Empirical and Experimental Design and Analysis of Standard Gain Ku-Band Horn Antenna

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Abstract— This Thesis designs a pyramidal horn antenna operating at Ku-Band. It covers the complete Ku band that has the frequency range of 12.4 GHz – 18 GHz. The horn antenna is attached to WR62 waveguide. The dimension of a WR62 waveguide is 0.622 × 0.311 inches (1.524 × 0.787 cm). The aperture of the horn antenna is 6.234 × 4.868 inches (15.91 × 12.37 cm). Neck to mouth (flange) length of the horn is 32 cm. Maximum gain of the designed horn antenna is more than 25 dB. All the dimensions of the horn antenna are similar to a standard gain Ku-band horn antenna. Also the gain of the designed antenna also matches a standard gain horn antenna. A horn antenna can be used as feed for parabolic dish, short range radar system like speed enforcement cameras and as gain standard in microwave test and measurement labs.

Keywords: Ku-band, Flange Length, Huygen's principle, E-plane horn, H-plane horn, Horn Design Optimization Parameter

I. INTRODUCTION

Antennas are a vital component of analog and digital communication systems. A transmission line when excited by alternating signal when flared at its open ends start radiating. Movement of accelerating electrons is converted into electromagnetic radiation. Antenna is the device for radiation receiving electromagnetic wave in free space. The antenna is the interface between transmission line and free space. It can be used for transmitting or receiving signal. An antenna is defined as a structure of metal (linear or planar) for radiating or receiving EM waves. It is the like a load resistor at the end of a transmission line but with radiating capabilities. In other words the antenna is a bridge between free space and the guiding device. It transmits signal from generator through transmission lines into free space. The input impedance of antenna under consideration must identically match with characteristic impedance of transmission line in order to achieve maximum energy transfer between a transmission line and an antenna. If there is a mismatch between input impedance of antenna and characteristic impedance of transmission line, a reflected wave will be generated at antenna terminal and travel back towards energy source. This reflection of energy results in impairment in overall system efficiency. If this inefficient antenna is used for transmission or reception will result in wastage of energy.

$$Z_A = R_A + jX_A \quad (1)$$

Where Z_A is antenna impedance, R_A is antenna resistance and X_A is antenna reactance

– VOLTAGE STANDING WAVE RATIO (VSWR)

VSWR is the ratio between the maximum voltage and the minimum Voltage along the transmission line. The equation of VSWR is given by:

$$\text{VSWR} = \frac{1+\Gamma}{1-\Gamma} \quad (2)$$

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (3)$$

Where Γ = reflection coefficient

Z_L= load impedance

Z_0= characteristic impedance

The VSWR indicate that how effectively an antenna's terminal input impedance is matched to the characteristic impedance of the transmission line. The large number of VSWR, the greater the mismatch between the antenna and the transmission line.

II. RESEARCH OBJECTIVE

The aim of this thesis is to design a standard gain horn antenna [5] operating at Ku band. The thesis must act as a manual for people who are trying to design a standard gain horn antenna. Following chapters describe all about horn antennas, different types of horn antennas, method of designing a pyramidal horn antenna using the design formula given in [1], [6] and various other literatures.

The proposed work aims to design a pyramidal horn antenna that has following features

Operating frequency range: 12 GHz to 18 GHz

Maximum gain: 25 dB

Efficiency: more than 50% at center frequency

Feed waveguide: WR62 (0.622 × 0.311 in)

Horn dimensions: A = 5.62 in, B = 4.18 in, C = 12.5 in

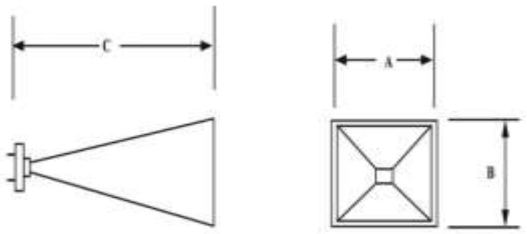


Fig. 1: Pyramidal Horn Antenna Dimensions (Miwave)

III. HORN ANTENNA DESIGN

Horn antennas are very popular at UHF (300 MHz-3 GHz) and higher microwave frequencies. Horn antennas often have a directional radiation pattern with a high antenna gain, which can range up to 25 dB in some cases, with 10-20 dB being typical. Horn antennas have a wide impedance bandwidth, implying that the input impedance is slowly varying over a wide frequency range (which also implies low values for S11 or VSWR). The bandwidth for practical horn antennas can be on the order of 20:1 (for instance, operating from 1 GHz-20 GHz), with a 10:1 bandwidth not being uncommon.

