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EFFICIENT TECHNIQUES TO MINIATURIZE THE SIZE OF PLANAR CIRCULAR MONOPOLE ANTENNA

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ABSTRACT

Recently different techniques have been adopted by many researcher to minimize the size of antennas being employed in compact devices. In this paper miniaturization of a planar circular monopole antenna (PCMA) has been introduced while maintaining its working range of frequencies covering the UWB range (3.1~10.6 GHz). Two different techniques are suggested; firstly, the PCMA radiator has been modified by eliminating areas with least concentrated current distribution, which led to generation of a crescent-shape radiator and the overall size reduction reached 11.76% of the original size. Secondly, the edge of the circular radiator has been corrugated according to some suggested formulas, which increased the size reduction to about 42.6%. Another advantage has been achieved for the corrugated PCMA by extending the upper limit of its impedance bandwidth to 13.85 GHz. All designed antennas have been fabricated and verified via practical experimental measurements. Simulated and measured results have shown that both techniques were succeeded in miniaturizing the overall size of PCMA antenna, but precisely, corrugation technique was more efficient.

Keywords: Miniaturized Antennas, PCMA, Crescent-Shaped, Corrugation, UWB.

1. INTRODUCTION

Since adopting the UWB standard by Federal Communication Commission (FCC) in 2002 [1] for short-range peer-to-peer ultra-fast communication, researchers competed in designing different types of antennas that obey the wideband range of frequencies (3.1 GHz ~ 10.6 GHz) which is required by this technology. Some of these antennas were planar and others were non-planar. Concerning to the planar microstrip antennas the main challenge was represented in its narrow band feature, which has been overcame via designing of a certain shapes of antennas having different aspect lengths in the way of the exciting current to be resonating with different wavelengths which in turn widening the range of frequencies to cover the UWB range. Among these shapes were; the triangular, elliptical, circular, ring, etc. [2, 3]. It has been concluded in [4] as a common silent characteristic for all designed antenna shapes that; the impedance bandwidths of these antennas will be wider as much as the edges of their radiating elements are having a round or smoothly curved shapes. In turn, this will be more convenient for their features with UWB requirements.

In spite of the complexity in designing of these UWB antennas but the challenges were raised up when different techniques suggested for miniaturizing them. For instance, symmetrical exponential corrugations have been introduced in the radiator of tapered slot antenna (TSA) by [5] which enables the antenna to resonate at lower frequencies with comparably smaller size structure. The depth of these corrugation slots has been selected to be less than quarter of the effective wavelength at the lowest operation frequency, and this presents an inductive reactance against the passing wave which in turn increases the effective electrical length of the structure. Although the TSA antenna in general, is characterized by its directional radiation pattern, but omnidirectional TSA has also been introduced as that in [6], where some corrugations have been made to miniaturize its size. In addition to these aforementioned benefits of corrugations in miniaturization of planar antennas, it has been shown in [7] that adding the corrugation slots could improve the antenna gain very efficiently, where several corrugation shapes like; rectangular, saw tooth and cosine shapes have been used. Therefore, corrugation technique has been suggested in this paper to modify the circular radiator of PCMA which gives 42.6% of reduction compared to the original antenna size. This miniaturization will be achieved via some suggested formulas Another technique of miniaturization is depending on the current distribution analysis to suggest elimination for some metallization areas of that antenna, like that performed in [8], in which a crescent-shape has been introduced as a miniaturized shape of original elliptical shape radiator. Another work by [9] evolved the crescent-shape antenna from elliptical shape by carving a circular hole inside the radiator symmetrically, which succeeded to remove 40% of the metallization and 60% of the ellipse area. But these aforementioned works have failed to make reduction in the overall size. Unlike other design in [10] which modified a slot antenna that enabled up to 63% of overall size miniaturization after removing some areas but the modification here was associated with major changes in the shape of the antenna by changing the U-shape radiator to cactus shape, and also the modified antenna has not stay slot antenna anymore .The elimination of undesired areas is also introduced in this paper due to the aforementioned reasons but with minor changes in the shape of the original antenna, in a trial to enhance the design procedure that might be extended to other shapes of planar antennas. The miniaturization process suggested here is considered as a complementary process for the main design procedure. The original antenna to be designed will be a PCMA as one of the common UWB antennas, and its current distribution will be simulated, to figure out the undesired or least current distributed areas. Then these areas will be eliminated to generate the planar crescent-shape monopole antenna (PCSMA) which will achieve a reduction in the overall size by not less than 11.76% while almost maintaining the same characteristics as that of the original antenna.

2. ANTENNA DESIGN

A PCMA antenna has been selected to be designed as one of the common and simple planar monopole antennas that covers the entire UWB frequency range. Figure 1 shows the PCMA antenna designed here, and the dimensions have been designed according to the relations suggested by [11] as follows:

$$f_L = \frac{c}{\lambda} = \frac{7.2}{(L + r + P) * k}\ GHz \qquad (1)$$

Where f_L is the lower band-edge frequency, r and L are deciding the size of a virtual cylindrical monopole antenna which corresponding to the values of its radius and effective height, respectively. The area of this virtual antenna is considered to be equal to the radiator area of PCMA antenna. And accordingly, they could be calculated as follow [11]:

$$L = 2\,R \qquad (2)$$

$$r = R/4 \qquad (3)$$

where R is the radius of the circular radiator, also one can say that P is the neck length in cm for the 50 Ω microstrip feed line between the radiator element and the ground plane, the width of the microstrip feed line is W_T, the value of $k = \sqrt{\varepsilon_{eff}}$ and P will be omitted or included in the L_C dimension as shown in figure 1. The approximated value of ε_{eff} has been calculated as [12]:

$$\varepsilon_{eff} \approx \frac{\varepsilon_r + 1}{2} \qquad (4)$$

The whole planar antennas designed here were using FR4 substrate with thickness of 1.6 mm, and ε_r = 4.3 which gives ε_{eff} = 2.65, accordingly k is

1.627. This value is suggested by [13] to be taken 1.15 as an empirical value. Therefore if the lower frequency is chosen to be 2 GHz, then R will be equal to 11.7 mm, but it has been taken as R = 12.5 mm to ensure earlier starting for the working band of frequencies.

