Reduced Cross-Polarization Patch Antenna with Optimized Impedance Matching Using a Complimentary Split Ring Resonator and Slots as Defected Ground Structure

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Abstract **─** An innovative method is proposed to improve the cross-polarization performance and impedance matching of a microstrip antenna by integrating a complimentary split ring resonator and slots as a defected ground structure. An equivalent circuit model (ECM) enables the design take into consideration the mutual coupling between the antenna patch and the Defected Ground Structure. The input impedance and surface current density analysis confirms that the integration of a CSRR within a rectangular microstrip patch antennaleads to uniform comparative cross-polarization level below 40 dB in the H-plane, over an angular range of ± 50°. Introducing parallel slots, as well, leads to a reduction of spurious antenna radiation, thereby improving the impedance matching. Measurements conducted on a fabricated prototype are consistent with simulation results. The proposed antenna has a peak gain of 4.16 dB at 2.6 GHz resonating frequency, and hence is good candidate for broadband service applications.

Index Terms **─** Cross-polarization, CSRR, defected ground structure, impedance matching, microstrip antenna.

I. INTRODUCTION

Microstrip antennas have gained a wide range of attention and have been elaborately studied due to their small footprint, lighter structure and inexpensive price. The impedance matching of microstrip patch antenna plays an import role in designing a good antenna. The antenna's input impedance depends on its size, profile, type of feeding, and the properties of the antenna material. Results obtained from experiments [1] reveal that, in particular cases, such as feeding from the probe of simple coaxial and a microstrip line, the input impedance is dependent on the feed position. In general, the cosine-square of the normalized distance of feeding point from the patch edge is proportional to the impedance of the input probe that feeds the microstrip patch antenna. However, with the use of a microstrip line, the dependence of impedance develops proportionate to the fourth-power cosine [2]. While the input impedance is zero for the feed probe at middle of the patch, the input impedance of inset-fed rectangular microstrip patch antenna is influenced by the notch dimensions and the aspect ratio of the patch [3]. This implies that the H-plane cross-polarization is influenced by the notch depth and width dimensions. For fixed input impedance, however, the cross-polarization level is largely insensitive to the notch width. Flexible impedance matching and low cross-polarization has been realized using a novel technique of loading the rectangular microstrip patch antenna with a pair of shorting pins [4]. The symmetric arrangement of the shorting pins retains the symmetric-odd pattern of surface current with respect to the H-plane, and therefore the level of cross-polarization is diminished considerably. The input impedance of the microstrip patch antenna also plays a role in achieving a suitable impedance-bandwidth. An improved bandwidth for a microstrip patch antenna in the X-band has been achieved by implementing a z-shaped defected ground structure [5]. However, the integration of a defected ground structure for enhancing input impedance matching has not been studied. The defected ground structure has also been used to boost the bandwidth of an ultra-wide band antenna along with the suppression of cross-polarization [6]. Although, the level of cross-polarization has been improved by between 10 dB to 25 dB in both the principal planes, a decline in matching can be observed after introducing the defected ground

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structure. Among various effects, a simple rectangular microstrip patch antenna is impinged by cross-polarized radiation in the far field, particularly the H-plane. Irregularities in the positioning of probes leads to this proportioned antenna near-fields, resulting in higher cross-polarized radiation in the H-plane. The reduction of cross-polarization using defected ground structure approaches have been studied, such as an arc-shaped symmetrical defected ground Structure [7]; a novel defected ground structure strategy [8]; a defected ground structure with dumbbell shape [9]; defected ground structure with asymmetry, non-affected pattern of co-polarized radiation [10]. From these studies, it can be observed that the reduction of cross-polarization along with proper impedance tuning is a challenging assignment for designers of microstrip patch antennas. Since, an asymmetric feed position is often required for accurate matching of impedance; this unfortunately plays a role in increasing cross-polarization in the H-plane. Although the reduction of the cross-polarization in bore sight is a comparatively easier task, it is difficult to maintain a regular and low cross-polarization over a wide angle range from – 50° to + 50°. In this work, a rectangular microstrip patch antenna, using a complimentary split ring resonator (CSRR) and slots as defected ground structure, is proposed and studied for improved impedance matching and lower cross-polarization level. The location of the defected ground structure is adjusted to obtain the anticipated x-axis directed odd-symmetric distribution of surface current, hence, negating the resultant far field radiation in the H-plane. Taking into the consideration the mutual coupling between the defected ground structure and patch, an equivalent circuit model (ECM) is first developed and analyzed using Advance Design System (ADS-2017). Enhanced input impedance between 2.4 GHz – 2.8 GHz, regular and low cross-polarization over a wide angle range from – 50° to + 50° and a reasonable peak gain of 4.16 dB will make these type of antenna appropriate for broadband services applications.

