7^{th} semester Open lab
Report

Designing a Horn Antenna to observe the 21 cm line of neutral Hydrogen using FEKO

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This report is submitted for the partial fulfillment of the course P-441/442

Contents

Abstract

In today's world antenna has become a very common part of the daily lives, every single gadget requires an antenna for signal transmission to receiving from a small television remote to a big radio station. In our experiment an antenna has been designed using the FEKO software for detecting 21 cm line coming from the transitions of hyper-fine splitting of the Hydrogen gas. The max gain for the designed horn antenna was found out to be 18.4 dB with the length of 120 cm and with the efficiency of 49.78 % for 1st horn and efficiency of 42.48 % of the 2nd horn.

1 Introduction

Neutral Hydrogen is the most abundant and simplest element in our Universe. It's exceptional abundance in the universe makes it very much significant in the understanding about our universe. It is simply consists of a single proton and a single electron. The interactions between the electron spin and the nuclear spin results of increase in energy when spins are parallel or decrease of energy when anti-parallel.

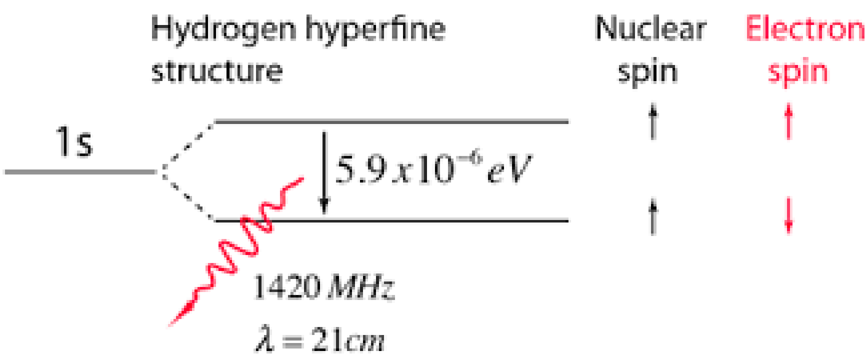

Figure 1: Hydrogen hyper-fine structure.

Whenever an electron goes into transition from the high energy state to the low energy state a radiation emission is observed. The frequency of this observed radiation is 1420.21 MHz (21 cm wavelength), it doesn't get blocked by dust clouds and other such particles like in the case of visible light. This splitting is known as the hyper-line splitting.

2 Antennas

An antenna is a metallic structure that captures and/or transmits radio electromagnetic waves. Antennas can be designed to transmit and receive radio waves in all horizontal directions equally (omnidirectional antennas), or preferentially in a particular direction (directional, or high-gain, or "beam" antennas).

The first antennas were built in 1888 by German physicist Heinrich Hertz in his pioneering experiments to prove the existence of waves predicted by the electromagnetic theory of James Clerk Maxwell. Hertz placed dipole antennas at the focal point of parabolic reflectors for both transmitting and receiving. Starting in 1895, Guglielmo Marconi began development of antennas practical for long-distance, wireless telegraphy, for which he received a Nobel Prize

2.1 Types of antenna

There are several types of antenna with examples:

- Wire antenna: Dipole antenna, Monopole antenna, Helix antenna, Loop antenna
- Aperture antenna: Waveguide (opening), Horn antenna
- Reflector antenna: Parabolic reflectors, Corner reflectors
- Lens antenna: Convex-plane, Concave-plane, Convex-convex, Concaveconcave lenses
- Micro strip antenna: Circular-shaped, Rectangular shaped metallic patch above the ground plane
- Array antenna: Yagi-Uda antenna, Micro strip patch array, Aperture array, Slotted wave guide array

In our experiment we are focusing on horn type antenna i.e. Aperture antenna.

2.2 Parts of antenna:

The Horn antenna usually comprises of two parts (i) Waveguide (ii) Horn :

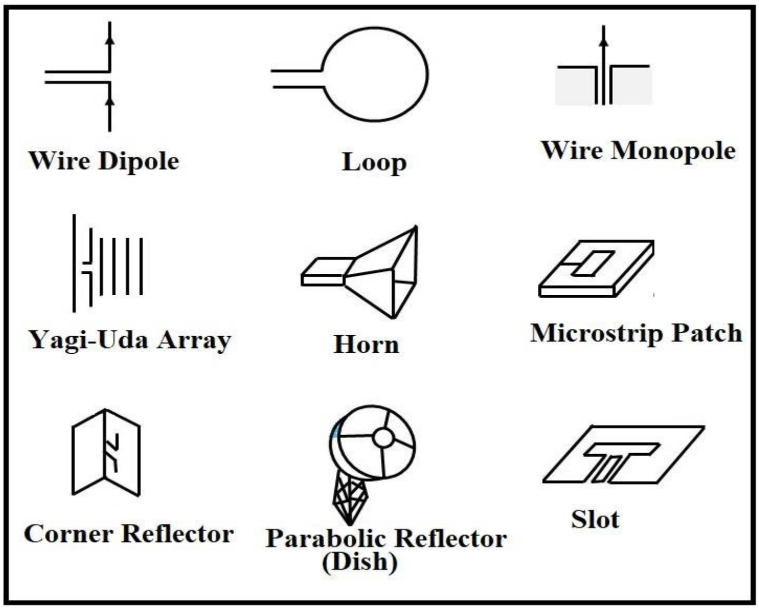

Figure 2: Different types of antenna.

