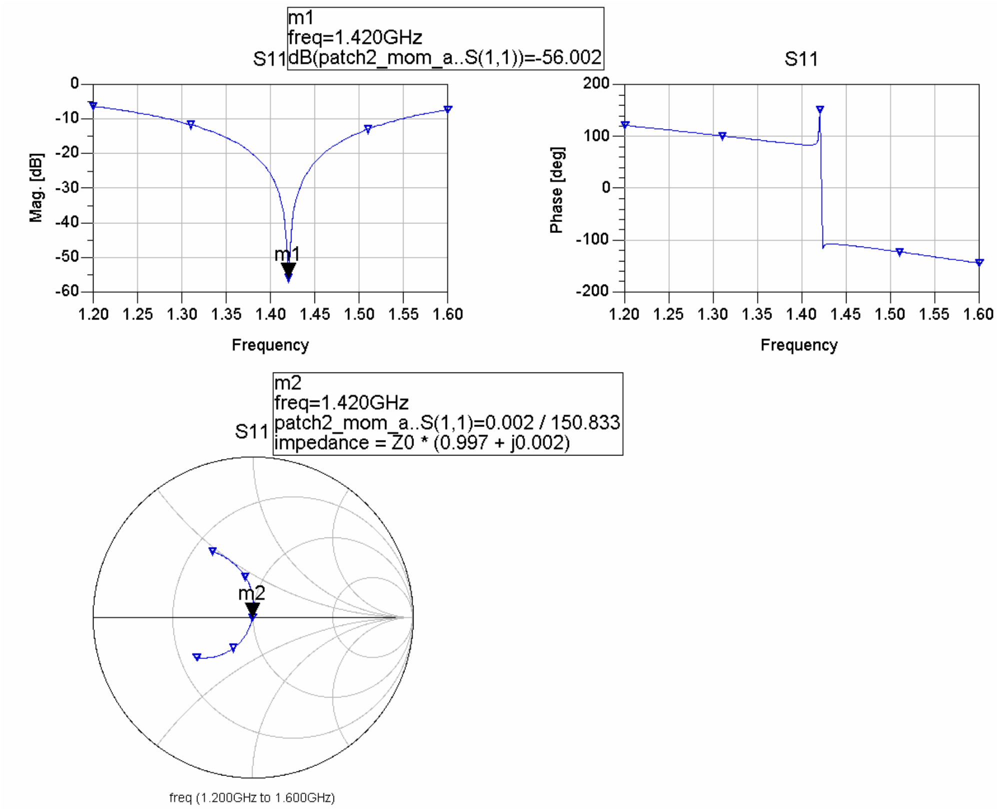


Figure 3.8 Simulation result of the rectangular patch antenna with a metal box; the dimension of the patch is 83.8 mm*105 mm, the length and width of the box are 200 mm*200 mm; the driven point is 16.3 mm to the radiation edge; the thickness of the air below the patch is 18 mm and that above the patch is 20 mm; port impedance is 50 ohms

Later we tried a rectangular patch antenna with a metal box; the dimension of the patch is 85.5 mm*105 mm, the length and width of the box are 200 mm*200 mm. We found the driven point is 1.5 mm to the radiation edge; the thickness of the air below the patch is 18 mm and that above the patch is 35 mm; port impedance is 113+j*16 ohms.

