Compact Tri-Band Microstrip Patch Antenna Using Complementary Split Ring Resonator Structure

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Abstract – In this letter, a compact complementary split ring based tri-band antenna is proposed. The proposed antenna resonates at 1.9 GHz (1.70-1.91 GHz), 2.45 GHz (2.23-2.52 GHz) and 3.2 GHz (2.9-3.25 GHz); the input match values are 24.56 dB, 27.21 dB and 22.46 dB, respectively. The antenna's realised peak gain is 4.15 dBm at 1.9 GHz, 4.25 dBm at 2.4 GHz and 4.74 dBm at 3.2 GHz, with approximately 42% of reduction in antenna size. The results demonstrate that the proposed metamaterial antenna is tunable, electrically small and highly efficient, which makes it a suitable candidate for RF energy harvesting. The antenna is numerically and experimentally analysed and validated with very good comparison between the simulated and measured results.

Index Terms – CSRR, patch antenna, radiation pattern, tri-band.

I. INTRODUCTION

In the advancement of wireless communication systems, low-profile interconnecting devices and non-complex proprietary structures are required, often operating in multiband frequencies [1]. L and S Band operating systems, with applications such as 3G (1.9 GHz), WLAN (2.45 GHz) and WiMAX (2.5-2.69 GHz) are size-constrained [2]. Although microstrip patch antennas are required to satisfy these requirements of modern communication systems, general microstrip patch antennas fail due to small bandwidths, radiation inefficiency, and heavy general weights [3]. In order to overcome the limitations of standard microstrip patch antennas, extensive research has been conducted by many investigators in an attempt to realize compact multiband designs [4].

Various methods have been reported to achieve a reduced size of the printed multiband antenna. Metamaterials have been used in designing low-profile multiband antennas [5]. Recent work in literature has shown that rectangular microstrip patch antennas loaded with mender lines facilitate multiband performance, with continuous size reduction [6]. In addition, a small-scale multiband antenna design by U and L strips, with a grounded defected structure to increase the antenna radiation strength and improve impedance simulation ability is shown in [7]. In [8, 9], fractal antennas with a magnitude associated with multiband performance are studied. In recent years, the coplanar waveguide (CPW) feeding approach has attracted a lot of research and development activities, as it improves the performance of multiband characteristics. Employing a single-metallic layer CPW has several advantages such as simple integration of passive and active elements, less dispersion, low cost, less surface waves and good omnidirectional pattern, compared to other feeding techniques [10-13]. Recent surveys introduce many CPW-fed microstrip patch antennas for WLAN and WiMAX applications

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[14-19]. A straight strip of CPW-fed antenna with asymmetrical ring and inverted L strip [14] achieved tri-band frequencies covering WLAN (2.4 GHz, 5.2 GHz, and 5.8 GHz) bands and WiMAX (3.5 GHz, 5.5 GHz) bands. A CPW-fed monopole antenna with a band-notch at 1.4 GHz was described in [15]. Inclusion of open split-ring resonator (SRR) antenna with tri-band metamaterial covering 2.4 GHz, 5.2 GHz and 5.8 GHz (WLAN), 5.5 GHz (WiMAX) and 7.4 GHz (C-band) applications are employed, as in [16]. The role of metamaterials in the development of electrically small antennas, and how the efficiency of antennas is improved, are demonstrated in [17]. In [18], the work demonstrates the electrically small printed monopole antenna with two SRRs to achieve multiple resonance and printed slot antenna using DGS also used to achieve multiband is studied in [20]. In [21], using non-foster active elements increased the bandwidth significantly for SRR-based monopole antenna. However, in [20-29] the individual SRR performances to achieve required resonant frequencies are not explained, in addition to increases in the turns to achieve the multiband performance. Even though various compact, multiband operation antennas have been proposed, most of the designed antennas incorporate additional elements to realize the design objectives. In this work, in order to overcome the above drawbacks, a new antenna is introduced, namely a tri-band Complementary Split Ring Resonator (CSRR) antenna for L band and S ban2l8/wk7fg. The antenna is designed based on the equivalent circuit of spiral inductor modelling, and it is converted into a complimentary split ring resonator. An efficient CSRR unit cell antenna can be radiated at three required frequencies. According to Babinet's principle, the CSRR structure can be obtained from a SRR by inverting the copper parts on the antenna patch. Due to the concept of duality, these two structures resonate at almost the same frequency. The resonance in quasistatic resonators such as CSRRs and SRRs is the result of the interplay between the distributed capacitance and inductance of the structure. However, the main difference between both is that the SRR has negative permeability features, while the CSRR has negative permittivity features. These resonators are considerably reduced in size compared to conventional resonators, which have dimensions comparable to the wavelength, and resonance occurring based on the phase distribution. The proposed antenna is printed on FR4 substrate with 1.6 mm thickness and modelled and analysed by using the ANSYS HFSS 16 simulator tool. Simulations and measurements show that the proposed antenna gives good results in terms of operating frequency bands and omnidirectional patterns, as well as stable gain and radiation efficiencies.

