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Bandwidth Improvement in Circular Microstrip Patch Antenna through Shape Modification

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Abstract: An antenna is used in a communication system to radiate or receive radio waves. The most desired antenna is one which is small in size, light in weight, cheap and can easily fit to the surface attached. All these features are inherently possessed by microstrip patch antennas. However, no antenna is perfect. Microstrip patch antennas like all other types of antennas do have their associated disadvantages. One of the major disadvantages of this type of antenna is narrow impedance bandwidth. In this study, the narrow impedance bandwidth of a circular microstrip patch antenna was improved through shape modification. The impedance bandwidth of the antenna was optimized by adding some parts to and removing some parts from the initial circular patch. Although the main aim was to improve the impedance bandwidth, it had to be ensured that other important parameters of the antenna such as radiation efficiency, impedance matching and gain are not degraded in the process. Microstrip line feeding technique was utilized in the design. HFSS 13.0 full wave simulator based on Finite Element Method (FEM) was used to simulate the antenna. Simulation results were then presented. Simulation results of return loss showed that the antenna achieved impedance bandwidth of 141 MHz (7.846%) at 1.797 GHz and a very broad impedance bandwidth of 16.14 GHz (898.16%) from 3.86-20 GHz. This is a great improvement when compared with the impedance bandwidth of a conventional microstrip patch antenna of less than 3%. Simulation results of Z_{11} parameter showed that the antenna achieved good impedance matching with a 50Ω transmission line at 1.797 GHz and 4.83 GHz and with a 75Ω transmission line at 7.346 GHz, 9.633 GHz, 11.198 GHz, 12.646 GHz, 14.382 GHz and 19.073 GHz achieving gains of 5.9821dB, 8.4615dB, 9.5274dB, 9.169dB, 8.8842dB, 10.1685dB, 9.8087dB and 11.1218dB respectively. The antenna achieved radiation efficiency of 98.97% at 1.797 GHz and radiation efficiencies of 100% in the other frequencies. The antenna can be used for a wide range of applications because of its wider bandwidth.

Keywords- Bandwidth improvement, Circular microstrip patch antenna, Shape modification, Simulation

1. Introduction

1.1. Background of the Study

Every radio transmitter requires an antenna in order to radiate radio waves and every radio receiver requires an antenna in order to receive radio waves. There are many antenna types such as wire, horn, reflector, aperture, microstrip and so on. Microstrip patch antennas are becoming more and more popular because they are light in weight, small in size, cheap and can easily fit to the surface attached. The features of microstrip patch antennas make them suitable for high performance aircraft, spacecraft, satellite and missile applications. However, microstrip patch antennas also have their own disadvantages. These include low radiation efficiency, low power, high Q (sometimes in excess of 100), poor polarization purity, poor scan performance, spurious feed radiation and very narrow frequency bandwidth [1].

A microstrip patch antenna consists of a radiating metallic patch separated from the ground plane by a dielectric substrate. The radiating patch can take any shape and is used to name microstrip patch antennas as square, rectangular, dipole, circular, elliptical, triangular, disc sector, circular ring, ring sector and many others. The mostly used microstrip patch antenna types are square, rectangular, dipole and circular. These categories of microstrip patch antennas are easy to design and analyze and have low cross-polarization radiation [1]. Circular microstrip patch antenna has additional advantages as compared to rectangular one. First, a circular microstrip patch antenna is smaller than rectangular one at the same design frequency [2]. Secondly, the radiation properties of a circular microstrip patch antenna can easily be changed by varying the radius only unlike for the rectangular in which length and width have to be varied [3]. This study focused on circular microstrip patch antenna. The basic structure of a circular microstrip patch antenna is shown in Fig. 1 [1].

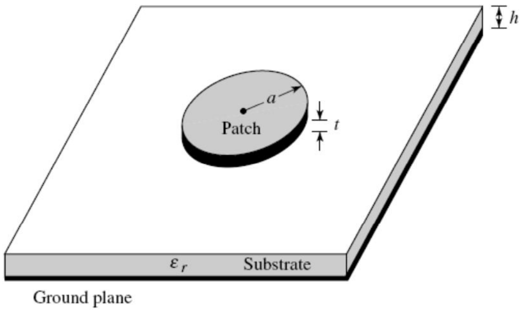


Fig. 1. Circular Microstrip Patch Antenna

The circular metallic patch is very thin, $t << \lambda_0$ (where λ_0 is free space wavelength). The substrate height is also very small compared to λ_0 ($h << \lambda_0$) and in most cases ranges from 0.003 λ_0 to 0.05 λ_0. Many substrates are available for the design of microstrip patch antennas. The common ones have dielectric constants ranging from 2.2 to 12 [1]. Thick substrates with low values of dielectric constants result in larger bandwidth, better efficiency and loosely bound fields that can easily be radiated. These features are suitable for good antenna performance. However, thick substrates result in larger element sizes [4].

