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Complementary Split Ring Resonator-Loaded Microstrip Patch Antenna Useful for Microwave Communication

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***Abstract*—**Complementary split-ring resonator (CSRR) loaded microstrip square patch antenna has been optimally designed with the help of high frequency structure simulator (HFSS). The antenna has been fabricated on the basis of the simulation design data and experimentally tested in anechoic chamber to evaluate its gain, bandwidth, efficiency and polarization characteristics. The CSRR loaded microstrip patch antenna has been found to realize significant size miniaturization (to the extent of 24%) compared to the conventional-type microstrip patch antenna both operating at the same frequency (5.2 GHz). The fabricated antenna could realize a maximum gain of 4.17 dB, 10 dB impedance bandwidth of 34 MHz, efficiency 50.73% and with maximum cross-pol of 10.56 dB down at the operating frequency. This practically designed antenna with its miniaturized size is expected to be useful for airborne and space borne applications at microwave frequency.

***Keywords*—**Split ring resonator, metamaterial, CSRR loaded patch antenna, microstrip patch antenna, LC resonator.

I. Introduction

MICROSTRIP patch antennae [1]-[3] were initially made for airborne applications to meet aerodynamic requirements while later on found to be an attractive antenna for commercial applications where light weight, size-miniaturization and low cost are important issues. Further, these antennae can be designed to have dual-polarization and multi-frequency operations which are the demand of modern communication systems. A conventional-type microstrip patch antenna being a resonant structure exhibit narrow band characteristics. Various techniques have been reported to improve its bandwidth of operation, like capacitive loading with parasitic patch [3] and inductive loading with slots cut on the metal patch [4]. In recent times, extensive research is going on to improve the bandwidth of operation of microstrip patch antenna by using magnetic inclusion type metamaterial unit cell like Split-ring Resonator (SRR) or its variants which results in resonant loading of the patch antenna [5], [6].

In this paper, we have reported a simulation based design (using ANSYS HFSS 3D FEM solver) and experimental characterization of a CSRR loaded square microstrip patch antenna (SMPA) at 5.2 GHz that can lead to 24% size reduction of the antenna when compared with a conventional-type patch antenna. The CSRR represents the complementary version of an SRR. Electrically, CSRR is the dual of SRR; the latter being a magnetic inclusion structure while the former is an electric one. The fabricated CSRR loaded microstrip patch antenna exhibit a realizable gain of 4.17 dB around 5.15 GHz. The impedance bandwidth for -10 dB return loss is 34 MHz. The overall efficiency of the antenna is 50.7%. Such an antenna can have many useful applications in microwave communication systems.

The paper also reports the studies on the orientation of the cut of the CSRR with respect to the coaxial feed line (refer Fig. 1). It has been found to control the nature of polarization of the CSRR loaded patch antenna. Only a particular orientation of the cut of CSRR with respect to the coaxial feed position permits the overall size reduction of the antenna in which the surface current gets coupled between the patch and the CSRR in the desired direction.

An estimation of the resonant frequency of the CSRR inclusion has also been included and compared with the simulation and experimentally observed results.

II. Antenna Design with 3D Electromagnetic Field Simulator

The antenna design has been carried out with ANSYS' HFSS which is a 3D electromagnetic field simulator based on Finite Element Method (FEM) of computational electromagnetics. The schematic sketches of CSRR, CSRR loaded SMPA and HFSS schematic of coaxial fed CSRR loaded metal patch are shown in Fig. 1.

At first, to identify a suitable antenna configuration which will lead to a reasonable antenna gain with possible size reduction of the antenna, the return loss for three different size of the CSRR inclusion has been studied. The simulation characteristics of CSRR loaded microstrip antenna are shown in Fig. 2. This indicates that the optimum choice of patch dimensions with acceptable return loss to realize size miniaturization corresponds to the second resonant dip. The resonance observed at the lowest of the three frequency dips for a particular inclusion size is highly lossy which is confirmed by the negative gain of the radiation pattern at this particular resonance, whereas, the one at higher frequency does not indicate any possibility of size-miniaturization. Only the intermediate one (with a = 5.5 mm) is of interest to the designer.