Other

TABLE 1.
Design parameters of PCMA antenna.

Parameter	Dimension (mm)
P	0.5
R	12.5
W_S	40
W_T	2.8
L_S	51
L_G	22.7
L_C	13

parameters were L_G = 22.7 mm, L_C = 13 mm and W_T = 2.8 mm. The all aforementioned design parameters are shown in the Table 1.

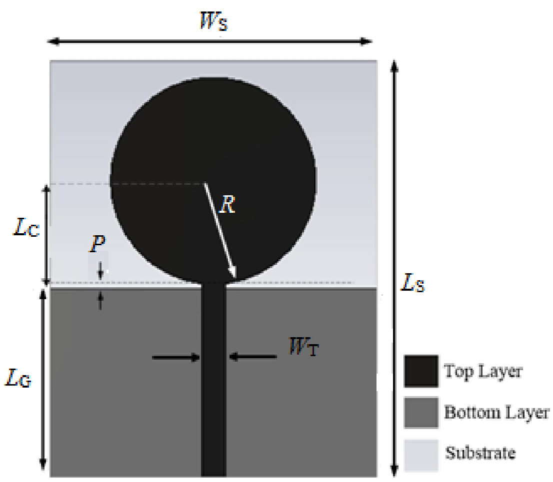


FIGURE 1. Geometry of the simulated PCMA antenna.

3. MINIATURIZATION

After designing the PCMA antenna, it is necessary to miniaturize it while preserving its features almost unchanged. The miniaturization process has been performed by two different methods. The first technique was achieved through eliminating the areas with least distributed surface current which generates a crescent-shaped radiator to decrease the overall height of the radiator while preserving those areas with most distributed surface current. Therefore the overall height has been reduced physically while the most important areas have been preserved in a trail to keep same antenna features as those of the original antenna. Figure 2 shows the PCSMA antenna and all of its parameters are listed in Table 2. The dimensions of this antenna have been optimized to get closer features to the parent antenna, and the overall size is reduced to 88.2% (40*45/40*51=0.882) of the original antenna.

TABLE 2.
Design parameters of PCSMA antenna.

Parameter	Dimension (mm)
L_{C1}	13
L_{C2}	19
L_S	45
L_G	22.75
W_S	40
W_T	2.8
P	0.5
R_1	12.5
R_2	11

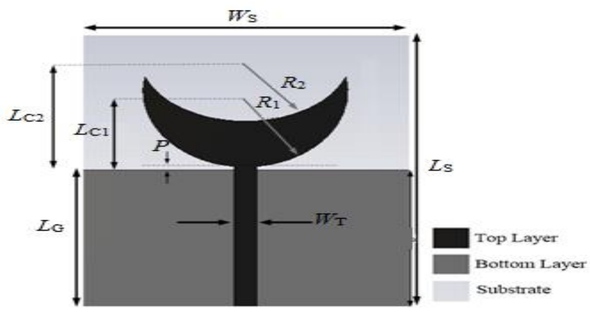


FIGURE 2. Geometry of the simulated PCSMA antenna.

The second technique of miniaturization for the PCMA antenna is performed by corrugating the edges of the circular radiator in somehow to get repeated slots around its round edge as depicted in figure 3. Due to the fact that the current flowing through the radiator will mainly be distributed at the edges, therefore the required electrical length of the circumference for the circular radiator of PCMA will be compressed physically via corrugations that maintains the same effective circumference electrical length as that of the original PCMA. Figure 4 shows a zoomed portion of the corrugated structure, and the required size of these corrugations could be calculated by equating the circumference of the circular radiator of PCMA antenna with that of the corrugated PCMA antenna as follow:

$$2\pi\, R_o = 2\pi\, R_1 - N\, R_1\, d\phi + 2\, N\, L_{Slot} + N\, R_2\, d\phi \qquad (5)$$

where R_o is the radius of the original PCMA before miniaturization, N is the number of corrugation slots, and the other parameters R_1, R_2 and $d\phi$ are as shown in Figure 4. The depth of corrugated slots is defined as L_{Slot} and could be calculated from R_1 and R_2 as:

$$L_{Slot} = R_1 - R_2 \qquad (6)$$

Performing some simplification on equation 5 then R_1 will be equal to:

$$R_1 = R_o - \frac{N\, L_{Slot}(2 - d\phi)}{2\pi} \qquad (7)$$

where $d\phi$ is in radians while other parameters are all in (mm). The number of corrugated slots N will not be related directly with $d\phi$ because in the case of this design two additional slots will be hidden within the microstrip feedline side therefore:

$$(N+2) = \frac{2\pi}{d\phi} \tag{8}$$

Now if N is taken as 28, R_o= 12.5 mm, L_{Slot} = 0.65 mm, then equation 8 gives $d\phi$ = π/30 (rad) which is equal to (6°) and equation 7 gives R_1 = 7.01 mm, which has been taken 7 mm in this design. The all design parameters are listed in Table 3. It is worthy to mention that for different number of corrugated slots more or less than 28 that used here then the number of hidden slots will be changed and equation 8 will be changed accordingly.

