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Dual-Band, Miniaturized, Enhanced-Gain Patch Antennas using Differentially-Loaded Metastructures

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Abstract

We propose a novel miniaturized dual-band microstrip patch antenna with improved gain for potential wireless applications. Two variants of the proposed configuration have been optimized and the analyzed results presented. The basic patch antenna is loaded with two pairs of Complementary Split Ring Resonators (CSRR's) on both sides of its non-radiating edges with different dimensions on both sides. The radiation performance of the first variant and its gain is further improved by etching four pairs of CSRR on the ground plane which controls the surface waves effectively. The proposed antenna shows an analyzed gain of 1.80 & 5.67 dB respectively in the two bands 1.68, 2.59 GHz. The antenna may find application in both the ISM (L band) and Wimax applications. In a second variant, the gain is further improved by employing a Reactive Impedance Surface (RIS). In this case, the analyzed gain is found to be 5.69 & 5.12 dB respectively at 2.05, 2.39 GHz. This antenna may be suitable for UMTS and ISM applications. The design dimensions of the patch, CSRR's and the RIS are obtained from expressions available in literature. Subsequently, simulation and optimization of the structures is carried out with Ansys HFSS®; a benchmarked E.M. simulator. The analyzed results are presented.

Keywords: Complementary Split Ring Resonator (CSRR), Metastructures, Miniaturization, Reactive Impedance Surface (RIS)

1. Introduction

Microstrip antennas find tremendous application in the wireless domain like in mobile communication, RFID, LAN, WAN, satellite communications, RADAR, etc. due to features like compactness, integrability to active devices, and low cost but they offer limited bandwidth and gain which need to be improved[1]. This is achieved by several means like increasing substrate thickness, introducing parasitic radiators, etc[2–4]. but in more recent research, has been done by employing a newer class of materials called Metamaterials which exhibit negative permeability and permittivity over a specific range of frequencies. They may consist of periodic structures butare not limited to that configuration[2]. Recently extensive utilization of such structures has been made for improving antenna characteristics. It has been shown that they can play a useful role in making the antenna geometry compact with improved gain and bandwidth[5–6].

Caloz et al. first proposed the dual-transmission line equivalent of combined right and left handed (CRLH) structures[7]; enabling the computation of their characteristics. Falcon et al. proposed the complementary split ring resonator (CSRR) structures[8]. The circuit equivalents of the Split Ring Resonator (SRR) and CSRR are analyzed in J D Baena et al.[9]. Spiral resonators and MSRR structures along with expressions of inductance and capacitance are addressed in Filberto Bilotti et al.[10]. Many researchers have reported different types of SRR's like square, circular, and triangular. The antenna, traditionally an appreciable fraction of the wavelength in size, is going through a trend of size reduction using a variety of miniaturization approaches of which; reactive loading using co-planar line elements or chip components is a popular method[11].

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Miniaturized dual band patch antennas are reported using CSRR structures and reactive impedance surfaces by Yuandong et al[12]. Wenquan Cao et al. used a CSRR on the ground layer for beam steering applications[13].

In this paper, we have proposed a newer method of obtaining dual-band characteristics with CSRR loading comprising of differential of loading on either half of the patch. The proposed method obviates the need for stacked patches/multi-layer antenna construction. Two different resonances of the CSRR structures embedded within the patch geometry yields two different resonant frequencies in the overall radiator. The antenna's co- and cross-polarization level are simultaneously improved in one version by etching the ground with CSRR, while in a second version, the gain of the perturbed, loaded antenna is to be improved by using the reactive impedance surface originally suggested by Mosallaei.

1.1 Reactive Impedance Surface (RIS)

These are essentially two-dimensional periodic planar structures over a grounded substrate. The periodicity of these structures is typically much smaller than the wavelength. They may be inductive or capacitive by design. The inductive RIS is used for miniaturization as well as for realizing wider bandwidth. An inductive RIS can store magnetic energy thereby it increases the inductance of the circuit. The impedance expression along with equivalent circuit is discussed in this paper in upcoming section.

1.2 Complementary Split Ring Resonators

These are a common instance of metamaterial-type of structures since they exhibit negative permittivity over a certain range of frequencies. They require an axial electric field excitation for the intended operation. Split ring resonators and Complementary split ring resonators are duals of each other. A CSRR is obtained when a shape congruent to an SRR is removed from a metallic plane. The CSRR has the same resonant frequency as the original CSRR. The relation between equivalent inductance and capacitance of SRR and CSRR is established[10]. When a CSRR is etched on to a radiating patch, they behave like electrical dipoles[10]. They are good resonators though not radiators. When loaded onto the patch, they modify the current paths across the patch surface to make the total structure resonate and effectively radiate at a lower frequency by means of magnetic and capacitive coupling leading to miniaturization[10].