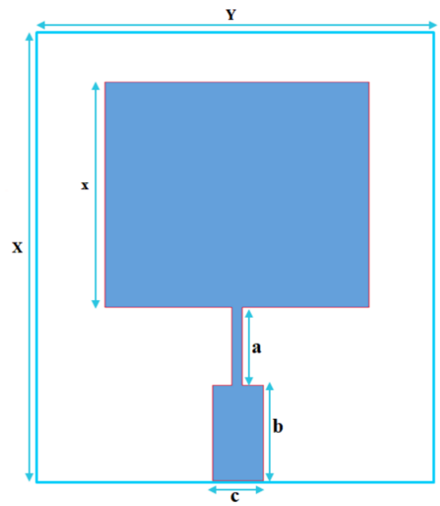
II. ANTENNA DESIGN

A. Antenna configuration

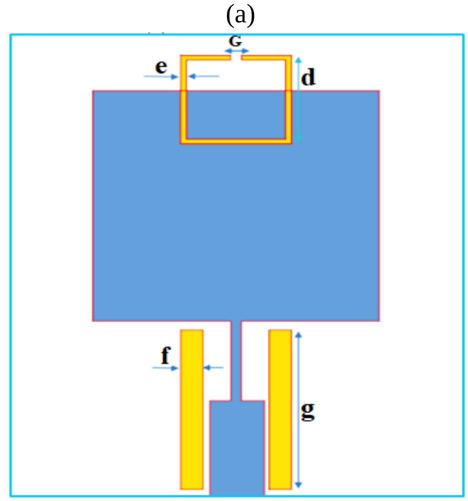
The proposed configuration for antenna and the model of equivalent circuit are elaborated in this section.

B. Equivalent circuit model

In Fig. 1 and Fig. 2, the descriptive sketch of recommended CSRR+Slots designed defected ground Structure incorporated in microstrip patch antenna and the equivalent circuit of CSRR defected ground structure with microstrip line feed microstrip patch antenna is presented respectively, in which the influence of the CSRR and slots aperture are accounted for by considering the mutual inductance between the patch and defected ground structure (i.e., the CSRR and slots). The input side, which models the equivalent circuit of the antenna patch, consists of a parallel capacitor (Cp), parallel resistance (Rp), and parallel inductance (Lp). As the defected ground structure involves the ground plane, a parallel circuit LC (L_{DG} and C_{DG}), equivalent to the defected ground structure is conjointly linked with the antenna patch circuit. The proposed antenna equivalent circuit shows the combination of equivalent circuit of radiating patch, the CSRR and the slots. The total value of L_{DG} and C_{DG} are the summation of CSRR and slots individual inductances capacitances. When the CSRR is placed in different positions, the total value of inductance and capacitance will change, and hence the impedance of the patch antenna varies. This leads to poor reflection coefficient.



(a)



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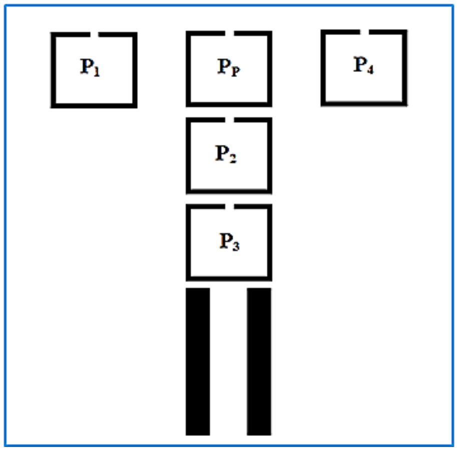

(c)

Fig. 1. Descriptive sketch of recommended complimentary split ring resonator+slots designed defected ground structure incorporated in microstrip patch antenna: (a) front view, (b) rear view superimposed on front view, and (c) different positions of defected ground structure in rear view.

