DESIGN OF HIGH GAIN WIDEBAND QUAD-RIDGED HORN ANTENNA FOR EMC TESTING

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DESIGN OF HIGH GAIN WIDEBAND QUAD-RIDGED HORN ANTENNA FOR EMC TESTING

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To My wife

ABSTRACT

This thesis presents a design and simulation of high gain wideband quad-ridged circular horn antenna for Electromagnetic Compatibility (EMC) testing. The selected operating frequency range of the antenna is from 1 GHz to 6 GHz, which is implemented for radiated emission and radiated immunity tests. The antenna is designed as a quad-ridged which is desired to be used in the horizontal and vertical polarization measurements simultaneously. To determine the antenna gain parameter, Vestel test systems are considered as well as actual needs. The gain of the horn antenna currently used in laboratories is not enough for the 3 meters testing. Therefore, 1 meter testing window method is used for radiated, radio-frequency, electromagnetic field immunity tests which are in the scope of EN61000-4-3 standard. Hence, the designed horn antenna gain is aimed to be have approximately 14 dBi. CST Microwave Studio is used in the design of the horn antenna and simulation results. The simulation results show that the antenna gain is approximately 14 dBi, also at least about 10 dB return loss (S_{11} and S_{22}) separately for each port providing horizontal and vertical polarization and the isolation of the ports is more than -27 dB.

ÖZETÇE

Bu tezde, Elektromanyetik Uyumluluk (EMU) testlerinde kullanılmak üzere tasarlanan geniş bantlı ve yüksek kazançlı quad-ridged dairesel horn anten anlatılacaktır. Anten çalışma frekans bandı 1 GHz - 6 GHz aralığında olup, ışınımla yayınım ve bağışıklık testlerinde kullanılabilmesi hedeflenmiştir. Antenin Quad-Ridged olarak tasarlanma nedeni, yayınım testlerinde aynı anda yatay ve dikey polarizasyonda ölçüm alınabilme isteğidir. Anten kazanç hedefi belirlenirken, kullanılması planlanan test sistemlerindeki gereklilikler temel alınmıştır. EN 55024 standardı kapsamında olan ışınımla Bağışıklık testinde horn antenin kazancı 3 metrede test yapılabilmesi için yeterli olmadığından dolayı pencere metodu ile 1 metrede test yapılabilmektedir. Bu nedenle tasarlanan antenin kazancı, 3 metrede test yapabilmek için 14 dBi olarak hedeflenmiştir. Bu amaçla tasarlanan Quad-Ridged Horn antenin simülasyonları, CST Microwave Studio programı ile gerçekleştirilmiştir. Bu simülasyonlar sonucunda, tasarlanan antenin bant boyunca kazancının 14 dBi civarında, yatay ve dikey polarizasyonu sağlayan her iki port için ayrı ayrı geri dönüş kayıplarının en az 10 dB civarında (S11 ve S22 saçılım parametrelerinin en fazla -10 dB civarında) ve portlar arası girişimin (bağlaşımın) ise 25 dBden fazla olduğu (S21 parametresinin -27 dBden az olduğu) görülmüştür.

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LIST OF ABBREVIATIONS

AF Antenna Factor.

a_i Radii of horn at feed point.

a_o Radii of horn at horn aperture.

DRH Double-Ridged Horn.

EMC ElectroMagnetic Competibility.

EMI ElectroMagnetic Interference.

ERP Effective Radiated Power.

EUT Equipment Under Test.

FAC Full-Anechoic Chamber.

GRP Ground Reference Plane.

L Taper Length of Horn.

OATS Open-Area Test Site.

PEC Perfect Electric Conductor.

R Exponential opening rate of horn.

RF Radio-Frequency.

SAC Semi-Anechoic Chamber.

θ_{3dB} Half-power beamwidth.

UFA Uniform Field Area.

UHF Ultra-High Frequency.

VSWR Voltage Standing Wave Ratio.

CHAPTER I

INTRODUCTION

1.1 Motivation

An antenna (aerial) is a transducer which converts electric power into radio-frequency (RF) field in transmitting or converts radio-frequency field to electric power in receiving [1]. Transmitter antennas radiate energy which is supplied from the input port, while the receiver antennas intercept the radiated energy in environment and converts that power to tiny voltage to read from the antenna input port. Typical antennas are produced by using metallic conductors (elements) that are connected to input terminal through a transmission line for transmitting or receiving energy. Horn shaped widening metal waveguide composes horn antenna instead of canalizing radio waves in beam pattern. Horn antennas are widely used at frequencies including ultra high frequency (UHF) and microwave frequencies, i.e., above 300 MHz [2]. Indian radio researcher Jagadish Chandra Bose analyzed one of the first horn antenna in his microwave experiments in 1987 [3], [4]. Horn antennas are mostly used in radar systems, satellite systems, standards gain measurements at antenna design, microwave radiometric and short range radar systems. Generally, gain and directivity of horn antennas are very close to each other due to almost perfect radiation efficiency. Most of them operate from 1 GHz to 18 GHz, however, antenna theory dictates that antenna gain and directivity are poor at lower frequencies. Furthermore, half-power beamwidth decreases dramatically as the frequency used by a horn antenna increases. In this thesis, designed horn antenna gain at 1 GHz is almost 14 dB and half-power beamdwith is almost stable in whole operation frequency owing to the ridges and utilized function for both ridges and the sidewall.

Horn antennas can be grouped in several types depending on sidewall shape. They are classified as pyramidal horns, sectoral horns which are divided into two parts (E plane horn and H plane horn), conical horns, corrugated horns, exponential horns and ridged horns. Operation of a horn antenna over a wide frequency range provides high performance since there is no resonant element. Owing to the special features of broadband Double-Ridged Horn (DRH) antennas such as high gain and directivity performance, low voltage standing wave ratio (VSWR) and acceptable half-power beamwidth over the entire frequency band, they are appropriate choices for Electromagnetic Compatibility (EMC) testing and standard antenna measurements. Moreover, features such as easy excitation, relatively simple construction and high peak power handling capability make these antennas widely used in other different areas such as satellite tracking systems, reflectors feeding and radars. Most popular type is the pyramidal horn because of easy design and less parameters that affect the antenna parameters, i.e., gain, bandwidth. Furthermore, hybrid antennas can be considered such that pyramidal horn and ridged horn can be combined for high gain projects. Designed horn antenna that will be mentioned in Chapter V, is similar to the exponential type (x^p function used instead of the exponential function). Besides, four ridges (two ridges for both polarizations) are added to the design to increase the gain.

Generally, the pyramidal horns with two ridges can be found on markets because pyramidal horn can be designed and fabricated easily. However, pyramidal horn antenna beamwidth decreases dramatically while frequency increases and low gain can be found at lower frequencies. In this thesis, designed horn antenna can change a bit this situation. On the other hand, designed horn antenna has minimum level of internal reflections, good impedance matching and almost constant gain over a wide frequency range. Therefore, many high performance applications, i.e., communication satellite systems, use horn antenna designed by using the exponential function.

Exponential antenna loaded with ridges increases the gain and bandwidth at lower frequencies. The designed horn antennas have usually one feed point. Therefore two ridges enough for regular operation. In our design, two input ports that are used for horizontal and vertical polarization simultaneously to minimize measurement time, are put with four ridges.

The designed horn antenna was build up on CST Microwave Studio by using Matlab. Matlab codes set the parameters affecting the horn shape physically, i.e., feed point radius, ridges gap. To determine the antenna type, all models that are mentioned in Fig. 3, are simulated and compared with the simulation results. Then, radius at the horn aperture is changed to find optimum gain and half-power beamwidth values. Scattering parameters and VSWR results are found by simulation after fixing all parameters.

EMC means avoiding disturbance (radiated or conducted) to other electronic equipment by producing Electromagnetic Interference (EMI) or performing without any degradation of normal operation in electromagnetic disturbances [5]. EMC test systems which are performed radiated, can be constituted in chambers, i.e., Semi-Anechoic Chamber (SAC) and Full Anechoic Chamber (FAC)) or Open Area Test Site (OATS. Generally, Horn antennas are used in radiated tests above 1GHz frequency. Horn antenna was designed with two input (or measurement) port to reduce test time due to using two polarizations (horizontal and vertical) at the same time. Another contribution of the designed antenna is to provide enough gain for radiated immunity test at 3 meters that decreases the test time nine times according to window method testing.

1.2 Contributions

The contents in this thesis is published in the following work :

B. Solak, S. Hilavin, E. Alan, M. Seçmen, "Design of High Gain Wideband Quad-Ridged Horn Antenna for EMC Testing", *The 3rd EMC Turkiye Conference*, 2015.

The main contributions achieved in this thesis are listed as follows:

- Firstly, quad-ridged horn antenna is examined with high gain at lower frequencies for EMC testing.
- x^p function profile with quad-ridged structure is analyzed.
- Antenna is designed with two input port for simultaneously testing dual polarization.
- Return losses, isolation of ports and VSWR ensure that the radiated signal is almost equilibrium state.

Parameter	Marketted Antenna R&S HF907	Designed Antenna
Minimum S Parameter	-7dB	-10dB
Minimum 3dB Beamwidth	20 degree	24 degree
Minimum Gain	6dBi	13.7dBi
Maximum Antenna Factor	34.79 dB/m	25 dB/m
Maximum Voltage Standing Wave Ratio	2.75	1.91

Table 1: Summary of the comparison with marketed antenna parameters

1.3 Organization

In this work, horn antenna structures, antenna parameters, EMC applications and simulation results are discussed.

Horn antenna geometries are classified into linear, sinusoid, tangential, x^p, hyperbolic, polynomial, asymmetric sine squared, exponential and elliptical geometries. All profile options are presented and mathematical expressions are given. Besides that, important antenna parameters, such as gain, antenna factor (AF), half-power beamwidth and VSWR are explained in details.

The most important part of radiated EMC test systems is the transmitter or receiver antenna. Several types of antennas are investigated for EMC testing that are fulfill the restrictions according to corresponding standards. Log-periodic antenna, biconical antenna, loop antenna, hybrid antenna and horn antenna that are used in different tests related to operation frequency range, are most popular antenna types for EMC testing. In this work, over 1 GHz radiated testing is focused on field strength (radiated emission) testing, effective radiated power testing and radiated immunity testing. Detailed explanations and antenna requirements are given in Chapter IV.

Many applications of antennas requiring wide bandwidth and high gain, utilizes the horn antenna at high frequencies. Prior works on horn antennas are designed with symmetrical ridges to obtain wide bandwidth. However, antenna design profiles for both sidewall and ridges affect the bandwidth and gain results. Generally, ridged horn antennas are designed by using mathematical functions which are given in fig. 3. All these functions are designed and compared with the simulation results to determine the best solution for EMC testing. Another parameter that is directly changes the beamwidth and gain results, is the ratio of a_o/a_i, where, a_o is the radius at horn aperture and a_i is the radius at feed point. In this work, the ratio of a_o/a_i is changed and simulated to observe the effects on the gain and the bandwith.

Simulation results chapter 6 simulates the scattering parameters, VSWR, gain and half-power beamwidth of the designed horn antenna. Moreover, the performance results of the designed antenna are compared with the EMC antenna restrictions. Results show that the designed antenna can be used for EMC testing above 1GHz.

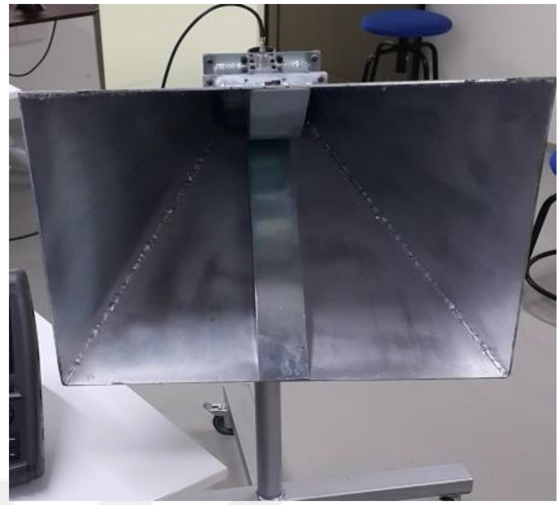
CHAPTER II

PREVIOUS WORK

Horn antennas can be classified into, pyramidal horn, sectoral horn, conical horn, exponential horn, corrugated horn, septum horn and ridged horn. The first example dates back to 1940s with the type pyramidal including dual-ridged waveguide based structure for ultra-wideband capabilities [7], [8]. Mainly part of first investigations depended on transverse-resonance routines and on determining equivalent circuits for the ridged waveguide to figure cut-off frequencies [31]. Then, in [9] Hopfer analyzed various performance parameters including cut-off frequency, attenuation, etc. A generalized analysis that complete eigenvalue spectrum is included in the structures was found by Montgomery [10]. These works proved that the dual-ridged waveguide has a larger bandwidth than hollow waveguides because of the ridges decreasing the dominant mode cutoff frequency. Dual-ridged waveguides and horns have practical disadvantages about supporting single linear polarization. Hence, quad-ridged structures have large bandwidths similarly and they can be utilized in dual linear polarization studies. Fig. 2 gives the picture two fabricated antennas. One of them is quad-ridged and circular horn antenna and the other one is double-ridged and rectangular horn antenna.

The finite element method in [13] and magnetic field integral equations defined in [14]and [15] have been used for examining the cut-off frequency of quad-ridged waveguides and generating mode fields as a function of ridge-ridge gap and ridge thickness. These analyses demonstrate that single-mode bandwidth of the waveguide is not as large as their dual-ridged counterparts while the dominant mode cut-off frequency in the quad-ridged design is decreased. The main reason of this is splitting

(a) Quad-ridged circular horn antenna [11]



(b) A double-ridged rectangular horn [12]

Figure 1: Circular and rectangular horn antennas with quad and double ridges

of TE_{21} and TE_{20} modes of the circular and square waveguides.

Generally, there are two ways to achieve broadband character and high gain which are modifying the feed or changing the sidewall and ridge shapes [16], [17], [18]. Most of prior works focussed on exponential and elliptical profiles for ridges and sidewall in horn antenna applications. Furthermore, pyramidal profile was preferred for sidewalls because of fabrication considerations and simple design [19], [20], [21]. We have worked on other profile options that are linear, sinusoidal, tangential, x^p, hyperbolic, polynomial, asymmetric sine squared, exponential and elliptical geometries, to find an optimal solution for EMC testing [22]. A new design profile that is x^p function for sidewalls and ridges, was used in this work in order to reach gain and half-power beamwidth specification. Quad-ridged horn antennas were considered for measuring in anechoic chambers but the designed antenna can be used with high power amplifiers at lower frequencies [23]. Therefore, the high gain quad-ridged antenna is analyzed in a whole frequency range (1 GHz- 6 GHz) for EMC testing.

