Development of compact UWB MIMO antenna with enhanced broadband performance and low reflection coefficient

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Abstract -**The demand for wireless communication systems that support higher data rates and reliability has led to increased interest in Ultra-Wideband (UWB) Multiple-Input, Multiple-Output (MIMO) antenna technology. UWB communication systems offer numerous advantages, including high data rates, low power consumption, and the ability to coexist with other wireless technologies. However, realizing the full potential of UWB communication systems hinges on the development of compact UWB MIMO antennas that can provide enhanced broadband performance and low reflection coefficients. This research paper presents a comprehensive investigation into the design, simulation, and experimental validation of such antennas. The objectives of this research are to address the limitations of conventional UWB antennas, which often struggle with achieving adequate bandwidth and maintaining low reflection coefficients. In our study, we employ advanced design techniques and innovative materials to develop a compact UWB MIMO antenna that excels in both broadband performance and reflection coefficient suppression. Our literature review reveals the current state of UWB antenna technology and the challenges faced in designing compact MIMO antennas. Key challenges include limited bandwidth, spatial diversity, and maintaining low reflection coefficients across a wide frequency spectrum. These challenges have driven our focus on enhancement techniques, including metamaterials, stacked or coupled elements, frequency-selective surfaces (FSS), and dielectric loading. The antenna design and simulation phase leverages cutting-edge simulation tools and software to analyze the proposed compact UWB MIMO antenna. The simulation results encompass parameters such as S-parameters, radiation patterns, and impedance matching. These results provide essential insights into the antenna's performance across the UWB frequency range. In addition to simulation, our research includes an experimental validation stage, which employs a carefully designed setup and measurement procedures to verify the antenna's real-world performance. This validation process not only confirms the simulation results but also highlights any variations or practical considerations that may impact the antenna's performance. The findings of this research underscore the significance of our compact UWB MIMO antenna in meeting the demands of modern wireless communication systems. By successfully enhancing broadband performance and minimizing reflection coefficients, our antenna contributes to the advancement of UWB technology, supporting applications in ultra-high-speed data transfer, wireless sensor networks, and radar systems. In conclusion, this research paper not only addresses the limitations of traditional UWB antennas but also paves the way for more efficient and reliable UWB communication systems. The developed compact UWB MIMO antenna represents a critical step toward the realization of UWB technology's full potential and provides a strong foundation for future research and innovation in the field.**

Keywords: **Ultra-Wideband, UWB, MIMO antenna, broadband performance, reflection coefficient, wireless communication, metamaterials, frequency-selective surfaces, simulation, experimental validation**.

I.INTRODUCTION

It has been claimed that some UWB antennas have been built and set up based on early research. A novel, compact ultra-wideband antenna based on the rectangular waveguide idea has been suggested [1]. Additionally, studies are underway to develop a planar dipole antenna with adjustable gain and impedance that can operate inside the UWB operating spectrum [2]. It is made up of a shorting bridge that connects two arms with semielliptical ends. Applying RF switches (PIN diode) to the feed line of a planar monopole antenna is an innovative way to produce reconfigurable UWB band to narrowband [3]. Microstrip square-ring slot antennas (MSRSAs) designed to cover the ultra-wideband (UWB) frequency band are achieved by splitting the square-ring slot and tuning the feeding network [4].

The huge capacity and high-speed wireless communication concentration of Multi-Input-Multi-Output (MIMO) antennas have attracted a lot of research attention [5-6]. In multiple-input multiple-output (MIMO) systems, the transmitter and reception antennas work in tandem. However, in order for MIMO to be effective, a number of issues and aspects must be resolved, including low correlation, extremely low mutual coupling, high diversity gain, and low total active reflection coefficient (TARC) [7-9].

This work presented the novel compressed co-located antenna that uses a duplicate of two antenna components. An outstanding reflection coefficient and operation at ultra-wideband frequencies characterise the proposed antenna. This exemplifies the use of UWB-MIMO antennas in wireless communication applications due to their small size, high bandwidth, diversity, and capacity. Building MIMO antenna systems also allows for the shortest possible inter-element spacing with very low mutual coupling.

