Radiation Analysis and Design of Pyramidal Horn Antenna

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Abstract:

In Modern times need for wideband applications has increased. In recent years there have been many research works are going on in the design of antenna system as it is the main source for any communication system. The horn is nothing more than a hollow pipe of different cross sections, which has been tapered (flared) to a larger opening. The type, direction, and amount of taper (flare) can have a profound effect on the overall performance of the element as a radiator. The Horn Antenna is widely used in the EMC measurement, radar and communication system. Especially for wireless broadband applications horn antennas are the best choice. Horn is one of the simplest and probably the most widely used microwave antenna. In this paper we present the design and radiation pattern analysis of a specific horn antenna i.e. Pyramidal Horn. The paper contains introduction to horn antennas, the pyramidal horn, design of Pyramidal horn and conclusion.

Key words: Horn Antenna, Pyramidal horn, Radiation pattern, Directivity.

I. INTRODUCTION

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The horn is widely used as a feed element for large radio astronomy, satellite tracking, and communication dishes found installed throughout the world [1]. Advantages of horn antenna over other types of antennas are: (a) Less Complexity involve in the design of horn antenna as compared to phased array antennas & corrugated cousins [3]. (b) High data rate systems needs to be operated at a higher frequency range in order to achieve higher bandwidth. This can be easily achieved using a horn antenna (c) complex feeding techniques are required to feed an antenna, rather feeding a horn antenna is less complex (d) If horn antenna is properly designed & optimized than side lobes can be suppressed to very low levels. (e) As the horn is waveguide fed antenna, its Power handling capability is superior to other antennas, especially in the use of TWTs used in satellites, radars and many other applications making it an ideal choice for space applications. Horns have conventionally been used in terrestrial microwave communications. They can also be found on many Line-Of-Site (LOS) microwave relay towers [1]. Among all the horns pyramidal horn has been attracting the designers because of its light weight, simplicity in its design, low VSWR and for its good results. 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. The applications of pyramidal horn antennas are a) they have been widely used for space applications from the very beginning due to their capability of being best operation from Megahertz to Terra hertz range, b) Used in remote sensing satellites, communication satellites, geographic information & weather satellite, c) Various space programs in which horn antennas are used by NASA, ESA, d) It is used when there is a high gain requirement and e) it is used when there is a high directionality requirement.

II. PYRAMIDAL HORN ANTENNA

The pyramidal horns are popular for their well known attractive features like light weight, low VSWR, low profile and compatibility. As it is being flared in both directions its radiations characteristics are essentially a combination of the e- and h-plane sectoral horns and its geometry coordinate system[7] is shown in Fig.1. The horn can be treated as an aperture antenna. To find its radiation characteristics the equivalent principle techniques can be utilized. To develop an exact equivalent of it, it is necessary that the tangential electric and magnetic field components over a closed surface are known. The closed surface that is usually selected is an infinite plane that coincides with the aperture of the horn. When the horn is not mounted on an infinite ground plane, the fields outside the aperture are not known and an exact equivalent cannot be formed [6]. However, the usual approximation is to assume that the fields outside the aperture are zero. The fields at the aperture of the can be found by treating the horn as a radial wave guide. The fields within the horn can be expressed in terms of cylindrical TE and TM wave functions which include Henkel functions. This method finds the fields not only at the aperture of the horn but also within the horn. To find the fields radiated by the horn, only the tangential components of the e- and/or h-fields over a closed surface must be known. The closed surface is chosen to coincide with an infinite plane passing through the mouth of the horn. The directivity is one of the parameters that is often used as a figure of merit to describe the performance of an antenna. To find directivity, the maximum radiation is formed.

So, the need to develop a Wideband horn antenna for communication and calibration purposes[6]. With the development of measurement, communication system, radar techniques and electromagnetic, the horn antenna has been widely used which made it one of the most practical antennas. This horn antenna can effectively extend the working bandwidth of the antenna and improve the impedance matching between waveguide and free space [2].

