Design of Horn and Open Waveguide Antennas at 915 MHz

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INTRODUCTION

This report documents the design and operation of a portable outdoor antenna range, as well as antenna design and fabrication, and measurement techniques of practical antennas for RF tag measurement. The site of our field work is on the roof of the Van Leer building where multipath interference is minimal. A rectangular waveguide and a pyramidal horn are designed and built for 915 MHz for RFID illumination. Both antennas are designed for maximum radiation at 915 MHz with minimal ohmic loss. There are several important factors taken into the design of these two antennas, such as skin depth factor, cut-off frequency, and the structure of the radiating element. These antennas were mounted on a manual controlled rotating mast, and their radiation patterns were measured. Using the maximum gain of the radiation pattern, we can use the link budget formula to calculate the gain of the antennas and compare it with theoretical calculations. These characteristics will then be evaluated for research in wireless sensors and RFID.

Designs and Calculations

2.1 Skin depth factor, and cutoff frequency

The material used for building the waveguide and the pyramidal horn is pure copper with thickness of 0.5486 of a millimeter. Copper has a very high electrical conductivity; its conductivity is second only to silver and the cost is significantly cheaper. This insures the radio wave transmitted in the waveguide is properly reflected and surface current on the waveguide does not produce much Ohmic loss. To ensure the copper used in construction is thick enough for a 915 MHz electromagnetic wave to propagate with the least amount of attenuation, the skin depth must be calculated. The skin depth or the depth of penetration of a conductor:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} meters$$

$$\sigma = 5.80x10^{7} S/m$$

$$f = 915x10^{6} Hz$$

$$\mu = 4\pi 10^{-7} H/m$$

$$\delta = 2.185 micrometers$$

The copper used in the construction is approximately 548.6 micrometers, which is much thicker then the skin depth. This ensures the waveguide will not be lossy.

Designs and Calculations

Radio waves can propagate in many different modes in a rectangular waveguide. For our purpose, the dominant mode of transverse electromagnetic propagation is selected. This TE_{10} mode has the lowest attenuation of all modes in a rectangular waveguide and its electric field is vertically polarized. In order to design the dimension of the waveguide, we must calculate the cut-off frequency for the dominant mode of propagation. For 915 MHz wave to propagate inside the waveguide, the cutoff frequency must be lower then the mode of propagation. Plotting the attenuation of the transverse electromagnetic wave in the dominant mode within the waveguide will give us a good idea of the cut-off frequency to choose.

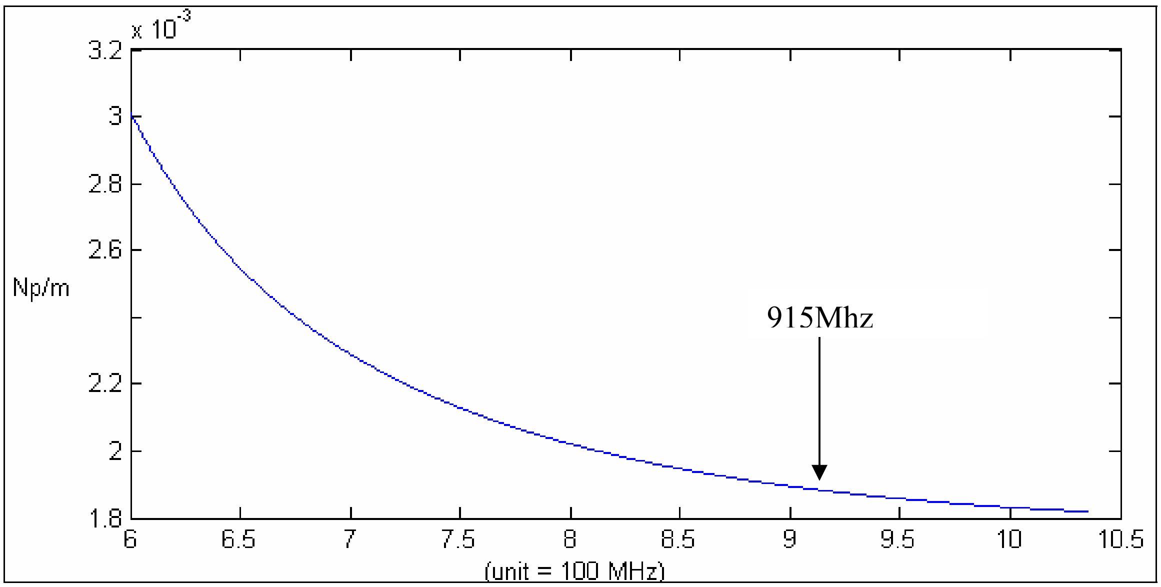


Figure 2.1 Attenuation vs. Frequency.

Choosing the cutoff frequency at 625 MHz allows little attenuation at 915 MHz.

Using $f_{c10} = \dfrac{1}{2a\sqrt{\mu\varepsilon}}$ we can find the width *a* = 24 cm, and the height of the wave guide is *b* = *a*/2 = 12 cm.

Designs and Calculations

2.2 Design of 915 MHz Pyramidal Horn

A pyramidal horn is a rectangular waveguide with a flare out at the end. This causes the antenna to have a higher directivity then a normal waveguide. The general form of a Pyramidal horn has the following design.

