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Antenna trainer experiments and observing 21 cm H_2 line using appropriate antenna (Before Midsem)

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Abstract

Antennas are devices used to transmit or receive signals. Starting from a TV remote to detecting signals from outer space, they play a significant role in today's communication system. Antennas can be classified in terms of sizes and shapes. Different types of antennas are built on the basis of different parameters in order to satisfy different practical purposes. Some of these parameters are Bandwidth, Directivity, Gain etc. In the first part of the experiment, these are studied and discussed in the report. The other objective of the experiment was to design an appropriate antenna and observe the 21 cm H_2 line. An antenna of high directivity, high gain and low bandwidth is required for that purpose. Although Horn antenna is the most appropriate and cost-effective for the purpose, possibility of making other kind of antenna for the same purpose is also explored in the report. Finally, two different simulations of Dipole and Horn antenna have been performed in the antenna simulating software FEKO. The field patterns have been generated and attached in the report.

Contents

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1 Objectives

1. To learn about different types of antennas and their uses
2. To learn different parameters of an antenna
3. To design an efficient antenna to observe the 21 cm H_2 line

2 Introduction

An antenna is defined as the structure associated with the region of transition between a guided wave and a free space or vice-versa [1]. In simple terms, any device that can be used to transmit or receive signals in form of EM waves can be called an antenna.

As per definition, an antenna can be as small as an open-ended wire to an array of large devices, spanning over an area of few kilometers. Some specific types of antennas are **Wire Antennas, Travelling Wave Antennas, Aperture Antennas** etc. Some examples of popular antennas are **Dipole antenna, Monopole antenna, Loop antenna** as wire antenna; **Yagi-Uda** as travelling wave antenna; **Telescopes and Horn antenna** as aperture antenna; **Dish Antenna** as parabolic reflector antenna etc.

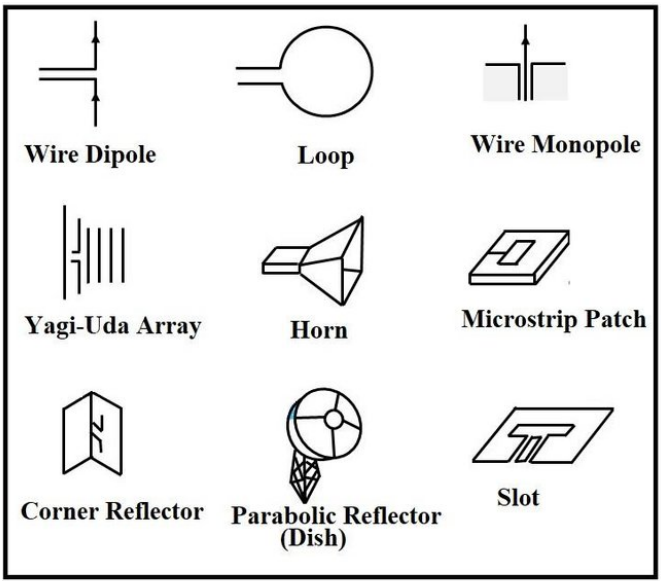

Figure 1: Different types of Antenna. Courtesy: *researchgate*

To satisfy practical purposes, an antenna is designed on the basis of different parameters. For example, to receive signals in mobile phones, we would need an antenna that can receive from any direction. In contrast of that, for applications in astronomy, we can specify the direction and an antenna that can work best in that particular direction would be preferred. The frequency and wavelength of our interest is another interesting factor. These parameters are discussed in the next section.

3 Basic Antenna Parameters

3.1 Bandwidth

Bandwidth of an antenna is the frequency range over which an antenna operates. For most antennas, the lower cut-off can be set by specifying the dimension of the antenna (this is discussed later with the example of dipole antenna and horn antenna). If the frequency of the input wave (ω) is less than the cutoff (ω_c), then the wave will attenuate exponentially along the guide direction. The higher cutoff need not to be set differently, it can be calculated mathematically (which is also shown later).

3.2 Field Pattern

Field pattern is the variation of power radiation as a function of direction. Some of the common types of radiation pattern are **Isotropic Radiation, Omni-directional Radiation and Directional Radiation**.

- If the radiation is equal in every direction, then the pattern will look like a sphere of equal potential at every point. This can be theoretically assumed as the radiation pattern of a point source, which is not connected to any wire or anything, but radiates power equally in all direction. Practically it is never possible to make such an antenna.