2.2.1 Waveguide:

A waveguide is a hollow metallic tube of the uniform cross section for trans-transmitting electromagnetic waves by successive reflections from the inner walls of the tube. In a waveguiding system, the solutions of the Maxwell's equations give the propagation of Electric and Magnetic fields along the guiding direction, the z direction:

$$\begin{aligned} E(x,y,z,t) &= E(x,y)e^{i\omega t - i\beta z} \\ B(x,y,z,t) &= B(x,y)e^{i\omega t - i\beta z} \end{aligned} \tag{1}$$

where β is the propagation wavenumber along the guide direction. The equations for phasor amplitudes E(x; y) and H(x; y) can be split into longitudinal (along z-direction) and transverse (along x,y directions) directions. The phasor amplitude for electric field is given as:

$$E(x,y) = \hat{x}E_x(x,y) + \hat{y}E_y(x,y) + \hat{z}E_z(x,y) \equiv E_T(x,y) + \hat{z}E_z(x,y) \tag{2}$$

The electric and magnetic fields satisfy the relation:

$$H_T = \frac{1}{\eta}\hat{z} \times E_T$$

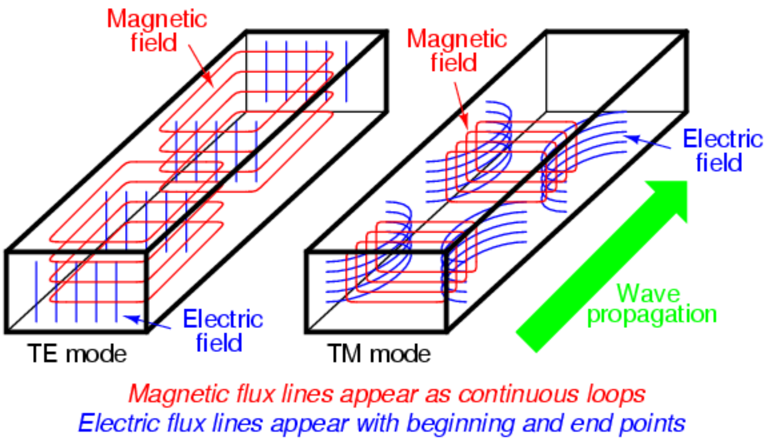

Figure 3: Pattern of Electric and Magnetic elds in TE and TM modes.

Depending on whether which of the longitudinal components are zero, the solutions can be stated as transverse electric and magnetic (TEM), transverse electric(TE), transverse magnetic(TM) or hybrid: $E_z = 0; H_z = 0$, TEM modes

$E_z = 0; H_z \neq 0$; TE or H modes

$E_z \neq 0; H_z = 0$; TM or E modes

$E_z \neq 0; H_z \neq 0$; hybrid or HE or EH modes

TEM modes are the dominant modes in two-conductor transmission lines such as the coaxial cable. The cut-off frequency and wavelength is found using cut-off wavenumber k_c as:

$$\begin{aligned} \omega_c &= ck_c \\ \lambda_c &= \frac{2\pi}{k_c} \end{aligned} \tag{3}$$

2.2.2 Rectangular waveguide:

A horn antenna is an antenna which consisting of a flaring which is shaped like a horn to direct radio waves in a beam to the waveguide. Here the horn shaped flaring is added to the rectangular waveguide to increase the directivity of the waveguide. Horns are widely used as antennas at UHF and microwave frequencies, above 300 MHz. A major advantage of horn antennas is that since they have no resonant elements, they can operate over a wide range of frequencies, a wide bandwidth. There are three types of horn antennas: H-plane sectoral horn where the horn is flared along 'a' side of the waveguide, E-plane sectoral horn, where the horn is falred along 'b' side of the waveguide, and the pyramidal horn the horn is flared along along both sides of the waveguide.

A rectangular waveguide is a conducting cylinder of rectangular cross section used to guide the propagation of waves. Rectangular waveguide is commonly used for the transport of radio frequency signals at frequencies in the SHF band (3–30 GHz) and higher. The fields in a rectangular waveguide consist of a number of propagating modes which depends on the electrical dimensions of the waveguide. These modes are broadly classified as either transverse magnetic (TM) or transverse electric (TE). In this section, we consider the TM modes.

The walls of the waveguide are located at $x = 0$, $x = a$, $y = 0$, and $y = b$; thus, the cross-sectional dimensions of the waveguide are a and b . The interior of the waveguide is presumed to consist of a lossless material exhibiting real-valued permeability μ and real-valued permittivity ϵ , and the walls are assumed to be perfectly-conducting.

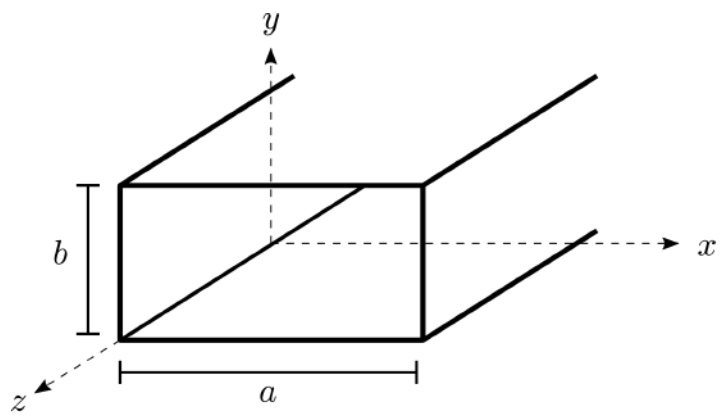

Figure 4: Geometry for analysis of fields in a rectangular waveguide

Solving the Helmholtz equation and using the boundary conditions we get the non-zero field components as:

$$H_z(x) = H_0 \cos k_c x$$
$$H_x(x) = H_1 \sin k_c x$$
$$E_y(x) = E_0 \sin k_c x$$

The boundary conditions require that no tangential electric field is present at the wall sides.

$$E_y(a) = E_0 \sin k_c a \Rightarrow k_c a = n\pi$$

The cutoff frequency for the TE_{n0} modes are:

$$\omega_{\mathrm{d}} = \frac{cn\pi}{a}, f_c = \frac{cn}{2a}, \lambda_c = \frac{2a}{n}$$

