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Design, Simulation and Measurement of Triple Band Annular Ring Microstrip Antenna Based on Shape of Crescent Moon

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Abstract

In this paper a novel structure of an annular ring patch microstrip antenna based on Shape of Crescents Moon (SCMs) is designed, simulated and measured to operating with multiband applications. It is different parameters such as input impedance, return loss, gain, surface currents and radiation patterns were studying. This design consists of five SCMs in different sizes. Three of SCMs are arranged inside the annular ring patch and the others two are located outside. It is found that the proposed antenna possess triple band frequency which signify the multiband and compactness of antenna. The fabricated antenna is resonating at threefrequencies11.30, 18.07 and 20.72 GHz. This design is simulated using Ansoft High Frequency Structure Simulator (HFSS) and it compared with the obtained measurement data. Interestingly, the comparison results are in good agreement. The bandwidths of measured return loss at -10 dB corresponding with the X-, Ku- and K-bands frequencies which are 474, 620 and 810 MHz, respectively. Also, the antenna designed is useful for many services operations at these bands frequency and it is applications.

Keywords: microstrip antenna, annular ring patch, multiband, triple band, X-band, HFSS.

1. Introduction

The communications become necessary in the modern world and the antennas become like the electronic eyes and ears of the world. Therefore, antennas occupy an important place in the communication technology [1-2]. Moreover, communication systems are rapidly growing due to the engineering revolution in the field of antennas and materials technology. Microstrip antennas (MSAs) are one of the most innovative developments in the field of size reduction of the microwave circuits and therefore and devices [3]. The applications of MSAs are broadly and increasingly used in a wide range of microwave systems from navigation, telemetry, radars, mobile, satellites communications, global positioning system for remote sensing, biomedical systems, and missile systems, etc. due to their unique characteristics such as: low cost, low profile, light weight, low volume, ease of fabrication and integration with the other components [4-5].Since 1950s the MSAs have been investigated. Moreover, due to the unique characteristics of the MSAs, these antennas played more and more significant role [6]. The researchers of MSAs have been suggested different shapes of these antenna's patches to obtain wideband, multi-band and miniaturization due to the rapid development of the antenna technology and substrate materials used in the wireless communication [7]. In addition to that, there are various techniques are used to obtaining dual-band frequency and good radiation parameters such as: multi-layers of dielectric substrate, stacked patch antenna, cutting slots in the conducting patch or ground plane and planar meta-loop antenna [8-9]. Furthermore, there are several approaches used to facilitate the multi-band operations, such as the embedding slots with different shaped in conducting parts (patch or ground plane). The performance of MSA is improving by using the metamaterials which have been proposed as a type of artificially structured media [10–16]. Split ring resonator is widely used in magnetic metamaterials as a basic unit cell for antenna miniaturization and multi-band applications [17-19].

In the modern systems of wireless communication, the multiband antennas have received wide interests. Interestingly, the numbers of required antennas can be reduced by using patch multiband antennas [20-21]. Therefore, the recent studies of the multiband applications are trying to design a single antenna instead of multiple antennas to obtain size reduction. The researchers have been designed novel structures of the MSAs which have triple band features, especially in X-, Ku- and K-bands. In wireless communication systems, MSAs at X-, Ku- and K-bands are widely used for point-to-point like as industrial scientific medical, imaging radar satellite communication and on air traffic. X-band application has broad area in the fields of radio location, mobile, satellite, etc., and the Ku- and K-band are firstly used for broadcasting satellite television and radar. Nowadays, the researches in the field of MSAs are largely confirming in the X, Ku, and K bands [22-29]. Triple band antennas, however, may provide an alternative to larger bandwidth by facilitating three services in same antenna using different techniques as suggested [30-31]. Such services are needed to operate at separate transmit-receive bands. The operation at two or more bands is desired feature, apart from compactness. In multiservice systems, to avoid the cases of multiple antenna installations or the lack of space is determinant constraint the multiband or wideband antennas are needed [32-34].

Basically, the conventional structure of MSAs consists of a metallic radiating patch element that is on top of a grounded dielectric substrate of specified thickness. On the other side this substrate has a ground plane of metal. Usually, the conducting patch and the source of feed line are photo etched on the dielectric substrate [35]. Generally, the patch is made from copper, gold or any conducting material that's has a good conductivity. The shape of the conducting patch may be of various shapes, the most common shapes are rectangular, circular and annular ring. The size of the annular ring microstrip antenna (ARMSA) when it operates at the dominant TM_{11}-mode for a given frequency will be smaller than rectangular or circular patch. This feature plays very important role in the application of array designs by allowing the antenna elements to be more densely packed and caused a reduction in the grating-lobe problem. Therefore, the researchers give this type of antenna more attention in any space saving applications [36-37].

