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Study on single sided comb shaped patch antennas with arm rotation allowing resonant frequency shift and pattern pivoting adaptable for sensing operations

Algılama uygulamaları için uyarlanabilir rezonans frekans kaymasına ve yayılım örüntüsü yönlenmesine olanak sağlayan kol dönüşüne sahip tek taraflı tarak şekilli yama antenler üzerine çalışma

Şaban Duran ŞANLIER[1], Hüseyin TOSUN[1], Veli Tayfun KILIÇ[1]*

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Abdullah Gul University, Kayseri, Turkey.
sdsanlier@gmail.com, huseyin.tosun@agu.edu.tr, tayfun.kilic@agu.edu.tr

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Abstract

In this paper single sided comb shaped patch antennas having different number of arms with various arm rotations are reported. With simulations S_{11} parameter changes and the far-field radiation patterns of the antennas are calculated. Results show that the first and the second resonances of the designed antennas shift to higher frequencies and their patterns pivot in certain directions as the antenna arms rotate. Among the designed antennas, the antennas having three arms on the side with different arm rotations are manufactured, too. Measured S_{11} parameter change results agree well with the simulation results. The findings indicate that the designed antennas are promising for size critical systems as well as sensing operations.

Keywords: Patch antenna, Comb shape, Arm rotation, Resonance shift, Pattern pivoting

Öz

Bu makalede farklı kol sayısına ve farklı kol dönme açılarına sahip tek taraflı tarak şeklindeki yama antenleri incelenmektedir. Simülasyon araçları kullanılarak antenlerin S_{11} parametre değişiklikleri ve uzak alan yayılım örüntüleri hesaplanmıştır. Sonuçlar, tasarlanan antenlerin anten kolları döndükçe ilk ve ikinci rezonanslarının daha yüksek frekanslara kaydıklarını ve uzak alan yayılım örüntülerinin belirli yönlere doğru döndüğünü göstermektedir. Tasarlanan antenler arasında, farklı kol dönüş açılarına sahip üç kollu antenlerin üretimleri gerçekleştirilmiştir. Ölçülen S_{11} parametre değişikliği sonuçları, simülasyon sonuçlarıyla iyi bir uyum göstermektedir. Bulgular, tasarlanan antenlerin boyut açısından kritik/sınırlı sistemler ve algılama uygulamaları için gelecek vadettiğini göstermektedir.

Anahtar kelimeler: Yama anten, Tarak şekli, Kol dönmesi, Rezonans kayması, Örüntü dönmesi

1 Introduction

Radio frequency (RF) systems are used in today's world in many different areas including defense industry, space applications, telecommunication systems, etc. [1-3] They consist of various units like power amplifiers, filters, power dividers, and processors. Antennas are one of the main components found in RF systems that convert radiating electromagnetic waves exist in a space into electronic signals when used in a receiving mode and transform electronic signals into radiating waves when used in a transmitting mode. [4, 5]

Depending on the application to satisfy the requirements such as directivity, gain, bandwidth, and physical sizes, different types of antennas are used in RF systems. For example, in the systems operating in a wide frequency band Vivaldi antennas are used [6, 7]. On the other hand, horn and dish antennas are employed in the systems such as satellite and radar systems that require high directivity [8, 9]. Also, in the systems where circular polarization is needed loop antennas are preferred [10].

Another type of antenna is a patch antenna. Patch antennas are commonly used in systems because of their compact structure, easy production process, low-cost fabrication and relatively small size [11, 12]. These features make patch antennas advantageous in RF applications.

Patch antennas with different geometries have been studied [13 - 17]. The most common patch antenna shapes are square [13], rectangular [14], triangle [15], circular [16] and elliptical shapes [17]. In addition, there are reports about comb shaped patch antennas [18-20]. Comb shaped patch antennas with arms on single and double sides enable to reduce geometry of an antenna beneficial to size critical applications. Also, in comb shaped patch antennas thanks to the variety of parameters in the geometry a resonance frequency can be arranged without changing the total area of the radiator patch.

In this study, different from the previous works single sided comb shaped patch antennas with arm rotation are investigated. A reference antenna resonating around 2.8 GHz and 4.5 GHz frequencies is initially designed and its resonance change together with the far-field radiation behavior are observed as its arms rotate. Results show that for the designed antenna the resonance frequencies shift to higher frequencies as the antenna arms rotate. Also, far-field pattern of the designed antenna is observed to pivot in certain directions with rotation of its arms.

In the following sections, more detailed information is given about the antenna design, physical parameters and arm

*Corresponding author/Yazışılan Yazar

rotation process. Also, the obtained results including the antenna reflection coefficient (S_{11}) parameter magnitude change with frequency and far-field patterns are presented. Significant outcomes are observed and explained in details, and in the conclusion part the findings of the study are described and commented on.

2 Antenna design

2.1 Reference antenna design with single sided comb shape

As a reference antenna, single sided three arm patch antenna with a comb shape is designed. In the antenna copper layers with 0.035 mm thickness exist on the top and bottom, and an FR4 dielectric substrate with a depth of 1.59 mm is sandwiched between the copper layers. The bottom copper plate is used as a ground plane and on the top copper plate a comb shaped radiator patch exists. The arms of the comb shaped patch have constant 5 mm width and 11.47 mm length. Similarly, the distance between the arms is 3.56 mm. Also, the feed line width is determined to be 3.31 mm such that the characteristic impedance of the line equals to 50 Ω. The reference antenna design and the radiator patch geometry having single sided comb shape with three arms on the side are illustrated in Fig. 1. In the figure geometrical parameters including arm sizes, width of the feed line and the arm separation are shown.

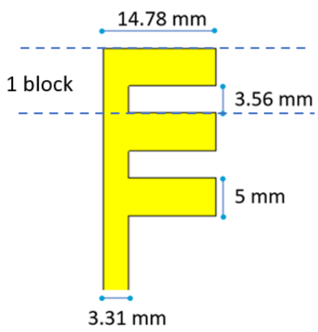

Figure 1. Radiator patch geometry having single sided comb shape with three arms.

In addition to single sided three arm patch antenna with the comb shape analyses are obtained for the four and five arm patch antennas. In all these antenna designs geometrical parameters except the number of the arms are kept constant. In the four arms antenna design a new arm with 5 mm width is added to 3.56 mm distance away from the top arm of the three arms antenna design and the feed line is extended by the same distance. The same procedure is applied while designing the five arms antenna. Single sided comb shaped radiator patch geometries with four and five arms on the side are shown in Fig. 2.

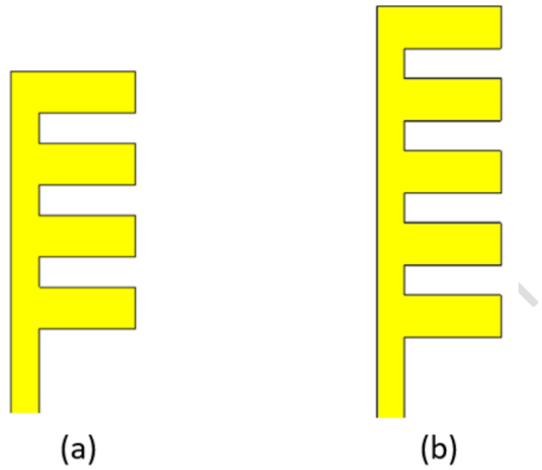

Figure 2. Radiator patch geometry of the single sided comb shaped antenna designs with (a) four arms and (b) five arms.

