Design of Waveguide Pyramidal Horn Antenna Using Microstrip Patch-Fed for Millimeter-wave Applications

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Abstract

Recently, radar technology to support safe driving is one of the sectors receiving a lot of attention for auto-navigation system of a vehicle. The adaptive cruise control (ACC) radar in W-band belongs to long range radar (LRR). In particular, the waveguide pyramidal horn antenna has advantages to achieve high gain and low VSWR in the millimeter-wave band because it is commonly simple structure. In this paper, a patch antenna was selected as a waveguide excitation for the horn antenna. In the millimeter wave band, the patch antenna is suitable for integration. As a result, this paper suggests the possibility of designing horn antennas for automotive radar systems in the millimeter wave band.

Keywords: *Antenna, Pyramidal horn antenna, Automotive radar system, Microstrip patch antenna, Millimeter-wave antenna*

1. Introduction

Vehicle radar technology is an important technology applied to help drivers to drive safely. It has been developed since 1970, and from 1980, radar systems using millimeter waves have become widespread. 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 [1-5].

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, long range radar in the W-band for ACC is very important. The size of radar antenna attached to a vehicle is 50x50x30 mm3 approximately. The beam width is designed to have a 3dB [6-8].

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 [9-11].

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 antenna. If we know the electromagnetic field in the aperture, we can see the radiated electromagnetic field from it [12-13].

Therefore, we have designed and analyzed waveguide pyramidal horn antenna using microstrip patch-fed for millimeter-wave applications with an optimum size 20x20x30mm3. As a result, we have proposed the possibility on the design of a millimeter-wave pyramidal horn antenna for automotive radar systems.

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2. Design Consideration

Generally a waveguide pyramidal horn antenna using microstrip patch-fed is like Figure 1. Figure 1 presents the xz plane (H-plane) (a), the yz plane (E-plane) with microstrip patch-fed (b), the microstrip patch antenna (c), and the overall structure (d).

Configuration of waveguide pyramidal horn antenna using a microstrip patch-fed in Figure 1 can be classified into three parts. One is the patch antenna consists of a microstrip patch-fed, 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 1, 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 patch antenna is electrically connected to back of the waveguide and the patch sizes have the dimension of width (W) and length (L) and placed on h mm (substrate thickness). In figure 1, the sizes R1 and R2 show the lengths from the horn apex in the waveguide to the horn aperture in the H-plane and E-plane, the sizes RH and RE represent the distances between the aperture plane and the WR-12 rectangular waveguide, the sizes LH and LE denote the diagonal lengths of the horn aperture; and the degrees θH and θE represent the flare angle in the H-plane and E-plane, respectively.

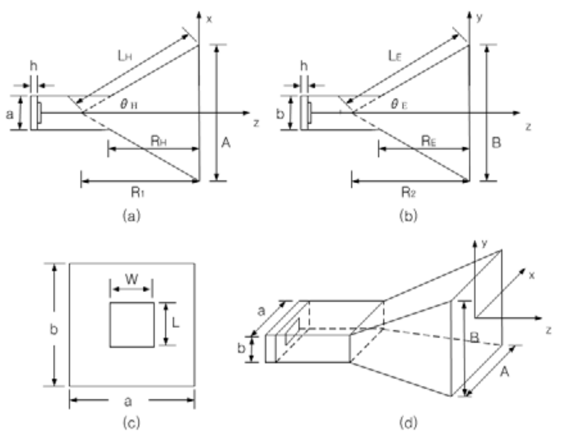


Figure 1. The microstrip patch-fed waveguide pyramidal horn antenna. (a) Cross section through the xz-plane, (b) Cross section through the yz-plane with the microstrip patch-fed, (c) The microstrip patch antenna (d) Overall geometry.

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[11].

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

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:

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

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

The geometry of the proposed microstrip patch-fed is shown in the Fig. 1 (c). The basic rectangular patch antenna has the dimension of width W and length L and substrate thickness h. The chosen substrate material is Rogers RT/duroid 5880 dielectric board with a dielectric constant of 2.2 and a loss tangent of 0.0009. The width W and length L of the patch can be approximated by using the equations from (12) to (15). The effective dielectric constant ε_{eff} need to be calculated to find the additional length ΔL on reach end due to the fringing field along the width:

$$W = \frac{v_c}{2f_o\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{12}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-\frac{1}{2}} \tag{13}$$

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{14}$$

$$L = \frac{v_c}{2f_o\sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{15}$$

Based on the above equations, theoretically calculated width and length of the patch for resonance frequency 77 GHz are found to be 1.15 mm and 1.1 mm, respectively.

3. Simulation Results and Analysis

Figure 2 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 blue solid line in the figure 2 represents the uniform amplitude aperture, the red solid line represents the monopole antenna, and the red dotted line represents the microstrip patch antenna in the rectangular waveguide. 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 in case of the uniform amplitude aperture, less than -12 dB in case of the monopole antenna, and less than -14 dB in case of the microstrip patch antenna.