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A) **Aperture Fields, Equivalent, and Radiated Fields**

The analysis of aperture antennas is typically quite different than the analysis of wire antennas. Rather than using the antenna current distribution to determine the radiated fields, the fields within the aperture are used to determine the antenna radiation patterns [1].

The tangential components of the *e*- and *h*-fields over the aperture of the horn are approximated by

$$E'_y(x',y') = E_0 \cos\left(\frac{\pi}{a_1}x'\right) e^{-j\left[\frac{k\left(\frac{x'^2}{\rho 2}+\frac{y'^2}{\rho 1}\right)}{2}\right]} \quad \text{--} \quad (1)$$

$$H'_x(x',y') = (-E_0/\eta) \cos\left(\frac{\pi}{a_1}x'\right) e^{-j\left[\frac{k\left(\frac{x'^2}{\rho 2}+\frac{y'^2}{\rho 1}\right)}{2}\right]} \quad \text{--} \quad (2)$$

and the equivalent current densities are approximated by

$$J_y(x',y') = (-E_0/\eta) \cos\left(\frac{\pi}{a_1}x'\right) e^{-j\left[\frac{k\left(\frac{x'^2}{\rho 2}+\frac{y'^2}{\rho 1}\right)}{2}\right]} \quad \text{--} \quad (3)$$

$$M_x\,(x^{'},y^{'}) = \; E_0 \cos\,(\frac{\pi}{a_1}\text{x'})\; e^{-j\,[\frac{k\left(\frac{x^{',2}}{\rho\,2}+\frac{y^{',2}}{\rho\,1}\right)}{2}]} \qquad \text{--} \qquad (4)$$

Now after formulating the normalized factors and they are given by

$$N_{\theta} = -\,(E_0/\eta)\cos\theta\,\sin\text{Ø}\;I_1\,I_2 \qquad \text{--} \qquad (5)$$

$$N_{\text{Ø}} = -\,(E_0/\eta)\cos\text{Ø}\;I_1\,I_2 \qquad \text{--} \qquad (6)$$

$$L_{\theta} = E_0\cos\theta\,\cos\text{Ø}\;I_1\,I_2 \qquad \text{--} \qquad (7)$$

$$L_{\text{Ø}} = -E_0\sin\text{Ø}\;I_1\,I_2 \qquad \text{--} \qquad (8)$$

The horn can be treated as an aperture antenna.By combining equations (5),(6),(7) and (8) its far-zone (In the far field zone only the θ *and* Ø components of e-field and h-field are dominant and the radial components (Er = 0) are negligible compared to θ *and* Ø components) e-field and h-field components are given by

$$E_{\theta} = -j\frac{k\,e^{jkr}}{4\pi r}\,[L_{\text{Ø}} + \eta\,N_{\theta}] \qquad \text{--} \qquad (9)$$

(or)

$$= -j\frac{kE_0\,e^{-jkr}}{4\pi r}\,[\sin\text{Ø}(1+\cos\theta)\;I_1\,I_2] \qquad \text{--} \qquad (10)$$

$$E_{\text{Ø}} = +j\frac{k\,e^{-jkr}}{4\pi r}\,[L_{\theta} - \eta\,N_{\text{Ø}}] \qquad \text{--} \qquad (11)$$

(or)

$$\underline{= j\frac{kE_0\,e^{-jkr}}{4\pi r}\,[\cos\text{Ø}\,(\cos\theta+1)\;I_1\,I_2]} \qquad \text{--} \qquad (12)$$

The above equations (9-12) represents the fields radiated by a pyramidal horn which are valied for all angles of observation and they shows that the principal E-plane pattern ($\text{Ø} = \frac{\pi}{2}$) of a pyramidal horn is identical to the E-plane pattern of an E-plane sectoral horn on neglecting a normalization factor.Similarly the H-plane pattern ($\text{Ø} = 0$) is identical to the H-plane sectoral horn.Therefore the radiation pattern of a pyramidal horn is very narrow in both E and H principal planes and, infact in all planes.Fig.2. illustrates the three-dimentional field pattern of a pyramidal horn($\rho_1 = \rho_2 = 6\lambda, a_1 = 5.5\lambda, b_1 = 2.75\lambda, a = 0.5\lambda, b = 0.25\lambda$).

