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Ultra Wide Band (UWB) Antenna with improvement in Miniaturization, Gain and Bandwidth performance with Annular Ring approach

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Abstract
In this paper, authors propose a new way of improving the gain-bandwidth performance of Ultra-Wideband (UWB) antenna using annular ring arcs. Annular ring arc is portion of the annular ring with specific length and sector angle that contributes to effective aperture area of the antenna. Hence, such structure helps to improve gain-bandwidth performance of antenna. Length, width, and angle of ring-arc was calculated mathematically based on effective aperture of antenna. Placement of annular rings is another important factor discussed in this paper that was found by experimentation. The antenna design is finished within three iterations and finalized antenna was fabricated and tested. Measurement results and simulation results of antenna agreed. The antenna frequency band ranges from 2.1 GHz to 10.4 GHz with achieved size reduction of 38.74%. The antenna was fabricated on FR4 epoxy substrate with 0.8 mm thickness and dielectric constant of 4.4 and achieves acceptable return loss over the band of operation.

Keywords: UWB; GHz.

1. Introduction

Ultra-wide band antennas offer high data rates, low power consumption, and low cost [1-2]. As wireless portable devices require antennas that operate in multiple frequencies for different wireless protocols, the number of operation bands and functions is increasing, which presents challenges in antenna design. However, UWB antennas can replace multiple narrow-band antennas, effectively reducing the number of antennas to be put inside the product [3]. Some of the recent applications of UWB are [4]:

a. Precision locating and tracking: UWB can provide precise location and tracking information for people, vehicles, and objects in real-time.
b. Wireless communication: UWB provides high data rates, low power consumption, and low cost and replaces multiple narrow-band antennas with single antenna [5].
c. Radar imaging: UWB radar imaging provides high-resolution images of objects, structures, and environments in various fields, including medical imaging, security, and automotive.
d. Non-destructive testing: UWB can detect and identify defects, cracks, and damages in various materials, including concrete, metal, and composites, without damaging the material.
e. Short-range communication: UWB can provide secure and reliable short-range communication.

One of the most widely used standards for UWB communication is IEEE 802.15.4a, which defines the physical layer and medium access control layer for UWB communication. This standard provides a data rate of up to 27 Mbps and a range of up to 100 meters. Another standard that supports UWB technology is the WiMedia Alliance's UWB Common Radio Platform (UWB-CRP) [6]. This standard provides a data rate of up to 480 Mbps and a range of up to 10 meters, making it suitable for high-speed wireless communication applications [7-9].

With the increasing miniaturization and complexity of electronic devices [10], UWB antennas with a smaller size and weight can improve the portability and usability of these devices [11]. The development of new UWB antenna designs can improve the performance and usability of UWB technology in various applications [12-13]. UWB antenna design continues to evolve, with researchers investigating new antenna materials, antenna array designs, and meta-surface antennas to improve antenna performance for various applications [14]. The literature survey shows that there is ongoing research in the field of printed monopole UWB antennas, with a focus on improving their performance and achieving wider bandwidth [15-22].

2. Overview of UWB design

2.1 Basic design steps

UWB antenna design involves iterative process to meet design targets and the steps are briefly stated as:

i. Requirement analysis: The requirements are usually determined by the specific needs of the application, such as the frequency range, bandwidth, gain, radiation pattern, antenna size and they guide the rest of the design process.
ii. Selecting antenna type and structure: The choice of antenna structure depends on major design target like wider bandwidth or higher gain or radiation pattern type. In this paper, authors have targeted wider bandwidth with consistent gain over the band of operation while having Omni-directional radiation pattern.
iii. Simulation: The antenna design is then simulated using electromagnetic simulation software to determine its performance characteristics. Authors have used Ansys HFSS to design and simulate the antenna structure. A detailed process is explained in subsequent sections.
iv. Antenna fabrication and testing: Antenna was fabricated using copper clad FR4 epoxy substrate with 0.8mm thickness. The test results are compared to the simulation results to verify that the antenna meets the desired requirements.

