A UWB-Specific Metasurface-Inspired MIMO Antenna with Enhanced Isolation and Gain

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Abstract: This study presents a lightweight, compact Metasurface-inspired UWB-optimized MIMO antenna featuring high isolation and substantial gain. The MIMO antenna design incorporates two identical patches arranged in parallel to boost overall performance. To enhance impedance matching, a trapezoidal defected ground with stepped features is employed. The antenna's feed, designed in a tapered shape, contributes to enhanced impedance matching. A metasurface isolation system is implemented, utilizing a hexagonal-shaped unit cell absorber, which is subsequently integrated into the middle of the defected ground. Metasurface achieves significant isolation, up to 25 dB. The antenna abilities to provide a wide operating bandwidth of 1.96 GHz to 13 GHz, suitable for UWB utilization, with a peak gain of 7.9 dBi at 7 GHz. A comparison with prior literature demonstrates size optimization and enhanced isolation through the novel metasurface absorber. The efficiency of the proposed antenna stands at 95.5%. Resonating at triple frequencies 5.2 GHz, 7.5 GHz, and 12.37 GHz, this MIMO metasurface antenna is well-suited for applications such as WPAN and WBAN.

1 INTRODUCTION

In the modern-day, ultrawideband antennas face numerous difficulties including miniaturization, cost-effectiveness, compactness, mechanical durability, and the attainment of high-performance metrics such as substantial gain, wider bandwidth to support wireless security. Overcoming these hurdles to develop a UWB antenna within a functional bandwidth of 3.1 to 10.6 GHz {(FCC.,2002, Balanis.,2016)} as specified by the FCC is a complex endeavour. The constraints mentioned above regarding UWB antennas can be addressed through the application of fractal geometry. Fractal geometry's characteristics like self-similarity with space-filling render it a suitable choice for UWB antenna (Bhatt et al.,2017, Tejaswita et al.,2024) For UWB applications, incorporating a Koch fractal structure around the outer edge of the octagonal patch in a MIMO antenna improves its efficiency and compactness in multiple important aspects. Since the antenna's fractal structure extends its electrical length without materially increasing its physical size, it can operate well at lower frequencies and still have a small form factor. For UWB applications that need wide frequency coverage, this functionality is essential. Furthermore, many resonant frequencies are supported by the self-similar patterns of fractal structures, which improves bandwidth and makes it possible for the antenna to effectively handle multiple signals in various frequency bands. Additionally, the Koch fractal's complex structure helps to realize enhanced impedance matching throughout the UWB band, which lowers return loss and increases efficiency. as it contributes to improved antenna performance. This assertion is supported by previous studies conducted by numerous researchers (Werner et al.,1999, J. Anguera et al.,2005, C. Borja et al.,2003). To enhance reliability and address the susceptibility to multipath fading inherent in communication systems, the MIMO antenna system has been integrated. This technology reduces transmission errors and improves communication range with data transfer rates. Ensuring ample isolation among MIMO antenna elements presents a notable obstacle when crafting compact antennas.

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Nonetheless, various approaches are being pursued in this direction, and implementations of MIMO antennas are being explored in the existing literature, as discussed below.

The antenna isolation is only 12.5 dB. A compact antenna featuring two elements was introduced in (Zhao et al.,2017). In (Hussain et al.,2019), A 4-elementMIMO antenna utilizing annular rings was devised for cognitive radio applications. (Chandel et al.,18) introduces a two-port antenna with tapered feeding and dual stop-band attributes, engineered to operate across the extensive frequency range of 2.9-20 GHz. Isolation methods employing standard ground stubs were applied, achieving isolation levels below -22dB. In (Hussain et al.,19), a four-port MIMO antenna with a pentagon shape was developed, catering to various wireless applications with reconfigurability as a key feature. Notably, no specific isolation mechanism was reported, with isolation primarily reliant on significant spacing between the radiators, resulting in a large antenna size. (Li, Zhenya et al.,2019) described a compact Vivaldi-shaped antenna, employing stub techniques. This work employed a novel design approach to reduce mutual coupling. In (Iqbal et al.,2017), a two-port antenna featuring F-shaped stubs was designed, achieving isolation of only -20 dB However, due to the large size of the patch, the overall dimensions of the antenna were considerable. (Zhao et al.,2019) presented a large-scale MIMO antenna measuring 120 x 60 mm, tailored for UWB applications. It is clear from the literature analysis that achieving the isolation in MIMO is very crucial, with the help of metasurface we can overcome this drawback.