II.EVOLUTION OF UWB ANTENNAS

An extensive and circuitous path has been laid out for the development of ultra-wideband (UWB) antennas, with several landmark advances and revolutionary breakthroughs in wireless communication technology serving as its pavement. Advancements in technology, new research endeavours, and increasing communication needs have shaped the evolution of UWB antennas from their first designs to their current tiny form factor. A comparison of the early designs with the current antennas reveals this development.

Early Developments: The first blueprints for ultra-wideband antennas were created during the mid-century as a result of research on impulse-based communication systems. These devices mostly functioned by transmitting short-lived pulses over a wide range of frequencies. Antennas used for ultra-wideband (UWB) applications used to be larger, heavier, and less efficient due to their complex construction and manufacturing limitations.

Regulatory Milestones: The advancement of ultra-wideband (UWB) technology is significantly affected by the changing nature of laws. Interest in and funding for ultra-wideband antennas increased around the turn of the millennium as the Federal Communications Commission (FCC) of the US allocated a significant chunk of spectrum for UWB transmission.

Miniaturization and Compact Designs: The increasing need for smaller, more efficient, and more adaptable communication systems prompted researchers to focus on miniaturizing ultra-wideband antennas. More efficient and smaller UWB antennas are now within reach, because to recent advances in electromagnetic theory, computational methodologies, and materials research. Fractal geometries, metamaterials, and novel feeding algorithms are some of the new methods that have been created to produce smaller designs with the same or better performance.

Multiband and MIMO Integration: A number of wireless communication protocols can now be supported by ultra-wideband antennas, which have evolved beyond the capacity to operate on a single frequency band. Furthermore, a notable development was the integration of Multiple Input Multiple Output (MIMO) technology into UWB antennas. This allowed communication systems to handle higher data rates, more reliability, and more geographic variety.

Advancements in Performance Parameters: One of the main goals of developing UWB antennas was to improve crucial performance aspects including radiation efficiency, gain, impedance bandwidth, and low reflection coefficients over the UWB spectrum. Modern optimisation methods, novel antenna topologies, and innovative materials were all explored by the study team in an effort to improve performance.

Emerging Trends and Future Directions: The importance of UWB antennas being able to adapt to changing communication environments, reconfigure themselves, and serve many purposes is growing in recent years. One of the main areas of research and development is the integration of ultra-wideband (UWB) antennas into compact and portable devices. These devices include sensors for the Internet of Things (IoT), wearable technology, and automotive systems. On top of that, researchers are always exploring new avenues for improving bandwidth utilisation and efficiency, and they're also fixing problems with interference mitigation and spectrum rules.

From their humble beginnings to the sleek, compact forms of today, UWB antennas have been a remarkable journey of constant improvement. This has paved the way for the realisation of versatile, low-power, high-speed wireless communication systems.

III.STATE-OF-THE-ART TECHNIQUES IN UWB MIMO ANTENNA DESIGN

In order to achieve better performance, compactness, and efficiency in wireless communication systems, the design of Ultra-Wideband (UWB) Multiple Input Multiple Output (MIMO) antennas is a confluence of creative ideas, techniques, and technologies. These methods are said to be cutting edge. A few of the most important approaches are as follows:

Geometrical Innovations:

Fractal Geometries: One way to create small UWB MIMO antennas is to use fractal geometries. Examples of such geometries include Koch, Sierpinski, and Minkowski fractals. While retaining acceptable radiation properties, these structures provide multiband features and enhanced miniaturization.

Metamaterials and Meta surfaces: Improved performance is possible via the manipulation of electromagnetic characteristics made possible by incorporating metamaterial structures into antenna designs. Controlling wavefronts and achieving desired radiation patterns is achieved via the use of meta surfaces, which consist of designed subwavelength features.

Advanced Optimization Algorithms:

Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO): In order to optimise antenna parameters for performance metrics including radiation efficiency, impedance matching, and bandwidth, these metaheuristic optimisation approaches are used to explore large design spaces.

Machine Learning (ML): Optimising antenna designs is one area where ML algorithms are finding more and more applications. Accelerating the design process, finding non-intuitive solutions, and anticipating ideal configurations are all made easier with the help of neural networks and genetic programming.

