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Design and Analysis of Conventional Antennas for the Applications in Millimeter-Waves

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Abstract—*In recent years antennas operating on millimeter-wave frequencies have generated a considerable demand. The various unique applications of millimeter-wave antennas along with the availability of the bandwidth makes them a very promising area which is yet to be explored. This paper is for designing of conventional antennas which can work for millimeter wave frequencies. This work includes mathematical analysis and designing of Horn and Yagi-uda antennas for mm-wave and simulation of basic parameters using HFSS. A rectangular shaped slot is incorporated into patch, and antenna structure is used as a patch with coplanar waveguide (CPW) as a feeding structure. A brief mathematical theory of both antennas, software introduction, design, applications and variations between calculated and observed values will be discussed along the result of our design. Our results and analysis show that the antennas are showing significant gain, so they can be applied for the applications we are aiming for.*

Keywords*: UHF, VHF, Horn antenna for millimeter-wave, Yagi antenna for millimeter-wave, CPW*

1. INTRODUCTION

The electromagnetic waves whose frequency lies between 300MHz to 30GHz refer as microwave range. In 1890's when Marconi were inventing radio communications at the same time his contemporaries J.C. Bose was one who experimenting with millimeter wave signals [1].

At millimeter-wave, the massive amounts of data can be sent over a local area with very high speed (billions of bits per second) for short range communication. Millimeter-wave antennas and components are very small in size due to this its fabrication cost with power consumption is low. At this frequency range, wide bandwidths available for carrying communications therefore there is an increasing interest to service providers and systems designers.

As it travel solely by line-of-sight, and blocked by building walls and attenuated by foliage. Therefore, the high free space loss and atmospheric absorption limits propagation to a few kilometers. Thus they are useful for densely packed communication networks such as personal area networks that improve spectrum utilization through frequency reuse.

In recent times, 7 GHz continuous in sequence bandwidth were allowed for unlicensed use at millimetre wave (mm-wave) frequencies around 60 GHz in the U.S. (57–64 GHz) and Japan (59–66 GHz). This opened bandwidth are widely utilized for many applications including gigabit/s point-to-point links, wireless local area net- works (WLANs) with huge capacity, short-range high data-rate wireless personal area networks (WPANs), and vehicular radar.

At conventional frequencies, the antennas which are use often in day today life i.e. yagi uda and horn antenna. This paper includes mathematical analysis and designing of these two antennas at millimeter wave range spectrum. The HFSS software is used for the design simulation.

2. ANTENNA THEORY

2.1 Yagi Antenna

Yagi antenna is a directional antenna consisting number of linear dipole elements, one of which is energized directly by a feed transmission line while the others act as parasitic radiators whose currents are induced by mutual coupling [2].

Printed Quasi-Yagi antennas allows variety of applications at microwave and millimeter wave frequencies as it was first introduced in 1998, its remarkable features are broad bandwidth, high efficiency, high gain, low profile, uniplanar structure, ease of fabrication, and low cost [5].

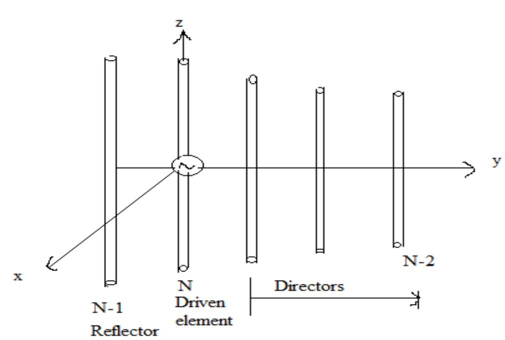

Fig. 1: Yagi Uda Antenna configuration

2.2 Horn Antenna

EMC measurement, radar, communication system are some applications where Horn Antenna is used.

As Pyramidal Horn has equal radiation patterns in both E-plane and H-plane along with its high gain and directivity, hence it consider as best horn. So, development of Wideband horn antenna for communication and calibration purposes is important [2]. Horn antenna, one of the most practical antennas has been widely used with the development of measurement, communication system, electromagnetic and radar techniques. The bandwidth of the antenna can effectively extend by horn antenna and improve the impedance matching between waveguide and free space [3].

