A compact metamaterial inspired UWB-MIMO fractal antenna with reduced mutual coupling

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Abstract
This article focuses on metamaterial inspired UWB-MIMO fractal antenna. Antenna loaded with the metamaterial structure achieved an impedance bandwidth of 5.8–15 GHz (98.63%). Mutual coupling between the two radiating elements is obtained to be less than −25 dB. The patterns of radiation are stable over the operating range and a peak gain of 6.2 dBi is obtained at 14 GHz. Throughout the operating range, the radiation efficiency is >88%. The obtained Envelope correlation coefficient-ECC (< 0.07), Mean effective gain-MEG (< 3 dB), Total active reflection coefficient-TARC (< −10 dB) and Diversity gain-DG (> 9.98) proved that the desired antenna has a good diversity performance. The measured and simulated results are well adjusted, so that the antenna can be used for ultra-wide band applications. Simulation is conducted using HFSS simulation tool and printed on a 30 × 30 × 1.6 mm³ FR4 material.

1 Introduction
Multi Input Multi Output (MIMO) technology is being widely used with the rapid development of wireless communication and its requirements for stable quality of transmission and high rate of transmission. For the transmission and reception of signals, MIMO antenna uses multiple antenna elements. Without increasing the transmitting power, MIMO technology will increase the capacity of the communication and the usage ratio of spectrum.

The high data rate transfer requirements have rendered UWB technology a significant candidates to design portable devices for today’s wireless communications (El Hamdouni et al. 2020). Modern wireless device users are demanding for the devices that are suitable for both long- and short-range transmission since the existing UWB systems are suitable for short range (El Hamdouni et al. 2020). Looking in to the older literatures on microstrip antenna, narrow bandwidth seems to be one of the disadvantages (Hota et al. 2020). After several researches, many techniques have been proposed to overcome this limitation. Out of several techniques proposed, most of the techniques focused on enhancing the bandwidth despite degrading the other parameters (Sivagnanam et al. 2019). So, techniques that enhances the bandwidth without degrading other parameters is most essential. UWB technology today has become an essential part due to its high bandwidth (Wu et al. 2018). In conventional UWB technology, multipath fading is a major problem caused by dense medium reflections and refractions. To mitigate the problem of multi path fading, MIMO technology has been proposed. Several studies have been carried out using MIMO technology to improve the reliability of UWB systems. However, the high isolation problem with in the entire operating band is serious, and several studies have been made on that.

Fractal geometries proved to be good candidates and efficient technique to reduce the size of antenna without affecting the stability of pattern and bandwidth. Fractal structures have self-similarity property that helps in compact antenna design.
Metamaterials are negative materials whose properties are based on its interatomic structure. Metamaterial based antennas result in extended bandwidth, miniaturization and enhanced properties of radiation (Ali and Ibrahim 2017). To design electrically small antennas metamaterials are engineered. Metamaterial considers better option to diminish the mutual coupling between the elements in MIMO antennas (Sultan and Abdullah 2019). Metamaterial loaded antennas are one of the best techniques of enhancing the bandwidth with improved efficiency.

MIMO antenna with grounded stubs and fractal geometry are used in (Tripathi et al. 2015), to improve isolation and to achieve wideband phenomena. A novel metamaterial superstrate included with S-shaped elements is reported in (Razi et al. 2015) for bandwidth and gain enhancement. In (Wang et al. 2015), a UWB-MIMO antenna using metamaterial is reported to achieve better bandwidth and dual-band-notch effect. F-shaped stubs are employed in the ground-plane in (Iqbal et al. 2017), to produce efficient isolation between two elements. In a four-element MIMO network that are very close to one another (Abdelhamid et al. 2019), 4 linear SRR structures are used between adjacent elements to ensure good isolation. In (Zhu et al. 2017), 6 FSS’s (Frequency Selective Structures) are positioned in the middle of UWB-MIMO antenna backside that reduced coupling by 7.2 dB. A novel SRR is used in (Wang et al. 2018), to reduce the coupling between two elements and C-SRR is used to enhance the bandwidth. A wideband neutralization line is proposed in (Zhang and Pedersen 2015), to deduce the coupling in a compact MIMO antenna.

In this communication, an UWB-MIMO antenna with low mutual coupling is designed loaded with metamaterial. The planned antenna consists of two hexagonal fractal monopoles fed by transmission lines. To achieve desired miniaturization fractal geometry is used in the design. Split ring resonator (Metamaterial structure) is used in the ground plane to obtain UWB and to reduce mutual coupling. The simulated and measured results are in wise agreement, showing that the proposed antenna can be used in portable devices because of its low ECC, high peak gain and diversity gain and moreover low mutual coupling.