Using the boundary conditions for the TE_{nm} modes, the cutoff wavenumbers of these modes is given as $k_c = \sqrt{k_x^2 + k_y^2}$:

$$k_c = \sqrt{\left(\frac{n\pi}{a}\right)^2 + \left(\frac{m\pi}{b}\right)^2}$$

The cutoff frequencies f_{nm} and λ_{nm} are

$$f_{nm} = c\sqrt{\left(\frac{n}{2a}\right)^2 + \left(\frac{m}{2b}\right)^2}$$
$$\lambda_{nm} = \frac{1}{\sqrt{\left(\frac{n}{2a}\right)^2 + \left(\frac{m}{2b}\right)^2}}$$

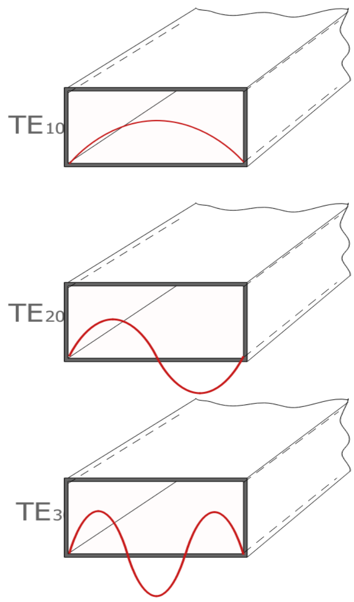

Figure 5: Transverse Electric modes in a waveguide.

The longitudinal electric fields are:

$$E_z(x, y) = E_0 \sin k_x x \sin k_y$$

Similary for the TM modes in a waveguide is shown as following:

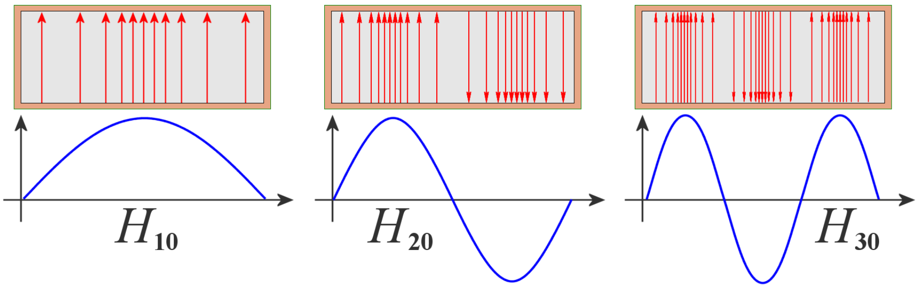

Figure 6: H modes in a waveguide.

2.3 Horn

If we use an ordinary open-ended waveguide, the sudden end of waveguide walls cause impedance change causing a part of the wave energy to be reflected back into the waveguide. The horn is a transitional structure, which matches the impedance of the waveguide to that of free space helping waves to radiate easily into space. There are three types of horn antennas: Hplane sectoral horn (the a side is flared), E-plane sectoral horn (the b side is flared), and the pyramidal horn in which both a and b faces are flared. The pyramidal horn is a widely used antenna. To study the geometry of pyramidal horn let's take A and B as the sides of the pyramidal horn. We get the following relationships from the geometry of the horn:

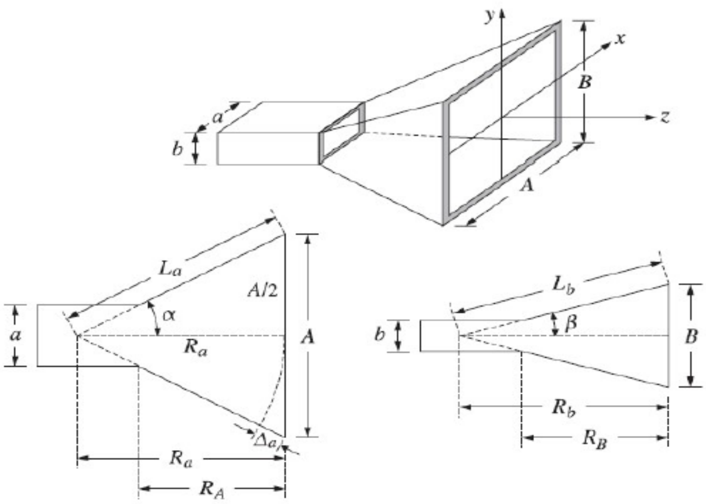

Figure 7: Geometry of a pyramidal Horn Antenna. Image Credit: Electromagnetic waves and Antennas

$$
\begin{aligned}
&\mathrm{R}_a = \frac{A}{A-a}R_A, R_b = \frac{B}{B-b}R_B \\
&L_a^2 = R_a^2 + A^2/4, L_b^2 = R_b^2 + B^2/4 \\
&\tan(\alpha) = \frac{A}{2R_a}, \tan(\beta) = \frac{B}{2R_b} \\
&\Delta_a = \frac{A^2}{8R_a}, \Delta_b = \frac{B^2}{8R_b}
\end{aligned}
$$

here R_a and R_b give the perpendicular distance from the plane of the waveguide opening to the plane of the horn. Hence, they must be equal $\mathrm{R}_a = \mathrm{R}_b$, and Δ_a and Δ_b represent the maximum deviation of the radial distance from plane of the horn[1].For any distance x along A and y along B the deviation of the radial distance is;

$$
\Delta_a(x) = \frac{x^2}{2R_a}, \Delta_b(y) = \frac{y^2}{2R_b}
$$

$\mathrm{k}\Delta_a(x)$ and $\mathrm{k}\Delta_b(y)$ are the relative phase differences at the point (x, y) on the aperture of the horn relative to the center of the aperture. We get the aperture electric field as:

$$
E_y(x, y) = E_0 \cos\left(\frac{\pi x}{A}\right) e^{-ik\Delta_a(x)} e^{-ik\Delta_b(y)}
$$

The tangential aperture magnetic field is specified as - $H_x(x, y) = -E_y(x, y)/\eta$