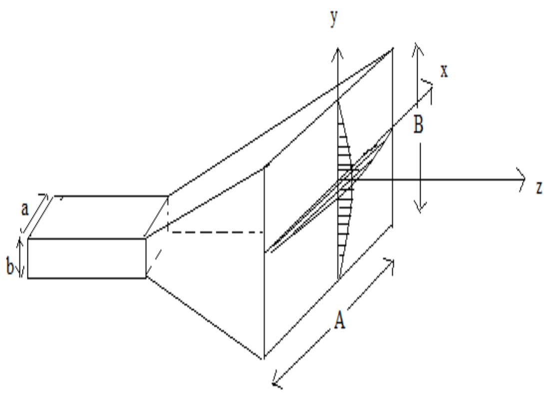

Fig. 2: Pyramidal Horn Antenna

3. MATHEMATICAL APPROACH

3.1. Yagi Antenna

A document has been published which provides data of experimental investigations carried out by the National Bureau of standards [4] to determine how parasitic element diameter, element length, spacing between elements, supporting booms of different cross sectional areas, various reflectors, and overall length affect the measured gain can be measured [2].

Using above document, calculated equations for designing at 4.4GHz are

$$Reflector\ length = 0.499\lambda$$

$$Active\ Element\ Length = 0.466\lambda$$

$$Director\ Length = 0.433\lambda$$

$$Spacing\ between\ elements, d = 0.13\lambda$$

$$\lambda = c/f$$

Where λ is the wavelength in meters, c is the velocity of light in free space ($c = 3 \times 10^8 m/s$), f is the operating frequency in GHz.

At 30GHz,

$$Reflector\ length = 0.505\lambda$$

$$Active\ Element\ Length = 0.466\lambda$$

$$Director\ Length = 0.425\lambda$$

$$Spacing\ between\ elements, d = 0.12\lambda$$

$$\lambda = c/f$$

3.2 Horn Antenna

To design a pyramidal horn, one usually knows the desired gain G_o and the dimensions a, b of the rectangular feed waveguide.

Few assumptions has to be done for calculations

1) First assume appropriate gain for getting value of $\boldsymbol{\varkappa}$ through this value we'll get one equation in form of two variables a and b

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

Use iterative technique & begin with trial value

$$\varkappa(trial) = \varkappa_1 = \frac{G_o}{2\pi\sqrt{2\pi}}$$

2) Once equation has been formed, determine ρ_e and ρ_h, using equation

$$\frac{\rho_e}{\lambda} = \boldsymbol{\varkappa}$$

$$\frac{\rho_h}{\lambda} = \frac{G_o^2}{8\pi^3}\left(\frac{1}{\varkappa}\right)$$

$$\lambda = c/f$$

3) find value of A & B, using

$$A = \sqrt{3\lambda\rho_h} = \frac{G_o\lambda}{2\pi}\sqrt{\frac{3}{2\pi\varkappa}}$$

$$B = \sqrt{2\lambda\rho_e} = \sqrt{2\varkappa}\lambda$$

4) Second assumption is that

$$P_e = P_h$$

$$P_e = (B - b)\left[\left(\frac{\rho_e}{B}\right)^2 - \frac{1}{4}\right]^{\frac{1}{2}}$$

$$P_h = (A - a)\left[\left(\frac{\rho_h}{A}\right)^2 - \frac{1}{4}\right]^{\frac{1}{2}}$$

Equating above equations we'll get the equation in form of two variable a and b.

Solving these two equations in form of variable, we'll get the value of a and b.

Using above steps, calculation of horn antenna can be done at any frequency.

4. ANTENNA DESIGN

The design consist of antenna which has been designed as a slot over a substrate. The microwave frequency 4.4GHz for yagi antenna and 5GHz for horn antenna use FR4 as a substrate ($\in_r = 4.4$) with the thickness of 1.6 mm, while at mmwave frequency 30GHz for both antenna use Gallium-Arsenide (GaAs) as a substrate ($\in_r = 12.9$) with thickness 0.5mm.

A copper sheet has been used over a substrate. Slots has been cut from this copper sheet. At microwave frequency copper sheet equal to feed length is used at bottom layer of the substrate, to get appropriate result. While at mmwave optimum result is achieved without using such copper sheet. The coplanar waveguide (CPW) line is used as a feeding structure.