2 Antenna geometry

The proposed structure consists of third iterative hexagonal slot loaded hexagonal radiator, fed by a transmission line. Use of transmission line feed gives freedom to cut fractals on the patch surface. The feedline dimensions are calculated using the standard equations (Balanis 2016). Table 1 illustrates the optimized dimensions of the structure. The used substrate material is 1.6 mm thick that has a loss tangent of 0.02 and $\varepsilon_r = 4.4$. In four corresponding steps the proposed structure is designed as shown in Fig. 1. The highest current density is found in the outer periphery of the hexagonal radiator and the focal section contains insignificant current. Therefore, expulsion of the zero current density parts doesn’t influence the performance of the antenna. Hence, hexagonal patch is chosen with fractal geometry in it.

![Fig. 1 Iterative fractal structures (a) 0th, (b) 1st, (c) 2nd and (d) 3rd iteration](image)

The geometry of hexagonal fractal is shown in Fig. 2a. By using the standard circular monopole design equations (Kumar et al. 2012), the circumradius of the hexagonal radiating element is calculated. Based on this circumradius and the standard relations between the circum-radius and polygon, the side length of the hexagonal patch is calculated. Here, hexagon is picked as the initiator shape and then it is taken to distinctive scaled version of the initiator shape as appeared in the Fig. 3. Initially a hexagonal
A radiator with a transmission line feed is designed achieving the 0th iteration of the structure. A hexagonal slot is then mounted on to the patch resulting in the structure’s 1st iteration. The 1st iterative structure is scaled down to 3rd iterative structure by an iterative factor. The subsequent iterative structure is put in the preceding iterative structure’s hexagonal slot. The successive iterative dimensions are calculated using the equations given in Singhal et al. 2015. The gap (G) between the two radiating elements is maintained to be very small because, large space would make over all antenna size large.

Ground layer configuration is demonstrated in Fig. 4 where, metamaterial-based structure is achieved (SRR). Figure 5 proves the metamaterial’s negative permeability due to SRR’s metallic property. This property enhances the antenna performance (Sugadev and Logashanmugam 2018).

3 Result analysis and discussion

Reflection coefficient comparison for all the iterative structure is shown in Fig. 6. The increase in number of iterations resulted in enhanced impedances matching. Because of fabrication imperatives iteration process is not repeated beyond 3. Also, no change in performance was observed beyond iteration 3. A bandwidth of 9 GHz (6–15 GHz) is obtained for the 3rd iterative structure with a return loss of below –10 dB throughout the band. Obtained bandwidth % is 98.63. Though 0th structure has obtained UWB characteristics, fractal geometry has been incorporated in the design in order to achieve size reduction. Antenna, without loading metamaterial-based structure exhibited resonant bands at 11 GHz and 12 GHz with a reflection coefficient of –22 dBi and –25 dB as displayed in Fig. 7.
The width of the splits (S1 and S2) in the resonators plays a vital role in achieving the perfect impedance matching over the operating band. The return loss variance for different S1 = S2 values is demonstrated in Fig. 8. From the plot it is observed that increasing the split width resulted in poor impedance matching when compared to the smaller widths. A split width of 2 mm resulted in
enhanced impedance matching throughout the operational band.

The gap (G10) between the two square split ring resonators also has an impact in achieving the ultra-wide band. Variation of return loss for different G10 values is depicted in Fig. 9. The gap between the resonators is varied from 1 to 5 mm by maintaining the split width of 2 mm. From the plot it is observed that a gap of 1 mm resulted in UWB with perfect impedance matching. Increased gap resulted in decreased impedance bandwidth so, the gap is maintained to be 1 mm.

So, it can be inferred that the dimensions of S1, S2 and G10 have major impact on the antenna’s resonating properties in the context of impedance matching. Poor impedance matching was observed with increase in S1 and S2 width dimensions but, the frequency of operation was almost similar for different values. Similarly, Increase in G10 dimension resulted in poor impedance matching but, the frequency of operation was different for different values. This is because the SRR in the ground plane changes the effective inductance and capacitance of microstrip line by adding slot capacitance, resistance, and inductance. This influences the resonating characteristics of antenna.