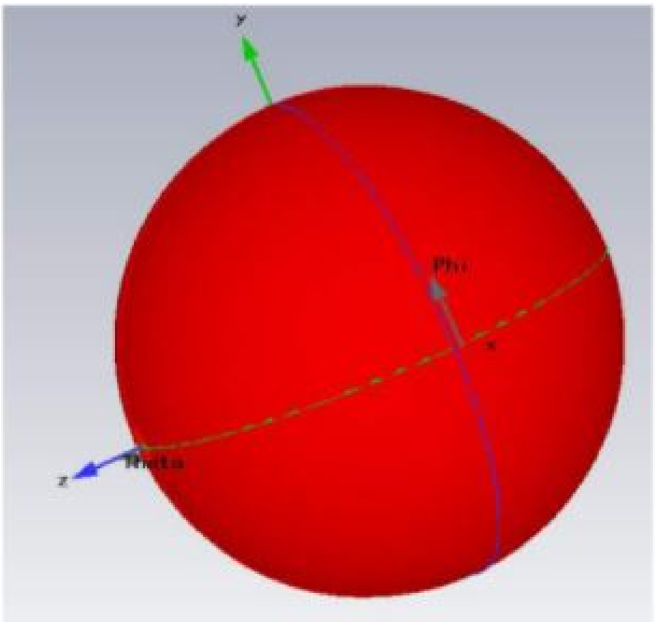

Figure 2: Isotropic Field Pattern, Courtesy: [2]

- In practical cases, the closest we can reach to isotropic field pattern is the omni-directional pattern. In this case, if we take one coordinate of a 3-dimensional coordinate system constant and measure the radiation as a function of rest of the two, then it remains constant. For example, in the image below, the radiation varies only with z direction. It remains constant with variation in θ or ϕ.

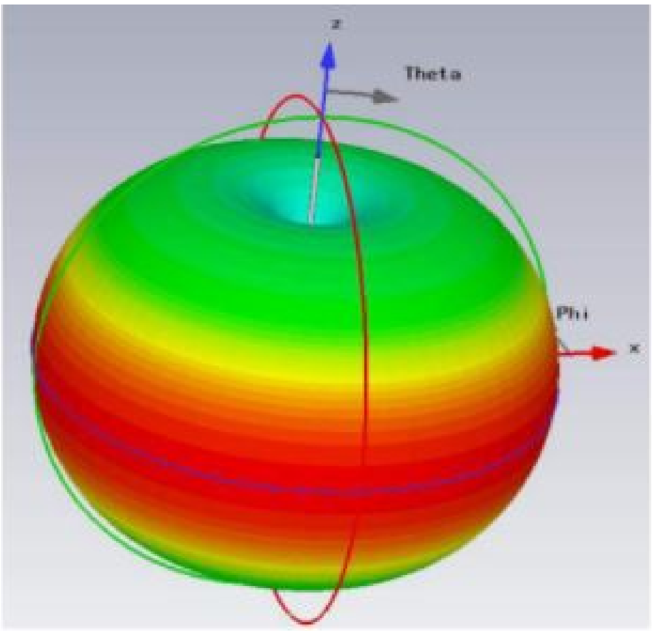

Figure 3: Omni-directional Field Pattern of a Dipole Antenna, Courtesy: [2]

- In most cases we observe a directional pattern in the field. The antenna radiates with maximum intensity towards a particular direction.

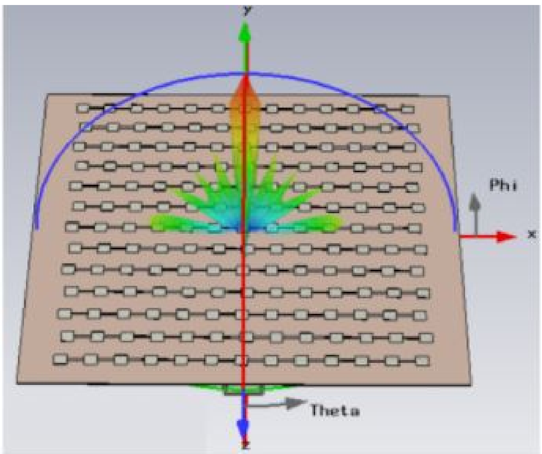

Figure 4: Directional Field Pattern, Courtesy: [2]

