Journal of Advances and Scholarly Researches in Allied Education
Vol. 16, Issue No. 4, March-2019, ISSN 2230-7540

Design and Analysis of Pyramidal Horn Antenna as Plane Wave Source for Anechoic Chamber

Ranu Sharma[1]* Dr. A. C. Suthar[2]

[1] Department of Electronics & Communication, LJIET Ahmedabad, Gujarat

[2] Director, Department of Engineering, LJIET Ahmedabad, Gujarat

Abstract – This paper describes the design and analysis of a pyramidal horn antenna having linear polarized, high gain, low side lobes and light in weight. This horn will be used in rectangular antenna test range as source to generate a quasi-plane wave in far field test zone. It specifies the straightforward procedure to determines the physical dimension of pyramidal horn as per the performance specifications generated for antenna test range. The antenna gives 15 dBi gain over 20% bandwidth with center frequency of 10 GHz. HFSS software was used to simulate the design of antenna. Here we describe the estimated dimensions and simulated radiation data.

Keyword: Gain, Efficiency, HFSS Software, Pyramidal Horn Design Parameter.

---------------------------------x---------------------------------

INTRODUCTION

A **horn** is an antenna that consists of a flaring metal waveguide shaped like a horn to radiate radio waves in a free space.

One of the first horn antennas was constructed in 1897 by Indian radio researcher Jagadish Chandra Bose in his pioneering experiments with microwaves**.** The development of radar in World War 2 stimulated horn research to design feed horns for radar antennas.

Horns are widely used as antennas at UHF and microwave frequencies, above 300 MHz. They are used as feed for large reflector antenna structures such as parabolic antennas, as standard calibration antennas to measure the gain of other antennas, as directive antennas for many devices, as microwave radiometers and as a transmit source of natural far-field plane wave generated in anechoic chamber.

A pyramidal horn is chosen for illuminating a plane wave test zone environment in anechoic chamber due to its equal radiation patterns in both E-plane and H-plane can be obtained. Another reason to use this antenna is its high gain and directivity. Also its major advantages are easy to fabricate due to simple construction, light in weight, moderate directivity (gain), low standing wave ratio (SWR) and broad bandwidth. Also feeding a horn antenna is less complex as compared to other antennas which require complex feeding techniques. Power handling capability of horn antenna is superior to other antennas as it is waveguide fed antenna.

To ensure the high reliability with precise repeatability we need to characterize the antenna system on ground prior launch. So we need a test range having plane wave environment to characterize it. The plane wave environment will be generated by test range transmit source antenna, so to ensure minimum measurement uncertainty the design of range source antenna is a challenging task.

The key characteristic of an anechoic chamber source is that it is designed to give a low taper field over the test zone (Quiet Zone), and also the incident energy on the walls should be low (side lobe power) so the bounce from the wall become low level signal after interaction with absorber material.

HORN ANTENNA THEORY

There are three basic types of rectangular horns.

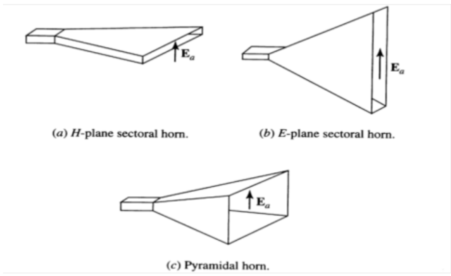

Fig 1: Different type of Rectangular Pyramidal Horn

The horns can be also flared exponentially. This provides better impedance match in a broader frequency band. Such horns are more difficult to make, which means higher cost. The rectangular horns are ideally suited for rectangular waveguide feeds. The horn acts as a gradual transition from a waveguide mode to a free-space mode of the EM wave. When the feed is a cylindrical waveguide, the antenna is usually a ***conical horn***.

The challenge is to control the phase error occurs due to the difference in length and which makes phase error. Designing of pyramidal horn antenna is accomplished with different approaches. One way is considering gain and frequency in calculating horn antenna parameters such as width and height of the horn antenna. To design different antenna parameters, horn antenna shown in Fig.2 is considered.

