Design of Millimeter-wave Pyramidal Horn Antenna with Dielectric Slab

Dong-Hee PARK
Department of Information Communication Engineering, Korea National Univ. of Transportation, Chungju, 380-702, Korea
dhpark@ut.ac.kr

Abstract

This paper presents the millimeter-wave pyramidal horn antenna with dielectric slab for radar system. The newly developed millimeter-wave radar is based on the FM-CW radar system. The FM-CW radar system allows a simple construction of the RF circuit. Moreover, the automotive radar system divided by a short range radar and a long range radar are being developed. The SRR and the LRR have been used for the K-band and W-band. In addition, it is necessary to cover the aperture of the horn in order to protect the horn antenna from the external environment using the dielectric slab. In this paper, we are designed and analysis to optimized a single pyramidal horn antenna which can operate at K-band and W-band. The aperture of horn is designed to have a dielectric slab. As a result, this paper is proposing the possibility of the design of a millimeter-wave pyramidal horn antenna with a dielectric slab for automotive radar systems.

***Keywords**: pyramidal horn antenna, automotive radar system, SR radar, LR radar, millimeter-wave antenna*

1. Introduction

Radar technology to support safe driving is one of the sectors receiving a lot of attention for the development of the automotive radar system for auto-navigation system of a vehicle. In particular, ACC(Adaptive Cruise Control) radar in the K-band and W-band is important. A radar antenna is necessary to have high gain because it is for increasing the range and resolution to detect the target. Therefore, the antenna is a very important part in the performance of the radar system [1-3].

The ARS(Automotive Radar System) divided by a SRR(Short Range Radar) and LRR(Long Range Radar) is being developed. The SRR was used for the 24 GHz and the LRR has been used the 77 GHz [4-7]. 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-band has been applied widely to wireless communication, electromagnetic sensing, RF heating and biomedical fields. In this application the horn antenna is operable to the impedance matching between the waveguide feeder and free space. Also the horn antenna is commonly used as a feed horn of reflector antenna, as well as a standard antenna for measurement [8].

In this paper, we designed and analyzed to optimize a single horn antenna which can operate at K-band and W-band. In addition, the aperture of horn is designed to have a dielectric slab to protect itself. As a result, this paper has proposed the possibility of the design of a millimeter-wave pyramidal horn antenna with a dielectric slab for automotive radar systems.

2. Design of pyramidal horn antenna with dielectric slab

We designed a pyramidal horn antenna with a dielectric slab, as shown in Figure 1. Shown in Figure 1, is the xz plane (H-plane), the yz plane (E-plane), and the overall structure. Configuration of the pyramidal horn antenna in Figure 1 can be classified into four parts. That is, the horn antenna consists of a rectangular waveguide for supplying electromagnetic energy, a pyramidal horn for the impedance matching, a dielectric slab for covering the aperture of horn and the free space region.

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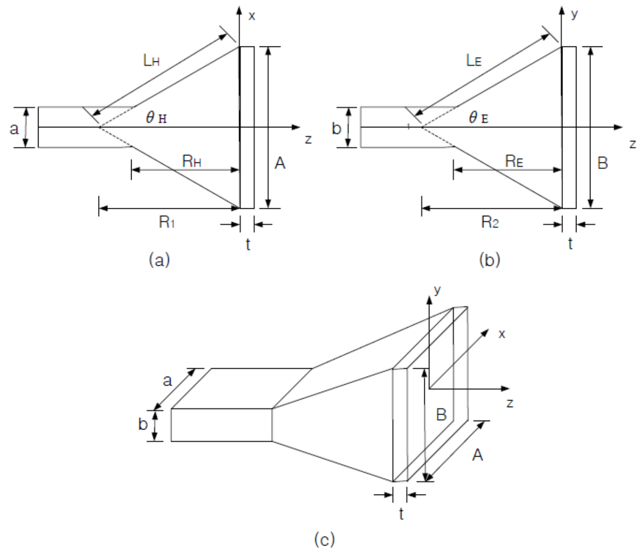


Figure 1. Pyramidal horn antenna. (a) Cross section through the xz-plane, (b) Cross section through the yz-plane, (c) Overall geometry.

In Figure 1, a and b are the width and height of the rectangular waveguide, A and B are the width and height of the aperture on the horn, and t is the thickness of the dielectric slab. In Figure 1(a) and (b), R_1, R_2, R_H, R_E, L_H, L_E and θ_H, θ_E denotes the apex-to-aperture axial horn length, the throat-to-aperture length, the slant length, and the flare angle in the H-plane and E-plane.

The size of the horn antenna is decided considering the impedance matching device between the waveguide feeder and the dielectric slab. Therefore in case of the receiving system, the horn antenna serves to collect the signal in first stage of processing the signal and the dielectric slab serves to protect the horn from changes of the external environment.

