Design and Analysis of Highly Isolated Slotted Circular Ring UWB MIMO Antenna with Band-Notched Characteristics

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Abstract

In this article, a novel and compact aperture area of 40 x 40 x 1.6 mm^3 four-port Slotted Circular Ring (SCR) Ultra Wideband (UWB) MIMO antenna with notch band characteristics and high isolation is proposed. This work is predominantly concentrated on development of an UWB-MIMO antenna with less design complexity and good performance, which emphasizes the concerted effort to enhance communication efficiency while minimizing the intricacies inherent in the design and implementation of UWB technology. Hexagonal structure merged with SCR enhanced the impedance bandwidth from 13.66 to 14.31 GHz, which is suitable for C-band, X-band and Ku-band applications. It covered the UWB from 4.19 to 18.5 GHz with a notch at C-band (5.06 to 5.64 GHz). In order to obtain isolation >25 dB, neutralization lines (NL) are placed between the antenna elements. Acceptable findings were obtained when evaluating the antenna's performance in terms of diversity characteristics such as ECC, TARC, and DG. The maximum return loss ($|S_{11}|$) of 24.94 dB is achieved at 4.77 GHz. The measured results of the fabricated prototype and the simulated results are in good agreement.

Keywords: Circular ring, Hexagonal, Notch band, UWB, MIMO, Isolation.

1. Introduction

Ultra-Wideband (UWB) technology operates over an extremely wide frequency band, enabling high data rates and precise localization [1]. The challenge lies in harnessing these capabilities to achieve superior performance in Multiple-Input Multiple-Output (MIMO) systems without introducing unnecessary design complexity. Simplicity in design is sought to minimize the challenges associated with system implementation, deployment, and maintenance. By mitigating complexity, the aim is to make the MIMO system more accessible, cost-effective, and easier to manage which involves striking a delicate balance between technological advancements that enhance communication capabilities and the pragmatic considerations [2].

In [3], the author developed a low-profile two-port fractal MIMO antenna and etched a U-shaped slot to achieve a notch band (3.3–3.7GHz) and horizontal stubs on the ground plane for second notch band. Even though, the design is compact in size, additional effort in terms of fabrication and tuning may require to ensure that the self-similar patterns are accurately replicated. Two monopole patches and stub with shared ground plane is proposed in [4], a rectangular slot is etched on the radiating element to attain the WLAN notch band from 5.1 GHz to 5.9 GHz. Different techniques were suggested by researchers to generate notch bands which includes band-stop filter [5], Defected Ground Structure (DGS) [6], Stub or Parasitic element [7], loading filter structures [8].

In order to enhance the antenna performance, isolation plays a key role in MIMO systems. Authors effectively used a shared radiator with small rectangular slots [9] to reduce the interference and achieved the bandwidth of 9.2 GHz. A four-port planar MIMO [10] combined with four different geometrical pairs achieved the UWB and the enhanced isolation of >35dB. The main drawback of this design is more complexity. By keeping in view of all the drawbacks from the literature survey, to overcome the disadvantage like complexity, a novel and compact SCR design without compromising the antenna performance, is proposed in this paper. The step-by-step design process of the proposed structure is described in Section II followed by the achieved simulated and the measured result analysis in Section III and concluded in Section IV.

2. Proposed Slotted Circular Ring UWB MIMO Antenna Design

The design evolution of proposed SCR UWB MIMO antenna is illustrated in Figure 1. The overall physical volume of the proposed design is 40 x 40 x 1.6 mm^3. It is printed on FR4_epoxy substrate with dielectric constant (ϵ_r = 4.4) and loss tangent (tan δ) = 0.02. This substrate is of low cost and available for fabricating the prototype in our laboratory. Initially, four solid circular radiating elements with radius $r_1 = 6$ *mm* are positioned orthogonal to each other on one side of the dielectric material and full ground on the other side as illustrated in Figure 1(a). Figure 1(a) covered multiple operating bands at higher frequencies. In order to cover the lower frequency bands, full ground plane is altered to partial ground plane as presented in Figure 1(b). Further, to enhance the impedance bandwidth circular slot with radius $r_2 = 4$ *mm* is etched on the solid patch to convert it as circular metallic ring as shown in Figure 1(c).

