Design of Aperture-Coupled Microstrip Array Antenna with the Modified T-junctions for Millimeter-wave Applications

* Donghee Park

Department of Information and Communications Engineering,
Korea National University of Transportation, dhpark@ut.ac.kr

Abstract

In this paper, we designed and interpreted the microstrip array antennas of the aperture-coupled operating at 24 GHz for the short range radar system. We achieved the proper impedance matching throughout the corporate feeding array configurations provides the lossless T-junction. In order to better exactly match in the T-junction, we added a slit in the junction. Also, we added slots to the patch to overcome it because general microstrip patch antennas have narrow band characteristics. The return loss of a single patch, 2×1, 2×2, 4×2, and 4×4 arrays with feed network using T-junction divider inserted the slit are analyzed here. The radiation patterns of these designed arrays are very simple and high efficiency for the applications in the millimeter-wave. The operating frequency of all our designed antennas is 24 GHz. As a result, this paper is available for short range radar applications in the millimeter-wave band. It can be positioned on the top of MMIC's. As a result, this paper has proposed the possibility of prototyping by design of array antennas in the millimeter-wave.

Keywords: Inset-feed patch antenna, T-junction power divider, Aperture-coupled antenna, millimeter-wave antenna, patch array antenna

1. Introduction

The study on millimeter-wave antennas have evolved continuously over the past 30 years, with the rapid development of microstrip antenna theories and techniques. The microstrip antenna has been applied to many fields because it can be integrated a small weight and volume. In recent years, millimeter-wave radar systems in the transport sector are being used widely in the automotive electronics sensors with the information and communication technologies. In the center of these changes, it is an Adaptive Cruise Control (ACC) system. The system is an active safety device that can predict the occurrence of an accident by sensing the external environment while driving car. In recently, the development of automotive radar systems divided by a short distance SRR (Short Range Radar) and long distance LRR (Long Range Radar) are being developed. The SRR was used of 24GHz band [1-4].

This paper is designed and interpreted microstrip array antenna (MAA) of the aperture-coupled microstrip antennas operating in the millimeter wave band. In this technique the feed network is separated from the radiating patch by a common ground plane. Energy is electromagnetically coupled through an aperture in the ground. This aperture is usually centered with respect to the patch where the patch has its maximum magnetic field. The MAA can be designed with a transmission line circuit and a matching circuit in the same substrate. Therefore it is easy to combine with the active elements of the system. Its main advantage is that it can be an overall design of the semiconductor integrated circuit. We add the slots to the patch to overcome it because general microstrip patch antennas have narrow band characteristics.

As a result, the proposed MAA with slots is well suited for integrating with existing MMIC's for SRR system. So this paper presents the possibility of the millimeter-wave MAA system implementations through the simulation results.

Received: Oct. 14, 2014, Revised: Dec. 03, 2014, Accepted: Jan. 06, 2015

2. T-junction Power Divider

The microstrip transmission line is the most widely used line, with applications in integrated circuits and microstrip feeders. Here we treat with lossless transmission line. Therefore, T-junctions are reciprocal and can be considered lossless if transmission line loss is not taken into account. A lossless T-junction can be modeled as a junction of three transmission lines, as shown in Figure 1. For the divider to be matched to the input line of characteristic impedance Z_o, the following must be true:

$$\frac{1}{Z_1}+\frac{1}{Z_2}=\frac{1}{Z_o} \tag{1}$$

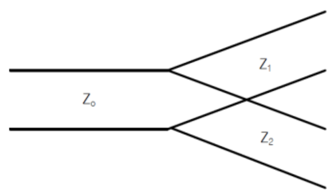


Figure 1. Transmission line model of a lossless T-junction

For an equal split power divider with Z_o = 50 Ω, Z_1 and Z_2 would be 100 Ω. Quarter wave transformers can be used to bring the output line impedances back to the characteristic impedance Z_o. A quarter-wave transformer matches the input and output impedances of a system by placing a lossless, λ/4-long transmission line of characteristic impedance $Z_o(\lambda/4)$, between the input and output lines. In order to match the load to the feed line, the impedance Z_{12} looking into the quarter-wave matching section must be equal to $Z_o = Z_L$.

$$Z_{o(\lambda/4)}=\sqrt{Z_{12}Z_o} \tag{2}$$

In actual design of microstrip, one wishes to determine the width W required to obtain specified characteristic impedance Z_o on a substrate of known permittivity ε_r and dielectric thickness h[5-7].

$$W=\frac{h}{\left[e^H/8-1/(4e^H)\right]} \tag{3}$$

Where,

$$H=\frac{Z_o\sqrt{2(\varepsilon_r+1)}}{119.9}+\frac{1}{2}\left(\frac{\varepsilon_r-1}{\varepsilon_r+1}\right)\left(\ln\frac{\pi}{2}+\frac{1}{\varepsilon_r}\ln\frac{4}{\pi}\right) \tag{4}$$

In this paper, we have designed a distributed structure of the T-junction classified into two types, as shown in Figure 2. The port 1, 2, and 3 has the characteristic impedance Z_o.