If it is desired to make the depth of the corrugated slots equal to their width which is the arc length then L_{Slot} will be given as:

$$L_{Slot} = R_1\, d\phi \tag{9}$$

Accordingly, if equations 8 & 9 are substituted into equation 7, then R_1 will be:

$$R_1 = \frac{2\pi\, R_o}{6\pi - 2\pi\, d\phi - 4\, d\phi + 2\, d\phi^2} \tag{10}$$

This technique has reduced the original size of the radiator while kept the required electrical length of the circumference unaffected via the compressing taken place in the corrugated circumference. Accordingly, the important characteristics of the antenna have been preserved while the overall size is reduced to 57.4% ((30*39/40*51)*100%=57.35%) of the original antenna size.

TABLE 3.

Design parameters of corrugated PCMA antenna.

Parameter	Dimension (mm)
L_C	7.65
L_{Slot}	0.65
L_S	39
L_G	22.75
W_S	30
W_{Slot}	1
W_T	2.8
P	0.5
R_1	7
R_2	6.35

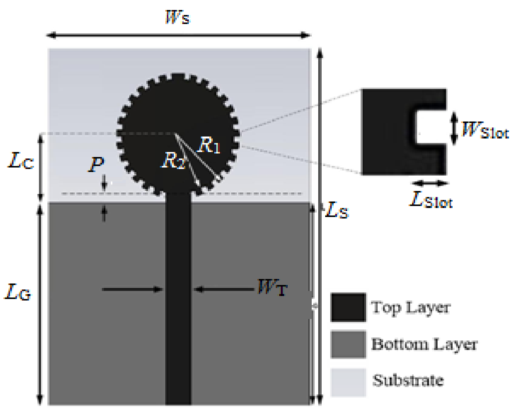


FIGURE 3. Geometry of the simulated corrugated PCMA.

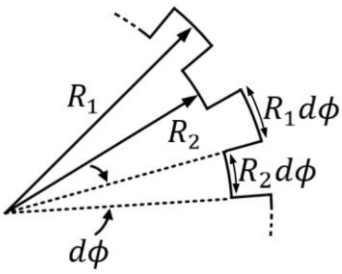


FIGURE 4. Details of the corrugated structure.

4.RESULTS AND DISCUSION

PCMA has been designed as one of the common UWB antennas with dimensions and geometry as mentioned in previous section, then two different techniques have been used; firstly, by eliminating the undesired or least current distributed areas to generate a planar crescent-shaped monopole antenna (PCSMA), secondly by corrugating the round edge of the circular radiator to miniaturize its circumference. All the designed UWB antennas have been simulated using CST Microwave Studio^{TM} software package. Figure 5 shows the simulation results of the return loss curves versus frequency for the PCMA, PCSMA, and Corrugated PCMA. It shows that all of these designed antennas are maintaining their working which covered the entire UWB. Investigating the surface current distributions for the three designed antennas are shown in figures 6 to 8 and they were plotted for 5 and 9 GHz of frequencies. The PCSMA will offer the required area of metallization in least size compared to the PCMA. Therefore, it has been concluded that the current will be concentrated at this miniaturized area which is almost distributed at the lower side edges of the radiator. While in corrugated PCMA the current will follow a corrugated path offered by the radiator edge and it will cross the required path with least height compared to PCMA, which validates the technique of eliminating the undesired areas.

After completing the design and simulation of the aforementioned antennas, the all three antennas have been fabricated as shown in figures 9 to 11, and tested via Rohde & Schwarz® ZVL13 VNA. The return loss data has been measured for the all three antennas and plotted in comparison with their simulation one as shown in figures 12 to 14. The measurement results are almost agreed with the simulation results except some shifting due to imperfection in the fabrication. However, the practical experimental measurements validate the design and its modification which performed to miniaturize the size of the PCMA. Therefore the miniaturized antennas will be working with almost the same features with least size which satisfy the goal of this research.

The simulated and measured radiation patterns in E and H planes for the three antennas are shown in figures 15 to 17 for 5 and 9 GHz of frequencies. Measured radiation patterns are almost meet the simulated patterns. And also the miniaturization techniques have nearly not affected the radiation pattern that performed by PCSMA nor corrugated PCMA. Finally, the simulated realized gain curves for PCMA, PCSMA and corrugated PCMA have been plotted as shown in figure 18. For PCMA it is noticed that almost the gain is increased with increments in the frequency, which is common in UWB antennas, while for corrugated PCMA and in spite of the great miniaturization occurred in its size but its gain (not less than 2 dB) was still having a reasonable value comparing to the gain of half wave dipole antenna (*i.e*. 2.15 dB), and getting up to (4.8 dB at 9.5 GHz). Although the miniaturization ratio in corrugated PCMA is greater than that of PCSMA but its gain still better than the gain of PCSMA, and this may back to the circumference length in the corrugated PCMA that has been maintained via corrugated edge, while it is truncated in PCSMA.