2.2 Arm rotation process

Arms of the designed antennas are rotated around their midpoints of the starting edges. In Fig. 3 midpoints of the starting edges of the arms are shown for the reference antenna design with the comb shape having three arms on its side.

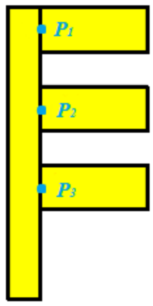

Figure 3. The midpoints of the starting edges of the arms for the reference antenna design with the comb shape having three arms on its side.

For various arm rotations (10, 20, 30, 40 and 50 degrees) response of the designed antennas are investigated. In each case, arms of the antennas rotate at equal angles in the direction away from the feed line, i.e., counterclockwise direction here. Because of the rotation of the arms around the midpoints of the starting edges, at one side of the midpoints arms overlap with the feed line and at the other side of the midpoints gaps occur between the arms and the feed line. These gaps are filled by extending the arms towards the feed line. The area of the extension in the arms equal to the area of the arms that overlap with the feed line. Therefore, the radiator patch's total area is not changed with arm rotations. The overlapping between the arms and the feed line together with the gaps occurred as a result of arm rotations are shown in Fig. 4a. Also, in Fig. 4b the ultimate design of the antenna obtained by filling the gaps with extensions of the arms is represented.

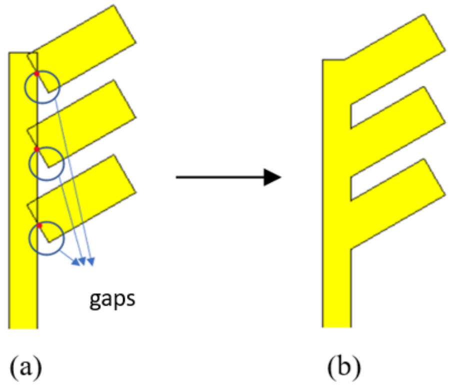

Figure 4. (a) Overlapping of the arms (b) the ultimate antenna design characteristics achieved by filling the gaps

As it is mentioned, arms of the designed antennas are rotated by different angles starting from 0 degree till 50 degree with 10 degree intervals. The angle of the rotation is limited to 50 degree because of the physical limitations. After 50 degree rotation, the arms start to overlap with each other in the designed antennas. The designed one sided five arm antenna having the comb shape with no arm rotation and with arms rotated by 10, 20, 30, 40, and 50 degrees is shown in Fig. 5.

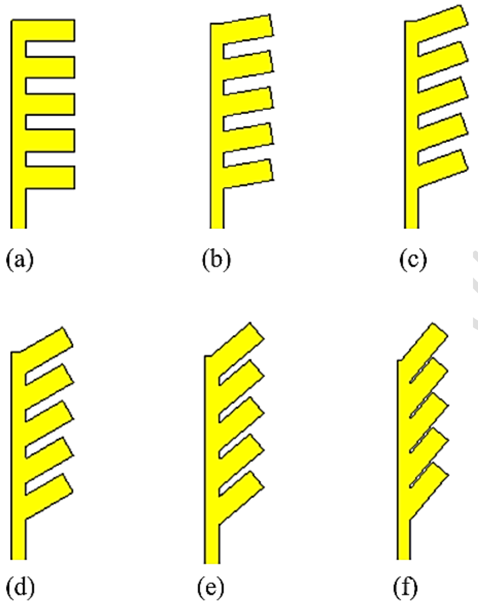

Figure 5. The single sided five arm antenna design having the comb shape (a) without any arm rotation and with arms rotated by (b) 10 degree, (c) 20 degree, (d) 30 degree, (e) 40 degree, and (f) 50 degree.

3 Results

The designed single sided comb shaped antennas with three, four and five arms are analyzed. In the analyses three-dimensional (3D) electromagnetic (EM) simulation tools are used such that in transient time domain hexahedral meshes and match boundary conditions are set. Simulations are performed for various arm rotations and reflection coefficient (S_{11}) parameter magnitude changes with frequency are calculated together with the far-field patterns of the antennas at their resonance frequencies. Change of the S_{11} parameter magnitude of the designed single sided three arm antenna with the comb shape as a function of frequency for 0°, 10°, 20°, 30°, 40° and 50° arm rotations are illustrated in Fig. 6. As seen from the figure the designed antenna features two resonances around 3.0 GHz and 4.5 GHz, respectively. Both of these resonances move to higher frequencies with rotation of the arms. Changes of the antenna's resonance frequencies with arm rotation are represented in Fig. 7. In the figure it can easily be observed that the resonance frequencies move to higher frequencies with the arm rotation.

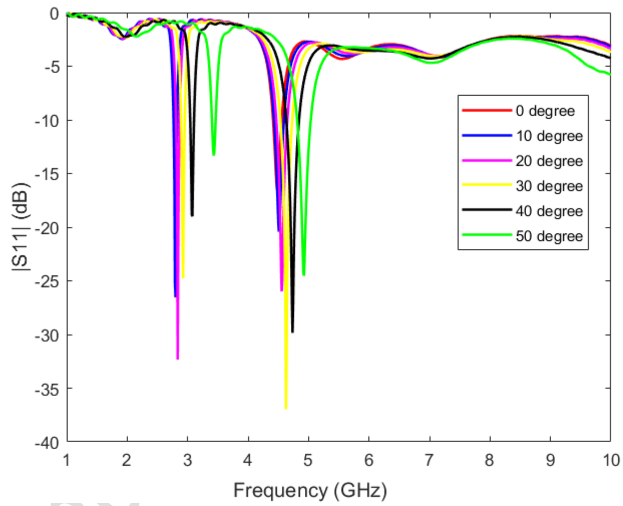

Figure 6. Change of the S_{11} parameter magnitude of the designed single sided three arm antenna with the comb shape as a function of frequency.