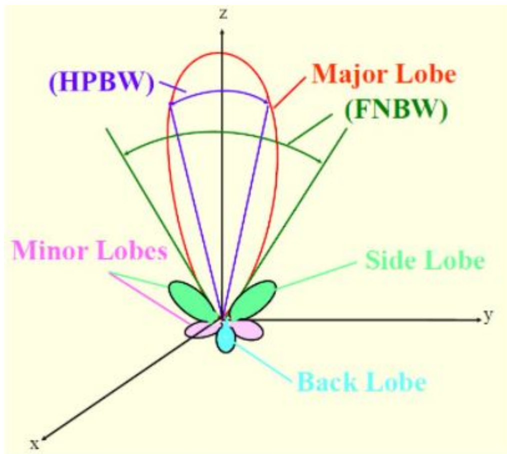

Figure 5: A typical schematic of directional field pattern

Figure 5 is a generic image of directional pattern. The lobe in the direction of maximum intensity is called the major lobe, while all other lobes are called minor lobes. The lobe in the exact opposite direction of major lobe is called back lobe. Other lobes are called side-lobes. HPBW and FNBW in the figure is discussed in next section.

3.3 Beam-width

- **HPBW:** Half Power Beam Width (HPBW) is the angular separation in which magnitude of the radiation is decreased by 50% or 3 dB from the peak intensity of the major lobe. The peak intensity is measured near the origin to the direction of major lobe [3].

- **FNBW:** Full Null Beam Width (HPBW) is the angular span between the first nulls adjacent to the main lobes. In practical cases, the side lobes are difficult to differentiate from the major lobe near origin. So, calculating FNBW from field pattern is difficult.

3.4 Field Regions

The field region can be divided into three different regions.

- **Reactive Near Field:** The immediate vicinity of the antenna is dominated by reactive field. Here, the electric and magnetic fields are orthogonal, but in phase. The boundary is given by the following equation,

$$R < 0.62\sqrt{\frac{D^3}{\lambda}} \tag{1}$$

- **Radiating Near Field:** This region is also called the Fresnel region. In this region, radiating fields begin to emerge. The boundary is given by,

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

- **Far Field:** In this region, the shape of radiation pattern does not change with increasing distance, only the intensity decreases. The power density decreases with square of distance. The electric and magnetic fields are inversely proportional to the distance and the region is dominated by radiating fields [2].

$$\frac{2D^2}{\lambda} < R, R >> \lambda, R >> D \tag{3}$$

3.5 Directivity

Directivity of an antenna is a measure of how directional the antenna is at a particular direction. Usually by directivity, we mean the peak directivity at the direction of the major lobe. It is defined by the ratio of maximum radiation intensity to the average intensity [1] [3].

$$D(\theta, \phi) = \frac{U(\theta, \phi)}{U_I} \tag{4}$$

If we can substitute the antenna with an imaginary antenna of isotropic field and same efficiency, then the intensity of the antenna at the direction of major lobe of the antenna of our intensity is represented by the U_I term.

3.6 Efficiency

Efficiency of an antenna is defined by the ratio of power radiated by the antenna to the power delivered to the antenna [1]. Efficiency of an antenna is dimensionless and the value lies in the range $0 \leq \mathrm{k} \leq 1$.

3.7 Gain

Antenna gain is the measurement of the power that is transmitted in the direction of peak radiation to the power that is given to the antenna. It can be calculated by multiplying the directivity with the efficiency of an antenna [1].

$$G = k \times D \tag{5}$$

3.8 Standing Wave Ratio

Standing Wave Ratio (SWR) or Voltage SWR (VSWR) is another measure of how efficiently power is transmitted from a source into a load through a transmission line. Mathematically, it can be given by the maximum to minimum voltage ratio of the signal on the transmission line. It can also be given in terms of reflection coefficient (Γ).

A wave experiences partial transmittance and partial reflectance when the medium through which it travels suddenly changes. The change of medium is defined in terms of impedance mismatch. The reflection coefficient determines the ratio of the reflected wave amplitude to the incident wave amplitude. If the load impedance and source impedance are given by Z_L and Z_0 respectively, then

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{6}$$

VSWR is given by,

$$VSWR = \frac{V_{max}}{V_{min}} = \frac{1+\Gamma}{1-\Gamma} \tag{7}$$

For ideal matching (no loss due to impedance mismatch), VSWR value should be 1 and Γ should be 0. However, it is never possible practically to meet that value. An antenna of VSWR 1.4 to 2 is considered best for data transmission requirements [4] [5].