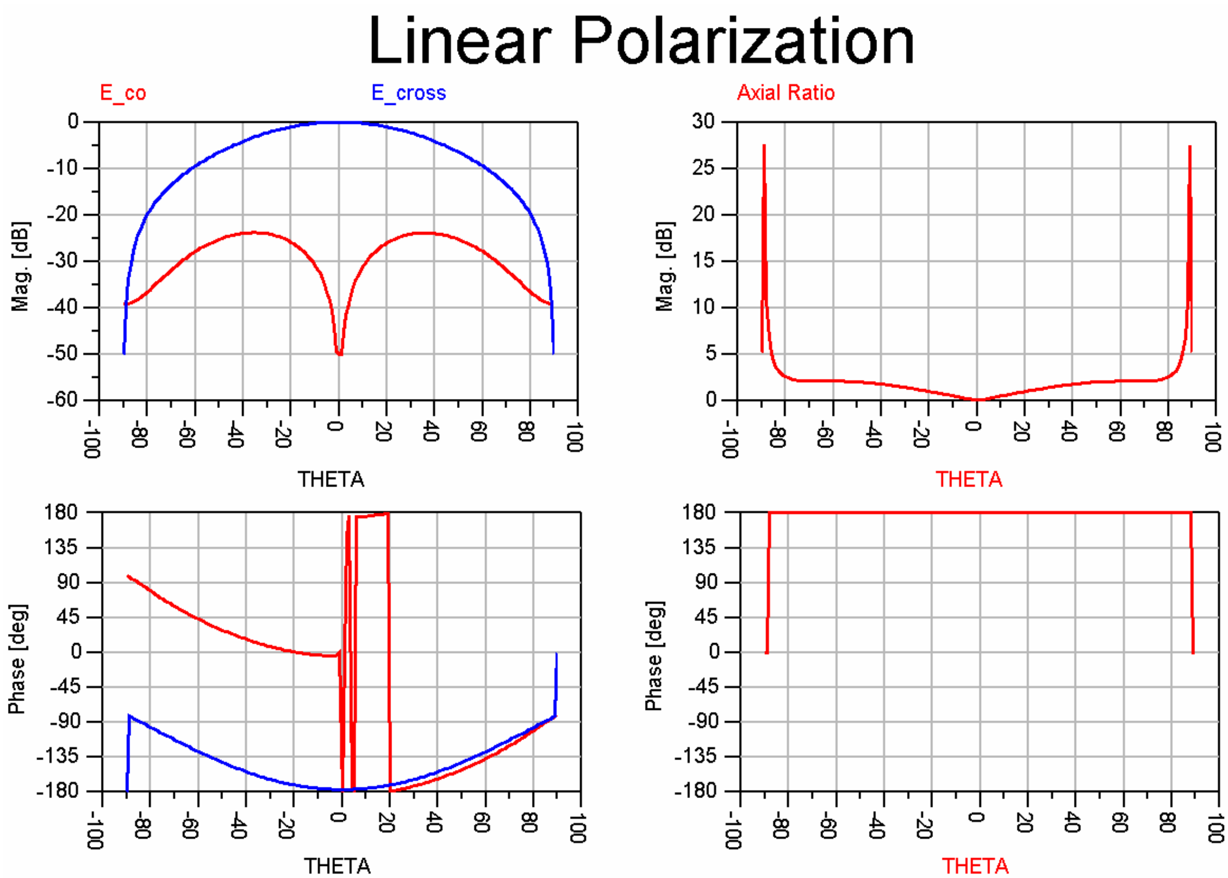
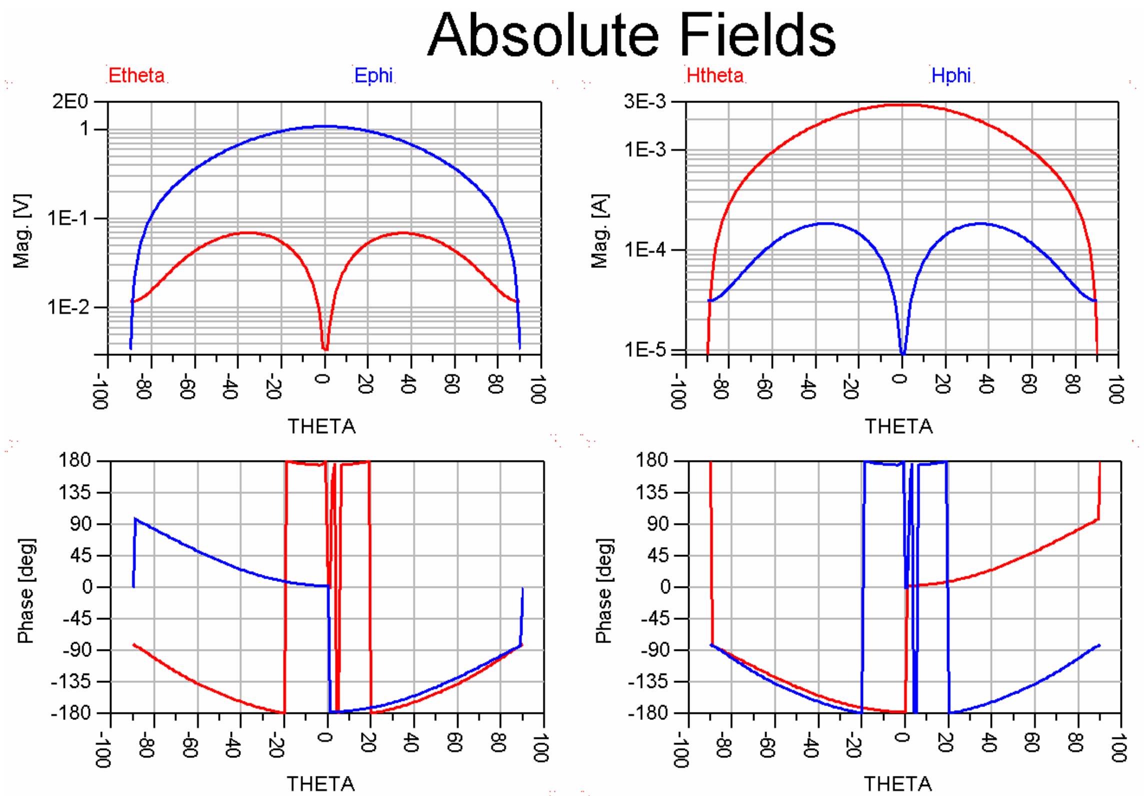
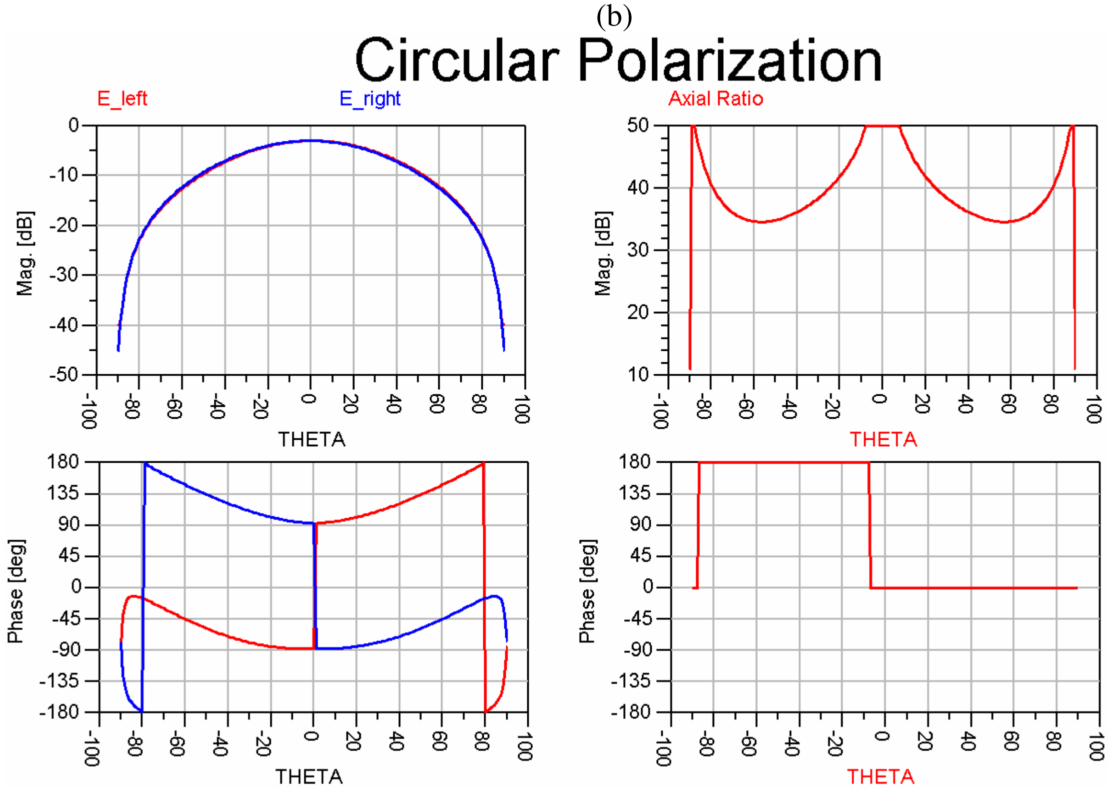


Figure 3.9 Radiation pattern of the rectangular patch antenna in *Figure 3.8* with $\theta=0^0,\phi=90^0$
（a）Linear polarization (continue)