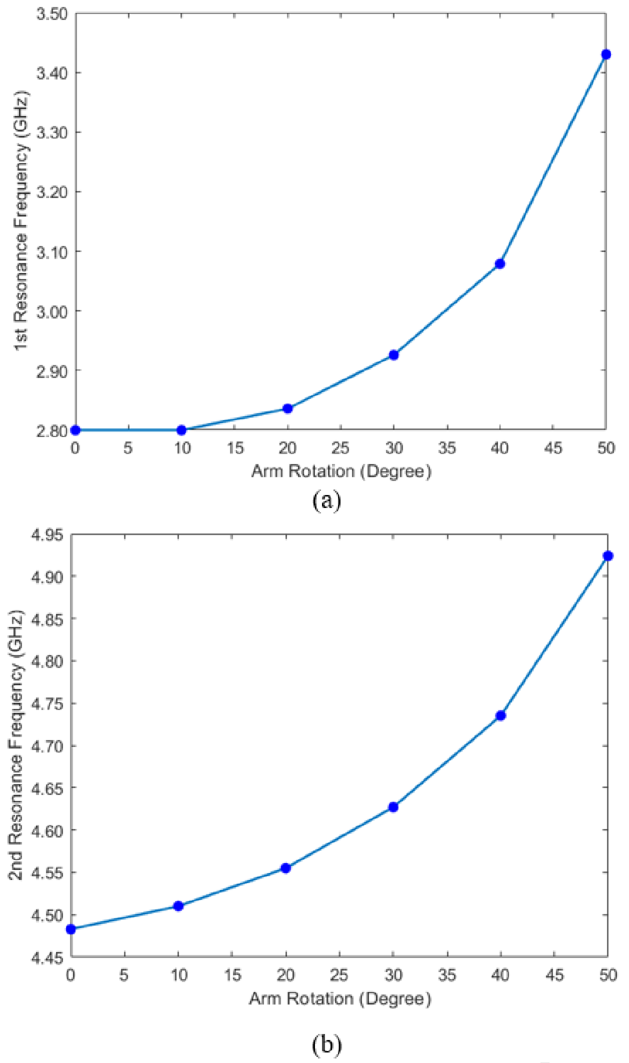

Figure 7. (a) The first and (b) second resonance frequency shifts of the designed single sided three arm antenna with the comb shape as a function of the arm rotation.

In addition, directivity patterns in far-field of the antennas at their first resonance frequencies of 2.8 GHz, 2.8 GHz, 2.836 GHz, 2.926 GHz, 3.079 GHz, 3.43 GHz are calculated. The patterns of the antennas are shown in Fig. 8 from a perspective view.

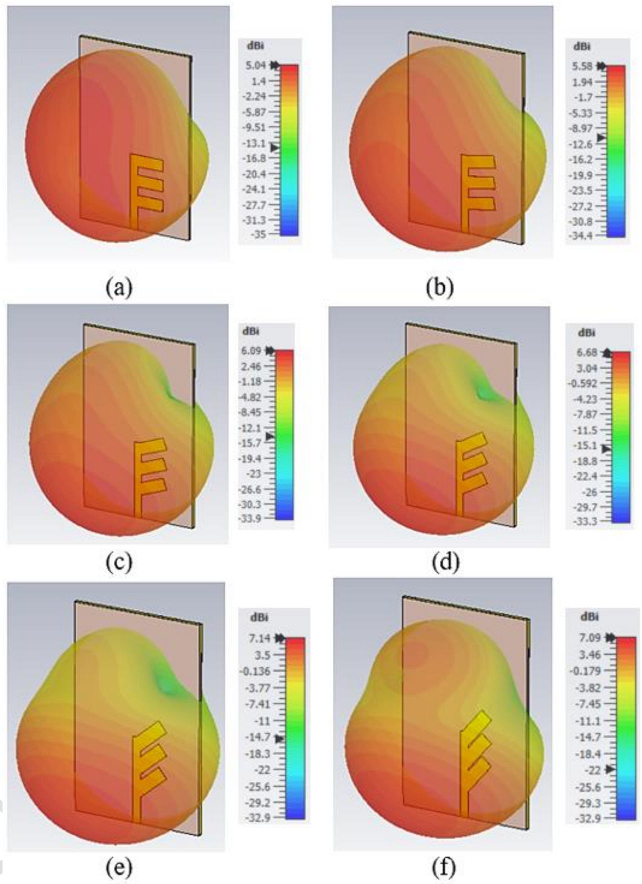

Figure 8. Directivity patterns (in far-field) of the designed single sided three arm antenna having the comb shape from a perspective view calculated in a 3D space at the first resonance frequencies. (a) With no arm rotation at 2.80 GHz, (b) with 10° arm rotation at 2.80 GHz, (c) with 20° arm rotation at 2.836 GHz, (d) with 30° arm rotation at 2.926 GHz, (e) with 40° arm rotation at 3.079 GHz, and (f) with 50° arm rotation at 3.43 GHz.

It is seen from the figure, the pattern of the antenna pivots as its arms rotate. This pivoting is in the direction towards the feed line, i.e., opposite to the arm rotation, for the arm rotation angles until 40° and after 40° rotation steering stops. This pivoting is more clearly seen in Fig. 9 where directivity patterns of the antenna are shown in polar coordinate system. Also, in Fig. 10 change of the angle at which the maximum radiation is achieved is plotted as a function of the arm rotation.

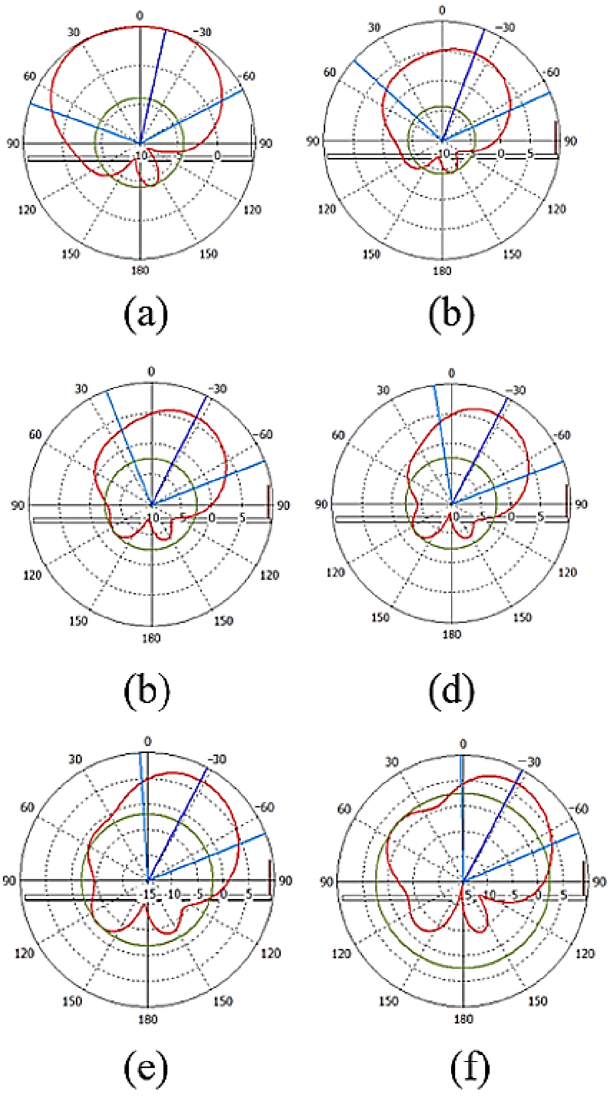

Figure 9. Directivity patterns (in far-field) of the designed single sided three arm antenna having the comb shape in polar coordinate system on y-z plane calculated at the first resonance frequencies. (a) With no arm rotation at 2.80 GHz, (b) with 10° arm rotation at 2.80 GHz, (c) with 20° arm rotation at 2.836 GHz, (d) with 30° arm rotation at 2.926 GHz, (e) with 40° arm rotation at 3.079 GHz, and (f) with 50° arm rotation at 3.43 GHz.