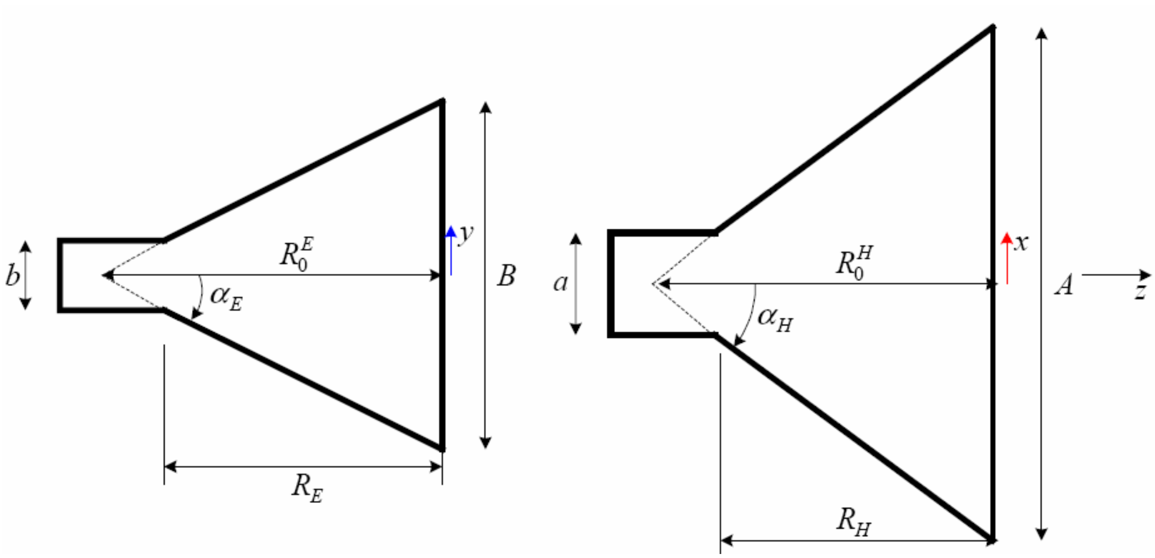


Figure 2.2.1 Side view (left) and top view (right) of a pyramidal horn.

$$R_E = R_H = R_P$$

$$\frac{R_0^H}{R_H} = \frac{A/2}{A/2 - a/2} = \frac{A}{A-a}$$

$$\frac{R_0^E}{R_E} = \frac{B/2}{B/2 - b/2} = \frac{B}{B-b}$$

Using the value for the width *a* and height *b* previously determined.

(A = 2 x *a* = 48cm, and B = 2 x *b* = 24cm.) we get the following design

Designs and Calculations

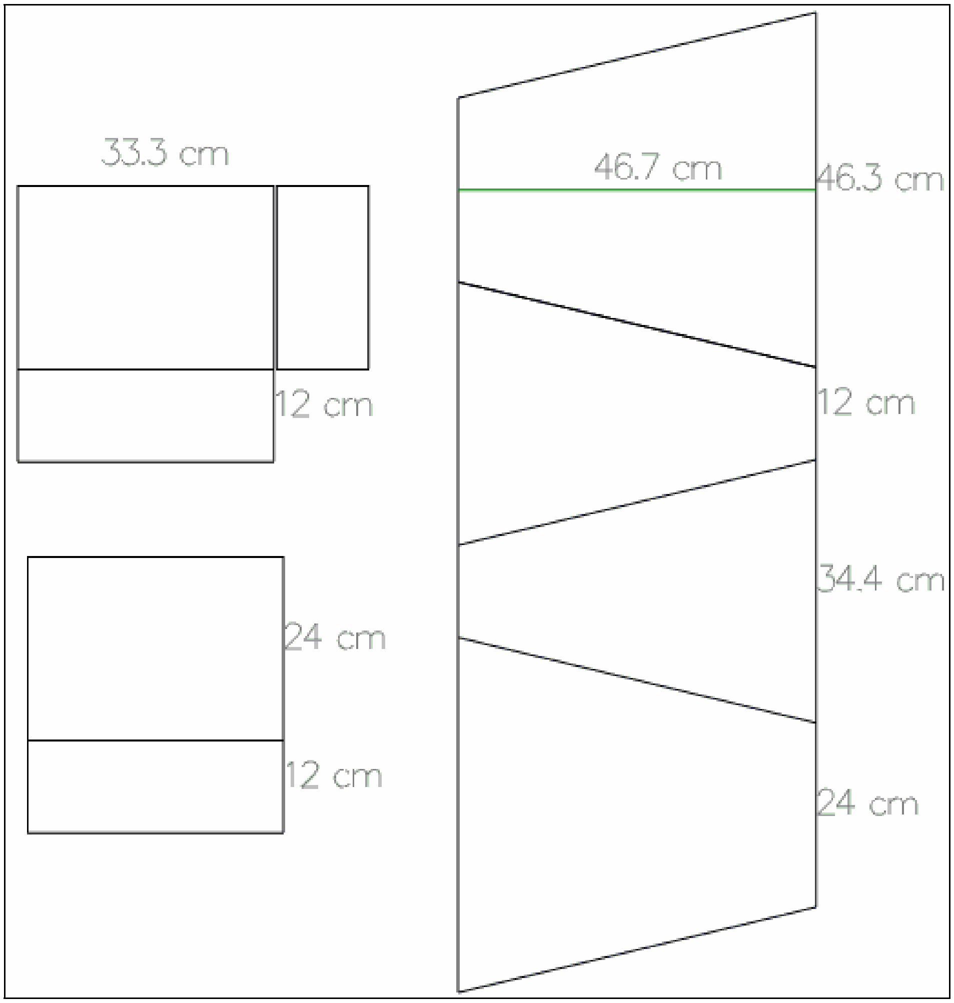


Figure 2.2.2 Copper sheet layout for waveguide and flare out.

