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REGULAR ARTICLE

Multiband Operational Antenna in Ultra Wide Band (UWB) Frequency Range with Substrate Structure Modification Approach

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In this paper, authors propose a new way of improving the gain-bandwidth performance of Multiband Operational Antenna in Ultra Wide Band (UWB) frequency range with substrate structure modification Approach. 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. The proper placement of annular rings is another important factor discussed in this paper was found by experimentation. The antenna design is completed 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. 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. The Antenna suggested in the paper is showing good improvement in the antenna parameters such as Gain, Bandwidth, Return loss etc. In this, Placement of arcs was determined by experimentation during simulation. Multiple arcs can be introduced for multiple stop band frequencies.

Keywords: Ultra Wide Band (UWB), Antenna design, Annular ring.

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1. INTRODUCTION

The Ultra-wide band antennas offer high data rates, low power consumption, and low cost [1]. 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 inside the product [2]. Some of the recent applications of UWB are [3]: Precision locating and tracking information for people, vehicles, and objects in real-time, Wireless communication: UWB provides high data rates, low power consumption and replaces multiple narrow-band antennas with single antenna [4].

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 and data rate of up to 27 Mbps [5]. 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 [6].

With the increasing miniaturization and complexity of electronic devices [7], UWB antennas with a smaller size and weight can improve the portability and usability of these devices [8]. The development of new UWB antenna designs can improve the performance and usability of UWB technology in various applications [9]. UWB antenna design continues to evolve, antenna array designs, and meta-surface antennas to improve antenna performance for various applications [10].

2. RELATED WORKS

2.1 Basic Design Steps

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

1. Requirement analysis: Requirement to the specific needs of the application, such as the frequency range, bandwidth, gain, radiation pattern, antenna size.
2. Selecting antenna type and structure: In this paper, authors have targeted wider UWB frequency band with consistent gain over the band of operation with Omni-directional radiation pattern.

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3. Simulation: In this paper Authors have used Ansys HFSS to design and simulate the antenna structure.

4. 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 fractional bandwidth, which is given with following equation:

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

The bandwidth ratio for antenna is defined as:

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

Here, F_H and F_L are upper and lower frequencies 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. 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 [11]:

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

Here, δF is variation in frequency, F_0 is the center 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 for Multiband Operations

Authors initiated work with stringent requirements of higher bandwidth, stable gain, and Omni-directional radiation pattern with size reduction with following techniques:

1. Bandwidth Enhancement Techniques: uses different feeding techniques and other techniques include using parasitic elements, such as slots or stubs, or using a fractal structure [12].
2. Miniaturization Techniques: Reducing the size of the antenna while maintaining its performance characteristics [13].
3. Polarization Techniques: includes circular polarization to provide better performance in multipath environments, or using dual-polarized antennas [14].

These techniques can be used to achieve the desired performance characteristics for a specific application. The authors used combination of (A) and (B) techniques to achieve design targets.

3. METHODS AND MATERIALS

3.1 Iteration 1: Antenna Design for Higher Gain

Initial design started with Circular patch design with resonance frequency and Actual radius of circular patch is calculated using,

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

$$F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}} \quad (5)$$

The effective antenna radius is calculated using,

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

Parameters and variables used in above equations are listed below:

Table 1 – Antenna design variables

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

After circular patch modification are done with concentric circular slot. The results of R_1 and R_2 variation and antenna performance is given in Table 3.

Table 2 – Antenna dimensions for iteration1

Variable	Value (mm)
R_1, R_2, L_f, L_g, L_s, W_s	10,6,11.2,10.8,45,42

Authors designed the antenna on FR4 epoxy substrate with thickness of 0.756 mm having dielectric constant of 4.4. Authors completed the first iteration with circular micro strip-fed antenna. To obtain the desired ultra-wideband the circular antenna was modified to ring shaped antenna, as shown in Fig. 3. R_1 is the radius of outer circle and R_2 is the radius of inner circle in the ring shape. Based on the Table 2 selected value of R_2 is 6 mm.