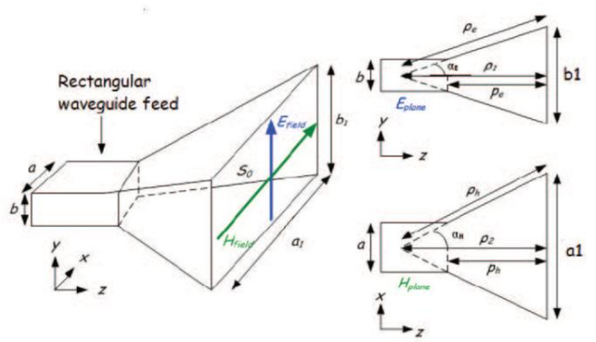

Fig 2: Horn antenna structure with E and H-plane view

Design of Pyramidal horn antenna can be done by knowing gain G and rectangular feed waveguide dimensions a and b, most commonly used design equations for gain related to its physical area is:

$$G = \frac{4\pi}{2\lambda^2} a_1 b_1 \tag{1}$$

where a1 and b1 are the horn aperture dimensions. From approximations specified for long horn antenna, it can be written as [4]

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

Where,

$$\frac{\rho_E}{\lambda} = \chi$$

Equation (2) is solved with iterations by trial and error method. Normally first value of χ can be considered as

$$\chi = \frac{G}{2\pi\sqrt{2\pi}} \tag{3}$$

Remaining parameters of horn are obtained using χ.

Slant height in E-plane, ρ_E is given by

$$\rho_E = \chi\lambda \tag{4}$$

Slant height in H-plane, ρ_H is given by

$$\rho_H = \frac{\lambda G^2}{8\chi\pi^3} \tag{5}$$

Using wavelength λ, width of horn antenna in both E and H plane is calculated.

Width in H-plane,

$$a_1 = \sqrt{3\lambda\rho_H} \tag{6}$$

Width in E-plane,

$$b_1 = \sqrt{2\lambda\rho_E} \tag{7}$$

To obtain flare angles, following equations can be used.

E-plane flare angle,

$$\alpha_E = \tan^{-1}\left(\frac{b_1}{2\rho_E}\right) \tag{8}$$

H-plane flare angle,

$$\alpha_H = \tan^{-1}\left(\frac{a_1}{2\rho_H}\right) \tag{9}$$

Radiated Electric field

$$E_y^{;}(x', y') = E_o \cos\left(\frac{\pi}{a_1}x'\right) e^{-j\left[k\left(\frac{x'^2}{2\rho_2} + \frac{y'^2}{2\rho_1}\right)\right]} \tag{10}$$

For physical realization and optimization

$$\rho_e = (b_1 - b)\left[\left(\frac{\rho_e}{b_1}\right)^2 - \frac{1}{4}\right]^{1/2} \tag{11}$$

$$\rho_h = (a_1 - a)\left[\left(\frac{\rho_h}{a_1}\right)^2 - \frac{1}{4}\right]^{1/2} \qquad (12)$$

$$\rho_e = \rho_h \qquad (13)$$

Directivity of pyramidal horn antenna can be obtained using Directivity curves for E-and H-planes sectoral horn antenna

$$D_P = \frac{\pi\lambda^2}{32ab} D_E D_H \qquad (14)$$

ANTENNA TEST RANGES

Two important components associated with the microwave electric field are far-field and near-field. The region far from the antenna is known as far-field, where the energy from the antenna is radiated only along the radial direction. Secondly, the region close to antenna is known as reactive near-field, where the energy is stored in electrical and magnetic field but is not radiated from them. It has its applications in primarily targeting the medical imaging and therapy techniques.

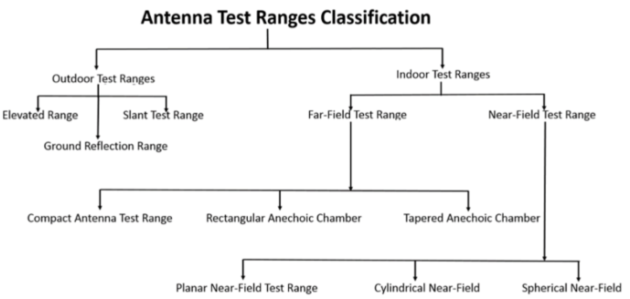

Fig 3: Classification of antenna test ranges (Courtesy to Antenna Measurement Documents)

Antenna Far–field test range is an important facility to certify the design of any antenna and ensure its usability in space or on ground. To characterize an antenna in test range it requires the DUT (device under test) should be illuminated by a plane wave microwave environment. But due to the closed (walled) environment test ranges, the reflection from walls will degrade the plane wave quality of test zone. So the available test environment is a partial-plane wave environment. To minimize the reflections from walls and to ensure the uniform field distribution over aperture is a task. This is the point where accurate design of source antenna for far-field illumination is required. The source antenna must be directive but give uniform illumination over test zone (govern by amplitude taper over FOV (field of view)), also the main lobe will be restricted with test zone dimension. It means the side walls must be illuminated by side lobes of antenna and it should below 10 dB from the main beam.