CHAPTER III

HORN ANTENNAS

3.1 Horn Antenna Parameters

For EMC test systems, antenna gain, AF, scattering parameters, VSWR and half-power beamwidth are significantly important parameters, so the ridged horn antenna is proper for EMC antenna design application. Practically, EMC test system suppliers have double-ridged horn antennas on the market, but quad-ridged horn antenna is not commonly used in EMC testing. The main difference of quad-ridged and double-ridged horn antenna is additional two ridges and one input port to use the antenna for both polarizations simultaneously (horizontal and vertical).

3.1.1 Gain

In literature, an antenna gain shows the performance of transforming the power of input port to radio beam to the specified direction. As a receiving antenna, antenna gain is called AF that is conversion of radio waves arriving from a specified direction to electrical power. However, AF and antenna power convert to each other by using below formulas:

$$Af = 20\,\log\,[\frac{2\,\pi}{\lambda}\sqrt{\frac{2.4}{10^{Gain\,/\,10}}}] \tag{1}$$

$$Gain = 10\,\log\,[2.4\,(\frac{2\,\pi}{\lambda\,10^{(Af\,/\,20)}}] \tag{2}$$

Antenna Gain is usually expressed in decibels and unit of antenna gain is "decibels-isotropic"(dBi). Moreover, the AF unit is dB/m.

3.1.2 Scattering Parameters

Scattering parameters (S-parameters) describe the input and output relationship between ports or terminals in an electrical system. For antenna theory, commonly used antennas have 1 port, so only return loss (S_{11}) is measured as scattering parameters. On the other way, antennas with two input port can be designed and measured S-parameters can be listed as S_{11}, S_{12}, S_{21} and S_{12} which is explained in Table 2 [24].

S_{11}	Reflection from port 1.
S_{12}	Transferred power from port 1 to port2. Furthermore, the isolation of input ports for the antenna designed in this thesis.
S_{21}	Transferred power from port 2 to port1. Furthermore, the isolation of input ports for the antenna designed in this thesis.
S_{22}	Reflection from port 2.

Table 2: Explanation of Scattering parameters

In general, S_{NM} presents the power transferred from Port M to Port N in a multi-port system or the isolation from port M to port N.

3.1.3 Half-power beamwidth

The half-power beamwidth is the angular separation in which the magnitude of the radiation pattern decreases by 50% (or -3 dB) from the peak of the main lobe. Fig. 2 is an example of the radiation pattern of the antenna and also, shows the main lobe and 3 dB beamwidth point. Furthermore, fig. 2 shows the 3 dB degradation point of the main lobe is approximately 18.7° and

$$\theta_{3dB} = 2x18.7^{\circ} = 37.4^{\circ}. \tag{3}$$

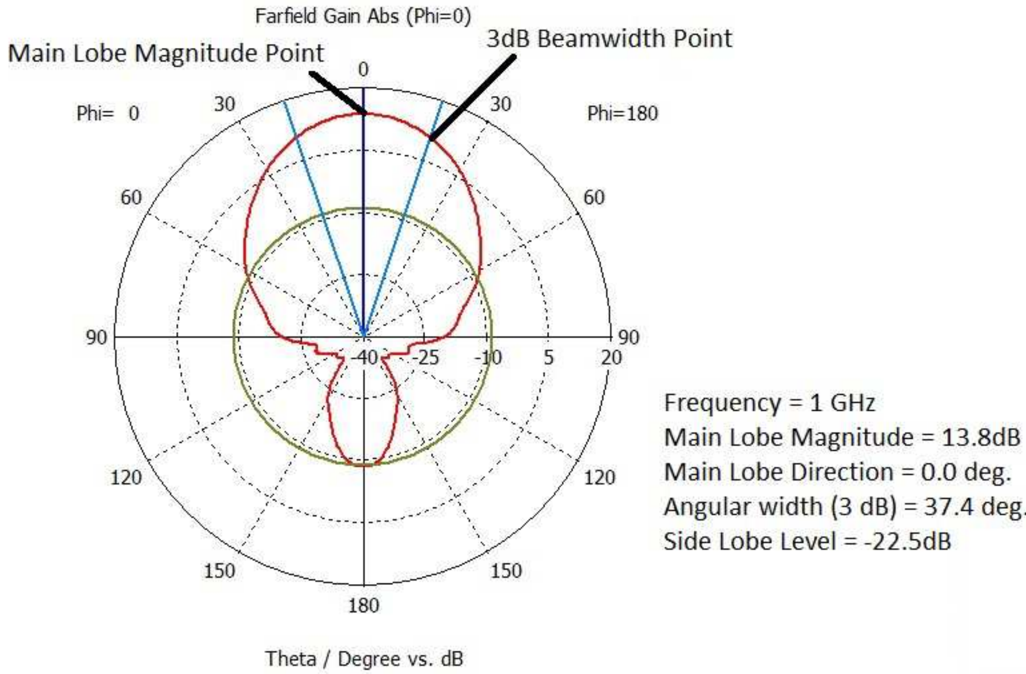


Figure 2: Example radiation pattern of antenna

3.1.4 Voltage Standing Wave Ratio (VSWR)

Measurement of antenna impedance matching to the connected line can be expressed numerically by VSWR. VSWR can be calculated by using the reflection coefficient, which presents reflected power from connection port. The VSWR calculation formula is

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{4}$$

where Γ is the reflection coefficient. The reflection coefficient is also known as S_{11} or return loss in dB as $-20\log_{10}|\Gamma|^2$.

3.2 Horn Antenna Structures

While there are many profiles for ridge and sidewall to achieve horn antenna limitations for EMC testing. Horn antenna geometry can be defined by using many parameters. These profiles can affect the antenna gain and half-power beamwidth significantly. While the majority of the prior work on double-ridged and quadruple-ridged horns focuses on exponential and elliptical profiles for both ridges and sidewall, we have investigated many other profiles in this research, most of which are from corrugated and smooth-wall horn literature [25].

Fig. 3 gives examples of horn geometries and expressions. As you can see, many different functions can be considered in a ridge and a sidewall of the horn antenna. All these expressions, you need to determine some parameters before building the geometry.

Profile name	Expression
Linear	$a(z) = a_i + (a_o - a_i)\frac{z}{L}$
Sinusoid	$a(z) = a_i + (a_o - a_i)\left[(1-A)\frac{z}{L} + A\sin^p\left(\frac{\pi z}{2L}\right)\right]$
Tangential	$a(z) = a_i + (a_o - a_i)\left[(1-A)\frac{z}{L} + A\tan^p\left(\frac{\pi z}{4L}\right)\right]$
x^p	$a(z) = a_i + (a_o - a_i)\left[(1-A)\frac{z}{L} + A\left(\frac{z}{L}\right)^p\right]$
Hyperbolic	$a(z) = \sqrt{a_i^2 + \frac{z^2\left(a_o^2 - a_i^2\right)}{L^2}}$
Polynomial	$a(z) = a_i + (p+1)(a_o - a_i)\left(1 - \frac{pz}{(p+1)L}\right)\left(\frac{z}{L}\right)^p$
Asymmetric sine-squared	$a(z) = \begin{cases} a_i + \frac{2(a_o-a_i)}{1+\gamma}\sin^2\left(\frac{\pi z}{4L_1}\right) & 0 \le z \le L_1 \\ a_i + \frac{2(a_o-a_i)}{1+\gamma}\left[\gamma\sin^2\left(\frac{\pi(z+L_2-L_1)}{4L_2}\right) + \frac{1-\gamma}{2}\right] & L_1 \le z \le L \end{cases}$ where $L = L_1 + L_2$ and $\gamma = \frac{L_2}{L_1}$
Exponential	$a(z) = (1-A)\left[a_i + (a_o - a_i)\frac{z}{L}\right] + A\left(c_1 e^{Rz} + c_2\right)$ where $c_1 = \frac{a_o - a_i}{e^{RL}-1}$, $c_2 = \frac{a_i e^{RL} - a_o}{e^{RL}-1}$.
Elliptical	$x = a_o + r_1\cos\theta\cos\phi - r_2\sin\theta\sin\phi$, $z = r_1\cos\theta\sin\phi + r_2\sin\theta\sin\phi$, where $r_1 = \max(a_o, L)$, $r_2 = \min(a_o, L)$, $\phi = \begin{cases} 0, & a_o > L \\ \pi/2, & \text{else} \end{cases}$

Figure 3: Profile options for ridge and sidewall. a_i and a_o are the radii at the feed point and horn aperture, respectively; L is the taper length; R is the exponential opening rate; p is the exponent of sinusoid, polynomial, x^p; and $\tan^p$ profiles and can take on values in the range [0;1] ; A is a parameter between [0; 1] that determines how much linear taper is added.

CHAPTER IV

EMC APPLICATIONS OF ANTENNAS

EMC is explained how well a device or system is able to operate in an electromagnetic environment without introducing electromagnetic disturbances that interfere with the operation of other electrical products in the environment. The EMC standards contain the qualification of a particular electronic product that depends on application area and the country in which the product is to be used. EMC studies the unintentional generation, propagation, and reception of electromagnetic energy [26]. EMC issues can be investigated into two main issues in order to achieve this. Emission issues are related to reducing the unwanted generation of the electromagnetic signal from designing products, which can involve proper working of the other products. Immunity or susceptibility issues interest the correct operation of equipment under test (EUT) in an electromagnetic field like a victim which is the reverse of emission.

4.1 Antenna Types for EMC Testing

The first log-periodic antenna array is published by R.H. Duhamel and D.E. Isbell in 1957. Uniform input impedance (low return loss), VSWR and radiation characteristics are the important features of the log-periodic antenna over wide frequency ranges. The invention of the first log-periodic antenna can be anticipated earlier because of design simplicity. The log-periodic antenna is built with a number of half-wave dipole antennas that increase length gradually to cover the whole frequency range, these dipole antennas are fed in a common transmission line. Most of the antenna designer investigates the log-periodic antenna even today since they are rugged, simple and versatile. EMC engineers think that log-periodic antennas are still the best available option for radiated test systems. The main disadvantage of the log-periodic antenna is the low gain over a wide bandwidth.

The using of wideband horn antenna technologies is being common for EMC testing by the day. Generally, several broadband antennas are used in EMC test systems to cover the whole frequency range. Using narrowband antennas have disadvantages for testing, so an efficient and accurate broadband antenna has to be developed [27]. Different types of wideband antennas are researched, i.e., biconical antenna, log-periodical antenna, helical antenna and ridged horn antenna.

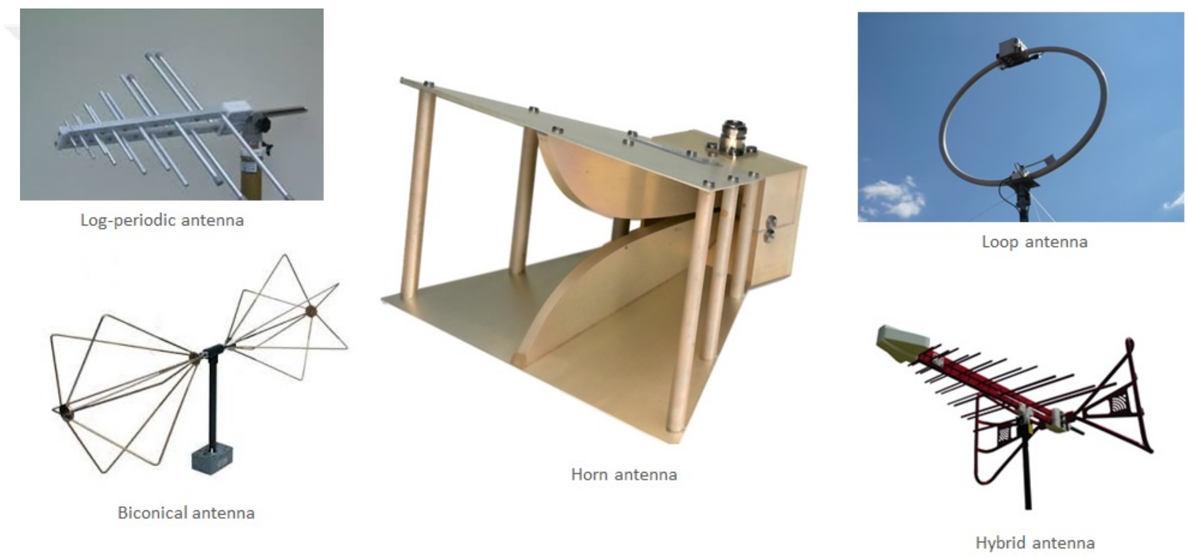


Figure 4: Example antennas for EMC testing

- Log-periodic Antenna: An antenna consists of a number of half-wave dipole driven elements of gradually increasing length, each consisting of a pair of metal rods.

- Biconical Antenna: A broad-bandwidth antenna made of two roughly conical conductive objects, nearly touching at their points.

- Loop Antenna: Consisting of a loop (or loops) of wire, tubing, or other electrical conductor with its ends connected to a balanced transmission line.

- Hybrid Antenna: By combining multiple types of antennas is the antenna to exploit the properties of all kinds of antennas. Today is the most widely used antenna type.
- Horn Antenna: An antenna that consists of a flaring metal waveguide shaped like a horn to direct radio waves in a beam.

4.2 Field Strength (Radiated Emission) Test

The field strength test is an emission test that controls the equipment's radiated electromagnetic emission level for not affect the other equipment's ordinary operation in the same environment. This test can be configured in two primary types of test sites that are Open Area Test Site (OATS) and Semi-Anechoic Chamber (SAC). The radiated emission test can be classified into two groups that are below 1 GHz and above 1 GHz. If the highest frequency of the internal sources of the EUT is above 1 GHz, the measurement shall be made up to 5 times the highest frequency or 6 GHz, whichever is less [28].

Ground reference plane (GRP) is included on the floor of fully compliant test site between EUT position and measuring antenna because of measuring reflected signals from the floor. EUT is positioned at 80 cm above GRP by using a non-conducted element like a wooden table and antenna mast is used for scanning in height from 1 m to 4 m and changing polarization (horizontal and vertical). Three measurement distances are mentioned in the commercial standards, which are 3 m, 10 m and 30 m. The measurement distance is considered according to the boundary of test setup which is mentioned in CISPR 22. The GRP is used to ensure predictable results irrespective of the actual ground material (wet or dry soil, concrete, etc.). However, actual cast may have complications in the test procedure (but it does introduce complications into the test procedure).