The gain of horn antennas often increases (and the beamwidth decreases) as the frequency of operation is increased. This is because the size of the horn aperture is always measured in wavelengths; at higher frequencies the horn antenna is "electrically larger"; this is because a higher frequency has a smaller wavelength. Since the horn antenna has a fixed physical size (say a square aperture of 20 cm across, for instance), the aperture is more wavelengths across at higher frequencies. And, a recurring theme in antenna theory is that larger antennas (in terms of wavelengths in size) have higher directivities.

Horn antennas have very little loss, so the directivity of a horn is roughly equal to its gain.

Horn antennas are somewhat intuitive and relatively simple to manufacture. In addition, acoustic horn antennas are also used in transmitting sound waves (for example, with a megaphone). Horn antennas are also often used to feed a dish antenna, or as a "standard gain" antenna in measurements.

WAVEGUIDES: Waveguides are basically a device ("a guide") for transporting electromagnetic energy from one region to another. Typically, waveguides are hollow metal tubes (often rectangular or circular in cross section). They are capable of directing power precisely to where it is needed, can handle large amounts of power and function as a high-pass filter.

The waveguide acts as a high pass filter in that most of the energy above a certain frequency (the cutoff frequency) will pass through the waveguide, whereas most of the energy that is below the cutoff frequency will be attenuated by the waveguide. Waveguides are often used at microwave frequencies (greater than 300 MHz, with 8 GHz and above being more common).

Waveguides are wideband devices, and can carry (or transmit) either power or communication signals. An example of a hollow metal rectangular waveguide is shown in the following figure 2.

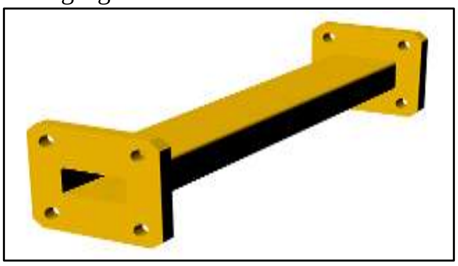


Fig. 2: Image of a Rectangular Waveguide

When other transmission lines propagate signals in TEM (transverse electromagnetic) mode, waveguides propagate waves in TE, TM and hybrid modes. Mode is the pattern that electric and magnetic field components make in a propagating EM wave.

TEM mode: Electric field and magnetic field vectors are perpendicular to each other and both of them are perpendicular to direction of propagation

TE mode: Only electric field vectors are perpendicular to the direction of propagation

TM mode: Only magnetic field vectors are perpendicular to the direction of propagation

Hybrid modes: None of the vectors (either E or H) are perpendicular to the direction of propagation

HORN ANTENNA DESIGN FORMULAE: A pyramidal horn antenna is made when a rectangular horn is flared in both E and H planes.

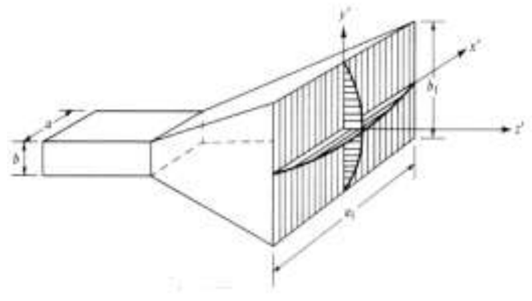


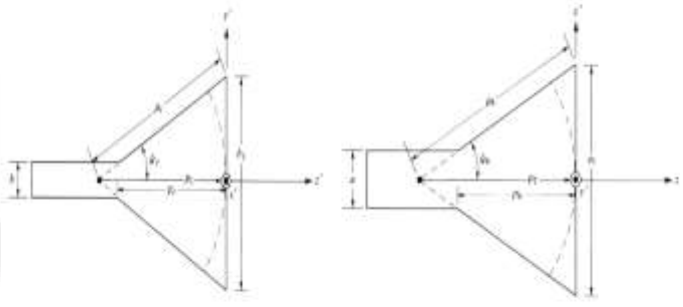
Fig. 3: Pyramidal Horn Antenna Design

The E and H field over the aperture of a horn is approximated by

$$E'_y(x',y') = E_0 \cos\left(\frac{\pi}{a_1}x'\right)\exp\left[\frac{-jk}{2}\left\{\frac{x'}{\rho_2}+\frac{y'}{\rho_1}\right\}\right]$$

$$\boldsymbol{H'_x(x',y') = \frac{-E_0}{\eta}\cos\left(\frac{\pi}{a_1}x'\right)\exp\left[\frac{-jk}{2}\left\{\frac{x'}{\rho_2}+\frac{y'}{\rho_1}\right\}\right]}$$

In the equations 3 & 4, exponential part denotes the phase of the radiated wave. It depends upon the length of the flare and aperture area of the horn.