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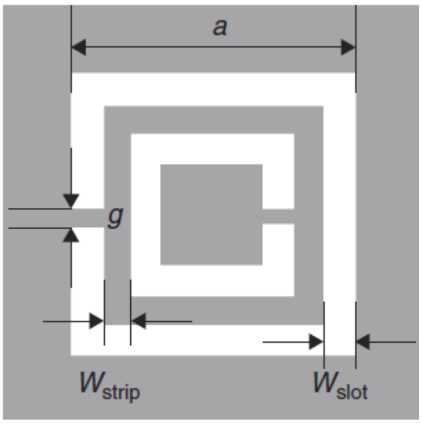
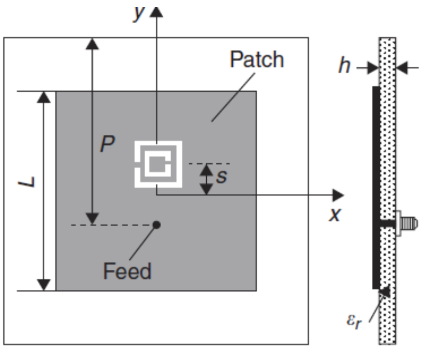
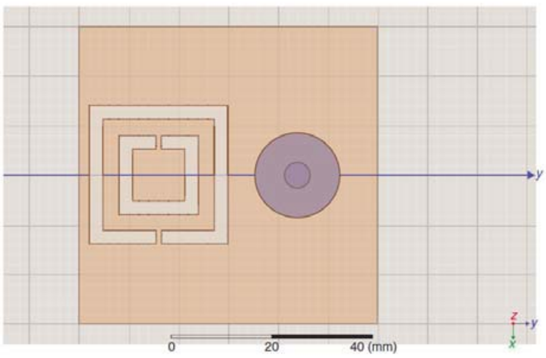
The surface current pattern and the simulated return loss for various positions (P) of the coaxial feed line on CSRR loaded patch (Fig. 1 (b)), with the cut on the CSRR aligned orthogonal to the coaxial feed line (as in Fig. 1 (c)), are shown in Figs. 3 and 4 respectively.



(a)



(b)



(c)

Fig. 1 (a) Schematic sketch of CSRR (b) CSRR loaded SMPA (c) HFSS schematic of coaxial fed CSRR loaded metal patch

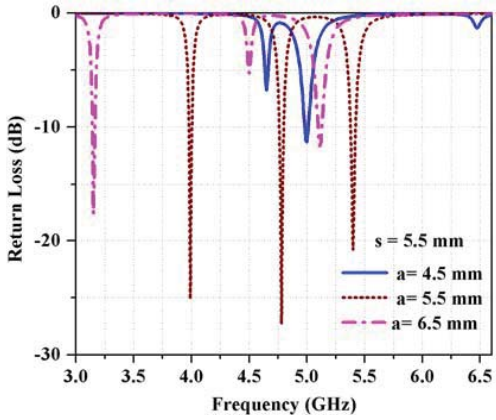


Fig. 2 Return loss with different size of CSRR loaded on the metal patch

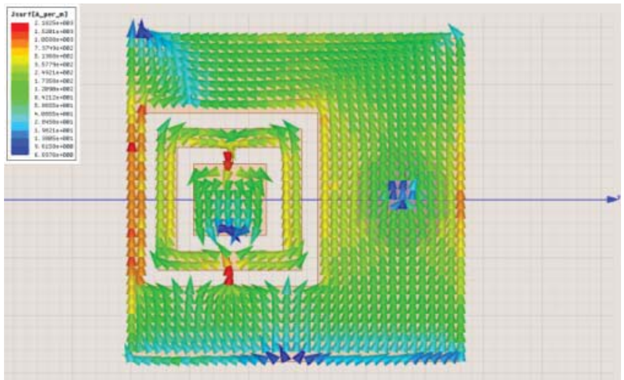


Fig. 3 Surface current pattern for particular orientation of CSRR which permits size reduction

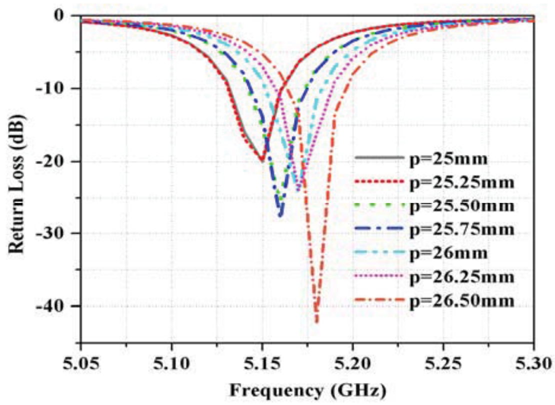


Fig. 4 Simulated return loss for various position of coaxial feed on CSRR loaded patch

The optimized return loss curve (Fig. 4) indicates that the patch resonates around 5.18 GHz. The optimized dimensions of the unloaded patch antenna and CSRR loaded patch antenna with optimized feed location are given in Table I. These patch antennae are simulated using 20 mil Arlon Diclad880 substrate having dielectric constant 2.2 and loss tangent 0.0009.