The maximum radiation for a pyramidal horn is not necessarily directed along its axis because,the phase error taper at the aperture is such that the rays emanating from the different parts of the aperture toward the axis are not in phase and do not add constructively.

To physically construct a pyramidal horn, the dimentions p_e of Fig.1(b) and p_h of Fig.1(c) should be equal and are given by[1]

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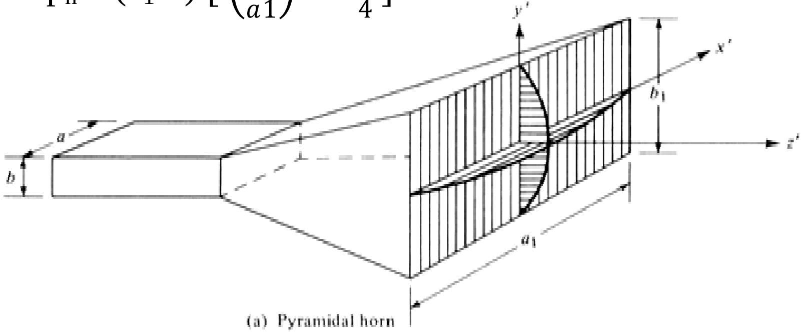
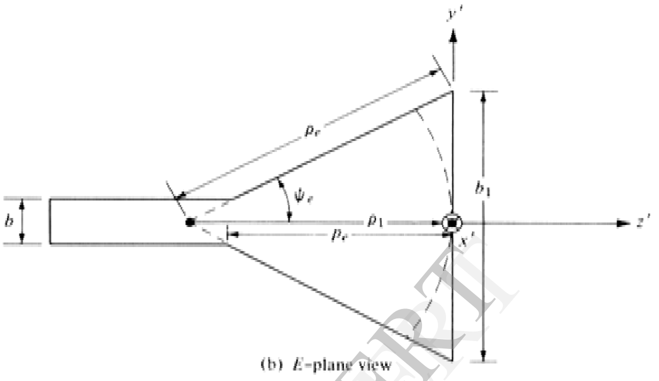
$$p_e = (b_1 - b)\left[\left(\frac{\rho_e}{a1}\right)^2 - \frac{1}{4}\right]^{1/2} \quad \text{--} \quad (13)$$

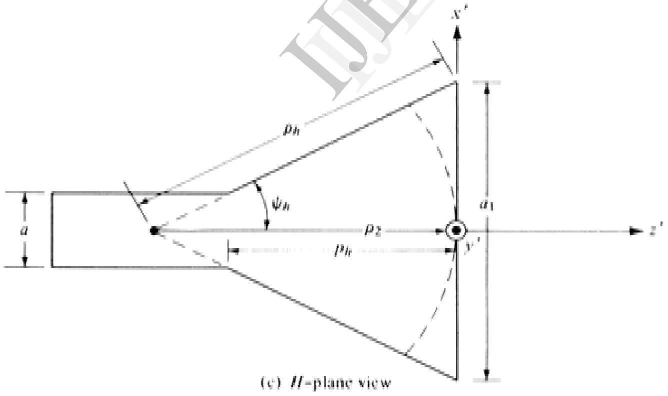
$$p_h = (a_1 - a)\left[\left(\frac{\rho_h}{a1}\right)^2 - \frac{1}{4}\right]^{1/2} \quad \text{--} \quad (14)$$



(a) Pyramidal horn



(b) E-plane view



(c) H-plane view

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Fig.1 Pyramidal horn and coordinate system