Compact Antenna Structures:

Printed Antennas: Many UWB MIMO designs choose for planar printed antenna configurations such patch, slot, and meander-line antennas because to their compactness and simplicity of integration.

Microstrip Antennas: Microstrip feeding methods enable ultra-wideband antennas to be small and unobtrusive. Broadband performance may be achieved by using different dielectric substrates and several layers.

Bandwidth Enhancement Techniques:

Dual/Tri-band and Wideband Antennas: It is essential to design antennas with broad properties or the ability to operate in numerous frequency bands for UWB applications. Improved data transfer rates are possible with the use of methods such as impedance matching networks, fractal geometry, and slotting.

Material Selection and Integration:

Metamaterial Integration: Functionalities like miniaturization, better gain, and lower losses are made possible by incorporating metamaterials into antenna systems, which allows for the control of electromagnetic characteristics.

Flexible and Tunable Materials: Antenna performance and adaptability are both improved by using flexible and tunable materials, which let the antenna to change with the environment and different frequency demands.

MIMO System Integration:

Array Configurations: Increasing spatial diversity via the use of various array topologies, such as circular arrays, uniform rectangular arrays (URA), or uniform linear arrays (ULA), allows MIMO systems to achieve faster data rates and better reliability.

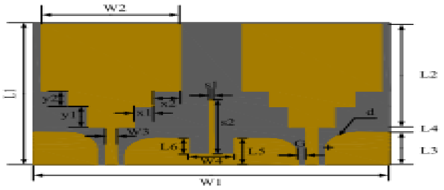
Efficiency Enhancement Techniques:

Radiation Pattern Engineering: In MIMO systems, interference may be reduced and efficiency increased by manipulating the radiation pattern of the antenna using array topologies or beamforming algorithms.

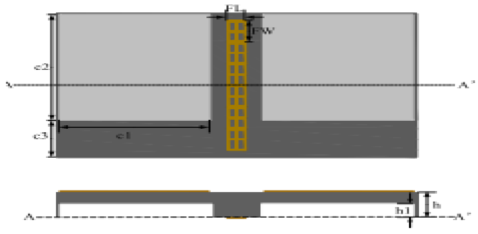
The integration of these state-of-the-art techniques drives the creation of miniature UWB MIMO antennas that exhibit enhanced performance attributes. Antennas like this are developed to address the growing need for reliable, high-speed wireless communication systems in many fields.

IV ANTENNA STRUCTURE DESIGN

In accordance with UWB technology seen in small mobile devices, the antenna is constructed on a planar microstrip transmission line with a coplanar waveguide (CPW) feeder. The antenna substrate is chosen to be a 400 µm thick silicon wafer. Because silicon has a relative dielectric constant of 11.9, MIMO antennas might be smaller than previously thought. Antennas, silicon substrate, and functional circuits may all be seamlessly integrated onto a single silicon wafer, the fundamental component of most integrated circuits. The proposed UWB-MIMO antenna configuration is shown in Fig. 1. Table 1 displays the finished antenna dimensions. Two similar rectangular radiation patches and CPW feeders are located on top of the array. Patches used to be rectangular, but now