The aperture of the flare out had to be decreased slightly due to size of the copper sheet that could be purchased without excessive cost. Due to manufacturing error, the final aperture is A = 41cm and B = 30cm. using

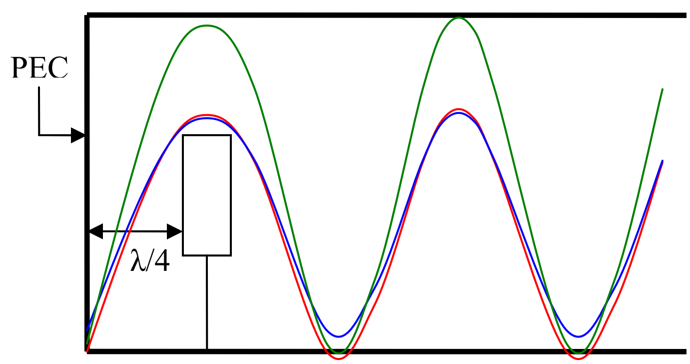
$$G = \frac{4\pi}{\lambda^2}\varepsilon_{ap}AB$$

λ = 32.78cm at 915 MHz, and aperture efficiency for standard horn is ε_{ap} = 0.51. The calculated gain for the pyramidal horn is approximately **7.33 dBi**, and the waveguide has an estimated gain of **1.72 dBi.**

Designs and Calculations

2.3 Radiating element

The radiating element is the element inside the waveguide, or a pyramidal horn that excites a radio wave to propagate. The radiating element is must be placed quarter wavelength from the back of the wave guide.



f = 915 MHz
λ/4 = 8.197 cm

Blue = incident wave
Red = reflected wave from PEC
Green = Total wave propagation

Figure 2.3.1 Sinusoidal wave inside the waveguide.

When the incident wave hits the back of the metallic waveguide, a reflected wave from the perfect electric conductor is generated. These two waves in the same phase will reinforce each other and cause a stronger radio wave to propagate. The height of the radiating element should also be quarter of a wavelength; this will cause the reflected wave from the bottom part of the waveguide to reinforce the incident wave instead of canceling the incident wave due to different phase.

Designs and Calculations

In order to build an antenna that radiates power into the open space, we have to tune the radiating element so it does not reflect power back into the source; this is done by changing the physical shape of the radiating element, and measuring the reflection coefficient of the antenna using a directional coupler.

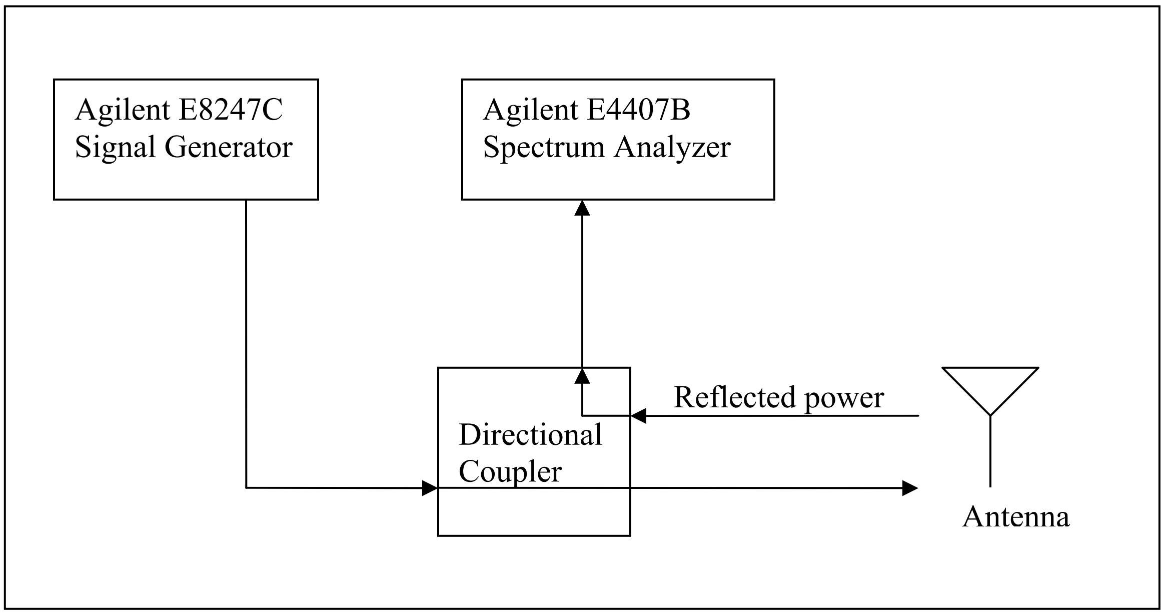


Figure 2.3.2 Block diagram for power reflection measurement.

The Agilent E8247C Signal generator sweeps through frequencies of interest, mainly 600 MHz to 1000 MHz. The power is sent from the signal generator through the three port coupler and out to the antenna. If the antenna is not attached to the coupler, the port can be treated as an open circuit. An open circuit has a reflection coefficient of 1, causing all the power sent from the signal generator directly to the spectrum analyzer. If the antenna is connected to the directional coupler at an impedance of 50 Ohms, without proper tuning and impedance matching, large amounts of power will be reflected back to the spectrum analyzer instead of radiating into free space.

Designs and Calculations

2.4 Antenna tuning

The rectangular waveguide and the pyramidal horn are both built for 915 MHz. The dimension of the antenna cannot be easily changed, however the radiating element is a small piece of copper which can be easily cut and bent. Bending and cutting the radiating element can change the impedance of the antenna and also the reflection coefficient at a given frequency. Figure 2.3.2 is used for the tuning setup. Below is a screen capture of the spectrum analyzer.

