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A Modified SRR-Based Miniaturized Monopole Antenna with Ultra-wide bandwidth for Wireless UWB Systems

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An offset fed split ring resonator (SRR) based compact printed antenna is analyzed for Ultrawide-band (UWB) applications. The suggested antenna has been designed and analyzed using High frequency structure simulator (HFSS) on a low-cost FR-4 substrate. The top plane of the designed antenna consists of circle and semicircle combined split ring resonator (SRR). The partial rectangular ground along with a semicircular slot is introduced on the back side of the substrate for impedance matching improvement in all over the wide range of frequencies. The offset feed is used for the adjustment of radiation pattern. The fabricated antenna prototype is realized and experimentally tested to authenticate the results obtained from simulation study. This proposed antenna covers the UWB range extending from 3.8 GHz to 14.9 GHz. The proposed compact antenna dimension is $18 \times 20 \times 1.6$ mm^3. The proposed antenna achieved a maximum gain of 15 dB at 3.8 GHz. It maintains stable radiation patterns across the operating band. Hence, the obtained results and compact size of the proposed antenna is ideally suited for various wireless applications including wireless local area network (WLAN), Internet of things (IOT), X-band satellite communication, and UWB systems.

Keywords: Microstrip Antenna, Partial ground plane, Split ring resonator, Wireless communication, UWB.

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1. INTRODUCTION

A wide-band antenna is a device that can operate across a wide range of frequencies, generally covering a large spectrum. These antennas transmit and receive signals efficiently throughout this wide frequency band, enabling high-data-rate communication in radar, sensing, and IoT applications [1-2]. These antennas offer advantages like less complexity, minimal power consumption, high data transmission, less interference, robust resolution in the time domain and resilience to intense multipath interference [3]. Adopted antennas are required based on the desired radiation characteristics for each application [4]. Because of high bandwidth, quick communication, low power consumption, and low-cost, the wide-band antennas gained more attention in new wireless communication applications [5-6]. One of the primary reasons for the vast studies being conducted in the UWB IoT antenna field is the ability to achieve location monitoring and positioning [7]. Hence, Wide-Band antennas are a promising technology that can offer significant benefits in various wireless communication applications.

Microstrip patch antennas are a more practical option due to their ease of integration with microwave circuit components, conformal structure, and low profile [8]. One of the main limitations of microstrip patch antennas is their narrow impedance bandwidth, which restrict itsapplication in wide-band systems. To overcome this issue, researchers have proposed various techniques such as increasing substrate thickness, using low permittivity substrates, loading the patch with slots [9], using parasitic elements [10], and incorporating electromagnetic band gap structures [11]. Then, metamaterial-based microstrip patch antennas are introduced for larger bandwidths [12-13]. In particular, Split Ring Resonators (SRR) based antennas have attracted significant interest due to their resonant property, which enables them to function as electrically compact resonators with small electrical sizes [14]. Each wide-band application demands customized antenna designs that meet specific radiation characteristics. Modern wireless systems like IoT-based wideband applications demand antennas with specific requirements, including compact physical size, wider operating bandwidth, and ease of implementation and development with electronic devices. Additionally, antennas must be easily integrated with electronic gadgets, enabling straightforward development and implementation.

This article presents a compact ultra-wideband antenna for WLAN, X-band satellite communication, IOT and UWB systems, featuring a dual semicircle and circle SRR-based design with an offset feed transmission line. The antenna operates across the vast communication spectrum (3.8 GHz to 14.9 GHz) and can maintain proper performance despite its small size. This design effectively addresses the challenge of confining wideband antenna dimensions in IoT applications, making it a practical solution for IoT devices where space is limited.