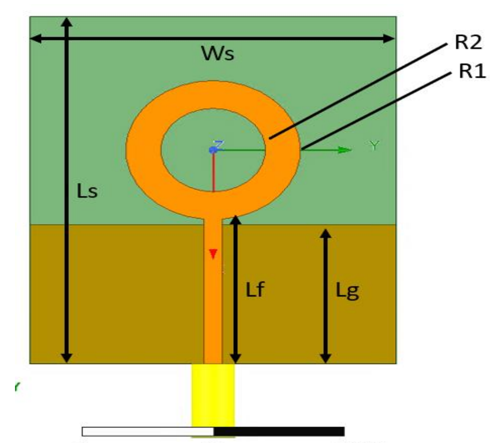
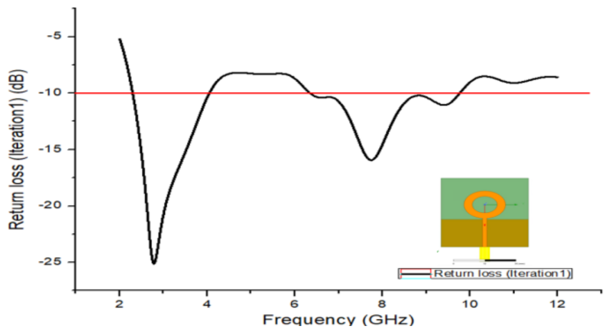


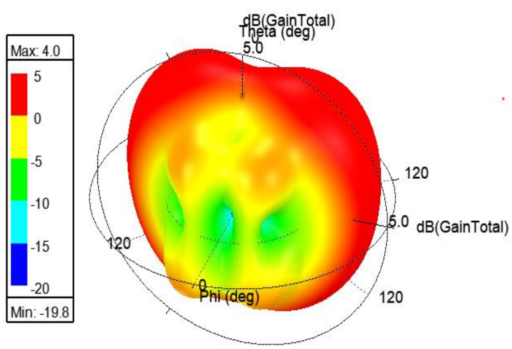
Fig. 1 – Structure of Iteration1 antenna with variables indicated

Table 3 – Variation of R_2 and frequency bands observed

R_1 = 10 mm R_2 (mm) below	Frequency bands (GHz)
0 & 1.5	(2.2-4.2)&(6.8-9.8), (2.2-4.2)&(6.8-9.8)
3 & 6	(2.2-4.2) & (6.8-9.8), 2.3-9.8 continue band
7	Bad response



a



b

Fig. 2 – (a) Return loss for Iteration1 antenna, (b) Radiation pattern of Iteration1 antenna

3.2 Iteration 2: Improving the Antenna Bandwidth

To improve antenna performance, Iteration 2 modified to semicircular shape with a notch by ND (notch depth) and NW (notch width). The notch as shown in Fig. 3 is characterized. Antenna dimensions are still same with. Antenna performances are shown in Fig. 5 (a, b). Observed maximum gain 5.6 dB.

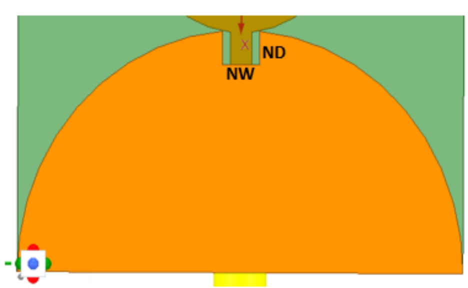


Fig. 3 – Semicircular ground for Iteration 2 and slot into ground

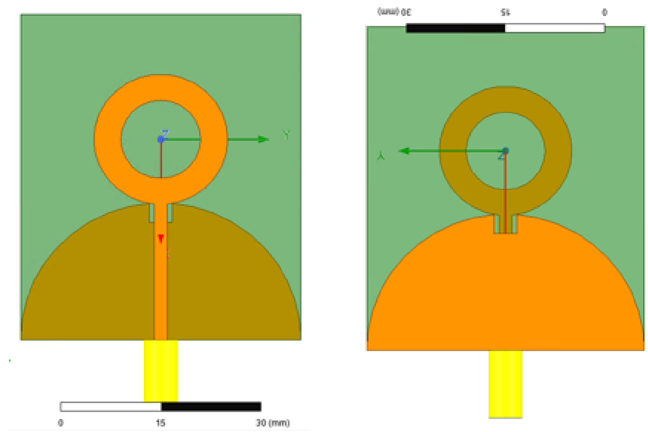
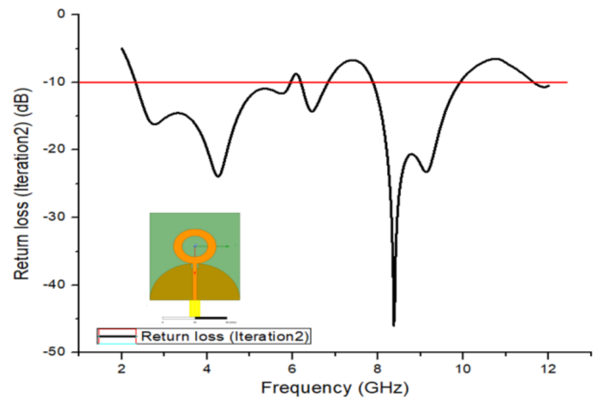
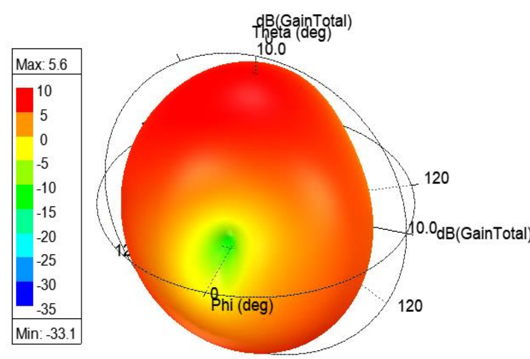