II. ANTENNA DEVELOPMENT

In [23], the authors present the individual performance of split ring resonators. The corrected mathematical model predicts the left-hand behavior of split ring resonator-based metamaterial that shows it could resonate at several frequency bands [24-29]. Figure 1 shows the equivalent circuit of individual split ring resonator turns. This in turn shows that this method could be a systemized approach to design multiband antennas. As per the Babinet principle, split ring resonators are changed into CSRR to obtain the required frequencies.

The calculation of resonance frequency uses the formula [20]:

$$f_n = \frac{1}{2\pi\sqrt{L_D C_n}}. \tag{1}$$

Based on [17], the equivalent inductors and capacitors are approximately calculated for the four side of the split ring resonators, as show in Fig. 1. The self-inductors L_1, L_2, L_3, L_4 can be directly calculated by using the formulas,

$$L_D = K\frac{\mu_0 n^2 L}{2\Pi}\ [ln(\frac{2}{\rho}) + 0.5 + 0.178\rho + 0.0146\rho^2 + \frac{0.5(n-1)S^2}{(\rho n)^2}\ 0.178\frac{(n-1)S}{n} - \frac{1}{n}ln(\frac{W+t}{W})], \tag{2}$$

$$\rho\ =\ \frac{nW+(n-1)S}{L}, \tag{3}$$

$$K\ =\ \frac{(2L-2S)-D}{(2L-2S)}, \tag{4}$$

where t, n, W, S indicate the thickness, number of turns, width, and space between inner and outer rings of SRR, respectively. The calculation of distributed capacitance of SRR depends on two parameters, namely, the coupling capacitance between the outer and inner rings (C_0), and electric charge capacitance at the split's gaps (CCi).

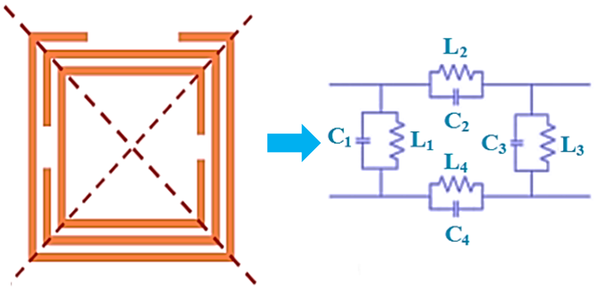


Fig. 1. Equivalent circuit model.

These capacitances can be estimated using the equations (5) and (6),

$$C_0 = \frac{1}{4}[0.06 + 3.5 \times 10^{-5}(R_{out} + R_{in})], \tag{5}$$

$$c_{ci} = \epsilon_0 \epsilon_r\ \frac{Wt}{ci}. \tag{6}$$

Here R_{out} and R_{in} indicate the radii of the outer and inner circumscribed circles of the SRR, respectively. The distributed capacitances of each side can then be calculated as the sum of these capacitances, using these equations,

$$C_1 = C_0 + C_{C1}, \tag{7}$$

$$C_2 = C_0 + C_{C2}, \tag{8}$$

$$C_3 = C_0 + C_{C3}, \tag{9}$$

$$C_4 = C_0 + C_{C4}. \tag{10}$$

By using these mathematical expressions, the dimensions of the SRR are calculated and then tuned to achieve the desired frequencies of interest. The SRR is changed into a CSRR by the Babinet principle. The Table 1 shows the L_D and C_n values for each frequency of antenna results and compares analytical and simulated results.

Table 1: Comparison of analytical and simulated frequencies

Inductor (L_D)	**Capacitor (C_n)**	**Analytical Resonating Frequency (GHz)**	**Simulated Resonating Frequency (GHz)**
5.01 nH	1.2 pF	2.05	1.9
4.16 nH	1.02 pF	2.44	2.45
3.57 nH	0.72 pF	3.14	3.2

The analysis shows the difference between the analytical and simulated resonate frequencies with respect to inductor and capacitor values. In order to gets desired frequency using antenna design software the dimensions are varied, and all the calculated parameter are simulated and optimized in order to obtain a tri-band antenna at desired operating frequencies.

