Single and Double Side Comb-Shaped Patch Antenna Design Evolved from Rectangular Shape for Reduced Sized Antenna Applications

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***Abstract*—This paper reports single and double side comb-shaped patch antennas to be used in reduced-sized antenna applications. The proposed antenna designs are evolved from regular rectangular shape antennas. The designed single and double side comb-shaped antennas were investigated in a complete set of study together with the rectangular shape antenna that resonates at 5 GHz frequency. Reflection coefficient (S_{11}) parameter of the designed comb-shaped antennas and the rectangular antenna were calculated together with three-dimensional (3D) directivity patterns in simulations for different arm lengths, arm widths, and arm numbers of the comb-shaped antennas. Results show that with the comb-shaped antennas it is possible to shift the resonance frequency of a regular rectangular shape antenna to a frequency lower than its half without enlarging the foot-print area or with the smaller foot-print area. Also, resonance frequency change and peak directivity variations at resonance frequencies of the antennas with geometrical parameters of the antennas were calculated, too. The findings indicate that due to the large number of geometrical parameters that come with the nature of the comb shape, comb-shaped antennas provide more flexibility while constructing an antenna.**

Keywords—patch antenna, comb-shaped, resonance.

I. Introduction

An antenna is a device that radiates or receives electromagnetic signals through the air [1]. Antennas are generally used for communication purposes. For instance, mobile communication systems operating on GSM frequency bands are very common examples that consist of antennas. Although different antenna types including wire antennas and reflector antennas are used [2, 3], microstrip antennas are widely exploited in communication systems. With the developments in manufacturing technology, microstrip antennas have become more popular in today's world. Because of their two-dimensional (2D) structure with a low thickness such that thickness in the mm and μm ranges, microstrip antennas are preferred to be used in applications where physical limitations are important. Microstrip antennas take place in a wide variety of applications including spacecraft, satellites, missiles, mobile devices, cars, etc. [1, 4].

Microstrip antennas have a simple structure. A metallic radiator patch, which could have different configurations, exists on one side, and on the other side, a ground plane is located. Between the metallic radiator patch and the ground plane, there is a dielectric substrate. Radiator patch geometry is one of the most important parameters that determine antenna characteristics. Different behaviors are observed for various radiator patch antenna geometries. However, due to their ease of analysis and fabrication circular and rectangular shapes are commonly used for radiator patch antenna geometries [5, 6]. Depending on polarization, microstrip antennas are generally constructed to have one of these regular patch geometries. However, in a regular shaped microstrip patch antenna, a very limited number of key parameters exist to determine antenna properties such as setting the resonance frequency. In rectangular patch antenna geometry, these parameters are its width and length. Therefore, in a regular shape antenna to obtain radiation at low frequencies, it is required to enlarge the antenna due to the extended wavelength of the radiated signal. To overcome this issue, in this study, single and double side comb-shaped microstrip patch antennas that radiate at low frequencies than regular rectangular shape patch antenna while having similar or smaller foot-print area occupied by the metallic radiator patch are proposed and demonstrated.

There are studies in literature in which comb-shaped microstrip antennas are reported [4, 7-9]. In some of these studies, a wide operating frequency band [4, 7] and multi-band [8] features of the single side comb-shaped antennas are examined. In other studies, on the other hand, double side comb-shaped antennas are investigated [9]. However, despite deep analysis in all the studies, there is no fair comparison between a regular-shaped patch antenna and the comb-shaped antennas. Also, a complete study of single and double side comb-shaped antennas including performance analysis and resonance change with the number of arms, arm lengths, arm widths, and arm distances, is missing.

In this study, single and double side comb-shaped antennas were investigated in a complete set of studies and the results were compared with a regular rectangular patch antenna. By evolving a rectangular patch antenna to single and double side comb-shaped antennas, also, will be called as E and F shapes, it is achieved to shift resonance frequency to lower frequencies. With help of a three-dimensional (3D) electromagnetic (EM) simulation tool, scattering (S) parameters, surface current, and far-field radiation were calculated and the antennas were analysed for different geometrical parameters including the number of arms, arm widths, the distance between arms, etc. This study demonstrates that it is possible to get radiation at lower frequencies with the single and double side comb-shaped patch antenna, instead of to increase the width of a patch. It is seen that the antenna with a smaller size provides the feature. Also, how antenna performance parameters and properties such as directivity, beamwidth, and resonance frequency, change with its geometrical parameters for a comb-shaped antenna is clearly expressed in this study.