To characterize the UWB antenna, most common measure is fractional bandwidth, which is given with following equation:

$$BW = \frac{F_H - F_L}{F_C} \times 100\% \qquad (1)$$

The bandwidth ratio for antenna is defined as:

$$BW = \frac{F_H}{F_L} : 1 \qquad (2)$$

Here, F_H and F_L are upper and lower frequencies of the antenna operating band while F_C is the center frequency of the band.

2.2 Impact of dielectric constant

The dielectric constant of the substrate affects the electrical length of the antenna. A higher value of dielectric constant will result in a smaller physical size of the antenna. However, a higher dielectric constant substrate can also lead to higher losses due to the increased dielectric loss tangent, leading to reduced efficiency of the antenna. Authors have selected FR4 epoxy substrate with loss tangent of 0.001. Other factors such as substrate thickness, conductor width, and ground plane size also need to be considered to ensure the best possible performance. Mathematically, relation between dielectric constant and frequency can be expressed as [23]:

$$\frac{\delta F}{F_0} = -\frac{1}{2}\frac{\delta \varepsilon_r}{\varepsilon_r} \qquad (3)$$

Here, δF is variation in frequency, F_0 is the centre frequency, $\delta \varepsilon_r$ is variation in dielectric constant and ε_r is actual dielectric constant.

2.3 Techniques of improving performance of UWB antennas

Authors have started this work with stringent requirements of higher bandwidth, stable gain, and Omni-directional radiation pattern with size reduction. For this, authors have done brief literature survey of UWB antenna performance improvement techniques:

a. Bandwidth Enhancement Techniques: Bandwidth enhancement techniques include using different feeding techniques, such as a tapered feeding line or a coplanar waveguide (CPW) feeding line. Other techniques include using parasitic elements, such as slots or stubs, or using a fractal structure. [24-26]
b. Miniaturization Techniques: Reducing the size of the antenna while maintaining its performance characteristics is another important design target many antenna designers have. Miniaturization techniques include using high dielectric constant substrates, such as ceramics or liquid crystals, or using metamaterial structures, which are artificial materials that exhibit properties not found in natural materials. [27-31]
c. Polarization Techniques: This technique includes using circular polarization, which can provide better performance in multipath environments, or using dual-polarized antennas, which can provide better performance in complex environments. [32-34]
d. Frequency Selectivity Techniques: This technique includes using band pass filters, such as lumped element filters or distributed filters, or using frequency selective surfaces (FSS), which are surfaces that can reflect or transmit specific frequencies. [35-38]
e. Radiation Pattern Techniques: This technique includes using directional antennas, such as patch antennas or horn antennas, or using omnidirectional antennas, which can provide better performance in multipath environments. [39-40]
f. Matching Techniques: This technique includes using baluns, which can match the antenna to the transmission line or the load impedance, or using impedance matching networks, such as lumped element networks or distributed networks. [41-42]

These techniques can be used individually or in combination to achieve the desired performance characteristics for a specific application. In this work, the authors have used combination (a) and (b) techniques to move closer to design targets.

Proposed Antenna Design

3.1 Iteration1: Antenna design for higher gain

Initial design started with Circular patch design with resonance frequency aimed at middle of the targeted frequency band. Actual radius of circular patch is calculated using,

$$a = \frac{F}{\sqrt{\left\{1 + \frac{2h}{F\pi\varepsilon_r}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}}} \quad (4)$$

$$F = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}} \quad (5)$$

The effective antenna radius is calculated using,

$$a_{eff} = a\sqrt{1 + \frac{2h}{\pi a}\left[\ln\left(\frac{a}{2h}\right) + 1.7726\right]} \quad (6)$$

Parameters and variables used in above equations are listed below:

Table I. Antenna design variables

Variable	Description
f_r	Resonant frequency
ε_r	Dielectric constant of substrate
h	Height of substrate
a	Patch radius
a_{eff}	Effective patch radius

Once circular patch was done, it was further modified with concentric circular slot, and radius of second circle was experimented to get wider bandwidth. The finalized antenna parameters are given in table II. The results of R1 and R2 variation and antenna performance is given in table III.