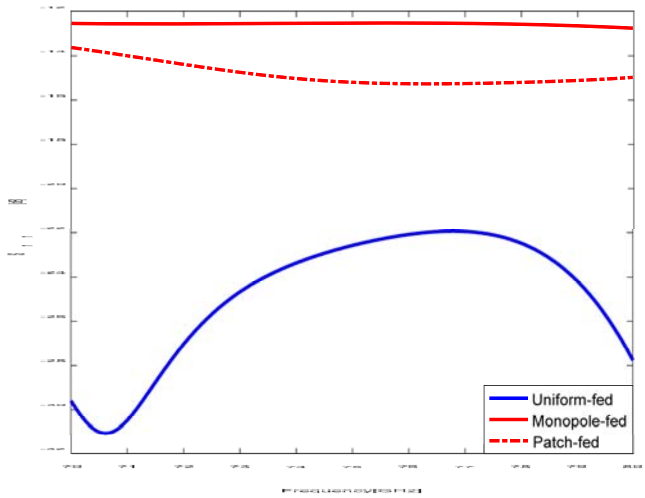


Figure 2. Return loss curves for rectangular waveguide with the uniform-fed, the monopole-fed, and the patch-fed in the rectangular waveguide.

The length of the monopole antenna $\lambda_o/4$ at operating frequency 77 GHz is 0.97 mm. The monopole antenna is generally offset from the back of the waveguide by $\lambda_g/4$, where λ_g is 5mm. The radius of probe is 0.2 mm. The monopole antenna is coaxial-convertor with SMA connector as the feed port. Fig. 3 shows the radiation patterns of the monopole antenna 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. As a result, the maximum radiation direction of the monopole antenna is ± 60°.

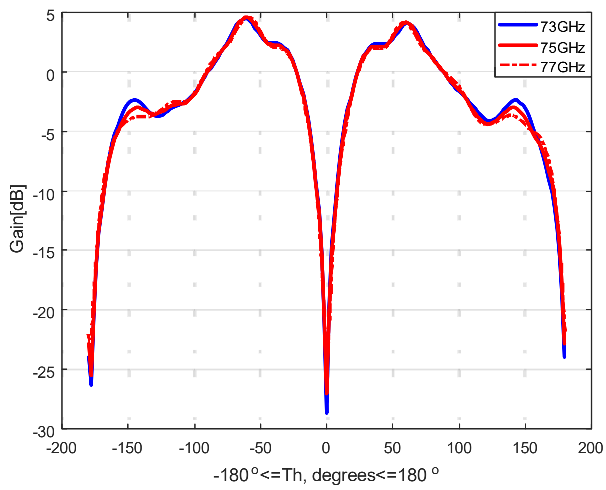
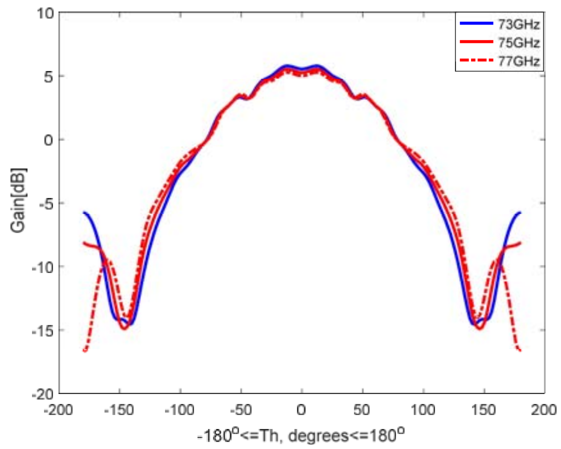
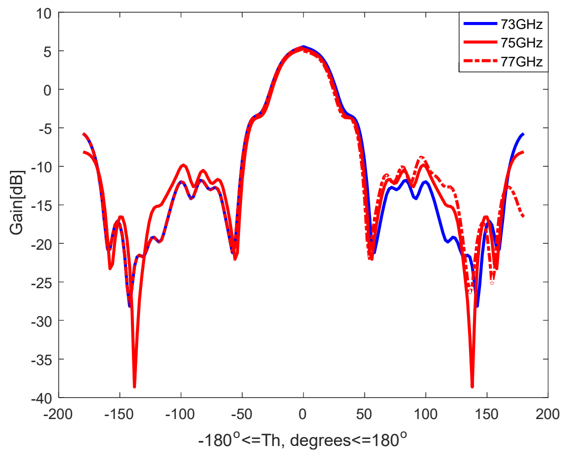


Figure 3. Radiation patterns of monopole antenna at the center frequencies of 73 GHz, 75 GHz, and 77 GHz.

From the results of Figure 3 and Figure 4 (a), the beam width is approximately 150 degrees at -10 dB gain. On the other hand, the result in Figure 4 (b) shows a beam width of about 50 degrees at -10 dB gain. That is, the patch-fed is narrower than the monopole-fed. The sizes of the designed feeder, waveguide, and pyramidal horn antenna are presented in Table 1 with respect to the W-band.