3 Basic antenna theory

3.1 Field Regions

The field surrounding an antenna are divide into 3 primary regions.[2] - Reactive Near Fields - Radiative Near Fields - Far Field 2.3.1 Reactive Near Fields In the immediate vicinity of the antenna, we have the reactive near field. In this region, E-fields and H-fields are out of phase by 90 degrees to each other. The boundary of this region is given by

$$
R < 0.62\sqrt{\frac{D^3}{\lambda}}
$$

3.1.1 Far Fields

The far field is the region far from the antenna.The further away from the antenna the observation point is, the antenna looks like a point source. In this region, the radiation pattern does not change shape with distance(R). However, the Electric and Magnetic fields die off as $\frac{1}{R}$, and thus the power dies off a $\frac{1}{R^2}$. The far field has no radial component. The following are to be satisfied by the far field region.

$$R > \frac{2D^2}{\lambda}$$
$$R >> D$$
$$R >> \lambda$$

The first and second equation above ensure that the power radiated in a given direction from distinct parts of the antenna are approximately parallel

3.1.2 Radiative Near Field Region

This is the region between the near and far fields. The shape of radiation pattern may vary appreciably with distance. The boundary is given by:

$$0.62\sqrt{\frac{D^3}{\lambda}} < R < \frac{2D^2}{\lambda}$$

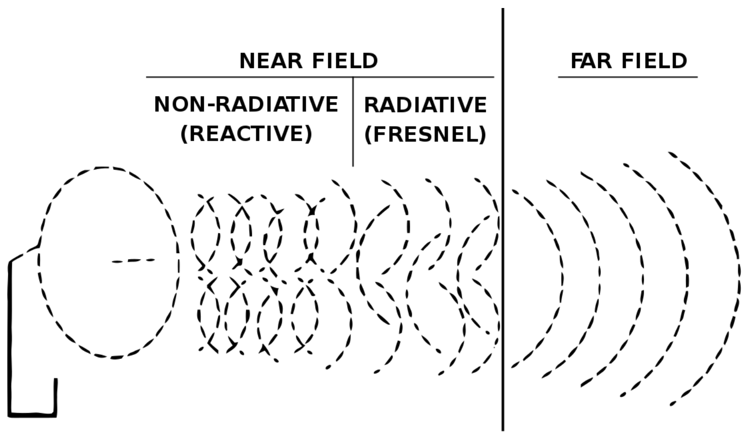

Figure 8: Field regions

3.2 Impedance

Antenna Impedance is related to the electric and magnetic fields and is defined at the terminal point of the antenna system as the ratio of voltage or current across the particular terminal. The impedance of free space in vacuum is:

$$Z = \sqrt{\frac{\mu_o}{\epsilon_o}} = 377\Omega \tag{4}$$

3.3 Directivity

Directivity gives us a measure of how directional the radiation pattern of the antenna is. The directive gain of the antenna in a given direction specified by (θ, ϕ) is the radiation intensity normalised by the isotropic intensity of the antenna. This can be written as [1]:

$$D(\theta, \phi) = \frac{U(\theta, \phi)}{U_I} = \frac{U(\theta, \phi)}{P_{\mathrm{rad}}/4\pi} = \frac{4\pi}{P_{\mathrm{rad}}}\frac{dP}{d\Omega}$$

The directive gain of an antenna gives us its ability to direct its power in a specific direction. The directivity of the antenna is defined as the maximum value of directive gain D_{max}:

$$D_{max} = \frac{U_{max}}{U_I} \tag{5}$$

3.4 Gain

Antenna gain calculates how much power is transmitted in the maximum directivity direction to that of an isotropic source. This value is usually calculated in terms of decibels (dB). Power gain is the radiation intensity normalised by the total power P_T accepted by the antenna terminals.

$$G(\theta, \phi) = \frac{U(\theta, \phi)}{P_T/4\pi}$$

The definition of power gain does not include reflection losses which can arise from the improper matching of the transmission line to the antenna input impedance. Hence we calculate the efficiency factor for this which is defined as:

$$\epsilon = \frac{p_{\mathrm{rad}}}{P_T}$$

The total amount of transmitted power in TE_{10} mode is proportional to the cross-sectional area of the guide, *ab*.

3.5 Beam width

Beam width is the aperture angle from where most of the power is radiated. To understand beam width fully let's first get the gist of half power beam width and first null beam width:

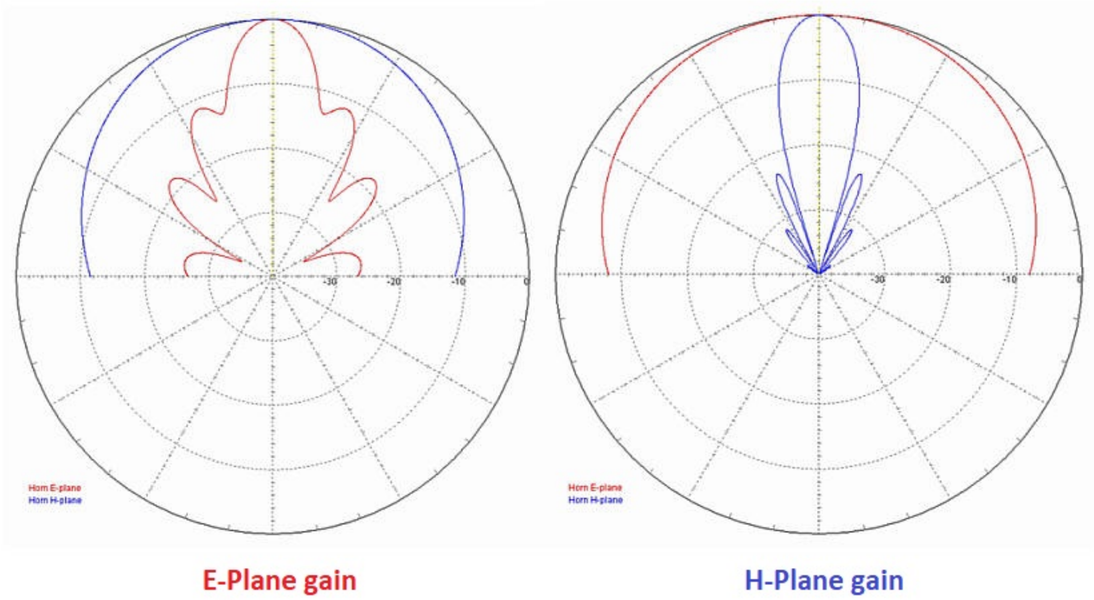

Figure 9: H-plane and E-plane gains of a horn antenna.