Table II. Antenna dimensions for iteration1

Variable	Value (mm)
R1	10
R2	6
Lf	11.2
Lg	10.8
Ls	45
Ws	42

The antenna design evolution here considers design background explained in previous sections. Authors have decided to design the antenna on FR4 epoxy substrate with thickness of 0.756 mm having dielectric constant of 4.4. FR4 was selected because it has optimum dielectric constant and efficiently utilizes the frequency bands. Authors have started the first iteration with circular microstrip-fed antenna. To obtain the desired ultra-wideband the circular antenna was modified to ring shaped antenna, as shown in figure 3. This antenna has substrate size of 42mmX45mm. R1 is the radius of outer circle and R2 is the radius of inner circle in the ring shape. Variation of R2 and its corresponding frequency bands observed in simulation are listed in table 2. Antenna return loss and radiation pattern are shown in figure 4(a) and 4(b). Based on the table 2 and figure 4, selected value of R2 is 6 mm. Maximum observed gain is 4 dB and return loss of -25 dB.

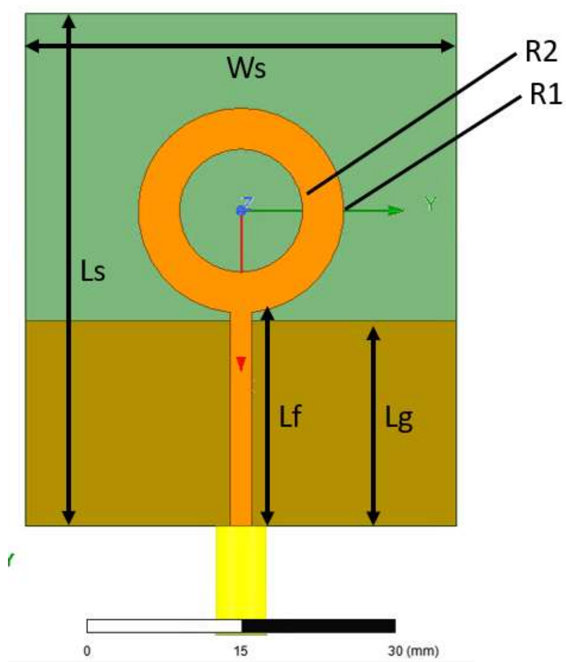

Fig. 1 Structure of Iteration1 antenna dimension variables indicated

Table III. Variation of R2 and frequency bands observed.

R1 = 10 mm R2 (mm) below	Freq bands (GHz)
0	(2.2-4.2) and (6.8-9.8)
1.5	(2.2-4.2) and (6.8-9.8)
3	(2.2-4.2) and (6.8-9.8)
6	2.3-9.8 continuous band