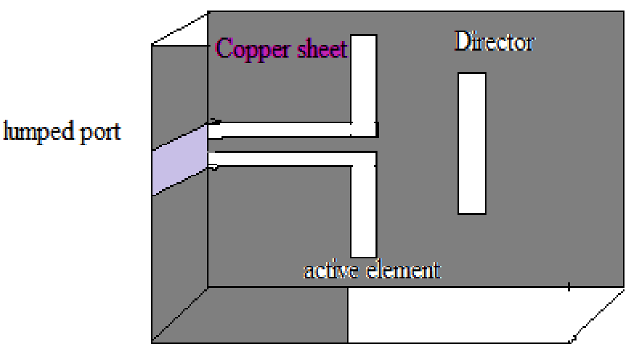

Fig. 3: Structure of Yagi-Uda Antenna at 4.4GHz

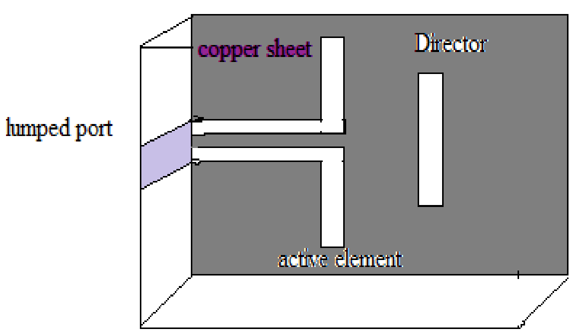

Fig. 4: Structure of Yagi-Uda Antenna at 30GHz

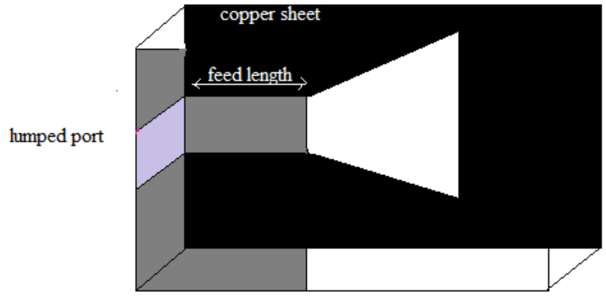

Fig. 5: Structure of Horn Antenna at 5GHz

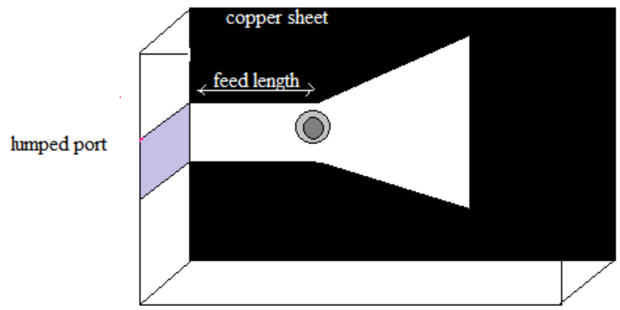

Fig. 6: Structure of Horn Antenna at 30GHz

At mmwave, there is a slight difference between these two antenna i.e. horn antenna uses coaxial transformation feed though lumped port while yagi uses direct feed through lumped port.

5. SIMULATION

An UWB antenna has to meet the following condition

$$\frac{B_f}{f_c} > 0.2$$

The bandwidth B_f is determined by the frequencies at which the return loss at the antenna input decreases below $-10\ dB$. The symbol f_c denotes the central frequency of the given frequency band [6].

Table I: Antenna Dimensions

Antenna	Yagi Uda		Horn	
Operating frequency	4.4GHz	30GHz	5GHz	30GHz
Wavelength	68.18mm	10mm	60mm	10mm
Substrate thickness	1.6mm	0.5mm	1.6mm	0.5mm
Feeder length	25mm	7.2mm	25mm	5mm
Feeder width	2mm	0.4mm	13.5mm	1mm
Driven element length	82mm	4mm	-	-
Director length	50mm	2mm	-	-
Element width	5mm	0.5mm	-	-
Flaring length	-	-	19mm	8.3mm
Flaring width	-	-	68mm	10mm

The simulated S_{11} of the yagi antenna is shown in Fig.7. The simulated return loss at 4.4GHz is -18.5dB with gain of -2.8dB at 90 degree.