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II. Antenna Designs and Simulations

The first step for the designs was building a rectangular shape patch antenna that resonates at 5 GHz frequency. In the antenna, Rogers 4003C with 0.508 mm thickness is used as the substrate material. Also, copper is used as the radiator patch and ground plane materials. The thickness of the patch and ground plane is selected to be 0.035 mm. In addition, the width and length of the rectangular radiator patch are set to be equal to 33.1 mm and 15.1 mm, respectively. The designed rectangular patch geometry is illustrated in Fig. 1.

Next, single- and double-sided F shape antennas, i.e., comb-shaped antennas with 2 arms on a single side, were investigated. Radiator patch geometries of the single- and double-sided F shape antennas are shown in Fig. 2(a) and (b), respectively. In both subfigures, arm width is represented with w. Similarly, the center-to-center distance between arms in both antenna geometries is labelled with d. On the other hand, in Fig. 2(a) length of arms in single-side is pointed out with l, whereas in Fig. 2(b) l shows the total length of arms on both sides.

After, the number of arms on each side was increased by 1, and single- and double-sided E shape antennas were obtained. Single- and double-sided E shape antenna geometries are represented in Fig. 3(a) and (b), respectively. As in F shape antenna geometry, here arm width and distance between the arms are indicated with w and d, respectively. Also, the length of arms in a single side and the total length of arms in double sides are represented with l in the first and second subfigures, respectively.

Single- and double-sided F and E shape antennas with various arm widths and arm distances were examined. For a fair comparison with the designed regular rectangular shape antenna, the total arm length of the double-sided antennas that equal to the width of the antennas is set constant to be equal to 33.10 mm. However, the arm length of the single-sided antennas is determined to be 16.55 mm, which is half-width of the initially designed rectangular shape antenna.

In the analysis, arm width is changed first. For the single- and double-sided F shape antennas arm width is varied between 1 mm and 7.5 mm with a 0.5 mm increment while the distance between the arms is 7.6 mm. On the other hand, for the single- and double-sided E shape antennas arm width is changed from 1 mm to 5 mm again with a 0.5 mm increment while the arm distance is 5.1 mm. With these values, the antenna is most like the initially designed rectangular shape antenna, when the arm width is maximum. Next, the distance between the arms is altered. For the single-sided F shape antenna, the arm distance is changed between 4.5 mm and 14 mm with 0.5 mm step size while the arm width is 4 mm, whereas for the double-sided F shape antenna the arm distance is varied from 6 mm to 15.5 mm again with 0.5 mm step size

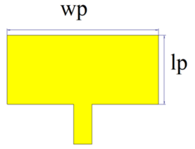

Fig. 1. Top view of a rectangular radiator patch geometry in the designed antenna. Here wp and lp represent the width and length of the patch, respectively.

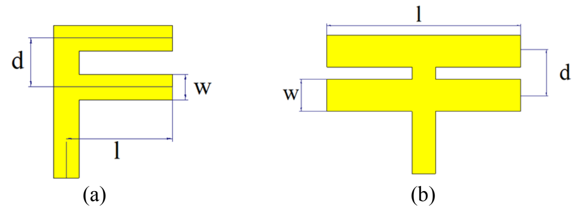

Fig. 2. Radiator patch geometries of the (a) single- and (b) double-sided F shape antenna.

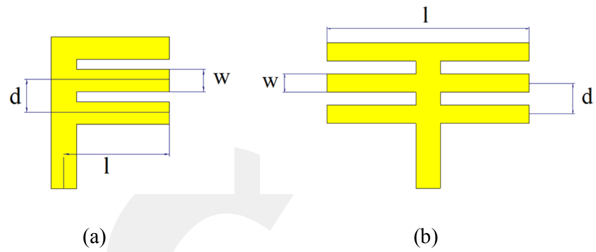

Fig. 3. Radiator patch geometries of the (a) single- and (b) double-sided E shape antenna.

while the arm width is 5.5 mm. These 4 mm and 5.5 mm constant arm widths in single- and double-sided F shape antennas are determined because in the first analysis while changing arm width the strongest resonances are obtained with these arm widths. For the single-sided E shape antenna, on the other hand, the distance between the arms is changed from 4.5 mm to 9.5 mm with a 0.5 mm increment while the width of arms is 4 mm. However, for the double-sided E shape antenna, the arm distance is varied between 3.5 mm and 10 mm with a 0.5 mm increment while the width of arms is 3 mm. As in F shape antennas, here 4 mm and 3 mm arm widths are selected because of the strongest resonances achieved with these arm widths in the before analysis.