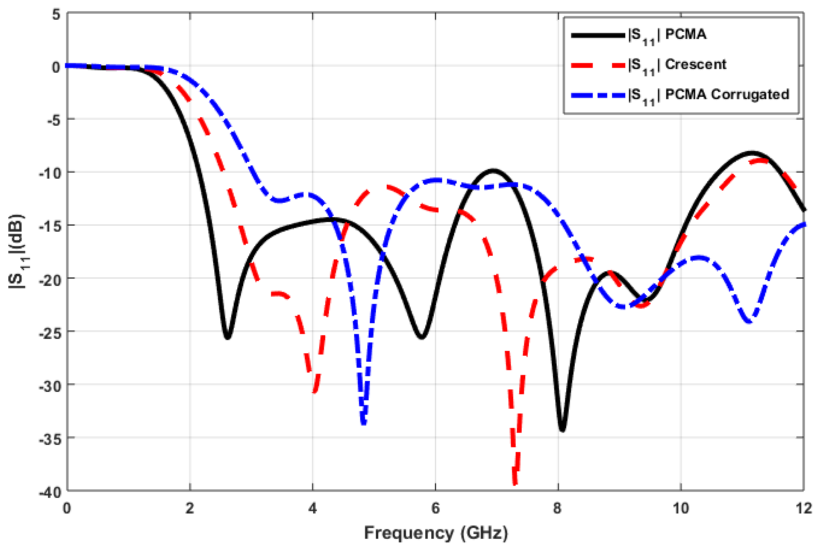
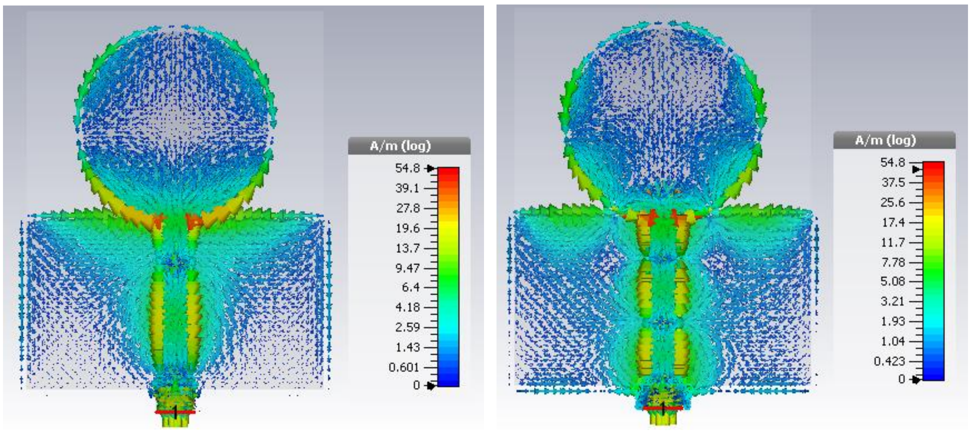
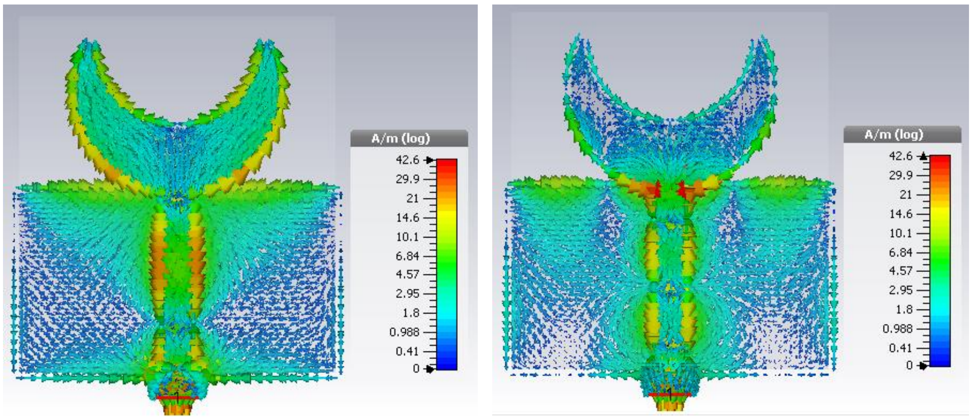


FIGURE 5. Comparison of simulated return loss curves for the PCMA, PCSMA and corrugated PCMA



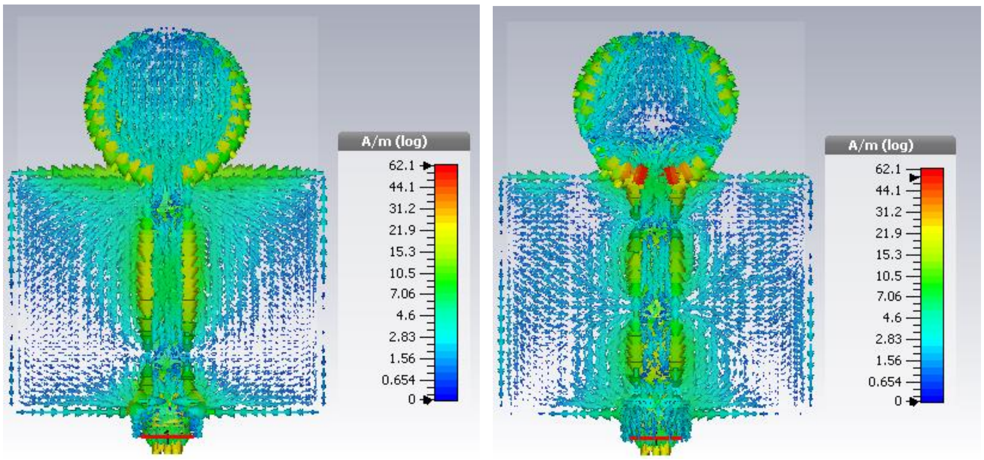
(a) (b)

FIGURE 6. Surface current distribution for the PCMA at (a) 5 GHz, and (b) 9 GHz.