(a) E-plane view (b) H-plane view

Fig. 4: E-Plane & H-Plane View

From figure 5 it can be seen that $\boldsymbol{\rho_1}$&$\boldsymbol{\rho_2}$ are the neck to mouth length of E plane and H plane sides of the pyramidal horn antenna. $\boldsymbol{\rho_e}$&$\boldsymbol{\rho_h}$ are the lengths of the horn aperture to the projected vertex in E plane and H plane.

Condition for physical realization of a horn antenna

$$\boldsymbol{\rho_e = (b_1 - b)\left[\left(\frac{\rho_e}{b_1}\right)^2 - \frac{1}{4}\right]^{1/2}}$$

$$\boldsymbol{\rho_h = (a_1 - a)\left[\left(\frac{\rho_h}{a_1}\right)^2 - \frac{1}{4}\right]^{1/2}}$$

$$\boldsymbol{\rho_e = \rho_h}$$

One of the starting points of design of horn antenna is usually gain.

$$\boldsymbol{G_0 = \frac{1}{2}\left(\frac{4\pi}{\lambda^2}a_1 b_1\right)} \tag{4}$$

Where $\boldsymbol{a_1}$ and $\boldsymbol{b_1}$ is the length and breadth of horn flared mouth.

$$\boldsymbol{a_1 \approx \sqrt{3\lambda\rho_2} \approx \sqrt{3\lambda\rho_h}} \qquad \boldsymbol{(\rho_2 \approx \rho_h)}$$

$$\boldsymbol{b_1 \approx \sqrt{2\lambda\rho_1} \approx \sqrt{2\lambda\rho_e}} \qquad \boldsymbol{(\rho_1 \approx \rho_e)}$$

A standard gain Ku horn antenna is built on WR62 waveguide. It has nominal gain of 25 dB. The range of frequency is 12.4-18 GHz.

– Horn Dimension

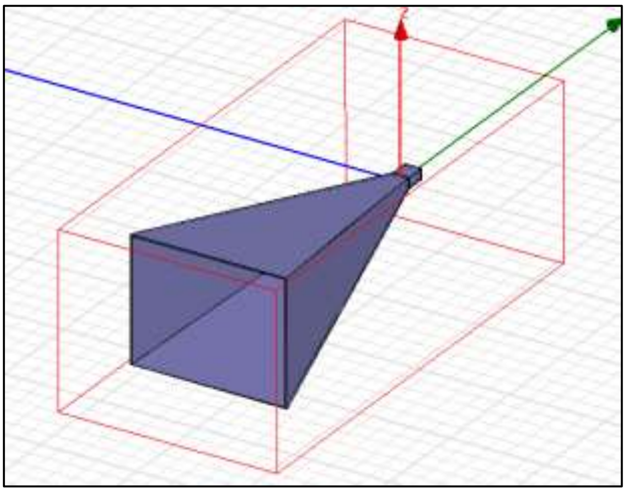


Fig. 5:1 Designed Pyramidal Horn Antenna

Length and width of waveguide of a standard horn antenna

$$a = 0.62\ in = 1.524\ cm$$
$$b = 0.31\ in = 0.787\ cm$$
$$G_0(dB) = 25 = 10\log_{10} G_0$$
$$G_0 = 10^{2.5} = 316.23$$

Wavelength and waveguide dimension calculation

$$f_0 = 15\ GHz \Rightarrow \lambda = \frac{30 \times 10^9}{15 \times 10^9} = 2\ cm$$
$$a = \frac{1.524}{2}\lambda = 0.762\lambda$$
$$b = \frac{0.787}{2}\lambda = 0.394\lambda$$