In this study, we propose a compact MSA design for triple band applications by introducing the ARMSA which contains five SCMs in different sizes. Three of SCMs are loading inside the annular ring patch (ARP) while the other two of SCMs are loading outside ARP. The triple band features of the proposed patch antenna make it appropriate for X-, Ku- and K- band applications. These applications are radar communication systems, satellite communication, medical applications, reception of TV signals and other wireless systems [26].

2. Antenna Design

Radiating patch is the main part of the antenna affecting antenna performance through changing impedance matching, bandwidth and radiation pattern, as well as surface current distribution. Different shapes of patch antennas are used to improve the conducting patch performance in antennas. However, we attempted to find more effective and simple ways to achieve desired results. A simple ARP has been assumed as a start point of the new patch design. Then, five SCMs in various sizes have been loading inside and outside ARP to create the proposed antenna. This antenna has been simulated by using the commercial tool Ansoft High Frequency Structure simulator (HFSS). This software is used for solving the problems of mathematical physics and engineering and is based on the finite element method and method of moments. Step by step the geometry design of the proposed antenna is shown in Fig. 1: a) ARMSA, b) one of SCM is loaded inside ARP, c) two of SCMs are loaded inside ARP, d) and e) three of SCMs are loaded inside ARP without and with slits between them, respectively, f) and g) two more SCMs are loaded outside ARP to mentioned designs in Fig. 1(d) and (e), respectively, finally, h) five of SCMs are loaded to the ARMSA with slits between all SCMs.

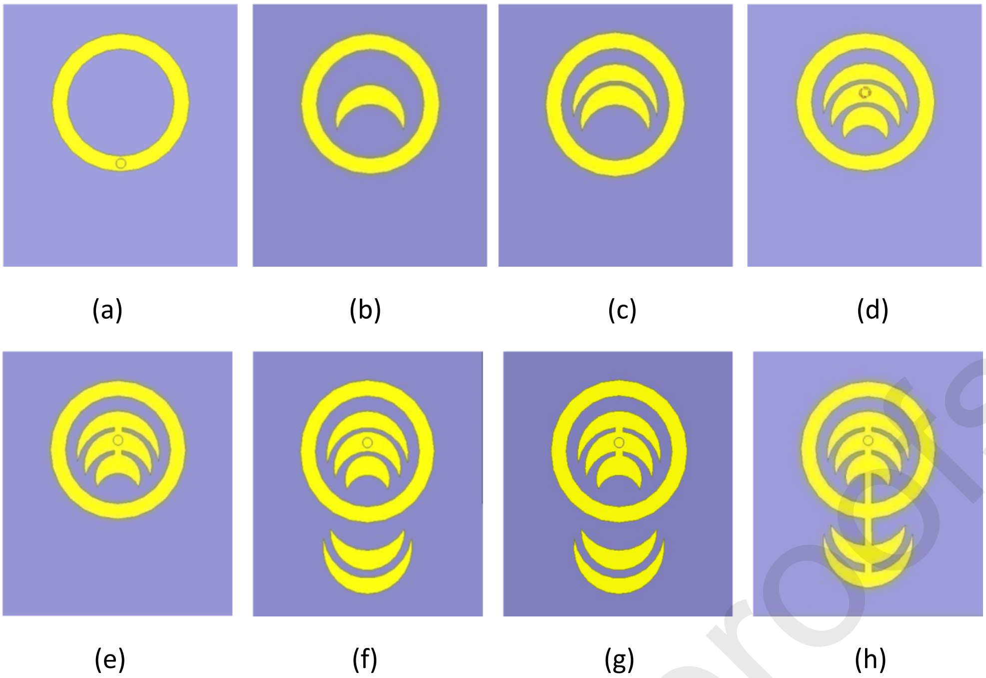


Fig. 1. Steps to choosing the proposed antenna.