III. Results and Discussion

The regular rectangular shape patch antenna and the proposed single- and double-sided E and F shape antennas were analysed with a 3D EM simulation tool. In the simulations, S-parameters, far-field radiations, and surface currents were calculated. The change of the S_{11} parameter that defines how much of the power at the antenna's input port is reflected back is shown in Fig. 4(a). As seen, the designed rectangular shape antenna resonates at 5 GHz frequency. Also, the directivity of the antenna calculated in far-field at 5 GHz resonance frequency is shown in Fig. 4(b). As seen in the figure, the maximum directivity is found to be 6.05 dBi occurring at broadside, i.e., at $\theta = 0°$ and $\phi = 0°$.

Similar to the rectangular antenna, S_{11} parameters of the single- and double-sided F shape antennas were calculated, too. As explained before, simulations were repeated for various arm widths between 1 mm and 7.5 mm with a 0.5 mm increment. Change of S_{11} parameter with frequency for single-sided F shape antenna is shown in Fig. 5(a) for different arm widths. In the figure, it is seen that the resonance frequency shifts to a lower frequency as the arm width increases. For a clear illustration, a change of resonance frequency with arm width is plotted in Fig. 5(b). However, as clearly seen in both figures, the resonance frequency is much higher than 5 GHz, despite in this study it is aimed to shift resonance frequency to lower frequencies while the foot-print area of the antennas remains similar or becomes smaller.

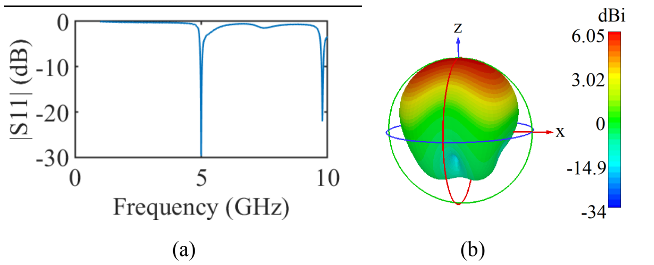

Fig. 4. (a) Change of S_{11} parameter with frequency and (b) 3D directivity pattern in far-field at 5 GHz resonance frequency calculated in simulations for the designed rectangular shape antenna.

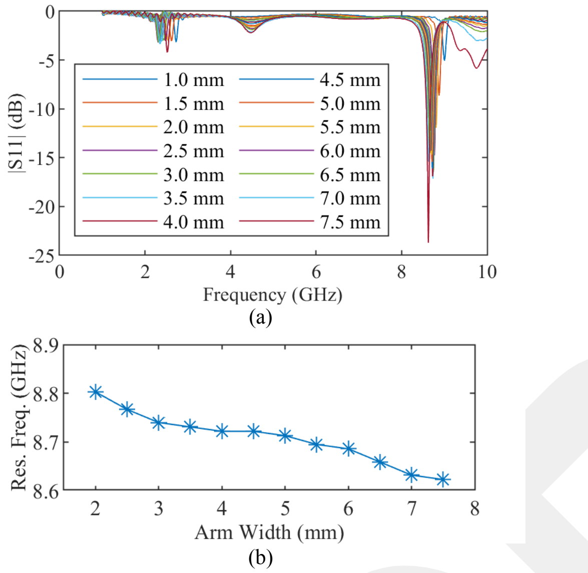

Fig. 5. (a) Change of S_{11} parameter with frequency calculated in simulations for the designed single-sided F shape antenna with different arm widths, (b) change of resonance frequency with arm width in subfigure (a).

In addition, for different arm distances, the S_{11} parameter change was calculated, too. The results are shown in Fig. 6(a). Again, the resonance frequency shifts to a lower frequency as the distance between the arms increases. The change of resonance frequency with arm distance is shown in Fig. 6(b). In the figure, it is seen that there is a discontinuity in the resonance frequency change plot, which is due to the fact that the antenna resonance dies out for the arm distance between 8 mm and 12.5 mm (see subfigure (a)). After 12.5 mm the resonance arises again.