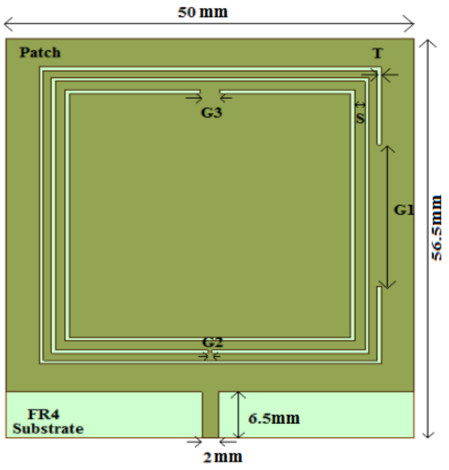


Fig. 2. Antenna geometry.

Then, the antenna is fabricated on FR4 substrate with 1.6 mm substrate height and a loss factor tan δ = 0.02. The final geometrical shape of the antenna is shown in Fig. 2 and its geometrical parameters are shown in Table 2.

Table 2: Design specification for the proposed antenna model

Parameter	**Specifications (mm)**
Substrate (FR4)	1.6
Length, width and thickness of substrate	50 × 56.5 × 1.6
Length and width of patch	50 × 50
Length and width of feed strip	6.5 × 2
Length of outer ring	42
Length of middle ring	39
Length of inner ring	35.5
Spacing between ring (S)	2
Thickness of the ring (T)	0.5
G1	20
G2	0.5
G3	1.5

III. PARAMETRIC ANALYSIS OF PROPOSED CSRR

The parametric analysis of Gap G1 in spiral rings plays an important role to determine the performance of the antenna. So, the analysis on the dimension of the Gaps G1 and their effect on Reflection Coefficient (dB) are shown in Fig. 3. From the graph, it is inferred that the antenna attains better impedance characteristics at G1=20 mm where it gives the triple operating band behaviour. It also shows that with G1 equal to 15mm and 25 mm, inferior triple band characteristics, as compared to G1=20 mm, are obtained. Hence G1=20 mm it considered an optimum dimension for G1. Next, The Gap G2 in spiral rings also plays a crucial role in determining the performance of the antenna and hence a parametric analysis on the effect of G2 on reflection coefficient (dB) is performed and shown in Figure 4. It is inferred that the antenna attains better impedance characteristics at G2=0.5 mm. Since this value provides better performance at desired operating bands, it is considered as an optimum dimension for G2.

Lastly, the impact of gap G3 on the performance of the antenna is shown in Fig. 5. It is shows that the antenna attains better impedance characteristics at G3= 2.5 mm at the desired operating bands, and hence it is considered as an optimum dimension for G3.

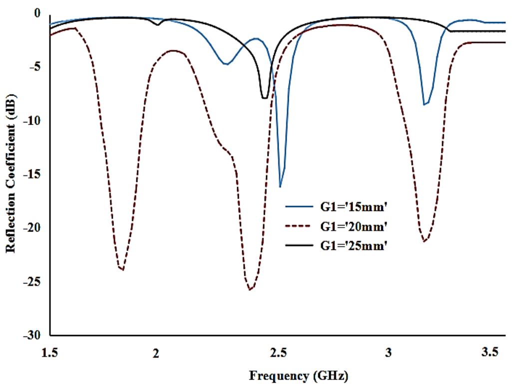


Fig. 3. Effect of Gap G1 on reflection coefficient (dB).

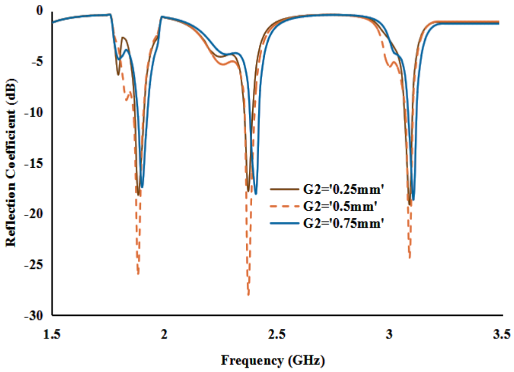


Fig. 4. Effect of Gap G2 on reflection coefficient (dB).

