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Design And Simulation Of A Pyramidal Horn Antenna For Ground Penetrating Radar Applications

Ndifreke Nsima Williams [1]
Dept. of Electrical/Electronic & Computer Engineering, University of Uyo, Nigeria.
ndifrekewilliams9 @gmail.com

Akaninyene B. Obot [2]
Dept. of Electrical/Electronic & Computer Engineering, University of Uyo, Nigeria.

Kufre M.Udofia [3]
Dept. of Electrical/Electronic & Computer Engineering, University of Uyo, Nigeria

Abstract— **This paper describes the design and simulation of a 5.85 GHz to 8.20 GHz antenna which can be used for ground penetrating radar (GPR) applications as well as for other purposes. The proposed antenna is achieved by first designing a pyramidal horn antenna with frequency that can be used from 5.85 GHz to 8.20 GHz. The antenna was fed with a rectangular waveguide (WR 137). The antenna is designed to have highest gain at 8.20 GHz. The simulated results show good and balanced impedance matching from under a return loss of $-10\ dB$ and good radiation pattern. The material used is perfect electric conductor (PEC). The designed antenna was simulated in contact with the ground and its capability to detect buried objects has been verified in the time domain by using Computer Simulation Technology (CST) Microwave Studio-v.2018) simulator. The results showed that the highest antenna gain of 18.3 dB was obtained at 8.20 GHz. The pyramidal horn antenna is fed with a rectangular waveguide (WR 137) as it provides moderate directivity, high gain, better return loss, wide bandwidth and matched voltage standing wave ratio (VSWR). The proposed antenna is cost effective with high gain and high directivity covering a wide bandwidth and ranging from 5.85 GHz to 8.20 GHz. The pyramidal horn antenna is suitable for GPR applications. It can be used to detect buried land mines to a depth of 30cm, and it is also suitable for oil exploration.**

Keywords: Pyramidal horn antenna, ground Penetrating Radar, Gain, Return Loss, Rectangular Waveguide, Return Loss , Voltage Standing Wave Ratio

I. INTRODUCTION

Over the years wireless communication technologies have been developed and widely deployed in many diverse applications [1, 2]. Today, wireless technologies have dominated other technologies in the communication industries, [3,4,5,6,7,8] with applications in real-time and non-real-time communications, terrestrial and satellite communications as well as in various sensor networks and the emerging Internet of Things applications [9, 10 ,111, 12, 13,14, 15, 16]. Consequently, nowadays, wireless technologies are among the main areas of research in the world of communication systems and a study of wireless communication systems is incomplete without an understanding of the operation of antennas [17, 18]. An antenna is device for radiating electromagnetic waves. It is also a transducer for coupling electromagnetic energy between free space and a wave guide, transmission line, or a receiver and a transmitter [19]. Antenna is a vital part in any communication system design, operation and in optimisation of key performance parameters of wireless communication system. Also, such proper knowledge of antennas are essential in wireless communication link budget analysis, ameliorating the effect of propagation loss, due to atmospheric parameters, environmental parameters and other wireless link parameters [20, 21, 22, 23, 24. 25 ,26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37].

Generally, antennas are categorised as wideband and narrow band based on their frequency range of operation [38]. In this paper our focus is on pyramidal horn antenna which comes under the class of wideband antennas and rectangular horn antennas. The pyramidal horns are the antennas in which the walls of the rectangular wave guide are flared out in both E-plane and H-plane directions[39].

The applications of pyramidal horn antennas are : remote sensing satellites, communication satellites, geographic information and weather satellites [40]. Pyramidal horn is one type of aperture antenna flared in both directions, a combination of E-plane and H-plane. Horns antennas are one of the most important parts of a communication chain. In Modern times the need for wideband applications has increased. The Horn Antenna is widely used in radar and communication system. A pyramidal horn antenna is said to be optimum when the aperture dimensions are adjusted to give maximum gain for given slant lengths in the E- and H-planes [41]. Pyramidal Horn is the best horn as it has equal radiation patterns in both E-plane and H-plane along with its high gain and directivity [42]. With the development of measurement, communication system, radar techniques and electromagnetic, the horn antenna has been widely used which make it one of the most practical antennas. Pyramidal horn antenna can effectively extend the working bandwidth of the antenna and improve the impedance matching between waveguide and free space.