Classification of Antenna Test Ranges

Far-field range (FF): The far-field range was the original antenna measurement technique, and consists of placing the AUT a long distance away from the instrumentation and transmit antenna. Generally, the far-field distance or Fraunhofer distance, d, is considered to be –

$$d = \frac{2D^2}{\lambda} \qquad (15)$$

where D is the maximum dimension of the antenna and λ is the wavelength of the radio wave. Separating the AUT and the instrumentation antenna by this distance reduces the phase variation across the AUT enough to obtain a reasonably good antenna pattern.

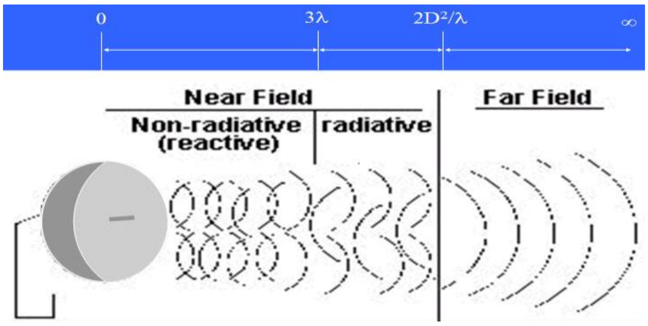

Fig 4: Distance criteria for far field

Rectangular Anechoic Chamber

An anechoic chamber (an-echoic meaning "non-reflective, non-echoing, echo-free") is a room designed to completely absorb reflections of either sound or electromagnetic waves. They are also often isolated from waves entering from their surroundings. This combination means that a person or detector exclusively hears direct sounds (no reverberant sounds). Anechoic chambers, a term coined by American acoustics expert Leo Beranek, were initially exclusively used to refer to acoustic anechoic chambers. Recently, the term has been extended to RF anechoic chambers, which eliminate reflection and external noise caused by electromagnetic waves. The size of the chamber depends on the size of the objects and frequency ranges being tested.

The internal appearance of the radio frequency (RF) anechoic chamber is sometimes similar to that of an acoustic anechoic chamber; however, the interior surfaces of the RF anechoic chamber are covered with radiation absorbent material (RAM). Uses for RF anechoic chambers include testing antenna, radars, and is typically used to house the antennas for performing measurements of antenna radiation patterns, electromagnetic interference.

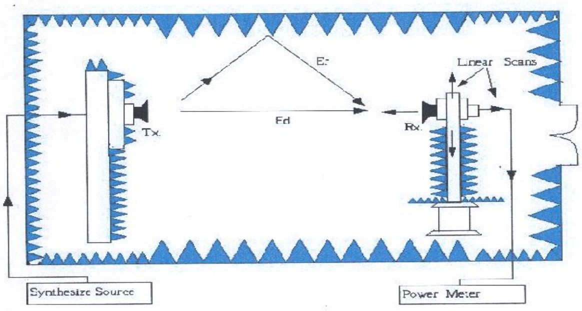

Fig 5: Rectangular Anechoic Chamber

Anechoic Chamber Antenna Test Facility was used for characterizing electrically small antennas and feeds in far field configuration. Mostly it is rectangular in shape and creates a natural plane wave environment.

DESIGNING A HORN ANTENNA

Our aim is to design a X-Band Horn (9.0 – 11.0 GHz), fc = 10.0 GHz having Gain = 15.0 dBi.

First of all, the design procedure used to implement the horn is presented here. Basic formulas are used to calculate the aperture size and other dimensions of horn antenna. Then these calculated dimension were optimized using iterative methods in MATLAB. After optimization of dimension, the finalized horn was simulated in HFSS to measure its radiation patterns, gain and VSWR. The length and aperture dimensions of the horn were further optimized over the 20% Bandwidth to obtain the optimum values of radiation characteristics [1].

Based on the chamber dimensions the feed range radiation pattern was decided.