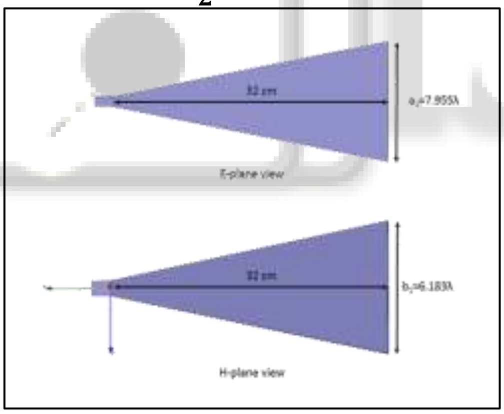


Fig. 6: E-Plane and H-Plane View Of Horn

Design procedure of Horn antenna:

Initial value of χ (design optimization parameter)

$$\chi_1 = \frac{G_0}{2\pi\sqrt{2\pi}} = \frac{316.23}{2\pi\sqrt{2\pi}} = 20.078$$

The value of χ_1 must be optimized to satisfy the following equation

$$\left(\sqrt{2\chi} - \frac{b}{\chi}\right)^2 (2\chi - 1) = \left(\frac{G_0}{2\pi}\sqrt{\frac{3}{2\pi}}\frac{1}{\sqrt{\chi}} - \frac{a}{\lambda}\right)^2 \left(\frac{G_0^2}{6\pi^3}\frac{1}{\chi} - 1\right) \qquad (5)$$

After few adjustments $\chi = 19.1122$

$$\rho_e = \chi\lambda = 38.22\ cm = 15.05\ in$$

$$\rho_h = \frac{G_0^2}{8\pi^3}\left(\frac{\lambda}{\chi}\right) = 42.18\ cm = 16.61\ in$$

$$a_1 = \sqrt{3\lambda\rho_2} \approx \sqrt{3\lambda\rho_h} = \frac{G_0}{2\pi}\sqrt{\frac{3}{2\pi\chi}}\lambda = 7.955\lambda = 15.91\ cm = 6.234\ in$$

$$b_1 = \sqrt{2\lambda\rho_1} \approx \sqrt{2\lambda\rho_e} = \sqrt{2\chi}\lambda = 6.183\lambda = 12.37\ cm = 4.868\ in$$

$$\rho_e = (b_1 - b)\left[\left(\frac{\rho_e}{b_1}\right)^2 - \frac{1}{4}\right]^{\frac{1}{2}} = 17.65\lambda = 35.3\ cm$$

$$\rho_h = (a_1 - a)\left[\left(\frac{\rho_h}{a_1}\right)^2 - \frac{1}{4}\right]^{\frac{1}{2}} = 18.73\lambda = 37.46\ cm$$

From step 5 and 6 the neck to mouth length is taken to be 32 cm to reduce phase error.

Symbol	Dimension	Description
Λ	2 cm	Wavelength
A	1.58 cm	Waveguide height
B	0.79 cm	Waveguide width
L	2 cm	Waveguide length
a1	15.91 cm	Horn aperture width
b1	12.37 cm	Horn aperture height
$\rho_e = \rho_h$	32 cm	Neck to mouth (flange) length
X	19.1122	Design optimization parameter

Table 1: Horn Dimension

IV. SIMULATION RESULTS

Antenna Parameters	Values
Operating Frequency Range	12 GHz to 18 GHz
Bandwidth (return loss < -20 dB)	4 GHz
Bandwidth (VSWR < 1.15)	4 GHz
Max Gain	25 dB
Minimum Return Loss	-40 dB approx. at 15.7 GHz
Radiation Pattern	Highly directive
Minimum VSWR	1.02 at 15.7 GHz

Table 2: Consolidated Results

Simulation software used is HFSS 11. The main problem that came after designing the horn antenna was auto mesh sizing did not work. The reason behind that was that the designed horn antenna has smallest to largest dimensions ranging from 0.7 cm to 32 cm. If the mesh dimension is kept according to largest dimension, accuracy will be compromised. If the mesh dimension is kept according to the smallest dimension, simulation time becomes too large. Also, if the solution frequency is kept more than 10 GHz, software starts showing mesh dimension problem.

HFSS gives a facility to specify mesh according to the length of the region. Smallest mesh size is taken as 0.4 cm and largest mesh size is taken as 7 cm.