(a) Front view



(b) Back view

Figure 1: UWB-MIMO antenna configuration. an aerial view. b Rear angle

Table 1: Dimensions of the UWB-MIMO antenna

Parameter	**mm**	**Parameter**	**mm**
W1	38.2	L1	26.6

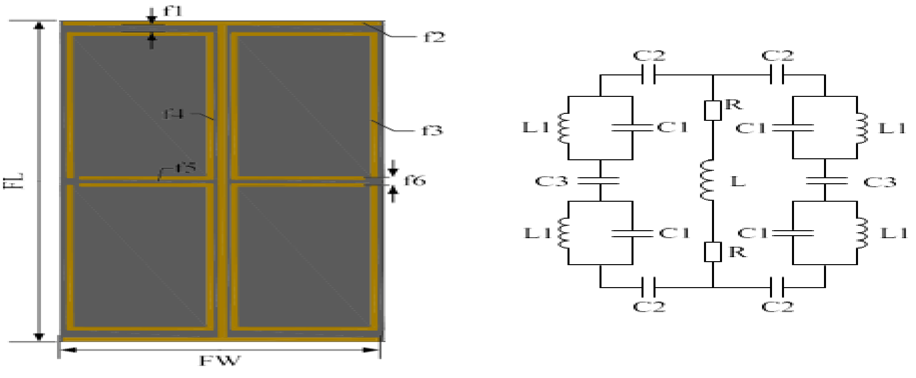
W2	14.88	L2	19.36
G	0.9	W3	1.2
W4	5	L3	6.01
L4	0.96	L5	4.91
L6	3	×1	2.1
×2	2.9	y1	3.95
y2	1.81	d	3.18
s1	0.4	s2	10.26
h	0.4	h1	0.2
c1	15.96	c2	19.54
c3	6.88	FW	2
FL	4	f1	0.04
f2	0.04	f3	0.03
f4	0.04	f5	0.06
f6	0.1		

Buildings cannot entirely encapsulate the ultra-wideband (UWB) frequency range. Modifying the bottom contour of patches is a simple approach to increase band width, since the current is concentrated at the antenna's base. The current route is widened by transforming the rectangular patch into a staircase profile. If the antenna feeder is microstrip constructed, the substrate and radiation patch are on opposite sides. The proposed antenna, however, makes use of a CPW feeder due to the fact that the patch and ground are in the same plane. Antennas with coplanar features are easy to construct since they have minimum radiation loss and dispersion. The grounds next to the feeder undergo arc processing to mitigate current losses caused by right-angled grounds; this operation has the potential to improve impedance matching and widen the frequency band width.

A decoupling FSS structure and two rectangular chambers make up the rear of the proposed antenna. Surface wave losses greatly affect antenna performance, even if a substrate with excellent transmittivity could assist reduce antenna size. The patches on the back of the substrate are carved to create two vertical chambers that reduce the visibility of surface waves. Antenna substrates that combine silicon with air cavities may have their effective dielectric constant calculated.

$$\varepsilon_e = \frac{\varepsilon_0 \varepsilon_r}{\varepsilon_0 + (\varepsilon_r - \varepsilon_0) h_1 / h} \tag{1}$$

The variables h1, εr, and ε0 represent the air cavity height, relative permittivity of silicon, and vacuum permittivity, respectively.



(a) FSS unit structure (b) FSS equivalent circuit

Figure 2 shows *the basic layout of the FSS unit and its comparable circuit. one FSS equivalent circuit, and two FSS unit structures*

the thickness of the silicon wafer. By lowering the relative dielectric constant, eliminating the surface wave problem, and improving MIMO antenna performance, vertical air holes are a boon to the field.

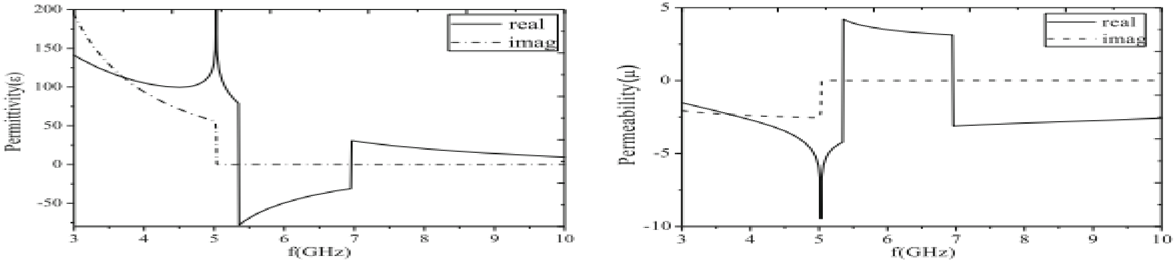
Decoupling Structure Design

Meta materials are synthetic composites with properties such as negative permeability, permittivity, or refractive index. A component of the subwavelength structure, metamaterial has a unit size much lower than the operational wavelength. The physical properties of metamaterials may be investigated by calculating their equivalent permittivity and permeability. The values of and indicate the electric field-magnetic field interaction, and the following is one way to define the electromagnetic wave propagation constant k:

$$k = w\sqrt{\mu\varepsilon} \tag{2}$$

If k is a positive integer, then the medium could be able to carry electromagnetic waves. For negative values of ε or μ, the propagation constant k takes on an imaginary value. The band gap appears and the propagation of electromagnetic waves is impeded under these conditions. So, when electromagnetic waves hit metamaterial surfaces, complete reflection phenomena will occur.