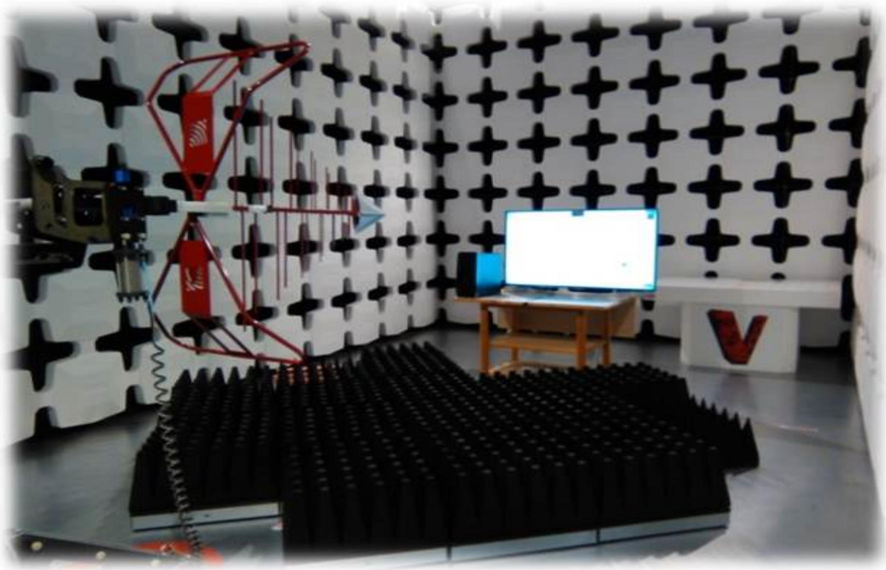


Figure 5: Example of radiated emission test setup above 1GHz

4.3 Effective Radited Power Test

Measurement of the radiated power due to the local oscillator at its fundamental and harmonic frequencies and due to all other sources. The measurements should be made by substitution method with the antenna having both horizontal and vertical polarizations and with a turntable to rotate EUT. The EUT is rotated by using the turntable until the highest level of emission is measured which shall be noted at each final measurement. Then, the EUT is placed by a transmitting antenna supplied by a standard generator and possessing the same characteristics as the receiving antenna.

For each measuring frequency, the output level of the generator is adjusted in order to give the same reference indication on the measuring receiver. The level of the available power of the generator, increased by the radiating antenna gain above the half-wave dipole, is taken as the level of the radiated power of the EUT at considered frequency. When a horn antenna is used instead of a dipole antenna, the measurement results shall be expressed in terms of effective radiated power (ERP). Furthermore, this test shall be made only having satellite receiver EUTs.

Figure 6: Example of effective radiated power test setup

4.4 Radiated Immunity

In some manner, most of the electronic equipment is affected by electromagnetic radiation. General purpose sources that are transceivers such as radio stations, television transmitters and industrial electromagnetic sources, generally generates this radiation which can affect the other equipment operation. In recent years there has been a significant increase in the use of radiotelephones and other RF emitting devices operating at frequencies between 0.8 GHz and 6 GHz.

For radiated immunity testing, electromagnetic field calibration is needed at 3m distance. The purpose of field calibration is to ensure that the uniformity of the field over the test sample is sufficient to ensure the validity of the test results. In a common procedure (field calibration), the capability of the test facility and the test equipment to generate such a field is demonstrated. The field calibration is performed with no EUT in place (see Fig. 7). Unless the EUT and its wires can be fully illuminated within a smaller surface, the size of the uniform field area (UFA) is at least 1,5 m x 1,5 m with its lower edge established at a height of 0.8 m above the floor.

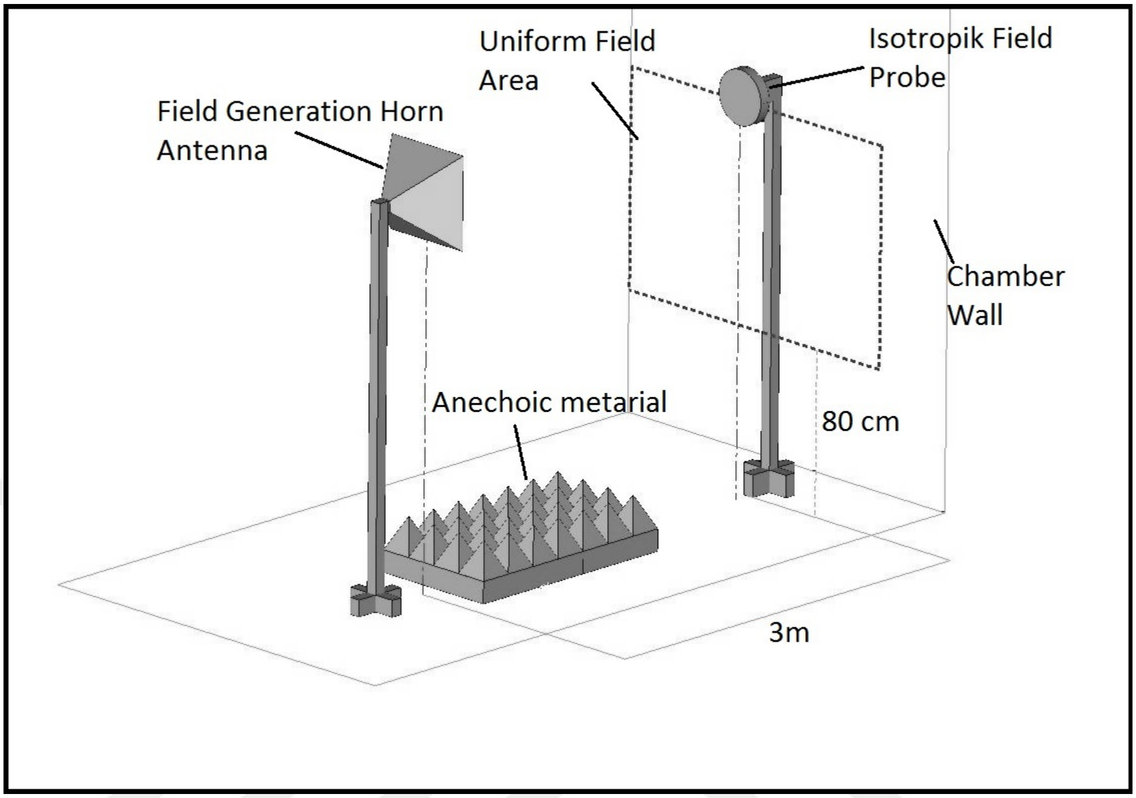


Figure 7: Schematic of field calibration

The UFA is subdivided into a grid with a grid spacing of 0,5 m (8 gives 1,5 m x 1,5 m UFA). At each frequency, a field is considered uniform if its magnitude measured at the grid points within from 0 dB to +6 dB of the nominal value. For the minimum UFA of 0,5 m x 0,5 m, the field magnitude for all four grid points shall lie within tolerance.

While testing above 1 GHz, it is hard to provide UFA at 3 m measurement distance. If UFA cannot be created above 1 GHz, the window calibration method can be done with a horn antenna at 1 m distance according to 61000-4-3 Annex H. The alternative method for frequencies above 1 GHz divides the calibration area into a suitable array of 0,5 m x 0,5 m windows such that the whole area to be occupied by the face of the EUT is covered. The field uniformity shall be independently calibrated over each window, using the procedure given by 61000-4-3 Annex H. Fig. 9 gives an

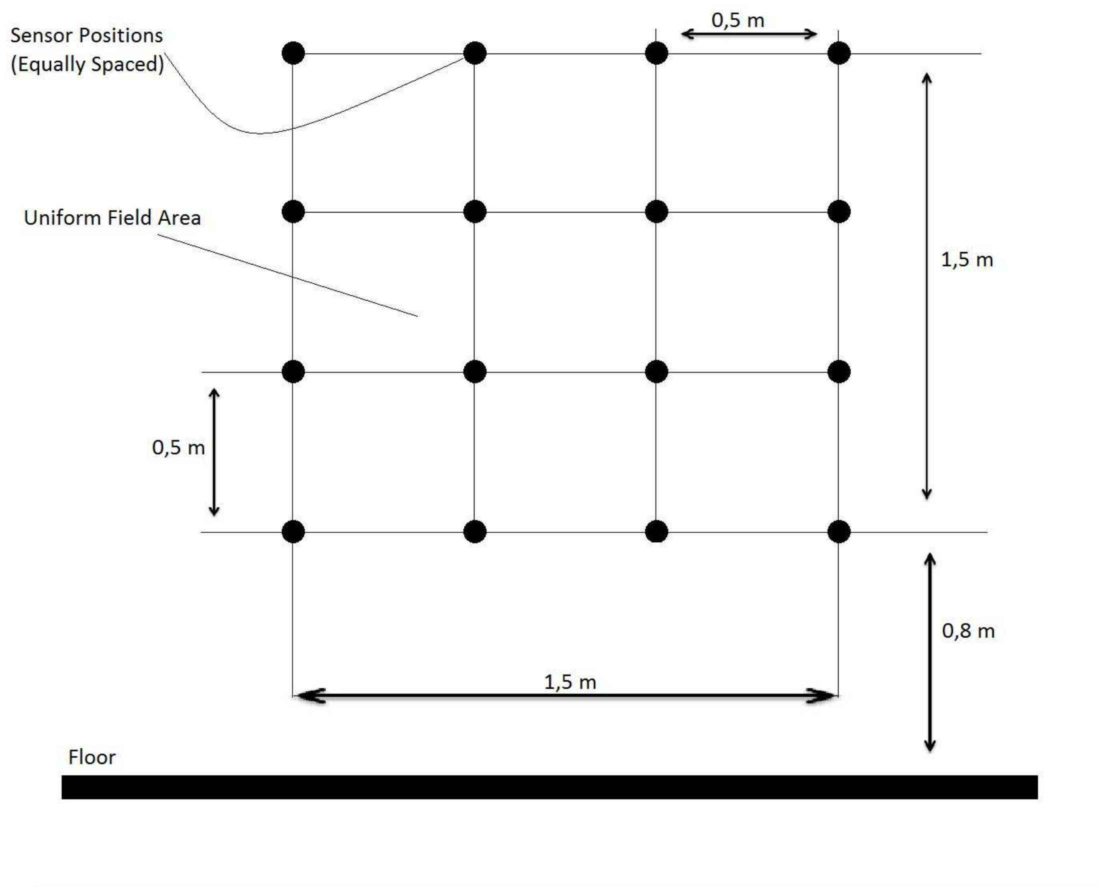


Figure 8: Example UFA with dimension 1,5 m x 1,5 m

example about testing above 1 GHz by using the window method. In this example, windows 1 to 6 are performed for calibration and test. However, this method testing can last 9 times longer compared to the other method. Providing UFA at 3m illuminating 1,5 m x 1,5 m area is mostly relevant to antenna gain and antenna half-power beamwidth.

UFA test level, i.e., 3 V/m, 6 V/m, can be adjusted to change amplifier gain or antenna gain. However, the problem of providing UFA at 16 point levels in Fig. 7 in tolerance 0 dB to +6 dB is exactly dependent on antenna half-power beamwidth values. Thus, an antenna with greater half-power beamwidth values is more suitable for radiated immunity testing.

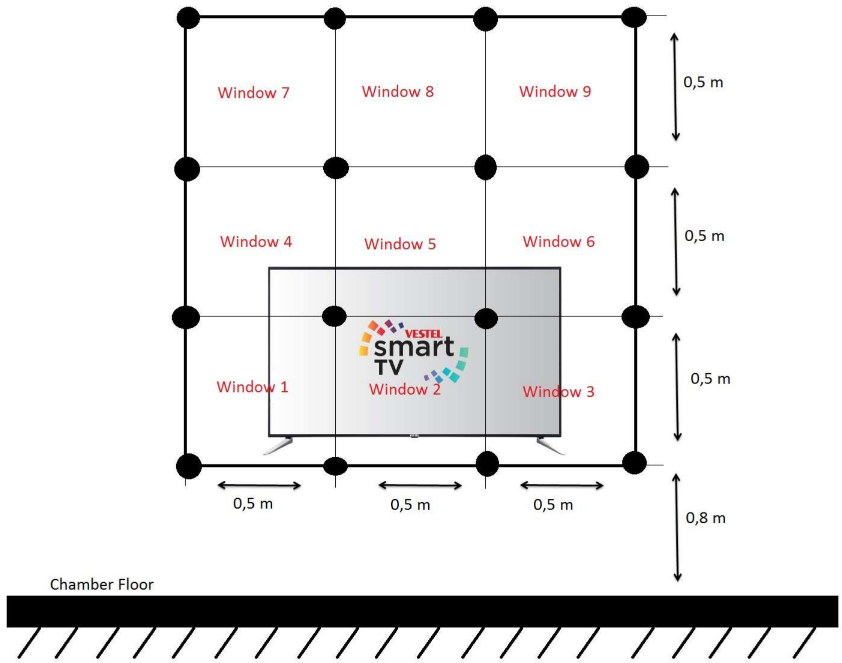


Figure 9: Example of testing above 1 GHz by using window method

4.5 Requirements for EMC Test Antennas

EMC ensures the correct operation, in the same electromagnetic environment of different electronic equipments which use or respond to electromagnetic phenomena and the avoidance of any interference effects. EMC tests can be examined in two classes of the issue. One of them is conducted tests that restrict the amount of interference your device can couple back onto a power supply or observation the equipment under test while electromagnetic interference injecting on a power supply. On the other hand, radiated tests restrict the amount of radiated electromagnetic interference from equipment under test or observation the equipment as a victim by applying the radiated electromagnetic interference by using an antenna. So, there are some restrictions in EMC test standards, i.e., CISPR 16 versions, for antenna parameters that are mentioned in section 1.2.

In radiated emission tests, system noise floor can be calculated by using eq. 5

while setting E (field strength) equals to 0. Antenna factor is one of the important parameters of an antenna that directly affect the system noise floor. EMC standards give limitation about system noise floor, according to the limit line. The system noise floor has to be 6 dB less than the limit line. If system noise floor is higher than the 6 dB to the limit line, preamplifier has to be used in the test system to reduce system noise floor.

$$V_{\mathrm{MEAS}}(dB\mu V) = E(dB\mu V/m) + AF(dB/m) + A(dB) \quad (5)$$

where V_{MEAS} is measured voltage at the EMI receiver, E is the field strength in the chamber, AF is the antenna factor and A is the cable and other losses between antenna EMI receiver.