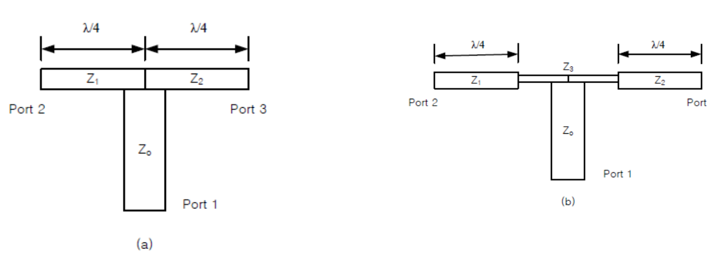


Figure 2. Designed T-junctions, (a) λ/4-transformer, (b) Z_3 and λ/4-transformer

In order to match in the T-junction, we have added the slit in the junction, as shown in Figure 3. The inductance value of the inserted slit is decided by its width and depth. Therefore, we could improve the electrical performance through optimization of inductance.

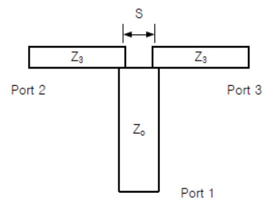


Figure 3. The inductive slit width S at the T-junction

3. Aperture-Coupled Microstrip Single Patch Antenna

The aperture-coupled microstrip single patch antenna used in this study is shown in Figure 4. This technique has several advantages, which makes it suitable for widespread applications in communication systems. The feed substrate is usually thin with high permittivity, whereas the patch substrate can be thick with low permittivity.

In this configuration the antenna system is composed of a conductive thin metal plate and an air layer to minimize the reflected wave, the feed line for supplying a signal, the dielectric layer for supporting a surface, a conductive ground plane that contains the aperture, the supporting dielectric layer physically and the patch [8-11].

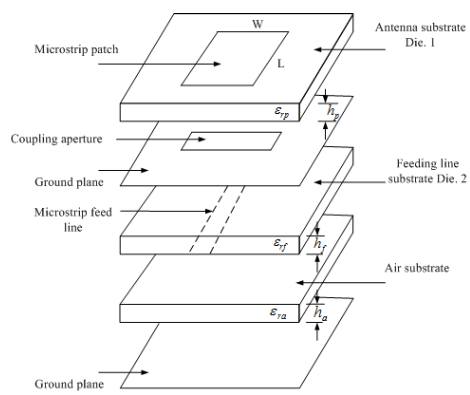


Figure 4. Aperture-coupled microstrip patch antenna

In general, the size of the patch is determined below half-wave by the fundamental resonance mode. In this case, the selected resonant frequency is 24 GHz. Therefore, practical length L and width W of the patch are obtained as follows.

$$L = \frac{c}{2 f_r \sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{5}$$

$$W = \frac{c}{2 f_r} \left(\frac{\varepsilon_{rp} + 1}{2} \right)^{-1/2} \tag{6}$$

In this equation (5), ε_{reff} is the effective dielectric constant of the substrate considering the edge effect, f_r is a resonance frequency of the antenna, c is the speed of light in free space region, ε_{rp} is the relative dielectric constant, and ΔL represents the equivalent length of the patch according to the size of the operating frequency. The value ΔL is determined from the following equation. The width W of the patch is mainly used to obtain the input impedance.

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)(W/h+0.264)}{(\varepsilon_{reff}-0.258)(W/h+0.8)} \tag{7}$$

The dielectric substrate Die. 1 is Rogers RT / duroid 5880 and it have the relative dielectric constant ε_{rp} = 2.2, the loss tangent tanδ = 0.0009, and the thickness of the substrate h_p = 0.5 mm. As shown in Figure 4, the substrate Die. 2 for a microstrip line is FR-4 epoxy and it is the relative dielectric constant ε_{rf} = 3.92, the loss tangent tanδ = 0.031, and a thickness h_f = 0.3 mm. Also the air layer with a thickness h_a = 1.6 mm to minimize the radiation of the strip line is added.