4 Dipole Antenna

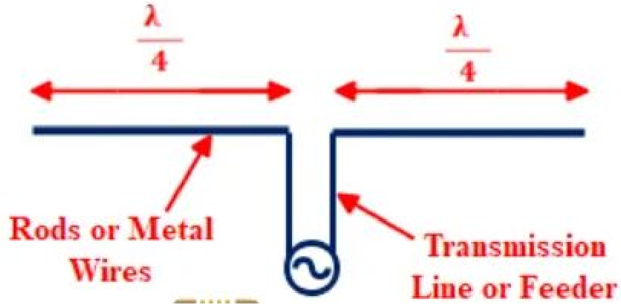

Figure 6: $\lambda/2$ dipole antenna

A dipole antenna consists of two conductive elements which are connected to the feeder or transmission line [3]. It is one of the most commonly used antennas. Based on its length and operating wavelength, it can be of different types. Two most common types are, **Short Dipole** and **Half-wave Dipole** Antennas.

1. **Short Dipole:** Length of a short dipole can vary from $\lambda/50$ to $\lambda/10$, where λ is the operating wavelength. Typical directivity of Short Dipole is 1.5 [2].
2. **Half-wave Dipole:** The length and typical directivity is $\lambda/2$ and 1.643 respectively. It is the most common type of dipole antenna which is used in electronic devices as receivers [2].

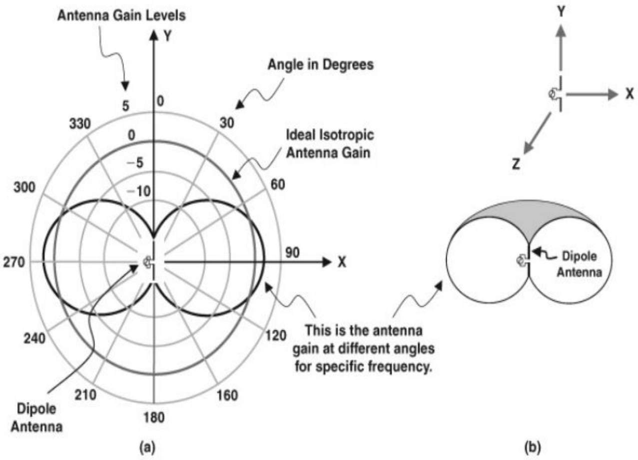

Figure 7: Cross-section of the radiation pattern of a dipole antenna

A half wave dipole is later simulated in FEKO, which is shown and discussed in later section.

5 21 cm line of Hydrogen

The collisions in gas clouds keep neutral hydrogen in an excited state. In the excited state, the nucleus and electron have parallel spins. However, the natural tendency is to get to a lower energy state level. Neutral Hydrogen goes to the lower state by emitting a photon. This is same as a hyper-fine splitting of 1s where two energy states are formed with a transition gap of 5.874 eV. This corresponds to the frequency around 1420 MHz and wavelength of 21 cm.

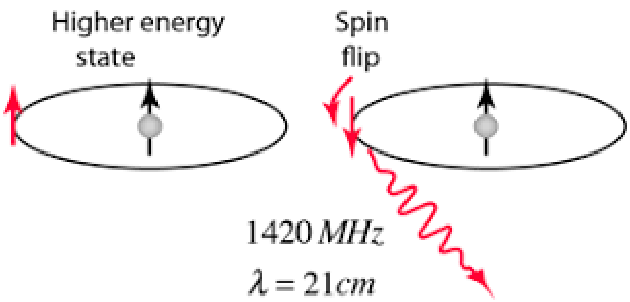

Figure 8: Spin flip in hydrogen

This line is extremely important for astronomy. Natural hydrogen is the most abundant element in the universe. Mapping the 21-cm hydrogen line essentially means mapping of the universe. Also the wavelength of the emission line falls in the radio range, so it doesn't get scattered easily by dust, as the wavelength is much larger than the size of the dust particles. Thus, it is a very useful method to map the universe. This emission can also be used to measure galaxy rotation curves and red-shift of a source.

5.1 Appropriate Antenna to observe the line

To observe the 21 cm line, we need an antenna that has high directivity and gain. Also, the cutoff of the antenna should be well-defined and the bandwidth should be in a small range. Horn antennas have a high directivity and low bandwidth. They are the most useful for this purpose. However, other types of antennas, such as dish antenna, can also be used. The possibility of using dish antenna is discussed later.

6 Horn Antenna

Horn antennas consist of a waveguide and a flare. While waveguides are part of lots of other types of antennas, the pyramidal flare is what makes horn antennas unique. Horn antennas usually use a dipole antenna as a transmitter or receiver. They are mostly used in the ultra high frequency range (above 300 MHz).