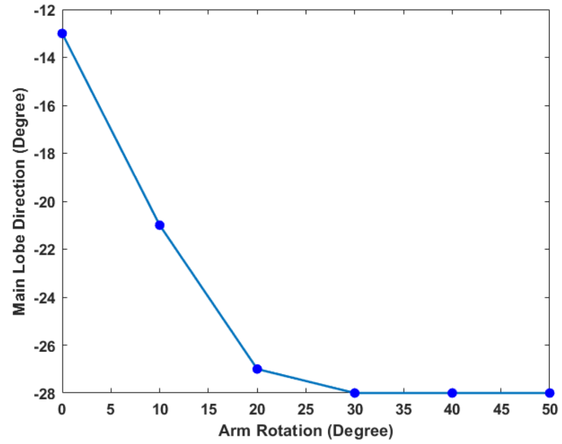

Figure 10. Change of the angle at which the maximum radiation is achieved as a function of the arm rotation at the first resonance of the designed single sided three arm antenna with the comb shape.

Next, simulations are done for the designed single sided four arm antenna having the comb shape. Again, arms are rotated in the direction opposite to the feed line and the shift in the antenna resonance is investigated together with the change of the radiation pattern. Change of the antenna's S_{11} parameter magnitude for various arm rotations calculated in the simulations over the frequency band from 1 GHz to 10 GHz is exhibited in Fig. 11. It is seen from the figure that the first two resonances of the antenna move to higher frequencies as the arms of the antenna rotate. This behavior is the same with that observed before for the designed single sided three arm antenna with the comb shape. As in the three arm antenna observation, variations of the resonance frequencies of the designed four arm antenna with arm rotation are presented in Fig. 12. It is again clearly seen in the figure that the resonance frequencies increase with the arm rotation. However, if one compares the figure with Fig. 7, it can be observed that the shifts in the resonance frequencies obtained for the antenna with four arms on its side are slightly slower than that found for the designed three arm antenna.

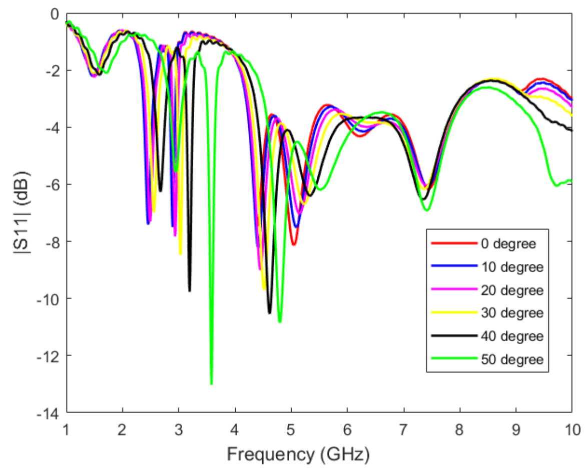

Figure 11. Change of the S_{11} parameter magnitude of the designed single sided four arm antenna with the comb shape as a function of frequency.

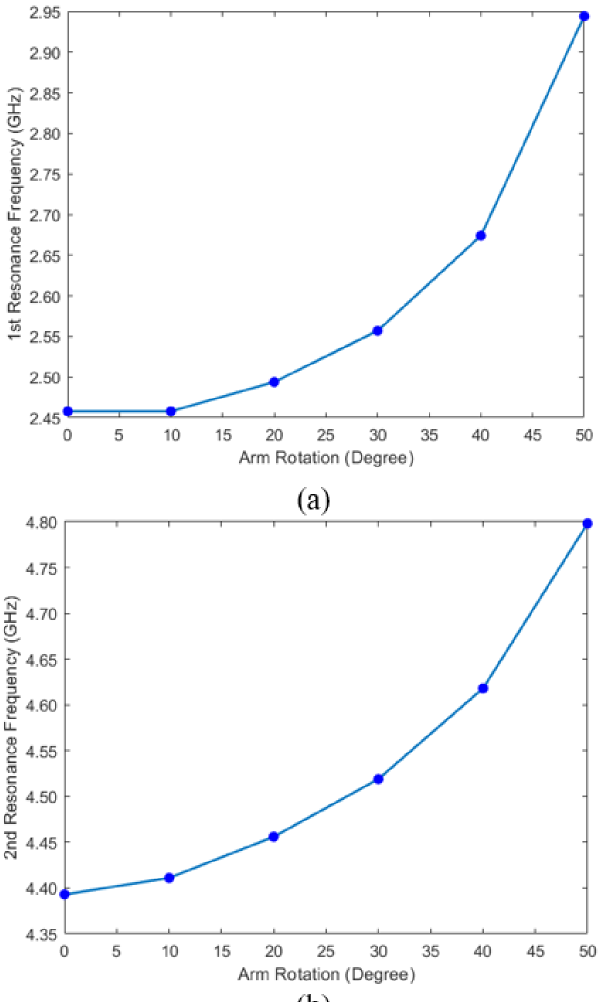

Figure 12. (a) The first and (b) second resonance frequency shifts of the designed single sided four arm antenna with the comb shape as a function of the arm rotation.

Moreover, directivities of the antennas with no arm rotation and with arms rotated by 10°, 20°, 30°, 40°, and 50° in far-field at their resonance frequencies of 2.458 GHz, 2.458 GHz, 2.494 GHz, 2.557 GHz, 2.674 GHz, 2.944 GHz respectively, are calculated. The patterns of the antennas in a 3D space are shown in Fig. 13.

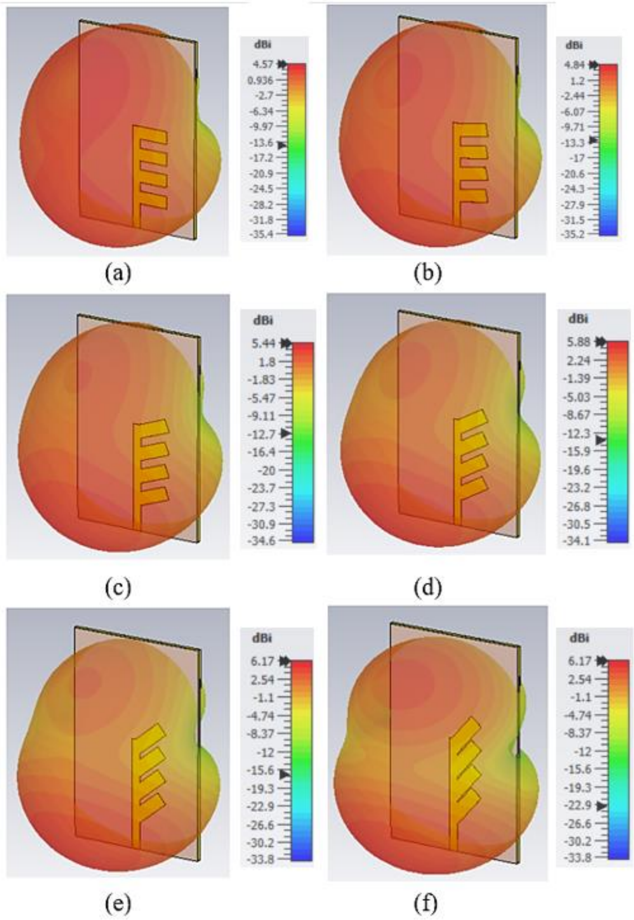

Figure 13. Directivity patterns (in far-field) of the designed single sided four arm antenna having the comb shape from a perspective view calculated in a 3D space at the first resonance frequencies. (a) With no arm rotation at 2.458 GHz, (b) with 10° arm rotation at 2.458 GHz, (c) with 20° arm rotation at 2.494 GHz, (d) with 30° arm rotation at 2.557 GHz, (e) with 40° arm rotation at 2.674 GHz, and (f) with 50° arm rotation at 2.944 GHz.