GPR is a rapidly growing field that has seen tremendous progress in the development of theory, technique, technology, and range of applications over the past 15 years to 20 years [43]. The diversity of GPR applications includes a variety of areas such as the study of groundwater contamination, geotechnical, engineering, glaciology, and archaeology. Ground Penetrating Radar (GPR) uses ultra wideband (UWB) frequency signal that is transmitted into the ground. The reflected signals are then returned to the receiver and stored on digital media for signal processing. The computer measures the time taken for a pulse to travel to and from the target which indicates its depth and location

II. REVIEW OF RELATED WORKS

The design, fabrication and testing of pyramidal horn antenna at 9.5 GHz is presented by [44]. The pyramidal horn antenna had a gain of 19.4 dB almost closed to the specific 20 dB. The authors did not captured return loss in his research and also a clear description of the feed of the antenna was not presented in his paper. The authors in [45] published a design of ultra high frequency pyramidal horn antenna. The pyramidal antenna was excited using a waveguide which was fed with a coaxial cable. The dimensions of the antenna was not stated.

III. METHODOLOGY

3.1 Design procedure of pyramidal horn antenna

The calculation of the pyramidal horn antenna dimensions is based on rectangular waveguide. The operating frequency and gain are important factor for designing. In order to achieve high gain, the horn antenna should have large aperture. On the other hand, aperture size depends on operating frequency and directivity depends on gain [46]. . The basic essential parameters for the design of 8.20 GHz Pyramidal horn antenna are: Selection of the operating frequency of the antenna, selection of the waveguide width (a) and waveguide height (b).

3.2 Waveguide design and calculation

A rectangular waveguide with dimensions axb is to be flared to a horn of aperture AxB. The carrier frequency with maximum radiated power was selected to be 8.20 GHz suitable for radar penetration applications. Waveguide dimensions are determined depending on the frequency of use The cross sectional view of flared wave guide in E and H planes and dimensions of horn are shown Figure 1.

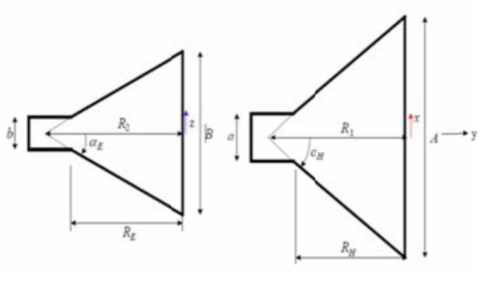

Figure 1: Dimensions of horn antenna.

Figure 2 shows the rectangular waveguide cross section, where a is the width and b is the height of the rectangular waveguide dimensions. Thus, the rectangular waveguide (WR 137) for width and height chosen were, a = 3.48488 cm and b = 1.57988 cm. In Figure 2, the depth of waveguide for frequency of 8.20 GHz is equal to the half cut-off frequency wavelength λg determined by Equation (1) where λ_0 is the wavelength in free space and λc is the wavelength of the cut-off frequency for the mode of transmission:

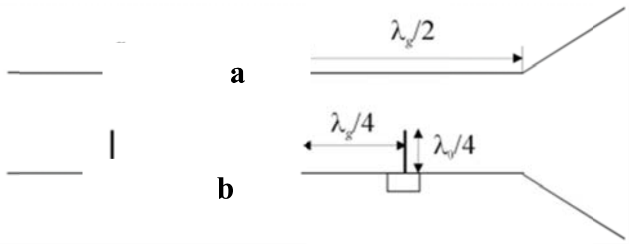

Figure 2: Waveguide design

$$\lambda_g = \frac{1}{\sqrt{\frac{1}{\lambda 0^2} - \frac{1}{\lambda c^2}}} \quad (1)$$

Wavelength in free space (λ_0) is determined by:

$$\lambda_0 = \frac{c}{f_r} \quad (2)$$

$$\lambda_0 = \frac{3 \times 10^8}{8.20 \times 10^9} \quad ; \lambda_0 = 3.75 \text{ cm} = 37.5\text{mm}$$

where c is the speed of light = 3 x 10^8 m/s ; f_r is the selected resonant frequency in GH_z and λ_0 is the wave length in free space.