(a) (b)

FIGURE 7. Surface current distribution for the PCSMA at (a) 5 GHz, and (b) 9 GHz.



(a) (b)

FIGURE 8. Surface current distribution for the Corrugated PCMA at (a) 5 GHz, and (b) 9 GHz.

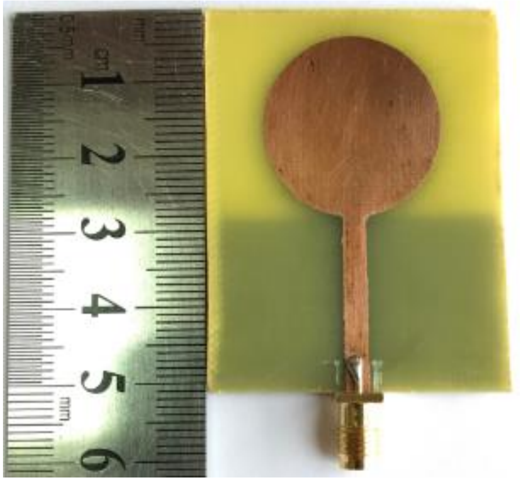


FIGURE 9. Fabricated PCMA.

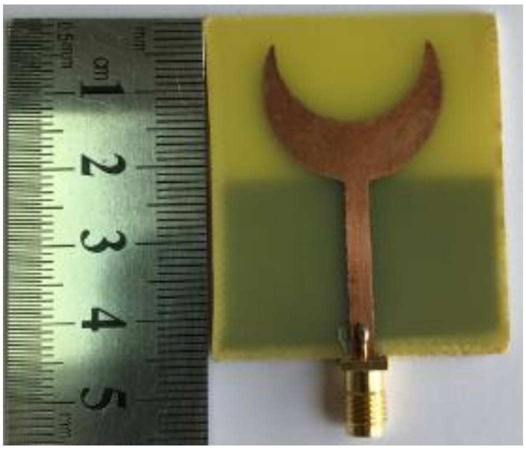


FIGURE 10. Fabricated PCSMA.

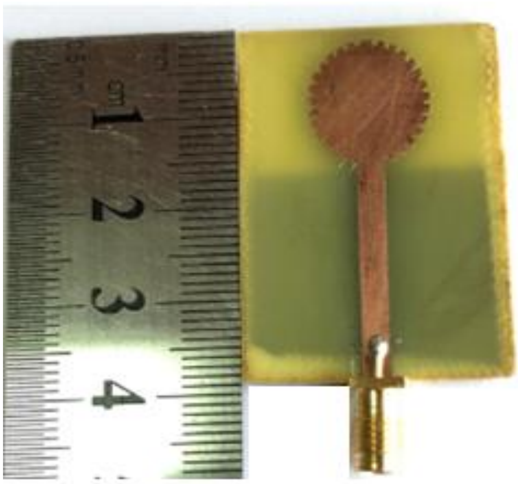


FIGURE 11. Fabricated corrugated PCMA.

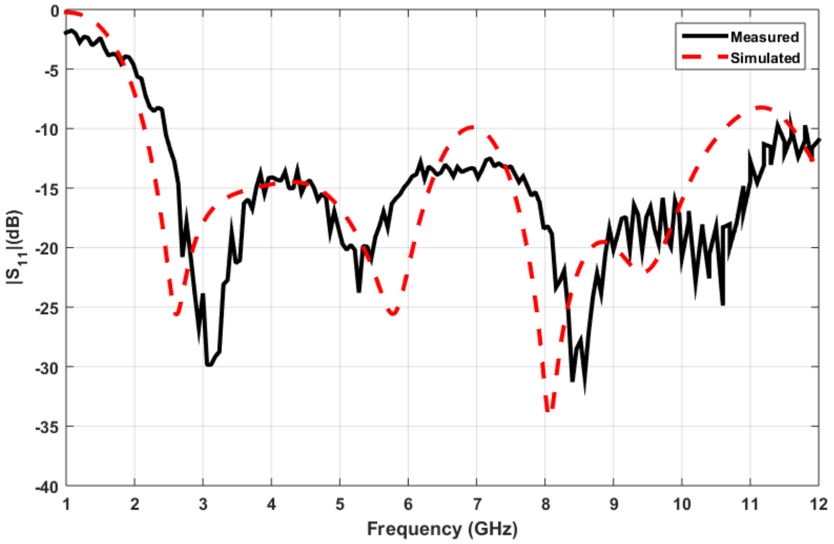


FIGURE 12. Return loss curves (measured and simulated) for the PCMA.

