Design of Pyramidal Horn Antenna with Monopole Yagi-Uda-Fed Waveguide at Millimeter-wave

*1Dong-Hee Park
1, *Department of Information Communication Engineering, Korea National Univ. of Transportation, Republic of Korea, dhpark@ut.ac.kr

Abstract

Recently, antennas and RF power amplifiers are based on platform technology. In this paper, we have designed and analyzed the pyramidal horn antennas with monopole Yagi-Uda-Fed waveguide at millimeter-wave. In particular, the maximum gain of the monopole Yagi-Uda antenna with the flat plate has 12 dB in the E-plane and 2 dB in the H-plane. The maximum gain of the waveguide-type reflector monopole Yagi-Uda antenna is 12 dB in the E-plane and -2 dB in the H-plane. As a result, the E-plane gain of the waveguide-type reflector monopole Yagi-Uda antenna is almost the same as that of the plane reflector antenna, whereas the H-plane gain shows a relatively low gain. The horn antenna has advantages to achieve high gain and low VSWR in the millimeter-wave band because it is commonly a simple structure. The monopole Yagi-Uda-fed waveguide pyramidal horn antennas that we design have an optimum size 20X20X30mm^3 to operate at the W-band. As a result, this paper presents the possibility of the design of a millimeter-wave pyramidal horn antenna for automotive radar systems.

Keywords: *Antenna, Pyramidal horn antenna, Automotive radar system, monopole Yagi-Uda antenna, Millimeter-wave antenna*

1. Introduction

The electromagnetic wave attenuation at higher frequencies is increased by the path loss, atmosphere, snow, and rain, etc. On the other hand, the greater frequencies, the more it is straight. If so it has a higher resolution components are miniaturized. For this reason, the millimeter-wave band has been studying actively [1-3]. The horn antenna is used to obtain high gain and a low VSWR in the millimeter-wave band due to simple structure. The horn antenna in the millimeter-wave band has been applied widely to wireless communication, electromagnetic sensing, RF heating and biomedical fields [4-7].

Also, the horn antenna is commonly used as a radar antenna for the ACC as well as a standard antenna for measurement. A horn antenna is a kind of aperture antenna. If we know the electromagnetic field in the aperture, we can see the radiated electromagnetic field from it. The size and shape of the horn vary over microwave. Probably the most popular form of the rectangular horn antenna is the pyramidal horn antenna [8-11].

Radar technology to support safe driving is one of the sectors drawing a lot of attention for auto-navigation system of a vehicle. In particular, the long range radar system is very important for ACC radar in the W-band. The size of radar antenna attached to a vehicle is 50x50x30mm^3 approximately. The beam width is designed to have a 3dB [12-14]. Also, the horn antenna is commonly used as a radar antenna for the ACC as well as standard antenna for measurement. A horn antenna is a kind of aperture

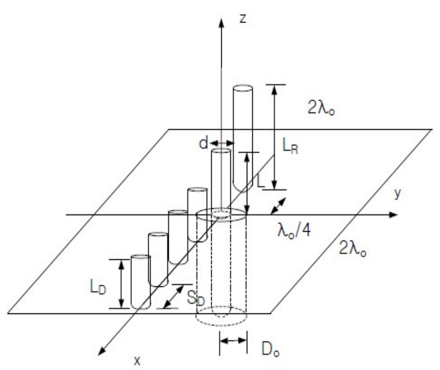
* Corresponding Author
Received: Jun. 7, 2017, Revised: Jun. 19, 2017, Accepted: Jun. 27, 2017

antenna. If we know the electromagnetic field in the aperture, we can see the radiated electromagnetic field from it [15-16].