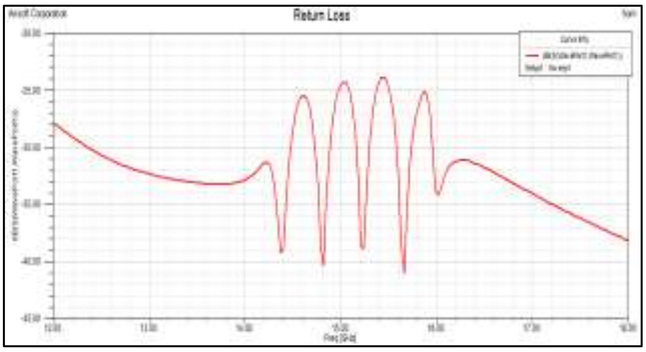


Fig. 7: Return Loss Vs Frequency Plot

Return loss is one of the scattering parameters (S11). It is also known as reflection coefficient. The value of return loss tells us the amount of power that is returned back from a load connected through a transmission line. This in turn tells the expected efficiency of the load. The load in this case is an antenna. It must be as low as possible (means largest value in negative) for the desired frequency of operation. Fig 18 shows the return loss vs frequency plot of designed horn antenna.

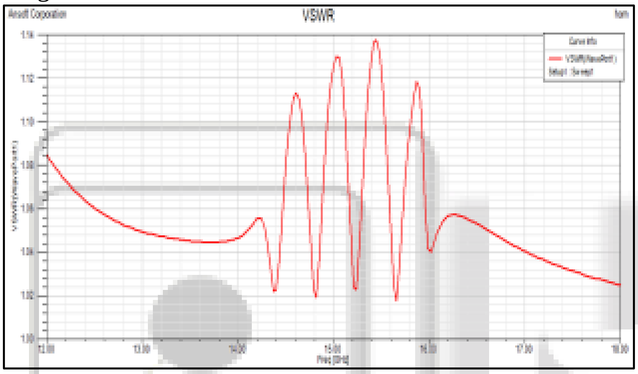


Fig. 8: VSWR Vs Frequency Plot

VSWR stands for Voltage Standing Wave Ratio. It is the ratio of maximum voltage and the minimum voltage of a transmission line feeding a load. VSWR tells the impedance matching qualities of the antenna. Ideal value of VSWR is 1 and practical value must be less than 2 and our antenna has VSWR below 1.15 for the given operating range. Fig 9 shows the VSWR of proposed antenna.

Both the return loss and VSWR plot can be used to find the bandwidth of antenna. The portion of the plot that lies below a specified return loss is called the return loss bandwidth and the portion of the plot that lies below a specified VSWR is called VSWR bandwidth. Fig 8 and 9 show that both return loss and VSWR bandwidth spreads beyond Ku-band i.e. 12 GHz to 18 GHz.

The antenna works between 12 GHz to 18 GHz. This frequency band is mostly used in satellite communication. Proposed antenna has a bandwidth of 4 GHz which is very high. The percentage bandwidth of the antenna is 26.67%.

Percentage Bandwidth can be calculated from the equation below

$$\boldsymbol{BW}\,\% = \frac{\boldsymbol{f_2 - f_1}}{\boldsymbol{f_c}} \times \mathbf{100}$$

$$\boldsymbol{BW}\,\% = \frac{\mathbf{18 - 12}}{\mathbf{15}} \times \mathbf{100} = \mathbf{26.67}\%$$

$\boldsymbol{f_1}$ and $\boldsymbol{f_2}$ are obtained by taking -20 dB reference.

A. Radiation Pattern:

The radiation pattern of antenna is the graphical representation of how the antenna radiates. It tells where the antenna can be used. Radiation pattern is highly directive in both XY and XZ plane. The radiation pattern is vertically polarized and the mode excited mode is TE_{10} mode. Figure 9 shows 3D radiation pattern. There are various side lobes present other than the main beam. They are present because the horn antenna thickness is less and the made of aluminum to make it light weight and cheap.