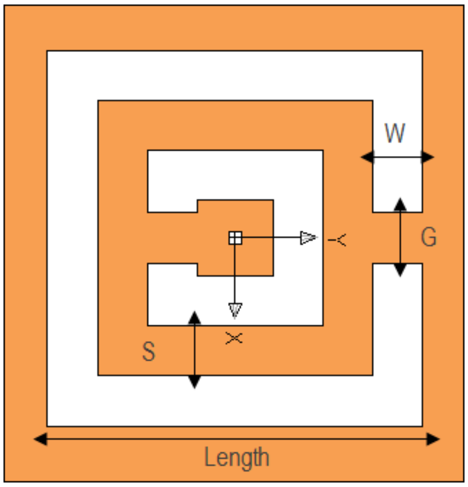

Figure 1. CSRR (white region represents air)[10].

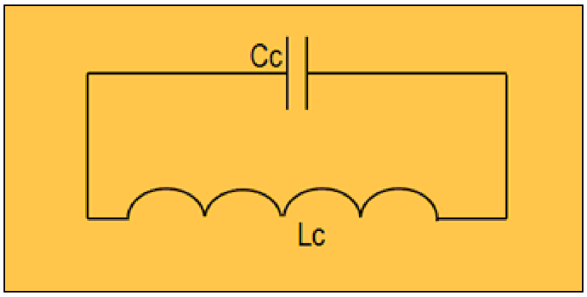

Figure 2. The Circuit Equivalent of CSRR[10].

In the present paper, we have loaded the basic inset-fed patch on either side with CSRR's tuned to two different resonant frequencies; paving the way to dual-band operation. Further, when the ground plane is etched with a CSRR; the propagation of surface waves is controlled by introducing a phase shift on the electromagnetic waves thereby improving the radiation features.

2. Design of Patch Antenna

A Rectangular Inset fed microstrip patch antenna is designed to resonate at 2.86 GHz. The substrate used is RT/duroid5880 with a dielectric constant of 2.2. The thickness of substrate is 60 mils. is fed with a microstrip line of impedance 50 ohms. The width and length of the line is 4 mm, 30 mm respectively. The return loss is found to be –28.3 dB. (Figure 3). Also another patch for variant 2 is designed with Rogers 3003 and is made to resonate at 2.41 GHz (not shown).

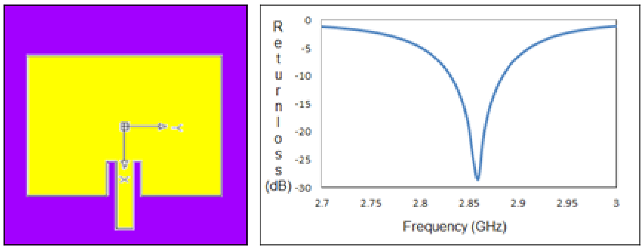

Figure 3. Original Inset fed patch; Analyzed Return loss

3. Design of Proposed Variants

The inset fed antenna described in the foregoing section is next loaded with two pairs of CSRR's. As mentioned earlier, the resonant frequency of the CSRR's towards the right and left sides are designed to be vividly different. The unit cell sizes along both sides are 7.1 mm & 9.3 mm respectively which is much smaller than a quarter of the guided wavelength satisfying the homogeneous condition.

The design equations for a CSRR with two turns are as below

The Resonant Frequency of the CSRR is given by

$$\omega_0 = \frac{1}{\sqrt{LcCc}} \tag{1}$$

$$L_c = \frac{4.86}{2}\mu_0(L - w - s)\left[\ln\left(\frac{0.98}{\rho} + 1.84\,\rho\right)\right] \tag{2}$$

$$\rho = \frac{w + s}{L - w - s} \tag{3}$$

$$C_c = (L - 1.5\,(2 + d)\,C_{pul} \tag{4}$$

Where 'w', 'L', 's' represent the width & length of the outer ring and space between rings respectively. ρ is the filling factor and C_{pul} is Per unit capacitance. Equation (2)–(4) stand for number turns being two.

$$Lc = 4\,\mu_0(L - 2(w + s))\left[\ln\left(\frac{0.98}{\rho} + 1.84\,\rho\right)\right] \tag{5}$$

$$\rho = \frac{2(w + s)}{L - 2(w - s)} \tag{6}$$

$$Cc = [2L - 5\,(w + s)]\,C_{pul} \tag{7}$$

Equations (5)–(7) stand for number turns of CSRR being three. Equation (1) is common for both the cases of 'n' being two or three.