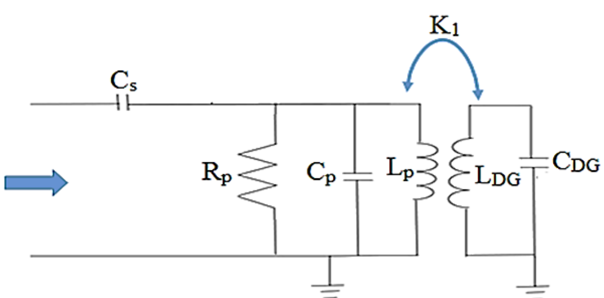

Fig. 2. Equivalent circuit of defected ground structure integrated with antenna.

Table 1: Antenna parameters with enhanced dimensions (in mm)

Parameters	Dimensions (mm)
Length of the Substrate (X)	52
Width of the Substrate(Y)	50
Length of the Patch(x)	26
Length of the Feed Line(a)	9
Width of a feed line	1
Length of the transformer (b)	9.2
Width of the transformer (c)	5
Length of the Complimentary Split Ring Resonator(d)	10
Width of the CSRR (e)	1
Gap of the CSRR (G)	1
Length of the slot (g)	16
Width of the slot(f)	2

The resonance frequency is given by the relation,

$$f = \frac{c_0}{0.89(L+W)\sqrt{\epsilon_r}}. \tag{1}$$

In which, c_0 is the velocity of light, while W and L indicate the width and length of the patch correspondingly, for a dielectric constant ϵ_r. A length 0.22 λ_0 of CSRR metal from the mid-upper portion of the ground plane has been imprinted to produce a Defected Ground Structure groove on the ground plane, where λ_0 is the free-space wavelength associated with the resonance frequency. The introduction of the defected ground structure adapts the bandpass and bandstop characteristics of the antenna, consequently leading to a display of new resonance behavior. A microstripline feeding technique is applied to feed the antenna structure. The parameters and dimensions details of the antenna are tabulated in Table 1. Equations (2)-(9) are used to extract equivalent circuit model values for the patch segment and defected ground structure [11], [12]:

$$C_s = \frac{\tan(\beta s)}{\omega_0 Z_0}, \tag{2}$$

$$C_P = \frac{\varepsilon_0 \varepsilon_e LW}{2h} cos^{-2}\left(\frac{\pi y_0}{L}\right), \tag{3}$$

$$R_P = \frac{Q}{\omega C_P}, \tag{4}$$

$$Q = \frac{c_0\sqrt{\varepsilon_e}}{4 f_0 h}, \tag{5}$$

$$L_P = \frac{1}{4\pi^2 f_0^2 C_P}, \tag{6}$$

$$C_{DGS} = \frac{\omega_c}{2Z_0\left(\omega_0^2 - \omega_c^2\right)}, \tag{7}$$

$$L_{DGS} = \frac{1}{4\pi^2 f_0^2 C_{DGS}}, \tag{8}$$

$$f_0 = \frac{1}{2\pi\sqrt{L_{DGS} C_{DGS}}}. \tag{9}$$

In these equations, s is the length of stub; Z_0 is the characteristic impedance, β is the wave number; C_S is the capacitance of source; h is the thickness of substrate; while L_{DGS} and C_{DGS} are the values of inductance and capacitance of the Defected Ground Structure equivalent circuit, respectively. Furthermore, ω_0 is the angular resonance frequency; yo is the distance from the patch edge to the feed point; and ω_c is the angular lower 3-dB cut-off frequency. The coupling coefficient (K_1) between the inductors is given by:

$$K_1 = \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2}. \tag{10}$$

Here, f_m and f_e are the frequencies consistent to the upper and lower 6-dB points around the resonance frequency, and these positions are referred to as the magnetic and electric walls, respectively. Using equation

(10) a value of K_1= 0.06 is obtained [13]. All known parameter values were substituted in equations (4)-(8), and the unknown parameters were found by the calculation - C_{DGS} = 2.25 pF, R_P = 59.8Ω, L_{DGS} = 2.77 nH, C_S = 22.5 pF, and L_P = 0.62 nH; since f_m and f_e are 2.25 GHz and 2.8 GHz respectively. Using the Advance Design System (ADS - 2017), the equivalent circuit model shown in Fig. 2 is simulated using the computed parameters. The reflection of measured coefficients (S_{11}) and simulated results are compared with the response of the ECM as depicted in Fig. 7. Meanwhile, the mutual coupling between the defected ground structure and patch leads to a variation of the antenna input impedance, due to a modification of the ground distribution. The fringing field effect is altered by these distribution variations, thereby changing the effective dielectric constant. According to the equation (5), the effective dielectric constant is directly proportional to the square of the quality factor (Q). Furthermore, the quality factor is inversely proportional to the antenna's bandwidth (BW), as can be observed from the relationship:

$$BW = ((VSWR) - 1)/Q\sqrt{VSWR}. \quad (11)$$

Hence, effective dielectric constant changes due to the introduction of a Defected Ground Structure influence the antenna bandwidth and the quality factor.