The higher order modes of transmission in a rectangular waveguide depend on its dimensions. The wavelengths of different modes are calculated by:

$$(\lambda_c)_{mn} = \frac{2}{\sqrt{\frac{m^2}{a^2} + \frac{n^2}{b^2}}} \quad (3)$$

where m and n are integer numbers, therefore giving as m =1 and n = 1 ;

$$(\lambda_c)_{mn} = \frac{2}{\sqrt{\frac{1^2}{34.8488^2} + \frac{1^2}{15.9988^2}}}$$

$$(\lambda_c)_{mn} = 29.1970 \text{ mm}$$

By introducing λ_0 and λ_c into Equation (1) , λ_g is given as 45.45 mm.

$$\lambda_g = \frac{1}{\sqrt{\frac{1}{37.5^2} - \frac{1}{29.1970^2}}}$$

$$\lambda_g = 45.45 \text{ mm}$$

Therefore, the depth of waveguide $\frac{\lambda g}{2}$ is given as $\frac{45.45}{2}$ = 22.725 mm

The distance of the feed antenna from the waveguide edge is given as:

$$\frac{\lambda g}{4} = \frac{45.45}{2} = 11.362 \text{ mm}$$

The height of the feed antenna is obtained as:

$$\frac{\lambda 0}{4} = \frac{37.5}{4} = 9.375 \text{ mm}$$

The specification for the design of the pyramidal horn antenna is shown in Table 1.

TABLE 2: DIMENSIONS OF 8.20 GHZ PYRAMIDAL HORN ANTENNA

Parameter	Value (mm)
Flaring angle in H- direction (θ_H)	18.52^0
Flaring angle in E- direction (θ_E)	14.46^0
Depth of the waveguide ($\frac{\lambda g}{2}$)	22.72 mm
Height of the feed antenna ($\frac{\lambda 0}{4}$)	9.375 mm
Distance of the feed antenna from the Waveguide edge ($\frac{\lambda g}{4}$)	11.362 mm
Wavelength (λ_0)	37.5 mm
Slant length in the H- plane direction (I_H)	293.353 mm
Slant length in the E- plane direction (I_E)	260.597 mm
Internal distance in the H- plane direction (R_1)	250.2 mm
Internal distance in the E- plane direction (R_2)	281.1 mm
Flaring horn length in the H- plane direction (R_H)	222.9 mm
Flaring horn length in the E- plane direction (R_E)	222.9 mm
Aperture dimension for Perfect electric conductor (PEC) thickness	2 mm

Basically, for an antenna horn to be realizable the following must be true [47]:

$$R_E = R_H \quad (4)$$

where R_E is the flaring length distance in the E- plane direction and R_H is the flaring length distance in the H-plane direction .

The expression for designing an optimum horn antenna dimensions is given in [48] as:

$$A^4 + aA^2 + \frac{3bG\lambda^2}{8\pi\varepsilon_{ap}}A - \frac{3G^2\lambda^2}{32\pi^2\varepsilon_{ap^2}} = 0 \quad (5)$$

where A= aperture width, a = waveguide width, b = waveguide height, G = gain,

ε_{ap} = effective aperture and λ = wavelength.

For a given gain (20 dB = 100), operating frequency 8.20 GHz) and with the dimensions of the width and height of the standard rectangular waveguide (WR 137) given as a = 34.8488 mm and b = 15.7988 mm. The detailed design procedure for the design of pyramidal horn antenna is obtained as follows :

Step 1: Calculation of the aperture width (A) in the H-plane direction . The aperture width (A) according to [49] is given by:

$$A = 0.45\lambda\sqrt{G} \quad (6)$$

Step 2: Calculation of the aperture height (B) in the E-plane direction. The horn length (B) is given in [50] as:

$$B = \frac{1}{4\pi}\frac{G\lambda^2}{0.51\,A} \quad (7)$$

Step 3: Calculation of the internal distance (R_1) in the H-plane direction. The distance (R_1) is given by [51] as:

$$R_1 = \frac{A^2}{3\lambda} \quad (8)$$

Step 4: Calculation of the internal distance (R_2) in the E-plane direction. The distance (R_2) is given by:

$$R_2 = \frac{B^2}{2\lambda} \quad (9)$$

Step 5: Computation of the flaring horn length (R_E) in the E- plane direction. The flaring horn length (R_E) is given as:

$$R_E = R_2\left(1 - \frac{a}{A}\right) \quad (10)$$

Step 6: Computation of the flaring horn length (R_H) in the H- plane direction. The flaring horn length (R_H) is given in [51] by:

$$R_H = R_1\left(1 - \frac{b}{B}\right) \quad (11)$$

Check if $R_E = R_H$ is satisfied or not.