The proposed antenna of Fig. 1(h) is selected as the optimum design due to the good simulation results of return loss and radiation pattern were found, as shown in the next section. By using the HFSS software the dimensions of the antenna designed are optimized, parameterization study, based on the basis of the best performance, as shown in Fig. 2. This antenna is fabricated on a cost-efficient FR4 substrate (Rogers (RO4003)) of size 35×31mm^2, dielectric constant of ε_r=3.55, loss tangent of 0.0027 and thickness of 1.6mm.ARP having inner radius, R_i= 14 mm and outer radius R_o = 16 mm, while the ground plane has the size 35×31mm^2. The feeding of the designed antenna is a coaxial line and the good impedance matching has been obtained by optimum selection of the dimensions for this antenna and the point of the feed location. Hence, the feed location was selected at x_f=-5.8 mm and y_f=0.0 mm with typical impedance value 50.0Ω which based on the matching process. The radii of the coaxial probe are r_o=2.05 mm (outer radius) and r_i=0.635 mm (inner radius).

To obtain triple bands and best return loss value with a good efficiency value, Fig.2shows the geometrical of antenna designed. While, Table 1 illustrates the dimensions and parameters that have taken to design and fabricate the proposed antenna. The proposed antenna has been fabricated and tested at Antenna Type Approval Laboratory in University of Tehran. Fig. 3 depicted the antenna designed and fabricated of the proposed antenna.

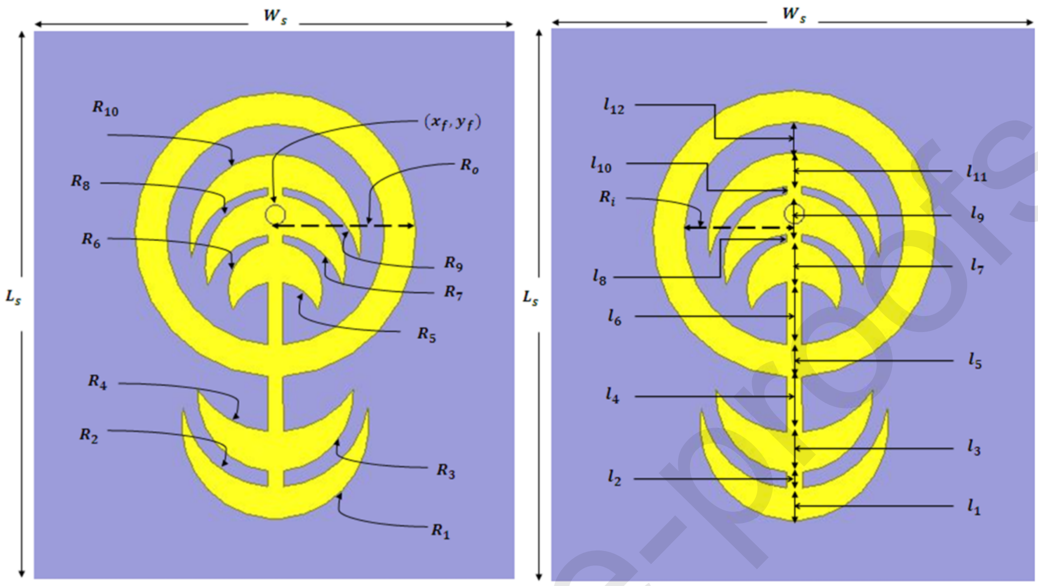


Fig. 2. Geometrical of the antenna designed.

(a) (b) (c)

Fig. 3. Proposed antenna (a) antenna designed, (b) prototype top view and (c) bottom view of fabricated antenna designed

Table 1 Dimensions of the antenna designed (all dimensions in mm).

parameters	Dimension	parameters	Dimension
L_s	35.0	R_{10}	18.52
W_s	31.0	l_1	2.0
R_i	14.0	l_2	1.0
R_o	16.0	l_3	2.5
R_1	18.84	l_4	3.6
R_2	18.21	l_5	2.0
R_3	15.70	l_6	3.9
R_4	15.12	l_7	2.5
R_5	9.15	l_8	0.6
R_6	9.73	l_9	2.5
R_7	16.92	l_{10}	0.6
R_8	17.90	l_{11}	2.1
R_9	17.95	l_{12}	1.8

2. Results and Discussion

In this study, the design of a single antenna instead of multiple antennas for multiband applications is presented. The proposed antenna geometry is shown in Fig. 2 which has been designed and fabricated to resonate in X-, Ku- and K-bands frequency. Therefore, this antenna has triple band features. A compact MSA design has been proposed and fabricated by introducing the ARMSA that contains three of SCMs in different sizes are loading inside ARP and two of SCMs are loading outside ARP. The proper sizes of SCMs, distances between these shapes, and the edges of ARP produce the proper phase reversal in surface currents. Therefore, the desired radiation patterns at the designed frequencies are obtaining by the proper choosing of phase reversal in surface currents. An improved performance of the proposed antenna has been obtained according to the simulation results of the return loss. It can be explained in a way that, embedding five of SCMs changes the surface current path, contributing to better impedance matching.