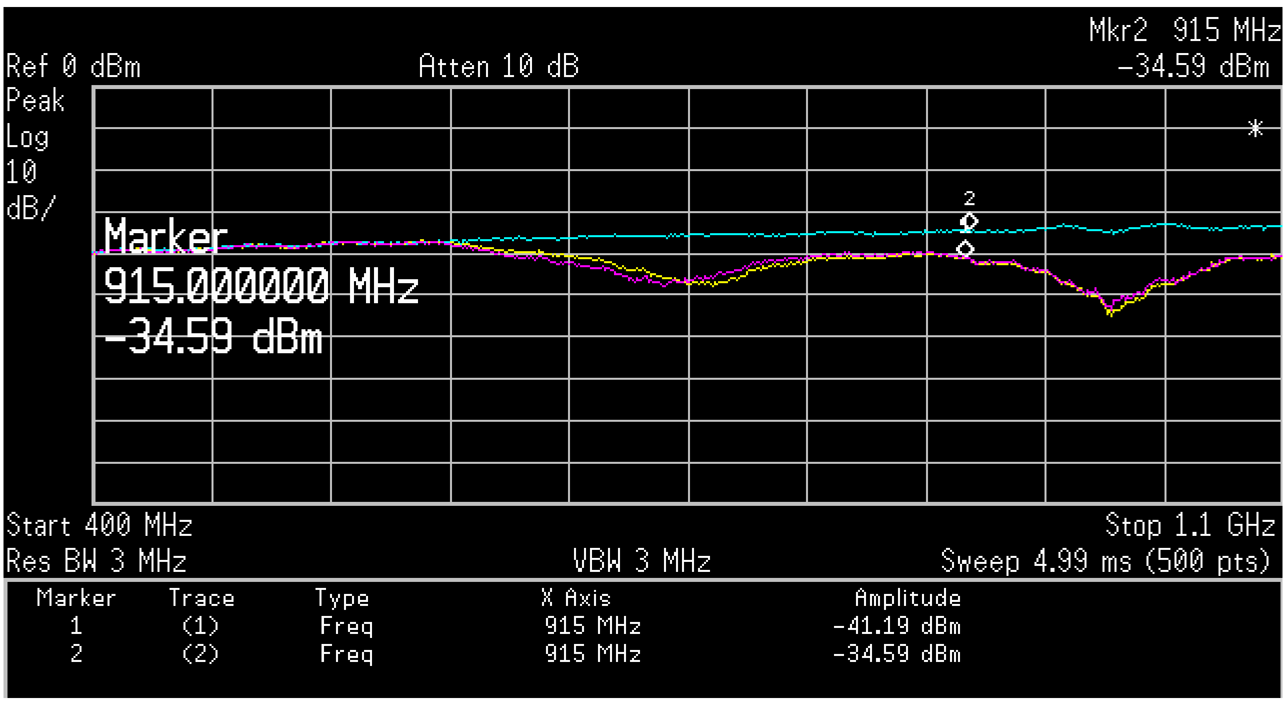


Figure 2.4.1 Reflected power vs. frequency with different length of radiating element.

The blue color trace is the reflected power when there is no antenna attached to the directional coupler; this is the maximum power that could be reflected. The pink color trace is the reflected power from the waveguide. The radiating element used is a 7.8cm x 1.5 cm piece of copper. The yellow trace represents the radiating element 0.3 cm shorter. From figure 2.4.1 we can conclude that shortening the element will shift the resonant frequency higher up.