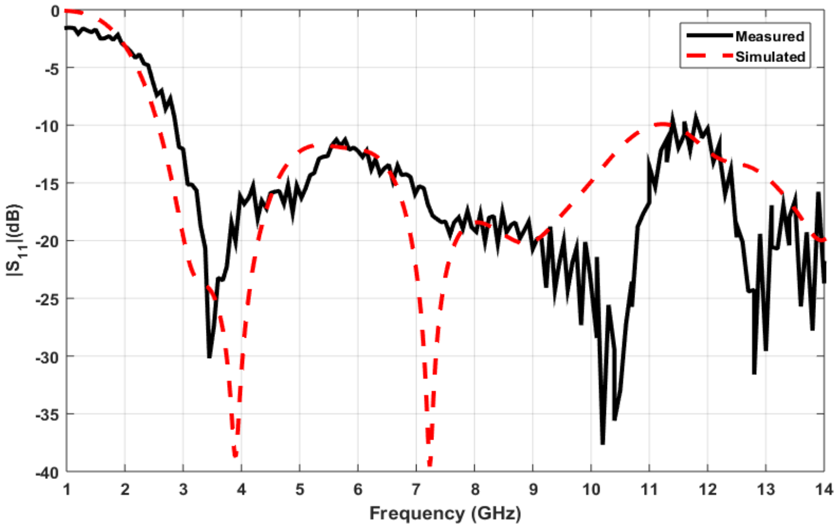


FIGURE 13. Return loss curves (measured and simulated) for the PCSMA.

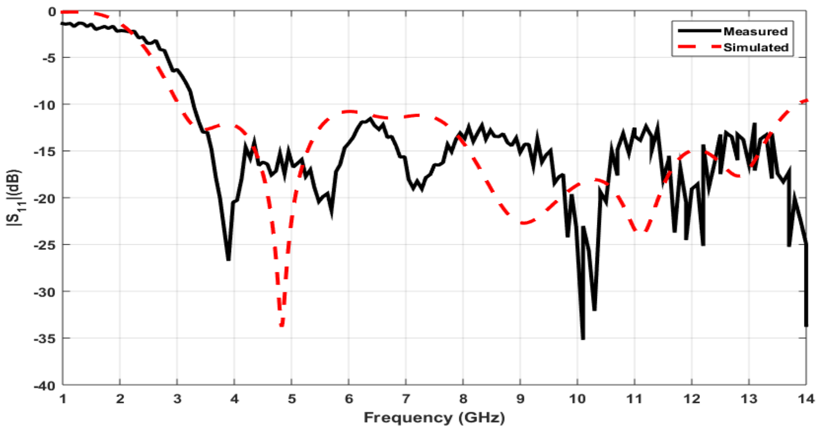


FIGURE 14. Return loss curves (measured and simulated) for the Corrugated PCMA.

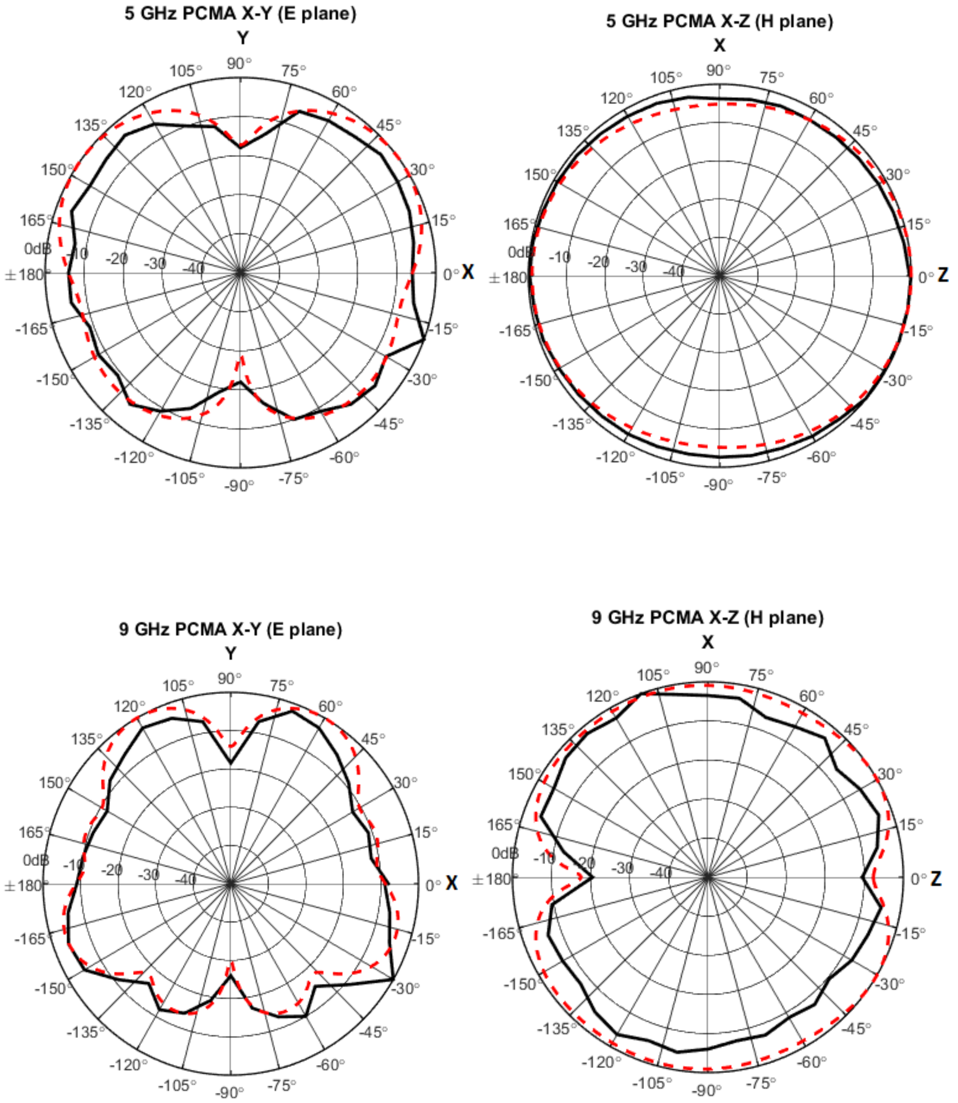


FIGURE 15. Radiation patterns simulated (- - -) and measured (—) of the PCMA in H and E planes, for frequencies of 5 and 9 GHz.