The proposed antenna has been simulated by using the commercial tool Ansoft HFSS as shown in Fig. 2. The antenna is fabricated on a cost-efficient FR4 substrate (Rogers (RO4003)) of size 35×31mm^2, dielectric constant of ε_r=3.55 and thickness of 1.6mm fed by a 50.02 Ω coaxial feed line as shown in Fig.3. The dimensions of the antenna designed are illustrates in Table 1.

The proposed antenna of Fig. 1(h) is selected as the optimum design due to the good simulation results of return loss, as shown in the Fig. 4. This figure contains a brief summary of selected results for the return loss which belong to several designs in Fig. 1.The features of simulated return loss of the designed antennas in Fig. 1 (a), (d), (g) and (h), are shown in Fig. 4.It is observed that the prototype antenna shows multiband resonance at 11.30 GHz, 17.97 GHz and 20.70 GHz. These results are confirmed by fabrication the proposed antenna.

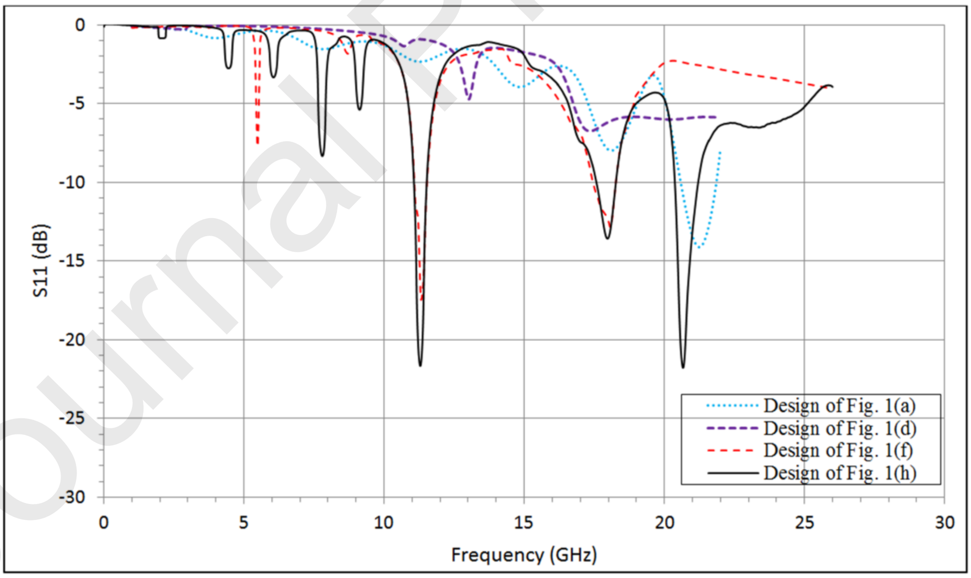


Fig. 4. Simulation results of return loss for proposed antennas in Fig. 1 (a), (d), (g) and (h)

Parametric study is carried out on the return loss features for the various dimensions and positions of the five SCMs and different coaxial feed position on the proposed antenna performance. To confirm good impedance matching, the coaxial feed position is studied on

ARP and five SCMs from the center patch position. The characteristic impedance 50Ω is obtained when the coaxial feed position located at the point of coordinate (x_f=-5.8,y_f=0.0) mm, as shown in Fig. 5. This point is located at the center of the middle of SCM which is located inside ARP. Hence, the triple resonance with better impedance matching is obtained by choosing the dimensions that depicted in Table 1.