The paper's newness lies in its inventive utilization of Koch fractal octagonal geometry and Metasurface in the ground plane to devise an ultrawideband MIMO antenna, which achieves notable characteristics such as high isolation, gain, miniaturization, compactness, wideband operation, high efficiency, and three resonant frequencies. The provided article encompasses an introduction in Section 1, detailing the stepwise and optimized outcomes, as well as the results and analysis depicted in Section 2. The research conclusions are drawn in sections 3, 4, and 5. With the aid of the ANSYS HFSS v21.0 R1 software environment, the entire structural design is completed (ANSYS., 2021).

2 ANTENNA DESIGN APPROACH & ANALYSIS

The suggested UWB antenna has been created by cutting an octagonal shape's edge using a Koch fractal. This suggested antenna combines antenna technology with fractal geometries. Fractal geometry, in general, is made up of repeated segments in varying scales. In terms of length and size (D. Li et al.,2012) derived by applying the following formula:

$$d = \frac{\log(n)}{\log(R)} \tag{1}$$

$$L = H\left(\frac{n}{R}\right)^{n} \tag{2}$$

In the equation, where 'n' represents the number of geometry segments, 'h' denotes the curve length, 'i' stands for the iteration number, and 'r' signifies the number of segments divided by each iteration.

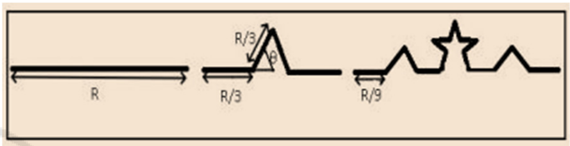

Figure 1: Koch fractal Generation in the patch.

Figure 1. shows the design of the iteration in the octagonal, the starting structure's length R is represented by θ, which provides the fractal geometry's convergence. When θ equals 45 degrees and R equals 1.6 mm, these values define the edge dimensions for the octagonal iterative subtraction process in antenna.

The two-element antenna design undergoes optimization and feature analysis using HFSS software v.21. FR4 substrate, is selected for its favorable attributes in providing wide bandwidth followed by radiation characteristics for fundamental design (Tasouji, N et al.,2013, Liu YY et al., 2016, Li et al.,2018, Hussain et al.,2017, Ibrahim et al.,20 17). Table 1 lists all of the optimized metasurface MIMO antenna's variables.

Table 1: Optimized metasurface MIMO antenna's variables.

Design Parameters	Value (mm)	Design Parameters	Value (mm)
Ls	35	d	10
Ws	35	e	7.6
a	5	f	5
b	13.7	g1	35
g3	3.06	g5	23
g4	9.4	c	27.5

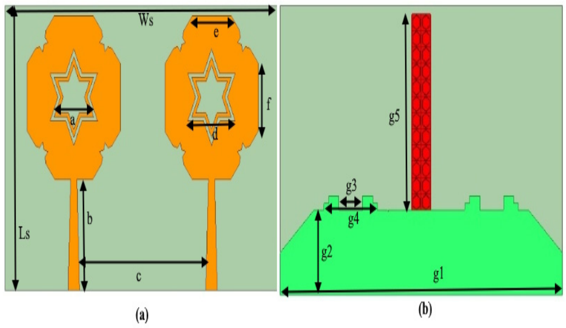

Figure 2: MIMO antenna with dimension (a) Patch with dimension (b) Ground with dimension metasurface