B) Directivity

The directivity is one of the parameters that is often used as a figure of merit to describe the performance of an antenna [1]. To find the directivity, the maximum radiation is formed. That is, the maximum radiation of the pyramidal horn is directed nearly along the *z*-axis ($\theta = 0^\circ$). Using equations (9) and (12), $|E_\theta|_{max}$, $|E_\varphi|_{max}$, and in turn U_{max} can be written as

$$|E_\theta|_{max} = |E_0 \sin \o| \frac{\sqrt{\rho_1 \rho_2}}{r}\{[C(u) - C(v)]^2 + [S(u) - S(v)]^2\}^{1/2}$$
$$\cdot \{C^2\left(\frac{b_1}{\sqrt{2\lambda\rho_1}}\right) + S^2\left(\frac{b_1}{\sqrt{2\lambda\rho_1}}\right)\}^{1/2} \quad \text{--} \quad (15)$$

$$|E_{\text{ø}}|_{\max} = |E_0 \cos \text{ø}|\, \frac{\sqrt{\rho_1\ \rho_2}}{r}\{[C(u) - C(v)]^2 + [S(u) - S(v)]^2\}^{1/2}$$
$$.\ \{C^2(\frac{b_1}{\sqrt{2\lambda\rho_1}}) + S^2(\frac{b_1}{\sqrt{2\lambda\rho_1}})\}^{1/2} \quad \text{--} \quad (16)$$

$$U_{\max} = \frac{r^2}{2\eta}\, |\boldsymbol{E}|^2_{\max} = |E_0|^2\ \frac{\rho_1\ \rho_2}{2\eta}\{[C(u) - C(v)]^2 + [S(u) - S(v)]^2\}$$
$$.\ \{C^2(\frac{b_1}{\sqrt{2\lambda\rho_1}}) + S^2(\frac{b_1}{\sqrt{2\lambda\rho_1}})\} \quad \text{--} \quad (17)$$

Where u and v are defined by

$$u = \frac{1}{\sqrt{2}}(\frac{\sqrt{\lambda\rho_2}}{a_1} + \frac{a_1}{\sqrt{\lambda\rho_2}}) \quad \text{--} \quad (18)$$

$$v = \frac{1}{\sqrt{2}}(\frac{\sqrt{\lambda\rho_2}}{a_1} - \frac{a_1}{\sqrt{\lambda\rho_2}}) \quad \text{--} \quad (19)$$

Since $P_{rad} = |\boldsymbol{E}|^2(\frac{a_1 b_1}{4\eta})$ -- (20)

The directivity of the pyramidal horn can be written as

$$D_p = \frac{4\pi\, U\max}{P_{rad}} = \frac{8\pi\,\rho_1\ \rho_2}{a_1 b_1}\{[C\ (u) - C\ (v)]^2 + [S\ (u) - S\ (v)]^2\}$$
$$.\ \{C^2(\frac{b_1}{\sqrt{2\lambda\rho_1}}) + S^2(\frac{b_1}{\sqrt{2\lambda\rho_1}})\} \quad \text{--} \quad (21)$$

which reduces to

$$D_p = \frac{\pi\lambda^2}{32ab}\, D_E\, D_H \quad \text{--} \quad (22)$$

Where D_E and D_H are directivities of the E- and H- plane sectoral horn and are given by

$$D_E = \frac{4\pi\, U\max}{P_{rad}} = \frac{64\pi\, a\, \rho_1}{\pi\lambda}\, |F(t)|^2 = \frac{64\pi\, a\, \rho_1}{\pi\lambda b_1}\, [C^2(\frac{b_1}{\sqrt{2\lambda\rho_1}}) + S^2(\frac{b_1}{\sqrt{2\lambda\rho_1}})] \quad \text{--} \quad (23)$$

$$D_E = \frac{4\pi\, U\max}{P_{rad}} = \frac{4\pi\, b\, \rho_2}{a_1\lambda}\, .\{[C\ (u) - C\ (v)]^2 + [S(u) - S(v)]^2\} \quad \text{--} \quad (24)$$

Equation (22) is a well known relationship and has been used extensively in the design of pyramidal horns. The directivity (*in dB*) of a pyramidal horn, over isotropic, can also be approximated by

$$D_p\,(dB) = 10[1.008 + \log_{10}(\frac{a_1 b_1}{\lambda^2})] - (L_e + L_h) \quad \text{--} \quad (25)$$

Where L_e and L_h represent, the losses (in dB) due to phase errors in the E- and H- planes of the horn respectively.