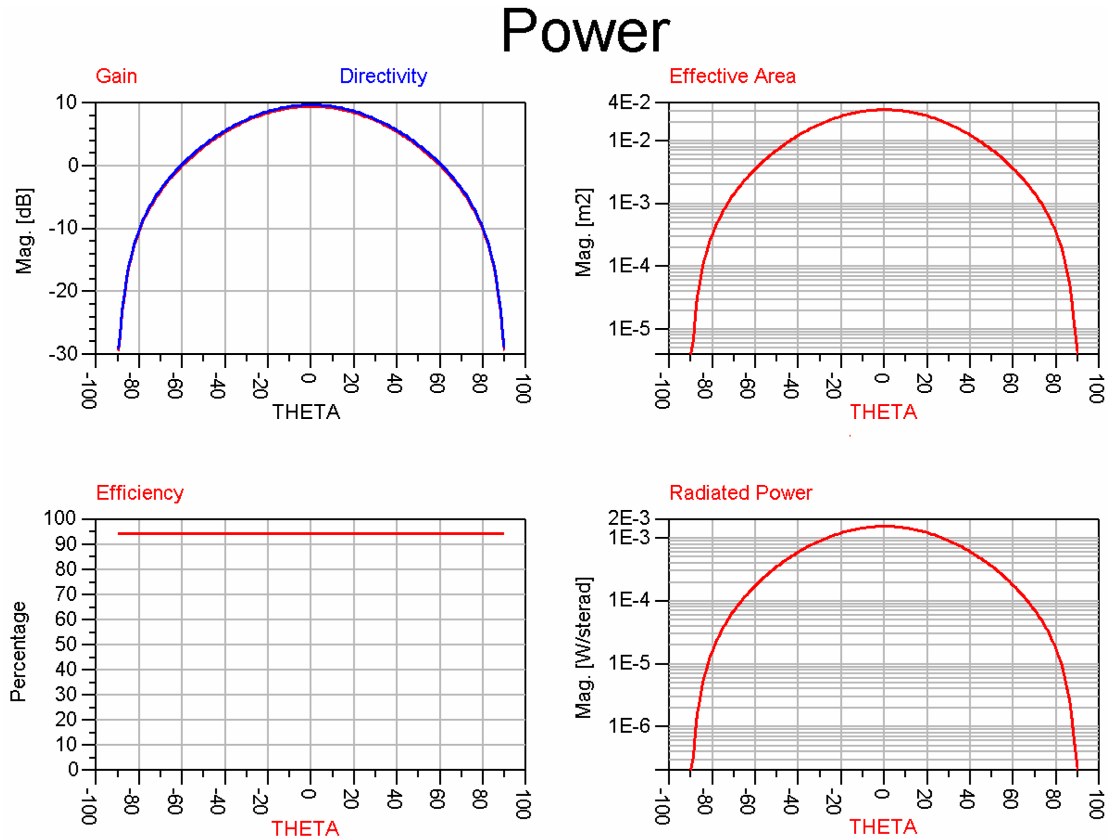


(b)



(c)

Figure 3.9 Radiation pattern of the rectangular patch antenna in *Figure*.3.8 with $\theta = 0^0, \phi = 90^0$. (b) Absolute fields (c) Circular polarization (continue)



(d)

Figure 3.9 Radiation pattern of the rectangular patch antenna in *Figure*.3.8 with $\theta = 0^0, \phi = 90^0$. (d) Power

3.2 Fabrication and test result

3.2.1 Fabrication descriptions

We chose brass (cooper zinc alloy) both for the patch and the ground plane material because of its good conductivity and permittivity characteristics. Thinking of there must be some tuning of the impedance matching point, we made a thin slot (around 3 mm in width and 25 mm in length) both on the patch and the ground plane, so that we can move the pin along the resonant dimension to find a good impedance matching point. The height of the wall of the box is at the same plane of the patch. We used some connector between the pin and the hole on the ground metal where the pin is through to keep them isolate to each other.

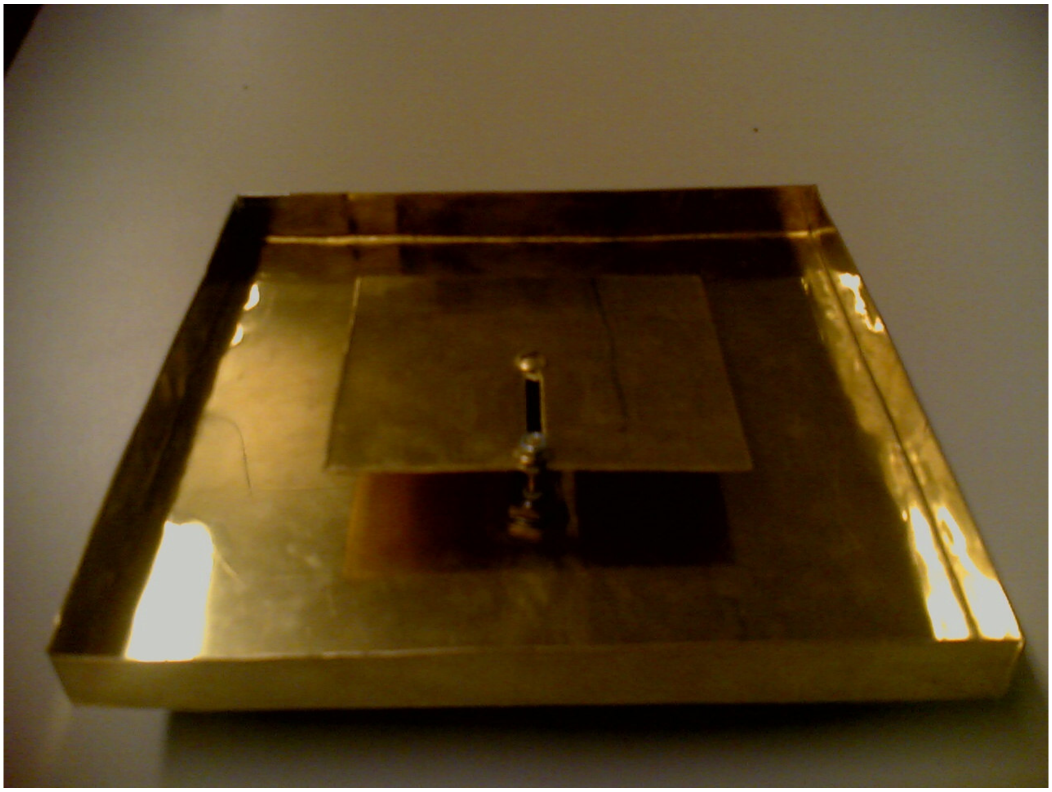


Figure 3.10 Patch antenna made of brass with ground dimension: 200 mm*200 mm, patch dimension: 90 mm*105 mm, substrate thickness and ‘wall’ height: 18 mm

3.2.2 Test equipment setup

It is usually most convenient to perform antenna measurements with the test antenna in its receiving mode. In this mode the measure result is identical to those transmitted by the antenna [7].In our measurement we employed another single patch antenna which works on dual frequencies (1.4 GHz and 2.4GHz).The next figure is the principle scheme.

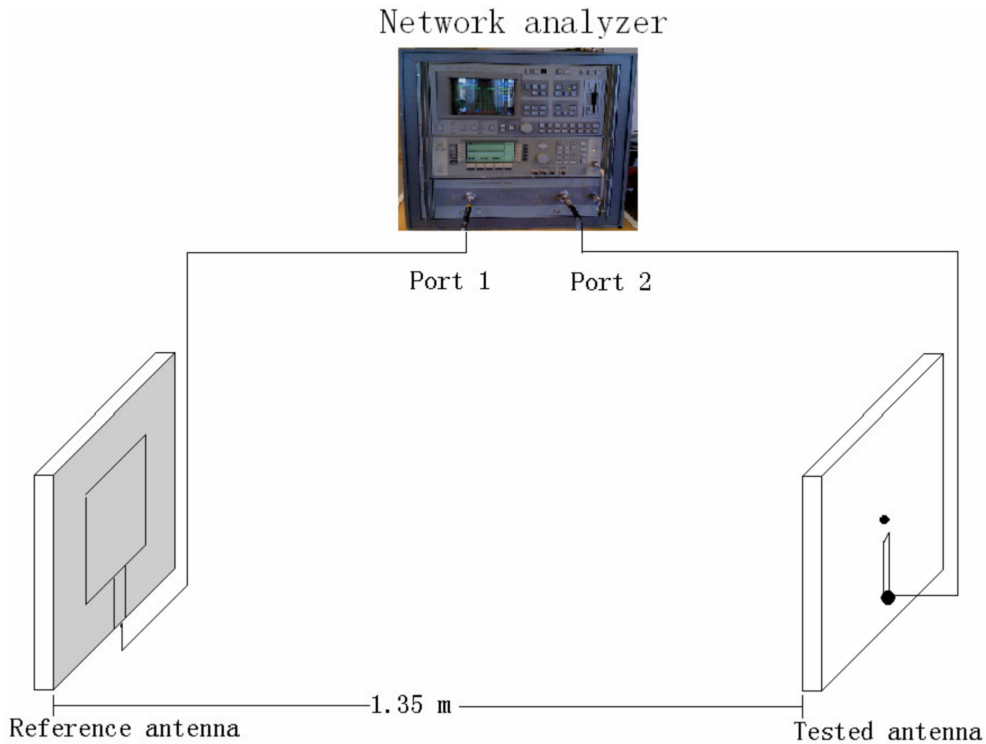


Figure 3.11 Setup of the far field radiation test of the patch antenna

We used WILTRON MODEL 360B network analyzer in the test. (See the picture above)
The far field refers to the distance that fulfilled equation