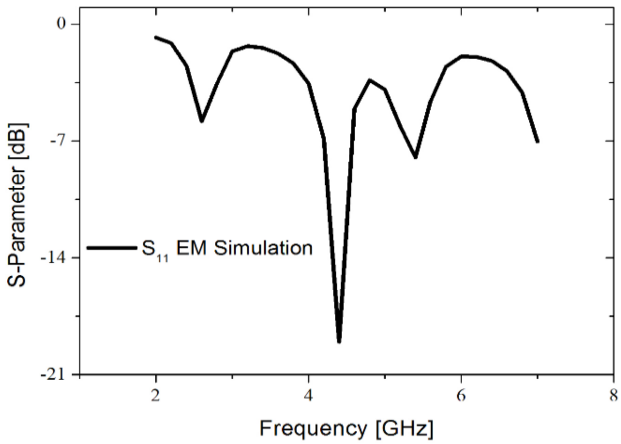

Fig. 7: S_{11} of 4.4GHz Yagi-Uda Antenna

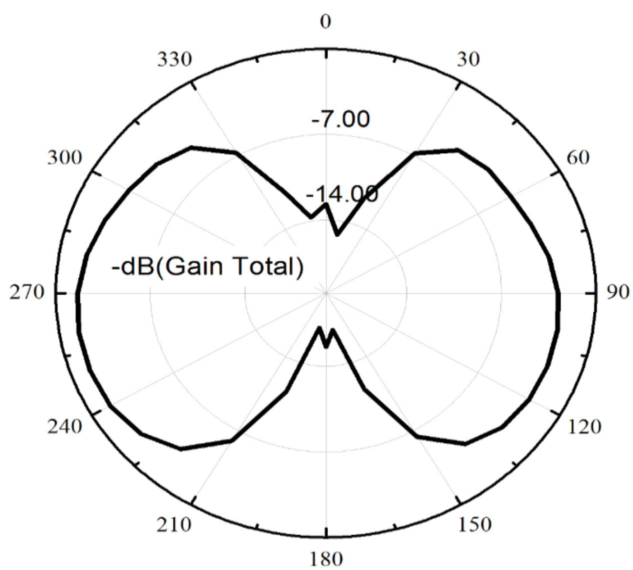

Fig. 8: Simulated radiation pattern of 4.4GHz Yagi-Uda Antenna

The simulated S_{11} of the yagi antenna is shown in Fig.9. The simulated return loss at 30GHz is -30dB with gain of 3.79dB at 160 degree

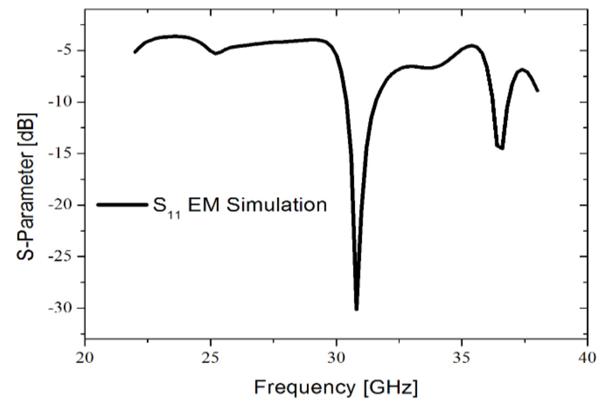

Fig. 9: S_{11} of 30GHz Yagi-Uda Antenna

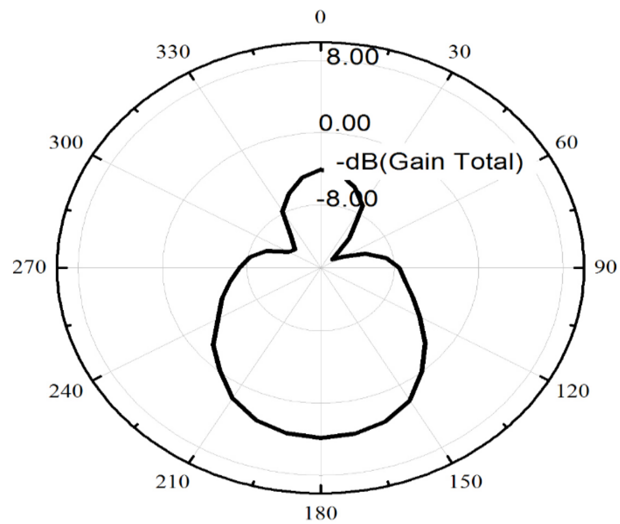

Fig. 10: Simulated radiation pattern of 30GHz Yagi-Uda Antenna

The simulated S_{11} of the horn antenna is shown in Fig.11. The simulated return loss at 5GHz is -39dB with gain of 3.36dB at 60 degree.