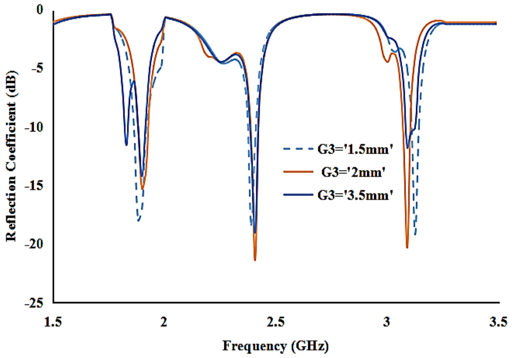


Fig. 5. Effect of Gap G_3 on reflection coefficient (dB).

IV. RESULTS AND DISCUSSIONS

The performance of the antenna is validated by fabricating the prototype on FR4 substrate and its characteristics are measured. The fabricated proposed CSSR antenna and the measurement setup are shown in Fig. 6 and Fig. 7, respectively. Figure 8 shows the impedance characteristics of the antenna. The antenna operates at three different bands in the L and S band regions. The -10 dB impedance bandwidth covers 1.78-1.91 GHz, 2.23-2.52 GHz and 2.9-3.25 GHz. In Fig. 8, it can be seen that the measured and simulated results are comparable. However, the shift in measurement results are due to imperfect fabrication processes. Also, while simulations are based on a perfect substrate material, there are slight variations in the thickness and dielectric constant of commercially available materials, which influence the measurement results.

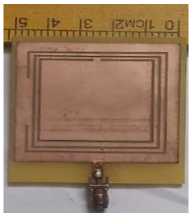


Fig. 6. Fabricated antenna.

Fig. 7. Network analyzer.

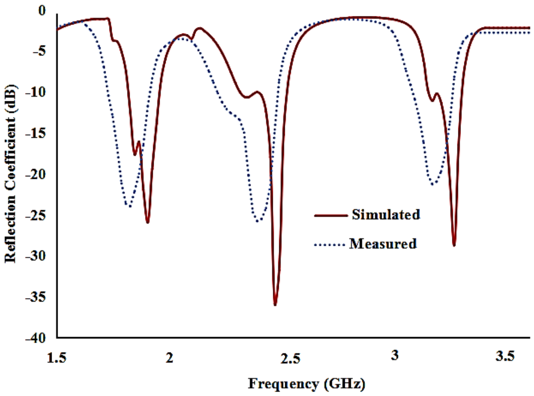
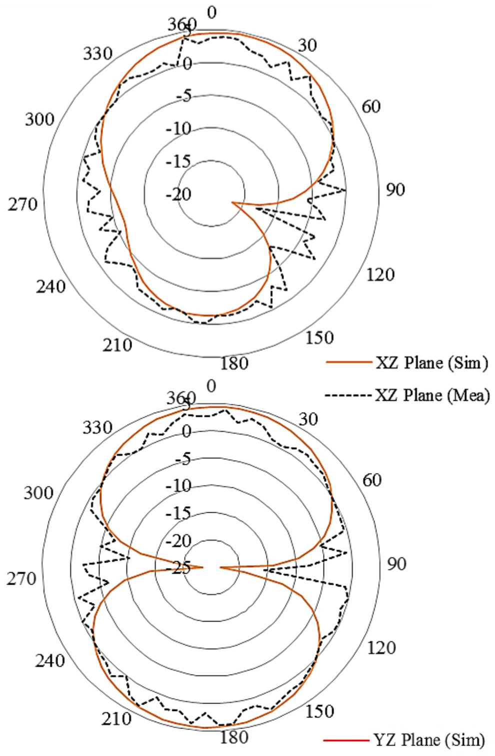


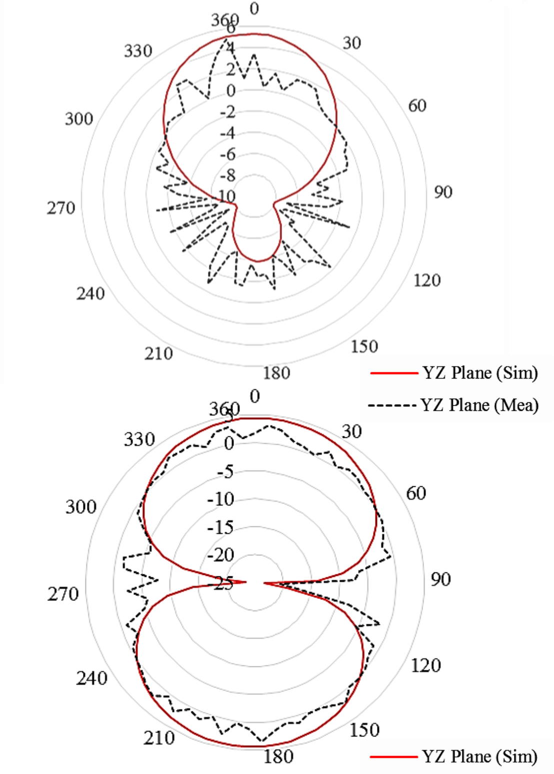
Fig. 8. Measurement and simulation impedance characteristics for proposed antenna.