If not, change the approximation of A and B, then repeat the above procedure till R_E=R_H is satisfied.

From equation (6), the aperture height (A) in the H-plane direction is obtained as :

$$A = 0.45 \text{ x } 3.75 \text{ x } \sqrt{100}$$

$$A = 16.875 \text{ cm} = 168.75 \text{ mm}$$

where λ = 3.75 cm and G = 100 (20 dB)

Similarly, from equation (7) the aperture width (B) in the E-plane direction is calculated as :

$$B = \frac{1}{4\ X\ 3.142}\ x\ \frac{100\ X\ 3.75^2}{0.51\ X\ 16.875}$$

$$B = 13.0011 \text{ cm} = 130.011 \text{ mm}$$

Also, using equation (8) for the internal distance (R_1) in H-plane direction, it is given as:

$$R_1 = \frac{16.875^2}{3 \text{ x } 3.75}$$

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$$R_1 = 25.3125 \text{ cm} = 253.125 \text{ mm}$$

Calculation of the internal distance (R_2) in the E- plane direction, from equation (9) is given as:

$$R_2 = \frac{13.0011^2}{2 \text{ x } 3.75}$$

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$$R_2 = 22.5368 \text{ cm} = 225.368 \text{ mm}$$

Also, from equation (10) , the flaring horn length (R_E) in the E-plane direction is given by:

$$R_E = 22.5368\left(1 - \frac{3.48488}{16.875}\right)$$

$$R_E = 17.8829 \text{ cm} = 178.829 \text{ mm}$$

where values of a = 3.48488 cm, R_2 = 22.5368 cm and A = 16.875 cm

The flaring horn length (R_H) in the H-plane direction is calculated as :

$$R_H = 25.3125\left(1 - \frac{1.57988}{13.0011}\right)$$

$$R_H = 22.237 \text{ cm} = 222.37 \text{ mm}$$

Since $R_E = R_H$, the values of A and B is changed and the above procedures is repeated until $R_E = R_H$ is satisfied.

First Values:

The first values of the Pyramidal Horn Antenna is obtained by choosing the following pyramidal horn dimensions values.

A = 16.81 cm = 168.1mm; B = 13.051 cm = 130.51 mm

a = 3.48488 cm = 34.8488 mm : b = 1.57988 cm = 15.7988 mm ; λ = 3.75 cm

Applying equation (8)

$$R_1 = \frac{A^2}{3\lambda} ,$$

$$R_1 = \frac{16.81^2}{3 \, x \, 3{,}75} = 25.117 \text{ cm} = 251.17 \text{ mm}$$

Applying equation (9)

$$R_2 = \frac{B^2}{2\lambda} ,$$

$$R_2 = \frac{13.051^2}{2 \, x \, 3{,}75} = 22.710 \text{ cm} = 2227.10 \text{ mm}$$

Applying equation (10)

$R_E = R_2(1 - \frac{a}{A})$, where R_2 = 22.710 cm, substituting

$$R_E = 22.710(1 - \frac{3.48488}{16.81})$$

$$R_E = 18.002 \text{ cm} = 180.02 \text{ mm}$$

Applying equation (11)

$R_H = R_1(1 - \frac{b}{B})$, where R_1 = 25.117 cm

$$R_H = 22.710(1 - \frac{1.57988}{13.051})$$

$$R_H = 22.077 \text{ cm} = 220.77 \text{ mm}$$

Second Values:

The second values of the Pyramidal Horn Antenna is obtained by choosing the following pyramidal horn dimensions values.