$$R \geq \frac{2D^2}{\lambda},$$

Where R=the distance between the transmitting antenna and the receiving antenna
D= the maximum distance of the tested antenna
λ=the wavelength of the signal
In our case, the far field $R \geq 0.757$ m, while here we chose 1.35 m.

The reference antenna is the dual frequency antenna which acted as the transmitting antenna in the test. The transmitting antenna and receiving antenna (tested antenna) were set in parallel to each other in the beginning. The tested antenna can be rotated over the vertical shaft. There are four combinations of the orientation of the antenna. It can be implied in *Figure* 3.12

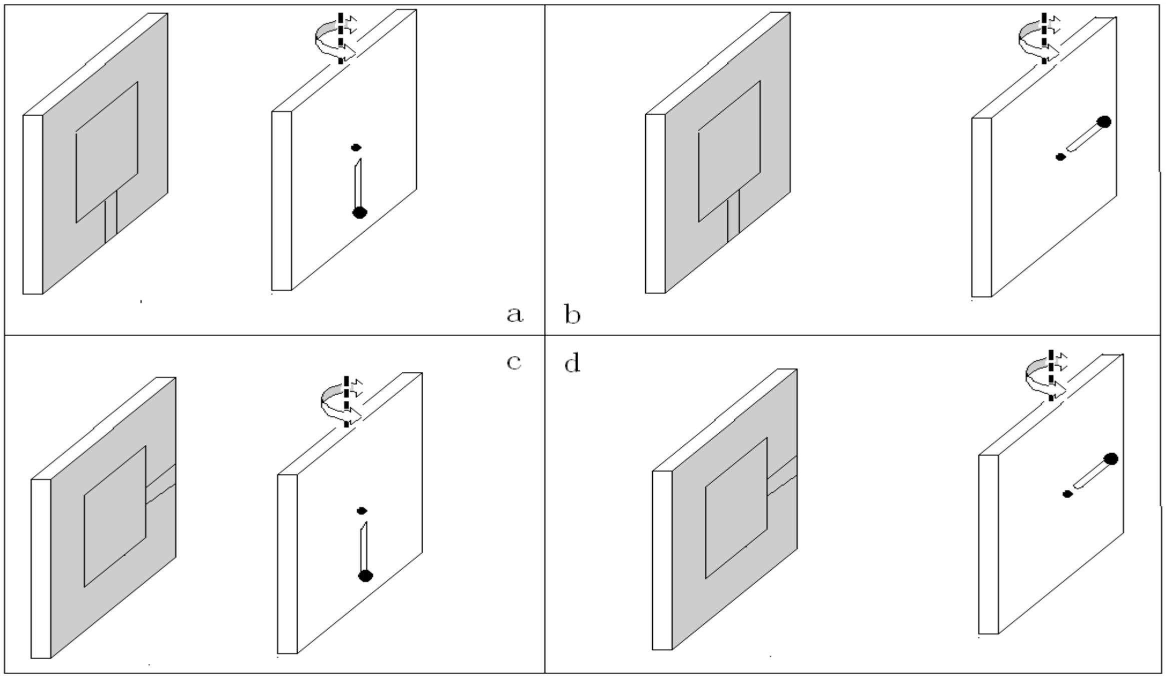


Figure 3.12 Four combinations of the orientation of the antenna (a) $0^0 \le \theta \le 180^0, \phi = 0^0$ (b) $\theta = 90^0, 0^0 \le \phi \le 180^0$ (c) $0^0 \le \theta \le 180^0, \phi = 0^0$ (d) $\theta = 90^0, 0^0 \le \phi \le 180^0$

3.2.3 Measurement Result

The losses that is caused by the cable can be measured by connecting the two cables to each other like the *Figure*.3.13 shows.