Table I. Dimensions of the proposed structure (in millimeter)														
Parameters	L_S	W_S	L_g	W_g	L_f	W_f	r_1	r_2	g_1	g_2	g_3	L_H	L_N	W_N
Dimensions	*40*	*40*	*20*	*6.2*	*7.29*	*3*	*6*	*4*	*2*	*2*	*8*	*2.9*	*9*	*1*

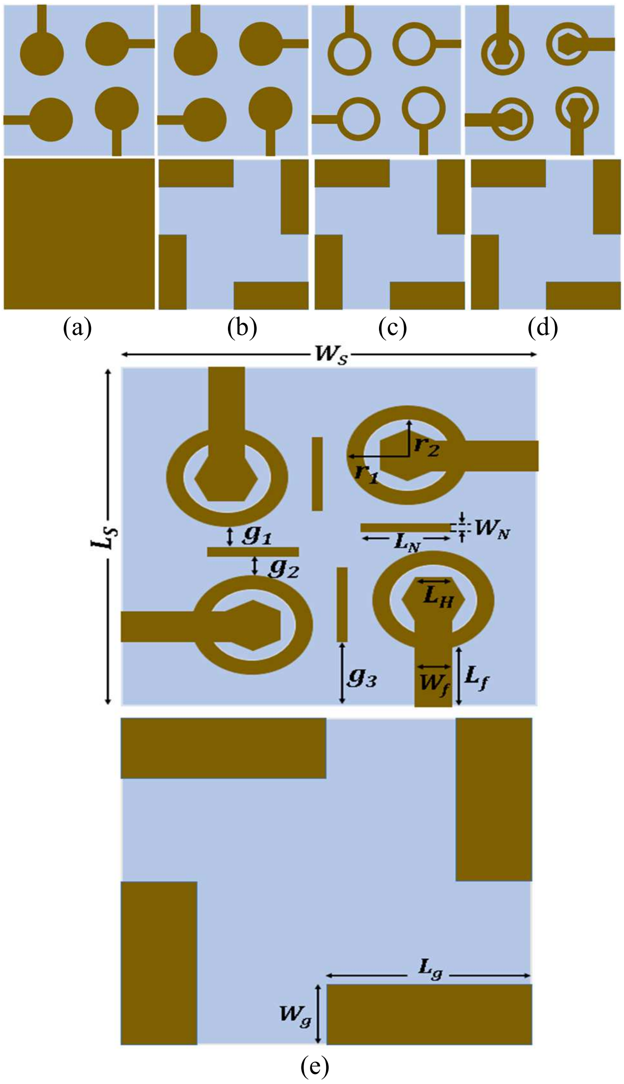


Figure 1. Design evolution of the SCR UWB MIMO

In addition, as illustrated in Figure 1(d), a hexagonal structure is embedded at the center of the patch with extension to the feedline which enhances the impedance bandwidth. Also, the open ring slot between the circular ring and hexagonal structure acts as a resonator and generated a notch band in C-band. Figure 1(e) shows the complete structure of the 4-port SCR UWB MIMO structure along with NL to enhance the isolation between the radiating elements and the optimized dimensions are tabulated in Table I.

3. Results and Discussion

The step-by-step design procedure and the optimized dimensions was discussed in Section II. The reflection coefficient (S_{11}) at different evolution steps is shown in Figure 2. It is observed that the solid patch with full ground (Figure 1(a)) achieved multiple bands from 10.93 GHz frequency. Figure 1(b) covered the lower frequency bands and covered the impedance bandwidth of 13.66 GHz (4.84 to 18.5 GHz), due to alteration of ground plane. Further, as a result of etching the circular slot on the solid patch (Figure 1(c)), the impedance bandwidth is enhanced from 13.66 GHz to 14.02 GHz (4.48 to 18.5 GHz).