(a) $\Phi = 0^o$



(b) $\Phi = 90^o$

Figure 4. Radiation patterns of microstrip patch antenna at the center frequencies of 73 GHz, 75 GHz, and 77 GHz.

Table 1. Sizes of the pyramidal horn and patch antenna in W-band, unit: mm

	Length		Length
a	3.098	R_H	20.97
b	1.549	R_E	20.97
A	17.276	λ_o	3.896
B	13.577	λ_g	5.0
R_1	25.55	W	1.15
R_2	23.671	L	1.1

From the results, we analyze the radiation patterns of the designed the uniform-fed, monopole-fed, and microstrip patch-fed waveguide pyramidal horn antennas at center frequency 77 GHz. Figure 5 and 6 show the radiation patterns of the pyramidal horn antenna with the uniform-fed, monopole-fed, and patch-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 $-180^o \leq \theta \leq 180^o$ on the horizontal axis. The blue line in the figure 5 represents the uniform-fed, the red line represents the monopole-fed, and the red-dotted line represents the patch-fed. The results for three different feds are compared. In this case, we have used HFSS software analysis.

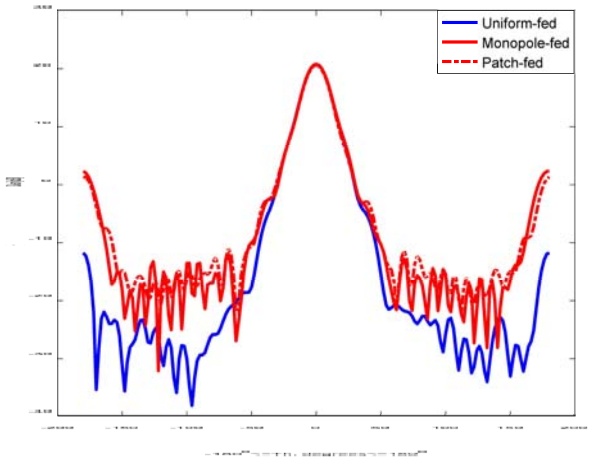


Figure 5. H-plane patterns of the pyramidal horn antenna with uniform-fed, monopole-fed, and patch-fed at 77 GHz.

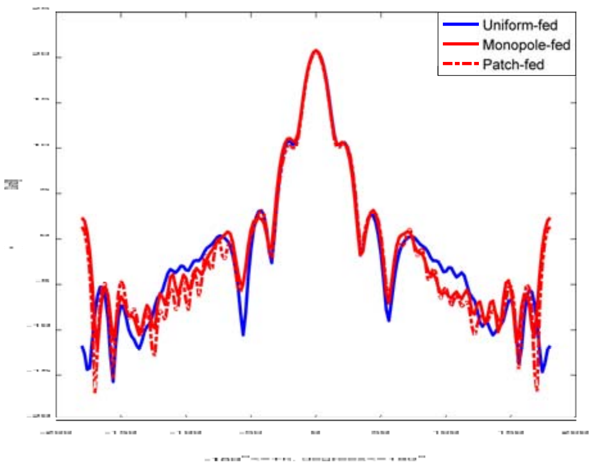


Figure 6. E-plane patterns of the pyramidal horn antenna with uniform-fed, monopole-fed, and patch-fed at 77 GHz.

The gain characteristics of the uniform-fed, monopole-fed, and patch-fed waveguide pyramidal horn antenna in the operating frequencies of 70 GHz – 80 GHz is depicted in Figure 7. All three types increase in gain as frequency increases. However, in the case of uniform-fed, it has a maximum at 77 GHz. Also, the case of microstrip patch-fed is closest to the 20dB gain designed within a given frequency range.

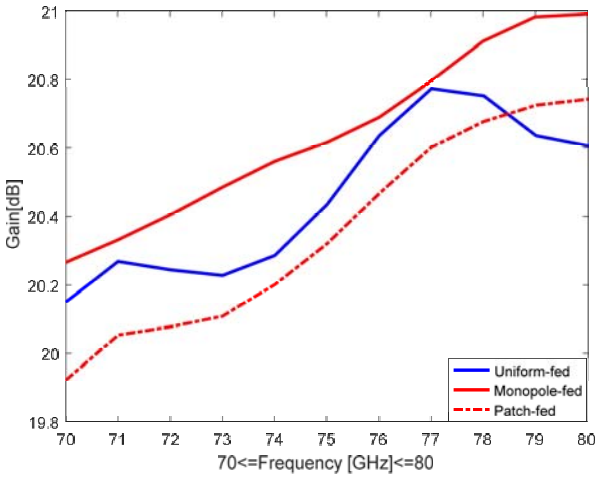


Figure 7. Gain characteristics of the pyramidal horn antenna with uniform fed and monopole fed.

4. Conclusions

This paper presents the possibility on the design of a millimeter-wave pyramidal horn antenna for automotive radar systems. We designed and analyzed the microstrip patch-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 of the patch-fed waveguide pyramidal horn antenna showed that the uniform-fed has a maximum gain at 77GHz and the 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 patch-fed. Further we required to extend from a pyramidal horn antenna using other feeding methods.

5. References

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