Fig. 4 – Structure of Iteration 2 front and back sides



a



b

Fig. 5 – (a) Return loss of Iteration 2 antenna, (b) Radiation pattern of Iteration 2 antenna

Table 4 – Antenna performance change with 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 & 6	(2.1-4.3) and (5.9-9.3),(2.1-4.2)and (5.4-8.8)

Table 5 – Antenna performance change based on 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 Iteration 3: 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 Fig. 8. This achieves bandwidth tunability and better S_{11}. However, the design sacrificed gain due to this modification. To improve the gain, one short circular stub was added inside inner circle. Fig. 9 shows author's mathematical logic behind introduction of the arcs to the structure of Iteration 2.

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

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

Design variables from above equation can be understood from Table 6.

Table 6 – Mathematical variables in annular arc

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

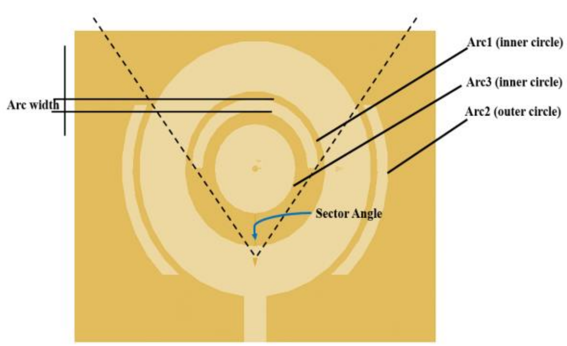


Fig. 6 – Introduction of arcs to the iteration2 structure

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

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

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

Effective area of Iteration 3 can be calculated as:

$Area(iteration3) = Area(iteration2) + Area(Arc1) + Area(Arc2) + Area(Arc3)$ (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 7.

Table 7 – Arc1 characterization when placed at opposite to feed

Arc annular width (mm)	Sector angle (◦)	Resonant frequency (GHz)
0.5	90	3.99
	120	3.81
1	90	2.92
	120	2.71
1.5	90	1.95
	120	1.84

Table 8 – Arc2 characterization when placed at 90° to feed

Arc annular width (mm)	Sector angle (◦)	Resonant frequency (GHz)
0.5	90	5.11
1	90	4.41
1.5	90	3.68

Table 9 – 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

Iteration 3 performance remains unchanged until final dimensions are achieved. The antenna dimensions are reduced from 50 mm × 42 mm × 0.8 mm to 41.5 mm × 31 mm × 0.8 mm. Reduction in surface area achieved is 38.74% from the Iteration 1 and Iteration 2. The designed antenna of Iteration 3 was fabricated and tested. The fabricated antenna with its dimensions is shown in Fig. 10.

4. RESULT AND ANALYSIS

UWB antenna performance improvement with annular ring and placement of gaps in annular ring was presented in paper [15] 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.