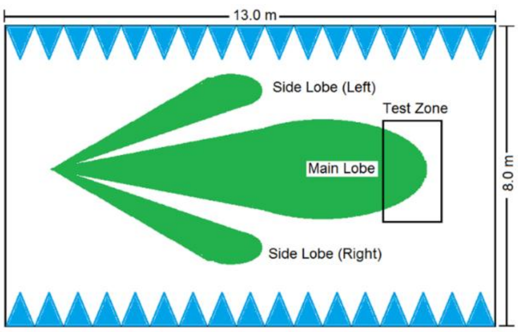

Fig 6: Test zone illumination in Anechoic Chamber

Size of test zone (QZ) = 1.0 m

$$R = \frac{2D^2}{\lambda} \qquad (16)$$

$$D = QZ \qquad (17)$$

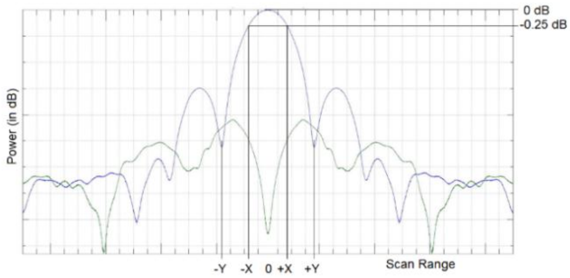

Fig 7: Test zone illumination in Anechoic Chamber

0.25 dB BW = 2X, Null location = ±Y

Calculation of Y:

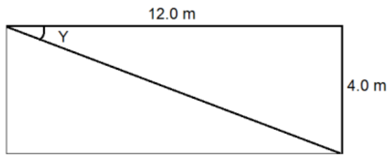

Fig 8: Calculation of Y

$$\tan y = \frac{4}{12} \qquad (18)$$

$$y = \tan^{-1}\left(\frac{4}{12}\right) = 18.4 \deg \qquad (19)$$

Calculation of X:

$$R = \frac{2D^2}{\lambda} = \frac{2(1)^2}{0.01} = 200m \qquad (20)$$

Center frequency = 10GHz, λ = 0.03 m, but available R_{max} = 11m, require clearance at QZ side is of 1m

So, D = size of QZ for 10GHz

$$D = \sqrt{\frac{R\lambda}{2}} = \sqrt{\frac{11 \times 0.03}{2}} = 0.4062m \qquad (21)$$

So maximum 0.41 m size antenna will be characterized in anechoic chamber @ 10GHz –

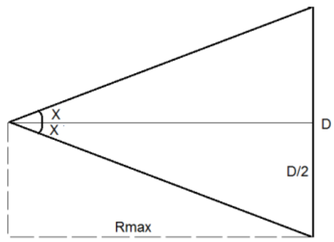

Fig 9: Calculation of X

$$\tan x = \frac{D/2}{R_{\max}} = \frac{D}{2R_{\max}} = \frac{0.4062}{2\times 11} = 0.0184 \qquad (22)$$

X = 1.05 deg

Finalized specification for designing Range Feed –

Main beam amplitude taper 0.25 dB for FOV (±1.05 deg), Null location will be ± 18.4 deg, Slide lobe level must be less than 10 dB down from main beam peak.

X-band waveguide WR90 (8.40 to 12.40 GHz)

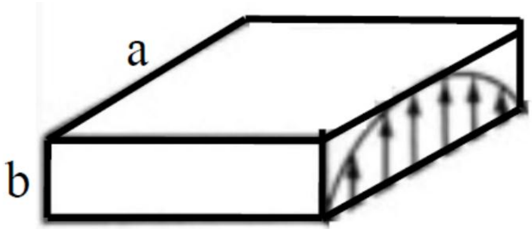

Fig 10: TE10 mode in Rectangular Waveguide

a = 0.9 inch and b = 0.4 inch, waveguide dimensions WR-90: a=0.9 inches (2.286 cm), b=0.45 inches (1.143 cm).