Fig. 10 presents the system noise floor measurement by using A.H. System SAS-571 horn antenna. As it is seen in the figure, the field strength is approximately over 3 dB from the limit line.

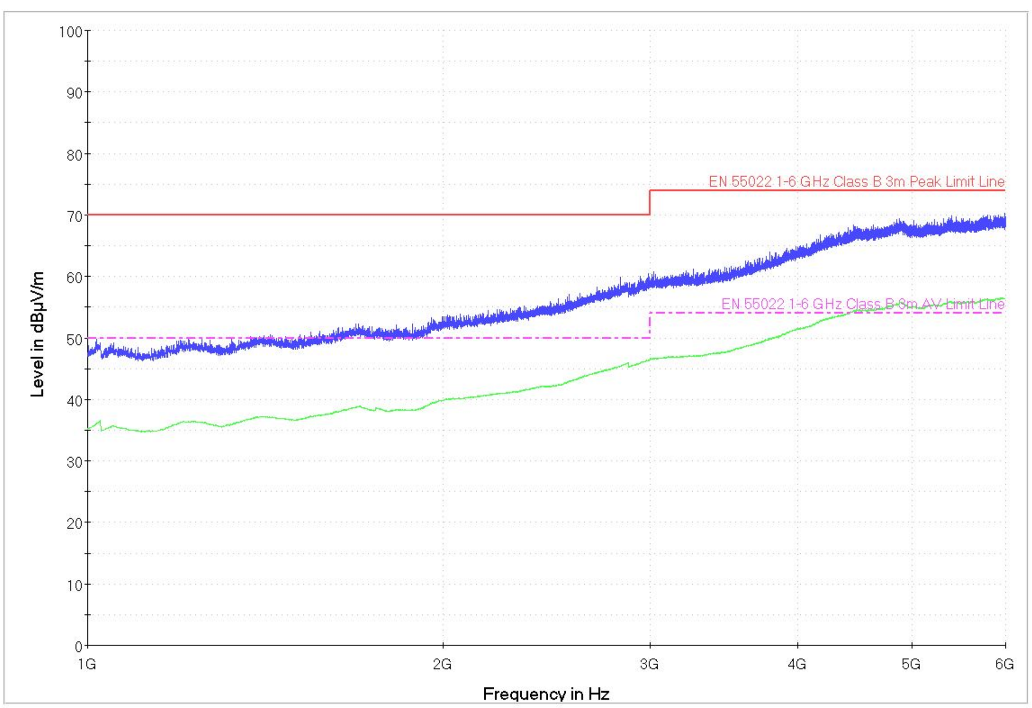


Figure 10: System noise floor in VESTEL chamber with SAS-571 horn antenna

VSWR gives information about the radiated signal is in an equilibrium state that means transmitted signal or received signal is almost perfect for reading or radiating. For Radiated Emission test, the receiver uses two different RF detectors that are Peak detector and RMS detector. Table 3 and Table 4 show the VSWR limits of a receiver input with different RF attenuation values for two detectors in CISPR 16-1-1 standard which gives technical information about radiated EMC test systems. In Table 3 and Table 4, RF Path Loss (dB) columns are total RF path attenuation from antenna to EMI receiver, i.e., total of cable loss, attenuator, connector loss. Practically, receiver input is connected to a cable which RF impedance is very close to 50 ohms in operation frequency range.

Frequency Range	RF Path Loss (dB)	VSWR
9 kHz to 1 GHz	0	2.0
9 kHz to 1 GHz	≥10	1.2
1 GHz to 18 GHz	0	3.0
1 GHz to 18 GHz	≥10	2.0

Table 3: VSWR limits for peak detector

Frequency Range	RF Path Loss (dB)	VSWR
9 kHz to 1 GHz	0	2.0
9 kHz to 1 GHz	≥10	1.2
1 GHz to 18 GHz	0	3.0
1 GHz to 18 GHz	≥10	2.0

Table 4: VSWR limits for RMS detector

The radiated field measurement method above 1 GHz is based on measurement of the maximum electric field emitted from the EUT. The dimension of the line tangent to the EUT formed by half-power beamwidth($\theta_{3\mathrm{dB}}$) at the measurement distance d. w values that are the dimension of the illumunating area, shall be calculated with the following formulation for each measurement distance.

$$w = 2\,d\,tan(0.5\,\theta_{3dB}) \tag{6}$$

where d is the measurement distance, and θ_{3dB} is half-power beamwidth of the antenna. Table 5 gives the w_{min} values for the illuminating area for in CISPR 16-2-3.

Frequency (GHz)	$\theta_{3dB,\,min}$; for d=1 m (°)	$\theta_{3dB,\,min}$; for d=3 m (°)	w_{min} (m)
1.00	60	22	1.15
2.00	35	12	0.63
4.00	35	12	0.63
6.00	27	10	0.48
8.00	25	9	0.44
10.00	25	9	0.44
12.00	25	9	0.44
14.00	25	9	0.44
16.00	5	2	0.09
18.00	5	2	0.09

Table 5: Minimum dimension of w (w_{min})

Consequently, all these limitations for EMC test antenna were considered while the quad-ridged horn antenna was designed. All profile functions were utilized for sidewall and ridges to find optimum results in the following chapter. Furthermore, the ratio of radii at feed point and radii at horn aperture was swept after profile function was determined.

CHAPTER V

QUAD-RIDGE HORN ANTENNA DESIGN

The high gain ridged horn antenna has the accomplishment of widening the bandwidth, which is based on the design theory of the horn antenna. Horn antenna with symmetrical ridges can suppress the transmission of higher harmonic mode TE_{20},so the horn antenna which loaded with ridges can widen the bandwidth in great degree [29]. The dual-ridged antenna can achieve wideband performance, and the quad-ridged horn antenna can employ the dual polarization characteristics.

In [30] and [18], the cylindrical and conical back cavities are implemented; however, the overall most of these structures were reported to yield no more than 3:1 bandwidth which is not sufficient for EMC emission and immunity tests. In this study, a transition depicted in Fig. 11 is designed to acquire satisfactory reflection and isolation performance. When the structure in Fig. 11 is investigated, there is a back-shorted part behind feed probes, which has the cross section of a quadruple circular waveguide with different ridge dimensions than feed quadruple circular waveguide. Therefore, hollow circular waveguide cavity used in [30] is replaced with a quadruple circular waveguide.

For aperture antennas such as horns, it is well known that maintaining constant beamwidth as a function of frequency implies that aperture fields must be tapered at the aperture edges with increasing frequency [31]. When the dimension of aperture enlarges some degree, the side lobe level will rise and electricity performance will be worse severely, as the field phase difference between edge and center of the aperture. So, the field phase difference is not greater than $\pi/4$. However, it depletes the gain performance.

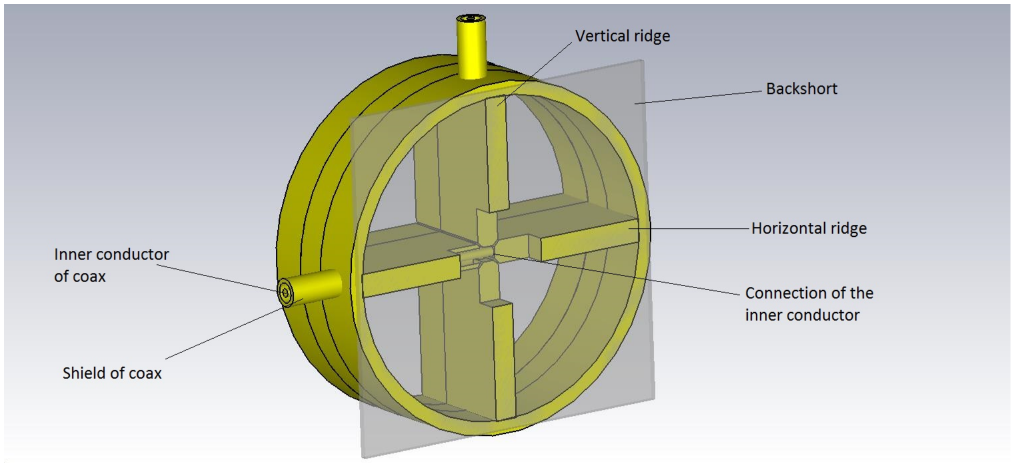


Figure 11: The designed structure for the transition from coaxial feeds to circular quad-ridged waveguide where back-short metallic wall is deliberately shown as transparent.

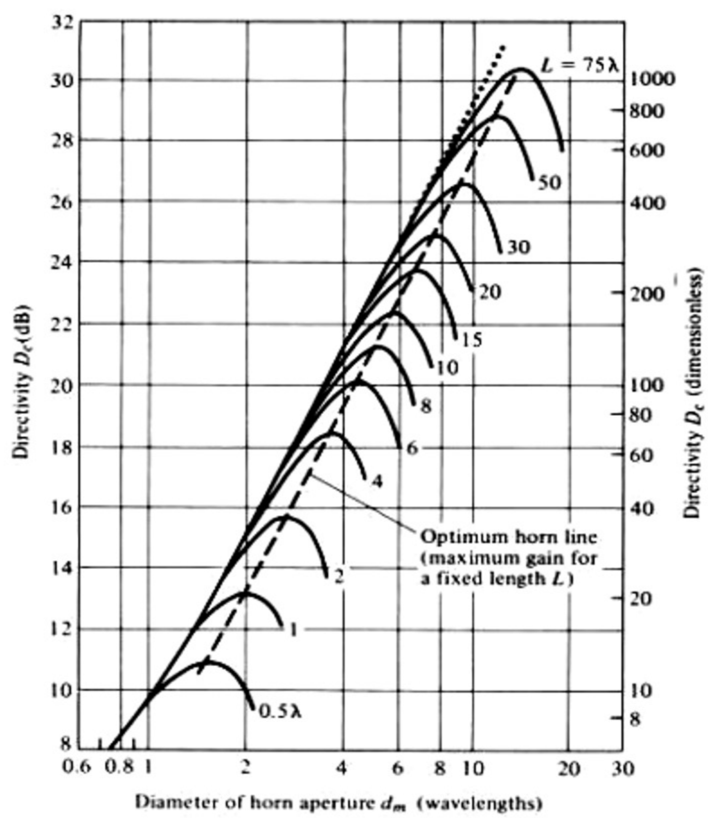


Figure 12: Directivity of a conical horn w.r.t. diameter of horn aperture and axial length [31]

Firstly, directivity (in dB) of horn antenna is decided to calculate radius at horn aperture with eq. 7.

$$D_{\mathrm{c}}(dB) = 10\,\log_{10}[\epsilon_{\mathrm{ap}}\,\frac{4\,\pi}{\lambda^2}\,(\pi\,a^2)] \tag{7}$$

where ϵ_{ap} is the appeture efficiency and a is the radius at horn aperture. Rewrite the eq. 7 for calculating a:

$$a = \sqrt{\frac{10^{D_{\mathrm{c}}(dB)/10}\,\lambda^2}{\epsilon_{\mathrm{ap}}\,4\,\pi^2}} \tag{8}$$

Using the eq. 8; aperture radius a is calculated as 28.7 cm where $\mathrm{D_c}$ equals 13 dB, λ is 30 cm (wavelength at 1 GHz) and ϵ_{ap} is 51% according to [31].

Another parameter is the length of the horn antenna. Eq. 9 and eq. 10 give the maximum phase deviation (in number of wavelengths) w.r.t. the diameter of horn aperture (2*a) and lambda and length of the horn for optimum horn dimensions.

$$s = \frac{{d_{\mathrm{m}}}^2}{8\,\lambda\,l} \tag{9}$$

$$\frac{l}{\lambda} - \frac{L}{\lambda} = 0.3 \tag{10}$$

In eq. 9,when s sets the $\pi/4$ and lambda is 5 cm (wavelength at 6 GHz), l is calculated as 112.3 cm where l is the radial length. According to eq. 10, the axial length of horn (L) is calculated by using l and λ, which equals to 110.8cm [32]. Furthermore, the scale of radius at the horn aperture and radius at the feed point set to 5. The axial length of horn antenna is 88.64 cm. However, chambers in Vestel city which are using for EMC measurements, have dimension restrictions. Maximum antenna length is measured as 61cm. So, the axial length of horn antenna is selected as 60.3cm. Profile examination results are given with calculated parameters above.

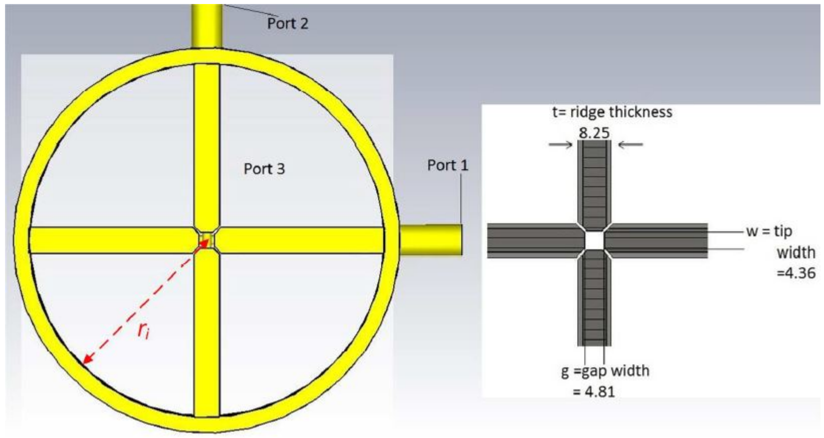
In the design, it is targeted to obtain reflection coefficient lower than -10 dB for both ports (S_{11} -10 dB and S_{22} -10 dB), isolation greater than 30 dB, and the transmission coefficients of all possible and effective higher order modes such as TE_{21}, TE_{01}, TE_{31} and TM_{01} modes lower than -10 dB for an effective suppression of these undesired modes. The dimensions of the designed transition structure are obtained after performing an optimization process in CST Microwave Studio. The corresponding dimensions are given in Fig. 13 along with relevant cut views of the structure.