7	Bad response

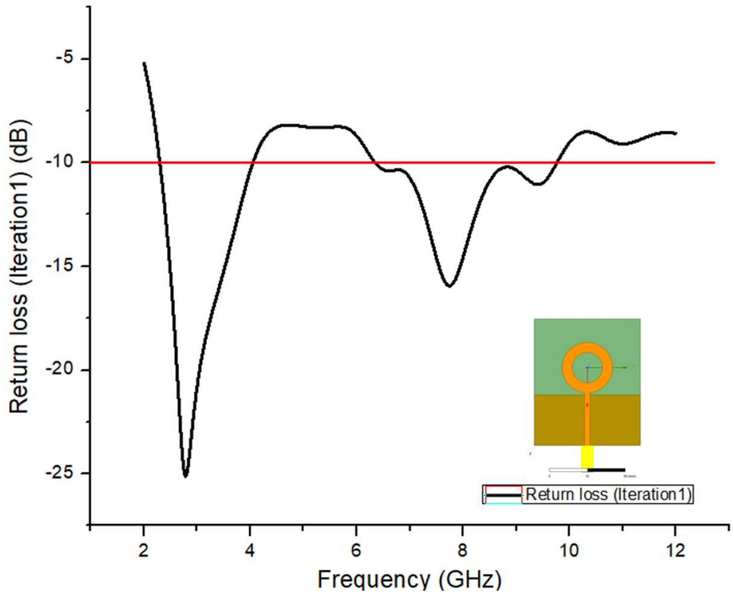

Fig. 2(a) Return loss for Iteration1 antenna

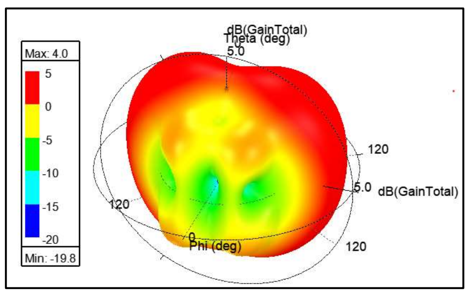

Fig. 2(b) Radiation pattern of Iteration1 antenna

3.2 Iteration2: Improving the antenna bandwidth

To further improve the antenna performance, Iteration2 was tried where antenna ground was modified from the rectangular shape to semicircular shape. Also, a notch was created in ground for further tuning. The notch as shown in figure 5 is characterized by ND (notch depth) and NW (notch width). Antenna dimensions are still same with 42mm X 45mm X 0.756mm. Multiple values of ND and NW are tried and are listed in table III and IV. A best possible combination of ND and NW are selected, and antenna geometry is finalized for antenna. Iteration2 formed an important step towards final targeted design. Antenna performances are shown in figure 7(a) and 7(b). Observed maximum gain 5.6 dB.

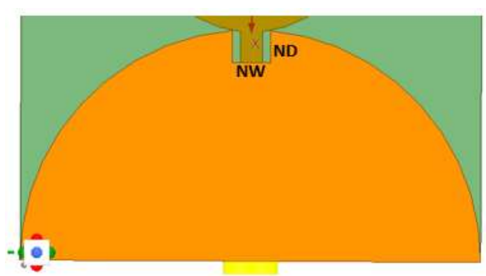

Fig. 3. Semicircular ground for Iteration2 and introduction of slot into ground

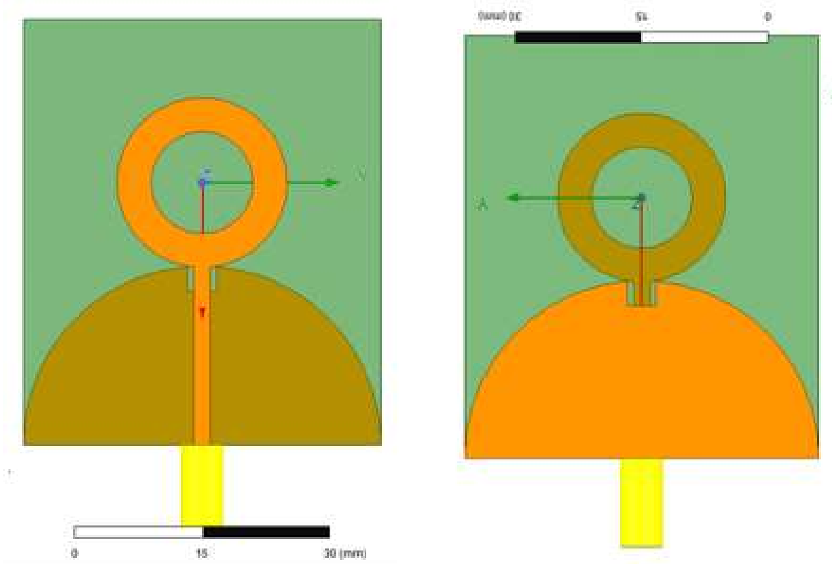

Fig. 4 Structure of Iteration2 front and back sides.