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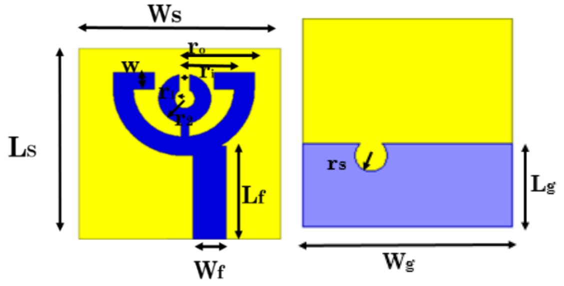
2. DESIGN CONFIGURATION OF PROPOSED MODIFIED SRR MONOPOLE ANTENNA

The antenna design process includes the configuration of both circle and semicircle combined SRR. The design of a circle and semicircle combined SRR antenna is printed on FR4-dielectric substrate material ($\varepsilon_r = 4.4$) with 1.6 mm thickness. To optimize and validate the antenna design HFSS simulation software has been utilized. The layout of the proposed antenna is depicted in Fig. 1. A partial ground structure and offset feed have been implemented to achieve ideal impedance matching across the entire wideband. The offset feed also provides an omnidirectional pattern at specific frequency points. The magnetic response is created by an additional circular SRR which is introduced along with the semicircle SRR. When the antenna is excited with a 50 Ω impedance, the feed induces an EM force around the SRR. Also, the current flows through each circle leads to the SRR as an LC resonator.



(a) (b)

Fig. 1 – Proposed Antenna Structure (a) patch (b) ground plane

The following formulas are used to determine the semicircle and circle diameters as well as the resonance frequency of the proposed antenna.

Total length of semicircle,

$$L = \pi r + l - w - 2s, \tag{1}$$

where *r, l, w, s* are radius, outer length, width of the strip, thickness of strip, respectively semicircle resonant frequency,

$$f_0 = \frac{c}{2L\sqrt{\varepsilon_{eff}}}, \tag{2}$$

where c – speed of light, L – total length of CSRR, ε_{eff} – effective permeability

$$\varepsilon_{eff} \approx \frac{\varepsilon_r + 1}{2}. \tag{3}$$

The Circle SRR resonant frequency formula is derived from the solution of the electromagnetic wave equation inside the resonator [15], subject to the boundary conditions at the interface between the metal and the dielectric.

$$f_r = \frac{c}{2\pi^2}\sqrt{\left(\frac{3(r_2 - r_1 - w)}{Re(\varepsilon_r) r_1^3}\right)}, \tag{4}$$

where r_1 – inner radii of the circle, r_2 – outer radii of the circle w – dielectric layer thickness, c – speed of light, ε_r – relative permittivity of the dielectric material, and Re denotes the real part of a complex quantity.

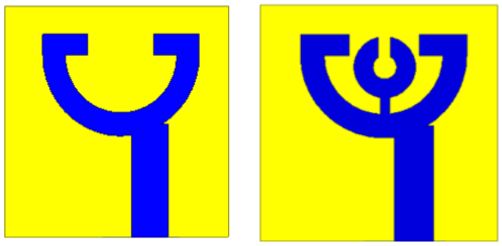
The optimized design values antenna geometries are given in Table 1.

Table 1 – Antenna dimensions

Parameters	Dimensions (mm)
Ls	20
Ws	18
Wg	18
Lg	8
Wf	3.25
Lf	9.75
rs	1.54
ro	7
ri	5
$r1$	2.6
$r2$	1
w	2