Microstrip line feed, coaxial line feed, aperture coupled feed and proximity coupled feed are the common feeding techniques for microstrip patch antennas. Microstrip line feed was used in this study. Microstrip line feed is a narrow conducting strip that connects to the radiating patch. It is easy to fabricate, simple to match and relatively simple to model. However, surface waves and spurious feed radiation increases with increase in substrate height thus limiting the bandwidth to 2-5% [1].

1.2. Problem Statement and Justification

The major target in antenna design is to come up with an antenna which is small, easy to construct, cheap, easy to integrate with monolithic microwave integrated circuits (MMIC) and wideband [5]. In practice, no antenna conventionally satisfies all the features. However, some antennas possess most of the desired features as compared to others. Microstrip patch antenna is one type of antenna that possesses most of the features. However, its major disadvantage is narrow impedance bandwidth. In an attempt to make microstrip patch antennas to be more competitive, the major disadvantage of narrow impedance bandwidth should be addressed. There are many methods that can be used to improve the impedance bandwidth of microstrip patch antennas. These include the use of a thick substrate with low dielectric constant, use of impedance matching network, use of more than one radiating patches in a co-planar or stacked arrangement, modification of the shape of the radiating patch [6] [7], use of tunable microstrip patch antennas [7] and use of proximity coupling [1].

In this study, the impedance bandwidth of a circular microstrip patch antenna was improved by modifying the shape of the radiating patch. A number of researchers have tried to improve the impedance bandwidth of circular microstrip patch antennas by modifying the shape of the radiating patch. An E-shaped circular microstrip patch antenna [8] achieved impedance bandwidth of 15.5% at 1.67GHz-1.95GHz and 10.6% at 2.23GHz-2.48GHz. The Circular Polarized two stacked cross slotted circular patches fed by L shape stepped microstrip line with phi shape slot in its ground [9] achieved impedance bandwidth of 690MHz (5.48 GHz-6.17 GHz). In [10], the use of 2-slit slots, 3-slit slots and 6-slit slots on the radiating patch achieved total impedance bandwidth of 204.1 MHz, 250.5 MHz and 98.5 MHz respectively. The microstrip line fed modified circular microstrip patch antenna [11] achieved total impedance bandwidth of 93% on an infinite ground plane while total impedance bandwidth of 69% was achieved on a finite ground plane. The modified circular microstrip patch antenna presented in [12] recorded a dual resonant characteristic at 3.34 GHz and 7.7 GHz achieving an improved impedance bandwidth. In [13] impedance bandwidth of 2.46 GHz was achieved by modifying the radiating patch and the ground plane. The operating band of the antenna is 4.97-7.43 GHz. A dual resonant antenna was achieved in [14] by modifying the shape of the radiating patch. The antenna resonated at 2.68 GHz and 4.12 GHz achieving impedance bandwidth of 180 MHz and 240 MHz respectively. In [15] impedance bandwidth of 9.68% was achieved at a centre frequency of 4.13 GHz by introducing slots on the radiating patch. The modified circular microstrip patch antenna presented in [16] achieved VSWR ≤ 2 from 2.9 GHz to 10 GHz and above with rejection bands around 3.3–4.2 GHz and 5.2–5.9 GHz. Impedance bandwidth of 0.87 GHz was achieved in [17] by introducing a diamond shaped slot on the radiating patch. In [18] impedance bandwidth of 24% was achieved at a centre frequency of 3.282 GHz by introducing a U shape slot on the radiating patch. The use of off-centered Y-slot [19] achieved impedance bandwidth of 7.5%. A dual resonant antenna was achieved in [20] by use of an off centered ring slot. The antenna achieved impedance bandwidth of 3.45% in the upper band and 3.03% in the lower band. When the off centered ring slot was further modified to form an off centered key shape slot, the antenna resonated at three frequencies achieving total impedance bandwidth of 15.25%.The use of narrow rectangular slit [21] achieved two resonant frequencies with impedance bandwidth of 5.5% and 7.5%. Based on this literature review, the maximum total impedance bandwidth that has been achieved is 5.5 GHz as recorded in [16].

In this study, the impedance bandwidth of the antenna was optimized by adding some parts to and cutting out some parts from the initial circular patch. Microstrip line feed was used to feed the antenna as it is easy to model and match. HFSS 13.0 software based on full wave model was used to simulate the antenna.

2. Antenna Parameters used in the Analysis of the Simulated Antennas

2.1. Return Loss

Return loss (S_{11} parameter) is a measure of the reflected power from the antenna. It therefore indicates the level of impedance matching between the antenna and its feed line [22]. The impedance bandwidth of an antenna is defined as the range of frequencies over which the VSWR is ≤ 2. VSWR of 2:1 is equivalent to a return loss of 9.5424dB. Therefore, the impedance bandwidth of an antenna is determined at -9.5424dB point of the return loss curve.

2.2. Z_{11}-Parameter (Input Impedance)

The input impedance of an antenna varies significantly with frequency [1]. Based on the maximum power transfer theorem, the real part of the input impedance of the antenna should be equals to the characteristic impedance of the transmission line used to feed the antenna at the frequency of operation. Since the characteristic impedance of the transmission line is real, the imaginary part of the input impedance should be zero at the frequency of operation.