The final size of the patch is designed to have the width W = 6 mm and length L = 4 mm. In addition, the width of the aperture coupled microstrip line with a 50 Ω characteristic is W_{01} = 0.6 mm. The width of the slot for aperture coupled inside ground plane is S_w = 0.1 mm and length is S_L = 4.5 mm. This paper is added the slots to the patch because it have narrow band characteristics within the millimeter-wave band.

4. Aperture-Coupled Antenna Arrays

The antenna arrays are designed starting with a single element using the transmission line model described in Section 3. Figure 5 shows the position of the feed structures and the elements of a 4×4 antenna array. This antenna is designed with microstrip line feed network employing a T-junction with slits. Each reactive T-junction used in the antenna feed network provides and equal or 3dB power split. The width W_{o1} of the characteristic impedance 50 ohm is 0.6 mm, and the width W_{o2} of the 70.7 ohm line is 0.35 mm, and W_{o3} of the 100 ohm line is 0.15 mm. The interval D_x and D_y between the patch and the patch are 5.4 mm.

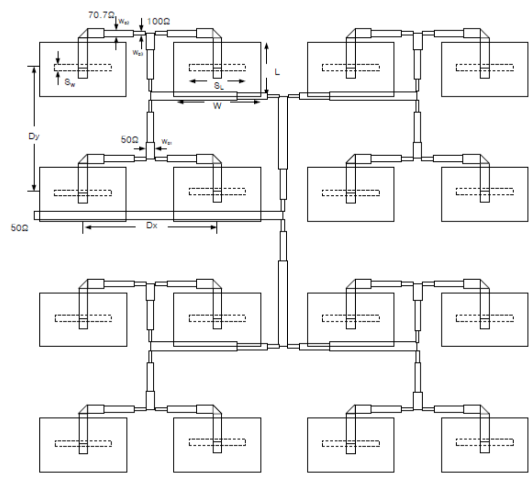
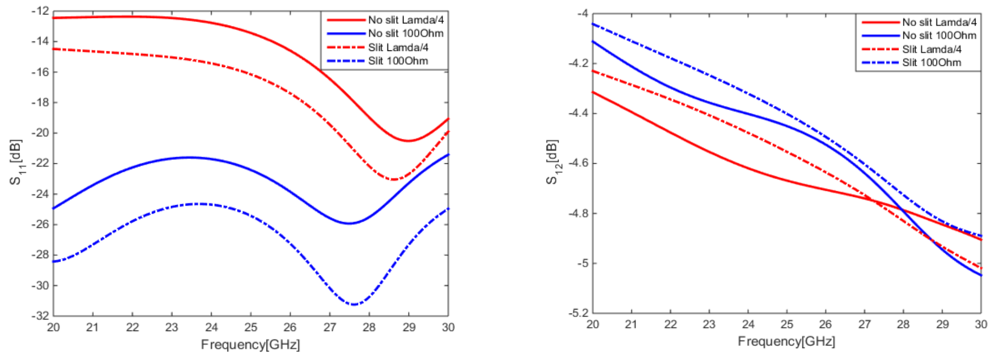


Figure 5. Layout of 4×4 array with the proposed T-junction dividers with slits

5. Results and Comparison

In this paper, we design and analysis of the microstrip line T-junction in the millimeter-wave band. We have designed the T-junction lines presented in Figure 2 at the center frequency 24 GHz. Here, the width of the line W_o is 0.6 mm, the width of the line W_1 = W_2 is 0.35 mm, and the width W_3 is 0.15 mm.

Figure 6 (a) shows the reflection coefficients S_{11} on the models of Figures 2 and 3. In Figure 6 (a), these reflection coefficients S_{11} represents the best results when the 100 Ω-slit is added to the T-junction part. Because the capacitance values of mismatching is being changed in the junction part. Figure 7 (b) shows the results for the transmission coefficient S_{12} from Port 2. It also shows the best results when the slit is added to the100 Ω line in the T-junction parts.



(a) The reflection coefficients S_{11} (b) The transmission coefficients S_{12}

Figure 6. S Parametric plots for T-junction without/with slit.

The variation of reflection coefficients versus frequency of the single patch antenna and 2╳1, 2╳2, 4╳2, and 4╳4 array antennas with feed network using T-junction dividers are shown in Figure 7. It clearly depicts that by increasing the number of elements in the array, the bandwidth at 24 GHz increases. In particular, the band width is represented more widely in the 4╳4 array. The proposed geometry is simulated using HFSS tool software.