As observed in the figure the antenna pattern pivots in the opposite direction to that of the arm rotations, which is the same within the three arm antenna simulations. To more clearly see the pattern pivoting the directivity patterns of the antennas in polar coordinate system are shown in Fig. 14. Also, change of the angle at which maximum directivity is achieved with arm rotation is represented in Fig. 15. In the figures it is observed that unlike the three arm antenna, the pattern of the antenna having four arms continuously pivots towards the same direction (clockwise direction), i.e., towards the feed line, for all the applied arm rotations.

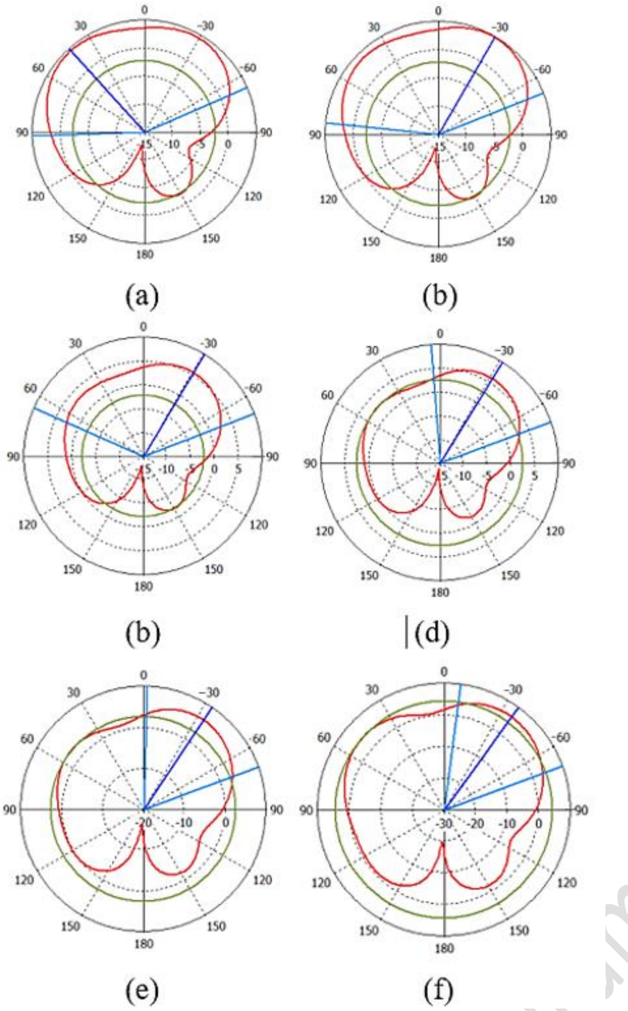

Figure 14. Directivity patterns (in far-field) of the designed single sided four arm antenna having the comb shape in polar coordinate system on y-z plane calculated at the first resonance frequencies. (a) With no arm rotation at 2.458 GHz, (b) with 10° arm rotation at 2.458 GHz, (c) with 20° arm rotation at 2.494 GHz, (d) with 30° arm rotation at 2.557 GHz, (e) with 40° arm rotation at 2.674 GHz, and (f) with 50° arm rotation at 2.944 GHz.

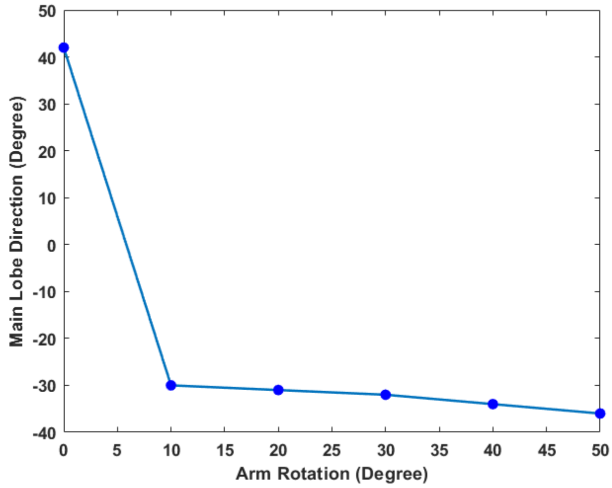

Figure 15. Change of the angle at which the maximum radiation is achieved as a function of the arm rotation at the first resonance of the designed single sided four arm antenna with the comb shape.

Lastly, the same analyses are done for the single sided five arm antenna with the comb shape. As for the designed antennas having three and four arms on the side, resonance behaviour of the antenna having five arms is calculated together with the far-field radiation pattern for different arm rotations. Change of the antenna's S_{11} parameter magnitude over the frequency band spanning from 1 GHz till 10 GHz calculated in simulations is shown in Fig. 16 for different arm rotations. Similar to the results found before for the modeled antennas with three and four arms on the side, the first and second resonances of the designed single sided antenna having the comb shape with five arms occur at higher frequencies when its arms rotate. The shifts in the resonance frequencies of the antenna are easily seen in Fig. 17, where the resonance frequencies of the antenna are plotted with respect to the arm rotation. It is seen from the figure that the designed single sided five arm antenna's resonance frequency increases as the arms of the antenna rotate and this increase is close to that found previously for the designed three and four arm antennas (see Fig. 7 and Fig. 12).

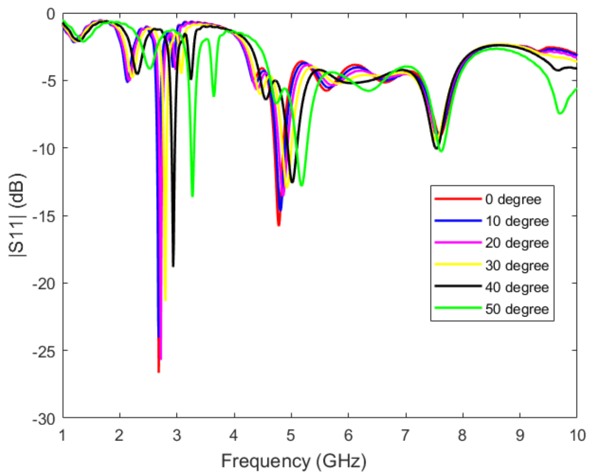

Figure 16. Change of the S_{11} parameter magnitude of the designed single sided five arm antenna with the comb shape as a function of frequency.