2.3. Gain

Gain of an antenna in a given direction is the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically [1]. The Gain of microstrip patch antennas is typically less than 8dBi [23].

2.4. Radiation Efficiency

Antenna radiation efficiency is the ratio of the power radiated by the antenna to the total power input to the antenna [24]. Typical radiation efficiency of microstrip patch antennas is between 70% and 90% [25].

3. Antenna Simulation, Analysis and Discussion

3.1. Circular Microstrip Patch Antenna

Conventional microstrip patch antennas have narrow bandwidth. To prove this, a circular microstrip patch antenna was designed at a centre frequency of 1.5 GHz using standard RT/Duroid 5880 substrate with a dielectric constant of 2.2 and a standard height of 0.1575cm. The corresponding radius was found to be 3.8cm using the design equations of circular microstrip patch antennas equations (1) and (2) [1].

$$a = \frac{F}{\left\{1+\frac{2h}{\pi F \varepsilon_r}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}} \qquad (1)$$

Where

$$F = \frac{8.791\times10^{9}}{f_r\sqrt{\varepsilon_r}} \qquad (2)$$

f_r- Resonant frequency
ε_r -Dielectric constant of substrate
h- Height of substrate
a- Radius of the patch

A microstrip line feed of width 0.48cm was used to feed the patch. The dimensions of the substrate were 12cm×12cm×0.1575cm while the waveport had dimensions of 9cm×0.8cm. The structure of the circular microstrip patch antenna is illustrated in Fig. 2.

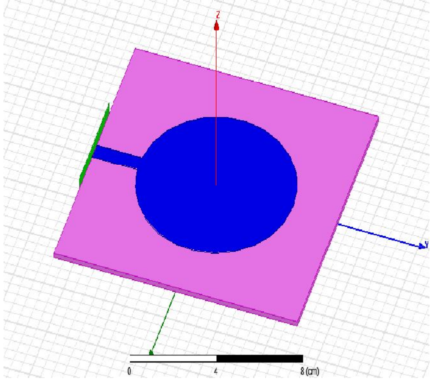


Fig. 2. Circular Microstrip Patch Antenna with Microstrip Line Feed

The antenna was simulated at a centre frequency of 1.5 GHz over the frequency range 1-2 GHz using HFSS 13.0

software. The simulation result of return loss is given in Fig. 3.

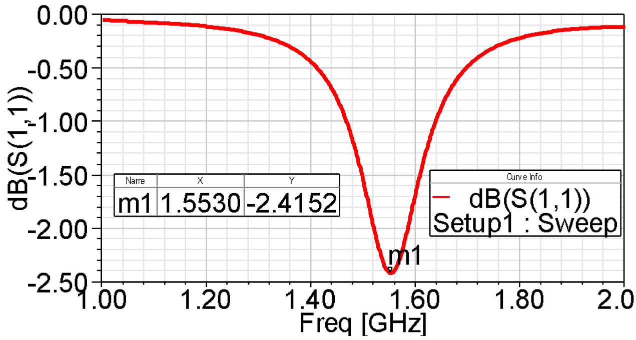


Fig. 3. Return Loss Variation

Based on Fig. 3, the return loss curve did not cross the -9.5424dB point. This indicates an impedance mismatch between microstrip line feed and the radiating patch. In order to improve the impedance matching, an inset feed was introduced. An inset feed of width 1.87cm recessed a distance of 2.48cm from the edge of the patch was used as in Fig. 4.

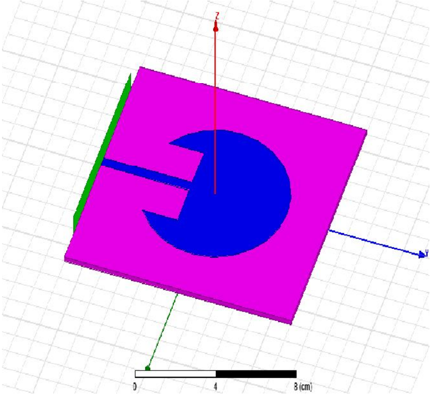


Fig. 4. Circular Microstrip Patch Antenna with Inset Feed

The inset-fed circular microstrip patch antenna was simulated and the simulation results are given in Fig. 5-12.