A = 16.761 cm = 167.61mm ; B = 13.101 cm = 131.01 mm

a = 3.48488 cm = 34.8488 mm : b = 1.57988 cm = 15.7988 mm ; λ = 3.75 cm

Applying equation 8)

$$R_1 = \frac{16.761^2}{3 \, x \, 3{,}75} = 24.96 \text{ cm} = 249.6 \text{ mm}$$

Applying equation (9)

$$R_2 = \frac{13.101^2}{2 \, x \, 3{,}75} = 22.88 \text{ cm} = 228.8 \text{ mm}$$

Applying equation (10)

$R_E = R_2(1 - \frac{a}{A})$, where R_2 = 22.88 cm, substituting

$R_E = 22.88(1 - \frac{3.48488}{16.76})$, = 18.143 cm = 181.43 mm

Applying equation (11)

$R_H = R_1(1 - \frac{b}{B})$, where R_1 = 24.96 cm

$R_H = 24.96(1 - \frac{1.57988}{13.101})$, = 24.96 cm = 249.6 mm

The pyramidal horn antenna dimensions is shown in Table 2.

TABLE 1: PYRAMIDAL HORN ANTENNA DIMENSIONS

S/N	Acm	Bcm	R_1cm	R_2cm	$R_H$cm	$R_E$cm	R_E cm − R_H cm
1	16.81	13.05	25.11	22.71	18.00	22.07	4.07
2	16.76	13.01	24.96	22.88	18.14	21.96	3.82
3	16.75	13.99	24.93	26.11	20.67	21.93	1.26
4	16.75	13.99	24.93	26.11	20.67	21.93	1.11
5	16.75	14.00	24.93	26.50	20.99	21.93	0.94
6	16.78	14.41	25.02	27.68	21.95	22.29	0.34
7	16.78	14.46	25.02	27.89	22.12	22.29	0.17
8	16.78	14.48	25.02	27.95	22.16	22.29	0.13
9	16.78	14.49	25.02	28.01	22.21	22.32	0.11
10	16.78	14.52	25.02	28.11	22.29	22.29	0.00

The geometry of the designed pyramidal horn antenna is shown in Figure 3. The simulation of the antenna was done using Computer Simulation Technology studio microwave version 2018.

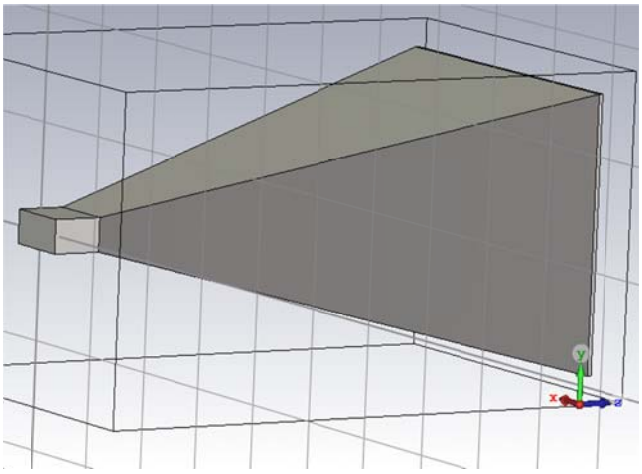

Figure 3: Geometry of the designed antenna (side view) in CST MW studio.

IV. RESULTS AND DISCUSSION

Antennas with lower frequencies detect large objects at larger depths with lower resolution and higher penetration whereas high frequency antennas detect small objects at small depths with higher resolution and lower penetration. On the other hand, aperture size depends on operating frequency and directivity depends on gain [52]. As the depth of the soil increases, signal attenuation also increases due to the fact that it has to penetrate the soil deeper. The simulation results shows that the pyramidal horn antenna with a frequency range of 5.85 GHz to 8.20 GHz can detect a target at a depth of about 30 cm from the soil surface. As the target depth increases, directivity likewise decreases and the beamwidth increases.

The results obtained from CST microwave studio are shown in Figure 4,5, 6 and 7 . Based on the return loss plot, the return loss at 5.85 GHz to 8.20 GHz were -26.429003 dB and -11.526981 dB respectively. The radiated power at 8.20 GHz is given as 0.00282W. The gain of the designed pyramidal horn antenna at 5.85 GHz is 16.04 dB. The gain of the designed pyramidal horn antenna at 8.20 GHz is 18.27 dB.