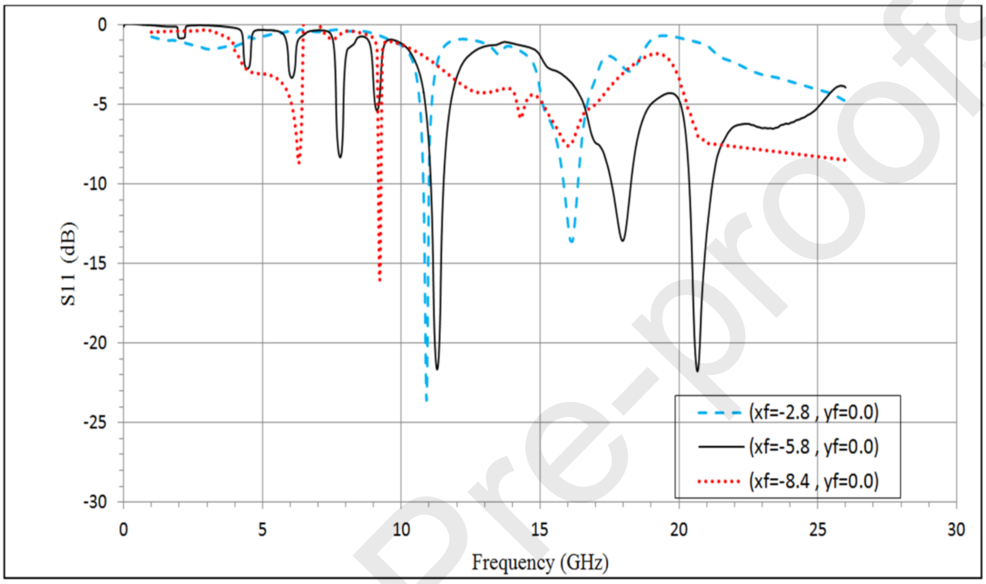


Fig. 5. Simulation findings of return loss characteristics of various coaxial feed positions.

To optimize the proposed antenna performance the other parametric study on the slit dimensions *l*2, *l*4, *l*6, *l*8 and *l*10 is done, as shown in Fig. 6. As a result, the electric resonance is produced with slits for generate a new resonance frequency at 20.70 GHz and increase the bandwidth with 832 MHz and return loss value -21.78 dB.

The simulation values of return loss have compared with the measurement values as shown in Fig. 7. Table 2 illustrates a good agreement of the simulation and measurement values of the return loss. The measured data displays a triple band with impedance bandwidth of 474 MHz (11.112−11.586 GHz), 620 MHz (17.748−18.368 GHz), and 810 MHz (20.405−21.215 GHz) at the resonance frequencies 11.30 GHz, 18.07 GHz and 20.72 GHz, respectively. The present study showed that the third frequency band has a large value of the impedance bandwidth compare with the first and second frequency bands. Therefore, the proposed antenna has three impedance bandwidths that are located within X, Ku, and K-band. These bandwidths are quite useful for X, Ku, and K-applications.

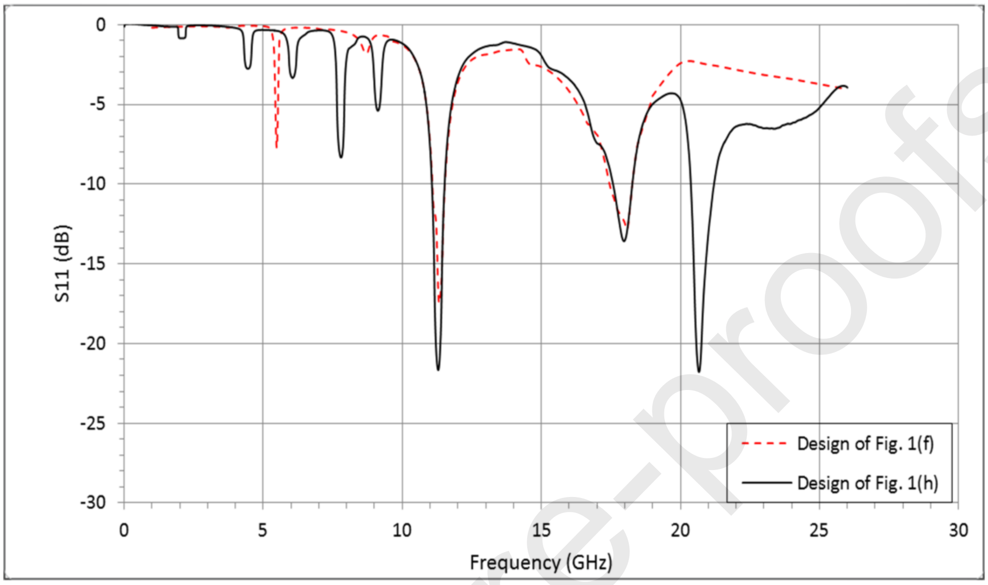


Fig. 6. Effects of slits on the simulated return loss features of designed antenna.