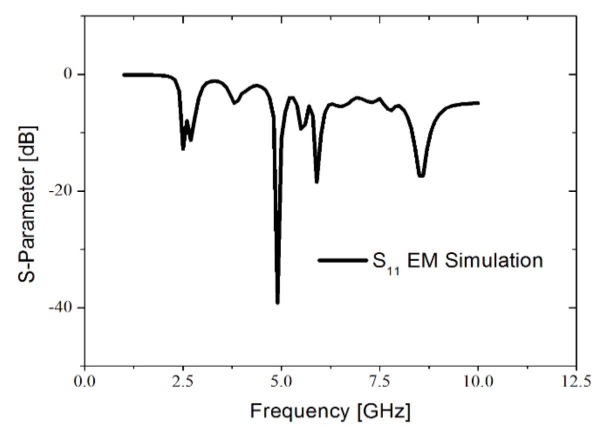

Fig. 11: S_{11} of 5GHz Horn Antenna

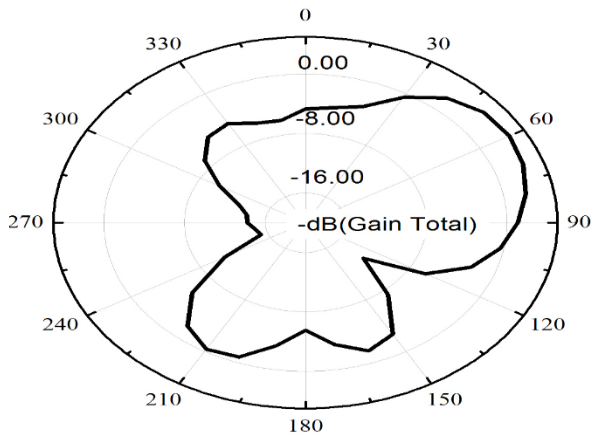

Fig. 12: Simulated radiation pattern of 5GHz Horn Antenna

The simulated S_{11} of the horn antenna is shown in Fig.13. The simulated return loss at 30GHz is -16dB with gain of 5.26dB at 40 degree.

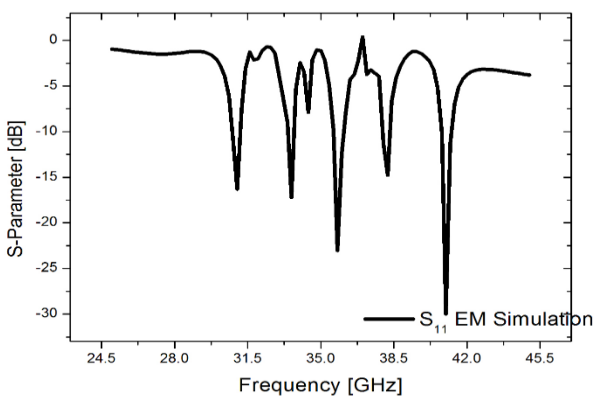

Fig. 13: S_{11} of 30GHz Horn Antenna

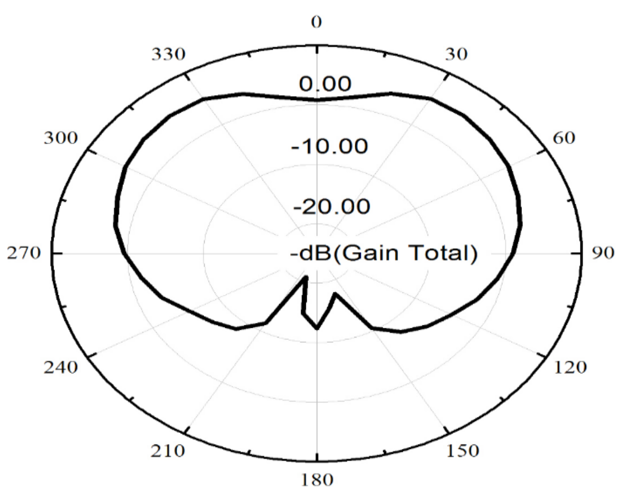

Fig. 14: Simulated radiation pattern of 30GHz Horn Antenna

6. MEASURED RESULT

6.1. Yagi Antenna

After design using hfss, the inverse calculated formulae's for parameters which are defined here, these are