Figure 2. shows the (a) Patch with dimension and (b) Ground with dimension metasurface. There are many antennas reported which show the metasurface helps to improve the characteristics of the antenna (Li et al.,2023, Kumar et al.,2022, Pandey et al.,2024, Wang et al.,2023, Saxena et al.,2023). Using a metasurface in the ground plane coupled with a two-element Koch fractal antenna MIMO configuration greatly improves isolation and gain for the UWB spectrum via several methods. By forming bandgaps that stop surface currents from propagating, the metasurface improves isolation and minimizes interference by suppressing surface waves also reducing mutual coupling. Furthermore, by reflecting electromagnetic waves with an in-phase reflection coefficient, metasurfaces function as artificial magnetic conductors. This optimizes the radiation pattern and total gain by concentrating more power in the desired direction. Over the UWB spectrum, the metasurface ensures clean operation by suppressing unsuitable modes and harmonics. By lowering ohmic losses and back radiation, it also increases radiation efficiency by turning a larger percentage of input power into usable radiated power Optimizing performance over the UWB range is possible because of the metasurface's precise control over electromagnetic wave propagation, which enables customized radiation patterns. Because of this integration, the design is efficient and compact, which is crucial for current UWB applications that have limited space. Moreover, metasurfaces' frequency-selective qualities optimize antenna efficiency in particular UWB bands, improving isolation and gain where it's most needed. All these elements work together to create a small, high-performance, and efficient UWB MIMO antenna system. The entire design process is described in the initial phase, with the following unit cell of the metasurface that will be designed and examined in the following section.

2.1 Unit Cell Development

On a FR-4 substrate, a hexagonal unit cell is fabricated with the required dimensions as shown in Figure 3, with a total size of 2 mm × 2 mm.

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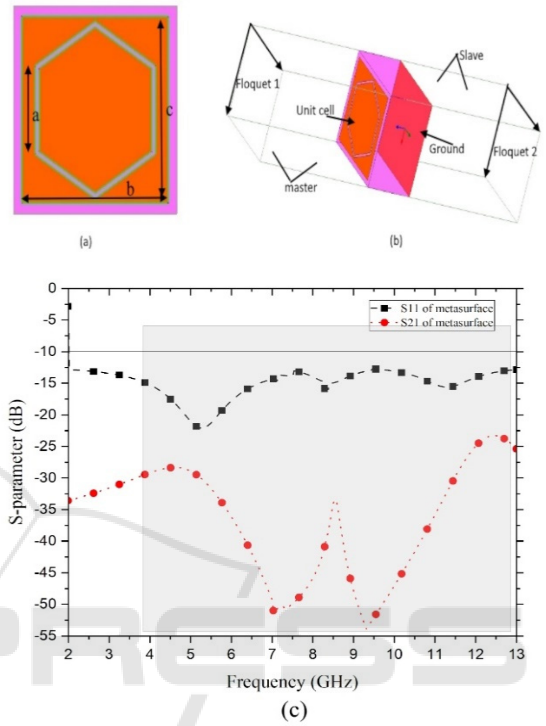

Figure 3: metasurface unit cell (a) hexagonal unit cell with dimension (b) unit cell under boundary condition (c) deployed metasurface unit cell S parameter.

In Figure 3 (a) a unit cell is shown with dimensions here a =, b =2 mm, c = 2 mm, and (b) a unit cell under the boundary condition. here a Floquet port is used to examine the unit cell and master-slave is used in the unit cell boundary. hexagonal unit cell's S-parameter analysis is in Figure 3 (c). As can be seen from the graph, S11 is continuously below -10 dB, and the unit cell shows effective absorption within the target range of 3.88-12.37 GHz. Additionally, the proposed antenna's ground plane has this unit cell arrayed repetitively across it. An analysis of the recommended antenna is shown on Figure 4. Figure 4 (a) depicts an individual antenna with a Koch fractal at the lower half of it. The antenna with a Koch fractal in its upper half is seen in Figure 4 (b). The two-element MIMO antenna is displayed in Figure 4 (c); the MIMO antenna combined with a metasurface is displayed in Figure 4 (d).

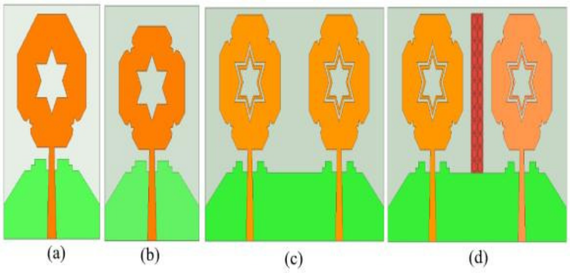

Figure 4: Step-wise evaluation of the MIMO antenna.