3.5.1 Half power beam width (HPBW)

The half power beam width is defined as the angular separation, in which the magnitude of the radiation pattern decreases by 50% (or -3dB) from the peak of the main beam.

Beam width is the area where most of the power is radiated, which is the peak power. Half power beam width is the angle in which relative power is more than 50% of the peak power, in the effective radiated field of the antenna.

When a line is drawn between radiation pattern's origin and the half power points on the major lobe, on both the sides, the angle between those two vectors is termed as HPBW, half power beam width.

The mathematical expression for half power beam width is :

$$\text{Half power Beam width} = 70\frac{\lambda}{D} \tag{6}$$

where λ is the wavelength and **D** is diameter. Units The unit of HPBW is radians or degrees.

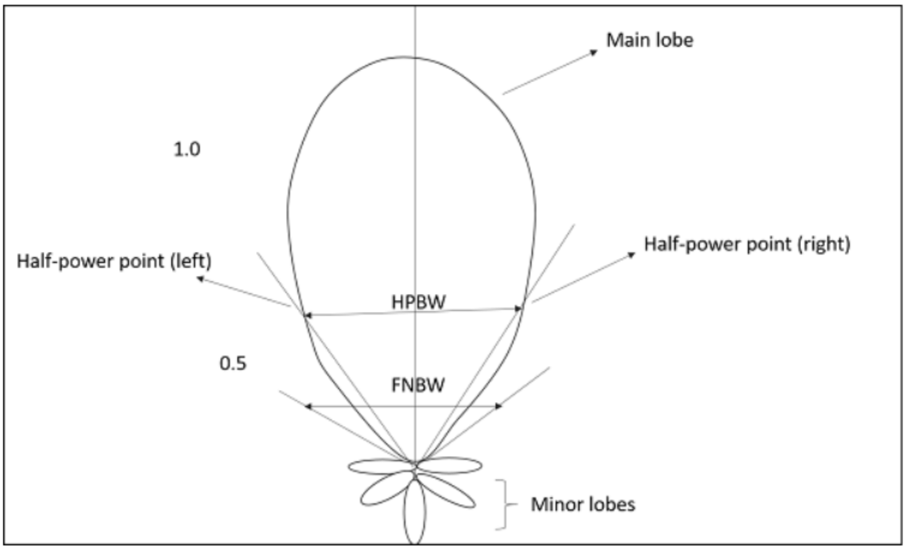

Figure 10: Polar radiation pattern with labelled beam-width points.

3.5.2 First null beam width (FNBW)

First null beam width is defined as the angular span between the first pattern nulls adjacent to the main lobe. In simple words FNBW is the angular separation, quoted away from the main beam, which is drawn between the null points of radiation pattern, on its major lobe.

The mathematical expression of First Null Beam Width is:

$FNBW = 2HPBW$

$FNBW2(70\lambda/D) = 140\lambda/D$

Where,

λ is wavelength ($\lambda = 0.3/$ frequency). **D** is Diameter.

The unit of FNBW is radians or degrees.

3.6 Effective length

Antenna Effective length is used to determine the polarization efficiency of the antenna.

It is defined as the Effective length is the ratio of the magnitude of voltage at the open terminals of the receiving antenna to the magnitude of the field strength of the incident wave front, in the same direction of antenna polarization.

When an incident wave arrives at the antenna's input terminals, this wave has some field strength, whose magnitude depends upon the antenna's polarization. This polarization should match with the magnitude of the voltage at receiver terminals.

The mathematical expression for effective length is -

$$l_e = \frac{V_{oc}}{E_i}$$

Where,

- l_e is the effective length.

- V_{oc} is open-circuit voltage.

- E_i is the field strength of the incident wave.

3.7 Effective area

Effective area(also called as effective aperture) in an Antenna design is the ratio of the received power which is available at the terminals of an Antenna to the power per unit area of the incident electromagnetic wave Effective area of an Antenna is related to the Gain of the Antenna as:

$$A_e = \frac{\lambda^2}{4\pi} G \tag{7}$$

4 Construction of horn antenna

For the construction of the antenna we have used FEKO software, which is is a computational electromagnetics software product developed by Altair Engineering.

4.1 About FEKO

FEKO is a Method of Moments (MoM) tool that can be used to calculate the radiation pattern, impedance and gain of an antenna while mounted on some defined geometry. In addition, it can calculate the isolation or mutual coupling (S12) between pairs of antennas, the near fields around an antenna and the electric currents that flow on an antenna or the surrounding structure.

4.2 Antenna dimensions

The sigma parameters are defined as ;

$$\sigma_a^2 = \frac{A^2}{2\lambda R_a}, \sigma_b^2 = \frac{B^2}{2\lambda R_b}$$

The optimum values are $\sigma_a = 1.2593$ and $\sigma_b = 1.0246$. The MABLAB/Octave library Ewa has the following functions [1]:

heff - used to calculate aperture efficiency

hgain - used to calculate H- and E-plane gains

hopt - outputs optimum horn design

hsigma - used to calculate optimum values of σ_a and σ_b

The necessary operating frequency is 1420.4MHz.

Operating wavelength $\lambda = 21.12$ cm

Waveguide cutoff frequency is taken as $f_c = 1000$MHz.

Waveguide cutoff wavelength, $\lambda_c = \frac{c}{f_c} = \frac{3\times10^8}{1\times10^9} = 30.0$ cm

Width of waveguide a $= \frac{\lambda_c}{2} = 15.0$ cm.