3. RESULTS AND DISCUSSION

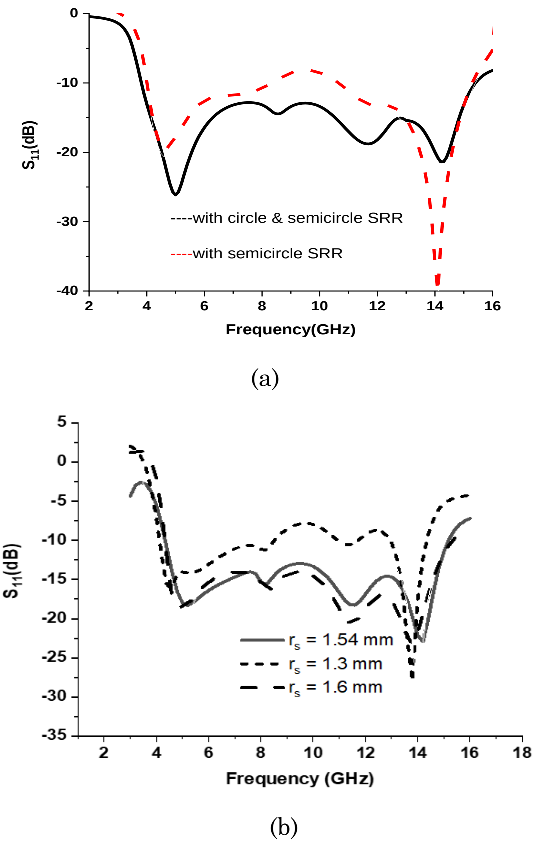
The implementation of split-ring resonators (SRRs) in antennas has gained much interest in recent years because of their potential to improve antenna performance over a range of frequency [16]. The design steps are shown in Fig. 2 (a-b). In Fig. 2 (a), the antenna with semicircle SRR is designed. Due to impedance loss in center frequencies, another circular SRR has been included along with semicircle SRR which gives better response over the designed frequencies. The modified design with the addition of circular SRR is depicted in Fig. 2 (b).



(a) (b)

Fig. 2 – Iterations of designed antenna (a) semicircle design (b) circle and semicircles design

The resonance frequency of the SRR is adjusted by its geometries, such as the ring diameter and gap width. Optimizing the SRR placement, dimensions, and material properties can influence the coupling effect. Also, the antenna with and without circle and semicircle SRR has been analyzed as shown in Fig. 3(a). Furthermore, the effect of circular slot radius embedded in the ground plane is analyzed parametrically. The results of S_{11} variations for various slot radius is illustrated in Fig. 3(b).

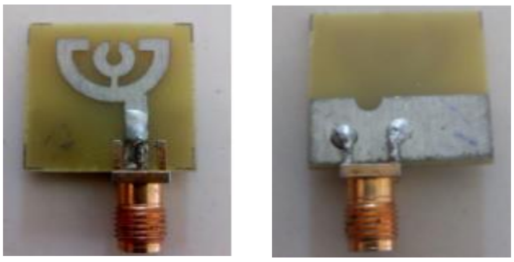


(a)

(b)

Fig. 3- S_{11} (dB) vs. Frequency (GHz) analyses for (a) design steps (b) ground plane circular slot radius variations

The proposed antenna structure was fabricated and tested using vector network analyzer. The proposed designed antenna both front and back sides are illustrated in Fig. 4.



(a) (b)

Fig. 4 – Fabricated Antenna structure (a) front view (b) back view

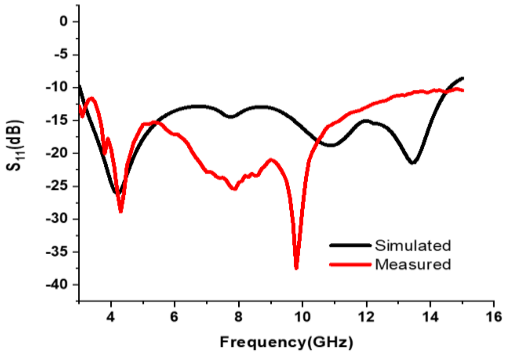


Fig. 5 – Simulated vs. measured reflection coefficient (S_{11})

The antenna's measured and simulation reflection coefficients (S_{11}) are shown in Fig. 5. According to the results, ultra-wideband frequency range was observed from 3.8 – 14.9 GHz in simulation and as per measurement, 3.8 to 15 GHz UWB range is covered at – 10 dB level of S_{11}. The simulated and measured S_{11} characteristics of the proposed antenna shows significant difference between them. This may be due to the fabrication process, minor deviations in component placement, material properties, or manufacturing tolerances can affect the antenna's performance. These variations may not be accounted for in the simulation, leading to inconsistencies with the measured data.

Fig. 6 depicts the proposed antenna gain plot for entire designed frequency range. Gain value varies from 0.05 to 15 dB across the entire operating range. A minimal gain of 0.05 dB was obtained at 14.9 GHz, while a maximum gain of 15 dB was observed at 3.8 GHz. Due to substrate material loss at high frequency range gain value decreased.