III.DESIGN OF PYRAMIDAL HORN ANTENNA

The Horn Antenna can be used as a transmit antenna, receive antenna or as a gain standard with gains from 9.5 to 22.0 dBi [5].It's wide bandwidth and predictability is ideal for many broadband applications. Horns covering different frequency bands with various beam width and gain options are needed. The pyramidal horn is widely used as a standard to make gain measurements of other antennas. To design a pyramidal horn, one usually knows the desired gain G_0 and the dimensions a, b of the rectangular feed waveguide. The objective of the design is to determine the remaining dimensions (a_1, b_1, ρ_e , ρ_h, p_e, and p_h) that will lead to an optimum gain. Optimum

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directivities for the E- and H- plane sectoral horns can be obtained by selecting values of b_1 and a_1. Since the overall efficiency (including both the antenna and aperture efficiencies) of a horn antenna is about 50%, the gain of the antenna can be related to its physical area. Thus

$$G_0 = \frac{4\pi\, a_1 b_1}{2\lambda^2} = \frac{2\pi}{\lambda^2}\sqrt{3\lambda\,\rho_2}\;\sqrt{2\lambda\rho_1} = \frac{2\pi}{\lambda^2}\sqrt{3\lambda\rho_h}\;\sqrt{2\lambda\rho_e} \quad \text{--} \quad (26)$$

Since for long horns $\rho_2 = \rho_h$ and $\rho_1 = \rho_e$ .For pyramidal horn to be physically realizable, p_e, and p_h must be equal.using this equality, it can be shown that equation(39) reduces to

$$\left(\sqrt{2\chi} - \frac{b}{\lambda}\right)^2 (2\chi - 1) = \left(\frac{G0}{2\pi}\sqrt{\frac{3}{2\pi}}\frac{1}{\sqrt{\chi}} - \frac{a}{\lambda}\right)^2 \left(\frac{G0^2}{6\pi^3}\frac{1}{\chi} - 1\right) \quad \text{--} \quad (27)$$

Where

$$\frac{\rho_e}{\lambda} = \chi \quad \text{and} \quad \frac{\rho_h}{\lambda} = \frac{G0^2}{8\pi^3}\left(\frac{1}{\chi}\right) \quad \text{--} \quad (28)$$