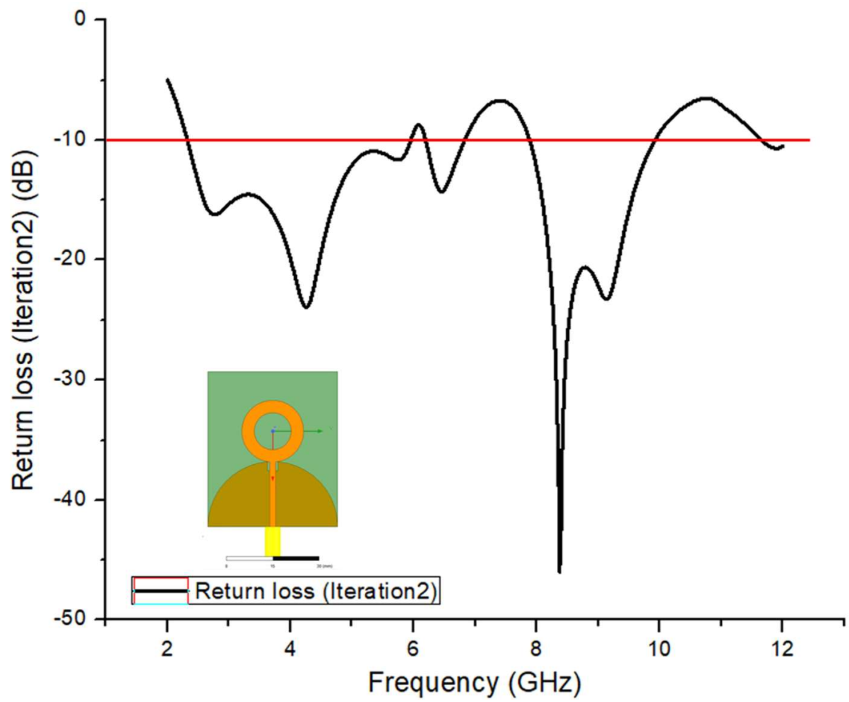

Fig. 5(a) Return loss of Iteration2 antenna

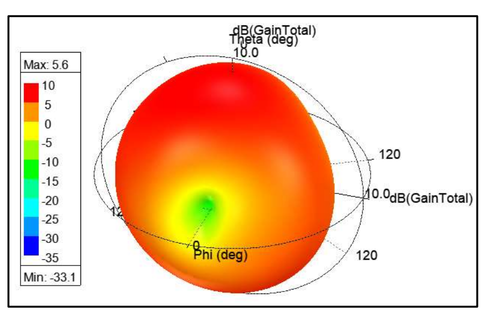

Fig. 5(b) Radiation pattern of Iteration2 antenna

Table IV. Antenna performance variation based on change in NW.

ND = 2 mm **NW (mm) below**	**Freq bands (GHz)**
3	(5.9-12) continuous band
4	(2.3-4.3) and (5.7-10.25)
5	(2.1-4.3) and (5.9-9.3)
6	(2.1-4.2) and (5.4-8.8)

Table V. Antenna performance variation based on change in ND.

NW = 4 mm **ND (mm) below**	**Freq bands (GHz)**
2	(2.3-10.5) continuous band
3	(2.3-9) continuous band
4	(2-6.7) and (7.8-9.3)
5	2.1-6.5

3.3 Iteration3: Development of Annular Ring Arc Method for antenna tuning

To optimize the antenna design further to obtain wideband, defected ground structure was created with two circular cutouts in the ground, as shown in figure 8. This achieves bandwidth tunability and better S11. However, the design sacrificed gain due to this modification. To improve the gain, one short circular stub was added inside inner circle. Figure 9 shows author's mathematical logic behind introduction of the arcs to the structure of iteration2.

In addition, we also know that, below equation was used to design arcs,

$$f_{Arc} = \frac{c}{2 \times \left(\frac{2A}{r}\right)\sqrt{\varepsilon_{eff}}} \tag{7}$$

Design variables from above equation can be understood from table VI.

Table VI. Mathematical variables in annular arc.

Variable	**Description**
f_{Arc}	Resonant frequency of the arc
A	Area of the arc
c	Speed of light in vacuum/air
r	Radius of arc
ε_{eff}	Effective dielectric constant of substrate
W_{Arc1}	Width of Arc1
W_{Arc2}	Width of Arc2
R_{Arc3}	Radius of Arc3
θ	Sector angle (arc angle)

Arcs were designed with lengths and angles to match and improve the antenna performance where return loss was more than -10 dB. Considering the radii of arcs Arc1, Arc2 and Arc3, their corresponding areas were calculated:

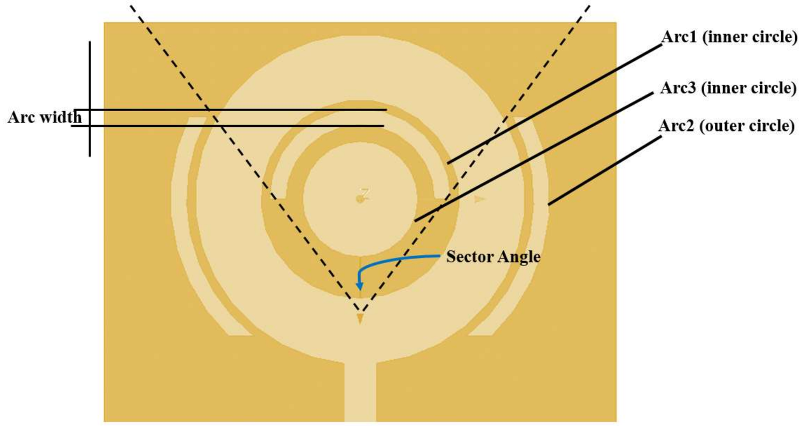

Fig. 6. Introduction of arcs to the iteration2 structure

$$Area(Arc1) = \frac{\theta}{2}W_{Arc1}^2 \quad (8)$$

$$Area(Arc2) = 2 \cdot (\frac{\theta}{2}W_{Arc2}^2) \quad (9)$$

$$Area(Arc3) = \pi R_{Arc3}^2 \quad (10)$$

Effective area of Iteration3 can be calculated as:

$$Area(iteration3) = Area(iteration2) + Area(Arc1) + Area(Arc2) + Area(Arc3) \quad (11)$$

After multiple simulations and performance evaluations of antenna the arc dimensions of all three arcs and their corresponding antenna performance are given in table VII.

Table VII. Arc1 characterization when placed at opposite end of feed.

Arc annular width (mm)	Sector angle (◦)	Resonant frequency (GHz)
0.5	90	3.99
	120	3.81
	150	3.67
	180	3.38
	210	3.11
1	90	2.92
	120	2.71
	150	2.55
	180	2.39
	210	2.21
1.5	90	1.95
	120	1.84
	150	1.69
	180	1.48
	210	1.02

Table VIII. Arc2 characterization when placed at 90 degrees with respect to feed.

Arc annular width (mm)	Sector angle (◦)	Resonant frequency (GHz)

0.5	90	5.11
	120	4.91
	150	4.82
	180	4.74
	210	4.58
1	90	4.41
	120	4.23
	150	4.15
	180	3.99
	210	3.85
1.5	90	3.68
	120	3.55
	150	3.41
	180	3.29
	210	3.01

Table IX. Arc placement and antenna performance relation.

Arc	Sector angle (◦)	Arc annular width (mm)	Resonant frequency (GHz)	Freq bands (GHz)
Arc1	180	1	2.39	2.1-3.2
Arc2 (left side)	120	1	4.15	3.8-4.4
Arc2 (right side)	120	1	4.15	3.8-4.4
Arc3	360	Radius = 3	8.2	8-10

For antenna size reduction, substrate was gradually cut from both sides in increments of 2 mm and antenna performance variation was observed. Iteration3 performance remains unchanged until final dimensions are achieved. The antenna dimensions are reduced from $50\text{mm} \times 42\text{mm} \times 0.8\text{mm}$ to $41.5\text{mm} \times 31\text{mm} \times 0.8\text{mm}$. Reduction in surface area achieved is 38.74% from the Iteration1 and Iteration2. The designed antenna of Iteration3 was fabricated and tested. The fabricated antenna with its dimensions is shown in figure 10.

3.2 Result analysis

UWB antenna performance improvement with annular ring and placement of gaps in annular ring was presented in [43]. Paper [43] proves that placement of gaps in annular ring UWB antenna can be used to tune the performance of antenna. Proposed structure in this paper also started as annular ring antenna, as discussed in previous sections. However, during design it was found that arcs with specific sector angle and annular widths can be used to tune the antenna bandwidth and stable radiation characteristics. The authors of this paper experimented with different version of arcs and the promising results are presented in table VII. Placement of arcs can be decided from effective aperture area required for the operational bandwidth of antenna. This is useful when antenna miniaturization is targeted without sacrificing its performance. Hence, the aperture area can be increased with placement of arcs. This is presented from equations (7) through (11).