The UWB-MIMO antenna's novel decoupling structures consist of a front faulty ground in addition to the back FSS framework. The CPW feeder of the antenna causes the middle grounds to be mutually linked in the UWB high-frequency band. Antennas are reflected off of the middle short-circuited strip, and coupled ground coupling is reduced by the faulty ground transition. Intersecting cavities provide the backbone of the broadband FSS structure. To minimise direct impact on the front radiation patches, the FSS should be placed on the back side of the small antenna dimension.



(a) equivalent permittivity (b) equivalent permeability

Figure. 3 Equivalent parameters of FSS unit. a Equivalent permittivity. b Equivalent permeability

Metal material is used to print on a 400 μm silicon substrate the four divided rectangles and one I-shaped strip that comprise the intended FSS unit. Figure 2 depicts the FSS structure and the comparable circuit. An I-shaped strip's equivalent resistance and inductance are represented by the letters L and R, respectively. L1 represents the equivalent capacitance and C1 represents the equivalent inductance of the divided rectangle. Capacitance C2 is the same for the bifurcated rectangle and the I-shaped strip. C3 is the capacitance that corresponds to the overlap of the two rectangles. A magnetic metamaterial with a strong magnetic sensitivity and negative equivalent permeability, the split rectangle structure resembles an LC resonance circuit. One kind of electrical metamaterial, the I-shaped structure may develop an electric resonance with negative permittivity by producing a significant induced electric field. An LC resonance circuit is a good analogy. An FSS cell that combines electrical and magnetic metamaterials has actually been proposed. The permeability and permittivity curves of the FSS cell are shown in Figure 3. The electric resonance phenomenon is seen in FSS in the frequency range of 5.36-6.96 GHz, where the equivalent permeability is positive and the equivalent permittivity is negative. Additionally, FSS displays magnetic resonance properties with contrasting parameter performances in different frequency bands. With S11 standing for the reflection coefficient and S12 for the transmission coefficient, the S parameters of the FSS unit are shown in Figure 4. The FSS unit may prevent electromagnetic wave transmission by acting as a band-stop filter, as shown in Fig. 4, all S12 values are below -20 dB over the full UWB spectrum. Therefore, the metamaterial FSS unit is suitable for UWB-MIMO antenna decoupling.

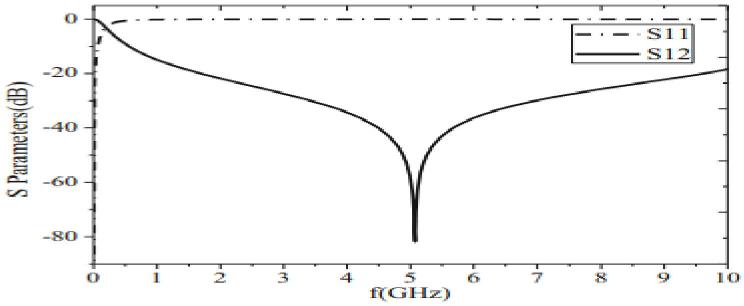
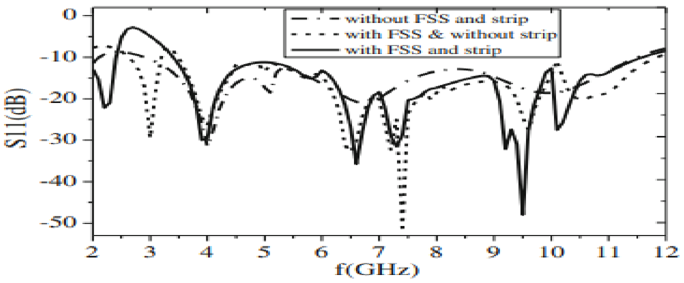
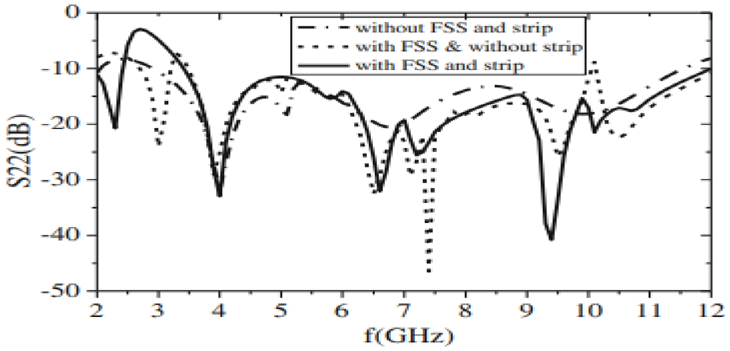