The third iterative structure is printed on a FR4 material as demonstrated in Fig. 10. The fabricated prototype is tested and is compared with the simulated outcome. The Inconsistency between the tested and measured result might be due to fabrication tolerance or imperfect soldering. Network Analyser measured return loss measurement is displayed in Fig. 11 and Table 2 where, the antenna works fine for the 5.8–15 GHz frequency.

Mutual coupling is an important factor to be considered in MIMO antennas which may affect the antennas efficiency and radiations properties. The distance between two radiating patches in this structure is maintained to be 3 mm. Though patches are placed very close to each other, mutual coupling is deduced due to the effect of loading SRR in the ground- plane. Mutual coupling in the desired design is observed to be below – 25 dB.

The mutual coupling characteristics (S21/S12) of the antenna with and without SRR are demonstrated in
Fig. 12a, b, which clears shows that the coupling is deduced by 15 dB when antenna is loaded with SRR. Figure 12a shows that the measured and simulated coupling outcomes are well agreed. Mutual coupling measurement becomes a challenge when the two patches are much close to each other. Due to the minimum gap between them, the SMA connectors that are soldered will obviously be very close to each other, which is difficult to connect both connectors at a time to the network analyzer probes. To overcome this and in order to proceed with the measurement, one of the patch is soldered with SMA straight jack and another is soldered with SMA ‘L’ shaped jack.

Figure 13 displays the desired antenna’s simulated real and imaginary parts of input impedance. The impedance values in both the plots are noticed to be varying around 50 \( \Omega \) and 0 \( \Omega \) respectively. These variations provide an estimated impedance of 50 \( \Omega \) i.e., the characteristic impedance of SMA connector. This matching between the characteristic impedance of SMA and the input impedance lead to reflection loss reduction.

The Envelope Correlation Coefficient (ECC, \( \rho_e \)) is significant for MIMO systems which is identified with the correlation between the antennas. The diversity performance is verified using ECC. The signal should be uncorrelated between the two ports of MIMO antennas in order to gain good diversity in radiation patterns. The ECC must be < 0.5 for a UWB-MIMO antenna (Vaughan and Andersen 1987). Based on the S-parameters (Matin 2012) the value of ECC can be calculated using the Eq. 1. The values of ECC plotted against frequency is shown in Fig. 14 which shows that the value is lower than 0.070 throughout the operating range. Also, ECC plot shows the value is below the acceptable limit 0.5 that ensures better diversity performance.

\[
ECC = \frac{|S_{11} \times S_{21} + S_{12} \times S_{22}|^2}{\left(1 - |S_{11}|^2 - |S_{21}|^2\right) \left(1 - |S_{22}|^2 - |S_{12}|^2\right)}
\]

(1)

The diversity gain (DG) is a function of ECC and is calculated to be almost 10 dB using Eq. 2 and is shown in Fig. 15. DG is an important parameter that assures the effectiveness of diversity.
Mean Effective Gain (MEG) is one of the important parameters to analyse the diversity performance (Man-teuffel 2009). MEG is a measure of received power level of a MIMO antenna to that of an isotropic radiator. The difference between MEG’s of the ports must be < 3 dB (MEGi – MEGj < 3 dB) in order to operate reliably in practice (Mao and chu 2014). The MEG of port 1 and 2 is calculated as MEGi = 0.5 × \left[1 - |S11|^2 - |S12|^2 \right] and MEGj = 0.5 × \left[1 - |S21|^2 - |S22|^2 \right], where i = 1 and j = 2. As shown in Fig. 16, the MEG of the projected MIMO is within acceptable limit throughout the operating range.

When the elements in a MIMO antenna are operating simultaneously, the elements impinge on each other that influences overall desired bandwidth, efficiency and gain (Liu et al. 2014). The performance of an actual MIMO system cannot be predicted by S-parameters alone, so TARC (Total active reflection coefficient) is taken into account which gives apparent return loss of antenna. For a side by side 2 port MIMO antenna, the TARC can be evaluated using Eq. 3 (Liu et al. 2015). TARC < 0 dB is essential for acceptable MIMO performance. Figure 17 depicts the TARC result, which is found to be below -10 dB throughout the operating range.

\[
DG = 10 \times \sqrt{1 - 0.99 \times ECC^2} 
\]

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\[
\text{TARC} = \sqrt{\frac{(S_{11} + S_{12})^2 + (S_{21} + S_{22})^2}{2}} 
\]
Fig. 13 Frequency vs. Input impedance characteristics, (a) real part and (b) imaginary part

Fig. 14 Envelope correlation coefficient (ECC)
Fig. 15  Diversity gain of antenna