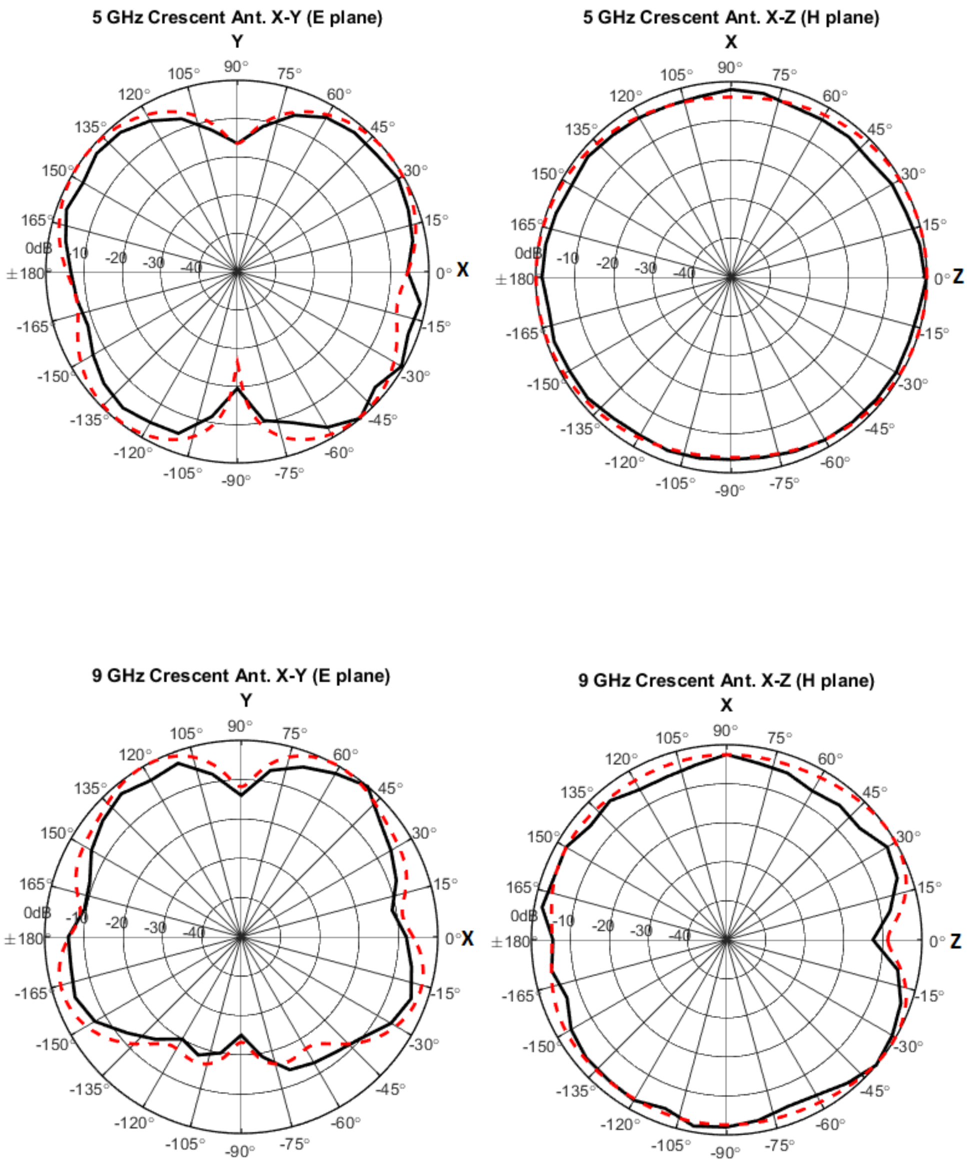


FIGURE 16. Radiation patterns simulated (- - -) and measured (—) of the PCSMA in H and E planes, for frequencies of 5 and 9 GHz.