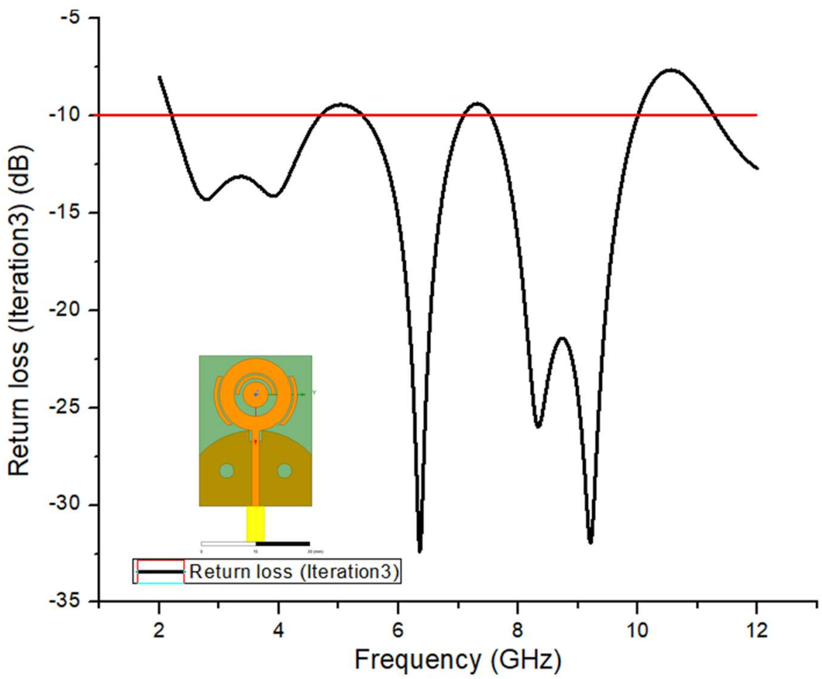

Fig. 7 Return loss of Iteration3 antenna.

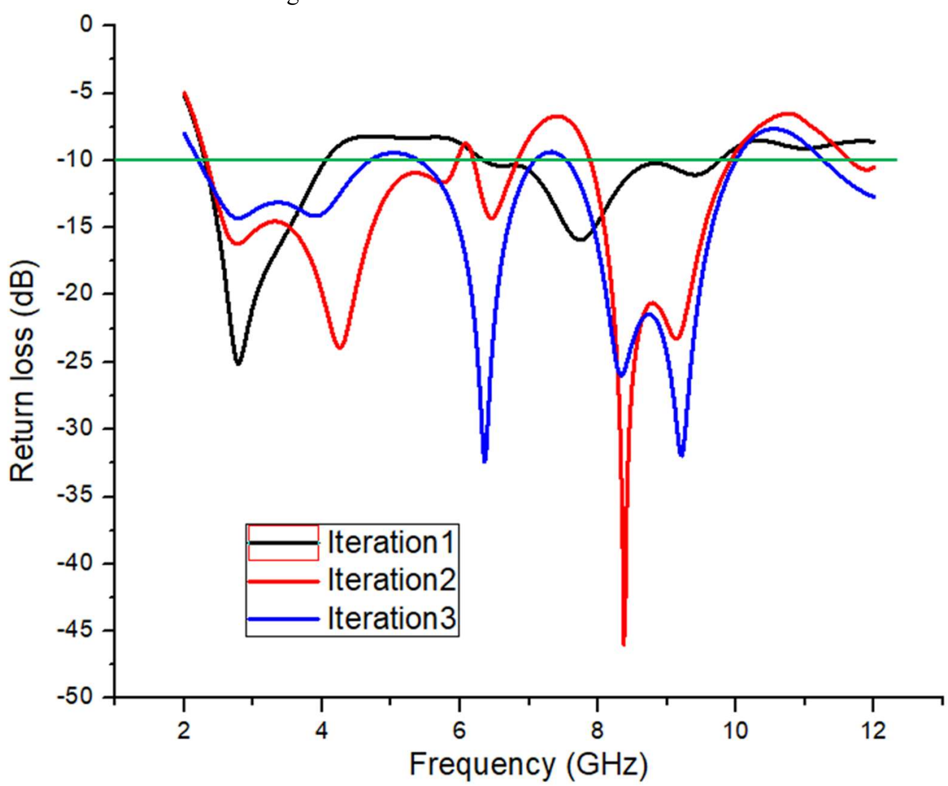

Fig. 8 Return loss comparison for Iteration1, Iteration2 and Iteration3.