$$G_o(\text{dBi})=15=10\log_{10}G_o,\ G_o=10^{1.5}=31.62$$

$$\text{At } f_c=10\text{GHz},\ \lambda=3\text{x}10^8/10\text{x}10^9\ \text{m} = 3.0\ \text{cm}$$

$$b=1.143\lambda/3 = 0.381\lambda\ \&\ a=2.286\lambda/3 = 0.762\lambda$$

Step-1: Initial value of χ:

$$\chi = \frac{G_o}{2\pi\sqrt{2\pi}} = \frac{31.262}{2\pi\sqrt{2\pi}} = 2.006$$

Put initial estimated value in –

$$(2\chi-1)\left(\sqrt{2\chi}-\frac{b}{\lambda}\right)^2 = \left(\sqrt{\frac{3}{2\pi}}\frac{G_o}{2\pi}\frac{1}{\sqrt{\chi}}-\frac{a}{\lambda}\right)^2\left(\frac{G_o^2}{6\pi^3}\frac{1}{\chi}-1\right) \qquad (23)$$

After few tries, a more accurate value of χ is derived (refer 5.2) χ=1.8348

Step-2:

$$\rho_E = \chi\lambda \quad = 0.055\ \text{m}$$

$$\rho_H = \frac{\lambda G^2}{8\chi\pi^3} = 0.0659\ \text{m}$$

Step-3:

$$a_1 = \sqrt{3\lambda\rho_H} \quad = 0.0059\ \text{m}$$

$$b_1 = \sqrt{2\lambda\rho_E} \quad = 0.0033\ \text{m}$$

Step-4:

$$\rho_e = (b_1 - b)\left[\left(\frac{\rho_e}{b_1}\right)^2 - \frac{1}{4}\right]^{1/2} = 0.1354\ \text{m}$$

$$\rho_h = (a_1 - a)\left[\left(\frac{\rho_h}{a_1}\right)^2 - \frac{1}{4}\right]^{1/2} = 0.1879\ \text{m}$$

Optimum design procedure with a numerical and an analytical solution:

To optimize the band performance that produce the same result in the gain, we have to find a single solution of the design, we have to obtain a minimum of equations relating the four dimensions that we want to achieve, given the value of the on axis gain, the operating frequency and waveguide [2]. The following constrain has to be enforced:

$$R_1\frac{A-a}{A} = R_2\frac{B-b}{B} \qquad (24)$$

For the optimum design, it is chosen *A* for a fixed value of R_1 that maximizes the gain curve in the *H*-plane. This is done by deriving the expression of the gain or directivity with respect to the dimension *A* and, through a numerical solution, it is determined the root of this expression, i.e., it is determined *A* in function of the independent value R_1:

$$f_1(A, R_1) = \frac{\partial D_H}{\partial A} \qquad (25)$$

$$A(R_1) = root(f_1) \qquad (26)$$

where root of above equation is a numerical function that calculates the zeroes of its argument.

The same have to be done to the *E*-plane, where *B* is obtained according to the value of R_2: However, these expressions do not have a single root, but many. Its curve of directivity has several points where its derivative is zero. This also happens with the directivity of the *H*-plane, although the oscillations of the curve are less intense.

$$f_2(B, R_2) = \frac{\partial D_E}{\partial B} \qquad (27)$$

$$B(R_2) = root(f_2) \qquad (28)$$

The estimated aperture efficiency is = 0.47

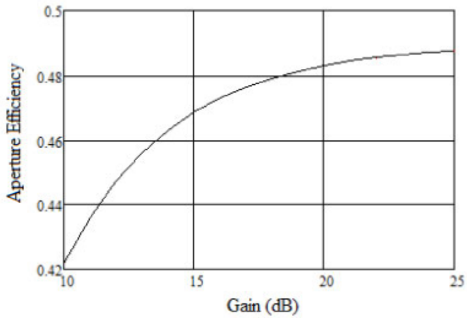

Fig 11: Variation of the aperture efficiency for optimum design with defined Frequency band

From the equation of gain G, the numerical solution of the design is found through the R_2 value, since all other dimensions are dependent on R_2

$$f_4(R_2) = G - \frac{\pi}{32}\left(\frac{\lambda}{a} D_E\right)\left(\frac{\lambda}{b} D_H\right) \qquad (29)$$

$$R_2 = root(f_4) \qquad (30)$$

When a waveguide dimension with 2 <= a/b <= 2.5 and the frequency in the range 1 < lambda/a < 1.7 are used, the change in optimal t and se become negligible with the variations of a, b and lambda. So the exact phase errors are dependent on the desired gain in accordance with the following approaches [3] –

$$t_e \cong 0,3967 + \frac{0,6281}{G} \qquad (31)$$

$$s_e \cong 0,262 + \frac{0,3178}{G} \qquad (32)$$

Where G is given in absolute value. These equations can be used for standard antennas with gains between 10 and 25 dB. So now the final aperture dimensions are –

$$A = 2\sqrt{t_e \lambda (t_e \lambda + 2R_1)} \qquad (33)$$

$$B = 2\sqrt{s_e \lambda (s_e \lambda + 2R_2)} \qquad (34)$$

Isolating *A* in eq 7.3 and substituting in eq 7.25, the following equation is obtained

$$R_1 = \frac{G^2 \lambda^4}{16\pi^2 \varepsilon_{ap}^2 B^2 8\lambda t_e} - \frac{t_e \lambda}{2} \qquad (35)$$