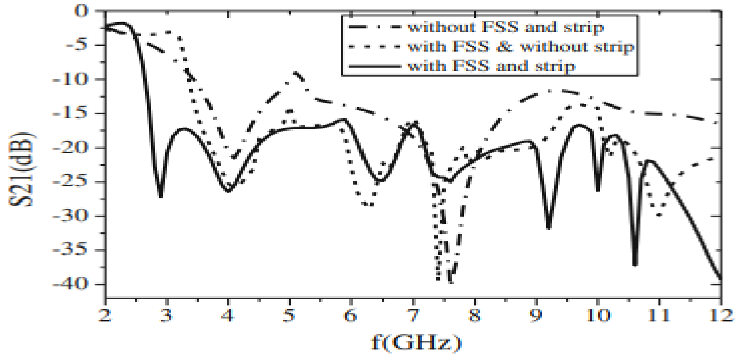
Figure.4 Coefficients of reflection and transmission of the FSS unit



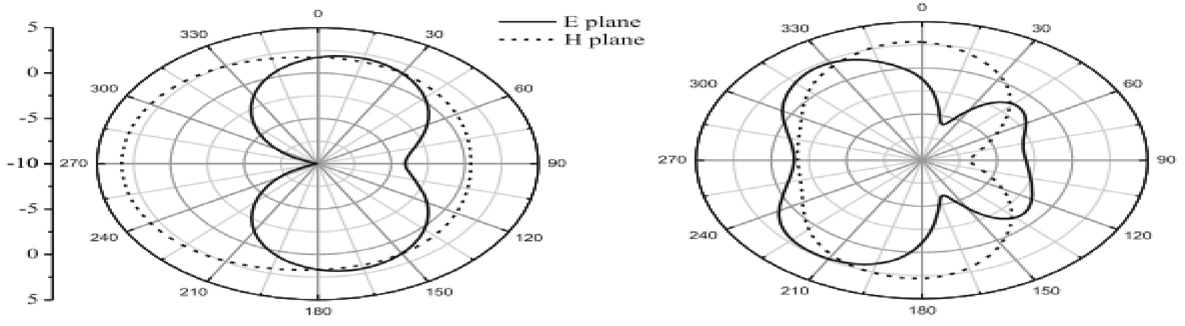
reflection coefficient of antenna I



reflection coefficient of antenna II



coupling coefficient between antenna I and IIThe isolation and return loss of the UWB-MIMO antenna are shown in Figure 5. The reflection coefficient of antenna I is denoted as a. A reflection coefficient of b.c. is associated with antenna II. The coupling coefficient between the two antennas



(a) 5GHz (b) 9GHz

Fig. 6 Radiation patterns of the UWB-MIMO antenna. a5 GHz. b 9 GHz

V.**ANTENNA PERFORMANCE: RESULT AND DISCUSSION**

Input Reflection Coefficient (|S11|)

We monitor the performance of the individual element before to combination as well as the MIMO antenna subsequent to combination. Both components' reflection coefficients under an acceptable return loss of less than 10 dB are achievable over the complete UWB frequency range, as shown clearly in Figure 2. At 3.15 GHz and 6.2 GHz in particular, the return loss of a multi-antenna system is lower than that of a single antenna. This is due to the impact of the adjacent element and the substrate's enlargement in both width and length.