We determined the approximate width of the aperture A_o to design the optimal pyramidal horn using the following equation [9, 10].

$$A_o = 0.45\lambda\sqrt{G} \qquad (1)$$

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 equation.

$$A^4 - aA^3 + \frac{3bG\lambda^2}{8\pi\epsilon_{ap}}A - \frac{3G^2\lambda^4}{32\pi^2\epsilon_{ap}^2} = 0 \qquad (2)$$

The aperture efficient ε_{ap} has a value between 0 and 1 and it decreases as the phase error of the aperture is increased. The height B of the aperture is determined as the following equation.

$$B = \frac{\lambda^2 G}{4\pi\epsilon_{ap}A} \qquad (3)$$

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.

$$R_1 = \frac{A^2}{3\lambda} \qquad (4)$$

$$R_2 = \frac{B^2}{2\lambda} \qquad (5)$$

As a result, the throat-to-aperture length R_H and R_E is determined by the similar triangles in Figure1 (a) and (b).

$$R_H = \frac{R_1(A-a)}{A} \tag{6}$$

$$R_E = \frac{R_2(B-b)}{B} \tag{7}$$

The dielectric slab with thickness t has a relative dielectric constant ε_r. The dielectric thickness t may be determined by a half-wave matching. M is an integer here.

$$t = m\frac{\lambda}{2\sqrt{\epsilon_r}} \tag{8}$$

3. Analysis of pyramidal horn antenna

We designed the rectangular waveguide feeders in the K-band and W-band respectively. The internal of the waveguide is filled with air. The ratio of the size of the waveguide width a and height b is 2:1. The results of the return loss in this case have less than –50 dB in the K-band and W-band respectively. The sizes of the designed waveguide feeder, pyramidal horn antenna, and the thickness of the dielectric slab are presented in Table 1 with respect to the K-band and W-band respectively.

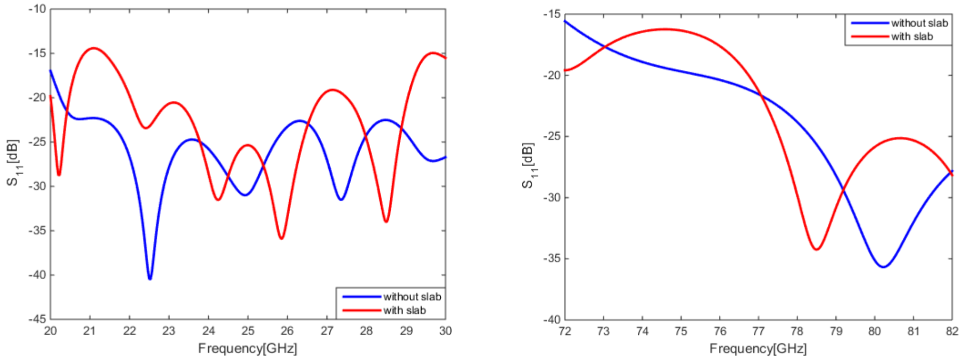
Table 1. The size comparison of the pyramidal horn antenna in K-band and W-band. unit: mm

	K-band	***W-band***
a	8	2.2
b	4	1.1
A	47.75	14.024
B	37.63	11.078
R_1	60.84	16.837
R_2	56.67	15.761
R_H	50.65	14.196
R_E	50.65	14.196
θ_H	21.43^o	22.61^o
θ_E	18.36^o	19.36^o
t	4.21	1.312

The selected aperture efficiencies are ε_{ap}=0.691 in the K-band and ε_{ap}=0.776 in the W-band. In addition, the relative dielectric constant of the dielectric slab was selected to have ε_r = 2.2. In this case, we used Ansys Inc. HFSS as design tool.

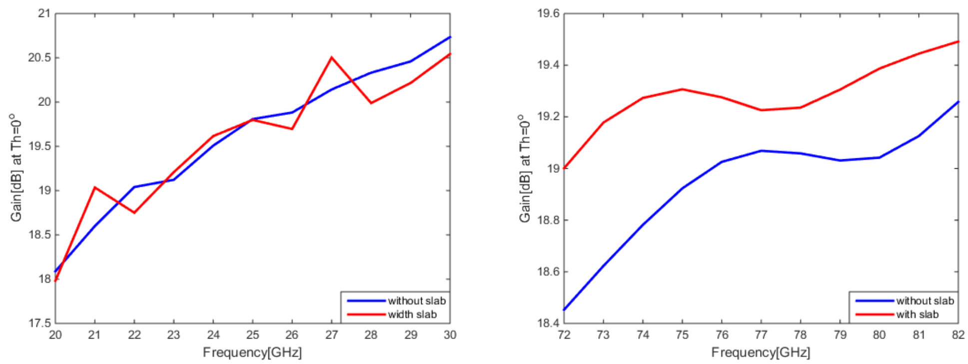
The return losses at the input of the horn antenna are presented in Figure 2 in case of with and without the dielectric slab respectively. For a K-band, the return loss with the dielectric slab is a little high compared to the absence of a dielectric slab. On the other hand it has little difference in the W-band.

Figure 3 shows the change in gain due to changes in frequency at the maximum gain of the horn antenna of the angle $\theta = 0^o$ in the K-band and W-band. These two results are compared with and without a dielectric slab respectively. Figure 3 (a) is a fine change of the gain in the K-band. Figure 3 (b) shows a difference of approximately 0.6 dB in the W-band. However, the difference of gain at 77 GHz is the smallest.