Results of the design of a Pyramidal Horn Antenna with Gain 15 dB using a WR-90 waveguide and frequency band 9 – 11 GHz are

Dimensions (cm)	Designs	
	Optimum for Band	Initial (as per center frequency)
R_2	13.48	13.54
R_1	17.42	18.79
B	4.2	3.3
A	6.1	5.9
Rρ	12.98	13.08

SIMULATION SOFTWARE

In the past, the analysis and design of pyramidal horn antennas were accomplished by using approximated methods. Recently, proliferations of the computer capabilities and the popularity of the pyramidal horn antennas have encouraged more analytic methods which provide efficient computer-aided analysis and design. The HFSS is highly efficient to analyze radiation apertures and pyramidal horn antennas (with or without corrugations) mounted on a ground plane.

A key feature of HFSS is automatic adaptive mesh refinement which generates an accurate solution based on the physics or electromagnetics of the design. It provides an effective means of accurately predicting the behavior and performance of antennas.

Finite Element Method – The finite element method is highly suited for 3D arbitrarily-shaped geometries. In this method, the geometric model is automatically divided into a number of tetrahedral elements conformal to all surfaces of the geometry. Tetrahedral elements are highly suited for this type of unstructured and non-uniform mesh since they can be stretched and pulled to fit any arbitrary geometry.

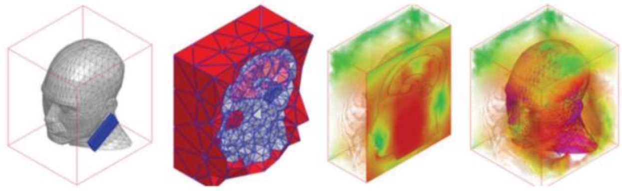

Fig 12: 3-d meshing of Model based on FEM (courtesy HFSS manual)

Simulation Results - Based on calculation made in earlier section, a simulation model of pyramidal horn was designed in HFSS as shown below in Fig 12. And the simulated radiation pattern is shown below in Fig 13.

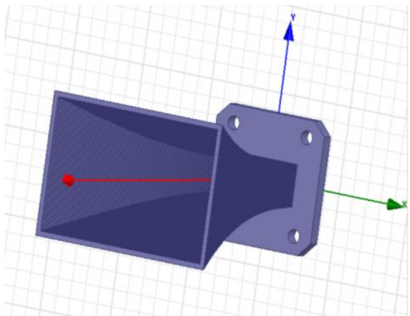

Fig 13: Simulation model in HFSS

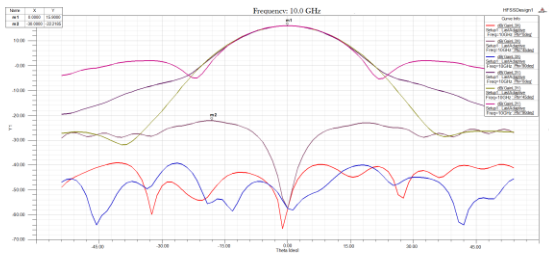

Fig 14: Simulated radiation pattern @ 10.0 GHz

REALIZED HARDWARE

Based on optimized pyramidal horn design, the mechanical dimensions were finalized. Fabrication of 10.0 GHz horn was completed successfully for 25% bandwidth.

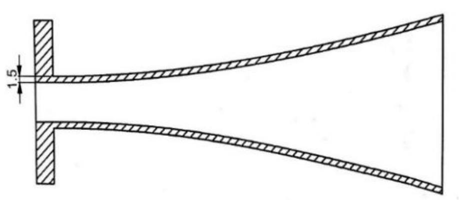

Fig 15: Mechanical design of Horn (1.5 mm thickness)

After the finalization of design in HFSS, the horn was manufactured.