For the height of waveguide, 2 cases are taken.

- Due to polarization signals moving parallel to the shorter side of the waveguide should have lesser effect, hence to block these signals, for b we take $\lambda_{\text{cuto } f,b} = 2$ b $= 20.8$ cm, which gives 1441MHz as the minimum frequency that can pass in this direction [2]. For this the the $_a$ and σ_b parameters are taken as 1.2593 and 1.0246 respectively. (Obtained from function hsigma)
- Commonly used rectangular waveguides have an aspect ratio of a/b = 0.5. Fot this we get $_a$ and σ_b parameters are taken as 1.4749 and 0.7375 respectively.

Using the values calculated for a and b and the σ-parameters, we can calculate the horn aperture height and width, as well as the length of the horn using the hopt function for a fixed gain of 18 dB.The function inputs and outputs are:

$$[A, B, R, \text{err}] = \text{hopt}(G, a, b, sa, sb, N)$$

where

G = required gain in dB

a, b = waveguide sides in units of lambda

sa,sb = sigma phase parameters

A, B = horn sides

R = axial length from waveguide end to horn plane

err = design error

The dimensions of the horn antenna calculated using the hopt function is obtained for both cases as:

Table 1: Horn 1 Dimensions

Section	Description	Dimension (m)
Waveguide	Width (a)	0.1500
	Height (b)	0.1040
	Length (l)	0.6000
Pyramidal Horn	Side (A)	0.7658
	Side (B)	0.5975
	Length (L)	0.7039

Table 2: Horn 2 Dimensions

Section	Description	Dimension (m)
Waveguide	Width (a)	0.1500
	Height (b)	0.0750
	Length (1)	0.6000
Pyramidal Horn	Side (A)	0.9718
	Side (B)	0.4859
	Length (L)	0.8692

The conversion of the received signal the antenna is then processed through the following steps:

5 Results and discussion

Two pyramidal horn antenna were designed using FEKO and the parameters for the design were calculated using FEKO. The aperture efficiency for the horn-1 was 49.78% and the aperture efficiency for horn-2 was 42.48 % which was calculated using the function heff.

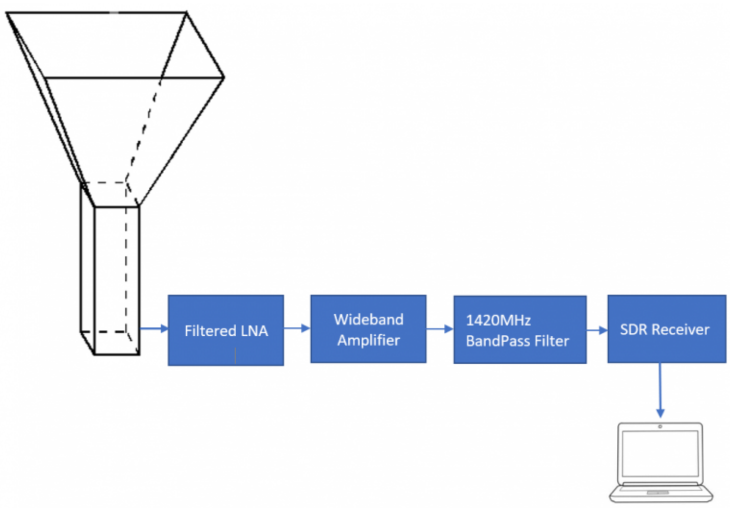

Figure 11: Image of components needed for processing of signal.