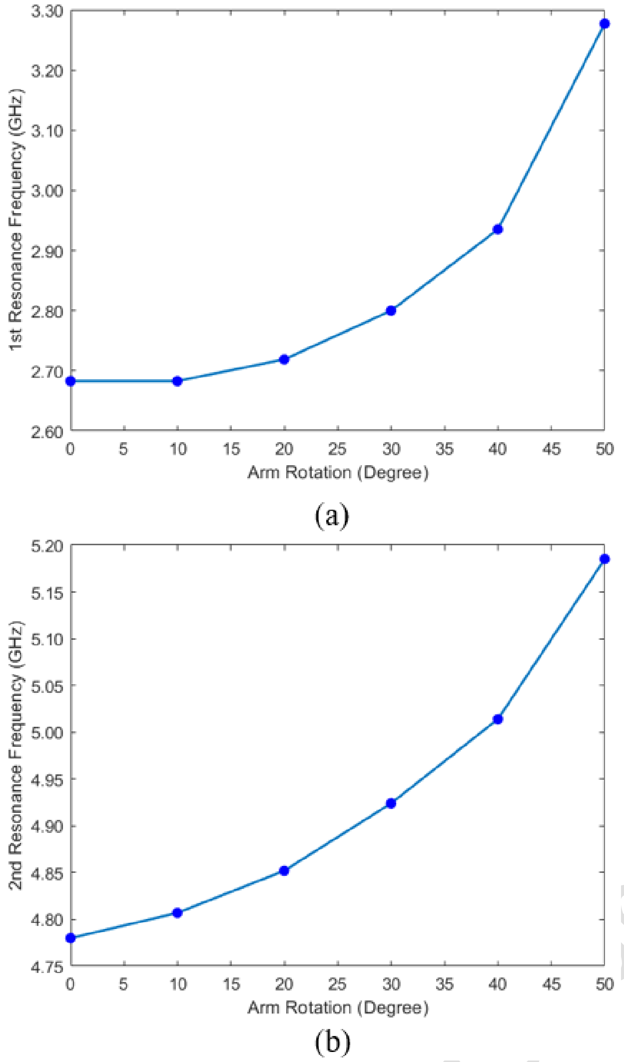

Figure 17. (a) The first and (b) second resonance frequency shifts of the designed single sided five arm antenna with the comb shape as a function of the arm rotation.

Furthermore, patterns of the antenna in far-field are calculated, too. Directivity patterns of the designed five arm antenna are shown in Fig. 18 from a perspective view in a 3D space for 0°, 10°, 20°, 30°, 40°, and 50° arm rotations.

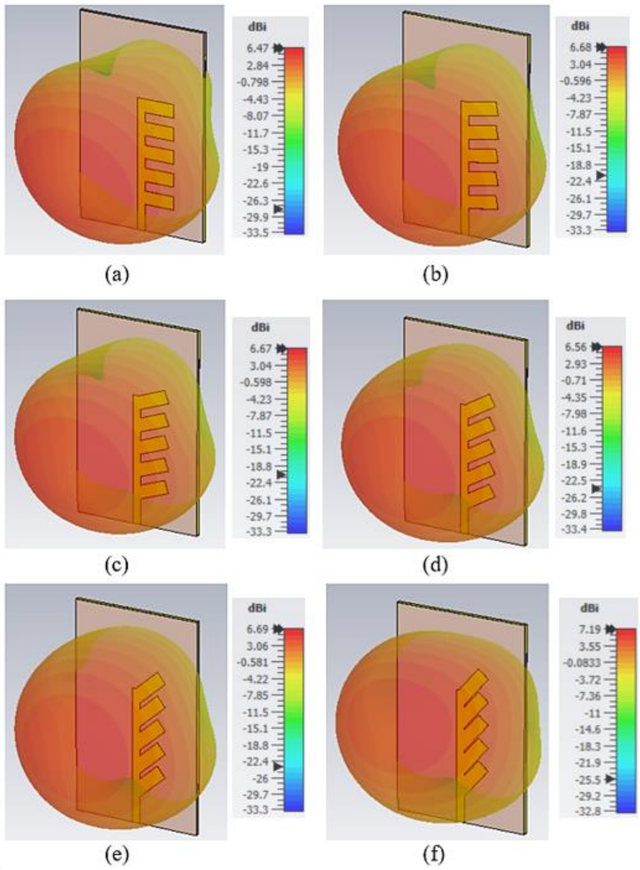

Figure 18. Directivity patterns (in far-field) of the designed single sided five arm antenna having the comb shape from a perspective view calculated in a 3D space at the first resonance frequencies. (a) With no arm rotation at 2.683 GHz, (b) with 10° arm rotation at 2.683 GHz, (c) with 20° arm rotation at 2.719 GHz, (d) with 30° arm rotation at 2.80 GHz, (e) with 40° arm rotation at 2.935 GHz, and (f) with 50° arm rotation at 3.277 GHz.

In the figure it is observed that the antenna radiation pattern pivots as its arms rotate such that the pattern rotation and the rotation of the arms are in the same direction. This observation is different from that obtained before for the designed antennas with three and four arms on the side (see Fig. 8 and Fig. 13). In the antennas with three and four arms on the side patterns pivot towards the feed line with arm rotation, whereas here for the designed antenna having four arms on its side pattern pivots away from the feed line as the antenna arms rotate. To better see the pivoting of the antenna pattern, directivity of the antenna is shown in Fig. 19 in polar coordinate system on constant y-z plane for different arm rotations. Also, change of the angle at which the maximum directivity value is reached with the arm rotation for the designed five arm antenna is depicted in Fig. 20.

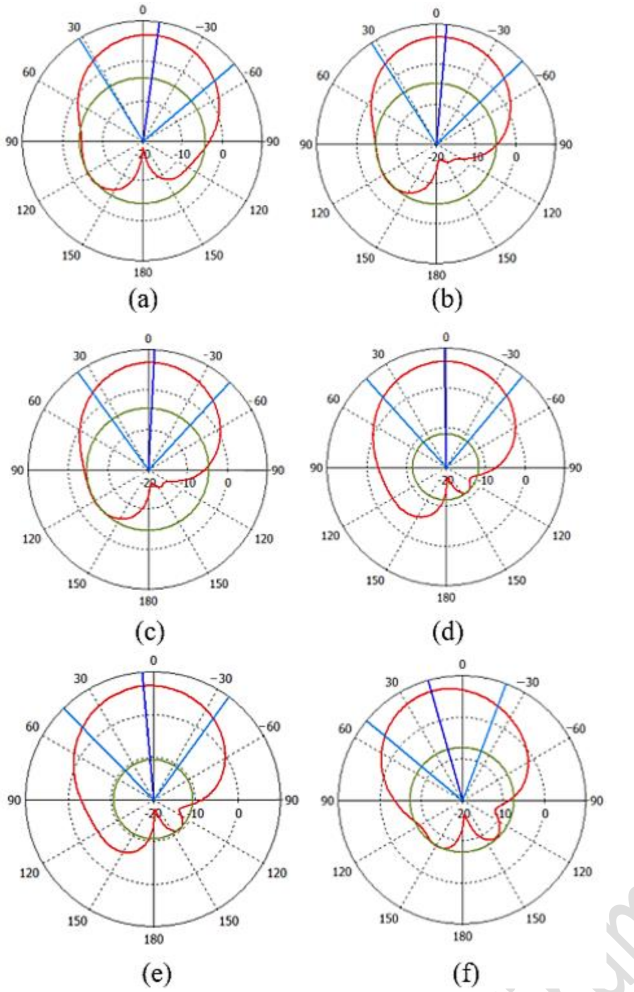

Figure 19. Directivity patterns (in far-field) of the designed single sided five arm antenna having the comb shape in polar coordinate system on y-z plane calculated at the first resonance frequencies. (a) With no arm rotation at 2.683 GHz, (b) with 10° arm rotation at 2.683 GHz, (c) with 20° arm rotation at 2.719 GHz, (d) with 30° arm rotation at 2.80 GHz, (e) with 40° arm rotation at 2.935 GHz, and (f) with 50° arm rotation at 3.277 GHz.