III. RESULTS AND DISCUSSION

A. Impedance of input

The computer-generated reactance (X_{in}) and input resistance (R_{in}) values with various defected ground structure placements are demonstrated in Fig. 3. The impedance of the antenna is matched to 50Ω through a quarter wave transformer. However, due to the resulting shape discontinuities, the antenna suffers from spurious radiations, which lead to increased cross-polarization. In this design, parallel slots are introduced near the edge feed to reduce cross-polarized radiation. The impact of shifting the CSRR defected ground structure to various positions is shown in Fig. 3 (a). The value of W_{SUB} is set at 50 mm, following which the placement of the CSRR defected ground structure is altered according to the positions illustrated in Fig. 1 (c). The position corresponding to the best impedance match is identified. Fig. 3 (a)-inset shows the antenna rear view with the final proposed position. The recommended placement of the defected Ground structure is position PP, where the best value of Rin= 50 Ω and Xin = 0 are attained at the resonance frequency of 2.6 GHz. The variation in values of the input resistance trail the Gaussian distribution, whereas where the changes in the input reactance approximate a cosine distribution, which further clarifies the choice of the recommended placement. Variations in the current distribution on the ground cause the impedance value to increase or decrease, depending on the position of the CSRR. Here, the impact of surface current distribution on the fringing effect is low at different positions. However, a maximum distribution occurs at the proposed position because of proper impedance matching and less spurious radiation. The proposed location of the defected ground structure is further investigated with respect to its impact on the antenna reflection coefficient, as displayed in Fig. 4.

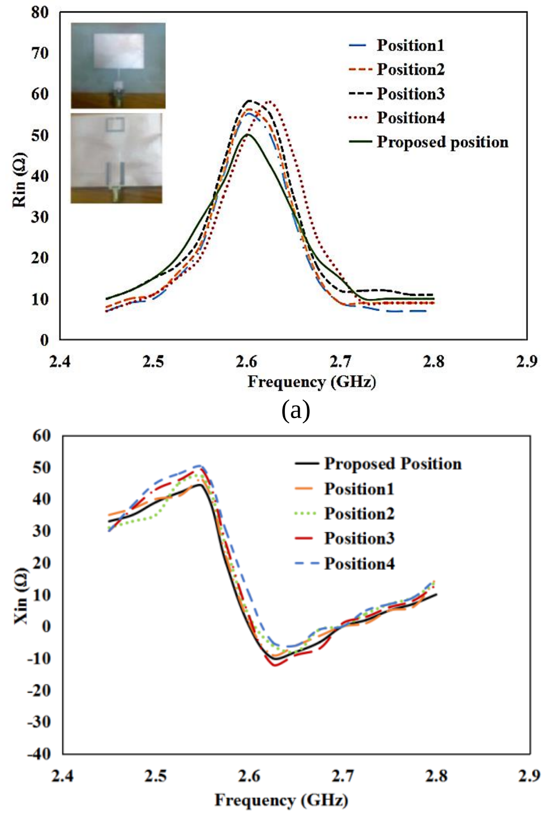

Fig. 3. Impedance of the defected ground structure loaded antenna for various locations of CSRR on the ground plane: (a) input resistance (R_{in}), and (b) input reactance (X_{in}).

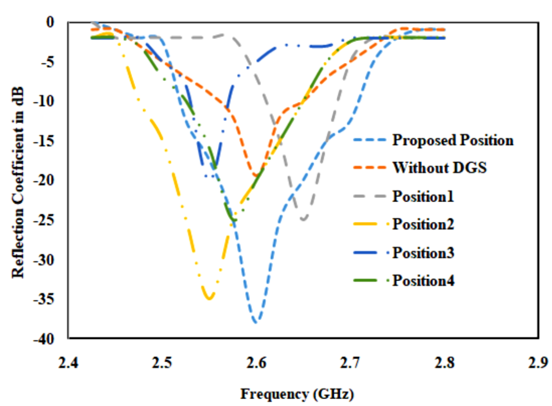

Fig. 4. Differences in simulated reflection coefficients for position deviations of the defected ground structure.