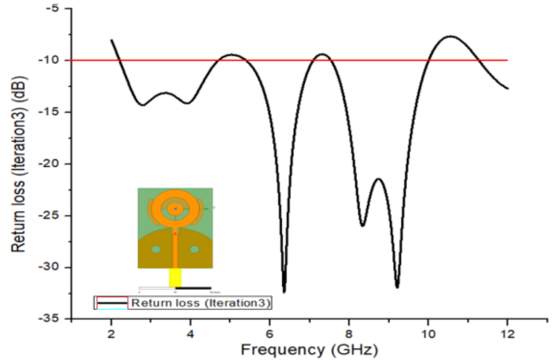


Fig. 7 – Return loss of Iteration 3 antenna

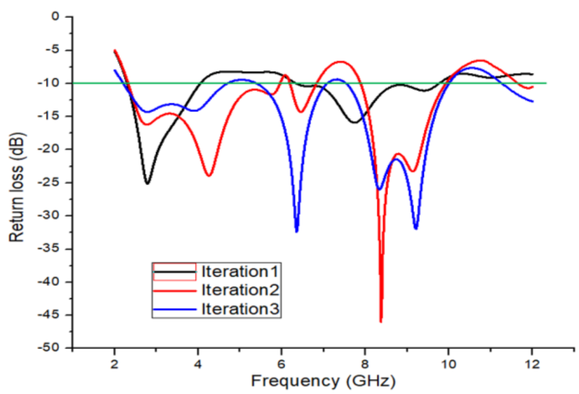


Fig. 8 – Return loss comparison for Iteration 1, 2 and Iteration 3

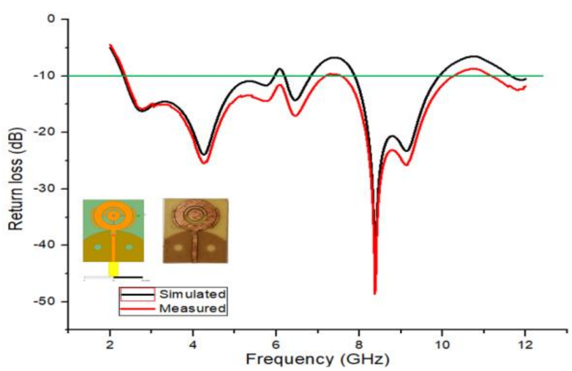


Fig. 9 – Return loss comparison for simulated and measured results for Iteration 3

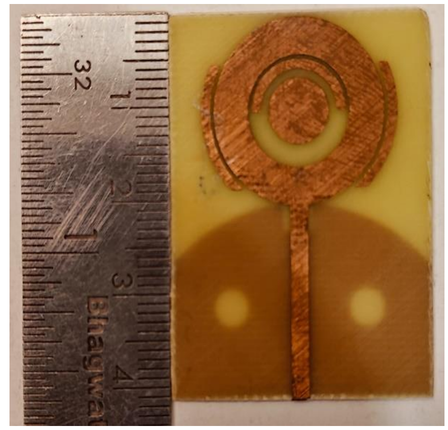


Fig. 10 – Fabricated antenna structure

The authors of this paper experimented with different version of arcs and the promising results are presented in Table 7. 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 presented from Eq. (7) through (11).

5. CONCLUSION

Authors targeted multiband operational antenna in UWB frequency range with stable gain, Omni-directional radiation pattern and size reduction. With three iterations and a modified method of annular ring-arcs authors were able to achieve the design target and also found the significant parameter enhancement. The designed antenna has multiband 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 %. This method can be used to tune the wideband antennas having multiple bands with targeted applications like Wi-Fi, WiMax, Bluetooth, WLan. 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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Багатодіапазонна робоча антена в ультраширокосмуговому (UWB) діапазоні з підходом до модифікації підкладки

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У цій роботі автори пропонують новий підхід до покращення характеристик коефіцієнта підсилення та смуги пропускання багатодіапазонної робочої антени в ультраширокосмуговому (UWB) діапазоні за рахунок модифікації структури підкладки. Дуговий сегмент кільця (annular ring arc) є частиною кільця з певною довжиною та секторним кутом, який впливає на ефективну апертуру антени. Така структура дозволяє поліпшити узгодженість смуги пропускання з підсиленням антени. Довжина, ширина та кут дуги кільця були визначені математично, виходячи з розрахунку ефективної апертури. Крім того, оптимальне розміщення дуг кільця було встановлено експериментально та розглядається як важливий фактор у підвищенні продуктивності. Проектування антени завершено за три ітерації, після чого виготовлено фізичний зразок та проведено випробування. Результати вимірювань та моделювання узгоджуються. Антена працює в частотному діапазоні від 2.1 до 10.4 ГГц, при цьому досягнуто зменшення розміру конструкції. Для виготовлення використано підкладку FR4 з товщиною 0,8 мм і діелектричною проникністю 4.4. Антена демонструє прийнятні значення зворотних втрат у всій робочій смузі. Запропонована конструкція демонструє значне покращення параметрів, таких як підсилення, смуга пропускання та зворотні втрати. Розміщення дуг було визначено експериментально під час моделювання, а для забезпечення кількох частот смуги загасання можна додати кілька дуг.

Ключові слова: Ультраширокосмугова (UWB) антена, Проєктування антени, Кільцева дуга.