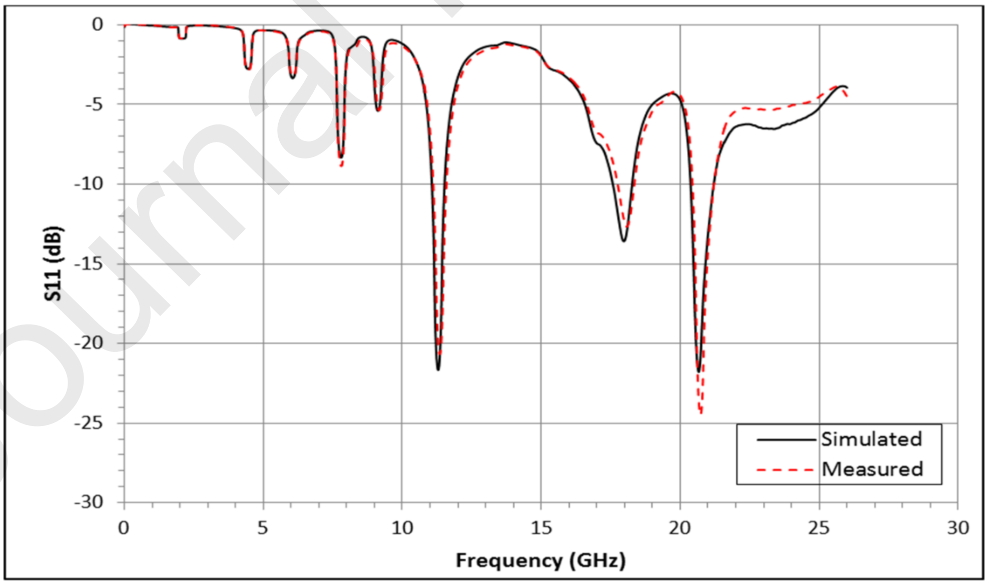


Fig. 7. Simulated and measured return loss features of proposed antenna.

Table 2 Comparison of the return loss features of simulated and measured values of the antenna designed.

Proposed antenna	Resonant frequency (GHz)	Return loss (dB)	Bandwidth (MHz)
Simulated	11.30	-21.70	456
	17.97	-13.58	695
	20.70	-21.78	832
Measured	11.30	-21.66	474
	18.07	-12.68	620
	20.72	-24.48	810

The definition of antenna gain is how much the transmitted power in the trend of high radiation. To characterize this, Table 3 depicts the simulated and measured gain of the proposed antenna. This table shows the measured gain around 7.11 dB, 6.53 dB and 8.96 dB gain in the first, second and third resonance frequencies, respectively. Hence, the proposed antenna provides accepted values of the antenna gain.

Table 3 Gain values of the triple band of antenna designed.

Proposed antenna	Resonant frequency (GHz)	Gain (dB)
Simulated	11.30	7.05
	17.97	6.60
	20.70	9.94
Measured	11.30	7.11
	18.07	6.53
	20.72	8.96

Fig. 8 shows the simulation results of the input impedance for proposed antenna as a function of frequency feature. It can be observed from this figure that the simulated input impedance values are very close to 50 Ω impedance of coaxial feed line. These values are 50.02, 48.81 and 49.64 Ω at the frequencies 11.30, 17.97 and 20.70 GHz, respectively.

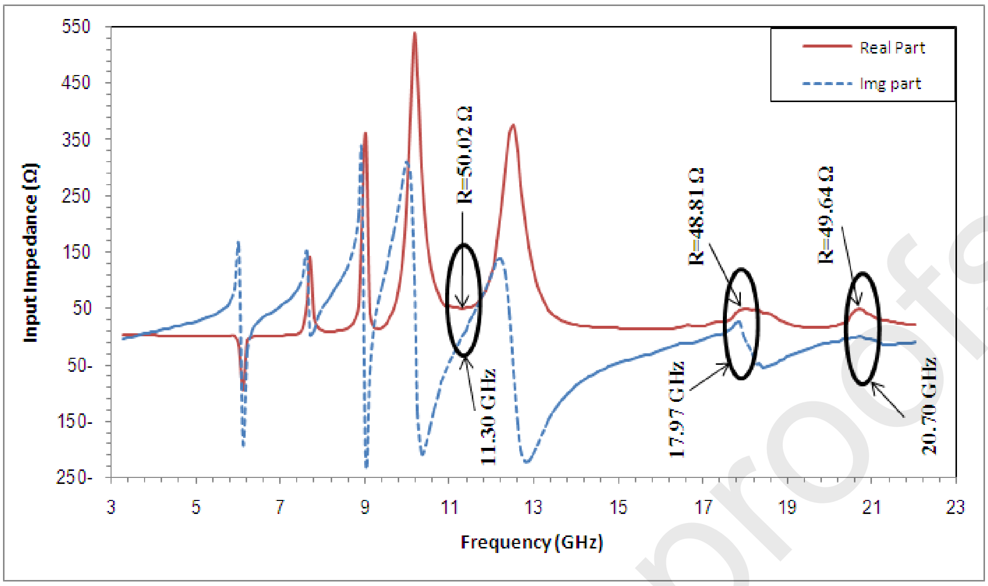
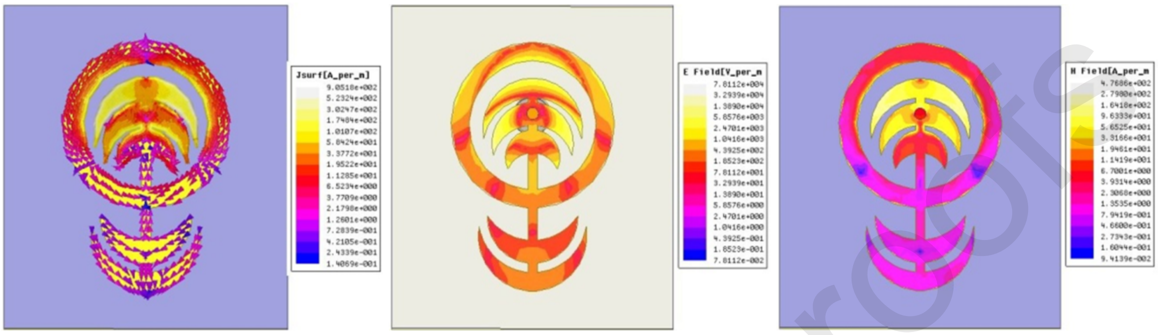