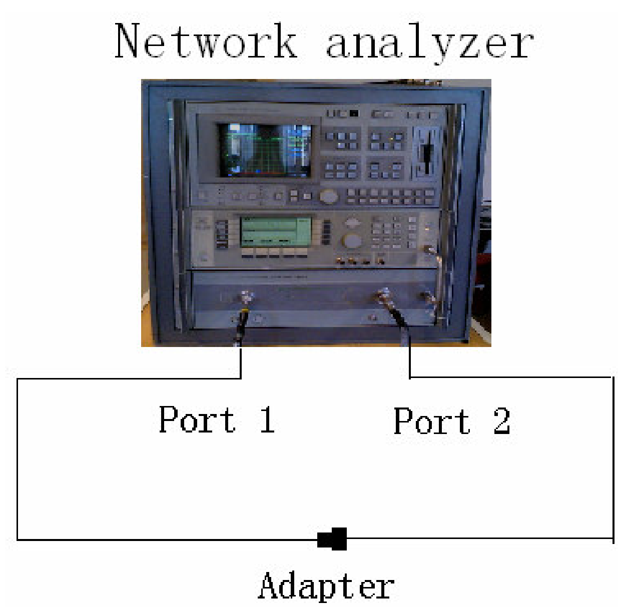


Figure 3.13 Setup of testing the losses of the cables

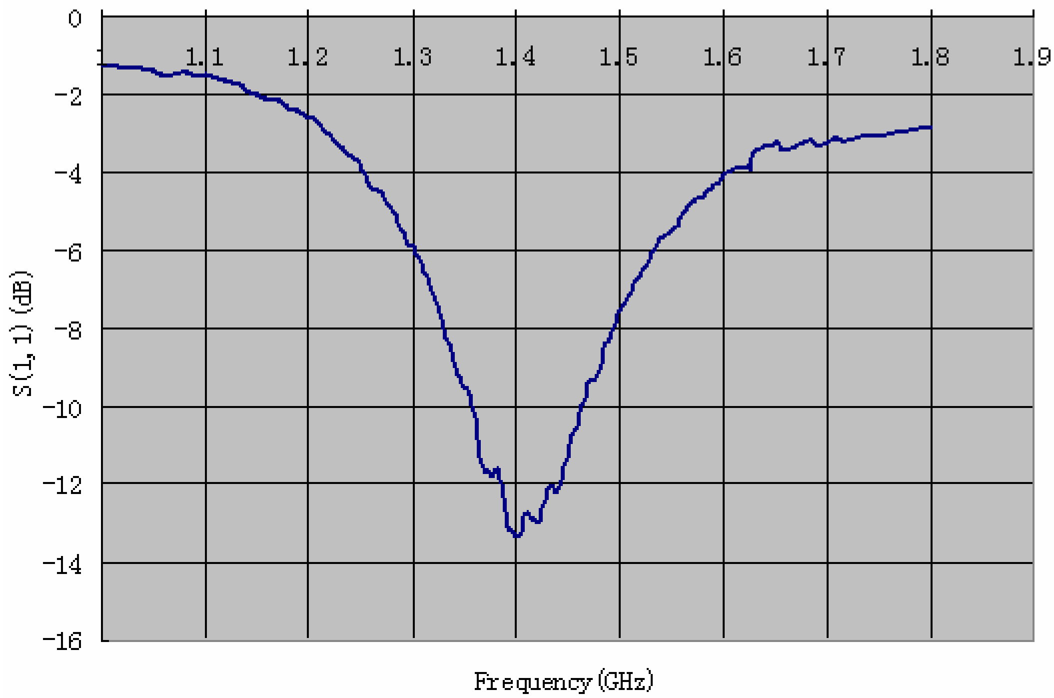
	1.4 GHz	1.42 GHz	1.44 GHz
S21(dB)	-5.66	-5.448	-5.426

Table 3.1 Losses in the cable

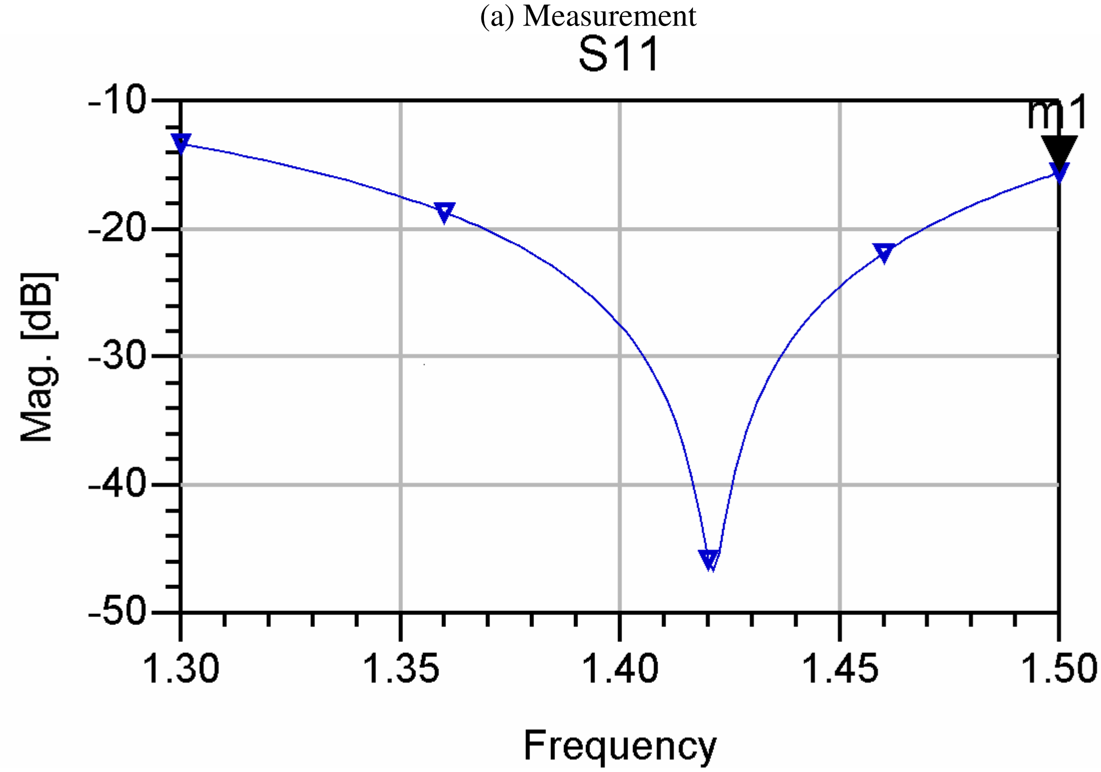
	S21 (dB)	1.4 GHz	1.42 GHz	1.44 GHz	Relative Gain	1.4 GHz	1.42 GHz	1.44 GHz
a	0°	-30.256	-32.633	-34.015	0°	0.26	0.17	0.092
	30°	-32.433	-35.027	-35.844	30°	-1.811	-2.022	-1.621
	45°	-35.999	-38.624	-40.623	45°	-5.589	-5.623	-6.109
	65°	-42.422	-43.522	-45.324	65°	-11.851	-10.566	-10.963
	90°	-49.521	-51.064	-46.856	90°	-17.158	-17.469	-16.557
b	S21(dB)	1.4 GHz	1.42 GHz	1.44 GHz	Relative Gain	1.4 GHz	1.42 GHz	1.44 GHz
	0°	-48.43	-48.27	-47.63	0°	3.717	-0.318	-1.206
	30°	-40.763	-45.377	-39.703	30°	11.04	5.223	6.715
	45°	-40.623	-43.192	-39.128	45°	11.199	4.702	6.358
	65°	-42.407	-46.051	-43.004	65°	9.625	2.529	2.778
	90°	-45.275	-50.227	-46.219	90°	6.611	-2.592	-0.617
c	S21(dB)	1.4 GHz	1.42 GHz	1.44 GHz	Relative Gain	1.4 GHz	1.42 GHz	1.44 GHz
	0°	-47.041	-49.323	-51.849	0°	1.478	-2.082	-0.094
	30°	-50.945	-51.946	-54.643	30°	-1.551	-5.955	-1.23
	45°	-48.431	-48.207	-49.721	45°	0.533	0.442	2.899
	65°	-48.167	-50.64	-50.722	65°	1.203	0.03	4.047
	90°	-50.024	-49.525	-51.492	90°	-2.087	-2.2	0.139
d	S21(dB)	1.4 GHz	1.42 GHz	1.44 GHz	Relative Gain	1.4 GHz	1.42 GHz	1.44 GHz
	0°	-32.749	-33.375	-33.17	0°	0.141	0.198	-0.158
	30°	-35.853	-36.399	-36.802	30°	-2.801	-2.708	-3.774
	45°	-42.303	-41.831	-43.687	45°	-9.439	-8.642	-10.912
	65°	-47.791	-56.081	-51.255	65°	-15.288	-22.97	-17.098
	90°	-47.357	-58.849	-46.462	90°	-14.662	-23.925	-12.46

Table 3.2 Measure result of the four combinations tests in *Figure*.3.12

From above table we can see that the antenna when the two antennas have different polarization orientation (b and c cases), less gain was achieved compared to the other two cases. The design specification in gain was well arrived. While the other important design specification in impedance matching to the 113+112j ohms was not brought out. The input impedance of the patch antenna at 1.42 GHz was 52.629-7.403j ohms.