The optimum circular waveguide radius is found to be about $r_i = 57.12$ mm, and the corresponding cutoff frequencies of TE_{11}, TM_{01}, TE_{21}, TE_{01} and TE_{31} modes can be calculated approximately as 1.54 GHz, 2.01 GHz, 2.56 GHz, 3.21 GHz and 3.52 GHz, respectively, for a standard hollow circular waveguide [24]. Therefore, this standard hollow circular waveguide without any ridges inside can only operate within 1.5-2 GHz for a single mode operation, and even TM_{01} mode is suppressed, its bandwidth is not more than 1.66:1. If a frequency band of 1-6 GHz is desired, the cutoff frequency of fundamental TE_{11} mode should be decreased to below 1 GHz.

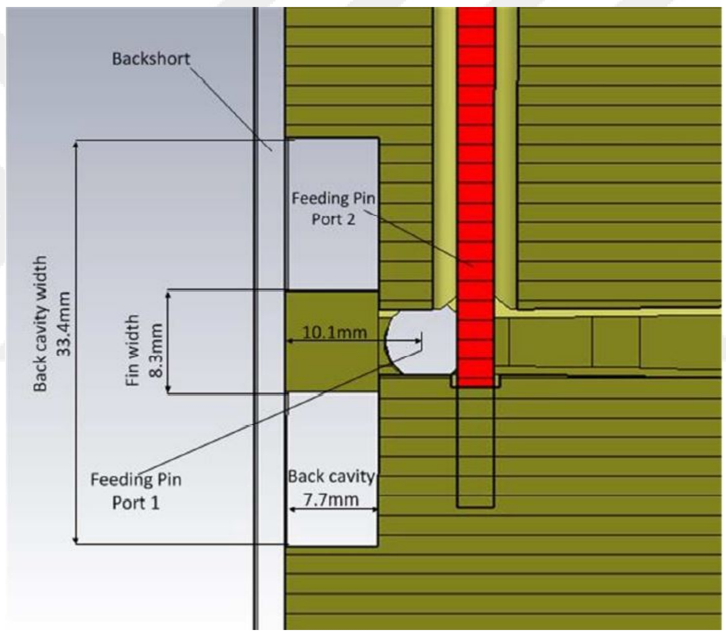
5.1 Profile Examination

Most of the prior works on quad-ridged horn antennas are designed by using exponential or elliptical for both ridges and sidewall. On the other hand, many profiles have previously been considered in the literature within the context of corrugated or smooth-wall horn designs. There are four most promising functions for the quad-ridge horns; exponential, elliptical, x^p, and $\tan^p$. Used profile function effects the characteristic and simulation results of the antenna. Therefore, all profiles in Fig. 3 is simulated and compared the simulation results for an optimal performance result of the designed antenna by using CST Microwave Studio.

Fig. 14 presents half-power beamwidth results for all profile functions in fig.3. This



(a) The front view of the designed transition structure and the relevant dimensions in mm



(b) The side view of the designed transition structure and the relevant dimensions in mm

Figure 13: The designed transition structure

figure is prepared by using simulation results over a whole operation frequency range. Sinusoidal, exponential, linear, asymmetric-sine and hyperbolic function results have many fluctuations that can make trouble while using in EMC test system. Besides, tangential function results over 3.5GHz are below 20 dB that is much smaller than x^p and exponential functions. Comparing the x^p and exponential function results, x^p is better than the other one below 2GHz. Hence, x^p function can be examined according to half-power beamwidth results. Fig. 15 shows gain results for all functions. There

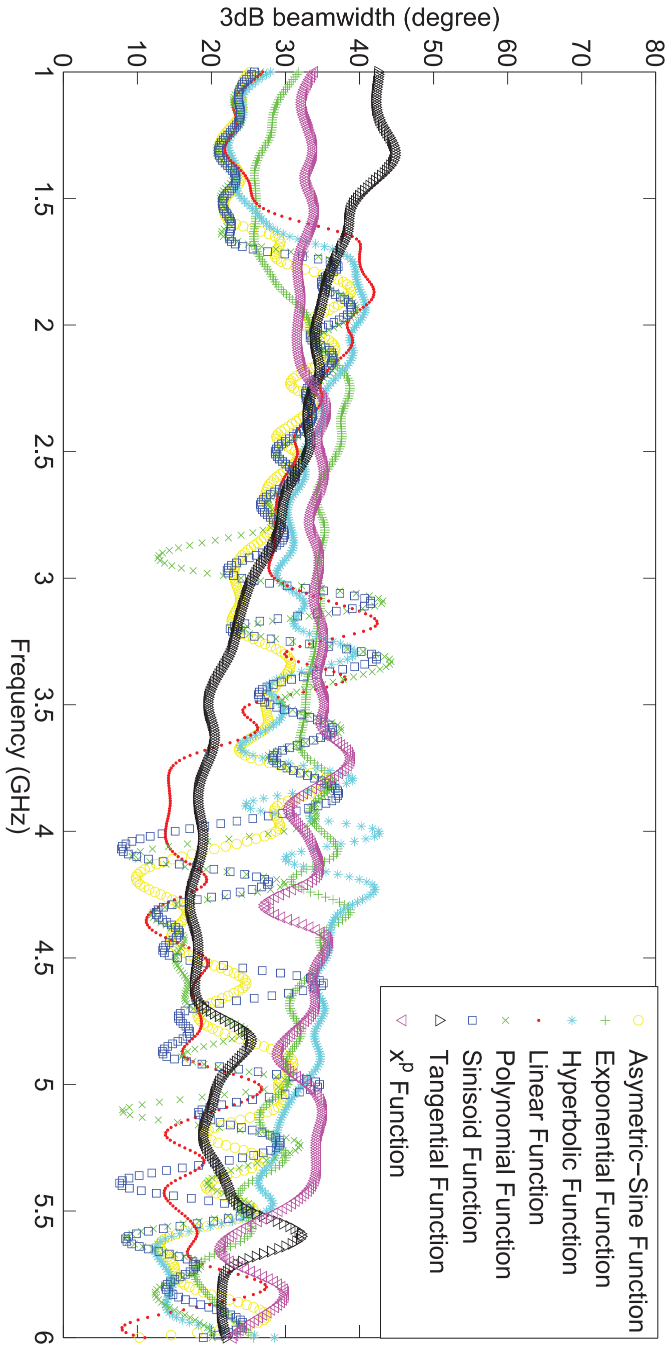


Figure 14: Half-power beamwidth results for all profiles

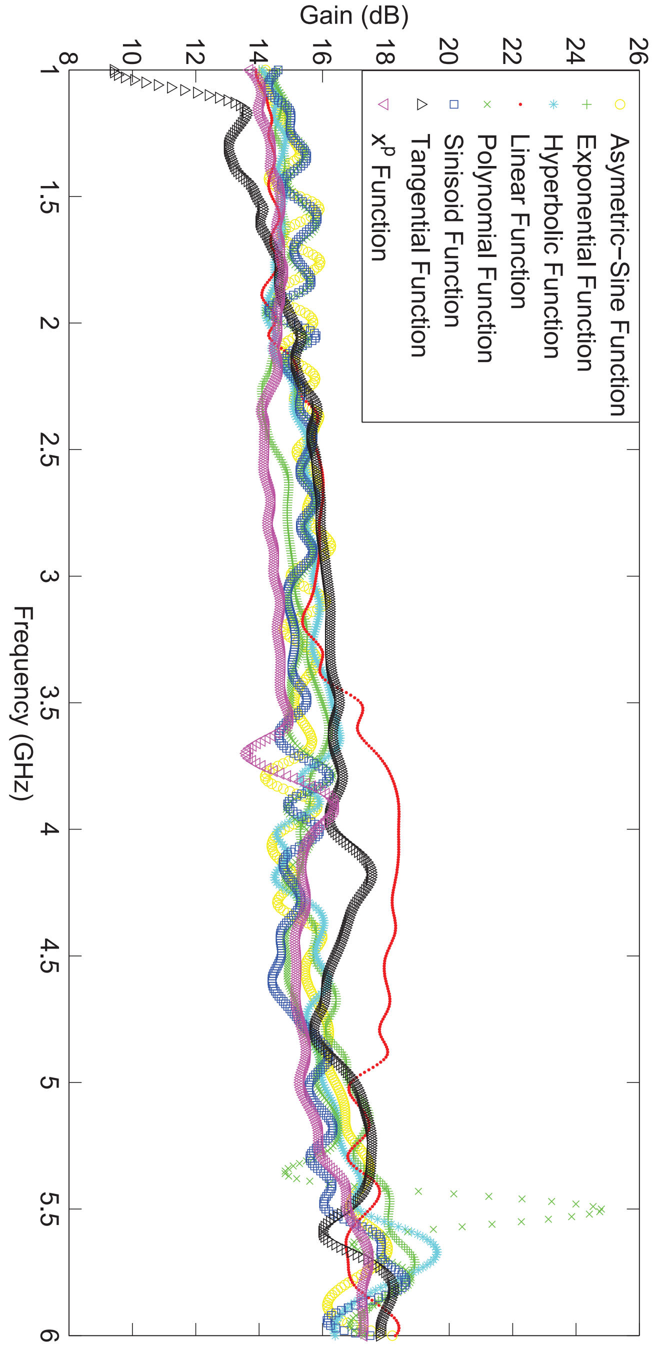


Figure 15: Antenna gain results for all profiles

are no big changes in gain results. The x^p profile can be considered as best option for this application. The x^p profile is used for both the ridge and sidewall tapers of the horn antenna presented in this thesis. It is defined as

$$a(z) = a_i + (a_o - a_i)[(1 - A)\frac{z}{L} + A(\frac{z}{L})^p] \tag{11}$$

Where; a_i is the radii at the feed point, a_o is the radii at horn aperture, L is the taper length, A is a parameter in the interval [0; 1] that determines how much linear taper is added and p is the exponent of x^p profile.

5.2 Parameter Sweep

Another consideration is the effect of the changing parameters on gain and half-power beamwidth results. The antenna length can be increased to obtain higher gain, but EMC test chamber sizes restrict the antenna length because of reflection RF signal from the chamber walls. Another consideration of higher gain is increasing the antenna radii at the feed point for horn antennas. Nevertheless, increasing the antenna radii at the feed point reduces the half-power beamwidth results. Figs. 16 and 17 represent decreasing a_o/a_i for gain and half-power beamwidth results in consequence of higher directivity. Considering the design restrictions, $a_o/a_i = 5{,}14$ and $a_o/a_i = 5{,}44$ results have over 13 dB gain and best half-power beamwidth.However, $a_o/a_i = 5{,}14$ has better gain at lower frequencies. Hence, $a_o/a_i = 5{,}14$ is utilized for the quad-ridged horn antenna design.

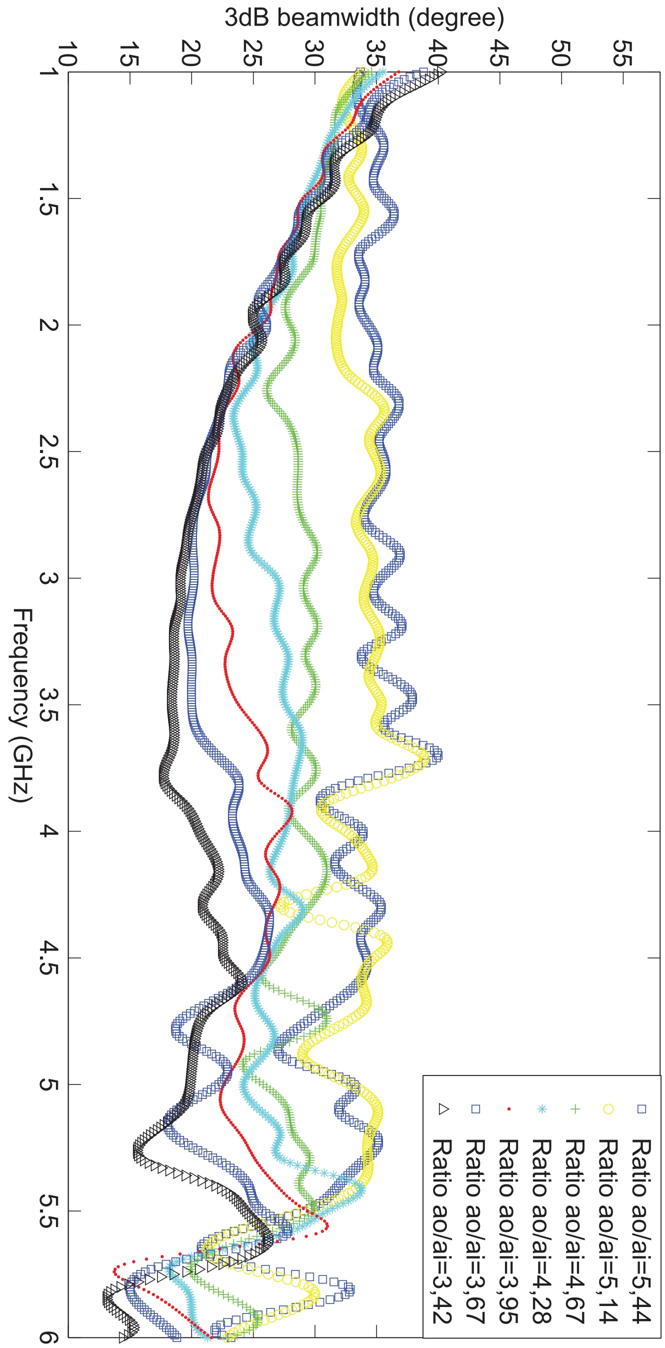


Figure 16: Half-power beamwidth results for different a_o/a_i. a_o is constant and a_i is increasing for this simulation.