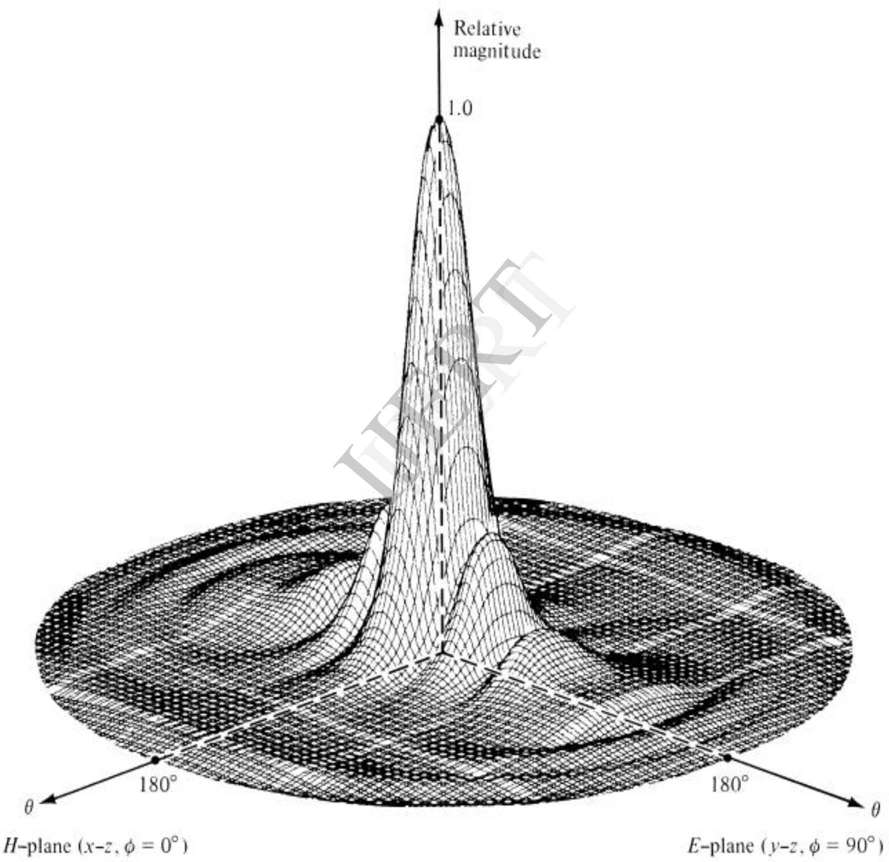

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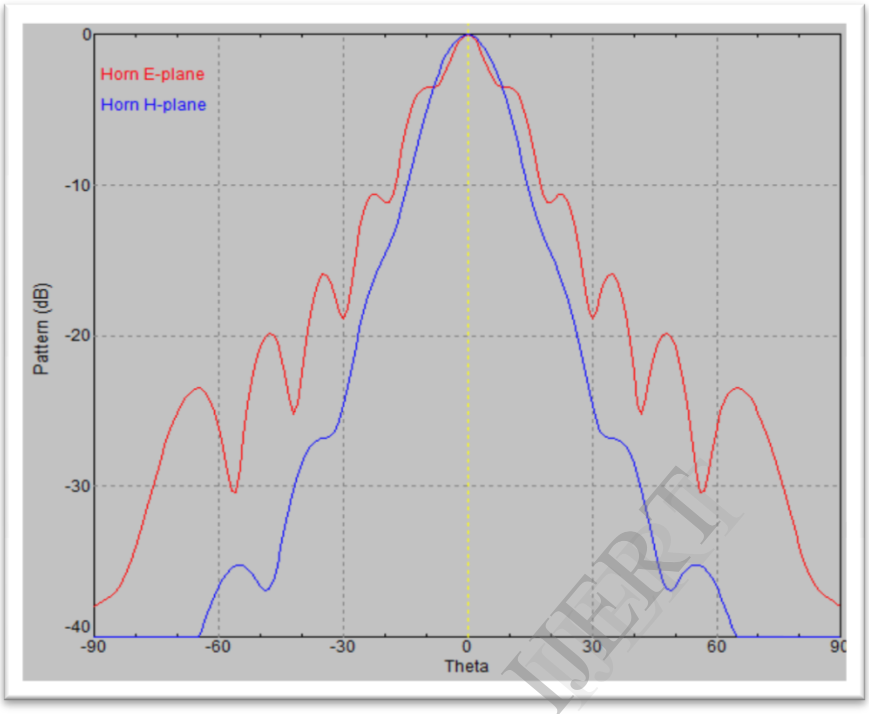
Fig.2 Three-dimensional field pattern of a Pyramidal horn for $\rho_1 = \rho_2 = 6\lambda, a_1 = 5.5\lambda, b_1 = 2.75\lambda, a = 0.5\lambda, b = 0.25\lambda$ and $\rho_e = \rho_h = 5.4544\ \lambda$.