(a) K-band (b) W-band

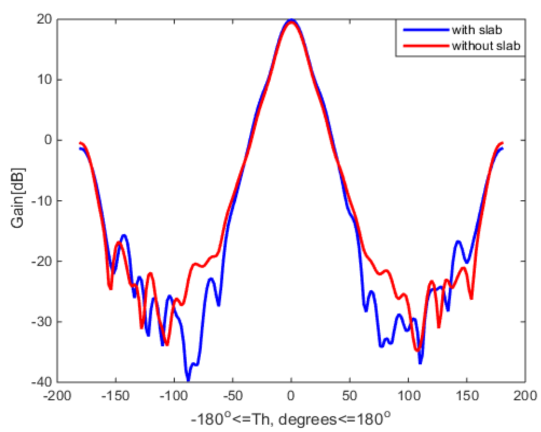
Figure 2. Simulated the return loss S_{11} in dB of the designed K-band and W-band horn antennas without and with dielectric slab.



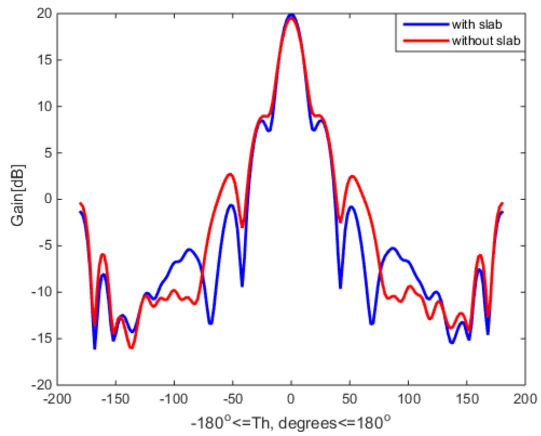
(a) K-band (b) W-band

Figure 3. Simulated the $G_{total}(\theta=0^o)$ in dB of the designed K-band and W-band horn antennas without and with dielectric slab.

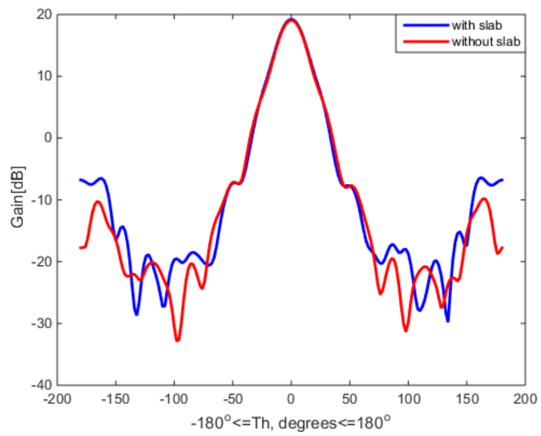
From these results, we selected the center frequency 24 GHz and 77 GHz for K-band and W-band respectively. The analysis of the radiation patterns are presented in Figure 4 for each case of with and without a dielectric slab at these center frequencies.



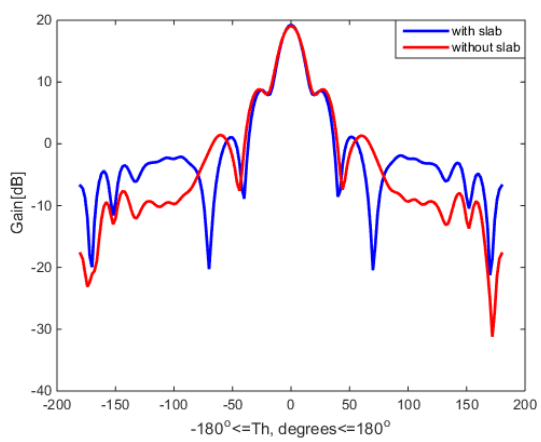
(a) The radiation patterns of the horn with/without slab at 24 GHz, $\phi=0^o$.



(b) The radiation patterns of the horn with/without slab at 24 GHz, $\phi=90^o$.



(c) The radiation patterns of the horn with/without slab at 77 GHz, $\phi=0^o$.



(d) The radiation patterns of the horn with/without slab at 77 GHz, $\phi=90^o$.

Figure 4. The radiation patterns of pyramidal horn antenna without/with slab in K-band and W-band.

4. Conclusions

This paper presents the pyramidal horn antennas for ACC radar at the 24 GHz and 77 GHz for detecting short and long distances. Also, we present the results of the return losses and the radiation patterns. When comparing with or without the dielectric slab, There was no significant difference in the gain change in the K-band and we found a slight difference in the W-band. Also, the size of the side lobe was reduced on both sides. Thus, we can see that the higher the frequency, the higher the aperture efficiency.

As a result, we propose the possibility of the design on the high gain pyramidal horn antenna. Further this paper is required to extend from a pyramidal horn array antenna to the millimeter-wave band.

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