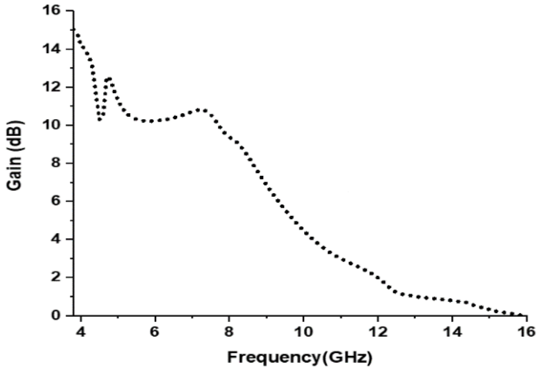


Fig. 6 – Simulated Gain vs frequency Plot

In Fig. 7, the proposed antenna current distribution is illustrated both on antenna surface and on the ground plane respectively at 5.08 GHz, 8.2 GHz, 11.44 GHz and 14.2 GHz. The observed current distribution indicated that semicircle monopole structure part is responsible for lower band frequency 5.08 GHz, whereas ground plane and circle shape SRR is responsible for 8.2 GHz and 11.44 GHz respectively. While circle together semicircle both together responsible for higher band frequency 14.2 GHz.

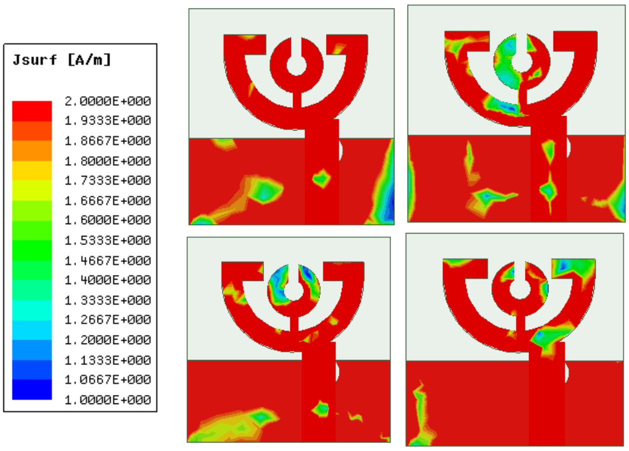
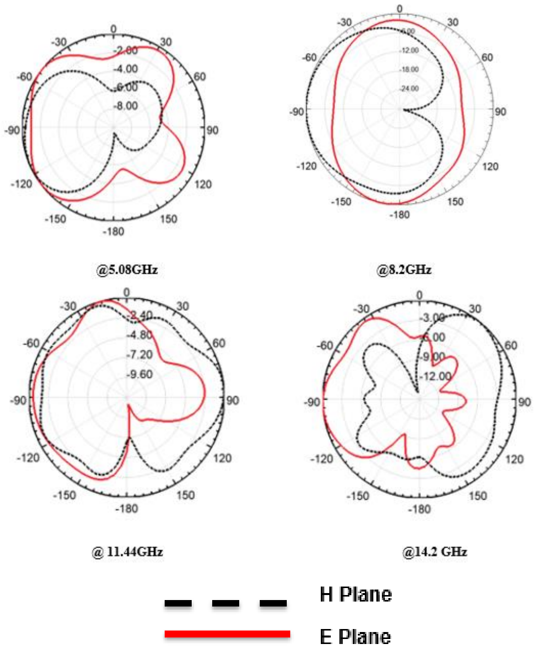


Fig. 7 – Current distributions at (a) 5.08, (b) 8.2, (c) 11.44 and (d) 14.2 GHz

Fig. 8 shows the simulated radiated patterns of proposed antenna along the vertical and horizontal plane at 5.08 GHz, 8.2 GHz, 11.44 GHz, and 14.2 GHz. The antenna exhibits bi-directional radiation pattern in the elevation plane and nearly omnidirectional radiation characteristics along the horizontal plane at 5.08 GHz frequency. When frequency range exceeds 8.2 GHz, the patterns deform and adopt a distorted omnidirectional pattern. Higher-order modes stimulated at such frequencies are responsible for these distortions.