Parametric study to investigate the effect of other parameters of the CSRR inclusion was also carried out and shown in Figs. 5 and 6. A simple calculation shows that to design the patch antenna with CSRR loaded on it, the patch size has to be reduced approximately by 4 mm (i.e. 24%) along either dimension to bring back the resonant frequency close to 5.2 GHz. This prompted us to use a modified and reduced patch size of 14 mm x 14 mm on the basis of optimization through simulation.

TABLE I
OPTIMIZED DIMENSIONS OF DIFFERENT PARAMETERS OF UNLOADED PATCH ANTENNA AND CSRR LOADED SMPA AT 5.2 GHZ

Parameter	Unloaded Patch antenna	CSRR loaded SMPA
Length of each side of the square patch *(L)*	18.45mm	14 mm
a	-	7.5mm
W_{strip}	-	0.8mm
W_{slot}	-	0.7mm
s	-	5.8mm
g	-	0.25mm
P	-	26.7mm

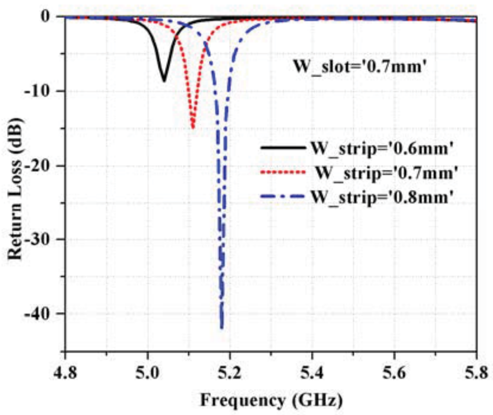


Fig. 5 Simulated return loss with different metallic widths of CSRR

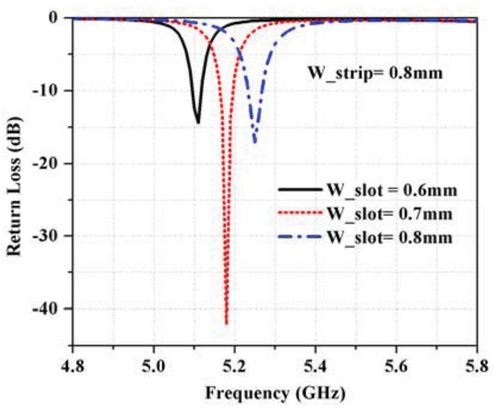


Fig. 6 Simulated return loss with different slot widths of CSRR

It was observed that for a particular orientation, the line of cut in the CSRR being aligned orthogonal to the coaxial feed as depicted in Fig. 1 (c) leads to size reduction. For other orientations of CSRR, one aligned with its line of cut along the line of the coaxial feed and facing the feed exhibits a lossy nature. While in the case, when the CSRR aligned with its cut along the coaxial line but rotated by 180^0 in the clockwise direction exhibits no possibility of size reduction as it exhibits resonance at 5.8 GHz. However, it has been observed that the orientation that leads to size reduction exhibits orthogonal polarization compared to unloaded patch antenna.

III. ESTIMATION OF THE RESONANT FREQUENCY OF CSRR

Babinet's principle suggests that CSRR is the dual of SRR, so the resonant frequency of SRR and CSRR are expected to be the same [7]. The SRR is basically an LC resonator. The total inductance of CSRR structure shown in Fig. 7 can be calculated as:

$$L_{equivalent} = \frac{L_{outer} + L_{inner}}{2} = 11.4nH$$

where L_{outer} and L_{inner} are calculated by considering each segment of the inner and outer rings as rectangular segments [8]. The evaluation of $L_{equivalent}$ as the average of the L_{outer} and L_{inner} is justified. This is because the presence of small slits in both the ring results in circulation of current between the two rings. Thus the closed current path formed by traversing through both the rings is exactly like a current in a single loop.

Method of Moments (MoM) has been used to find the capacitance per unit length between the two adjacent strips of SRR. Each strip is divided into N number of small rectangles such that surface charge distribution is nearly constant in a rectangle. The thickness of strips is very small (17 µm – 35 µm) compared to other dimensions and hence contribution due to this thickness in overall capacitance is neglected. Assuming unit potential on the strips, charge distribution on each rectangle is calculated from Poisson's equation which results in a $2N$ x $2N$ matrix of $2N$ unknown variables. This matrix is solved using MATLAB to find the surface charge density on each rectangle. From surface charge density, total charge on a strip is calculated to find the capacitance for a given strip of width w, gap g and length l. It is observed that capacitance between two adjacent plates is a linear function of the length of strips. So, capacitance per unit length can be determined and used for further calculations. For our case of SRR, the capacitance calculated using MoM between the split rings is 0.016 pF where the width of the strip is 0.7 mm, gap between split rings is 0.8 mm. The half of SRR covers effective length of 10.5 mm and hence C_p (vide Fig. 7) will be 0.16 pF. The total capacitance for the full SRR structure is a series combination of two capacitors of value C_p. So the total equivalent capacitance for the SRR will be 0.08 pF.