Moreover, the change of the S_{11} parameter with frequency for the double-sided F shape antenna is represented in Fig. 7(a). Unlike the single-sided F shape antenna results, here antenna resonance does not shift to lower frequencies as the arm width increases. There is no regular increase or decrease in the resonance frequency, but the resonance frequency has a general trend of increase with the increase in arm width. This is clearly seen in Fig. 7(b), where a change of the resonance frequency with the arm width in double-sided F shape antenna is plotted. Also, for various arm distances change of S_{11} parameter with frequency for the double-sided F shape antenna was calculated, too. The results are plotted in Fig. 8(a). In the figure, it is seen that the resonance frequency decreases with the increase in arm distance, which is similar to the behaviour obtained with the single-sided F shape antenna. Change of the resonance frequency with the arm distance is shown in Fig. 8(b). As in single-sided F shape antenna, here the antenna resonance disappears for the arm distance between 8.5 mm and 12 mm.

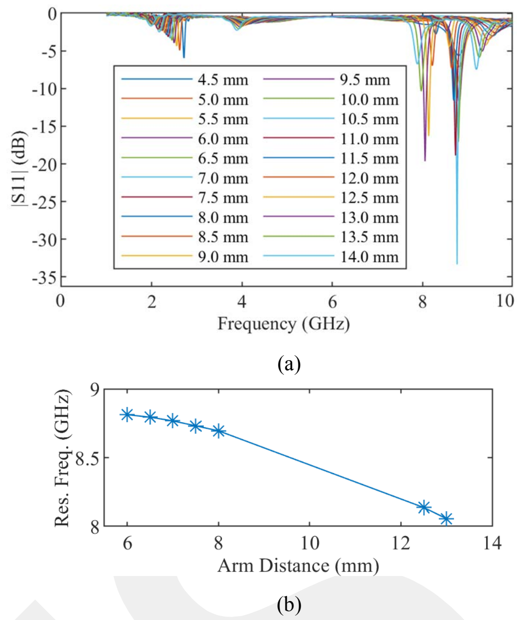

Fig. 6. (a) Change of S_{11} parameter with frequency calculated in simulations for the designed single-sided F shape antenna with different arm distances, (b) change of resonance frequency with arm distance in subfigure (a).

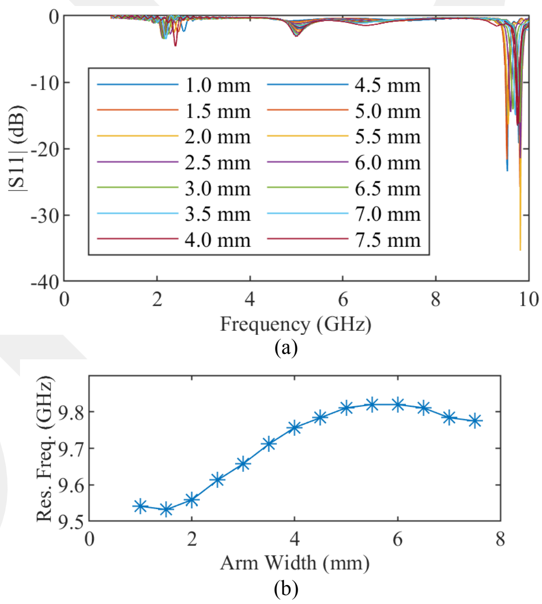

Fig. 7. (a) Change of S_{11} parameter with frequency calculated in simulations for the designed double-sided F shape antenna with different arm widths, (b) change of resonance frequency with arm width in subfigure (a).

In addition to S-parameters, directivities of the antennas in far-field were calculated, too. As an exemplary, 3D far-field radiation patterns of the designed single- and double-sided F shape antennas with 5.5 mm arm width and 6 mm arm distance are illustrated in Fig. 9(a) and (b), respectively. As seen, two main lobes arise in different directions symmetric with respect to broadside direction at the resonance frequency for both antennas.

Furthermore, systematic simulations show that directivity of the single-sided F shape antenna increases with arm width, whereas with the extension of arm distance it increases until a specific arm distance. Directivity of the double-sided F shape antenna, on the other hand, does not have a continuous increase or decrease. As the arm width increases, it first increases and then decreases, and as the arm distance is increased, it exhibits more complex behaviour. Change of the maximum directivity with arm width and arm distance in single- and double-sided F shape antennas is represented in Fig. 10(a) and (b), respectively. Discontinuities in variations of the directivity with arm distances are because of the disappearing of antenna resonances.