Designs and Calculations

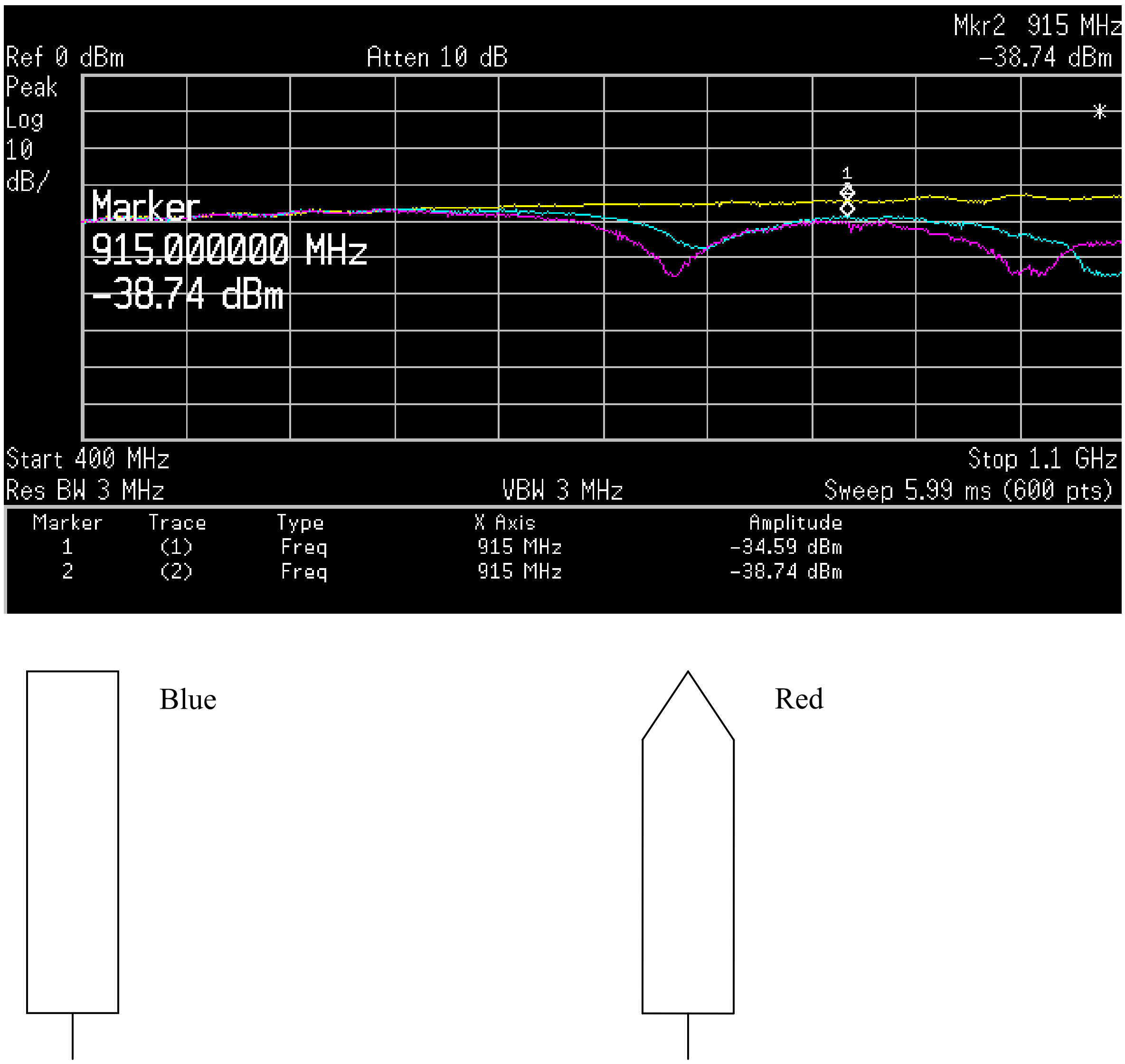


Figure 2.4.2 Reflected power vs. frequency with different shapes of radiating element.

Radiating elements with the same length but different shapes can also change the power reflected at certain frequencies. This is especially true near the null of the trace. From Figure 2.4.2 we can conclude broader element will generally increase the bandwidth of minimum reflection coefficient, and also the amount of power reflected.

Designs and Calculations

Using these characteristics found, the following radiating elements were made.

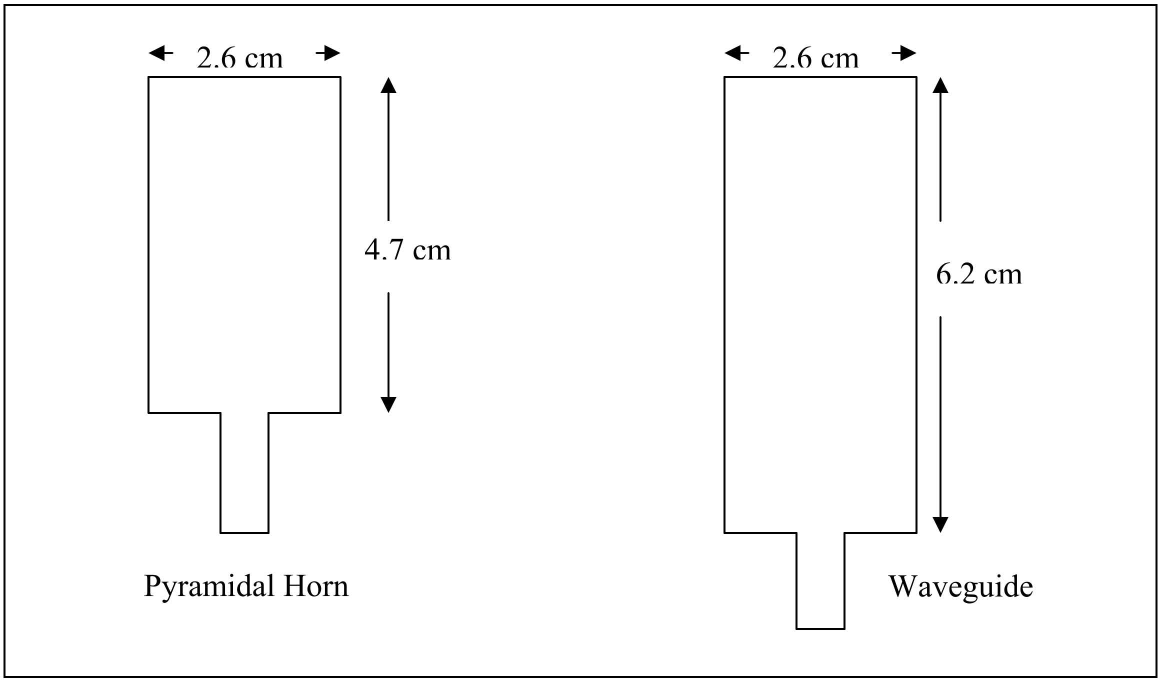


Figure 2.4.3 Radiating element for pyramidal horn, and rectangular waveguide.

Both elements were soldered to an SMA connector pin at the narrower edge and placed approximately 8.2 cm (quarter wavelength) away from the back of the waveguide. Using the setup in Figure 2.3.2, the amount of power reflected was measured using the spectrum analyzer.