Using $L_{average}$ = 11.4 nH and C = 8.4 x 10^{-14} pF, the resonant frequency of the SRR, f_o is found to be 5.14 GHz. The CSRR loaded patch antenna uses Arlon Diclad 880 substrate of dielectric constant 2.2 that has $\varepsilon_{\text{eff}} = (\varepsilon_r+1)/2$ =1.6. Thus, the resonant frequency of the CSRR will be approximately $f_o/(\varepsilon_{\text{eff}})^{1/2}$ = 4.06 GHz. One thing is to be noted that f_o is the resonant frequency of the SRR whereas the metallic patch upon which the complementary form of SRR has been loaded is not an exact dual of SRR since the latter has been cut on a finite metal sheet (i.e. the patch). Due to this reason, some undue loading might slightly change the resonant frequency value of the CSRR. Possibly, this is the reason why the resonant frequency calculated analytically (4.06 GHz) and that obtained with simulation (3.03 GHz) of CSRR differs.

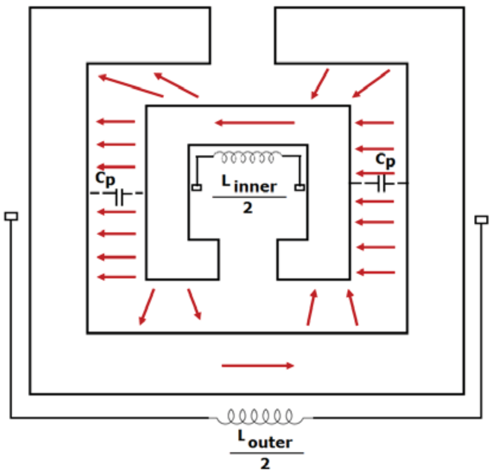
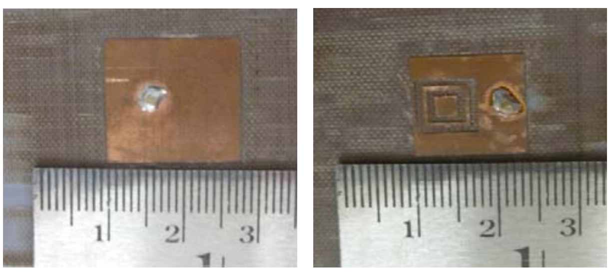


Fig. 7 Equivalent circuit diagram for SRR to calculate resonant frequency

IV. Experimental Results and Discussion

The fabricated antennae are shown in Fig. 8 from which their relative size can be compared. The return loss for the fabricated antennae is measured in Agilent's E8363B series VNA (Vector Network Analyzer). The radiation pattern of the designed antennae is measured in an anechoic environment using C-band horn as transmitting antenna to excite the Antenna Under Test (AUT). Duly mounted AUT at the receiving end is rotated through -180^0 to $+180^0$ with MI-4190 Position Controller. The antenna pattern is generated by using MI-3000 software.



