

Analysis of Aperture-Coupled Microstrip Antenna Array on LTCC by FDTD

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Abstract

In this paper, we designed and analysis the aperture-coupled microstrip array antennas for the short range radar (SRR) system. These antennas can be designed with transmission lines and matching circuits in the same substrate LTCC. 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 slit in the junction. The return loss of arrays with feed network using T-junction dividers are analyzed using SEMCAD X tool using the finite difference time domain (FDTD) method to analyze such structures. 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 proposed the possibility of prototyping by design of array antennas in the millimeter-wave.

Keywords: Millimeter-Wave Antenna, T-Junction with Slit, Aperture-Coupled Patch Antenna, SRR System, Automotive Radar System

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, the millimeter-wave radar systems in transportations are being used widely in automotive electronics sensors with the information and communication technologies[1-4].

In the center of these changes, it is an adaptive cruise control (ACC) system. This system is an active safety device that can predict the occurrence of an accident by sensing the external environment while driving car. Further automotive radar system (ARS) uses a millimeter wave sensor that can provide information about the environment around the front, rear and sides of the automobile to control the cruising car [5-6].

Further the technology of the structurally size has been applied in the system-on-package (SOP). This technology is mixed small power consumption of the active device component based on the silicon technology and the multi-layer substrate with the low temperature co-fired ceramic (LTCC). Therefore, this package technology of laminate is used in order to combine the antenna and the ARS into one. But a disadvantage of planar antenna using LTCC is narrow bandwidth because high dielectric constant. Also the efficiency of the antenna is less by surface wave as increases the height of the substrate [7].

In this paper, we use a multi-layer LTCC substrate having a high dielectric constant. In addition, we design the aperture-coupled microstrip array antenna (MAA) in order to improve the radiation characteristics. Also, we use the SEMCAD X tool using the finite difference time domain (FDTD) method to analyze such structures[8][9]. This analysis method has an advantage that can obtain a wide range of structures with multiple dielectric boundaries and wide frequency response characteristics. In this technique the feed network is separated from the radiating patch by a common ground plane. Then the 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.

As a result, the proposed aperture-coupled MAA with slots in the patches of array element is well suited for the multi-layer packaging technologies for SOP. So this paper presents the possibility of millimeter-wave MAA system implementations through the simulation results.

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 a transmission line on LTCC substrate. 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 [10]:

$$\frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_o} \quad (1)$$

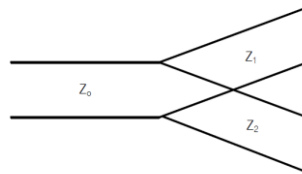


Figure 1. Transmission Line Model of a Lossless T-Junction

For an equal split power divider with $Z_o = 50 \Omega$, Z_1 and Z_2 would be 100Ω . 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, $\lambda/4$ -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 $Z_o = Z_L$.

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

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 .

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 .

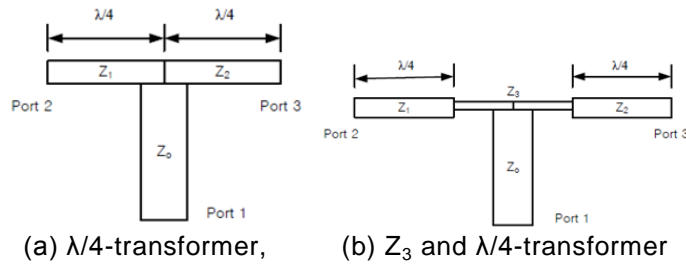


Figure 2. Designed T-Junctions

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.

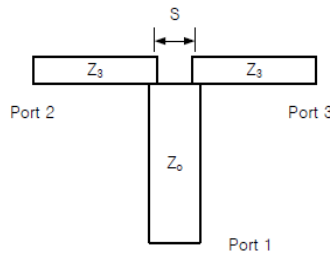


Figure 3. The Inductive Slit Width S At The T-Junction

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 the same 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 LTCC dielectric two layers for supporting a surface, a conductive ground plane, the supporting LTCC dielectric four layers physically and the patch.