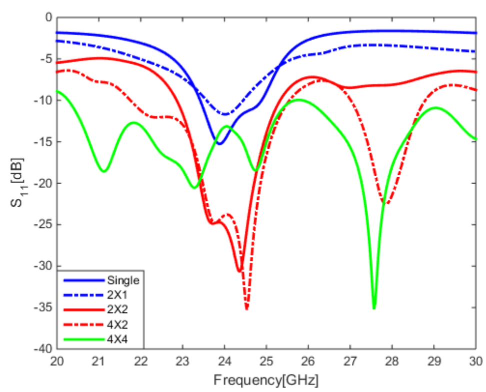


Figure 7. The reflection coefficient curves for the single patch, 2╳1 array, 2╳2 array, 4╳2 array, and 4╳4 array

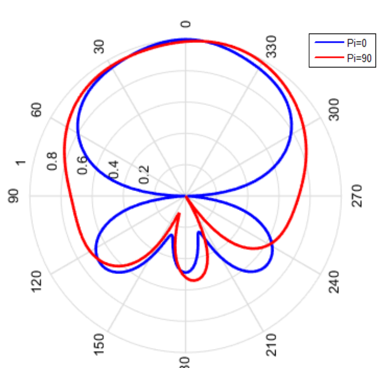


Figure 8. The radiation patterns of single patch antenna at 24 GHz

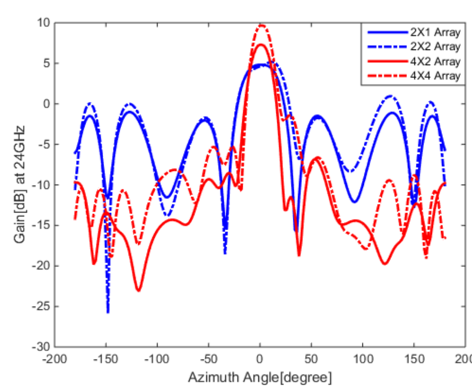


Figure 9. The comparison of simulated results on radiation pattern of array antennas

Figure 8 presents the results of the radiation pattern at the center frequency 24 GHz of the single patch antenna. The radiation patterns of the array are shown in from Figure 9. It clearly depicts that by increasing the number of elements in the array, the gain and directivity increases with decrease in the beam width. The 4╳4 array as a maximum gain of 10 dB and beam width of 20 degree which satisfies the requirement for short range radar applications. Because of its compactness, it can also be integrated with the existing MMIC's.

The radiation patterns of the arrays from Figure 10 to Figure 13 are shown that the simulated gain is normalized at Φ = 0 degree and Φ = 90 degree for the operating frequency 24 GHz.