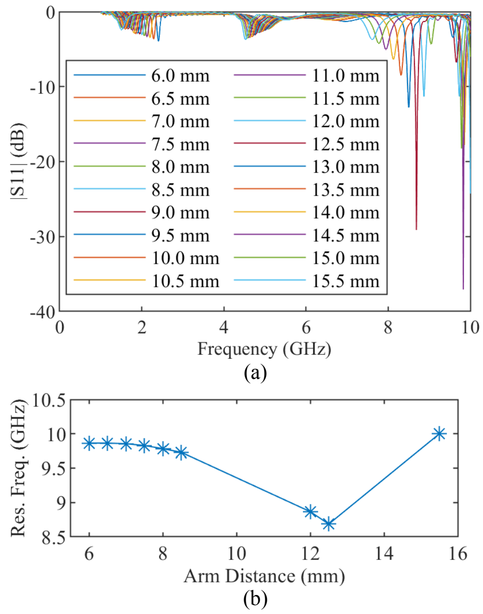

Fig. 8. (a) Change of S_{11} parameter with frequency calculated in simulations for the designed double-sided F shape antenna with different arm distances, (b) change of resonance frequency with arm distance in subfigure (a).

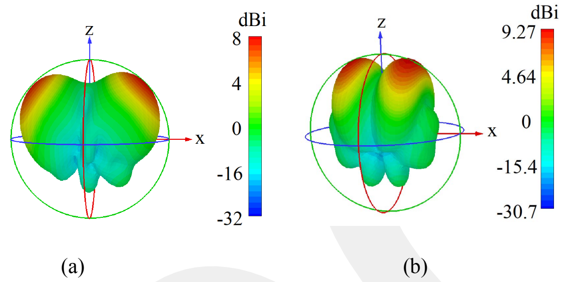

Fig. 9. 3D directivity pattern of the designed (a) single- and (b) double-sided F shape antenna with 5.5 mm arm width and 6 mm arm distance calculated in simulations at the resonance frequency of the antennas in far-field, where the resonance frequency of the first antenna is 8.713 GHz and the second antenna is 8.865 GHz.

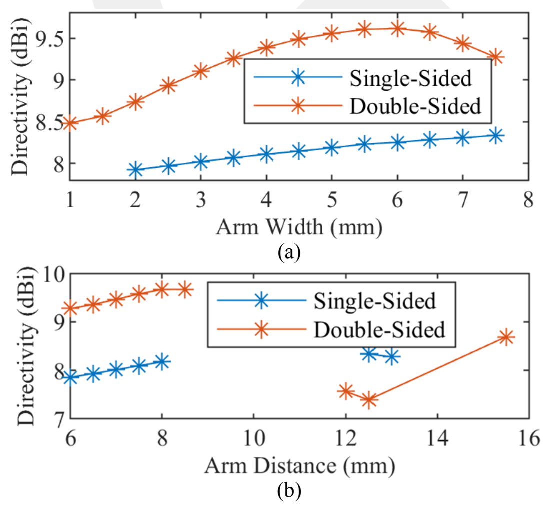

Fig. 10. Change of the peak directivity value with (a) arm width and (b) arm distance calculated in simulations at the resonance frequency for the designed single- and double-sided F shape antenna.

As can be seen from the results, the main issue with single- and double-sided F shape antennas is the resonance frequency arisen at frequencies much higher than 5 GHz resonance frequency of the initially designed regular rectangular shape antenna. To overcome this problem, E shape antennas were investigated. To realize the E shape antennas one more arm is added to each side of the F shape antennas. Similar to the F shape antenna analysis, the calculations were begun with the single-sided E shape antenna. After, simulations were repeated for various arm widths and arm distances. The change of the S_{11} parameter with frequency is represented in Fig. 11(a) for different arm widths. Unlike single-sided F shape antenna, here there is no continuous shift in resonance frequency with the antenna arm width. This is clearly shown in Fig. 11(b), where the variation of the resonance frequency with the arm width is illustrated. However, it is very important that resonance frequencies obtained with the single-sided E shape antenna are around 2.75 GHz, which is almost half of the 5 GHz designed regular rectangular shape antenna resonance frequency. In Fig. 12(a) and (b), on the other hand,change of S_{11} parameter with frequency for different arm distances and resonance frequency shift with arm distance are shown, respectively. In the figures, it is seen that there is a continuous decrease in resonance frequency as the arm distance increases. This is similar to what was observed for single-sided F shape antenna but behaviour and speed of the decreases in the E and F shape antennas are different.