Fig. 8. Simulation results of the input impedance for proposed antenna.

The results of X-, Ku- and K-bands that belong to the electric surface current density, electric and magnetic fields and radiation patterns have same manners and good results. A brief summary of X-band results was chosen to present in this study. Fig. 9 shows the simulations of the surface current distributions, electric and magnetic fields on novel patch of proposed antenna at the resonance frequency 11.30 GHz. Fig. 9(a) shows the current distribution on ARP structure possesses three half-wavelength variations in current, each one on the one third of ARP. However, it can be found that ARP has variations in the current with three half-wavelengths, as three 120^o sectors on ARP. It is seen from Fig. 9(a) that the surface current density is concentrated at the upper half of ARP and on the first and second of SCMs which inside ARP and become low around the connection feed. Also, the antenna current distributes with more symmetrical manner on the outer SCMs and the lower half of ARP that next to outer SCMs. The electric and magnetic fields distribution on ARP at X-band frequency are shown in Fig. 9(b) and (c). Increased electric and magnetic fields variations will results causing surface currents, as in Fig. 9. In proposed antenna design, the electric and magnetic fields confirm the behavior of the associated surface currents. Thus, at some points on ARP, currents will be in phase and then will give maximum radiation, while at the other points will be out of phase and will give minimum radiation.



(a) Surface currents (b) Electric field (c) Magnetic field

Fig. 9. Surface currents, electric and magnetic fields on the patch of proposed antenna.

Simulated and measured results of radiation patterns of the proposed antenna at resonance frequency 11.30 GHz are shown in Fig. 10. Simulated results of radiation patterns in three and two dimensions are illustrated in Fig. 10(a) and (b), respectively. It is shown from Fig. 10(b) that the half power beam width in the principle planes E- and H-planes are 48^o and 42^o, respectively. While the measured results of the radiation patterns in the principle planes E- and H-planes are shown in Fig. 10(c)-(f), in Cartesian and polar coordinates. The half power beam width in E- and H-planes at 11.30 GHz are 56^o and 60^o, respectively. The maximum and minimum powers in the principle planes are -69.99/-104.92 dBm and -70.99/-105.55 dBm, respectively. Furthermore, the radiation patterns characteristics of the proposed antenna are desired for wireless applications.