(a) Measurement



(b) Simulation

Figure 3.14 S (1,1) parameter comparison between measurement and simulation over frequency

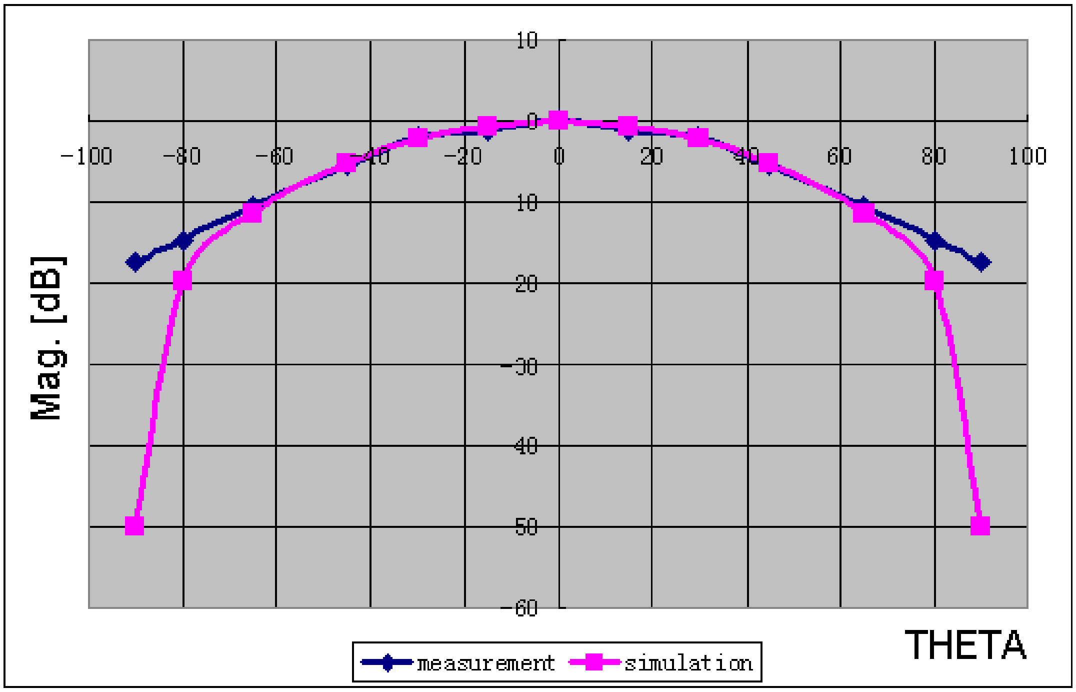


Figure 3.15 Comparison of relative gain between the simulation in ADS and the measurement

3.2.4 The influence of the radiation pattern of the patch antenna to the radio telescope

The measurements were all carried out inside the lab room in which the unexpected reflection is difficult to be totally kept away, for example the reflection from the walls, the ground and other equipments, even our body. While in the real circumstance where the patch will be mounted (the parabolic dish), these unwanted reflection can be more or less decreased. In the measurement result when we turn THETA 180 degree to the transmitting antenna, we got the back lobe radiation as -11.8 dBi which is very low and is good for the patch radiate most of the electromagnetic power in the main lobe normal to the surface. As for the telescope, it is helpful to "gather" more electromagnetic energy from the space.

3.2.5 Summary and tolerance analysis

We made a numerical summarization of the design into the next table:

comparision items	LxW (mmxmm)	feed point (mm)	feed impedance (Ω)	cover height (mm)	S(1,1) (dB)
calculation	82*105	22.69	50	no cover	~
simulation 1 (momentum)	81.9*105	20.9	50	no cover	-52.445
simulation 2 (equivalent circuit)	89.07*105	22.57	50	no cover	-69.824
simulation 3 (momentum)	83.8*105	16.3	50	20	-56.002
simulation 4 (equivlent circuit)	90.8*105	3.3	113+j112	no cover	-49.58
measurement	90*105	tunable	tunable	no cover	tunable

Table 3.3 Parameters comparison between the calculations, simulation and measurement results

Comparing the calculation to the simulation result and the tolerance between the simulation and measurement we found they are not identical to each other, and small tolerance always exists within some ranges. We believe the main aspects are:
Nonuniformity in the substrate thickness and slightly variations in finished antenna length and width
In ADS the walls of the antenna are as high as the cover while in reality we made it at the same level as the patch
Tolerances from the approximate equations
Fabrication inaccuracies
Test tolerances

4 Conclusions

In the project, we designed, fabricated and tested a rectangular single patch antenna, with Advanced-design-system as simulator. We got much hand on experience on RF design technical.

From the work conduced on simulation and test of fabricated product, we found computer added design is absolutely helpful in the design, but it still has some limitation. For example in ADS, we can not simulate the patch with a box that made of material other than metal, and the walls of the box can not be the same height when the height above the patch is not zero. The performance of the finalized antenna was acceptable in general, while there are still many other things we can try on it such as adding a plastic cover to the antenna box and test it. The feeding point of the patch antenna is far more sensitive than our imagination, and even a little bit change in position or connection may cause very different result. So the construction of the feeding part is critical for the whole work.

1) The design specification in gain was well arrived. While the other important design specification in impedance matching to the 113+112j ohms was not brought out.
2) The input impedance of the patch antenna at 1.42 GHz was 52.629-7.403j ohms.

5 References

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Appendix 1

Patch antenna simulation procedure

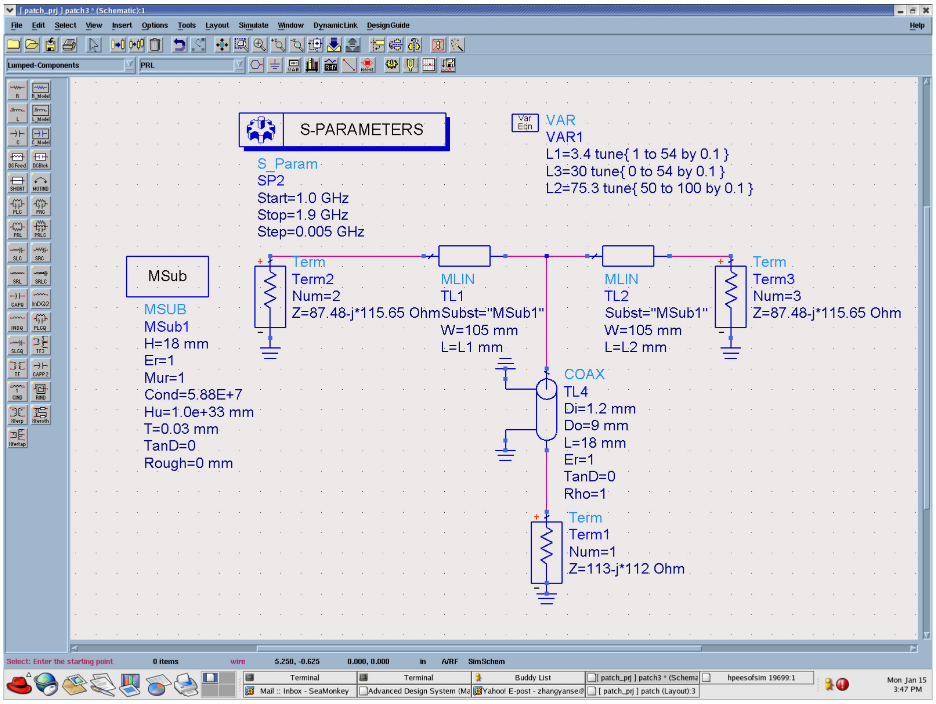
The simulation procedure was carried out with the Advanced Design System developed by Agilest Technology, USA. Here are some important procedures during the simulation:

1) After starting the ADS system, set up a .prj file in the root directory.
2) Open a new layout window; define the dielectric layer and metal layer.
Momentum->Substrate->Create/Modify.....
Note: If it is designed to simulate the antenna with a box, then the "Freespace" layer must be set as "Closed".
3) Layout the antenna components, such as port, rectangular metal.
4) Presetting.
Momentum->Mesh->Setup, choose "Global" label.
5) Simulation
Momentum->Simulation->S-parameter
6) Optimize the design. This can be done either in a layout window or a schematic window.