Designs and Calculations

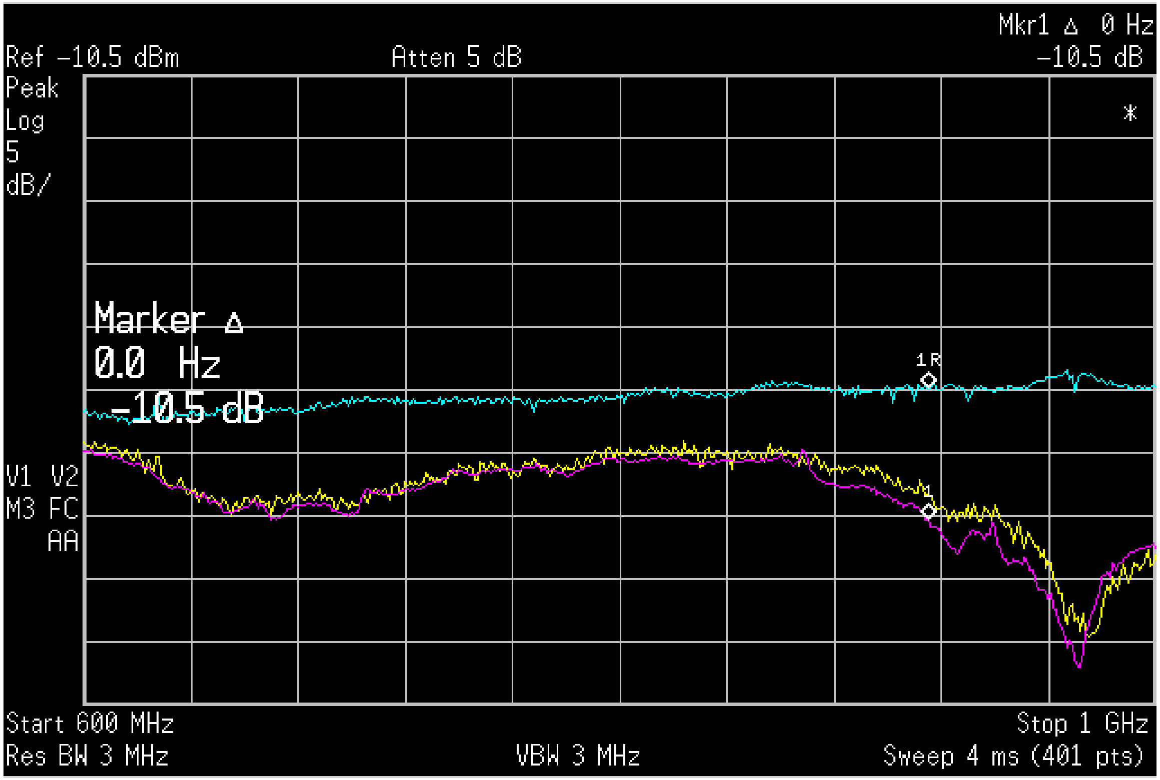


Figure 2.4.4 Reflected power for rectangular waveguide.

In Figure 2.4.4 the new element (red trace) is the improved version of the old element (yellow trace), which is the final result for the rectangular waveguide. The blue trace is the maximum power that could be reflected. From the figure we can see that at 915 MHz the waveguide reflects 10.5 dB less power than an open circuit. This means over 91% of power is radiated into free space.

Designs and Calculations

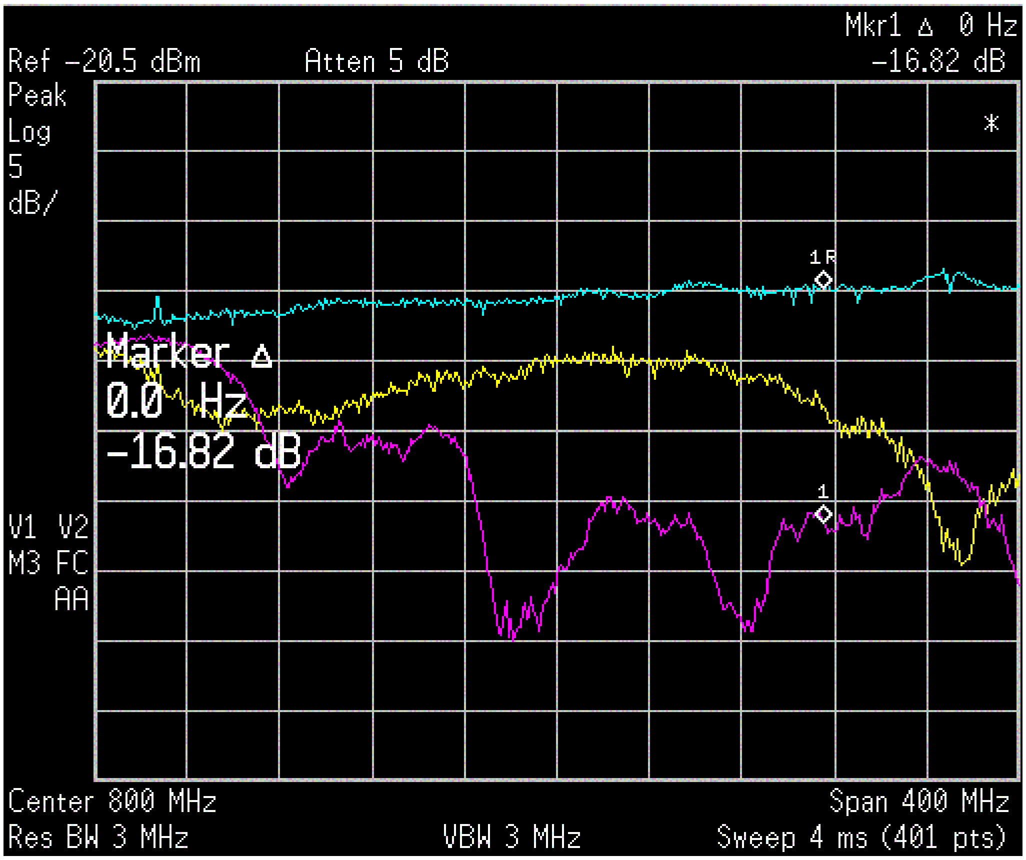


Figure 2.4.5 Reflected power of pyramidal horn vs. rectangular waveguide.