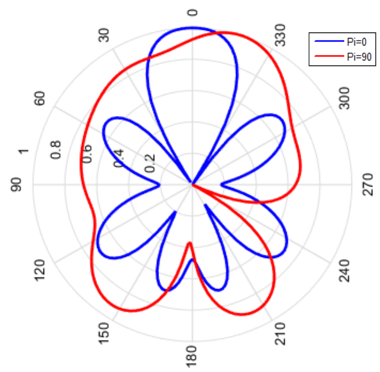


Figure 10. The normalized radiation patterns of 2╳1 array antenna

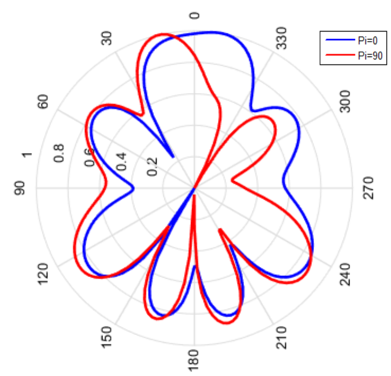


Figure 11. The normalized radiation patterns of 2╳2 array antenna

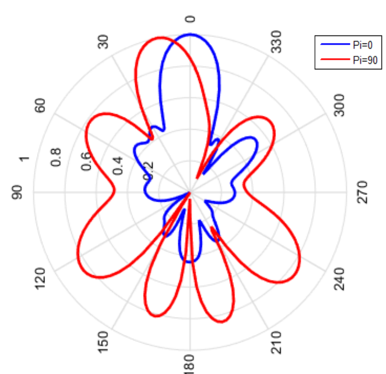


Figure 12. The normalized radiation patterns of 4╳2 array antenna

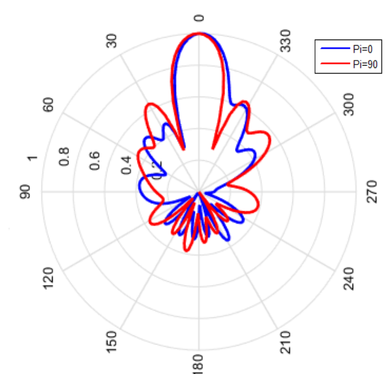


Figure 13. The normalized radiation patterns of 4╳4 array antenna

6. Conclusion

In this paper, we designed and interpreted the MAA of the aperture-coupled microstrip antennas operating at 24 GHz for the short range radar SRR system. The MAA can be designed with a transmission line circuit and a matching circuit in the same substrate. Therefore it is easy to combine with the active elements of the system. We achieved the proper impedance matching throughout the corporate feeding array configurations provides the lossless T-junction. In order to more exactly match in the T-junction, we have added the slit in the junction. The inductance value of the inserted slit is decided by its width and depth. Therefore, we could improve the electrical performance through optimization of inductance.

In this paper, the antenna systems are composed of a conductive thin metal plate and an air layer to minimize the reflected wave, the feed line for supplying a signal, the dielectric layer for supporting a surface, a conductive ground plane that contains the aperture, the supporting dielectric layer physically and the patch. We add the slots to the patch to overcome it because general microstrip patch antennas have narrow band characteristics.

The return loss of a single patch, 2×1, 2×2, 4×2, and 4×4 MAA with feed network using T-junction divider inserted the slit are analyzed here. It clearly depicts that by increasing the number of elements in the array, the bandwidth at 24 GHz increases. In particular, the band width is represented more widely in the 4×4 array. The radiation patterns of these designed arrays are very simple and high efficiency for the applications in the millimeter-wave. The optimum design parameters are used to achieve the compact dimensions and high radiation efficiency. The operating frequency of all our designed antennas is 24 GHz. It would also be possible to design an antenna operating in any other frequency bands by changing the design parameters.

As a result, this paper is available for short range radar applications in the millimeter-wave band. It can be positioned on the top of MMIC's. In future, we will investigate the 16×16 array antennas with different feeding techniques which seem to be having more improved performances for the corporate feed networks.

7. References

[1] M. Stotz, G. Gottwald, H. Haspeklo, and J. Wenger, "Planar Millimeter-Wave Antennas Using SiNx-Membranes on GaAs," *IEEE Trans. Microwave Theory Tech.*, Vol. 44, No. 9, pp. 1593–1595, Sept. 1996.

[2] M. Slovic, B. Jokanovic and Kolundzija, "High efficiency patch antenna for 24 GHz anticollision radar," in Proc. of 7th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services, Vol. 1, 2005, pp. 20–23.

[3] Y. P. Zhang, M. Sun, and L. H. Guo, "On-chip antennas for 60-GHz radios in silicon technology," *IEEE Trans. Electron Devices*, Vol. 52, No. 7, pp. 1664–1668, July 2005.

[4] C. H. Doan, S. Emami, D. A. Sobel, A. M. Niknejad, and R. W. Brodersen, "Design considerations for 60 GHz CMOS radios," *IEEE Comm. Mag.*, pp. 132–140, Dec. 2004.

[5] D. M. Pozar, "Considerations for Millimeter Wave Printed Antennas," *IEEE Trans. Antennas Propagat.*, Vol. AP–31, No. 5, pp.740–747, Sept. 1983.

[6] D. M. Pozar, "A Microstrip Antenna Aperture Coupled to a Microstrip Line," *Electronics Letters*, Vol. 21, pp. 49–50, Jan. 1985.

[7] C. A. Balanis, Antenna Theory Analysis and Design, 2nd ed., New York: John Wiley & Sons, 1997.

[8] S. C. Shrivastava and Z. Aijaz, "An Intriduction of Aperture Coupled Microstrip Slot Antenna," *International Journal of Engineering and Technology*, Vol. 2, No. 1, pp. 36–39, 2010.

[9] Kamil Pitra, and Zbynek Raida, "Planar Millimeter-Wave Antennas: A Comparative Study," *Radio Engineering*, Vol. 20, No. 1, pp. 263–269, April 2011.

[10] P. Pursula, T. Vähä-Heikkilä, A. Muller, G. Konstantinidis, D. Neculoiu, A. Oja, and J. Tuovinen, "Millimeter wave identification—New radio system for low power, high data rate and short range," *IEEE Trans. Microw. Theory Tech.*, to be published.

[11] M. T. Ali, T. A. Rahman, M. R. Kamarudin, and M. N. Md Tan, "A Planar Antenna Array with Separated Feed Line for Higher Gain and Sidelobe Reduction," *Progress In Electromagnetics Research* C, Vol. 8, pp. 69–82, 2009.