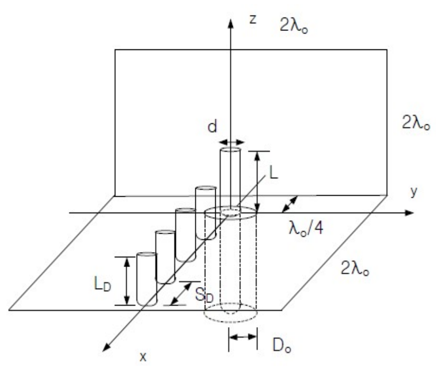
Recently, antennas and RF power amplifiers are based on platform technology. Therefore, we have designed and analyzed the monopole Yagi-Uda-fed waveguide pyramidal horn antenna operating in the W-band with an optimum size about $20x20x30mm^3$. In case of designing a horn antenna with 20dB gain, we found that monopole Yagi-Uda-fed is more effective than single monopole-fed in this work. In these monopole Yagi-Uda antennas, the maximum gain of the flat plate reflector antenna is 12 dB in the E-plane and 2 dB in the H-plane. The maximum gain of the corner reflector antenna is 7 dB in the E-plane and 7 dB in the H-plane. Also, the maximum gain of the waveguide-type reflector monopole Yagi-Uda antenna is 12 dB in the E-plane and -2 dB in the H-plane. As a result, the E-plane gain of the waveguide-type reflector monopole Yagi-Uda antenna is almost the same as that of the plane reflector antenna, whereas the H-plane gain shows a relatively low gain. We also compared the gains of the monopole Yagi-Uda-fed waveguide to the microstrip patch-fed waveguide [17].

As a result, we have proposed the possibility on the design of a millimeter-wave pyramidal horn antenna for automotive radar systems.

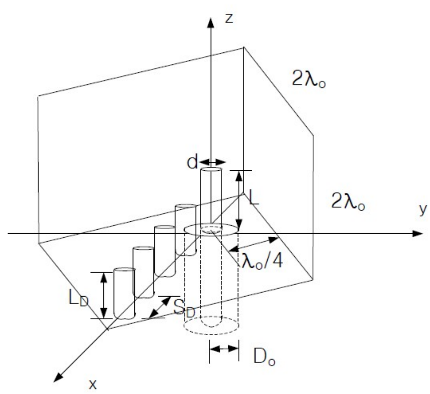
2. Design Consideration



(a) The monopole Yagi-Uda antenna.



(b) The plane reflctor monopole Yagi-Uda antenna.



(c) The corner reflector monopole Yagi-Uda antenna.

Figure 1. The monopole, the plane reflector, and the corner reflector Yagi-Uda antenna.

A monopole Yagi-Uda antenna, a flat reflector, and corner reflector Yagi-Uda antennas are constructed as shown in Fig. 1. These kinds of Yagi-Uda antenna are designed to cause the radiate of the electromagnetic energy in the front direction. Fig. 1 (a) is a monopole Yagi-Uda antenna with four directors. The size of the monopole antenna L on the ground plane is slightly less than $\lambda_o/4$. Also, the size of the reflector L_R is slightly larger than $\lambda_o/4$, and the reflector spacing is $\lambda_o/4$. The reflector size L_D and the reflector spacing S_D of the monopole Yagi-Uda antenna are smaller than $\lambda_o/4$. The wire diameter for all is approximately $\lambda/20$.

We have selected the outer radius Do of the coaxial line to have characteristic impedance 50Ω. In this paper, the final size of the monopole Yagi-Uda antenna has a millimeter wave characteristic of 77 GHz. In Fig. 1 (b) and (c), the size of the reflector was chosen to have a double wavelength (2λoX2λo). In this case, the radiation direction of the reflection plate and the edge reflector gain are designed to have the x-axis direction. This paper extends this design to waveguide feeders for horn antennas.

Generally a monopole Yagi-Uda-fed waveguide pyramidal horn antenna is like Figure 2. Figure 2 is the xz plane (H-plane), the yz plane (E-plane) with coaxial-fed, and the overall structure. Configuration of a monopole Yagi-Uda-fed waveguide pyramidal horn antenna in Figure 2 can be classified into three parts. One consists of a Yagi-Uda-fed monopole antenna, the other is rectangular waveguide for supplying electromagnetic energy and another is pyramidal horn for the impedance matching between waveguide and free space region.