Later, simulations were repeated for the double-sided E shape antenna with various arm widths and arm distances. In Fig. 13(a) and (b), variations of the S_{11} parameter with frequency for different arm widths and change of resonance frequency with arm width are shown, respectively. In the figure, it is seen that the resonance frequency decreases as the arm width increases till 3 mm but after 3.5 mm width, the resonance frequency increases with the arm width. Also, the variation of the S_{11} parameter with frequency for different arm distances and resonance frequency change with arm distance are illustrated in Fig. 14(a) and (b), respectively.

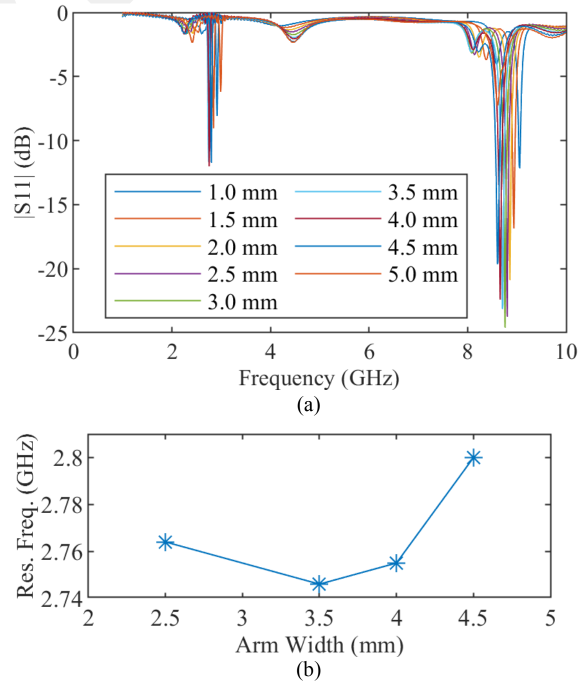

Fig. 11. (a) Change of S_{11} parameter with frequency calculated in simulations for the designed single-sided E shape antenna with different arm widths, (b) change of resonance frequency with arm width in subfigure (a).

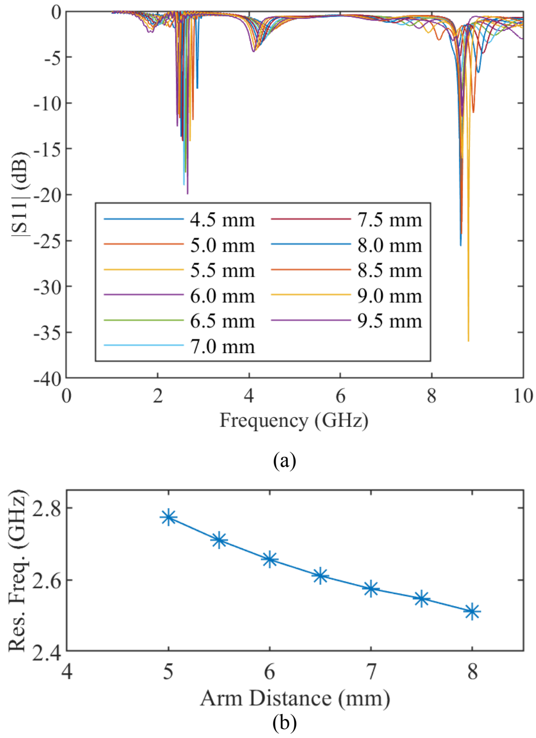

Fig. 12. (a) Change of S_{11} parameter with frequency calculated in simulations for the designed single-sided E shape antenna with different arm distances, (b) change of resonance frequency with arm distance in subfigure (a).