5.1 Horn 1 observations

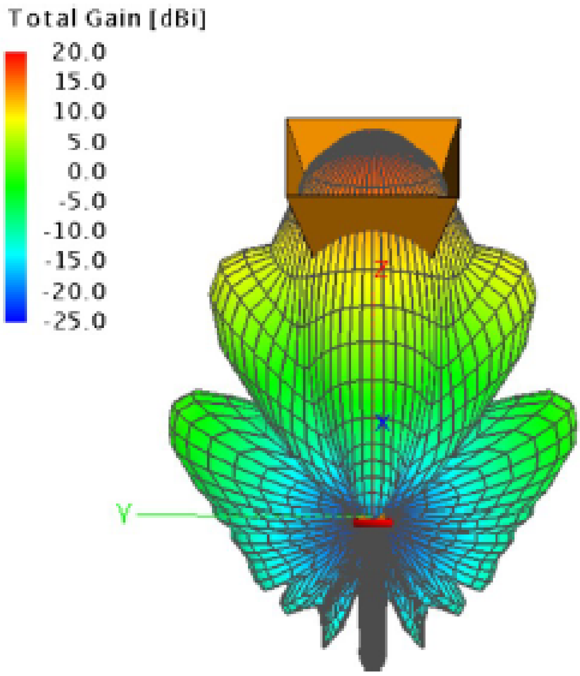

Figure 12: Far field

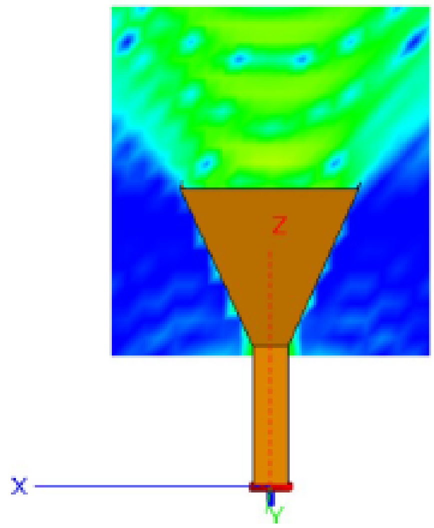

Figure 13: Near fields at the aperture

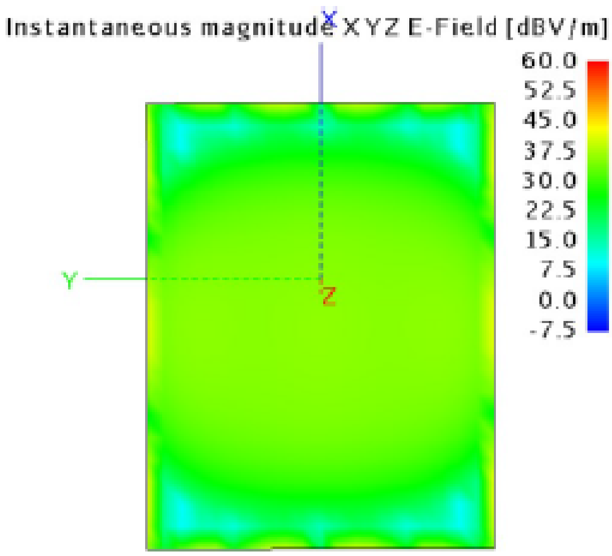

Figure 14: Near fields perpendicular to the aperture

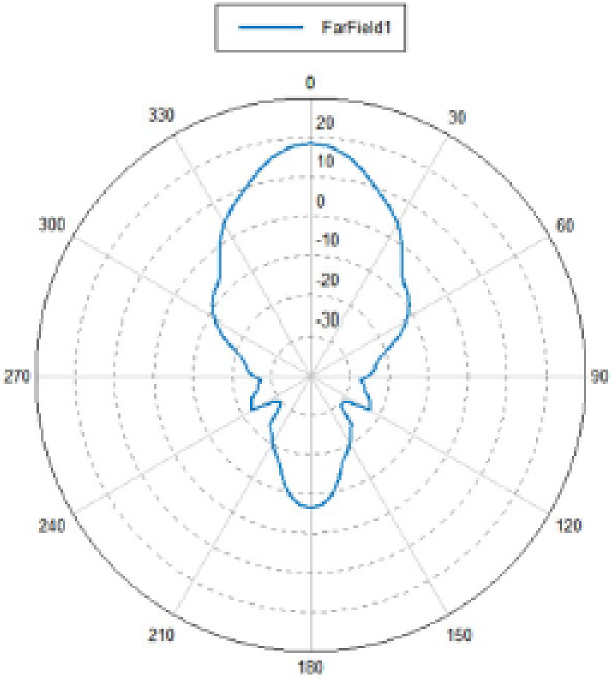

Figure 15: Far field polar radiation pattern

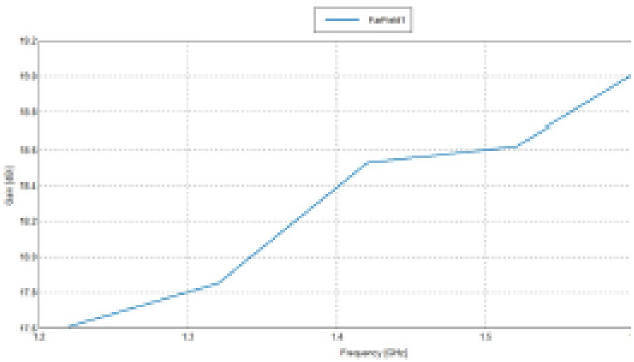

Figure 16: Frequency vs Gain

5.2 Horn 2 observations

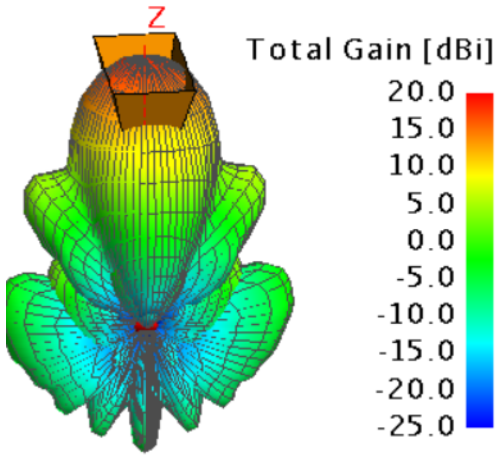

Figure 17: Far field

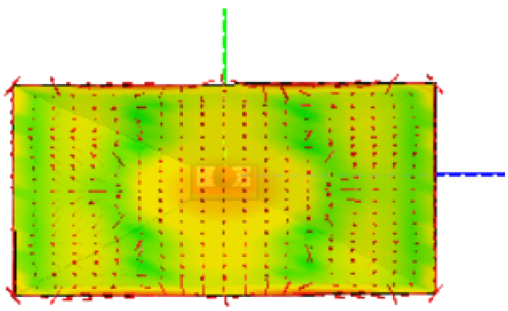

Figure 18: Near fields at the aperture

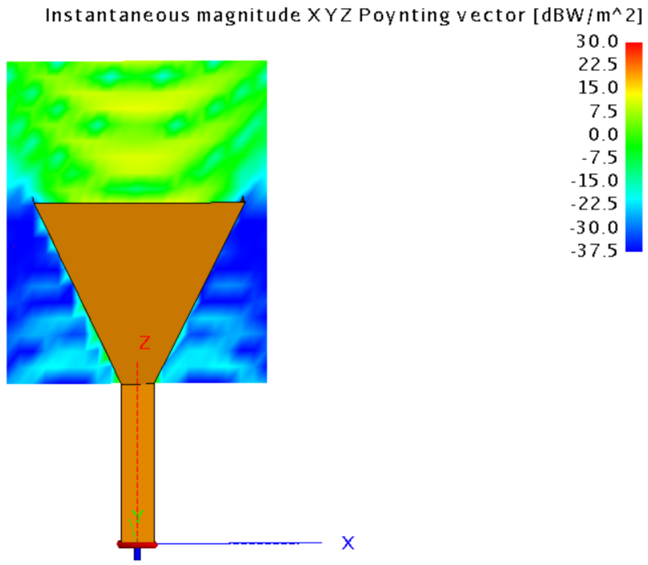

Figure 19: Near fields perpendicular to the aperture

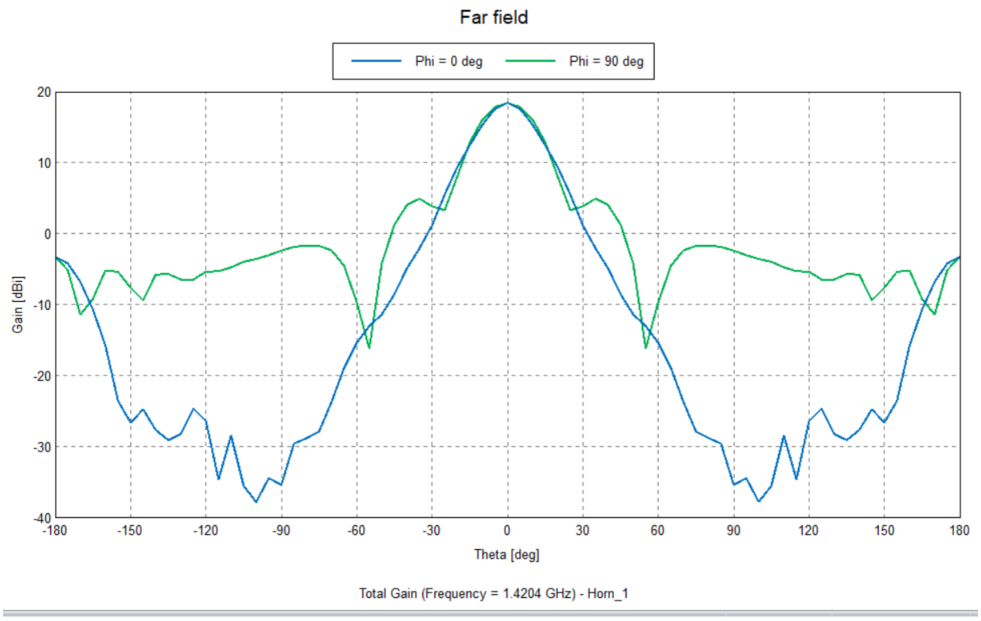

Figure 20: Cartesian plot of radiation pattern for different phase $\theta = 0\,\mathrm{deg}$ & $\theta = 90\,\mathrm{deg}$

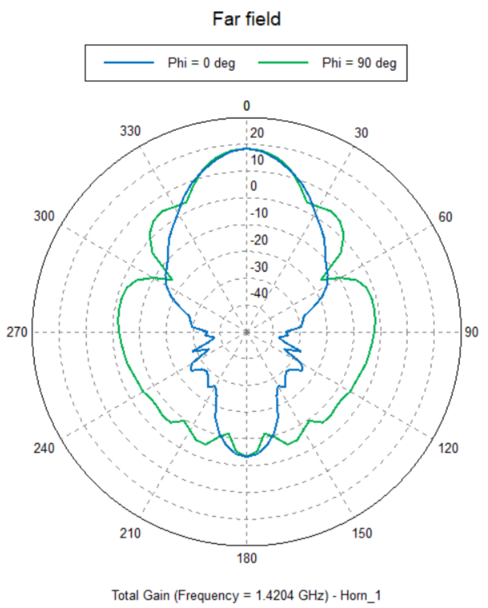

Figure 21: Far field polar radiation pattern

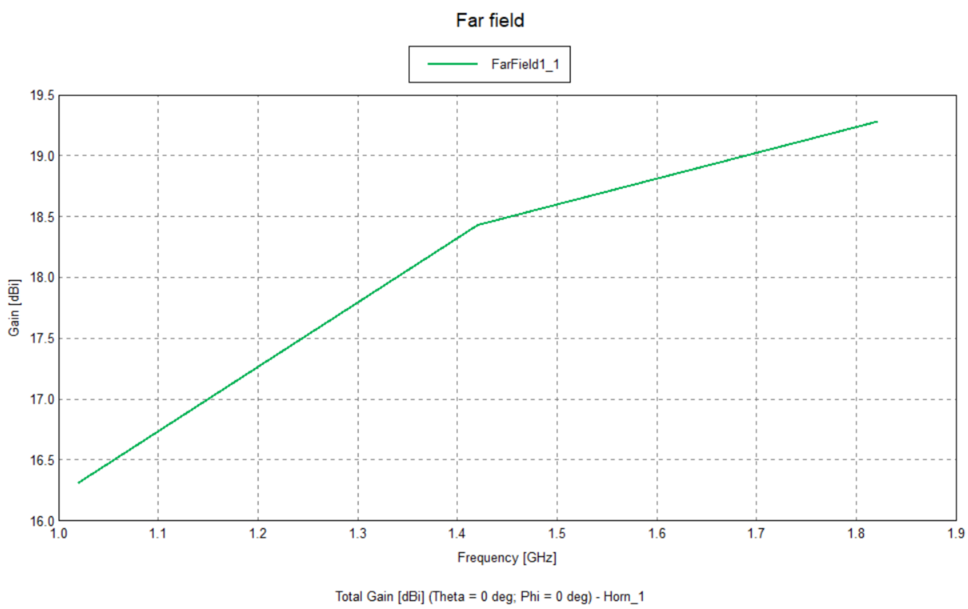

Figure 22: Gain at different frequencies

6 Conclusion

In this project we calculated the parameters and simulated the antenna properties like gain and directivity using Octave(MATLAB) and FEKO. Important parameters such as directivity, field pattern, bandwidth upon which the design depends upon were studied. The antennas designed were for the frequency of 1420.4MHz and a gain of 18dB. Cut-off was taken to be 1000MHz for both the cases. We realise that for any antenna ease of fabrication of the antenna is an important parameter. In this project two antennas were constructed based on two approaches and it was observed that taking $b = a/2$ resulted in a larger antenna for the same gain making fabrication of the antenna more difficult. So we understand that taking the a/b ratio as 2 is able to give us the same gain keeping the size of antenna small.

7 references

- Designing a horn antenna to probe the Milky way rotation curve using the 21-cm line of neutral hydrogen
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