$$Active\ element\ length = 1.202\lambda$$

$$Director\ length = 0.733\lambda$$

$$Spacing\ between\ elements = 0.22\lambda$$

$$Width\ of\ elements = 0.0733\lambda$$

$$Feed\ length = 0.366\lambda$$

$$Width\ of\ feed\ element = 0.029\lambda$$

The above formulae's are derived for 4.4GHz operating frequency.

$$Active\ element\ length = 0.40\lambda$$

$$Director\ length = 0.20\lambda$$

$$Spacing\ between\ elements = 0.38\lambda$$

$$Width\ of\ elements = 0.05\lambda$$

$$Feed\ length = 0.720\lambda$$

$$Width\ of\ feed\ element = 0.04\lambda$$

The above formulae's are derived for 30GHz operating frequency.

6.2. Horn Antenna

After designing, the observed result defined here, these are

$$Flared\ Width, A = 68mm$$

$$Flared\ Thickness, B = 1.6mm$$

$$Feed\ width, a = 13.5mm$$

$$Feed\ Thickness, b = 1.6mm$$

The above results are for 5GHz operating frequency

$$Flared\ Width, A = 10mm$$

$$Flared\ Thickness, B = 0.5mm$$

$$Feed\ width, a = 1mm$$

$$Feed\ Thickness, b = 0.5mm$$

The above results are for 30GHz operating frequency.

Considering the structure at conventional range, to get appropriate return loss with gain requires copper sheet at bottom layer of substrate. For yagi antenna still conventional device has not get sufficient gain i.e. -2.8dB gain with return loss -18.5dB. In case of horn antenna, device has sufficient gain i.e. 3.36dB with return loss -39dB.

While at mmWave range, the optimum return loss with sufficient gain is achieved without using copper sheet at bottom layer of substrate. This makes structure less complex and low cost. For yagi antenna at mmwave range has achieved sufficient gain i.e. 3.79dB gain with return loss -30dB. In case of horn antenna, device has achieved more sufficient gain at mmWave i.e. 5.26dB with return loss -16dB.

7. APPLICATIONS

The conventional ranges has many applications like microwave links, military, satellite communications, WiFi directional antennas, etc. Inspite of number of applications present at conventional ranges, the mmwave range growing rapidly in many segments and applications.

As reference to measured parameters, the dimensions at mmwave frequency is very small as compared to conventional frequency. Therefore, ICs keep the circuitry small in size and light weight makes it very convenient for PCB technology.

High speed wireless communication rapidly growing which increases demand of high data rate with massive amount of data achieved at mmWave frequency for short range. The antennas at mmwave ranges has advantage of high bandwidth, interference immunity, frequency re-use potential.

Particularly yagi antenna at frequency 4.4GHz has application in radio altimeter antenna, military communication. While at 30GHz frequency, it has application in MMIC power amplifier, *wireless / wired communication, Cellular Infrastructure, Fiber Optics & Networking.*

In case of horn antenna, at 5GHz has application in automative, radio astronomy. While at 30GHz has Cryogenic and multibeam space application, Wideband telecommunication, imaging applications for security screening.

8. CONCLUSION

Design of conventional antennas like Yagi-Uda and Horn antenna for the applications in millimeter-waves is presented here. Mathematical analysis of both antennas are also discussed. As mmwave structures does not require copper sheet at bottom layer, this makes structure less complex and ease of fabrication. The size of antenna at mmwave is also very small as compare to conventional frequency. Both has achieved better return loss with efficient gain at millimeter-waves than conventional range. But Horn antenna shows better result than yagi antenna at same frequency with respect to gain.

The proposed designs at mmWave helps to achieve high data rate transmission for small area, also has interference immunity, ease of fabrication, less complex which makes antennas useful for high speed wireless communication for short range.

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