In this study, it can be observed that the resonance frequency increases as the CSRR is shifted vertically downwards. In addition, shifting the CSRR position to the left or right of the center axis changes the anticipated resonance frequency, with lower levels of reflection coefficient attained in both cases than with vertical displacement of CSRR position. Therefore, the location of the defected ground structure plays a crucial role in input impedance matching. The cross-polarization performance is affected by the surface current distribution. The patterns of surface current distribution are likewise dependent on the position of the defected ground structure (i.e., CSRR+slots). An odd-symmetric pattern is needed to reduce the cross-polarization. As a result of proper impedance matching with respect to the CSRR position, the reflection coefficient and surface current distributions are optimum and hence the cross polarization performance changes.

B. Distribution of surface current and performance of cross polarization

In Fig. 5, the surface current vector for the proposed location of the defected ground structure is demonstrated. As a result of the inclusion of a defected ground structure, surface current distribution is altered. The defected ground structure location is adjusted to provide an odd-symmetric pattern in order to reduce the cross-polarization.

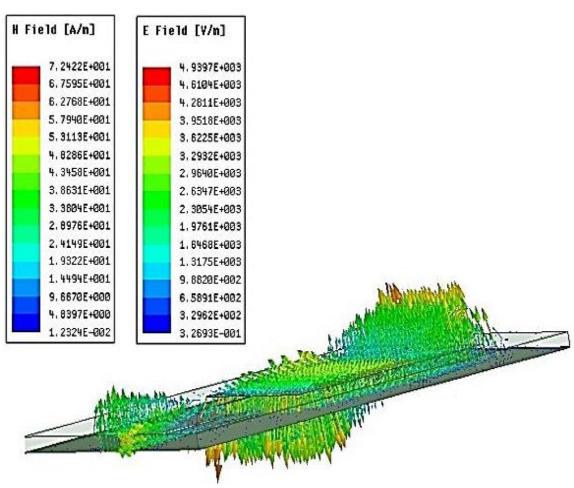

Fig. 5. Distribution of surface current vector and magnetic field paths of CSRR defected ground structure slots of proposed antenna.

No other defected ground structure positions were observed to show the x-axis oriented odd-symmetric surface current paths in the H-plane, as depicted in Fig. 6. Hence, the recommended defected ground structure positioned at middle leads to acceptable surface current vector distributions and lower levels of cross-polarization.

There is no significance alteration in the observed co-polarization patterns as a consequence of the positioning of the defected ground structure. However, the H-plane cross-polarization patterns posted significant changes. The proper termination of radiated fields for the recommended location of defected ground structure containing the CSRR shape leads to a regular cross-polarization pattern in the H-plane, with a comparative decline in cross-polarization of 44 dB over ± 50°, compared to the other defected ground structure locations.

C. Measurement results

Using an appropriate experimental setup in order to authenticate the performance of the proposed prototype antenna, the reflection coefficient and the radiation patterns are measured after the model fabrication. Figure 7 summarizes a comparison of simulated and measured reflection coefficients, with and without the Defected Ground Structure over an operating frequency range.

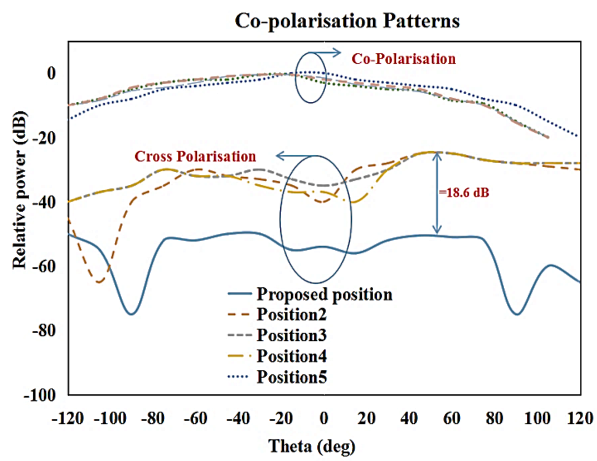

Fig. 6. Patterns of co-polarization for the H- and E-planes and the patterns of cross-polarization for the H-plane.