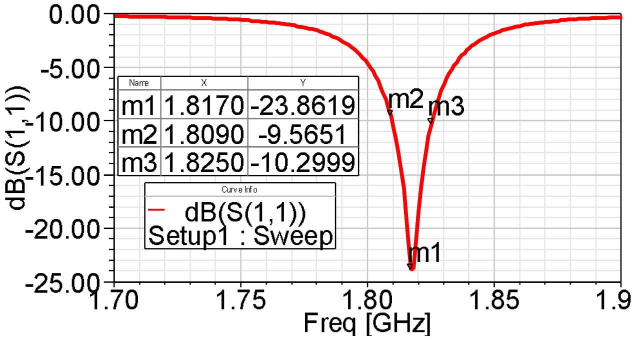


Fig. 5. Return Loss Variation

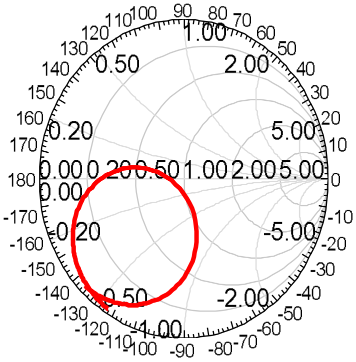


Fig. 6. Impedance Variation

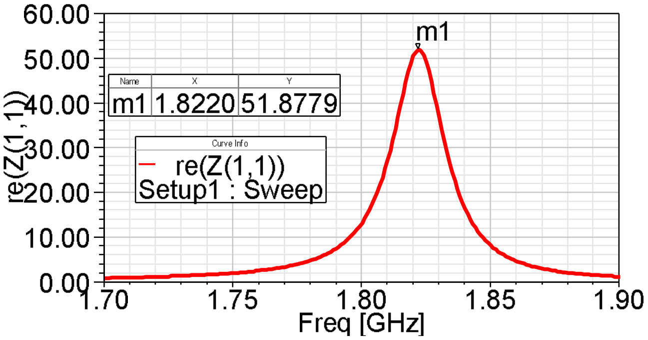


Fig. 7. Input Resistance Variation

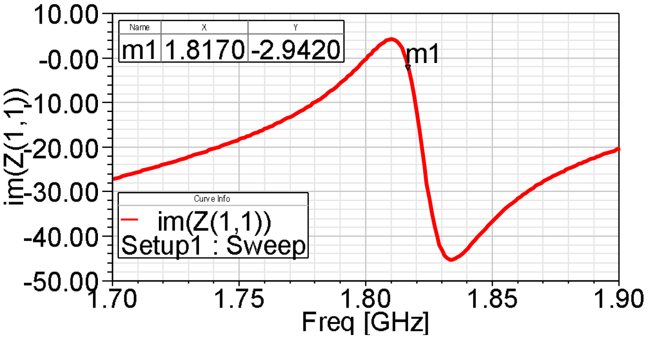


Fig. 8. Input Reactance Variation

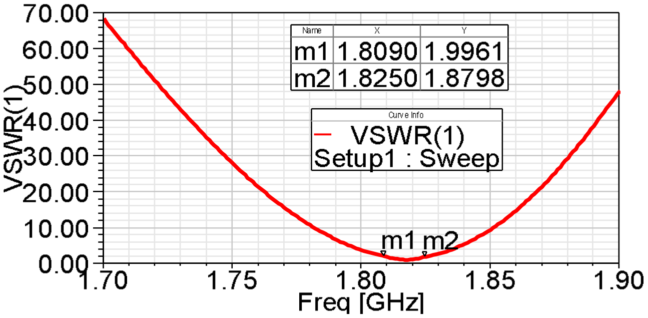


Fig. 9. VSWR Variation

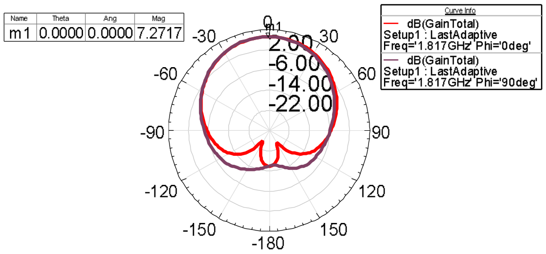


Fig. 10. Radiation Pattern of Gain

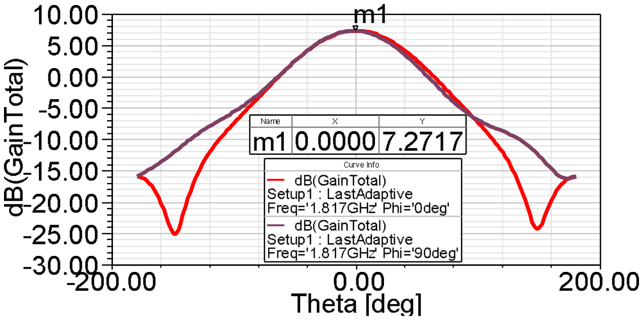


Fig. 11. Gain Variation

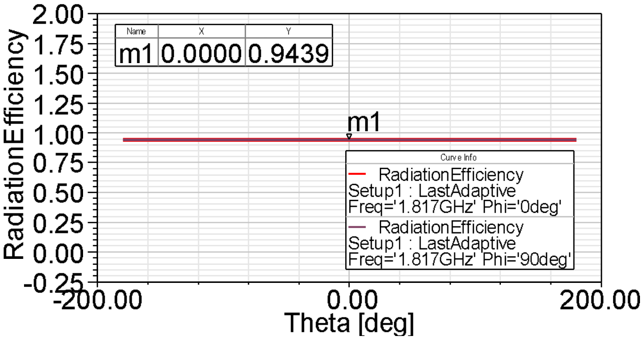


Fig. 12. Radiation Efficiency

With the inset feed, the return loss curve of the antenna crossed -9.5424dB as illustrated in fig. 5. The antenna resonated at 1.817 GHz achieving a return loss of less than -9.5424dB in the frequency range 1.809-1.825 GHz. The antenna achieved an absolute bandwidth of 16 MHz representing 0.8806% of the resonant frequency. The shift in the resonant frequency from the 1.5 GHz used in the design is associated with the fact that HFSS 13.0 which is based on full wave model is more accurate than the cavity model in which the design equations of circular microstrip patch antennas is based.