Figure 9: A horn antenna

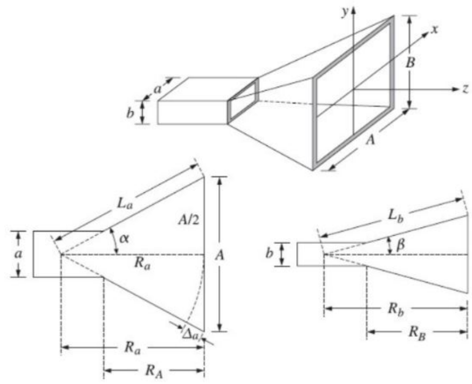

Figure 10: Dimension of a horn antenna

6.1 Waveguide Modes

waveguide is a hollow metallic tube with uniform cross section. It allows multiple successive reflections from the inner walls. The solutions of the Maxwell equations give the propagation of Electric and Magnetic fields along guiding direction in different modes. If we take z as the guiding direction, then z is the longitudinal direction and x-y is the transverse plane. Now,

$$E(x,y,z,t) = E(x,y)e^{i\omega t - i\beta z} B(x,y,z,t) = B(x,y)e^{i\omega t - i\beta z} \tag{8}$$

β is called the propagation wavenumber along the guide direction. The phasor amplitude equation can be split into two longitudinal and transverse directions [3].

$$E(x,y) = E_x(x,y)\hat{x} + E_y(x,y)\hat{y} + E_z(x,y)\hat{z} \equiv E_T(x,y) + E_z(x,y)\hat{z} \tag{9}$$

Depending upon which of the components are kept zero, the waveguide can be operated in different modes:

1. **TEM Mode:** $E_z = B_z = 0$
2. **TE Mode:** $E_z = 0; B_z \neq 0$
3. **TM Mode:** $E_z \neq 0; B_z = 0$
4. **Hybrid Mode:** $E_z \neq 0; B_z \neq 0$

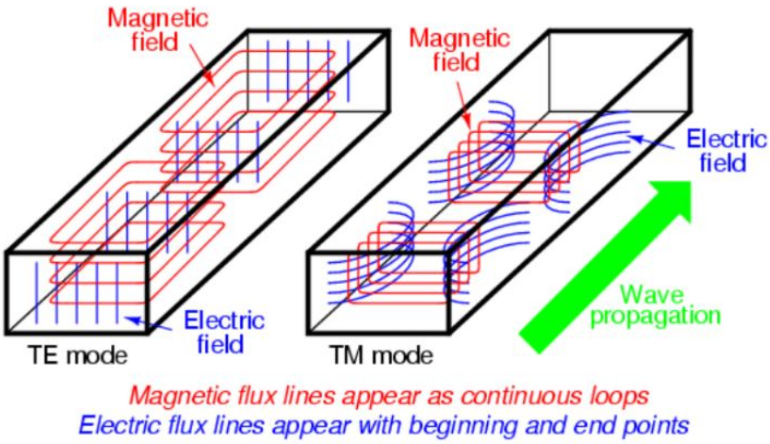

Figure 11: Electric and Magnetic field propagation in TE and TM modes

In horn antenna, rectangular waveguides are used. Solving Helmholtz equation with boundary conditions give us the cutoff wavenumber and consequently the cutoff frequency. Now, in rectangular waveguide, TEM mode is not allowed as it is a single conductor system. The most commonly used mode is the TE_{mn} mode. The general formula for cutoff in this mode is given by,

$$k_c = \sqrt{(\frac{n\pi}{a})^2 + (\frac{m\pi}{b})^2} \tag{10}$$

$$f_{nm} = c\sqrt{(\frac{n}{2a})^2 + (\frac{m}{2b})^2} \tag{11}$$

Now, TE_{10} is called the dominant mode as it has the lowest cutoff frequency. The cutoff is given by,

$$(f_c)_{10} = \frac{c}{2a} \tag{12}$$

The TM_{00}, TM_{10} and TM_{01} are non-propagating modes in rectangular waveguide as E_z becomes 0 along longitudinal direction [3].

6.2 Discussion on dimension of Waveguide and Flare

- To set the dimension of the horn antenna, first we need to set the cutoffs. As we are going to use the TE_{10} mode, the lower cutoff is already set by the equation 12. However, it is recommended to set the lower cutoff in such a way that the operating frequency is at least 1.25 times the cutoff. The reason being, the highest gain does not start at the cutoff. Plotting the cutoff and gain gives a positive slope first, then it becomes constant at ∼1.25 times the cutoff.