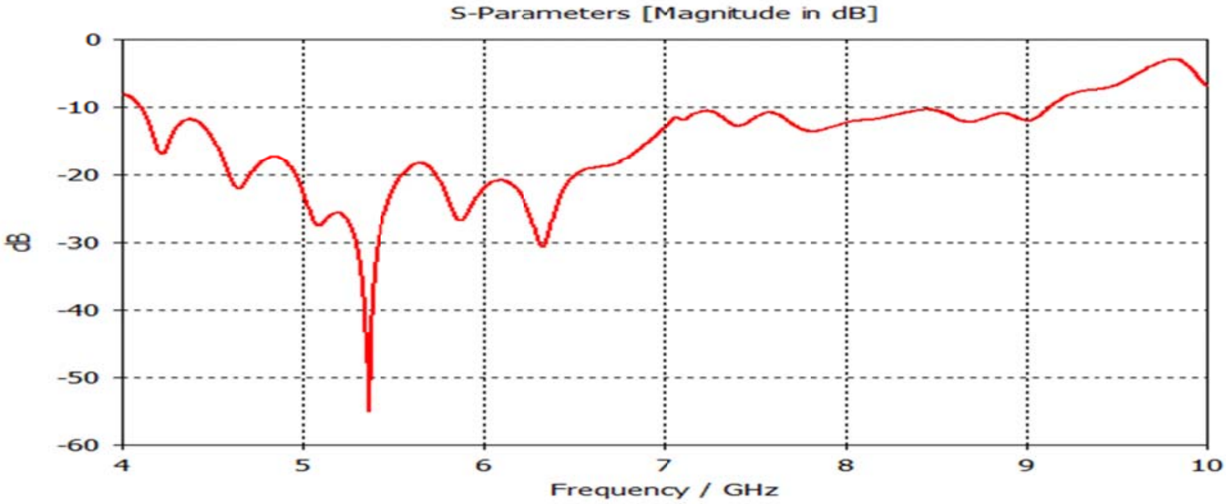

Figure 4: Return loss plot for pyramidal horn antenna at 5.85GHz and 8.20 GHz.

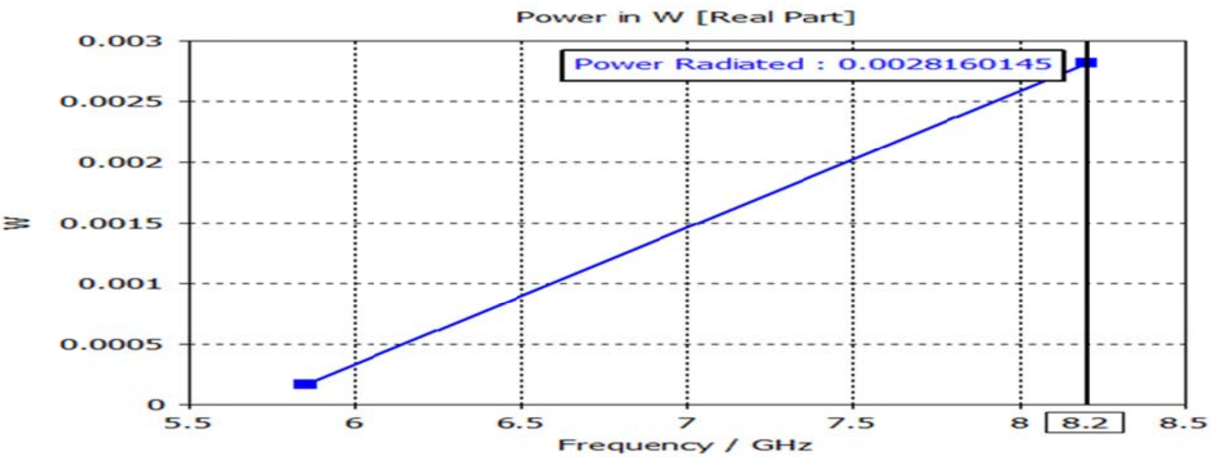

Figure 5: Radiated power on the designed horn antenna at 8.20 GHz.