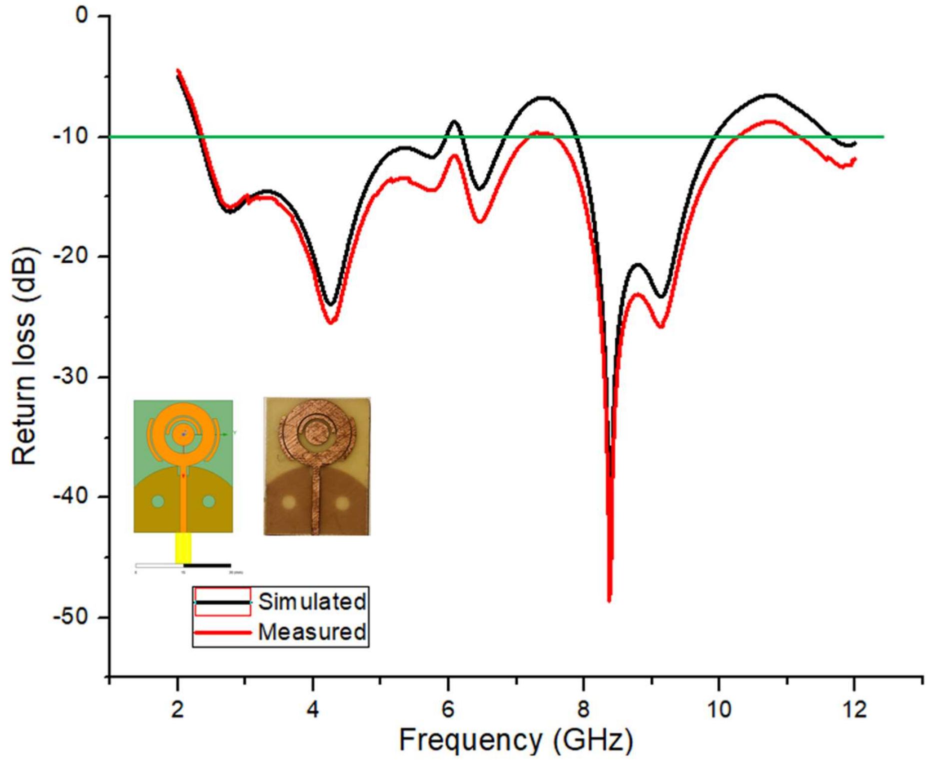

Fig. 9 Return loss comparison for simulated and measured results for Iteration3.

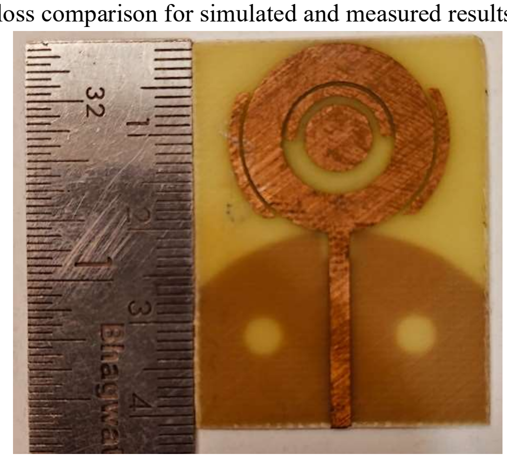

Fig. 10 Fabricated antenna structure.

Conclusion

Authors had started with design target of UWB antenna with stable gain, Omni-directional radiation pattern and size reduction. Within three iterations and a modified method of annular ring-arcs authors were able to achieve the design target. The designed antenna of third iteration has operation bandwidth of 2.1 to 10.4 GHz with peak gain of 5.2 dB. The antenna has Omni-directional radiation pattern and achieved size reduction without affecting antenna performance was 38.74%. During design it was found that by placing multiple annular ring arcs with specific resonant frequencies can improve antenna return loss at specific frequencies. This method can be used to tune the wideband antennas having multiple band stops. It was also found that the width of annular ring arc is inversely proportional to resonant frequency. Angle of arc is also inversely proportional to resonant frequency. Placement of arcs was determined by experimentation during simulation. Multiple arcs can be introduced for multiple stop band frequencies.

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