(a) Conventional patch (b) CSRR loaded patch

Fig. 8 Fabricated antennae

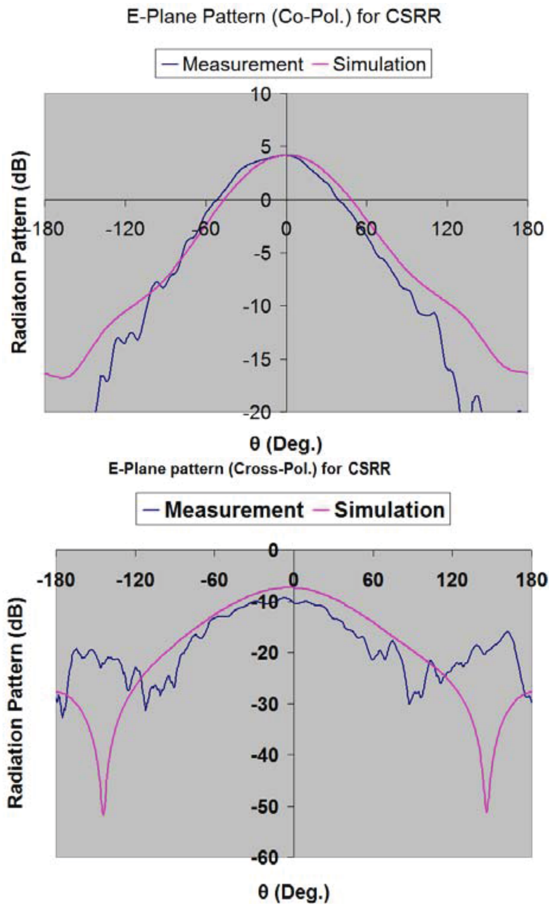


Fig. 9 E-plane Co and Cross-pol radiation pattern of CSRR loaded patch antenna at 5.15 GHz

TABLE II
PERFORMANCE OF CONVENTIONAL-TYPE PATCH ANTENNAE

Parameter	Simulated Result	Measured Result
10dB Impedance Bandwidth	170.1 MHz	60 MHz
Gain	6.86 dBi	6.11 dBi
E-Plane Cross-pol level at boresight	63.21 dB down	37.21 dB down
H-Plane Cross-pol level at boresight	58.46 dB down	26.51 dB down
Efficiency	81.89%	-

TABLE III
PERFORMANCE OF CSRR LOADED PATCH ANTENNAE

Parameter	Simulated Result	Measured Result
10dB Impedance Bandwidth	32.5 MHz	34 MHz
Gain	4.2 dBi	4.17 dBi
E-Plane Cross-pol level at boresight	11.63 dB down	14.53 dB down
H-Plane Cross-pol level at boresight	11.63 dB down	10.56 dB down
Efficiency	50.73%	-

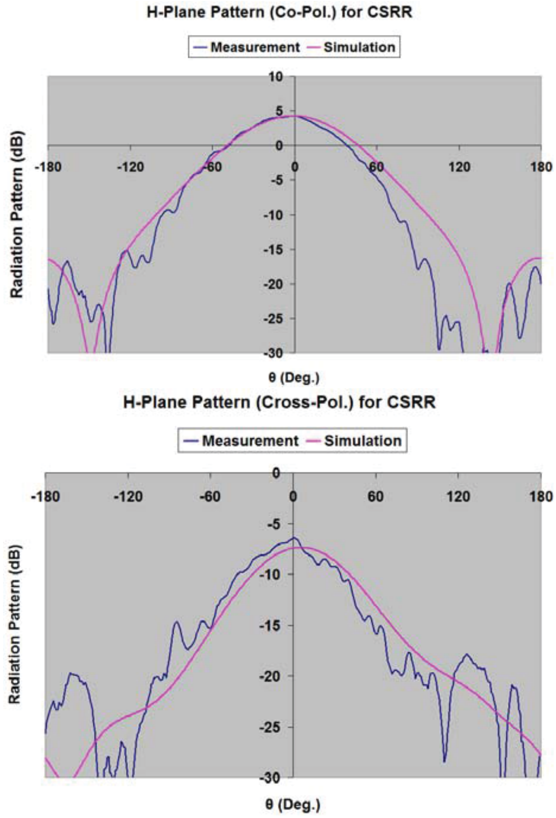


Fig. 10 H-plane Co and Cross-pol radiation pattern of CSRR loaded patch antenna at 5.15 GHz

The measured return loss of the fabricated conventional-type patch antenna is 29.8 dB at 5.33 GHz and that for the CSRR loaded patch antenna is 34.2 dB at 5.15 GHz. In comparison to the HFSS simulation results, a shift in the resonant dip was observed for both types of fabricated patch antennae. This may be due to fabrication errors caused by under-etching/over-etching of the metal patch/CSRR pattern on the metal patch. The maximum gain, Co and Cross-polarization radiation patterns in both planes for CSRR loaded patch antennae are shown in Figs. 9 and 10. It can be observed that the simulated and measured results match with minor deviations. Tables II and III shows the simulated and measured results for conventional-type and CSRR loaded patch antennae respectively.

V. Conclusion

A conventional-type square microstrip patch antenna has been size-miniaturized by CSRR loading at an operating frequency of 5.2 GHz. The designed CSRR loaded patch antenna can realize a 24% size-reduction in comparison to the conventional-type patch antenna. The simulation results have been validated by measurements. The fabricated CSRR loaded patch antenna resonates at 5.15 GHz with 34.27 dB return loss and has a realizable gain of 4.17 dB. The resonant frequency of CSRR structure has been analytically determined (4.06 GHz) and compared to the value obtained from simulation (3.06 GHz). The size-miniaturized antenna is expected to be useful for microwave communication systems designed for air borne and space borne applications.

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