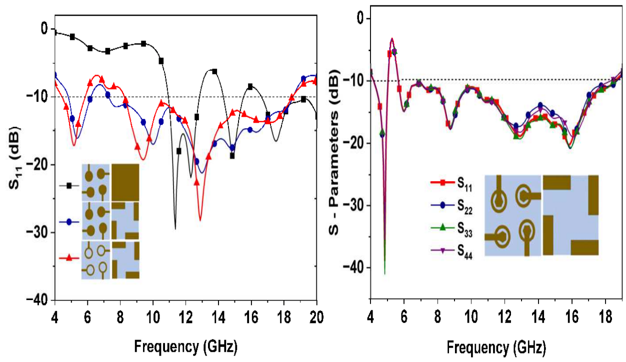


Figure 2, 3. Reflection coefficient at different evolution steps and UWB MIMO slotted patch

Figure 3 represents the S_{11}, S_{22}, S_{33}, S_{44} vs. frequency of the SCR with hexagonal structure embedded at the center of the metallic ring. (Figure 1(d)). From the results obtained through simulation, it is clearly observed that the impedance bandwidth is further increased from 14.02 to 14.31 GHz (4.19 GHz to 18.5 GHz) by embedding the hexagonal structure. It is also noted that the maximum $|S_{11}|$ of 24.94 dB is attained at 4.77 GHz frequency. An open ring slot can be observed between the circular strip and hexagonal structure which acted as a $\lambda/2$ resonator and generated a notch at C-band (5.06 - 5.64 GHz) with notch center frequency of 5.35 GHz. The length of the slot is based on (1) [11]

$$L_{Notch} = \frac{c}{2f_{Notch}\sqrt{\epsilon_{reff}}} \qquad (1)$$

Where L_{Notch} represents the slot length, f_{Notch} is the desired notch frequency, $\epsilon_{reff} = \frac{1+\epsilon_r}{2}$ and 'c' is the speed of the light.

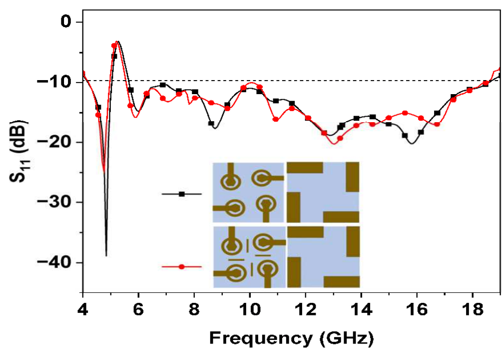


Figure 4. S_{11} of the proposed design with and without NL

MIMO comprises the use of multiple antenna at both transmission and reception ends, where multiple data streams are transmitted simultaneously. To achieve high data rates and to avoid cross-talk, isolation among the antenna elements helps to decrease the interference between them.

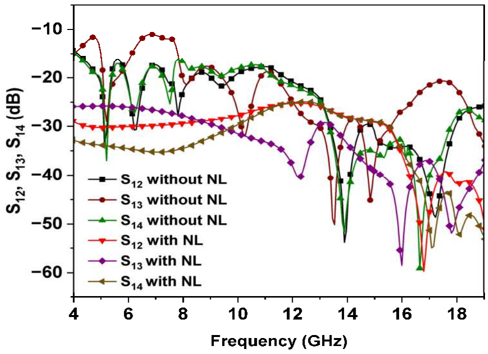
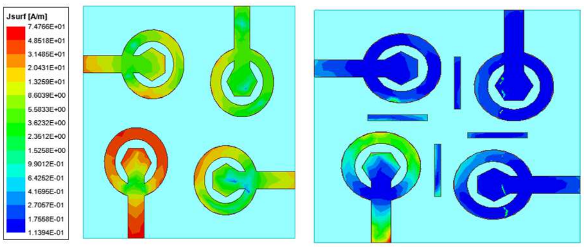


Figure 5. Isolation comparison with and without NL



(a) (b)