The input resistance of the antenna at 1.817 GHz was 51.8779Ω while the input reactance was -2.942Ω as reflected in fig. 7 and 8 respectively. Based on fig. 9, the antenna achieved a VSWR of less than 2 over the bandwidth. Fig. 10 and 11 show that the gain of the antenna at 1.817 GHz was 7.2717dB at $\theta, \varphi = 0°, 0°$ direction (where $\theta, \varphi = 0°, 0°$ is the direction normal to the center of the radiating patch). 99.59% of the incident power was accepted by the antenna out of which 94% was radiated giving radiation efficiency of 94.39% indicated in Fig. 12.

3.2. Modified Circular Microstrip Patch Antenna.

The main aim of this study was to improve the impedance bandwidth of a circular microstrip patch antenna through shape modification. A number of researchers have improved the impedance bandwidth of microstrip patch antennas through shape optimization. Each of the researchers employed the addition of different shapes and/or subtraction of different shapes in the process. In this study, addition of two arcs, subtraction of two arcs and subtraction of two rectangles of appropriate dimensions resulted in the most optimal shape.

In contrast to the circular microstrip patch antenna designed in section 3.1, the modified circular microstrip patch antenna was designed on RT/Duroid 5880 substrate of height 0.7875cm rather than the standard height of 0.1575cm. The design frequency was maintained at 1.5 GHz. Applying these parameters and dielectric constant of 2.2 in the design equations of circular microstrip patch antennas (equations 1 & 2), the radius of the initial circular patch was found to be 3.6cm.

The shape of the initial circular microstrip patch antenna was then optimized to achieve a wide bandwidth. In the process of optimization, two arcs were added to the initial circular patch. This was achieved in the simulation by drawing two circles each of radius 2cm positioned at coordinates (-2.6cm, 0cm) and (2.6cm, 0cm) with the centre of the patch reference at coordinate (0cm, 0cm) and uniting them to the initial circular patch. Two arcs were also subtracted from the initial circular patch. This was achieved in the simulation by drawing two circles each of radius 1.6cm positioned at coordinates (0cm, -4.6cm) and (0cm, 4.6cm) with the centre of the patch reference at coordinate (0cm, 0cm) and subtracting them from the initial circular patch. These adjustments were made so as to come up with a radiating patch of different radii and thus a possibility of achieving more than one resonant frequency. The shape of the radiating patch that was achieved was as shown in Fig. 13.

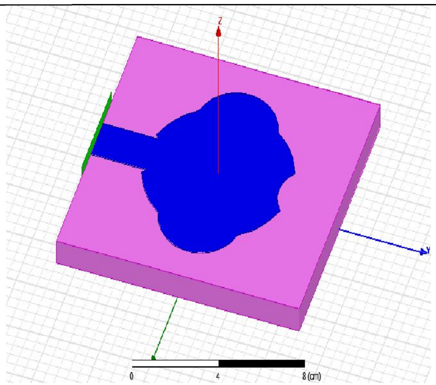
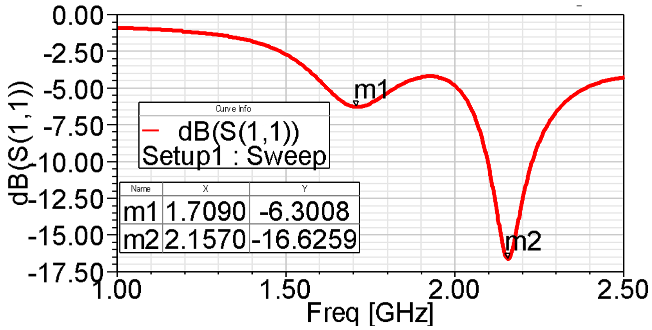


Fig. 13. Modified Circular Microstrip Patch Antenna 1

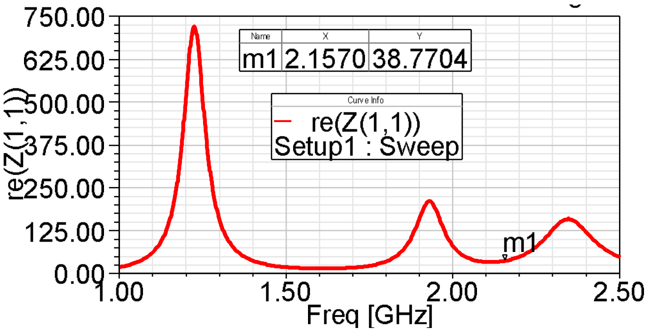
The dimensions of the substrate were 12cm×12cm×0.7875cm. The antenna was fed by a microstrip line feed of width 1.8cm. The dimensions of the waveport were 4.4cm×1.73cm.