- For the higher cutoff, the TE mode becomes TE_{20}. Putting the values in equation 11, we get the upper cutoff as 2 times the lower cutoff. However, the gain starts to die off from 1.9 times lower cutoff.

- Now, as our interest is to observe 1400 MHz line, we set the cutoff at 1000 MHz, which corresponds to a wavelength of 30 cm. The longer side of the rectangular waveguide is set as 15 cm ($\lambda_c/2$).

- For the smaller side, there are two methods. First method is to take the half of the longer side ($\lambda_c/4$). However, that leads to the length to be $\sim$ 7.5 cm, which is less than half of 21 cm, wavelength of our interest. Some papers suggest that it stops the wave propagation along the smaller side of the waveguide. They suggest to use $\lambda/2$ directly as the length of smaller side.

- The length of waveguide should be an integer multiple of the cutoff wavelength.

- For the dimension of the flare, we use the formulas given in [**?**] and use the MATLAB/ Octave library Ewa to get the values.

- The dipole, which is the wave transmitter or receiver, is set at a distance $\lambda_w/4$ from the closed end of the waveguide, where λ_g is the guide wavelength. Guide wavelength is associated with the phase velocity and group velocity of the guided wave. They are related by,

  $$v_p \times v_g = c^2 \tag{13}$$

  The guide wavelength is given by,

  $$\lambda_w = \frac{c}{\nu}[1-(\frac{\nu_c}{\nu})^2]^{-1/2} \tag{14}$$

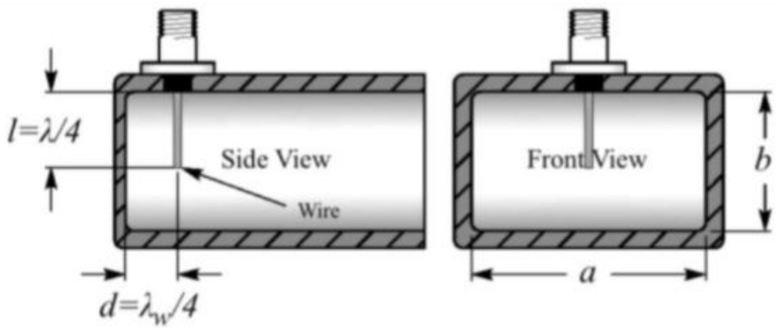

Figure 12: Placing of dipole antenna inside waveguide

6.3 Processing of signal

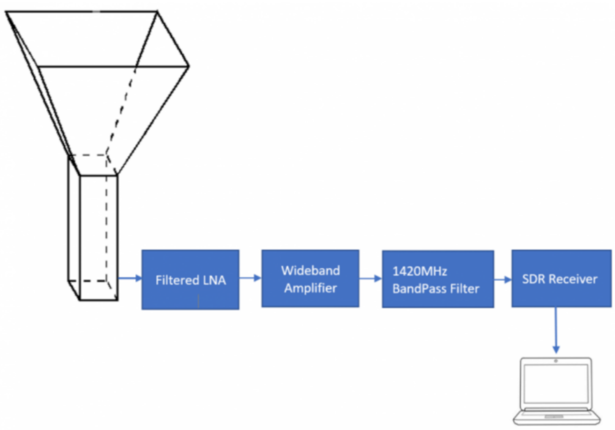

Figure 13: Processing of signal after detection

The detected analog signal is passed through a low-noise amplifier, a 1420 MHz band pass filter and a software defined radio, which converts the analog signal to digital.

7 Simulations in FEKO

We used the antenna simulation software FEKO to simulate the radiation pattern of a dipole antenna and a horn antenna. The working mechanism of FEKO [6] is discussed in Appendix 1.

7.1 Dipole Antenna

We simulate a short wave dipole antenna of 2.4 GHz frequency and l=59 mm. The field pattern is in following diagram.