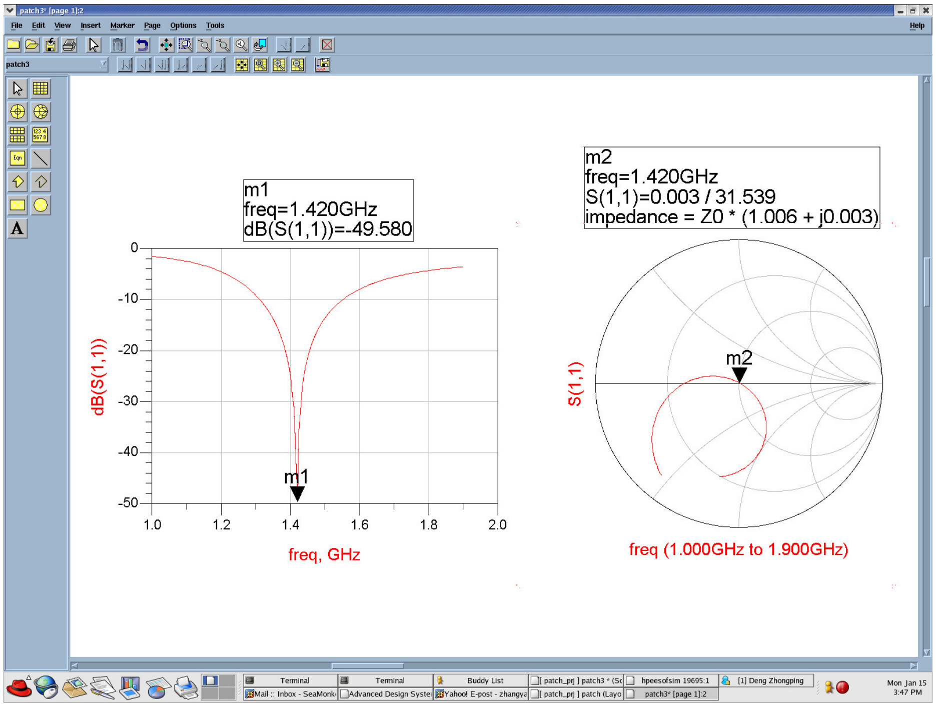
The "via", "coaxial", "SNP" and many other elements can be found in the component library.

Appendix 2

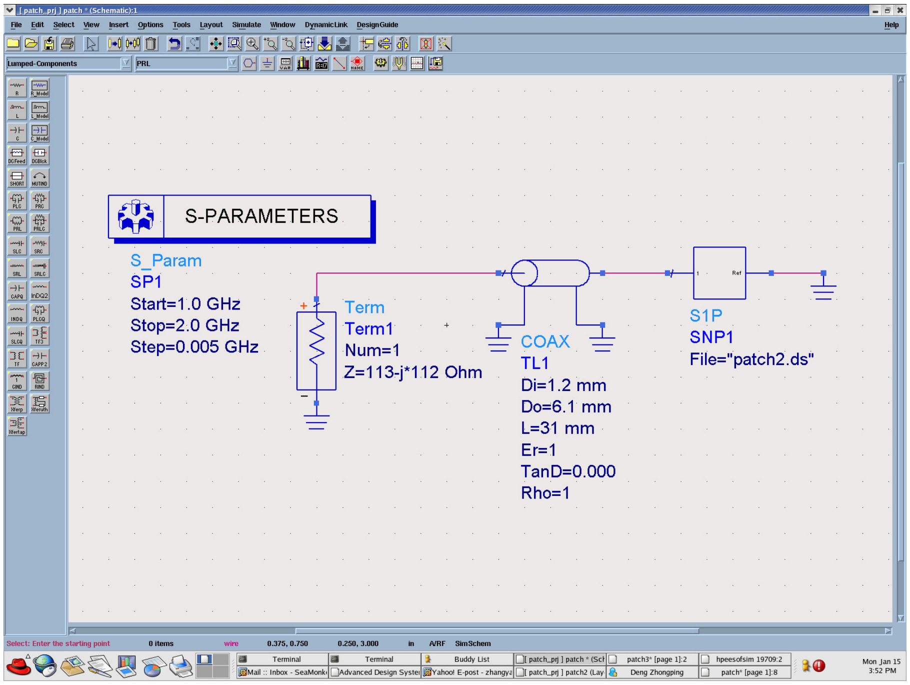
Some simulation schemes



A.1. Equivalent circuit of the patch antenna with a coaxial probe connecting the patch to the LNA