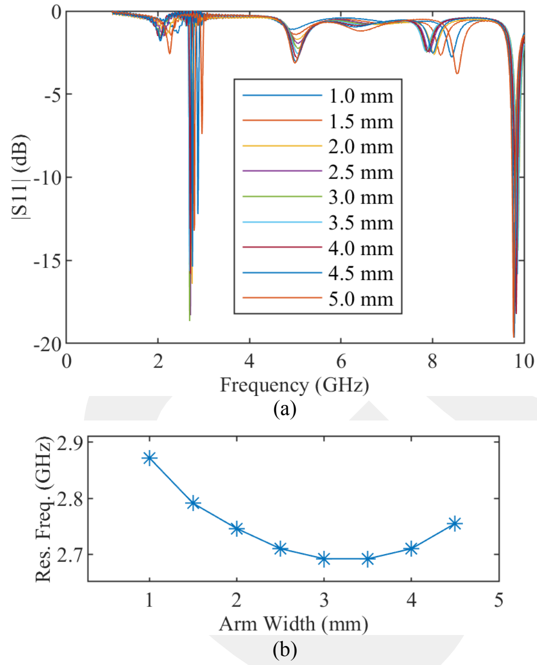

Fig. 13. (a) Change of S_{11} parameter with frequency calculated in simulations for the designed double-sided E shape antenna with different arm widths, (b) change of resonance frequency with arm width in subfigure (a).

As in single-sided E shape results, here resonance frequency almost linearly decreases with an increase in the arm distance. In addition, it is a very important result that the resonance frequency of 2.46 GHz that is lower than half of the 5 GHz resonance frequency of the designed rectangular antenna is achieved with a 7.5 mm arm distance, which yields the proposed double-sided E shape antenna to have the same foot-print area with the initially designed rectangular antenna.

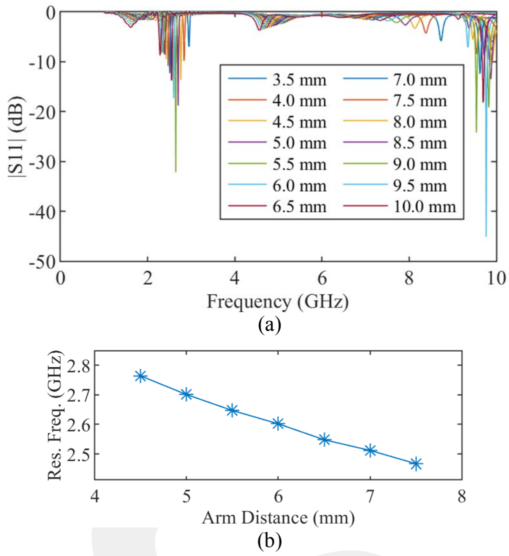

Fig. 14. (a) Change of S_{11} parameter with frequency calculated in simulations for the designed double-sided E shape antenna with different arm distances, (b) change of resonance frequency with arm distance in subfigure (a).

All the antennas that are designed and investigated in this study have sharp resonances, which might make it difficult to get the same resonance frequency seen in the simulation tools after the fabrication of the antenna. However, the bandwidth of the antennas can be enlarged by applying techniques that exist in literature such as defecting and reshaping the ground plane [4]. In this study since the aim is to examine the change of the behaviour with geometrical parameters in the designed comb shape patch antennas, the ground plane is not defected or reshaped.

Lastly, as for the F shape antennas, far-field radiations and directivities of the designed single- and double-sided E shape antennas were calculated, too. 3D patterns calculated in far-field for the designed single- and double-sided E shape antennas with 3 mm arm width and 7 mm arm distance are shown in Fig. 15(a) and (b), respectively. As seen, at low resonance frequencies there is a single main lobe. However, as it is observed in Fig. 15(c), at higher-order resonance frequencies there are two main lobes as with the F shape antennas.

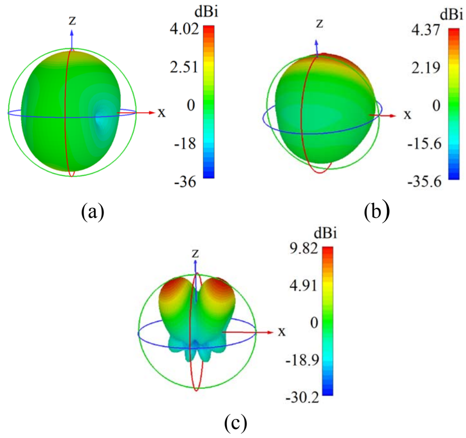

Fig. 15. 3D directivity pattern of the designed (a) single- and (b) double-sided E shape antenna with 3 mm arm width and 7 mm arm distance calculated in simulations at the resonance frequency of the antennas in far-field, where the resonance frequency of the first antenna is 2.62 GHz and the second antenna is 2.512 GHz. (c) 3D directivity pattern of the designed doubled-sided E shape antenna with 3 mm arm width and 7 mm arm distance calculated at 9.622 GHz frequency.