In figure 2, small letters a, b are the width and height of the rectangular waveguide WR-12. Also capital letters A and B are the width and height of the aperture on the horn. The ground of the coaxial line is electrically connected to the waveguide and center connector is connected to the $\lambda_o/4$ driven monopole which is inside the waveguide. The driven monopole is generally offset from back of the waveguide by $\lambda_g/4$ where λ_g is the guided wavelength.

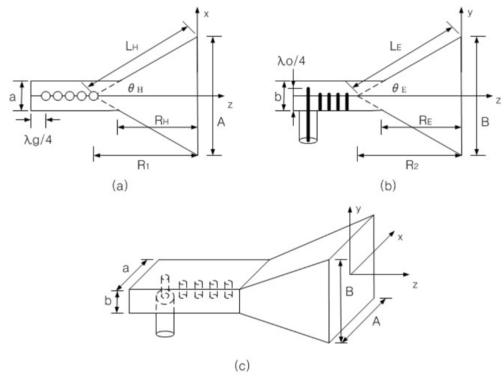


Figure 2. The monopole YagiUda-fed waveguide pyramidal horn antenna. (a) Cross section through the xz-plane, (b) Cross section through the yz-plane with coaxial-fed, (c) Overall geometry.

The W-band Yagi-Uda-fed consists of several vertical metal posts standing on ground plane. The driven monopole is fed by a coaxial cable. The parameters of monopole Yagi-Uda-fed for optimization include director spacing, number of directors, director height and driven monopole height.

In figure 2, R_1 and R_2 show the lengths from the horn apex in the waveguide to the horn aperture in the H-plane and E-plane, R_H and R_E represent the distances between the aperture plane and the WR-12 rectangular waveguide, L_H and L_E denote the diagonal lengths of the horn aperture; and θ_H and θ_E the flare angle in the H-plane and E-plane, respectively. The electromagnetic wave in the horn antenna can be considered as a transition from the waveguide mode to the free-space mode. This transition reduces reflected waves and emphasizes the traveling waves.

The electromagnetic wave in the horn antenna can be considered as a transition from the waveguide mode to the free-space mode. This transition reduces reflected waves and emphasizes the traveling waves. Therefore, in case of the receiving system, the horn antenna collects the signal in first stage of processing the signal. The aperture efficiency ε_{ap} in the pyramidal horn antenna is the measure of how efficiently the antenna physical area is utilized. It has a value between 0 and 1. And it is decreases as the phase error of the aperture is increased. That is, as the radiation efficiency ε_r is close to unity, so we can take gain to be equal to directivity.

The two efficiencies that must be considered are the aperture taper efficiency ε_t and phase efficiencies ε_{ph}^{H}, ε_{ph}^{E} in the H- and E-plane[6, 8].

$$\varepsilon_{ap} = \varepsilon_t \varepsilon_{ph}^{E} \varepsilon_{ph}^{H} \tag{1}$$

The aperture taper efficiency ε_t represents gain loss strictly due to the aperture amplitude distribution. The amplitude of this is tapered from the center to the edges of an aperture intentionally to reduce side lobes.

Therefore the aperture taper efficiency can be calculated as follows:

$$\varepsilon_t = \frac{D_t}{D_u} \tag{2}$$

Above D_u is the directivity of the same aperture uniformly illuminated and D_t is the directivity of the computed with only the amplitude taper present. We can determine the approximate width of the aperture A_o to design the optimal pyramidal horn using the following equation.

$$A_o = 0.45\lambda\sqrt{G} \tag{3}$$

Where the gain G[dB] is given to the design at the operating wavelength λ. Therefore, the actual length of the aperture is determined from the following fourth-order equation.