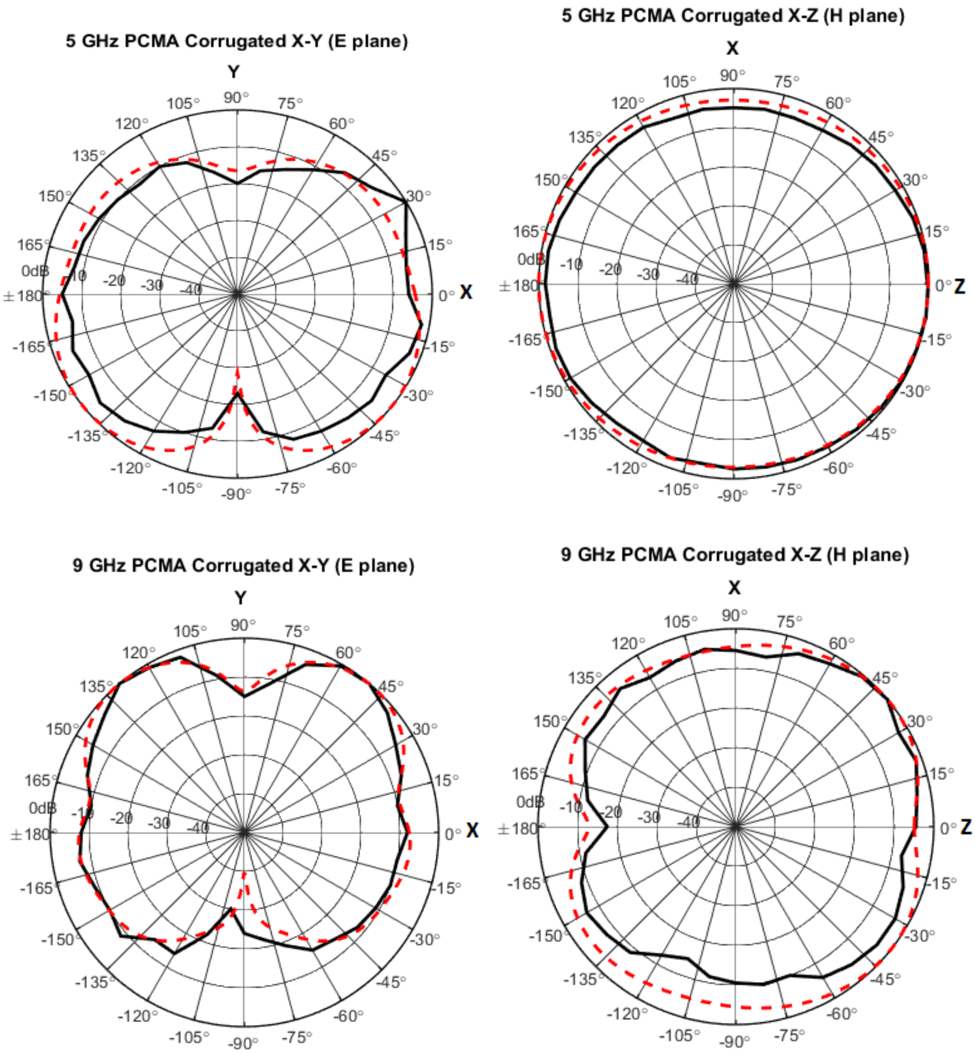


FIGURE 17. Radiation patterns simulated (- - -) and measured (—) of the Corrugated PCMA in H and E planes, for frequencies of 5 and 9 GHz.

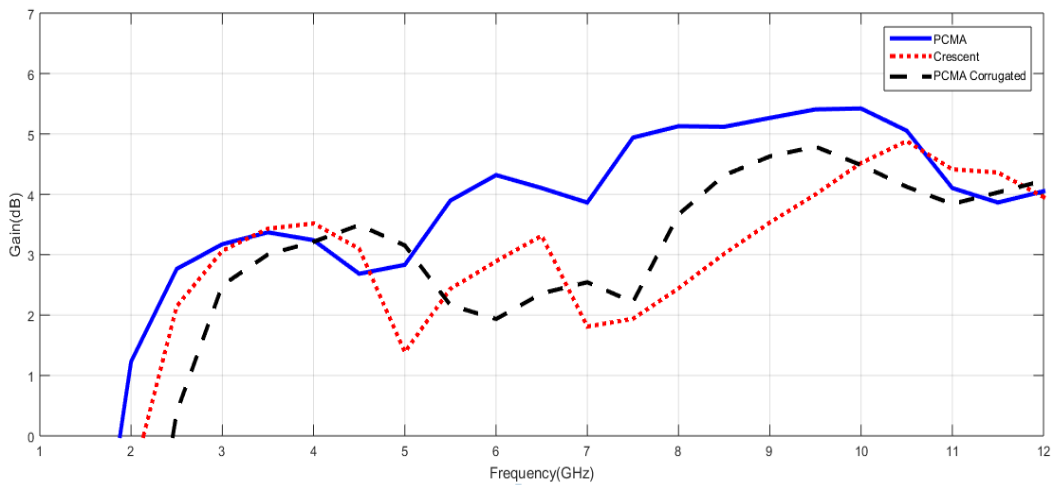


FIGURE 18. Comparison of simulated realized gain curves for the PCMA, PCSMA and corrugated PCMA.

5. CONCLUSIONS

Two techniques have been suggested here to miniaturize the overall size of PCMA; the first technique has been performed by eliminating the least current distributed areas, which resulted in a crescent-shaped radiator. While the second technique introduces corrugated slots around the round edge of the PCMA radiator, in which a 57.4% of overall size reduction has been achieved while its gain was still maintaining more than (2 dB), which is comparable with that of half wave dipole antenna. Results shown that corrugation technique was more efficient due to the reduction in size was 42.6% which is more than 11.76% for the other techniques, also the upper limit of the impedance bandwidth for the corrugated PCMA has been extended to 13.85 GHz. Another advantage of the corrugation technique has been shown that the gain characteristics was better than that of area eliminating technique, and the reason may back to maintaining the perimeter electrical length in corrugated PCMA as much as that of the original PCMA antenna, while in PCSMA a certain portion of the perimeter's upper side has been truncated. However, both miniaturized antennas are still having the required characteristics just like the original parent PCMA antenna that obey the UWB requirements.

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