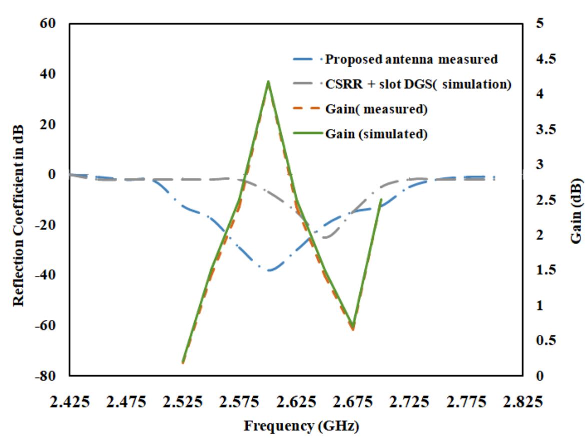

Fig. 7. Characteristics of S_{11} vs frequency, and gain vs frequency.

Table 2: Comparison of the performance of the proposed structure with related works

S. No	Methodology	Frequency (GHz)	Cross Polarisation Reduction (dB)	Improvements in Impedance Matching (dB)	Year
[4]	Pair of short pins	2.241,2.478	16	No data	2009
[6]	DGS+Slotted patch	2-21	Reduced by H-Plane by 20 dB	Impedance matching reduced after insert DGS	2016
[7]	DGS	5.83-6.03	7-12	5.2	2016
[8]	DGS	9-10	15	Not mentioned	2014
[9]	Parallel slots as DGS	2.9,6	For both band 15 dB reduction is achieved	No data	2018
[14]	Horizontal meandered dipoles and vertical parasitic elements	1.71-2.69	10	No data	2019
Proposed	**CSRR+Slots parallel to feed line**	**2.59-2.75**	**18.6**	**24**	

From this result, it can be determined that, on introducing a Defected Ground Structure will make a change in the operational band of 2.62 GHz –2.70 GHz to 2.59 GHz–2.75 GHz. In addition, the resulting impedance matching upgrades the reflection coefficient from 30 dB (S_{11}without Defected Ground Structure) to 54 dB (S_{11} with Defected Ground Structure). A close agreement is observed between the results of ECM response and measured electromagnetic model as shown in Fig. 8.

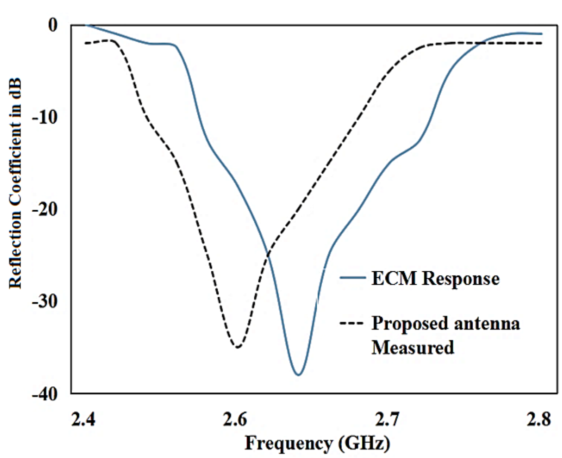

Fig. 8. Proposed antenna measured vs equivalent circuit model response (ECM).

Over the whole functioning band, the advantage is in the range of tolerance and it demonstrates a maximum peak gain of 4.16dB at the resonance frequency. In this investigation, the improvement of bandwidth using defected ground structure, comprising of a CSRR and slots, is around 200 MHz. Although the level of bandwidth improvement is modest, this approach can be useful to the study of any defected ground structure shape to improve impedance matching, as well as increase microstrip patch antenna bandwidth. To further clarify the benefits of the proposed method over the earlier reported methods, the Table 2 shows that the proposed design is much simpler and can achieve greater levels of cross-polarization reduction, alongside a better matching of impedance.

IV. CONCLUSION

The applicability of a defected ground structure for better impedance matching and a lower level of cross-polarization have been successfully studied. The use of an ECM enabled an understanding of the impact of the inclusion of a CSRR and slots as a defected ground structure on the rectangular microstrip patch antenna. The CSRR positioned at the mid-upper region of the ground plane was shown to offer improved impedance matching results, and a low, uniform cross-polarization over an angle range of $\pm 50°$.The achieved performance is encouraging when compared to the similar reported works. Finally, this study presents a useful insight to optimizing the location of a defected ground structure for a deliberate suppression of cross-polarization and impedance matching improvement.

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