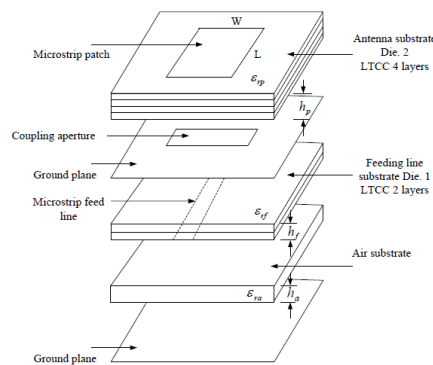


Figure 4. Aperture-Coupled Microstrip Patch Antenna

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[11-12].

$$L = \frac{c}{2f_r \sqrt{\epsilon_{reff}}} - 2\Delta L \quad (3)$$

$$W = \frac{c}{2f_r} \left(\frac{\epsilon_{rp} + 1}{2} \right) \quad (4)$$

In this equation (3), 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.

$$\Delta L = 0.412 h \frac{(\epsilon_{reff} + 0.3)(W/h + 0.264)}{(\epsilon_{reff} - 0.258)(W/h + 0.8)} \quad (5)$$

The LTCC dielectric substrate Die. 1 is Ferro A6S and it have the relative dielectric constant $\epsilon_{rp} = 5.9$, the loss tangent $\tan\delta = 0.002$, and the thickness of the LTCC substrate two layers $h_f = 0.2$ mm. As shown in Figure 4, the substrate Die. 2 for a microstrip line is LTCC four layers and it is the relative dielectric constant $\epsilon_{rf} = 5.9$, the loss tangent $\tan\delta = 0.002$, and a thickness $h_f = 0.4$ 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 $L = 4.9$ mm. In addition, the width of the aperture coupled microstrip line with a 50Ω characteristic is $W_{01} = 0.3$ 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 an equal or 3dB power split. The width W_{01} of the characteristic impedance 50Ω is 0.3 mm, and the width W_{02} of the 70.7Ω line is 0.15 mm, and W_{03} of the 100Ω line is 0.06 mm. The interval D_x and D_y between the patch and the patch are 5.4 mm.

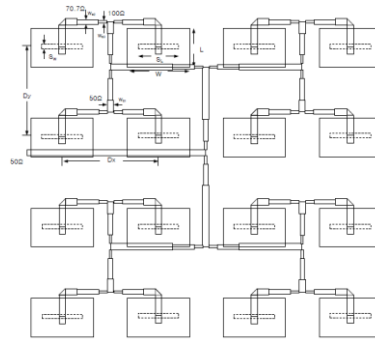


Figure 5. Layout of 4×4 Array with the Proposed T-Junction Dividers with Slits

5. Results and Comparison

In this paper, we design and analysis of the microstrip line T-junction in the millimeter-wave band on the LTCC substrate. We have designed the T-junction lines presented in Figure 2 at the center frequency 24 GHz. Here, the width of the line W_0 is 0.3 mm, the width of the line $W_1 = W_2$ is 0.15 mm, and the width W_3 is 0.06 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 6(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 the 100 Ω line in the T-junction parts.

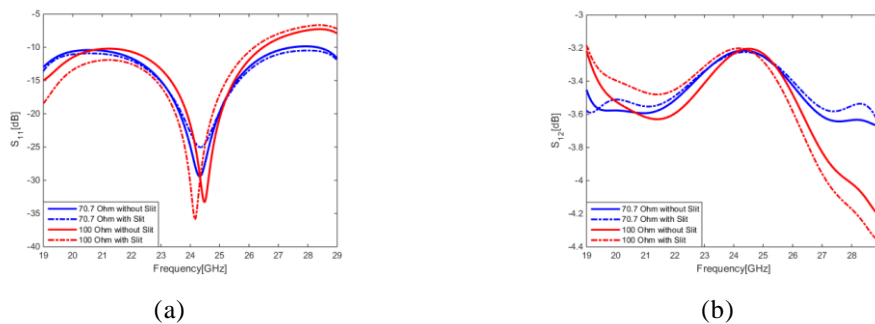


Figure 6. S Parametric Plots for T-Junction Without/With Slit. (A) The Reflection Coefficients S_{11} , (B) the Transmission Coefficients S_{12}

The variation of reflection coefficients S_{11} versus frequency of the single patch antenna, 2×1 , and 2×2 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 bandwidth is represented more widely in the 2×2 array. The proposed geometry is simulated using SEMCAD X tool.