IV.RESULT & CONCLUSION

In this paper we have presented the design and radiation pattern analysis of Pyramidal Horn Antenna. It was designed using advanced PCAAD 5.0 [8] with the following dimensions : E-plane aperture dimension a_1=16.370cm and H-plane aperture dimension b_1=12.859 cm, E-plane axial horn length p_e= p_h =27.286 cm . Low aperture diameter is used to have high aperture efficiency low phase factor resulting in compact size. The design was performed to accomplish an ultra-wide bandwidth (more than 50%), with low side-lobe and cross polar levels. The selected frequency bands were X and Ku. Higher order modes are excited at junction between aperture and waveguide due to large flare angles. The simulation results directivity as 20.8 dB, the horn E-plane 3 dB beam width is 12.60^0 , the horn H-plane 3 dB beam width is 15.36^0 maximum E-plane phase error is 162^0 and maximum H-plane phase error is 100^0.The results of rectangular radiation pattern, polar pattern and 3D patterns are shown in Fig.3,Fig.4 and Fig.5 respectively.



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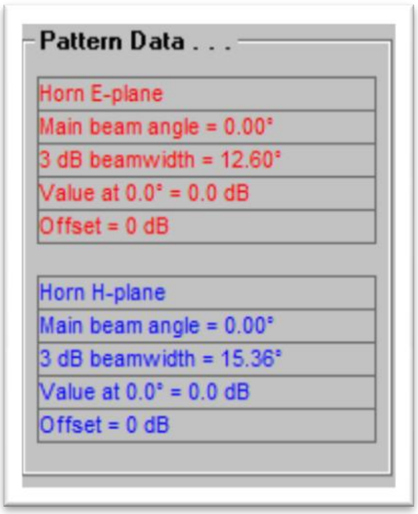
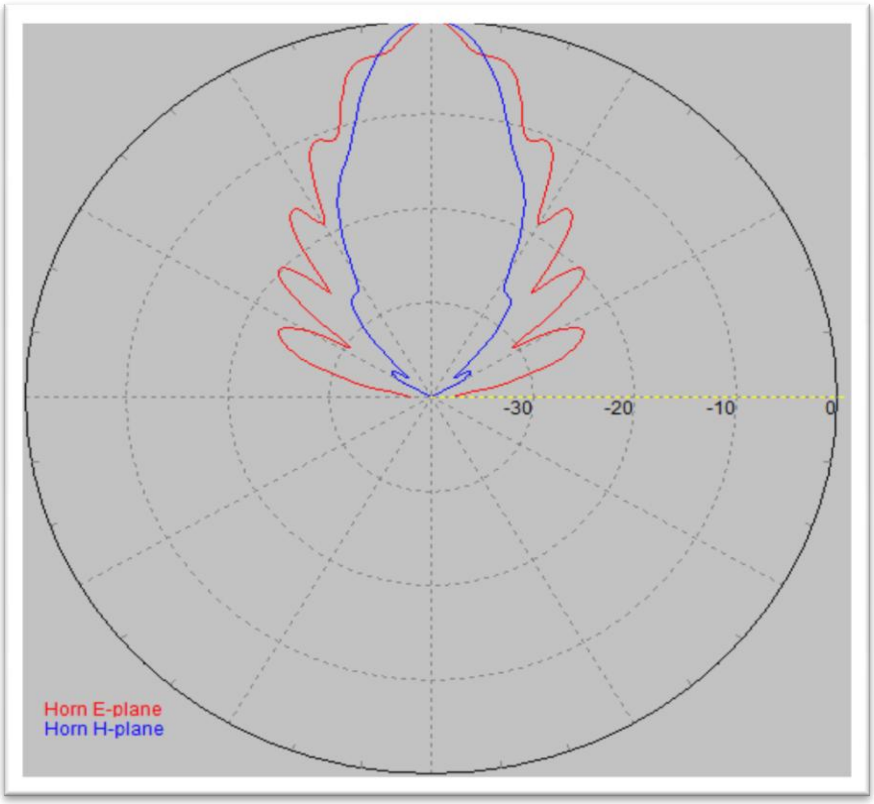
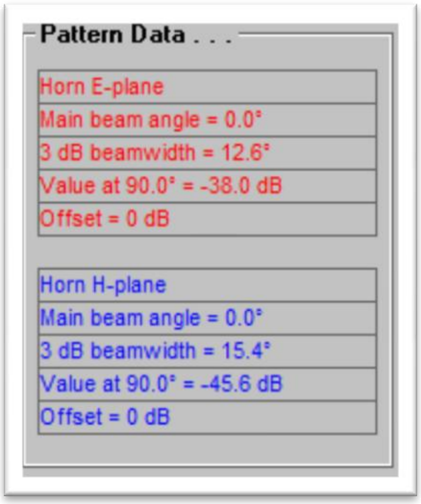

Pattern Data . . .