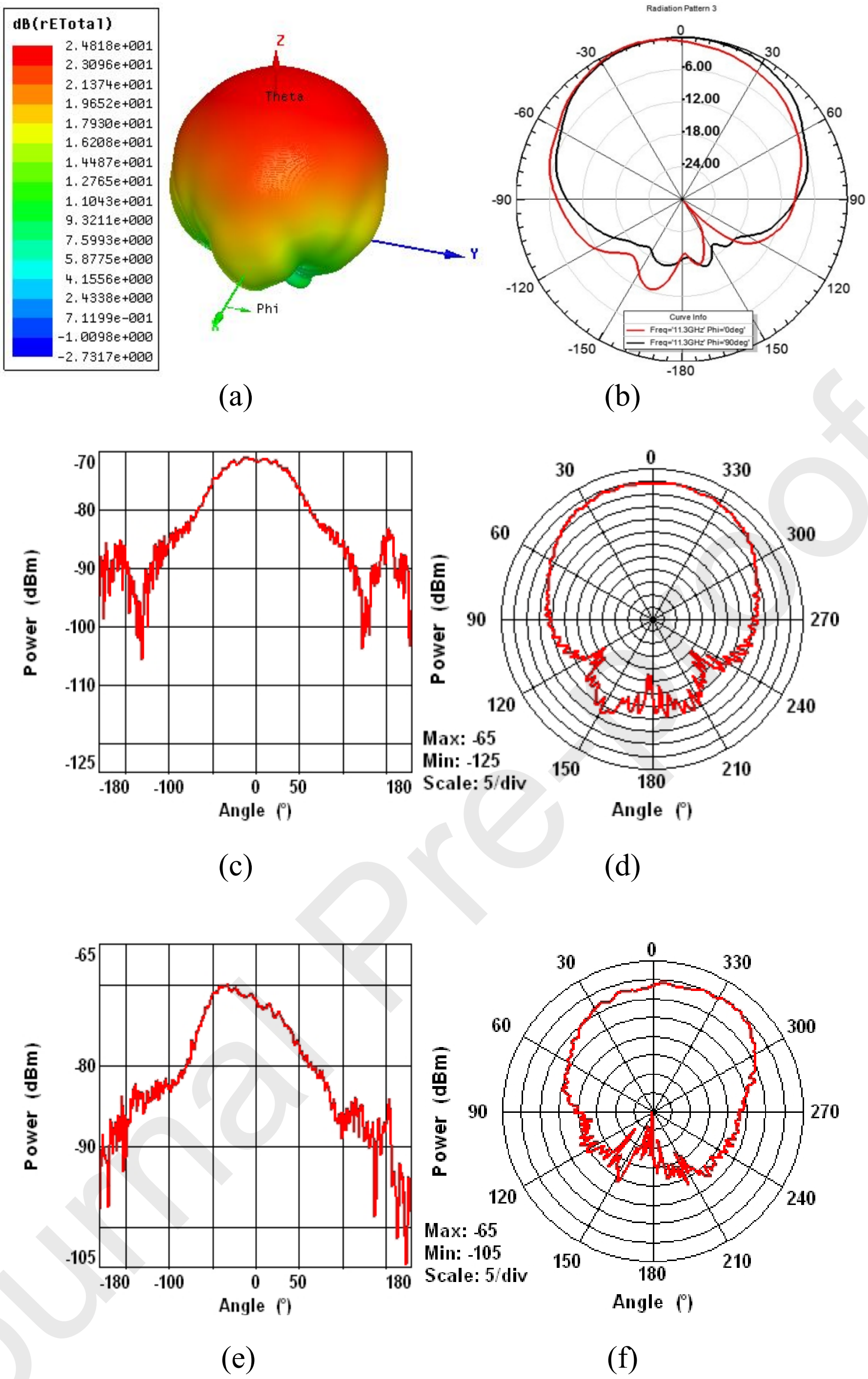


Fig. 10. Simulated and measured results of radiation patterns of the proposed antenna.

4. Conclusions

An ARMSA loaded with five SCMs is proposed for multiband applications, with a small size of 35 ×31 ×1.6 mm^3. Hence, the optimum dimensions and positions of these SCMs are used to obtain good impedance matching. The new patch antenna is able to produce new resonance frequencies. Triple band features of the proposed antenna are obtained by loaded SCMs. The proposed antenna has been designed, simulated and fabricated and its return loss and radiation patterns features are measured. The simulated and measured findings agree with one another. Due to measured values of triple band characteristics, small size and symmetric radiation patterns, the proposed antenna is desirable for X-band (11.112−11.586 GHz), Ku-band (17.748−18.368 GHz) and K-band (20.405−21.215 GHz) applications.

Author Contributions

Wa'il Al-Tumah and Raed Shaaban conceived of the presented idea, developed the simulation and performed the computations. Akeel Tahir discussed the results. Wa'il Al-Tumah wrote the manuscript and approved the final article.

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Notes

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Abbreviations

SCMs, shape of crescents moon; MSAs, microstrip antennas; ARMSA, annular ring microstrip antenna; ARP, annular ring patch

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Declaration of interests

✓The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- The novel design has three impedance bandwidths located within X, Ku, and K-band
- Radiation patterns characteristics of the proposed antenna are desired for wireless applications
- The new patch antenna provides accepted values of the antenna gain
- A large value of the impedance bandwidth was obtained at K-band