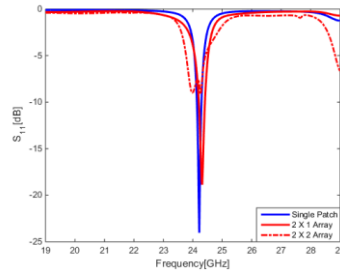


Figure 7. The Reflection Coefficient Curves for the Single Patch, and 2×1 , and 2×2 Array

Figure 8 presents the results of the radiation pattern on the E_{Pi} and E_{Th} at the center frequency 24 GHz on the single patch antenna. In this case we can see that gain is greater as compared to the case when there is no slot.

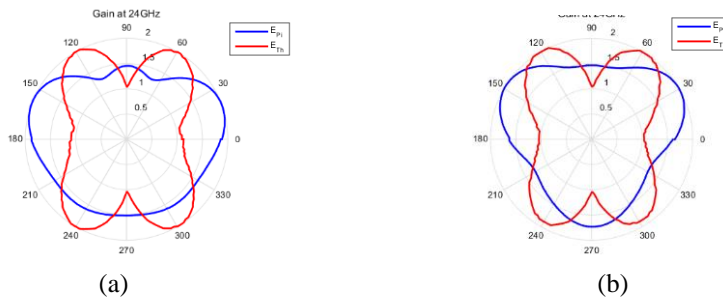


Figure 8. The Radiation Patterns of Single Patch Antenna at 24 Ghz. (A) Without Slots on Patch (B) With Slots On Patch

The radiation pattern of the arrays at $\phi = 90^\circ$ 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. Figure 9 presents the results of the radiation pattern on the E_{Pi} and E_{Th} at the center frequency 24 GHz on the 2×1 , 2×2 , and 4×4 array.

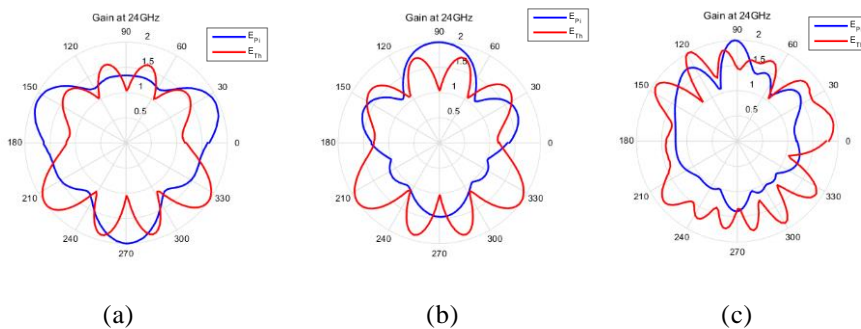


Figure 9. The Normalized Radiation Patterns of 2×1 , 2×2 , 4×4 Array Antenna

6. Conclusions

In this paper, we designed and interpreted the aperture-coupled MAA operating at 24 GHz for the SRR system. The MAA can be designed with a transmission line circuit and a matching circuit in the same substrate LTCC. Therefore it is easy to combine with the active elements of the SOP. 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.

Also, we use the SEMCAD X tool using the finite difference time domain (FDTD) method to analyze such structures. This analysis method has an advantage that can obtain a wide range of structures with multiple dielectric boundaries and wide frequency response characteristics. The return loss of a single patch MAA with feed network using T-junction divider inserted the slit are analyzed here. The coefficients S_{11} and S_{12} on the T-junction without/with slit represent the best results when the 100 Ω -slit is added to the T-junction part. Because the capacitance values of mismatching are being changed in the junction part. 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 SRR applications in the millimeter-wave band. It can be positioned on the top of multi-layer packaging technologies for SOP. So this paper presents the possibility of millimeter-wave MAA system implementations through the simulation results. 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.

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