Figure 6. Surface current distribution (a) without and (b) with NL

A Neutralization line (NL) is placed between the antenna elements to improve the isolation between the radiating elements. In many wireless communication systems, this method of improving the isolation between neighboring elements is more simple and efficient. In order to decouple the current flow between the closely spaced radiating elements, NL facilitates the field cancellation between the adjacent elements. The characteristics like antenna impedance are altered by this field cancellation, improving the isolation. The S_{11} of the proposed antenna with and without NL is shown in Figure 4. It is observed that the isolation technique does not effected the impedance bandwidth. The isolation between the adjacent elements with and without NL is verified and plotted as Figure 5. Results shows that the isolation enhanced from 12 dB to >25 dB, due to the incorporation of NLs. And the effect of current distribution with and without isolation technique is shown in Figure 6.

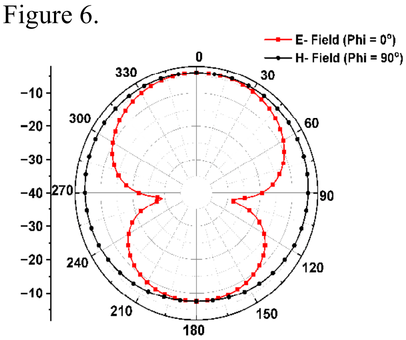


Figure 7. Radiation pattern at 4.25 GHz frequency

The far-field radiation pattern of the proposed antenna at 4.25 GHz frequency is depicted in Figure 7. The proposed SCR UWB MIMO antenna with partial ground plane radiates effectively for the entire UWB. The E-Plane (Phi = 0^0) exhibits the dipole like pattern and the H-Plane (Phi = 90^0) exhibits the omnidirectional pattern. The performance parameters of the proposed design is also investigated in terms of Envelope Correlation Coefficient (ECC), Total Active Reflection Coefficient (TARC), Diversity Gain (DG). Low ECC value usually < 0.5 indicates less correlation between the signals received by various antennas. ECC can be calculated using (2) [12],

$$ECC = \frac{\left|\iint_{4\pi}[E_i(\theta,\phi) \times E_j(\theta,\phi)]d\Omega\right|^2}{\iint_{4\pi}|E_i(\theta,\phi)|^2\, d\Omega \times \iint_{4\pi}\left|E_j(\theta,\phi)\right|^2 d\Omega} \quad (2).$$

The ECC of the proposed design is shown in Figure 8 and it is < 0.07 which is in acceptable range. Greater TARC value represents performance reduction, minimizing TARC becomes essential. The TARC value is < -10 dB, depicted in Figure 8 indicates good isolation and antenna performance.

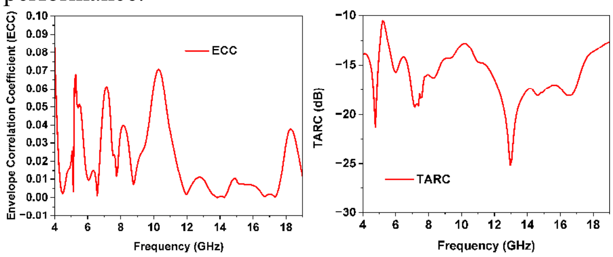


Figure 8. ECC and TARC

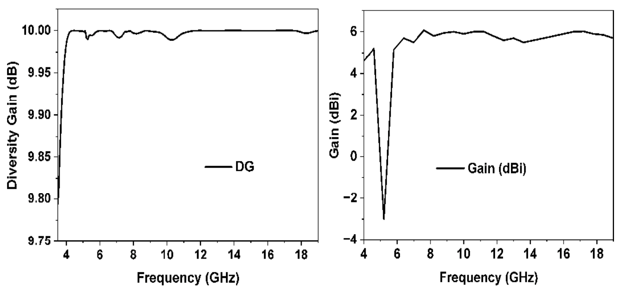


Figure 9, 10. Diversity gain and Gain (dBi)