When the antenna of Fig. 13 was simulated, the simulation results are shown in Fig. 14 and 15.



Name	X	Y
m1	1.7090	-6.3008
m2	2.1570	-16.6259

Fig. 14. Return Loss Variation



Name	X	Y
m1	2.1570	38.7704

Fig. 15. Input Resistance Variation

Based on Fig. 14, antenna of fig. 13 indicated two resonant frequencies. The one at 2.157 GHz cross -9.5424dB point while the one at 1.709 GHz did not. Despite the fact that the return loss crossed -9.5424dB at 2.157 GHz, there was a mismatch between the input impedance of the antenna at this point and a 50Ω transmission line as reflected in Fig. 15. Efforts were therefore made to make the two resonant frequencies of Fig. 14 overlap so as to achieve a wide bandwidth while at the same time improving the impedance matching. In the process, two rectangles were subtracted from the antenna of fig. 13. One was positioned at coordinate (-2cm, -0.5cm) and had a length of 4cm and width of 1.2cm. The other one was positioned at coordinate (-3.3cm, -4cm) and had a length of 2.6cm and width of 1.8cm both with the centre of the patch reference at coordinate (0cm, 0cm). The shape of the radiating patch that was achieved is shown in Fig. 16.

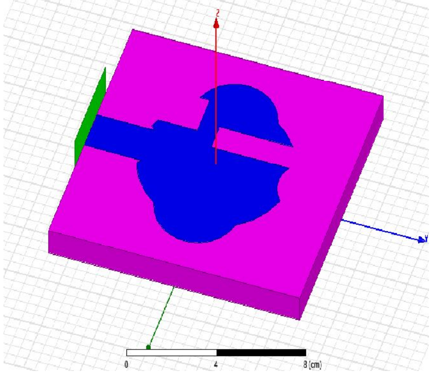
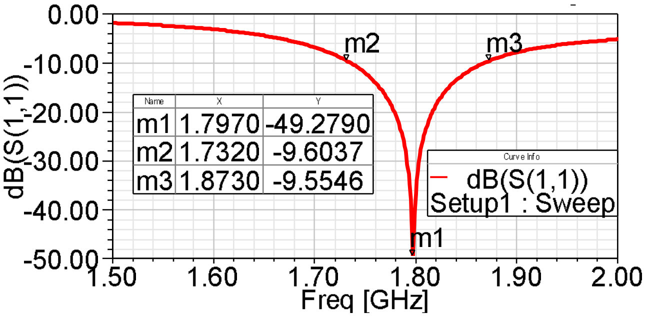


Fig. 16. Modified Circular Microstrip Patch Antenna 2

Antenna of Fig. 16 was analyzed over the frequency range 1-2 GHz and the simulation results are given in Fig. 17-24.