3 RESULTS

3.1 Gain and Efficiency

The peak gain Two-element meta surface UWB MIMO antenna of 7.9 dBi at 7 GHz is in Figure 5 (a). and followed by Figure 5 (b) is the overall efficiency of the 2-element MIMO antenna 95.5%.

3.2 S-Parameter

Figure 5 (c) shows a Simulated S11-parameter of novel UWB two-element MIMO Koch fractal antenna with a metasurface. suggested antenna achieves three resonant frequencies 5.2 GHz, 7.5 GHz, 12.37 GHz, and a wide bandwidth of 1.96 GHz to 13 GHz. The isolation between the two antenna is also very good below 25 dB for the entire bandwidth.

3.3 CCL / TARC

Figure 5 (d). shows Channel capacity loss (CCL) and the TRAC of the MIMO antenna. Ideally, the CCL value is 0 and the practical value is between 0 to 0.4. The proposed antenna CCL value is up to the mark.

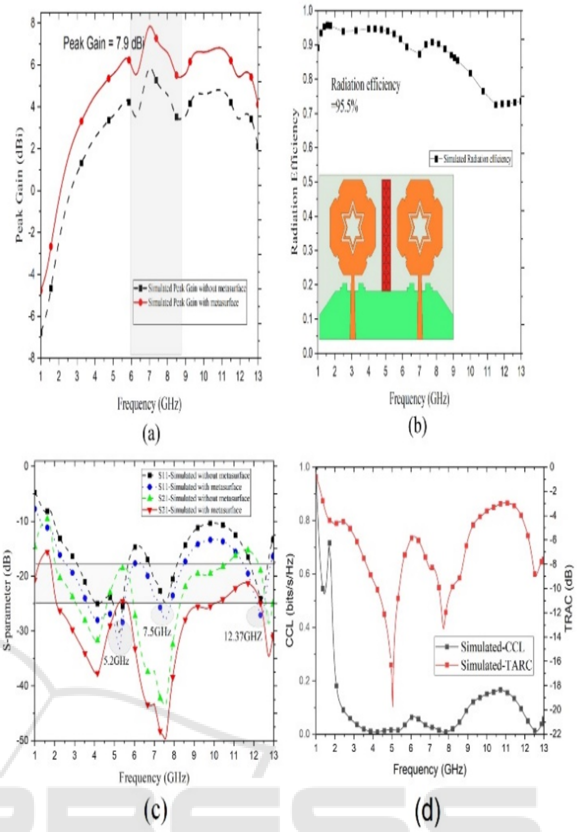

Figure 5: (a) Simulated Peak Gain with and without metasurface and (b) Efficiency of Two-element meta surface UWB MIMO antenna. (c) S parameter of the MIMO antenna with and without meta surface and S21 graph for isolation. (d) Simulated CCL and TARC of Two-element meta surface UWB MIMO antenna.

3.4 Radiation Pattern

Figure 6 shows the generated radiation patterns for metasurface MIMO antenna. The E-plane followed by H-plane patterns are shown for resonant frequencies of 5.2 GHz, 7.5 GHz, and 12.37 GHz.

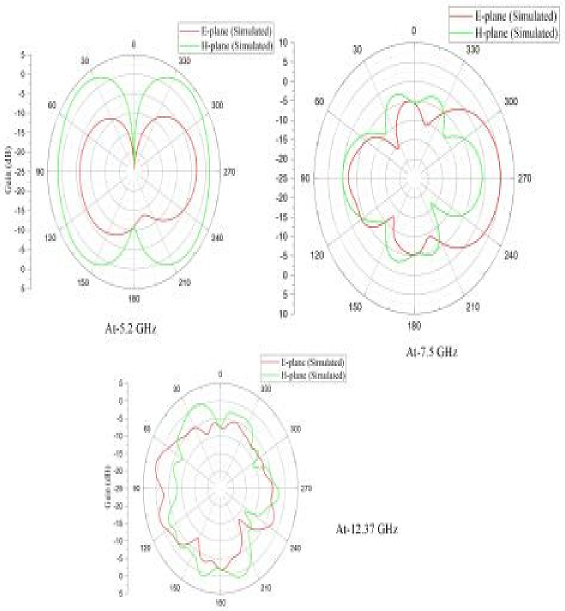

Figure 6: S parameter Simulated Radiation Pattern at the resonant frequency 5.2 GHz, 7.5GHz, and 12.37 GHz of metasurface MIMO antenna.