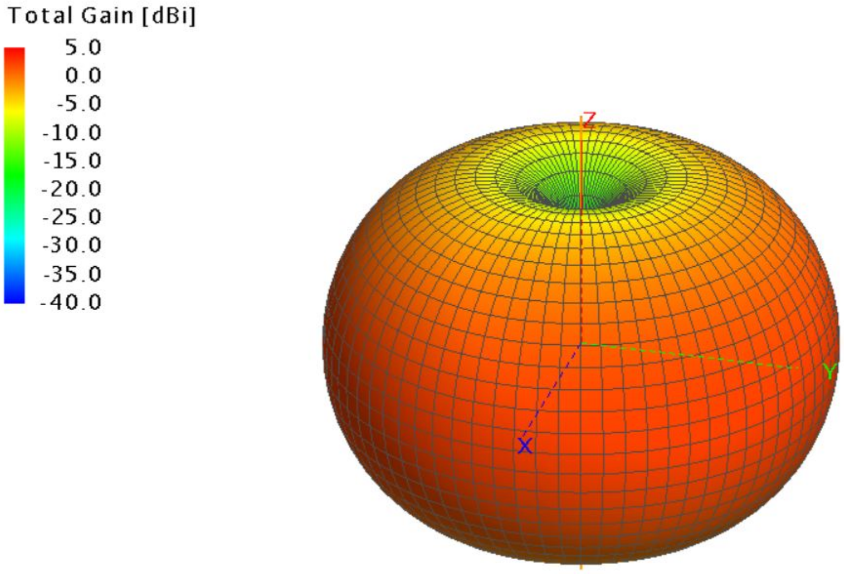

Figure 14: The gain in a 3 dimensional image

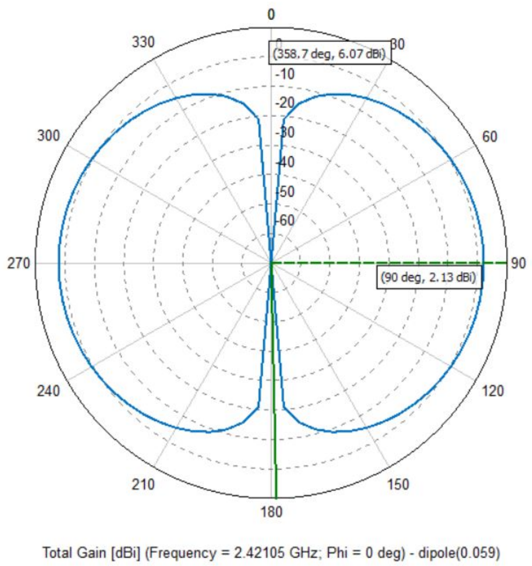

Figure 15: Gain in a polar 2D graph

7.2 Horn Antenna, Frequency= 10 GHz

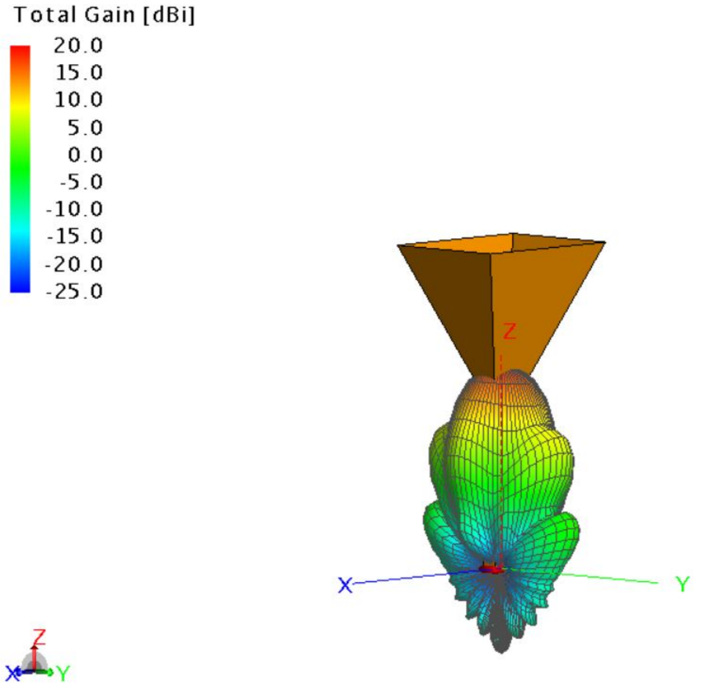

Figure 16: The gain in a 3 dimensional image

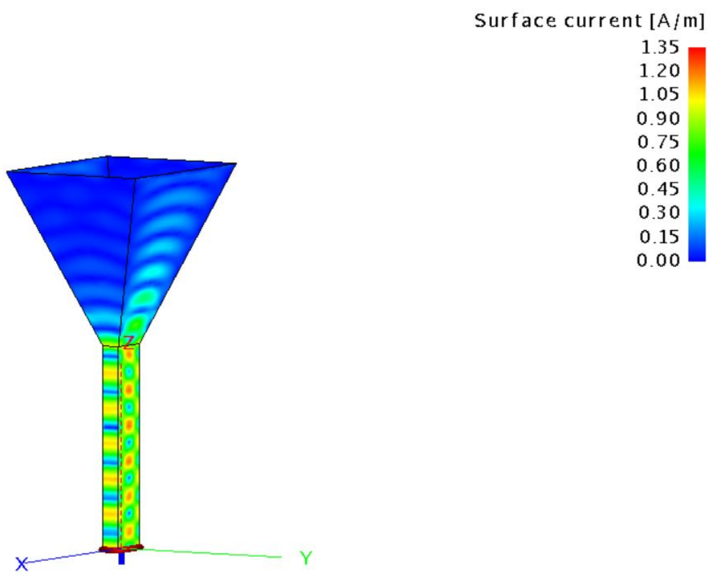

Figure 17: Surface current on the waveguide and flare

8 Future Plans

8.1 Possibility of using a dish antenna instead of horn antenna

As discussed earlier, the higher bandwidth is the main problem to use dish antenna for this purpose. However, there have been attempts to use dish antenna to observe a particular wavelength. The reports by Radio Physics Laboratory [7] and Massachusetts Institute of Technology [8] discuss the possibilities. The first one [7] talks about antennas used in IUCAA, Pune to observe the 21 cm line. Although it mentions the use of dish antenna, but it mostly talks about using a horn antenna with cylindrical waveguide. The second paper by MIT [8] mentions a dish antenna used by NASA, but the use of horn antenna is cost-effective for this purpose. An website by Canadian Centre for Experimental Radio Astronomy, Citizen Science and Radio Astronomy [9] also talks about the possibilities, however it is better to stick to horn antenna for our purpose.

8.2 Our Plan of Work