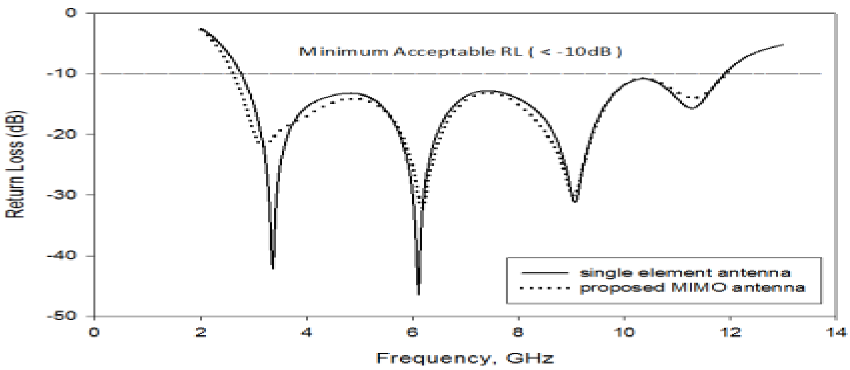


Figure 7: The returns loss of the presented antenna

This input reflection coefficient has been studied with respect to the effect of inter-element spacing, D. Fig. represented the MIMO antenna's return loss. spanning the interval 38–43 mm for D=39, 40, 41, 42, and 43. When D is 38mm, impedance matching at 6GHz is optimal compared to other frequencies. At the same time, when D values increase, the frequency resonance at 9 GHz becomes increasingly populated with perfect matches. Within the range of 3.1 to 10.6 GHz, the MIMO antenna continues to operate, regardless of the D values that have been investigated. According to this article, the value of D is 38mm, including both the performance limits of the antenna and the effect of antenna compaction.

Mutual Coupling

Mutual coupling occurs when nearby antenna components come into electromagnetic (EM) contact with one another. A high mutual coupling coefficient will reduce the antenna's efficiency. A mutual coupling coefficient (MKC) may be determined using the forward transmission coefficient (S12) and the reverse transmission coefficient (S21) [8, 13]. Papers [8, 10, and 13] state that the mutual coupling is below -14 dB, -11 dB, and -9.5 dB, respectively.

As shown in Figure 5, the example research examines the effect of different D values on the S12 and S21. Based on the results shown in Figure 5, the mutual coupling is consistently less than -11.5 dB across all UWB frequencies. When D = 38 mm, the S21 and S12 overlap. With the exception of frequencies operating between 2GHz and 3GHz, when comparing D is 38mm (no gap between elements) to other Ds, mutual coupling reduces as inter-element spacing rises.

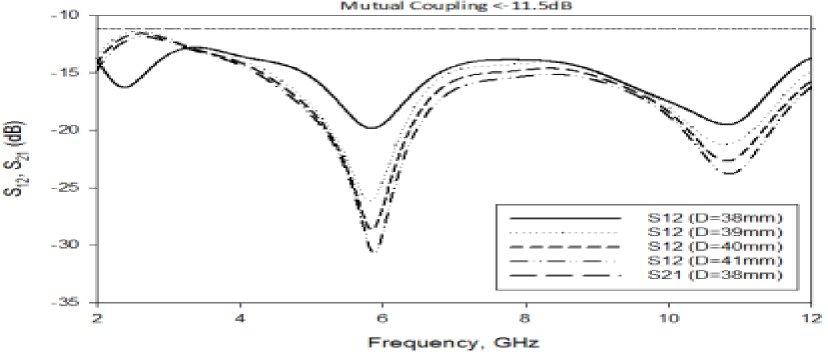


Figure 8: The mutual coupling against frequencies

CONCLUSION

A novel architecture of similarly built 2x2 MIMO antennas working in UWB is presented in this paper. The same kind of study was also performed on MIMO antennas both before and after combining, as well as on single element antennas. A reflection of antenna performance, the unique design of the MIMO antenna has been the subject of analysis. The research presents a multiple-input multiple-output antenna that has a minimum input reflection coefficient of -10dB and a mutual coupling of less than -11.5dB. Additional research will be conducted to determine the optimal UWB impulse response and low correlation coefficient. These prove that the proposed antenna works well with UWB-MIMO networks. Because of its diminutive size, it might potentially be marketed as a communications gadget of the future.

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