Name	X	Y
m1	1.7970	-49.2790
m2	1.7320	-9.6037
m3	1.8730	-9.5546

Fig. 17. Return Loss Variation

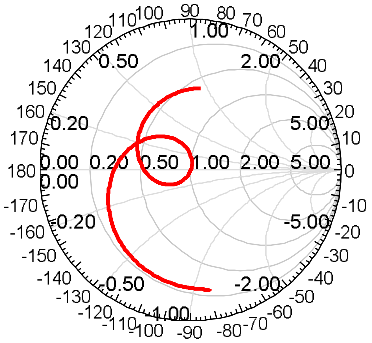


Fig. 18. Impedance Variation

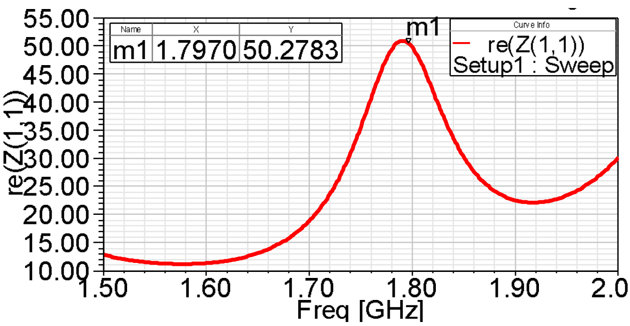


Fig. 19. Input Resistance Variation

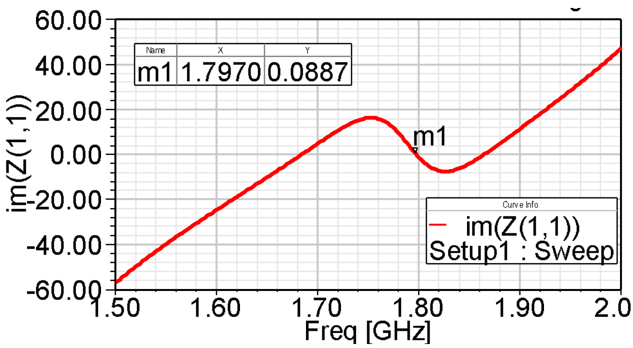


Fig. 20. Input Reactance Variation

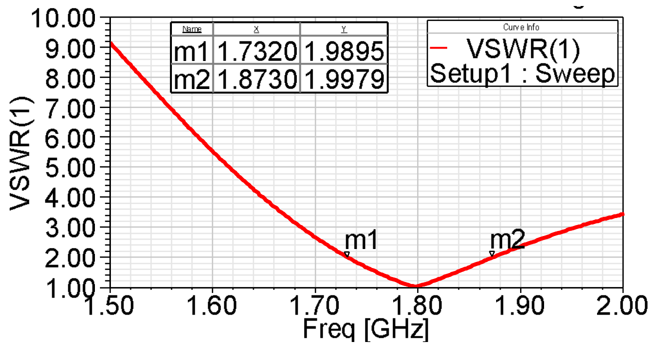


Fig. 21. VSWR Variation

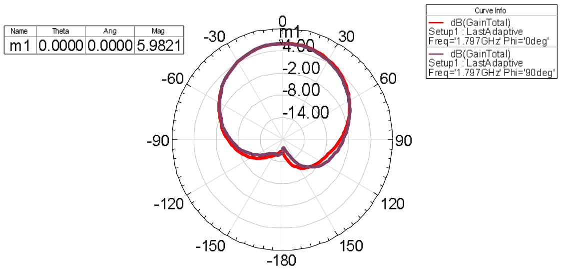


Fig. 22. Radiation Pattern of Gain

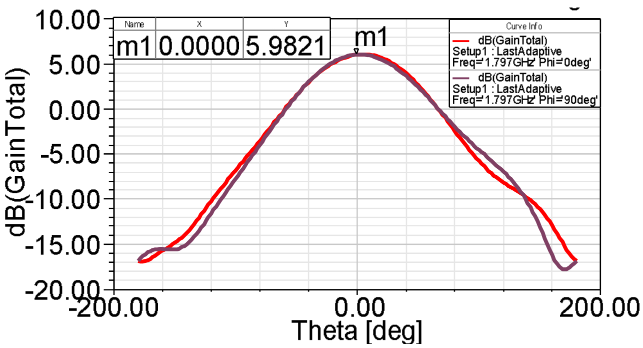


Fig. 23. Gain Variation

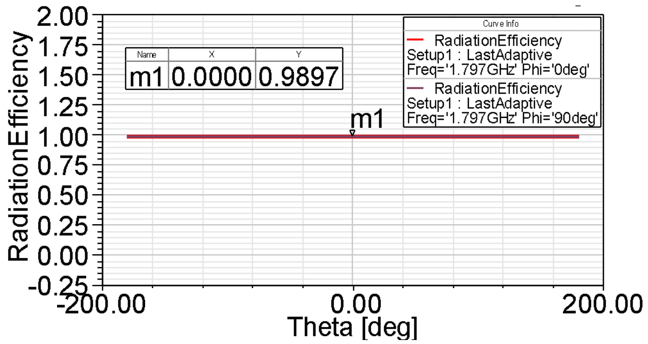


Fig. 24. Radiation Efficiency

Based on Fig. 17, the two resonant frequencies of Fig. 14 indeed overlapped with the introduction of the two rectangular slots thus producing a wide bandwidth. The antenna resonated at 1.797 GHz. The shift in the resonant frequency is associated with shape modification and the fact that the design equations of circular microstrip patch antennas (equations 1 and 2) are based on cavity model which is less accurate than full wave model in which HFSS 13.0 is based. The antenna achieved a return loss of less than -9.5424dB in the frequency range 1.732-1.873 GHz achieving a bandwidth of 7.846% of the resonant frequency. The input resistance of the antenna at the resonant frequency was 50.2783Ω while the input reactance was 0.0887Ω as indicated in fig. 19 and 20 respectively. Based on Fig. 21, the antenna achieved a VSWR of less than 2 over the bandwidth. The gain of the antenna at the resonant frequency was 5.9821dB at $\theta, \varphi = 0°, 0°$ as indicated in Fig. 22 and 23. 100% of the incident power was accepted by the antenna out of which 98.97% was radiated giving radiation efficiency of 98.97% indicated in Fig. 24.

Further analysis of the antenna of Fig. 16 was carried out by extending the frequency range up to 20 GHz. Based on Fig. 25, the antenna also achieved return loss of less than -9.5424dB in the frequency range 3.86-20 GHz recording a number of resonances. The VSWR of the antenna was also less than 2 over this frequency range as indicated in Fig. 26.