The above set of equations were suitably employed to obtain the design dimensions of the CSRR's. We next consider the design aspects of the ground plane reactive loading.

3.1 Reactive Impedance Surface

The reactive impedance surface proposed in[11] is effectively utilized in the present work (Figure 4) and its dimension and spacing are so adjusted as to increase the gain of the proposed antenna. This gain compensation is important as the antenna gain reduces when it is loaded with a larger number of CSRR's. Before applying the RIS layer to the structure comprising the Patch loaded with CSRR, its utility was verified. The radiator was first analyzed without the RIS loading and it is found to produce miniaturization and dual-band operation but gain factor is relatively poor. Subsequently, when analyzing with the perturbed ground-plane, the loaded patch yielded improved results as also confirmed in[11].

The equivalent circuit of the RIS is essentially the L-C resonator (Figure 4). For illustration, a pair of elements comprising the RIS are shown but the actual array consists of several elements. The formula for the impedance of the RIS is:

$$Z_{ris} = \frac{X_L C_C}{X_L - X_C} \qquad (8)^{11}$$

The equation of X_L and X_C can be obtained from[11]; where X_L and X_C stand for inductive and capacitive reactance. In the equivalent circuit shown the resistance portion is neglected. A rigorous analysis of the RIS is not attempted in this work. The equations from[11] are applied and later the dimensions of the RIS are optimized to achieve the desired gain improvement. Optimization of the total

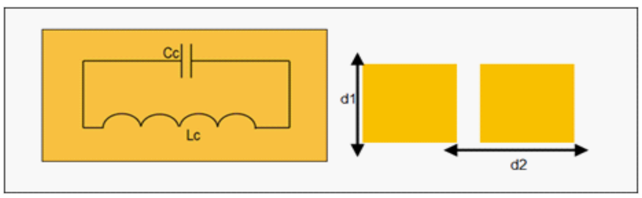

Figure 4. Equivalent Circuit of Reactive Impedance Surface; Printed RIS (only two elements shown)[11].

antenna element structure is carried out using Ansys HFSS®, a benchmarked e.m. simulator based on the Finite Element Method (FEM). The optimized dimensions for the CSRR's and RIS are listed below, corresponding to the desired frequencies of operation.

In Table 1, Length R stands for length of the CSRR on the right-hand side, Length L stands for length of CSRR on the left-hand side, width denotes width of the ring, space for the space between the rings, gap for the end gap in one ring. The dimension of two dimensional RIS unit cell is marked in Figure 4. and the cell size is 9 mm while spacing between cells is 1 mm. An array of 5 × 5 RIS elements is placed over the first substrate layer The RIS cells are assumed to have 1 micron thickness in the analysis. The RIS used in the present work has a nearly square unit cell. This was chosen on account of simplicity and compatibility to the operating mode supported by the patch. This is now limitation, however, and other shapes for the RIS may be explored e.g. round or elliptical. The configurations of two variants of the proposed CSRR/RIS-loaded microstrip patch radiator are shown below (Figure 5 and Figure 6)[12,13].

The Variant 2 has two layers of an identical substrate; each with a thickness of 60 mils while the RIS is placed over substrate 1.

Table 1. Details of Optimized Dimensions of the CSRR's & RIS

CSRR (PATCH)	CSRR (PATCH)	CSRR (GROUND)
Length R–7.1 mm		
Length L–9.3 mm	Length–9.3 mm	d1–9 mm
Width–0.5 mm	Width–0.5 mm	d2–10 mm
Space–0.5 mm	Space–0.6 mm	Number of RIS–25
Gap–0.5 mm	Gap–0.5 mm	5 × 5

4. Analyzed Results of the Proposed Variants and Discussion

Analyzed Return Loss characteristics of both the variants show a clear set of two resonances each (Figure 7). The first variant also shows several minor resonances that may be attributed to surface-wave propagation or spurious interactions. The far-field patterns for both variants are nearly omni-directional as expected for the patch antenna (Figures 8 and 9).

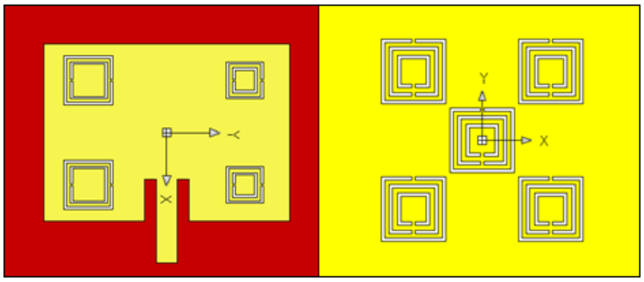

Figure 5. Top and Ground-Plane Views of the Proposed Variant 1.