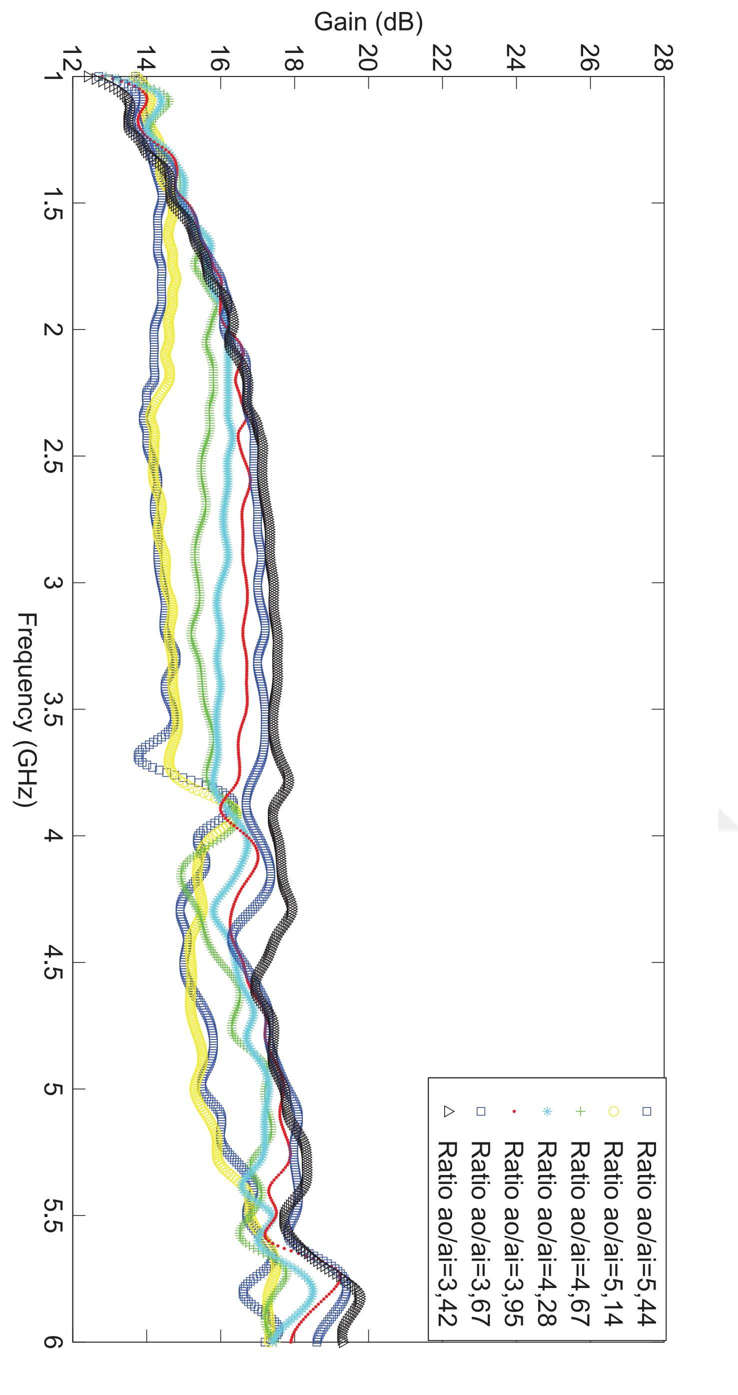
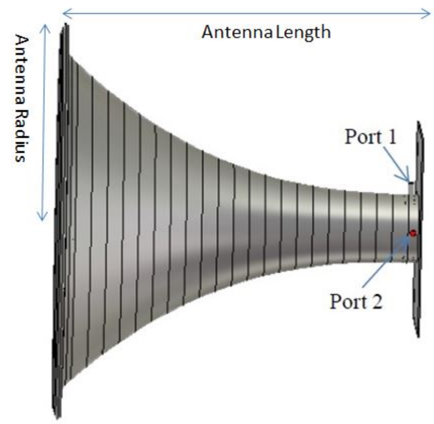


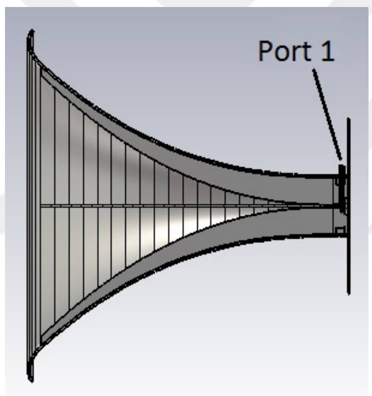
Figure 17: Gain results for different a_o/a_i. a_o is constant and a_i is increasing for this simulation.

5.3 Designed Horn Antenna

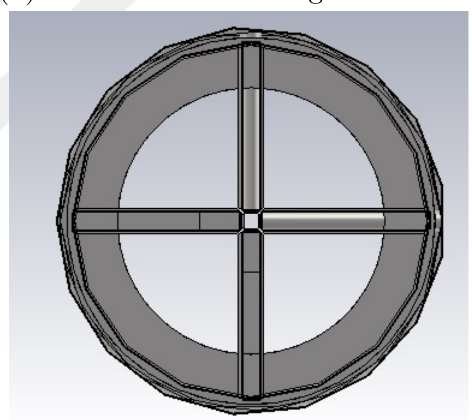
(a) Front view of the designed antenna



(b) Side view of the designed antenna



(c) Cutting plane side view



(d) Designed quad-ridge circular waveguide

Figure 18: The designed horn antenna length is 60.3 cm, and the radius of at the aperture of horn antenna is 28.0 cm and radius at the feed point of antenna is 5.45cm.

Consequently, the horn antenna is designed by using above results. Fig. 18 gives the front and side view of the designed antenna from the CST Microwave Studio. Fig. 18c shows the four ridges that are positioned symmetrically. In fig. 18c, curved surface is attached to the outside of the aperture which reduces the diffractions [31]. That means, attachment of curved surface provides smooth matching between the horn modes and free-space radiation. Furthermore, input (measurement) ports can be seen with x^p profile sidewall shape of the horn antenna in fig. 18d. Table 7 in appendix A presents the x-y coordinates of the horn and the ridge profile geometries.

CHAPTER VI

SIMULATION RESULTS

In chapter V, horn antenna profile and parameters are determined to design. Fig. 18 gives the antenna view which is produced by using the CST Microwave Studio. In CST Microwave Studio, simulation mesh setting is $\lambda/20$ and meshcell can be calculated as 80 million. This chapter will show the simulation results which are scattering parameters, VSWR, gain and half-power beamwidth. Moreover, simulation results are compared to the EMC antenna restrictions that are given in EMC applications of antenna chapter 4.

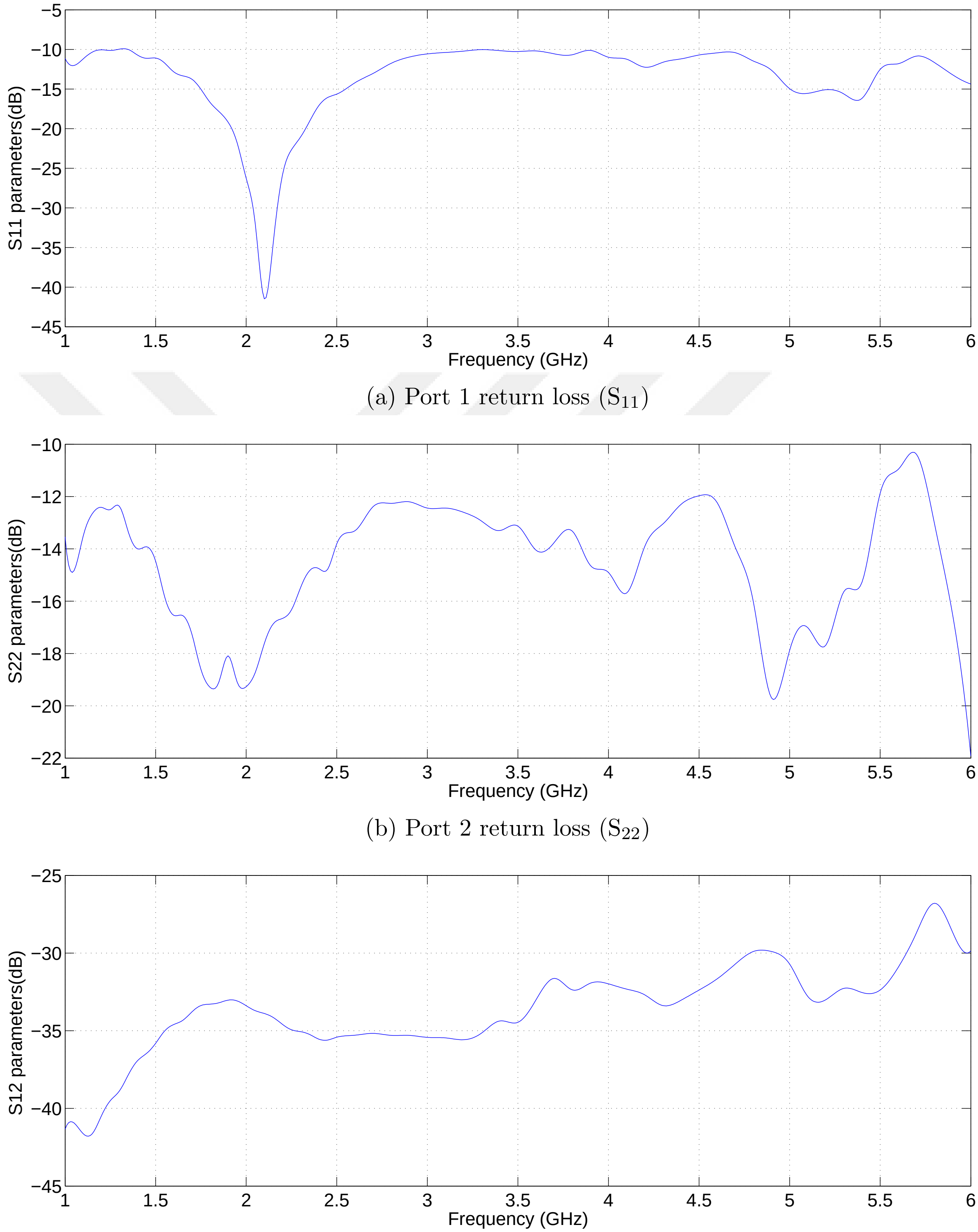
6.1 Simulation Results with Perfect Electric Conductor (PEC)

6.1.1 Scattering Parameters

Figs 19 refer to the S_{11}, S_{22} and S_{12} parameters. S_{11} and S_{22} are return loss of the horn antenna and S_{12} is the isolation of the input ports. S_{21} result is exactly same with S_{12}. The return losses from 1 GHz to 6 GHz are below -10 dB and it indicates almost 90% of the signal transmitted through the antenna had been received with minimum loss. Isolation of the ports (S_{12}) is maximum -27 dB and two ports can be used simultaneously while testing. This is verified by the calculated VSWR during the simulation.

6.1.2 Voltage Standing Wave Ratio

The fig. 20 presents the amount of VSWR which is calculated by using the simulation program. The maximum value of VSWRs is 1.92, which is found to be less than 2. Consequently, it is considered fairly well for the signal transmission with lower attenuation.

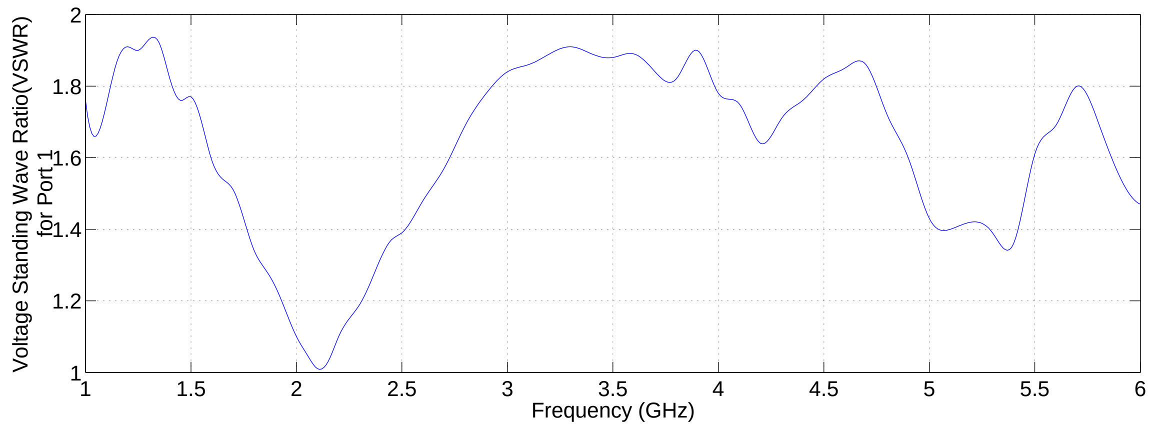


(a) Port 1 return loss (S_{11})

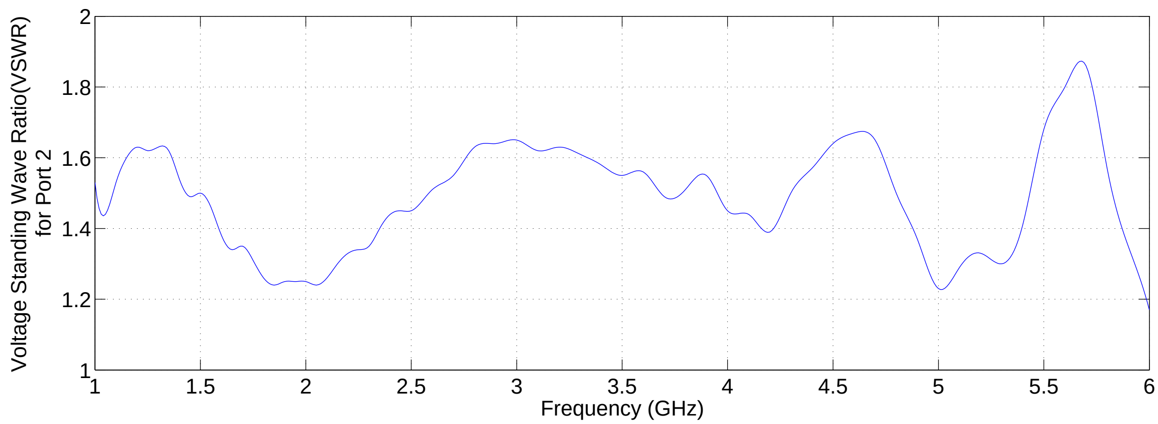
(b) Port 2 return loss (S_{22})

(c) Isolation of Port 1 and Port 2 (S_{12})

Figure 19: Scattering parameters of Designed Horn Antenna



(a) Port 1 VSWR



(b) Port 2 VSWR

Figure 20: The designed antenna VSWR Results

6.1.3 Gain

Antenna gain is one of the most important parameters for an EMC antenna because good matching cannot be used if the antenna does not radiate. The antenna gain refers how good an antenna radiates or receives power. According to the simulation results, the gain of the designed antenna varies from 13.72 dB to 18.26 dB which can be observed from Fig. 21, is sufficient for 3 meters EMC testing. In fig. 22, gain and 3D radiation patterns of the designed antenna can be shown at 1 GHz, 2GHz, 3.5 GHz, 5 GHz and 6 GHz for two ports. Besides, the radiation efficiency of the designed antenna is sufficiently high, which is above 99 percent.