Fig. 16  Simulated MEG

Fig. 17  TARC result of desired antenna
Fig. 18 Radiation patterns at (a) 5.8, (b) 7.5 GHz and (c) 12.5 GHz, solid line (Measured) and dotted line (Simulated)

Fig. 19 Radiation efficiency of proposed antenna
of 97.5% is observed at 7 GHz. Simulated efficiency is also compared with the theoretical efficiency. Based on wheeler and Chu formula (Eqs. 4 and 5) (Sievenpiper et al. 2011), theoretical efficiency is depicted in Fig. 20. A theoretical efficiency of 99.99% is obtained.

\[
Q = \left( \frac{1}{ka} + \frac{1}{(ka)^3} \right)
\]

(4)

Where, \( k \) = wave number \((2\pi/\lambda)\) and ‘a’ (2.1 cm) is the dimension of the sphere that circumscribes the proposed antenna.

\[
\eta = \frac{1}{1 + Q \tan \delta}
\]

(5)

As discussed in (Uvarov et al. 2019), the radius of chu sphere for an antenna with the lower frequency of the operating range of 5.8 GHz will be 8.5 mm, which is 2.5 times less than the radius described around the proposed antenna. Therefore, the dimension efficiency \((1/2.5)\) of antenna is found to be 0.4.

Figure 21 displays the realized peak gain vs frequency of the final iterative structure where the maximum peak gain of 6.2 dBi is obtained at around 14 GHz.

Distribution of surface current on the radiating element and on the ground plane is displayed in Fig. 22 at three different frequencies (5.8, 7.5 and 12.5 GHz), which clearly shows that current is uniformly distributed. High current density is observed at some parts of the spit ring resonator and in the feed line Table 3.
Fig. 22  Distribution of surface current at three different frequencies. (a) 5.8 GHz, (b) 7.5 GHz, (c) 12.5 GHz

Table 3  Current work comparison with previously reported antennas

| Size (mm²)          | Bandwidth (GHz) | Mutual coupling (dB) | ECC  | Diversity gain (dB) | Peak gain (dBi) | Radiation efficiency |
|---------------------|-----------------|----------------------|------|---------------------|-----------------|----------------------|
| 48 × 48 (Mao and Chu 2014) | 3.2–11          | < − 17               | < 0.1 | NA                  | 5               | > 75%                |
| 60 × 41 (Liu et al. 2014)  | 3.28–11.07       | < − 17               | < 0.25 | > 9                 | 6.5             | > 70%                |
| 36 × 40 (Liu et al. 2015)  | 3–12            | < − 19               | < 0.03 | > 9.5               | 4               | > 70%                |
| 55 × 33 (Rajkumar et al. 2018) | 1.92–10.6        | < − 18               | < 0.019 | > 9.95             | NA              | > 91%                |
| 50 × 40 (Lin et al. 2016)  | 2.5–11          | < − 15               | < 0.02 | > 9.65              | NA              | > 69%                |
| 40 × 40 (Sarkar and Srivastava 2017) | 2–6              | < − 15               | < 0.1  | > 9.95              | 4.3             | > 85%                |
| 50 × 25 (Khan et al. 2020)  | 2–12            | < − 17               | < 0.15 | NA                  | 5.8             | NA                   |
| 35 × 38 (Banerjee et al. 2020) | 2.7–11.22       | < − 20               | < 0.035 | > 9.98             | 4.5             | > 72%                |
| 34 × 30 (Gurjar et al. 2020) | 3–12.6          | < − 16.3             | < 0.06 | > 9.95             | 4.8             | NA                   |
| 30 × 30 (proposed)    | 5.8–15          | < − 25               | < 0.013 | > 9.99             | 6.2             | > 88%                |
4 Conclusion

A compact metamaterial inspired UWB-MIMO fractal antenna is designed and analyzed. The simulated and experimental results are validated justifying the antenna ability for UWB. Measured third iterative antenna achieved an impedance bandwidth of 9.2 GHz (5.8–15 GHz) with the mutual coupling below –25 dB. The stable radiation patterns and a peaks gain of 6.2 dBii shows the proposed antenna appropriate for UWB applications with an efficient radiation efficiency (>88%). The obtained ECC (<0.07), MEG (<3 dB), TARC (<–10 dB) and DG (>9.98 proves that the proposed antenna has good diversity performance. On comparing this work with previously reported similar works, the designed structure is compact. The impedances bandwidth of this antenna covers WLAN, WIMAX, UWB applications etc.

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