Also, with the simulations, it is deduced that the maximum directivity of the single-sided E shape antenna increases as the arm width extends, whereas it decreases if the arm distance increases. However, for the double-sided E shape antenna, there is no regular change in the maximum directivity. The variations are easily observed in Fig. 16, where the change of the maximum directivity with the arm width and arm distance in single- and double-sided E shape antennas is represented.

Furthermore, in Fig. 17 surface current distribution over the double-sided E shape antenna with 3 mm arm width, and 4.5 mm and 7 mm arm distances are shown. In the figure it is seen that the current distribution changes with arm distance. As the distance between the arms increases, path length of the current flow increases, too. As a result, resonance wavelength becomes longer and the antenna resonance frequency shifts to a lower frequency.

IV. Conclusion

In this study, single and double side comb-shaped patch antennas evolved from regular rectangular shape antenna are analysed. For different arm widths, arm distances, and arm numbers comb-shaped antenna simulations were obtained, and the reflection coefficient (S_{11}) parameter of the antennas was calculated together with a 3D directivity pattern. Comparisons were done with initially designed rectangular shape antenna that resonates at 5 GHz frequency. Results show that single- and double-sided E shape antennas resonate at frequencies lower than that of regular rectangular shape antenna despite the foot-print area of the E shape antennas is similar to or smaller than the foot-print area of the rectangular antenna. It is demonstrated that the resonance frequency of the rectangular antenna can be shifted to lower than its half value via comb-shape without increasing the antenna sizes.

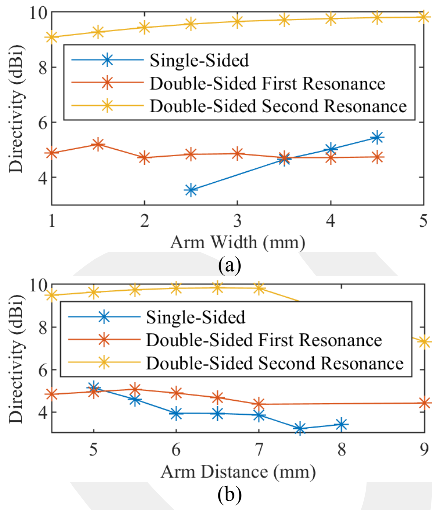

Fig. 16. Change of the peak directivity value with (a) arm width and (b) arm distance calculated in simulations at the resonance frequency for the designed single- and double-sided E shape antenna.

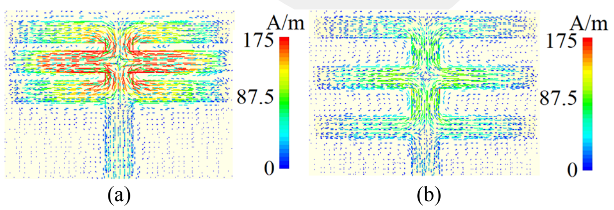

Fig. 17. Surface current distribution over the designed double-sided E shape antenna with 3 mm arm width and (a) 4.5 mm, (b) 7.5 mm arm distance.

In addition, systematic simulations show that for single-sided F shape antennas the resonance frequency shifts to a lower frequency as the arm width increases and it has a tendency to shift to a lower frequency as the arm distance increases, whereas for double-sided F shape antennas there is no regular change of resonance frequency with arm width but the resonance frequency shifts to a lower frequency as the arm distance is increased except some arm distance values. On the other hand, for single- and double-sided E shape antennas resonance frequency shifts to a lower frequency as the arm distance extends but there is no regular change of the resonance frequency with the arm width. Moreover, 3D directivity patterns of the antennas were calculated, too. It is shown that the peak directivity values of the antennas at resonance frequencies change differently for both shapes.

It is believed that the proposed antenna design method is beneficial for applications where the physical dimensions are limited and antennas with sizes smaller than regular antennas are required such as the Internet of Things (IoT), space, commercial communication (5G) and RFID applications.

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