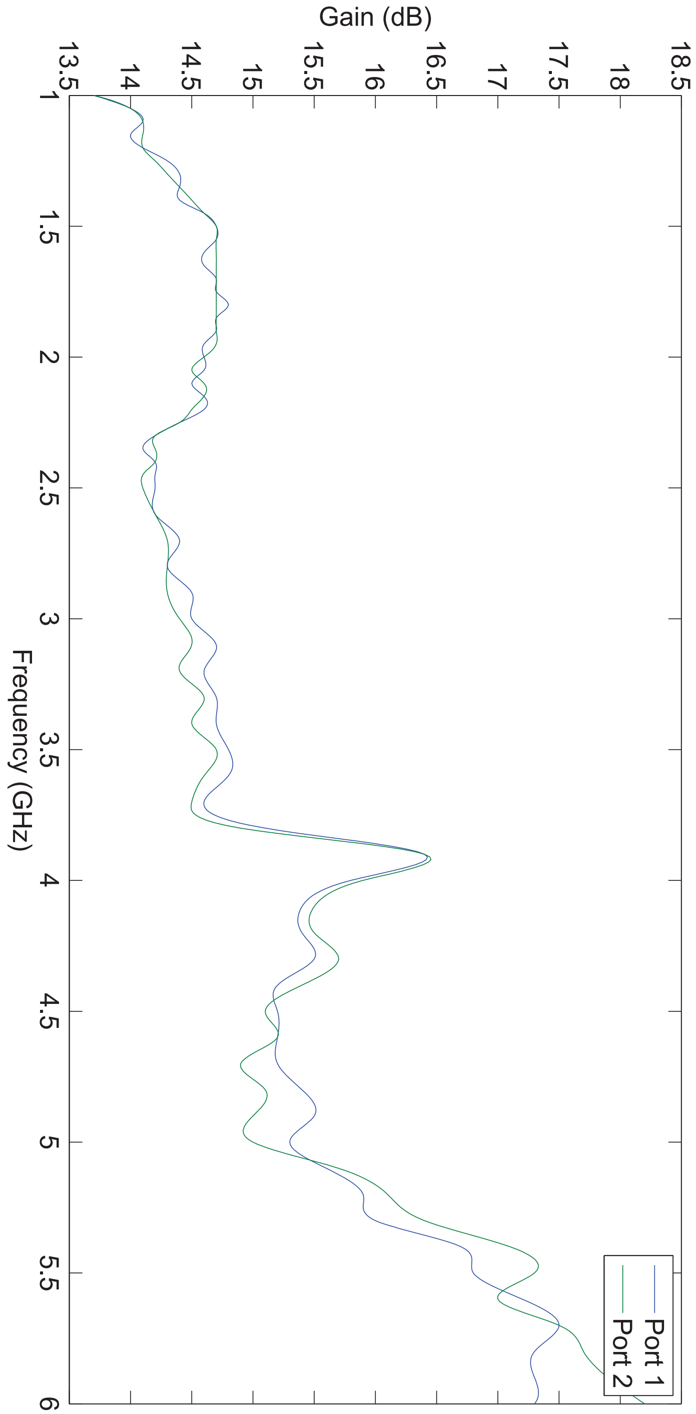
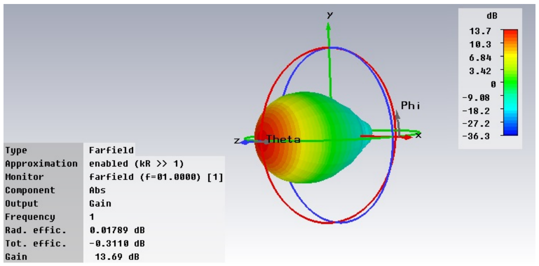
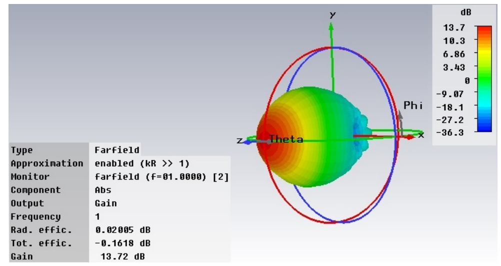


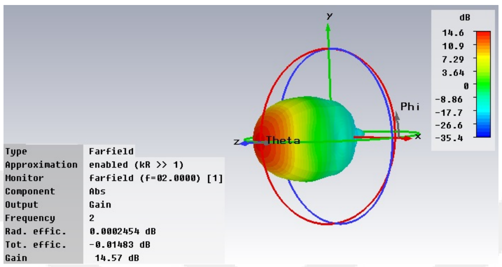
Figure 21: Gain of the designed antenna



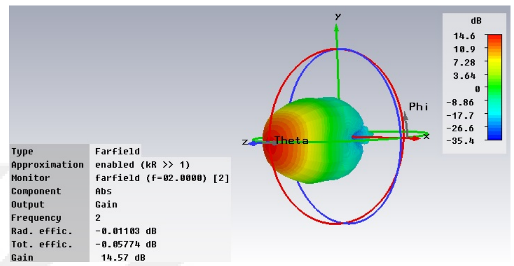
(a) Port 1 Radiation Patten at 1 GHz



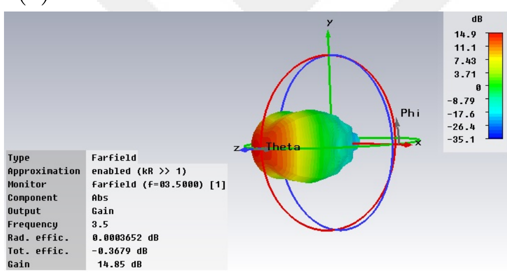
(b) Port 2 Radiation Patten at 1 GHz



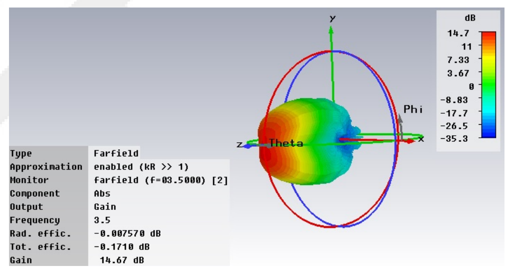
(c) Port 1 Radiation Patten at 2 GHz



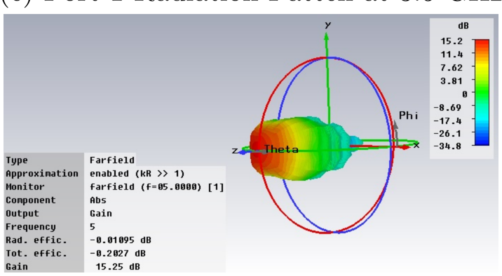
(d) Port 2 Radiation Patten at 2 GHz



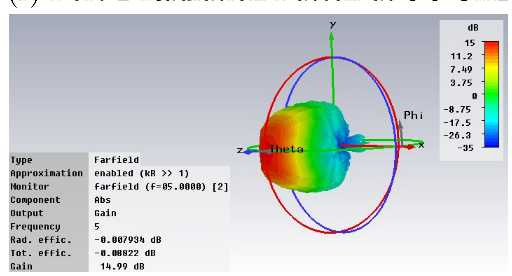
(e) Port 1 Radiation Patten at 3.5 GHz



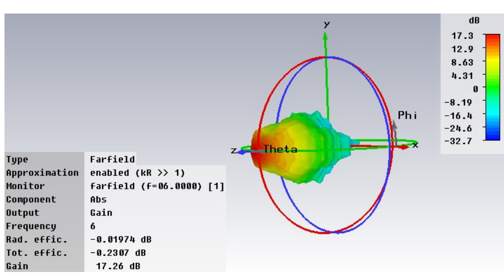
(f) Port 2 Radiation Patten at 3.5 GHz



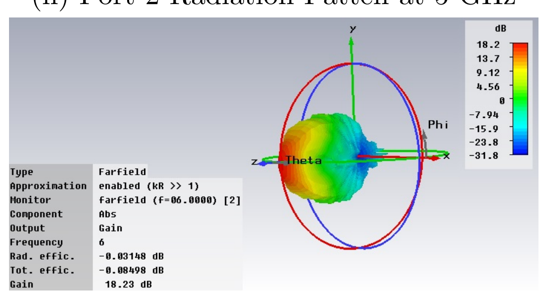
(g) Port 1 Radiation Patten at 5 GHz



(h) Port 2 Radiation Patten at 5 GHz



(i) Port 1 Radiation Patten at 6 GHz



(j) Port 2 Radiation Patten at 6 GHz

Figure 22: Gain and 3D radiation patterns

Fig. 22 presents the 3D radiation patterns for both ports of the horn antenna. The radiation pattern is the graphical representation of the electromagnetic power distribution in free space. As can be seen from fig. 22d, the magnitude of the main lobe is 14.5 dB while the side lobe is -24.9 dB. This difference means that more power radiates through the main lobe direction compared to the other directions.

6.1.4 Antenna Factor

Fig. 24 shows the antenna factors of the designed horn antenna. These values are calculated from gain results by using eq. 5. Fig. 23 gives the system noise floor measurement with the designed horn antenna. The system noise floor is less than the limit line approximately 13 dB. Thus, radiated emission test system from 1 GHz to 6 GHz is proper without preamplifier.

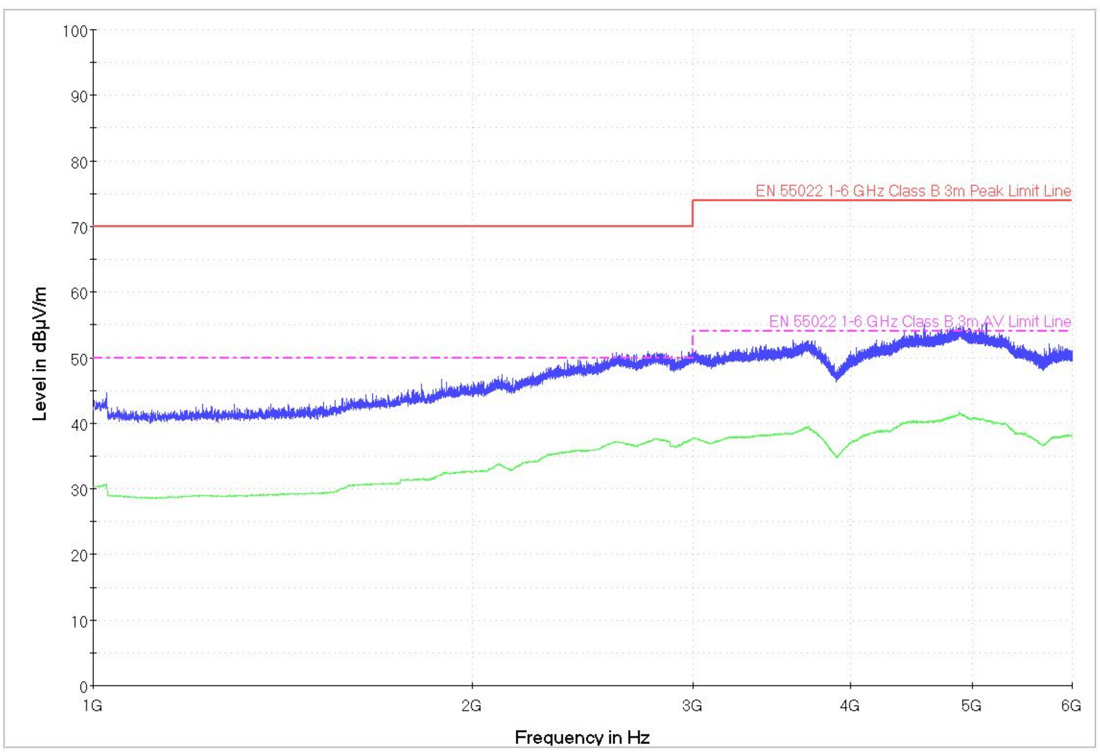


Figure 23: System noise floor in VESTEL chamber with the designed horn antenna

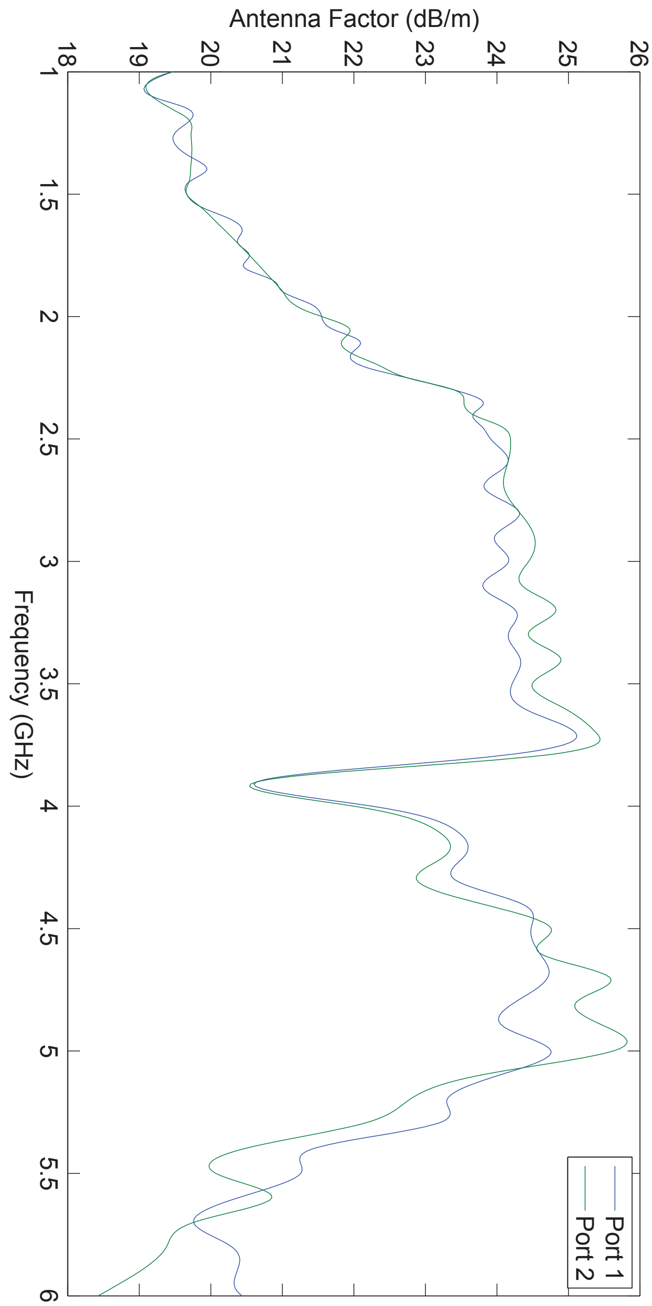


Figure 24: Antenna factors of the designed horn antenna

6.1.5 Half-Power Beamwidth

In the EMC test systems, half-power beamwidth of an antenna is most critical one of the antenna parameters because radiating or receiving area shall be in 3 dB beamwidth of the antenna. Fig. 25 gives the simulation results of 3 dB beamwidth values of the designed antenna. These results must achieve the EMC restriction that is given in Table 5. Eq. 6 will be used to calculate w values that show the dimensions of the illuminating area.