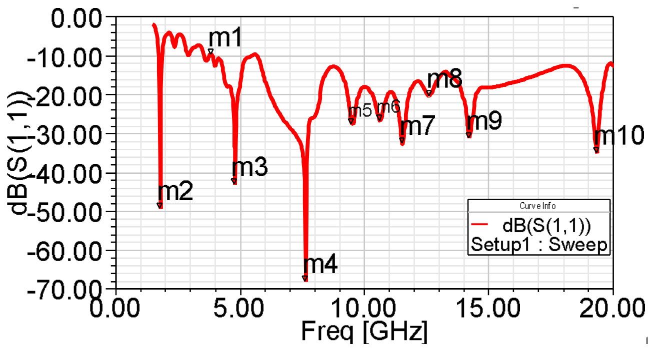
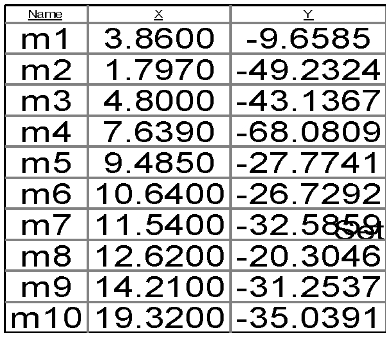


Fig. 25. Return Loss Variation

Where



Name	X	Y
m1	3.8600	-9.6585
m2	1.7970	-49.2324
m3	4.8000	-43.1367
m4	7.6390	-68.0809
m5	9.4850	-27.7741
m6	10.6400	-26.7292
m7	11.5400	-32.5859
m8	12.6200	-20.3046
m9	14.2100	-31.2537
m10	19.3200	-35.0391

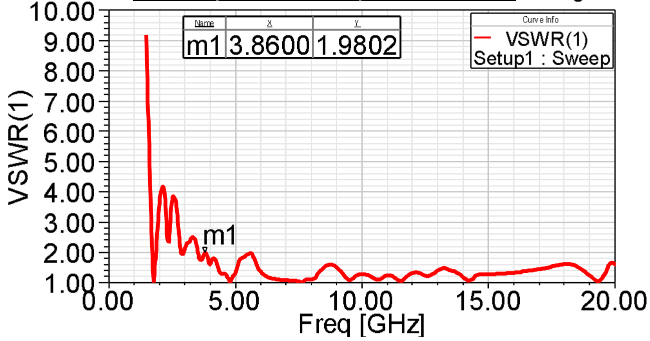


Fig. 26. VSWR Variation

The impedance matching of the antenna was investigated in the frequency range 3.86-20 GHz around the resonant frequencies indicated in Fig. 25 and it was found that the antenna achieved a good impedance matching with a 50Ω transmission line at 4.83 GHz and with a 75Ω transmission line at 7.346 GHz, 9.633 GHz, 11.198 GHz, 12.646 GHz, 14.382 GHz and 19.073 GHz. The radiation properties of the antenna at these frequencies are summarized in Table 1.

4. Conclusions

The modified circular microstrip patch antenna 2 developed in this study recorded a remarkable improvement in impedance bandwidth when compared with the impedance bandwidth of a conventional circular microstrip patch antenna and those of existing literature. The antenna also achieved better radiation efficiencies and better gains in all the resonant frequencies when compared with the control results of the conventional circular microstrip patch antenna except at 1.797 GHz where the antenna experience a slight decrease in gain. The antenna achieved an impedance bandwidth of 141 MHz (7.846%) at 1.797 GHz and a very broad impedance bandwidth of 16.14 GHz (898.16%) from 3.86-20 GHz giving total impedance bandwidth of 16.281 GHz. The total impedance bandwidth achieved is greater than the maximum value of 5.5 GHz that was achieved by Shi et al. using the same method. The antenna recorded good impedance matching with a 50Ω transmission line at 1.797 GHz and 4.83 GHz and with a 75Ω transmission line at 7.346 GHz, 9.633 GHz, 11.198 GHz, 12.646 GHz, 14.382 GHz and 19.073 GHz achieving gains of 5.9821dB, 8.4615dB, 9.5274dB, 9.169dB, 8.8842dB, 10.1685dB, 9.8087dB and 11.1218dB respectively. The antenna achieved radiation efficiency of 98.97% at 1.797 GHz and radiation efficiencies of 100% in the other frequencies. The antenna is suitable for wide range of applications because of its wider bandwidth.

Table 1. Radiation Properties of the Antenna in the frequency range 3.86-20 GHz.

Resonant frequency (GHZ)	Optimized waveport size	Input impedance		VSWR	Maximum gain (dB)	Incident power	Accepted power	Radiated power	Radiation Efficiency (%)
		Input Resistance	Input Reactance						
4.83	3.95cm × 1.13cm	51.4986	5.3528	1.1145	8.4615	1	0.9974	0.9974	100
7.346	4.86cm × 1.13cm	75.0136	0.0416	1.0019	9.5274	1	1	1	100
9.633	3.6cm × 1.13cm	76.1753	-1.0221	1.0211	9.169	1	0.9999	0.9999	100
11.198	3.631cm × 2.05cm	74.9481	0.0019	1.0109	8.8842	1	1	1	100
12.646	3cm × 1.13cm	74.2142	-0.2979	1.013	10.1685	1	1	1	100
14.382	2.52cm × 1.13cm	79.1137	0.9409	1.0541	9.8087	1	0.9991	0.9991	100
19.073	1.9252cm × 1.13cm	74.9917	-2.2055	1.0303	11.12 18	1	0.9998	0.9998	100

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