3.5 Surface Current Distribution

Figure 7. depicts the two-element meta surface antenna's current distribution at resonance frequencies (a) 5.2 GHz, (b) 7.5 GHz, and (c) 12.37 GHz. From the Figure, it is evident that the Meta surface unicell absorbed the radiation very well.

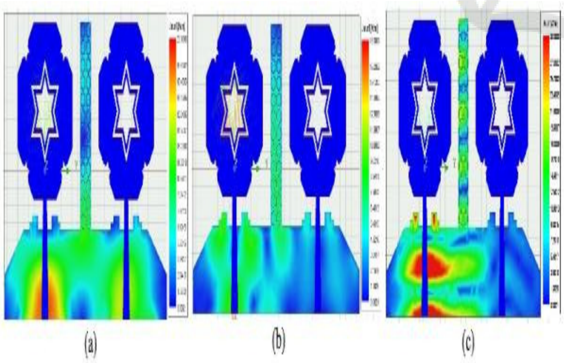

Figure 7: Current Distribution of Two-element meta surface UWB MIMO antenna at (a) 5.2 GHz, (b) 7.5 GHz, and (c) 12.37 GHz.

4 ANALYSIS IN RELATION

Table 2: shows the analysis relation with another MIMO antenna and the suggested antenna.

Ref. No.	Dimension (mm)	Isolation (dB)	Bandwidth
Liu YY,2016	44×44	less than 15.5	2.95-10.8 GHz
Li, 2018	30×30	less than 20	2.8-19.2 GHz
Hussain, 2017	60×120	less than 20	1.77- 2.51 GHz
Ibrahim, 2017	$6cm^2 \times 5cm^2$	10-18	3-10.6 GHz
Li, 2023	60×60	30	3.66-16.61 GHz
Kumar, 2022	45×45	20	4.5-16.4 GHz
Pandey, 2024	32×48	27	1.87-13.82 GHz
Wang, 2023	68×68	20	2.14-14.95
Saxena, 2023	29×23	20	6.75-14.6 GHz
SW	35×35	25	1.96 - 13 GHz.

[SW= suggested Work]

5 CONCLUSION

In light of Metasurface inspiration, a Koch fractal octagonal MIMO antenna is presented in this research for Ultrawideband (UWB) frequency range applications. The suggested antenna can be made smaller and more compact for UWB operations by utilizing a Koch fractal structure around the octagonal patch's edges. Additionally, a two-element Koch fractal antenna MIMO configuration is coupled with a Metasurface in ground plane to expand antenna properties like isolation and gain. With this setup, the 1.96 - 13 GHz UWB spectrum is achieved. This antenna is a viable choice for UWB applications because of its very low ECC (Envelope Correlation Coefficient) of 0.3, peak gain of 8 dBi, isolation below 25 dB, and adequate transmission coefficients. Due to its affordable substrate and advantageous antenna properties, in terms of important performance metrics, the UWB-specific Metasurface-inspired MIMO antenna performs significantly better than current alternatives for WPAN and WBAN applications. Due to mutual coupling and surface wave suppression by the metasurface, it obtains a reduced Envelope Correlation Coefficient (ECC). Better signal diversity and reliability are the outcome of this. In addition, the antenna has a larger peak gain, which concentrates more energy in the desired direction and improves signal coverage and intensity. Maintaining high data speeds is dependent on its remarkable isolation, which guarantees little interference and crosstalk between antenna elements. The metasurface also shows minimum signal leakage by reducing transmission coefficients. These advantages make it ideal for high-performance, reliable communication in WPAN and WBAN environments.

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