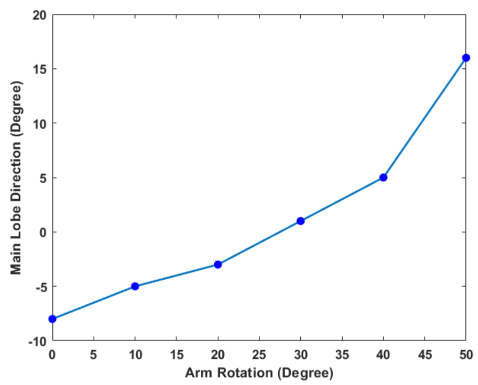

Figure 20. Change of the angle at which the maximum radiation is achieved as a function of the arm rotation at the first resonance of the designed single sided five arm antenna with the comb shape.

To understand the differences in pattern pivoting of the antennas surface current distributions are investigated, too. The surface current distributions over the antennas with 0 degree and 50 degree arm rotations at the first resonances are shown in Fig. 21.

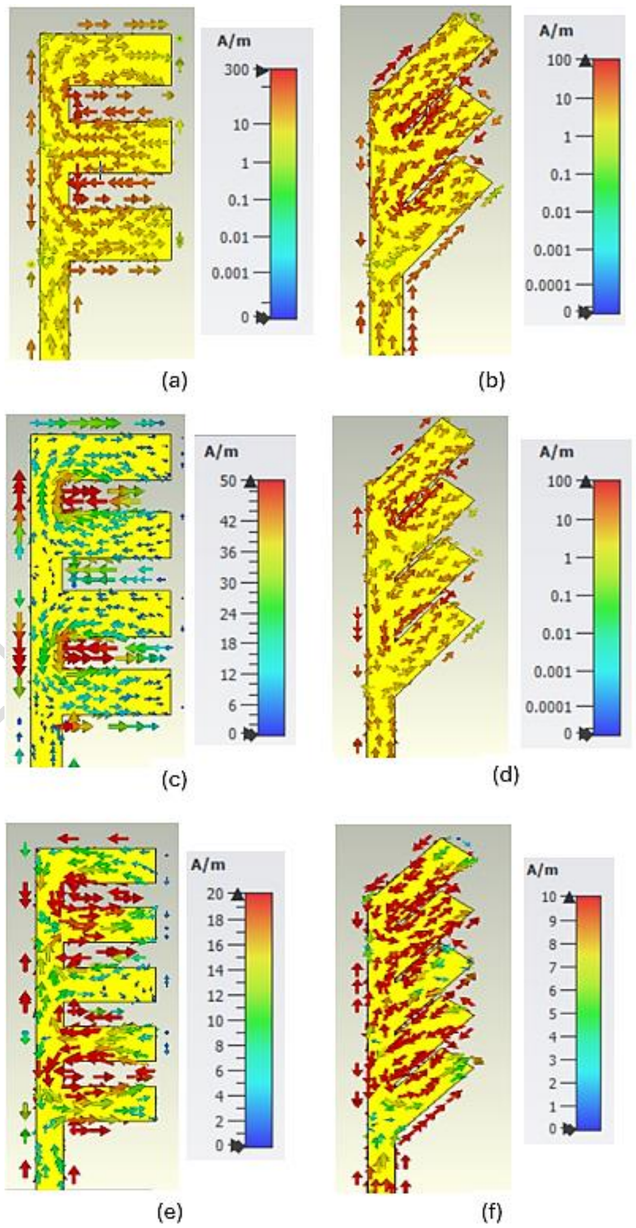

Figure 21. The surface current distributions calculated in the simulations at the first resonances of the single sided comb shaped antennas having (a) three arms with 0° arm rotation, (b) three arms with 50° arm rotation, (c) four arms with 0° arm rotation, (d) four arms with 50° arm rotation, (e) five arms with 0° arm rotation, (f) five arms with 50° arm rotation.

As seen in the figure, current distributions over the antennas are different depending on the antenna geometry. Over the antennas having 3 and 4 arms (see Fig. 21(a-d)) the currents on the arms that are closest to and furthest away from the feed point are in the direction from the feeding line to the arms' end, whereas the currents on the inner arms are in the opposite direction. Resultantly, over the antennas it is like two separate current loops, i.e., one is in clockwise direction and the other is in counterclockwise direction, exist from the inner arms towards the outer arms. Over the antenna with 5 arms (see Fig. 21(e-f)), on the other hand, the currents on the arms that are closest to and furthest away from the feed point are in different directions such that the current on the first arm is in the direction from the feed line to the arm end but the current on the fifth arm is in the opposite direction. In addition, the currents on the inner arms are in different directions, too. Therefore, over the antenna with 5 arms it is like two separate current loops rotating in the same direction exist from the inner arms towards the outer arms. Moreover, for the antenna having 5 arms the current density on the middle arm is too low with respect to the other arms. This is different from that observed for the antennas having 3 and 4 arms. Because of all these differences the antenna radiation patterns are distinct and beam rotates differently.

The designed antennas are manufactured, too. In Fig. 22 the produced antennas with three arms on the side for six different arm rotation cases are shown from the top view.