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

The height B of the aperture is determined as the following equation.

$$B = \frac{\lambda^2 G}{4\pi\varepsilon_{ap}A} \tag{5}$$

The optimum values for the values of R_1 and R_2 in the H-plane and E-plane are corresponding to the peak of each universal directivity curves. The curves fit to pairs of values of A, R_1 and B, R_2 for optimum conditions yields follows.

$$R_1 = \frac{A^2}{3\lambda} \tag{6}$$

$$R_2 = \frac{B^2}{2\lambda} \tag{7}$$

As a result, the distances between the aperture plane and the WR-12 rectangular waveguide R_H and R_E are determined by the similar triangles in Figure 1 (a) and (b).

$$R_H = \frac{R_1(A-a)}{A} \tag{8}$$

$$R_E = \frac{R_2(B-b)}{B} \tag{9}$$

From equation (8) and (9), the distance R_H and R_E are always the same in case of the optimum conditions. The flare angles θ_H and θ_E in the waveguide are as follows:

$$\theta_H = \tan^{-1}\left(\frac{A}{2R_1}\right) \tag{10}$$

$$\theta_E = \tan^{-1}\left(\frac{B}{2R_2}\right) \tag{11}$$

A pyramidal horn antenna is often using a coaxial line with a $\lambda_o/4$ length driven element. The ground of the coaxial cable is electrically connected to the waveguide and the center connector is connected to the $\lambda_o/4$ driven element which is inside the waveguide. The driven element is generally offset from back of the waveguide by $\lambda_g/4$ where λ_g is the guided wavelength.

$$\lambda_g = \frac{\lambda_o}{\sqrt{1-\left(\frac{\lambda_o}{\lambda_c}\right)^2}} \tag{12}$$

Above λ_o and λ_c are the operating wavelength and the cut-off wavelength respectively. The director is shorter than the driven element length. We designed the 4-elements array of the monopole Yagi-Uda-fed.

3. Simulation Results and Analysis

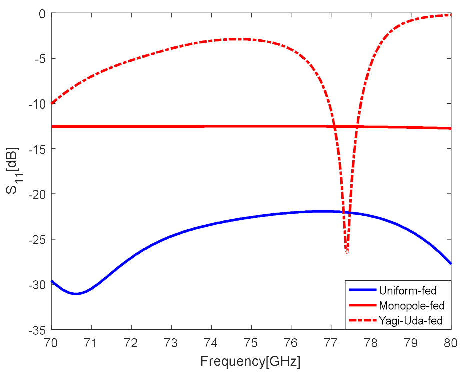


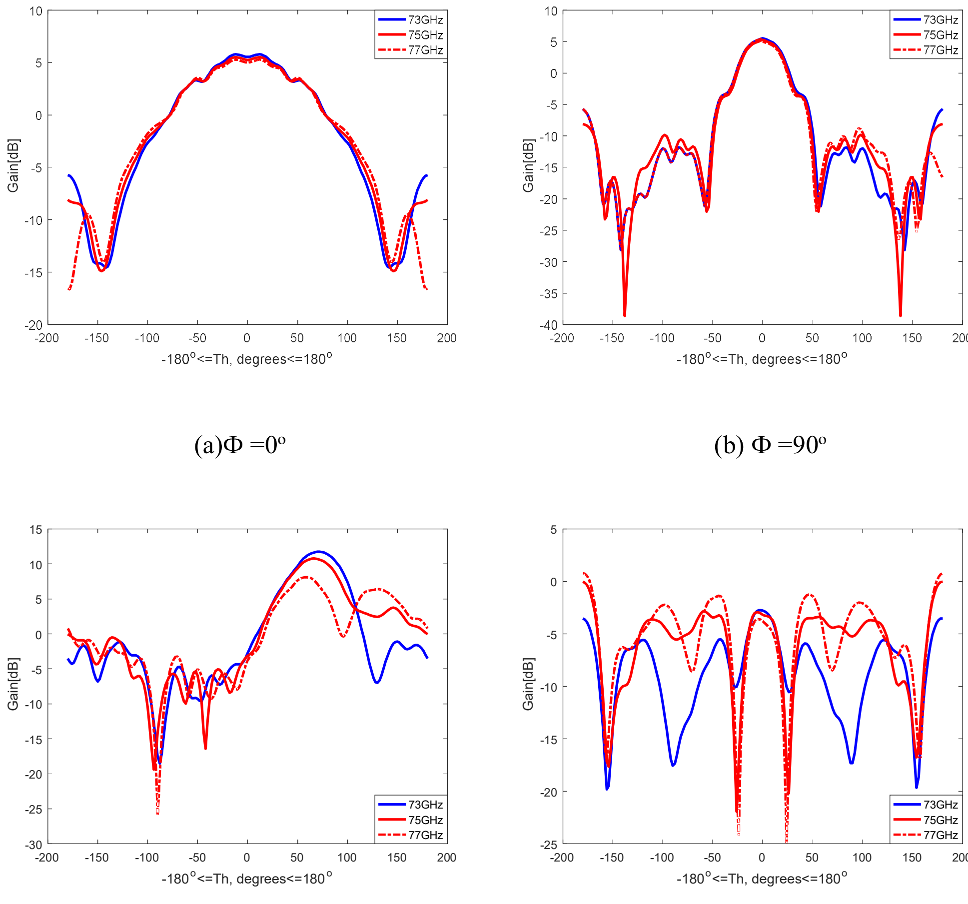
Figure 3. Return loss curves for rectangular waveguide with the uniform-fed, the monopole-fed, and the monopole Yagi-Uda antenna in the W-band.