@5.08GHz @8.2GHz

@ 11.44GHz @14.2 GHz

Fig. 8 – Simulated radiation pattern of proposed antenna structure

Table 2 – Comparison of proposed work with recent existing work

Ref	**Structure of antenna**	**Operating frequency band (GHz)**	**Bandwidth (GHz)**	**Antenna Dimensions (mm³)**
[17]	defected ground plane based compact monopole antenna	3.89 GHz – 8.35 GHz	4.46	38.92 × 40 × 1.6
[18]	Square gap defected ground structure based dielectric resonator antenna (DRA)	3.5 – 11.6	8.1	35.3 × 30.6 × 1.6
[19]	Defected ground plane with SRR based Nested Circular Ring–Shaped Antenna (NCRA)	3.13 – 15.0	11.87	30 × 30 × 1.6
[20]	umbrella-shaped metallic ground plane	3.65 – 11.41	7.76	22 × 28 × 1.5
Proposed	Semicircle and circle SRR shape	3.8 – 14.9	11.1	18 × 20 × 1.6

Table 2 compares the performance of the proposed design with other significant existing antennas [17-20] in the literature with respect to structure, dimension and operating bandwidth. Similarly, other type of split ring resonators and other shapes of antenna structures occupies more area with complex structure to cover wide band spectrum. In comparison with existing structures, the proposed semicircle and circle combined SRR shape occupied just 18 mm × 20 mm ×1.6 mm = 576 mm^3 of volume with adequate gain for overall frequency bands and had a greater performance bandwidth of 11.1 GHz (3.8 to 14.9 GHz).

4. CONCLUSION

A miniaturized offset-fed monopole antenna with semicircle and circle SRR design has been developed, analyzed and tested experimentally. A perfect impedance matching and an ultra-wide bandwidth of 3.8 to 14.9 GHz are achieved. The designed antenna has increased bandwidth with reduced antenna space by 73.37% due to its optimum designed features of antenna parameters. The proposed antenna structure is simply adoptable with various modern wireless terminal devices as it holds a compact physical footprint of 18 mm × 20 mm × 1.6 mm. Moreover, it provides good average gain, nearly stable radiation pattern characteristics with compact design which makes it compatible for different wireless applications covering the bandwidth requirements of WLAN, X-band satellite communication, IOT and UWB systems.

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Модифікована мініатюрна монопольна антена на основі SRR із надширокою смугою пропускання для бездротових систем UWB

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Компактна друкована антена на основі розщепленого кільцевого резонатора (SRR) із зсувним живленням аналізується для застосувань у надширокому діапазоні (UWB). Запропонована антена була розроблена та проаналізована за допомогою симулятора високочастотної структури (HFSS) на недорогій підкладці FR-4. Верхня площина розробленої антени складається з комбінованого кільцевого роз'ємного резонатора (КРР) по колу та півколу. Часткове прямокутне заземлення разом із напівкруглим прорізом введено на задній стороні підкладки для покращення узгодження імпедансу в усьому широкому діапазоні частот. Виготовлений прототип антени реалізовано та експериментально перевірено для підтвердження результатів, отриманих у результаті моделювання. Ця запропонована антена охоплює діапазон UWB від 3,8 ГГц до 14,9 ГГц. Розмір запропонованої компактної антени становить 18 × 20 × 1,6 мм^3. Запропонована антена досягла максимального посилення 15 дБ на 3,8 ГГц. Він підтримує стабільні діаграми спрямованості в робочому діапазоні. Отже, отримані результати та компактний розмір запропонованої антени ідеально підходять для різноманітних бездротових застосувань, включаючи бездротову локальну мережу (WLAN), Інтернет речей (IOT), супутниковий зв'язок у діапазоні X та системи UWB.

Ключові слова: Мікросмужкова антена, Часткова заземлена площина, Розділений кільцевий резонатор, Бездротовий зв'язок, UWB.