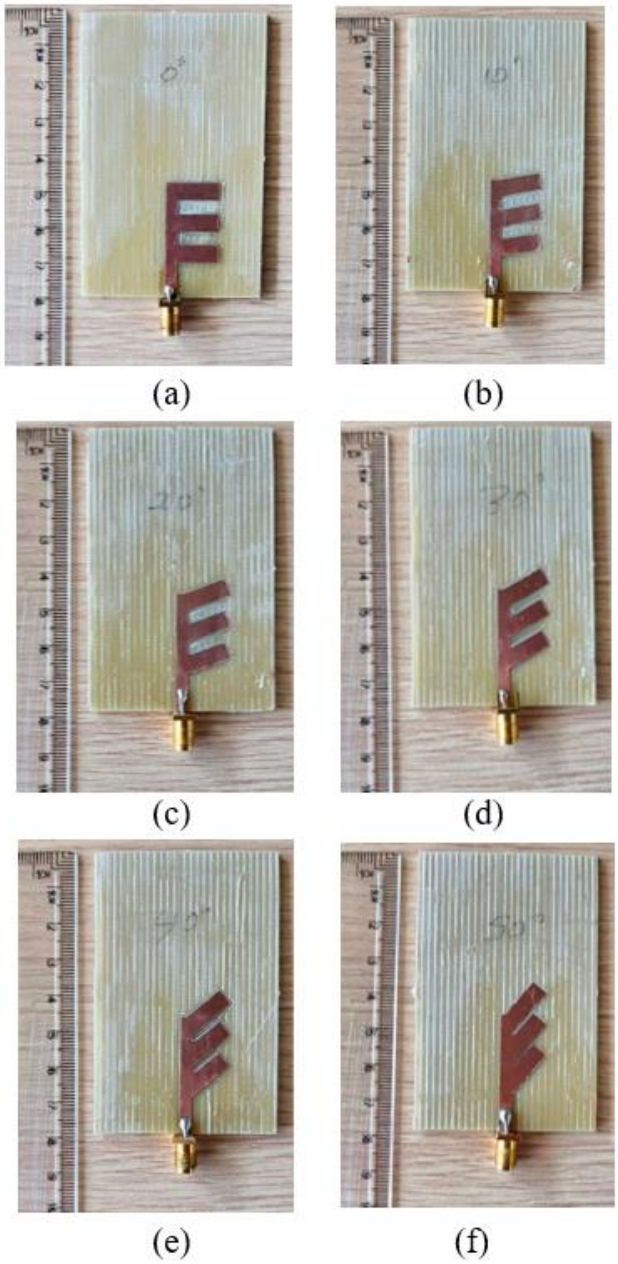

Figure 22. The produced single sided three arm patch antennas having the comb shape (a) with no arm rotation, (b) with 10° arm rotation, (c) with 20° arm rotation, (d) with 30° arm rotation, (e) with 40° arm rotation, and (f) with 50° arm rotation.

The S_{11} parameters of the fabricated antennas are measured by using a Vector Network Analyzer. S_{11} parameter magnitude changes with frequency between 2.5 GHz and 5.5 GHz obtained in measurements and calculated in simulations for the designed single sided three arm antenna having the comb shape with various arm rotations are shown in Fig. 23. In the figure, it is observed that the measurement results agree well with the simulation results. As in the simulation results, the measured resonance frequencies of the antenna shift to higher frequencies with the rotation of the arms. On the other hand, small differences between the results might be due to limited accuracy of the simulations and measurements together with the finite precision of the manufacturing.

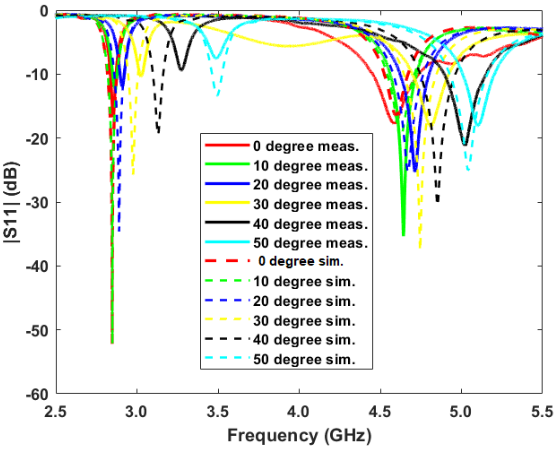

Figure 23. Change of the S_{11} parameter magnitude of the designed single sided three arm antenna with the comb shape as a function of frequency over the band from 2.5 GHz to 5.5 GHz calculated in simulations and obtained in measurements for various arm rotations.

Additionally, the literature comparison of the work has been done. As it can be seen in Table 1 below, similar structures exist in the literature. In those studies, resonance frequency change is used for sensing operation. On the other hand, with the proposed design in this work both shifts in the resonance frequencies and far-field pattern pivoting can be used for sensing.

Table 1. Comparison of our work with antennas reported in literature in terms of sensing type, operating frequency, antenna geometry and fabrication process simplicity.

Work	Sensing Type	Operating Frequency	Antenna Geometry	Fabrication Process Simplicity
[22]	Resonance Frequency Shift	2.9 and 5.7 GHz	Dual-Feed Rectangular Patch	Moderate
[23]	Resonance Frequency Shift	5.8 GHz	Rectangular Patch Antenna	Simple
[24]	Resonance Frequency Shift	900 MHz	Patch Antenna with RFID chip	Moderate
[25]	Resonance Frequency Shift	2.4 GHz	Inverted E Shape Patch Antenna on Flexible Substrate	Not Specified
Our work	Resonance Frequency Shift and Pattern Pivoting	2.4 and 4.8 GHz	Comb Shaped Patch Antenna	Simple

4 Conclusions

In this paper, single sided comb shaped patch antennas having different number of arms with various arm rotations are reported. A comb shaped three arm antenna resonating around 2.8 GHz and 4.5 GHz frequencies is designed initially and the antennas with four and five arms on the sides are generated by adding new arms to the initially designed antenna. Except the number of the arms, geometrical parameters of the designed antennas are all kept the same.

With 3D EM simulations S_{11} parameter change of the antennas with frequency and the radiation patterns of the antennas in far-field at resonance frequencies are calculated for various arm rotations of the antennas. In the antennas all the arms are rotated at the same angles around the midpoints of their edges in contact with the feed line. The results show that the antennas' first and second resonances move to higher frequencies with rotation of the arms. It is found that the resonance frequency increases are faster than a linear increase. On the other hand, from the calculated far-field radiation patterns it is seen that the patterns of the antennas pivot as the antenna arms rotate. For the designed three arm antenna, this pivoting occurs in opposite direction to the rotation of the arms for rotations up to 40 degrees, whereas after 40 degrees arm rotation beam steering of the antenna stops. Similar pivoting is observed for the designed four arm antenna such that as its arms rotate the antenna pattern continuously pivots in the direction opposite to that of the arm rotation. For the designed five arm antenna, however, as the arms rotate the antenna pattern pivots in the direction same with that of the arm rotation. The designed three arm antennas with different arm rotations are produced, too. S_{11} parameter magnitude changes calculated in simulations and obtained in measurements agree well.

In practice, the proposed design with solid substrate (FR4), can be used for resonance frequency tuning applications. The resonance shift of the antennas achieved without any change in antenna sizes but only with rotation of the arms. It is promising for size critical systems while setting the operation frequency. In addition, pivoting of the antenna pattern with arm rotation is adaptable for sensing operations together with biomedical applications, conformal structures and surface strength measurement systems. As a future study, it is possible to design the antennas on a flexible substrate, which display resonance shift and pattern pivoting with arm rotation that occurs as a result of applied forces and tensions to the antennas in certain directions.

5 Author contribution statement

The first author contributed to the simulation studies of the designed antennas, the fabrication-measurement processes of the antennas, result analysis studies and preparation of the publication. The second author contributed the conceptual design processes and simulation stages. The third author contributed the conceptual design, obtained results observations/evaluation and the preparation of the publication as advisor.

6 Ethics committee approval and conflict of interest declaration

There is no need to get ethics committee permission for the prepared article. There is no interest conflict with any person or institution in the prepared publication.

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