Figure 3 shows a plot of the return loss (S_{11}) on the vertical axis versus the frequency on the horizontal axis on the WR-12 waveguide in the W-band. The solid line in the figure represents the uniform amplitude-fed, the dotted line represents the tapered rectangular aperture with the single monopole-fed, and the double-dotted line shows monopole Yagi-Uda-fed.

The internal of the waveguide is filled with air. The ratio of the size of the waveguide width and height is 2:1. The results of the return loss in this case have less than -22 dB on the uniform amplitude aperture, and less than -12 dB on the tapered rectangular aperture, and -25dB at 77GHz on the monopole Yagi-Uda antenna.

The length of the driven element at operating frequency 77 GHz is 0.9 mm shorter than $\lambda_o/4$. The driven element of monopole Yagi-Uda antenna is generally offset from the back of the waveguide by $\lambda_g/4$, where λ_g is 5mm. The radius of the coaxial probe is 0.2 mm. The driven element is coaxial-convertor with SMA connector as the feed port.

Figure 4(a) and (b) show the radiation patterns of the single monopole antenna and the monopole Yagi-Uda array at the center frequencies of 73 GHz, 75 GHz, and 77 GHz. The size of ground plane is almost same to the back plane of the waveguide.



(a)Φ =0° (b) Φ =90°

(c) Φ =0° (d) Φ =90°

Figure 4. Radiation patterns of microstrip patch-fed (a), (b) [14] and Yagi-Uda-fed (c), (d) at the center frequencies of 73 GHz, 75 GHz, and 77 GHz.

As a result, in case of the single microstrip patch-fed antenna, the maximum radiation direction in Figure 4(a) is ± 0º. The maximum radiation direction on the monopole Yagi-Uda-fed in Figure 4(c) is 80º. The maximum gain of the patch-fed antenna is 5 dB in Φ=0º and 5 dB in Φ=90º. Also, the maximum gain of the waveguide-type reflector monopole Yagi-Uda antenna is 12 dB in Φ=0º and -2 dB in Φ=90º.

The sizes of the designed waveguide feeder and pyramidal horn antenna are presented in Table 1 with respect to the W-band.