The yellow trace in figure 2.4.5 represents the reflected power vs. frequency for the rectangular waveguide, and the red trace is for the pyramidal horn. From this figure we can see the pyramidal horn exhibits a lower reflection with a much wider bandwidth. The power reflected at 915 MHz is 16.82 dB down from an open circuit. Using the following equation we can calculate percents of power radiated.

$$\%Radidated = 1 - (10^{\frac{db}{10}})x100$$

This gives us 97.9 % of power radiated at 915 MHz.

Data Acquisition and Measurements

3.1 Antenna range setup

The antenna range is set on the roof of Van Leer building where multipath interference is at a minimum. The pyramidal horn antenna was mounted on a manual controlled rotating mast.

Figure 3.1.1 Antenna measurement setup.

A Berkeley Varatronics Gator Transmitter was connected to a stationary full-wave dipole transmitting one watt of power at 915 MHz. The pyramidal horn is connected to the spectrum analyzer with 84 feet of low loss coaxial cable with a 900 MHz high pass filter, and a 1200 MHz low pass filter. The total loss due to the cables, filters, and connectors is only 4.84 dB.

Data Acquisition and Measurements

The received power by the pyramidal horn was captured by the spectrum analyzer, and the data is sent to the laptop computer using a MATLAB function originally written by Joshua Griffin. The MATLAB function was modified so the data capturing time was cut down to fraction of a second. This allows the operator to keep the rotating mast turning continuously, while recording the data using the laptop by hitting space bar. The collected data is used to plot an antenna pattern using MATLAB.

3.2 Radiation Patterns

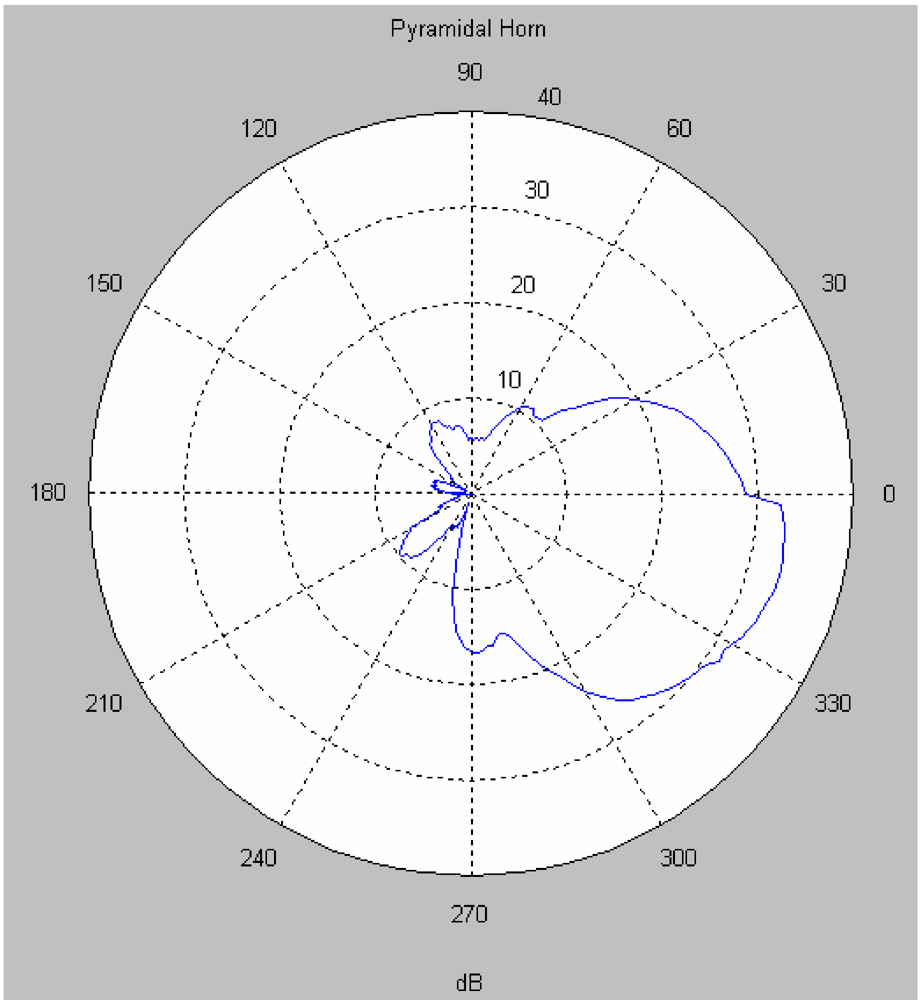


Figure 3.2.1 Radiation pattern for a pyramidal horn antenna.

Data Acquisition and Measurements

Looking at Figure 3.2.1 the front-to-back ratio for the pyramidal horn is approximately 26 dB. The half power bandwidth is approximately 40 degrees.