Fig 16: Fabricated Pyramidal Horn

Return Loss (S11) parameter - Return loss is the loss of power in the signal returned/reflected by a discontinuity in a transmission line. This discontinuity can be a mismatch with the terminating load. It is usually expressed as a ratio in decibels (dB);

$$RL(\mathrm{dB}) = 10\log_{10}\frac{P_i}{P_r} \qquad (36)$$

Return loss is related to both standing wave ratio (SWR) and reflection coefficient (Γ). Increasing return loss corresponds to lower SWR. Return loss is a measure of how well devices or lines are matched. A match is good if the return loss is high. A high return loss is desirable and results in a lower insertion loss.

Measured Return Loss (S11) plot –

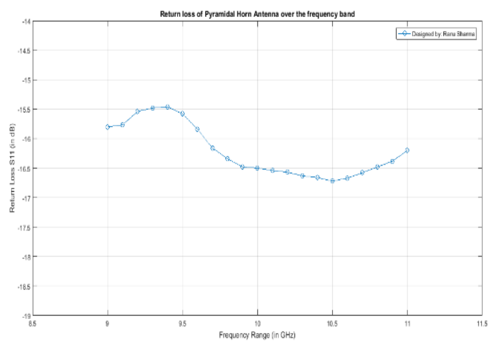

Fig 17: Measured Return Loss (S11) of Fabricated Pyramidal Horn

An antenna test procedure was carried out to measure the gain and radiation patterns of the horn. The measured results are plotted in fig 19. The optimized and practically measured results are very close to each other.

Fig 18: Pyramidal Horn mounted in Anechoic Chamber

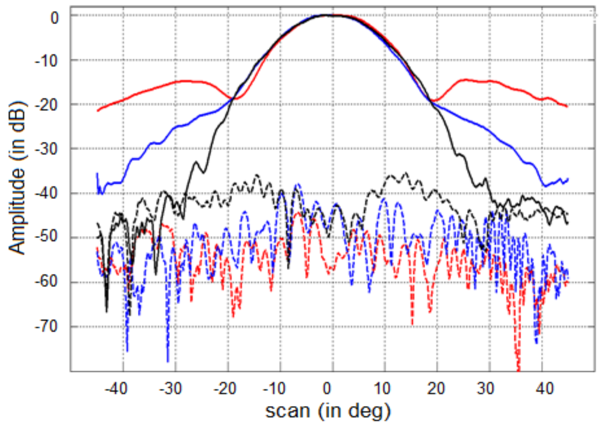

Fig 19: Measured Radiation Pattern in Anechoic Chamber

CONCLUSION

The detailed analysis of a pyramidal horn is successfully completed. The realized horn gain is 14.89 dBi which is very close to specification of 15 dBi. Further there is very good agreement between theoretically simulated and fabricated horn radiation characteristics.

REFERENCES

1. E. V. Jull (1973). "Errors in the Predicted Gain of Pyramidal Horns" in *IEEE Trans Antennas Propagat.*, vol. AP-21, pp. 25-31, January 1973.

2. K. T. Selvan (1999). "An Approximate Generalization of Schelkunoff's Horn-Gain Formulas", in *IEEE Trans Antennas Propagat.*, vol. 47, pp. 1001-1004, June 1999.

3. W. T. Slayton (1954). "Design and Calibration of Microwave Antenna Gain Standards" U.S. Naval Res. Lab., Washington, D.C., Rep. 4433, November 1954.

4. J. L. Teo, K. T. Selvan (2006). "On the Optimum Pyramidal-Horn Design Methods", in *Int J RF and Microwave CAE 16*, pp.561-564, September 2006.

5. M. J. Maybell, and P. S. Simon (1993). "Pyramidal Horn Gain Calculation with Improved Accuracy", in *IEEE Trans Antennas Propagat.*, vol. AP-41, pp. 884-889, July 1993.

6. J. F Aurand (1988). In "A New Design Procedure for Optimum Gain Pyramidal Horns", in *Antennas and Propagation Society International Symposium,* AP-S Digest, 1988.

7. Y. Najjar, M. Moneer, N. Dib (2007). "Design of Optimum Gain Pyramidal Horn with Improved Formulas Using Particle Swarm Optimization", in *Int J RF and Microwave CAE 17*, pp.505-511, June 2007.

Corresponding Author

Ranu Sharma*

Department of Electronics & Communication, LJIET Ahmedabad, Gujarat

ranujsharma1991@gmail.com