Table 1. Sizes of the monopole Yagi-Uda-Fed waveguide pyramidal horn in W-band, unit: mm

	Length		*Length*
Coaxial-a	0.2	A	17.276
L	0.9	B	13.577
L_D	0.72	R_1	25.55
S_D	0.95	R_2	23.671
a	3.098	R_H	20.97
b	1.549	R_E	20.97

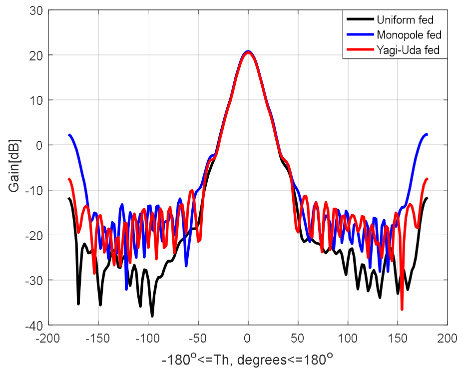


Figure 4. H-plane patterns of the pyramidal horn antenna with uniform fed, monopole fed, and monopole Yagi-Uda fed at 77 GHz.

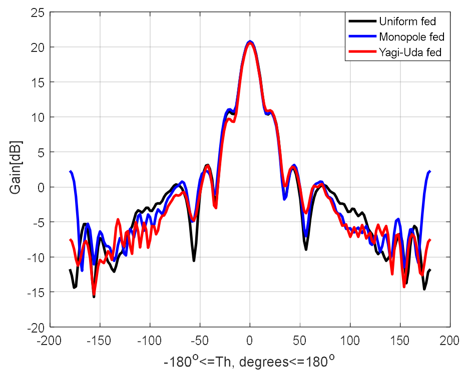


Figure 5. E-plane patterns of the pyramidal horn antenna with uniform fed, monopole fed, and monopole Yagi-Uda fed at 77 GHz.

From the results, we analyze the radiation patterns of the designed monopole Yagi-Uda-fed waveguide pyramidal horn antenna at center frequency 77 GHz. Figures. 4 and 5 show the radiation patterns of the pyramidal horn antenna with uniform-fed and single monopole-fed and monopole Yagi-Uda-fed in the H-plane and E-plane. The H-plane and E-plane radiation patterns are plotted based on the vertical axis versus rotating angle θ with -180º<= θ <=180º on the horizontal axis.

The black lines in the figures represent the uniform-fed and the blue lines represent the single monopole-fed and the red lines represent the monopole Yagi-Uda-fed. The results for three different feed are compared. In this case, we have used HFSS software analysis.

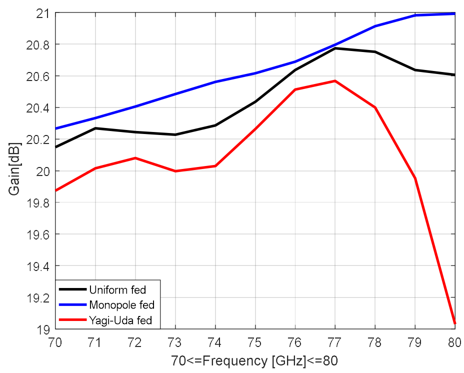


Figure 6. Gain characteristics of the pyramidal horn antenna with uniform fed, monopole fed, and monopole Yagi-Uda fed.

The gain characteristics of the uniform fed, the single monopole fed and the monopole Yagi-Uda fed waveguide pyramidal horn antenna in the operating frequencies of 70 GHz – 80 GHz is depicted in Figure 6. The uniform fed and the monopole Yagi-Uda fed have a maximum gain at 77GHz but the single monopole fed is increased proportionally with the increase of frequency.

4. Conclusions

This paper presents the possibility on the design of a millimeter-wave pyramidal horn antenna for automotive radar systems. Recently, antennas and RF power amplifiers are based on platform technology. Therefore, we designed and analyzed the monopole Yagi-Uda-fed waveguide pyramidal horn antenna capable of operating in a W-band with an optimum size 20x20x30mm^3. We present the results of the return losses, the radiation patterns, and the gains. The gain characteristics showed that the uniform-fed and the monopole Yagi-Uda-fed have a maximum gain at 77GHz and the single monopole-fed is increased proportionally with the increase of frequency. As a result, we propose the possibility of the design on the high gain pyramidal horn antenna using the monopole Yagi-Uda-fed. Further we required to extend from a pyramidal horn antenna using other feeding methods.

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