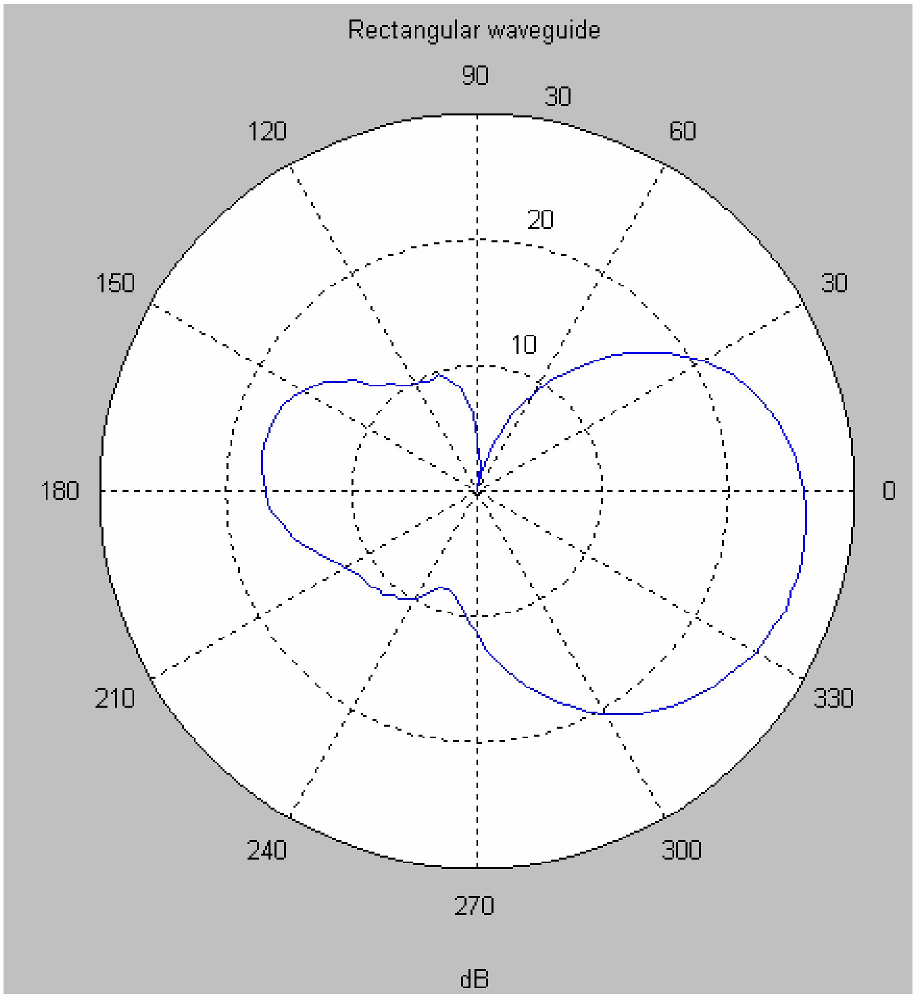


Figure 3.2.2 Radiation pattern for a rectangular waveguide antenna.

The front-to-back ratio for the rectangular waveguide is approximately 9.5 dB. The half power bandwidth is approximately 60 degrees. The pyramidal horn has a much better directivity and front-to-back ratio then the rectangular waveguide. This makes the pyramidal horn much more suitable for back scatter measurements in RFID applications.

Appendix

```
%**************************************************************************
%Data Collection Script
%5/26/04
%Joshua Griffin
%Modified by Yenpao Lu
%**************************************************************************
current_angle = 0;
count2 = 0;
ESA4407 = serial('COM4','BaudRate',115200,'DataBits',8,'InputBufferSize',6000);
file_directory = 'C:\Documents and Settings\Albert Lu\Desktop\';
filename = input('Input the output file name:  ','s');
file_header_1 = '**************************RFID Antenna Test*****************************';
file_header_2 = fix(clock);
file_header_3 = 'File name :';
file_header_4 = '**************************************************************************';
file_header_5 = 'Data Pt.   Pwr (dBm)   Angle (relative to reference)';
tot_file_name = strcat(file_directory,filename);

outputfile = fopen(tot_file_name,'w');

fprintf(outputfile,'%s\n',file_header_1);
fprintf(outputfile,'                          %d/%d/%d %d:%d:%d\n',file_header_2);
fprintf(outputfile,'%s %s\n',file_header_3,tot_file_name);
fprintf(outputfile,'%s \n \n \n',file_header_4);
fprintf(outputfile,'%s \n \n \n',file_header_5);

fopen(ESA4407);
fprintf(ESA4407, '*RST');
fprintf(ESA4407, ':INIT:CONTINUOUS OFF');
fprintf(ESA4407, '*WAI');
fprintf(ESA4407, ':SENSE:FREQUENCY:CENTER 915MHz');
fprintf(ESA4407, ':SENSE:FREQUENCY:SPAN 0Hz');
fprintf(ESA4407, ':SENSE:BANDWIDTH:RESOLUTION 1kHz');
fprintf(ESA4407, ':UNIT:POW DBM');
fprintf(ESA4407, ':FORM:DATA ASC');

data_pts = input('Enter the number of data points (even numbers only): ');
angle_increment = 360/data_pts;

for count = 1:data_pts
   current_angle = angle_increment*count2;
   sprintf('Press any key to record a data point %d at angle %d away from the reference angle',count, current_angle)
   pause;
   fprintf(ESA4407, ':INIT:IMM');
   fprintf(ESA4407, '*WAI');
   fprintf(ESA4407, ':TRAC:DATA? TRACE1');
   raw_data = fscanf(ESA4407);
   formatted_data = strread(raw_data,'%f','delimiter',',');
   avg_data(count) = mean(formatted_data);
   fprintf(outputfile,'%d \t %d \t %d \n',count,avg_data(count),current_angle);
   count2 = count2+1;
end

fclose(ESA4407);
delete(ESA4407);
clear ESA4407;
fclose(outputfile);
```

Data collection script.

Appendix

```
data = 'C:\Documents and Settings\Albert Lu\My Documents\Design\Antenna Data\HornAntenna.txt';

figure(1)
[gain, theta_degree_2] = textread(data,'%*d %f %d');
theta_radian_2 = theta_degree_2.*pi./180;
normgain = gain - min(gain);
polar(theta_radian_2,normgain);
title('Pyramidal Horn')
xlabel('dB')
```

Antenna pattern plotting script.