The performance of the systems improves with increase in diversity gain which is ≅ 10 dB and it is calculated using (3) [13],

$$\text{DG} = 10\sqrt{1-(ECC)^2} \quad (3)$$

The diversity gain of the proposed antenna is ≥ 9.998 dB, depicted in Figure 9. The proposed design achieved maximum gain of 6.24 dBi illustrated in Figure 10 and observed low gain at notch band. The fabricated prototype and the measurement setup of the proposed design are displayed in Figure 11. The simulated and the measured S_{11} and isolation parameters are in good agreement, represented in Figure 12. Slight distortions are observed in the measured results due to fabrication losses. The simulated and fabricated design is compared with conventional MIMO designs and tabulated in Table II.

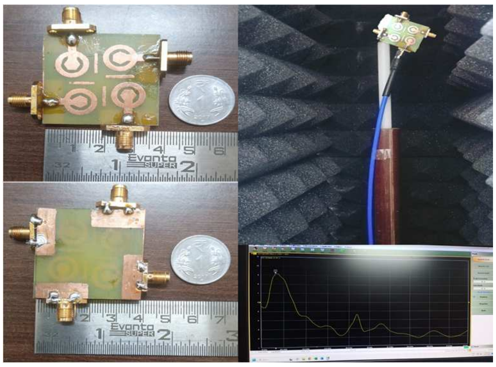
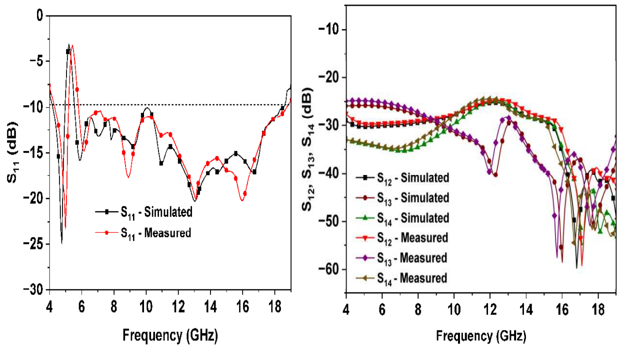


Figure 11. Top, bottom view of the fabricated prototype and Measurement setup



(a) (b)

Figure 12. Simulated vs. Measured results

Table II. Comparative analysis of the proposed antenna with conventional designs

Ref.	*Geometry mm²*	*Bandwidth (GHz)*	*Frequency range (GHz)*	*No. of elements*	*Notch bands*	*Isolation (dB)*	*Gain (dBi)*	*ECC*	*TARC (dB)*	*Diversity Gain (dB)*
[3]	*26 x 35*	*8.6*	*2.0–10.6*	*2*	*2*	*> 22*	*≥ 3.5*	*0.2*	*-*	*-*
[4]	*22 x 30*	*10.9*	*3.1-14*	*2*	*1*	*>23*	*5.8*	*<0.002*	*-*	*>9.98*
[9]	*52 x 26*	*9.2*	*2.3-11.5*	*2*	*-*	*>16*	*5*	*<0.005*	*-*	*9.998*
[10]	*35 x 35*	*7.5*	*3.1-10.6*	*2*	*-*	*>35*	*-*	*<0.001*	*<-10*	*9.999*
This work	*40 x 40*	*14.31*	*4.19-18.5*	*4*	*1*	*>25*	*6.2*	*<0.07*	*<-10*	*≥ 9.998*

4. Conclusion

A simple and low-complex SCR UWB MIMO antenna is designed using ANSYS HFSS and fabricated. The proposed structure covered the impedance bandwidth of 14.31 GHz suitable for C, X, Ku applications. A notch band is achieved at C-band with the center frequency of 5.35 GHz. It also attained the maximum return loss of 24.94 dB at 4.77 GHz. Neutralization line effectively reduced the mutual coupling and enhanced the isolation to 25 dB. Diversity parameters like ECC<0.07, TARC <-10 dB and DG ≥ 9.998 are achieved. The measured results and the S_{11}, S_{12}, S_{13}, and S_{14} simulation results correspond well.

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