Horn E-plane
Main beam angle = 0.00°
3 dB beamwidth = 12.60°
Value at 0.0° = 0.0 dB
Offset = 0 dB

Horn H-plane
Main beam angle = 0.00°
3 dB beamwidth = 15.36°
Value at 0.0° = 0.0 dB
Offset = 0 dB

Fig.3. Rectangular field pattern




Pattern Data . . .

Horn E-plane
Main beam angle = 0.0°
3 dB beamwidth = 12.6°
Value at 90.0° = -38.0 dB
Offset = 0 dB

Horn H-plane
Main beam angle = 0.0°
3 dB beamwidth = 15.4°
Value at 90.0° = -45.6 dB
Offset = 0 dB

Fig.4. Polar field pattern

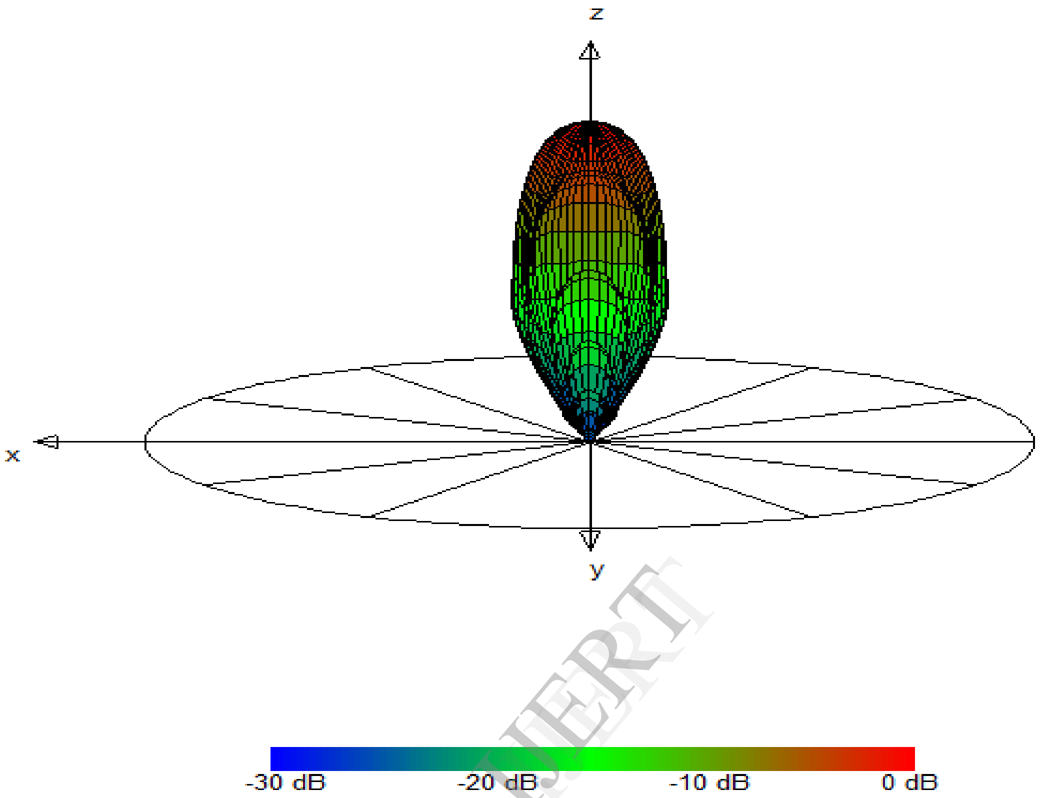


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Fig.5. 3D field pattern

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