In addition, the insertion loss of SMA connectors used, and connector losses have an effect on the response of the antenna. The radiation characteristic of the antenna is depicted in Fig. 9. It comprises of the radiation beam measured in both the E-plane and H-plane, and are compared with simulated results. The simulation and measured radiation characteristics of the proposed antenna operating at three different frequencies are plotted and compared. The results show clearly that the antenna gives symmetrical radiation and achieves a peak gain of 4.15 dBm at 1.9GHz, 4.25dm at 2.4GHz and

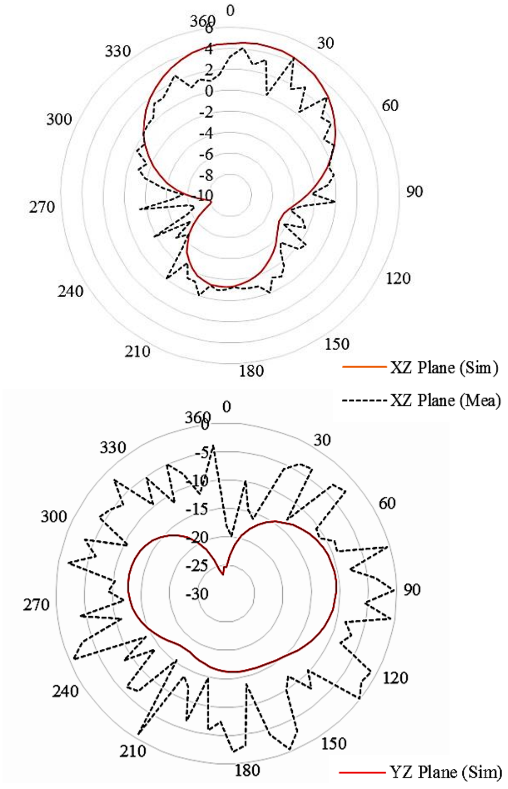
4.74dBm at 3.2GHz. A comparison of the proposed antenna with existing designs is presented in the Table 3.



(a)



(b)



(c)

Fig. 9. Radiation characteristics of the antenna E-plane and H-plane: (a) (1.9GHz), (b) F_2 (2.45GHz), and (c) F_3 (3.2GHz).

It shows that the physical size of the proposed antenna is reduced by ~42 %. Due to its compact size, the proposed antenna is suitable for in-door wireless applications.

V. CONCLUSION

A novel metamaterial based antenna etched with a spiral shaped structure to behave as a complimentary split ring resonator (CSSR) antenna is presented. The antenna is fabricated on low cost FR4 substrate, and the geometrical parameters are optimized to yield better performance. The antenna operates at three distinct bands in the range 1.9 GHz (1.78-1.91 GHz), 2.45 GHz (2.23-2.52 GHz) and 3.2GHz (2.9-3.25 GHz). The peak gains of the proposed antenna are 4.15 dBm at 1.9 GHz, 4.25 dBm at 2.45 GHz and 4.74 dBm at 3.2 GHz, respectively. The design also accomplishes a miniaturization in size of around 42 % compared to existing solutions in the literature. The metamaterial antenna is tunable, electrically small and highly efficient, which makes it a suitable candidate for RF energy harvesting.

Table 3: Comparison of proposed antenna with existing antenna

Ref.	Year	Frequency Bands (GHz)	Return Loss (S11) (dB)	VSWR	Size of Antenna (mm^2)	Area (mm^2)
[30]	2013	1.81-1.87, 2.11-2.17	≈ 14,16	No data	145 × 55	7975
[31]	2018	1.8-2.45	≈ 18,26	No data	77 × 98	7546
[32]	2018	1.74-1.97, 2-2.22, 2.41-2.59	Not Mentioned	No data	70 × 65	4550
[33]	2019	1.7-1.925	≈ 30	No data	70 × 70	4900
This work		**1.9,2.45,3.19**	**24.56,27.21,22.46**	**1.09,1.05,1.12**	**50 x 56.5**	**2825**

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