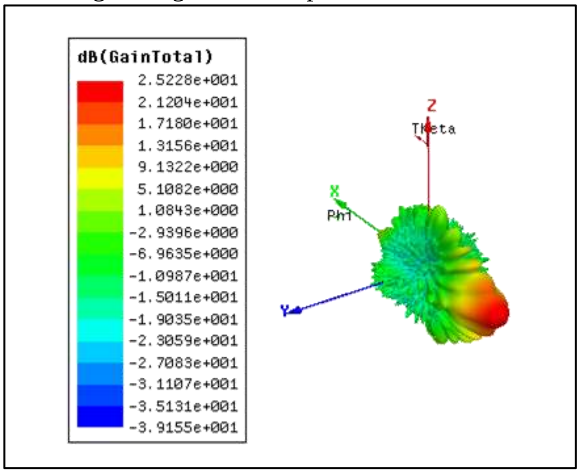
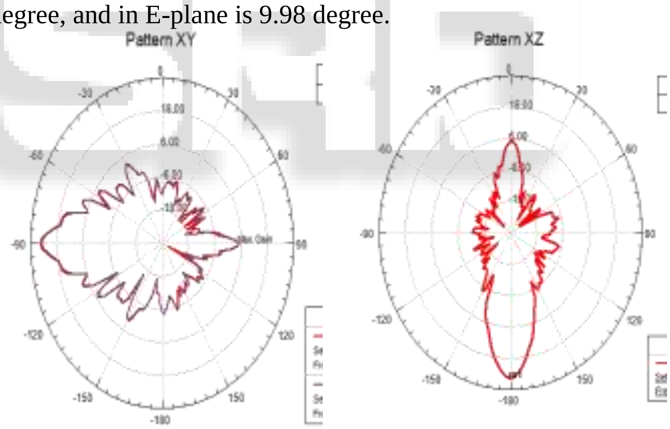


Fig. 9: 3D Radiation Pattern

Fig 10 shows H plane and E plane of the radiation pattern respectively. The beamwidth in H-plane is 6.88 degree, and in E-plane is 9.98 degree.



H-PLANE RADIATION PATTERN

e-PLANE RADIATION PATTERN

Fig. 10:2 2D Radiation Pattern

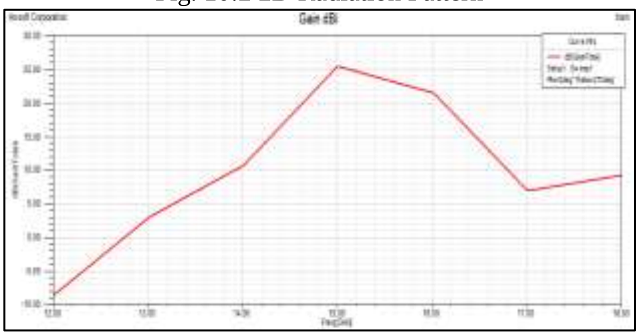


Fig. 11: Gain Vs Frequency Plot

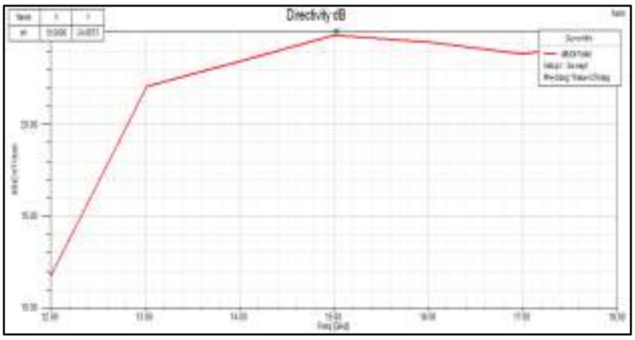


Fig. 12: Directivity Vs Frequency Plot

From fig 11, the gain of the antenna is maximum 25.45 dB at 15 GHz. Gain of the antenna is above 10 dB between 13.8 GHz to 16.8 GHz. Average gain is 11.35 dB. The directivity of antenna is shown in figure 12. Maximum directivity of antenna is 24.87 dB. Average directivity is 22.78 dB.

Parameter	Value
Max Gain	25.45 dB
Max Directivity	24.87 dB
Average Gain	11.35 dB
Average Directivity	22.78 dB
Average efficiency of Horn	50% approx

Table 3: GAIN, DIRECTIVITY AND EFFICIENCY

V. CONCLUSION

The horn antenna is a directional antenna that is usually connected to a waveguide. It works in microwave frequency band. The designed pyramidal horn antenna has 25 dB gain that is very good. It is same as a standard gain horn antenna of similar type. The antenna dimension is same as a standard gain horn antenna of Ku band.

Maximum antenna gain and directivity is approximately 25 dB and 24 dB respectively. Average efficiency of antenna is about 50%. Bandwidth of the antenna is more than 30%. The designed antenna which is manufactured can be used as standard gain antenna. This horn can either be used as a feed of a parabolic dish or a test equipment of microwave testing lab. The flare length of the horn antenna can be tuned to reduce phase error and get better efficiency. The flare length E-plane and H-plane must be adjusted so that the phase error is less than 45^0 and 90^0. There are various other configurations can also be explored like conical horn antenna, stepped horn antenna, corrugated horn antenna, dual ridged horn etc.

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