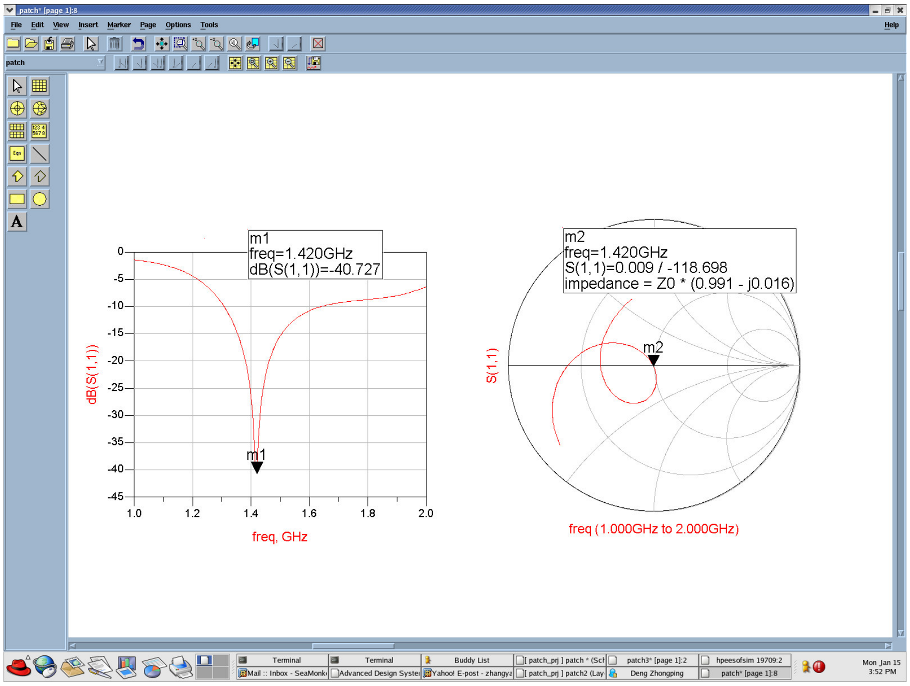


A.2 Simulation result of the equivalent circuit of the patch antenna in A.1

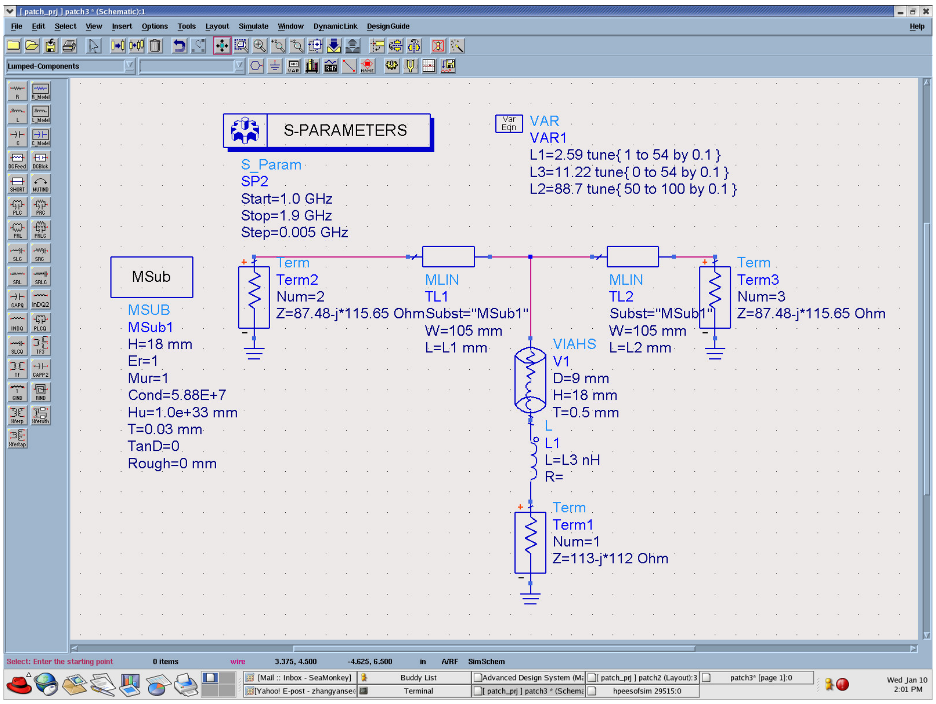


*A.3*Equivalent circuit of the patch antenna.

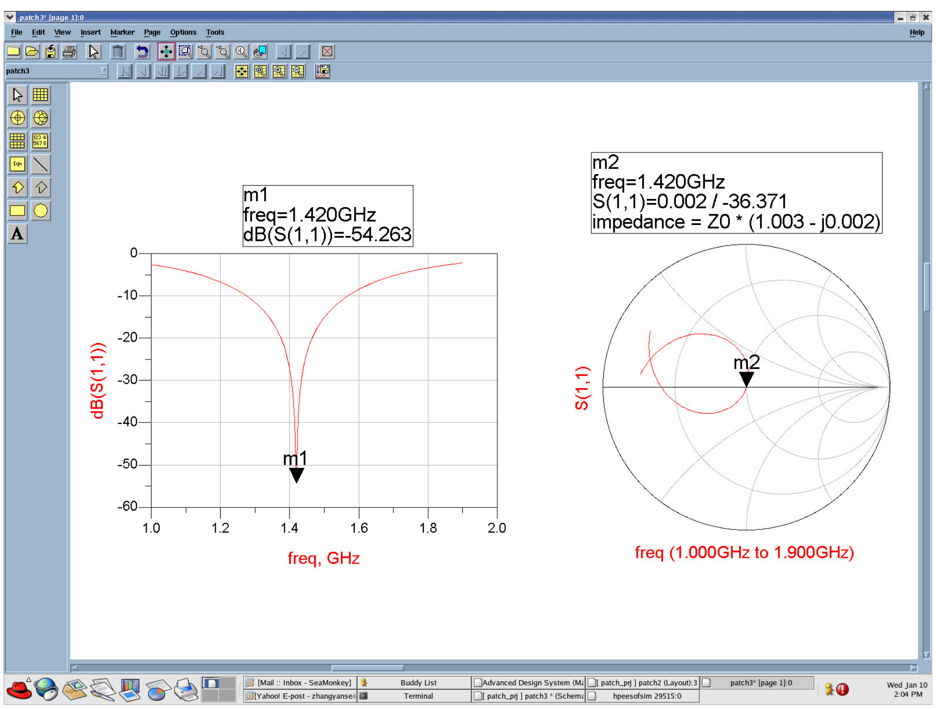
SNP is a function in ADS, here it represents the patch antenna, with the same parameters in file "patch2.ds" (*Figure* 3.1)



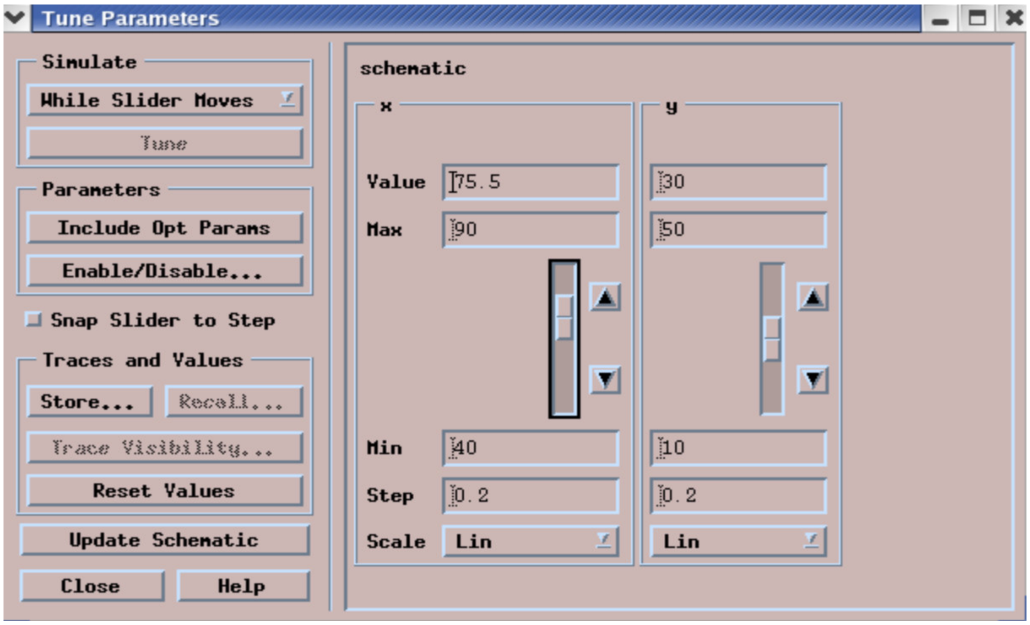
A.4 Simulation result of the equivalent circuit in A.3



A.5. Equivalent circuit of the patch antenna with a via connecting the patch to the LNA



A.6 Simulation result of the equivalent circuit in A.5



A.7 The “tune’ function window in ADS