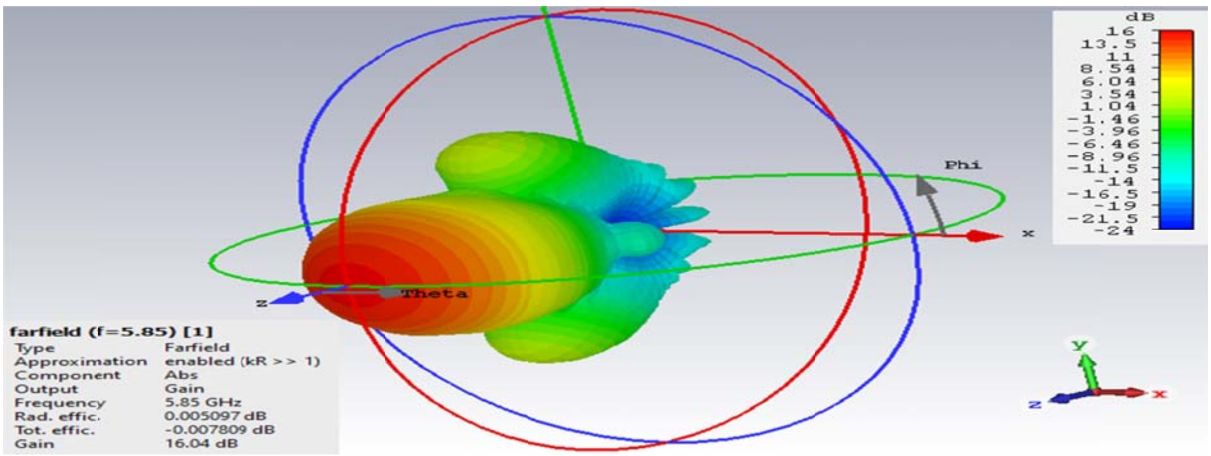

Figure 6: 3-D Standard gain of proposed horn antenna at 5.85 GHz.

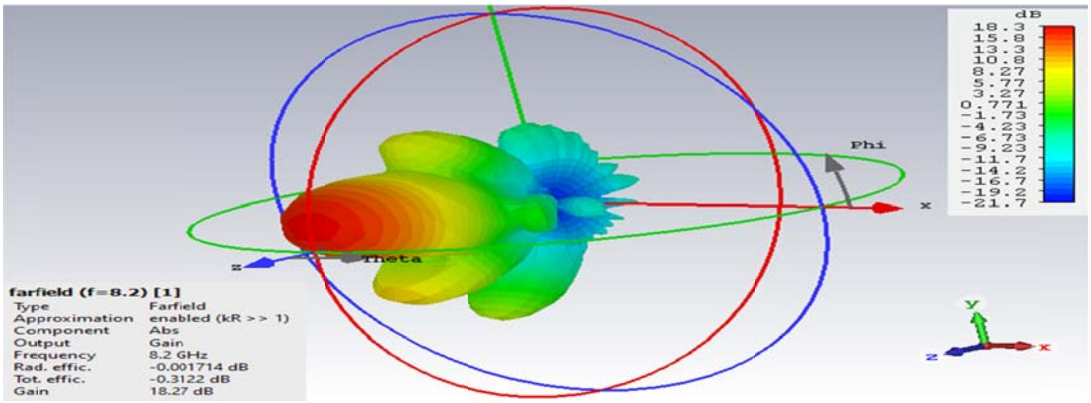

Figure 7: 3-D Standard gain of proposed horn antenna at 8.20 GHz.

V. CONCLUSION

In this paper, a rectangular waveguide was used to feed the designed and simulated pyramidal horn antenna using CST microwave studio software. Various antenna parameters such as return loss, VSWR, gain, directivity and impedance bandwidth were obtained in the simulation. Also the designed pyramidal horn antenna is considered stable and suitable to be operated within the given frequency range of 5.85 GHz to 8.20 GHz. The lower return loss and voltage standing wave ratio assures that the signal radiated is almost in equilibrium state. It means that the signal transmitted and the signal received is almost perfect with lower attenuation. The higher gain of 18.27 dB obtained proves that the antenna preferentially radiate in a particular direction with higher radiated power. The higher directivity attained indicates the strengthen region where the maximum gain is accumulated

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