We are aiming to complete the experiment in next half of the semester. The works we are planning to do include,

- Measuring the SWR of a dipole antenna and observe the polar 2D graph of field using Scientech software.
- Observing the 21 cm Hydrogen line using Horn antennas that are already there in lab
- Working with few other antennas such as monopole, Yagi-Uda etc.
- Simulating the same using FEKO

A FEKO Software

FEKO is an antenna design and simulation software by Altair University [6]. It consists of two parts,

1. **CADFEKO:** CADFEKO allows users to design the geometry of the antenna. The dimension, parameters, numerical analysis techniques are specified by user in this step.

2. **POSTFEKO:** POSTFEKO shows us the results in interactive user interface. It can either be on a 2D graph or in a 3D plot as combinations of geometry.
   The techniques used by FEKO are called Method of Moments, Multilevel Fast Multipole Method, the Finite Element Method, Uniform Theory of Diffraction, Geometrical Optics and Physical optics. FEKO solves electrically large problems with appropriate assumptions and accelaration techniques [6].

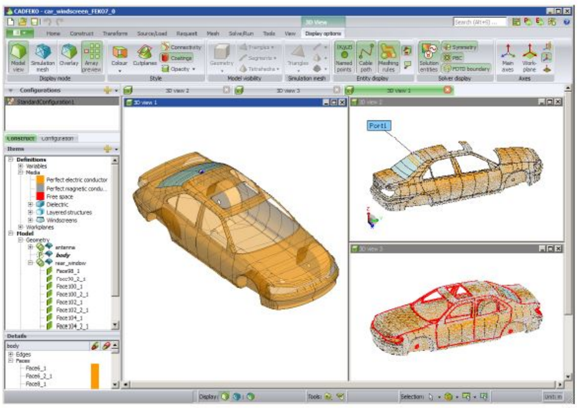

Figure 18: CADFEKO

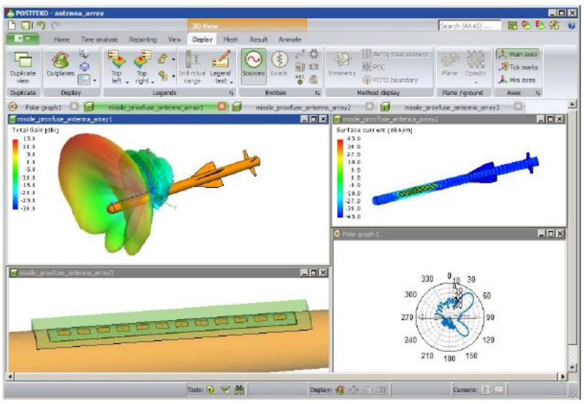

Figure 19: POSTFEKO

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