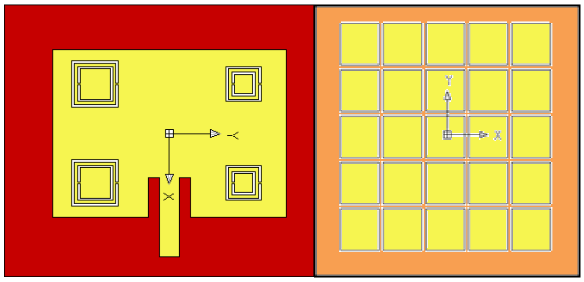

Figure 6. Top-View and RIS Layer over Substrate 1 of the Proposed Variant 2.

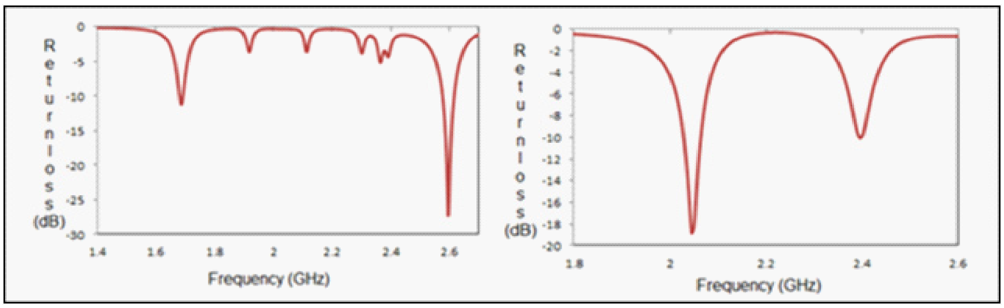

Figure 7. Analyzed Return Loss Plots of the Proposed Variants 1 and 2.

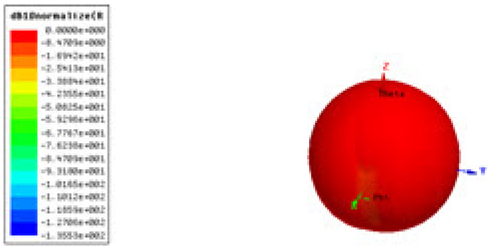

Figure 8. Normalized Radiation Pattern Plot (Gain) of Variant 1.

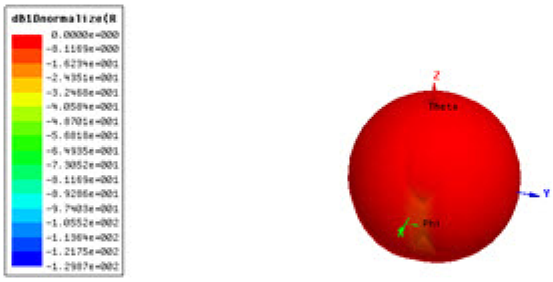

Figure 9. Normalized Radiation Pattern Plot (Gain) of Variant 2.

Table 2. Performance Summary of Variants 1 and 2

Variant	Return loss (dB)	Gain (dB)	% Efficiency
Variant 1			
First Band(1.68 GHz)	−11.2	1.8	49 %
Second Band(2.59 GHz)	−27.2	5.67	77 %
Variant 2			
First band(2.05 GHz)	−18.4	5.69	79.4 %
Second band(2.39 GHz)	−10.7	5.12	81.8 %

As evident from Table 2, acceptable return loss performance is achieved at both of the resonant frequencies by both variants. Good gain values are achieved, although only linear-polarization has been targeted at present. As a subsequent avenue of research, the elements may be suitable adapted for circular polarization also. The aperture efficiency of the radiators is relatively high (except for the first resonance in Variant 1). It is possible that this value may be improved with further optimization although this has not been attempted presently. The amount of miniaturization achieved for the presented elements shows that a considerably compact radiating structure has been obtained as against the standard microstrip patch antenna. Since the radiators are planar in configuration, they retain all the features of such antennas i.e. ease of fabrication using photolithography, cost-effectiveness and ease of integration with other subsystems like chip components, amplification blocks, etc.

5. Conclusion

The two variants of the proposed CSRR/RIS-loaded microstrip patch antenna that are analyzed show good return loss, improved gain (compared to the unloaded patch) and good efficiency in the two resonant bands. They are compact structures and can be integrated easily with other devices on the circuit board. They are cost effective and can be easily fabricated with photolithographic techniques as they are planar structures. The proposed radiators are linearly polarized and circularly-polarized operation may be a future scope of improvement for these antennas. The RIS layer may also be configured to have other shapes, this may be a possible future scope of this work.

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