Table 6 gives the calculated w results for both ports by using eq. 6 at 3 m distance. Comparison of calculated results and w_{min} shows that the designed antenna can be used in EMC emission test systems.

Frequency (GHz)	w_{min} (m)	$w_{\mathrm{calculated}}(Port1)$ (m)	$w_{\mathrm{calculated}}(Port2)$ (m)
1.00	1.15	1.83	2.03
2.00	0.63	1.71	1.82
4.00	0.63	1.75	0.95
6.00	0.48	1.22	0.68

Table 6: Calculated dimensions of w for 3 m measurement

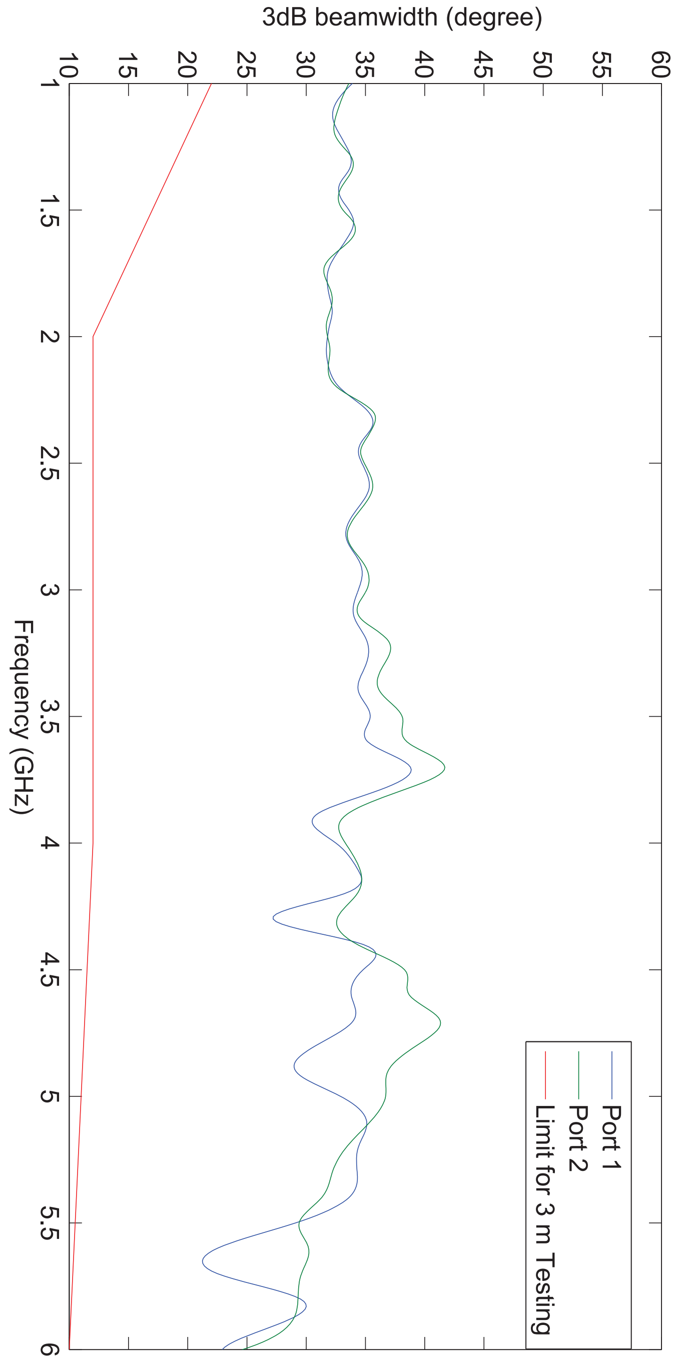


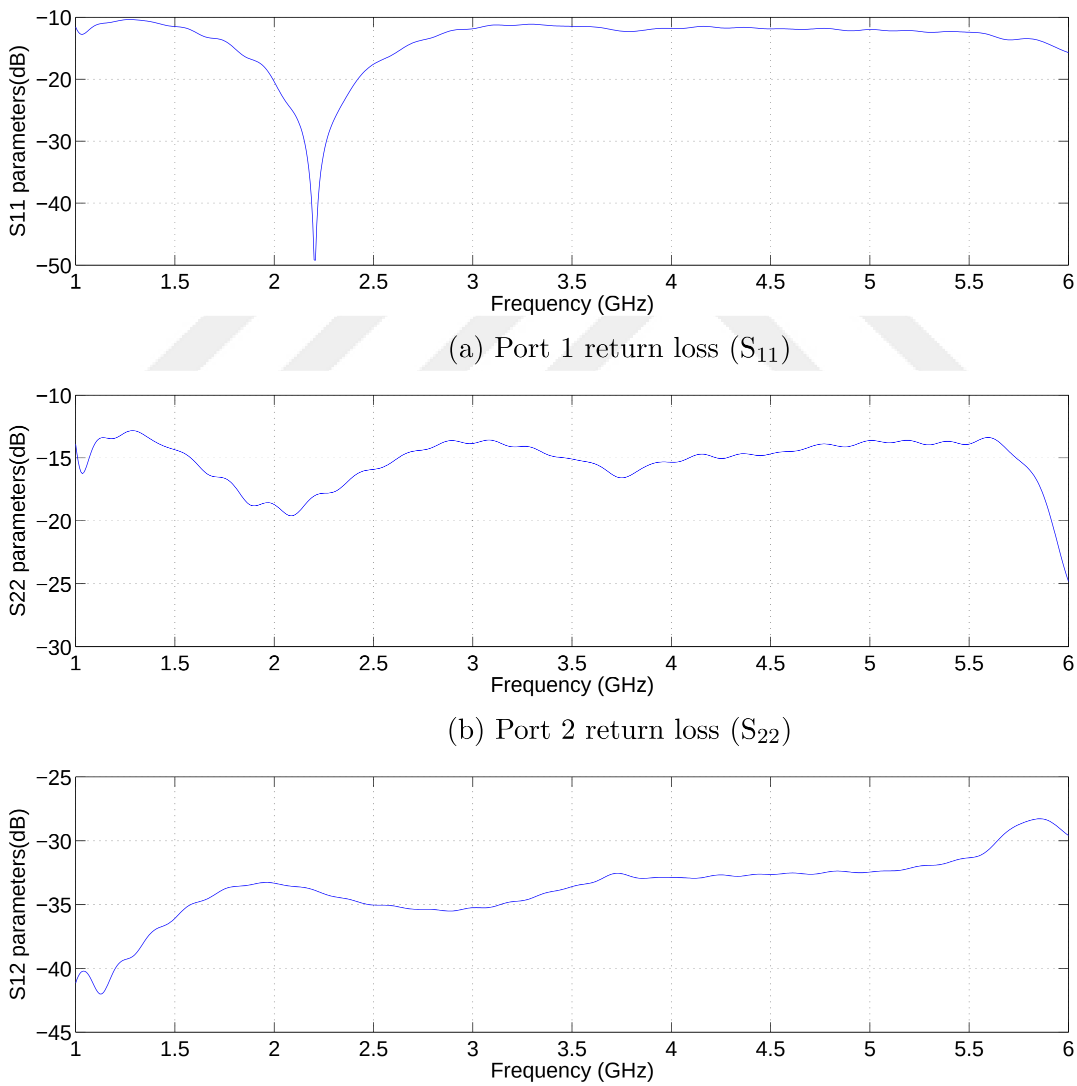
Figure 25: 3 dB Beamwidth of the designed antenna

6.2 Simulation Results with Aluminium

Above results give general information about antenna parameters. However, while fabricating the horn antenna, aluminium is used for production in general. This section gives the simulation results with aluminium material.

6.2.1 Scattering Parameters

In fig. 26, S_{11}, S_{22} and S_{12} results are shown. S_{21} result is exactly same with S_{12}. These results are better than the PEC results because aluminium is a lossy metal. Furthermore, VSWR results are better according to scattering parameters. These results could be similar with the fabricated antenna.



(a) Port 1 return loss (S_{11})

(b) Port 2 return loss (S_{22})

(c) Isolation of Port 1 and Port 2 (S_{12})

Figure 26: Scattering parameters of Designed Horn Antenna with Aluminium

6.2.2 Gain and Half-power Beamwidth Results

Changing the material of horn antenna did not demonstrate the fundamental change in gain and half-power beamwidth results. Difference in gain results are less than 0.5 dB and difference in half-power beamwidth results are less than 0.7 degree.

6.2.3 Antenna Volume and Mass

Fig. 27 presents the information about the designed antenna mass and volume. As it is seen in the figure, mass of the antenna is approximately 12.3 kg with aluminium material. Besides, volume of the designed antenna is 4.56 liters (4557 cm^3). The designed antenna can be carried in a box which dimensions are 73.5 cm x 73.5 cm x 65.5 cm.

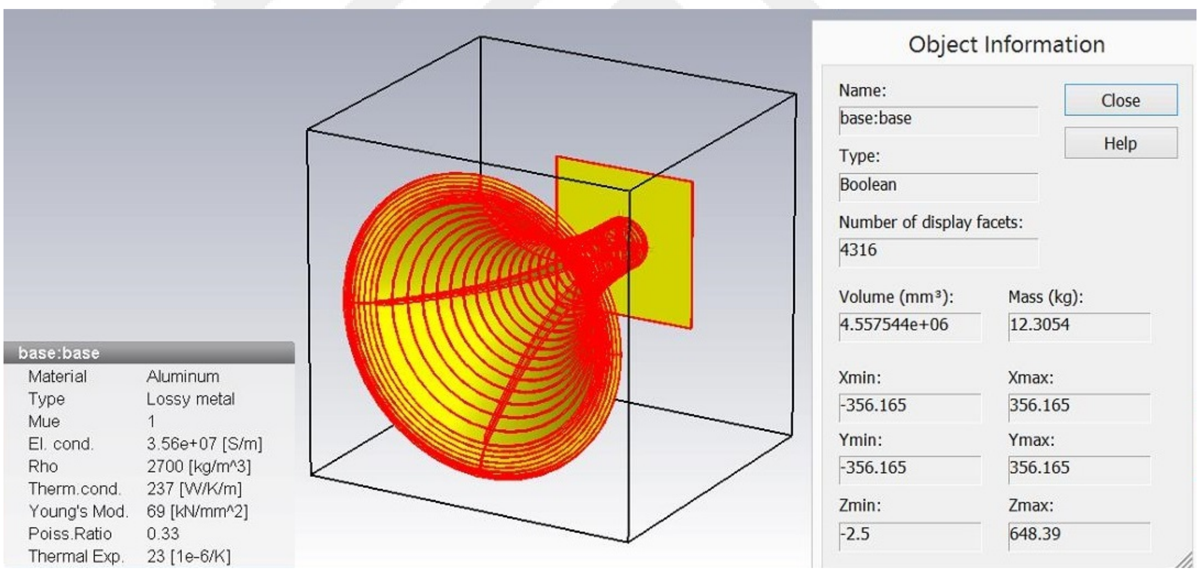


Figure 27: Mass and Volume information about the designed antenna

CHAPTER VII

CONCLUSION

According to the results above, the designed wideband quad-ridged horn antenna is suitable for EMC testing within given operation range 1-6 GHz. Return loss of the ports (S_{11} and S_{22}) are less than -10 dB. Isolation of the ports (S_{12} and S_{21}) are less than -27 dB. Return losses, isolation of the ports and VSWR ensure that the radiated signal is almost in an equilibrium state that means transmitted signal or received signal of the horn antenna provides high performance with lower attenuation. Furthermore, higher gain shows that antenna radiates in the desired direction with higher radiated power. The antenna gain range changes from 13.72 dB to 18.26 dB within the overall antenna operation frequency band. That refers the gain target is achieved. Radiation pattern shows the main lobe is larger than side lobes and back lobe. 3 dB beamwidth is greater than 30 degrees and designed quad-ridged horn antenna is suitable for using Emission and Immunity testing.

APPENDIX A

GEOMETRY OF HORN ANTENNA

Ridge Profile		Horn Profile	
x	y	x	y
54.51	7.71	54.51	0
54.51	0	54.51	18.41
14.09	0	54.69	47.17
14.09	7.71	55.34	75.93
0	7.71	56.65	104.68
0	18.41	58.78	133.44
0.9	44.44	61.73	162.19
2.47	70.47	65.72	190.95
4.81	96.5	70.72	219.71
7.95	122.53	76.78	248.46
12.07	148.56	84.11	277.22
17.06	174.59	92.57	305.97
22.96	200.62	102.35	334.73
29.76	226.65	113.48	363.49
37.66	252.68	125.88	392.24
46.52	278.7	139.83	421
56.34	304.73	155.18	449.75
67.14	330.76	171.98	478.51
76.58	351.59	190.45	507.26
86.68	372.41	210.37	536.02
97.46	393.23	231.98	564.78
108.93	414.06	255.25	593.53
121.08	434.88	280.07	622.29
133.92	455.7	290	632
147.46	476.53	301.07	639.8
161.71	497.35	312.71	645.29
176.66	518.17	324.35	648.2
192.32	538.99	335.39	648.39
208.7	559.82	345.3	645.84
225.79	580.64	353.56	640.69
243.62	601.46		
262.17	622.29		
280.07	622.29		
255.25	593.53		
231.98	564.78		
210.37	536.02		
190.45	507.26		
171.98	478.51		
155.18	449.75		
139.83	421		
125.88	392.24		
113.48	363.49		
102.35	334.73		
92.57	305.97		
84.11	277.22		
76.78	248.46		
70.72	219.71		
65.72	190.95		
61.73	162.19		
58.78	133.44		
56.65	104.68		
55.34	75.93		
54.69	47.17		
54.51	18.41		
54.51	7.71		

Table 7: x-y coordinates of the Ridge and Horn profile

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