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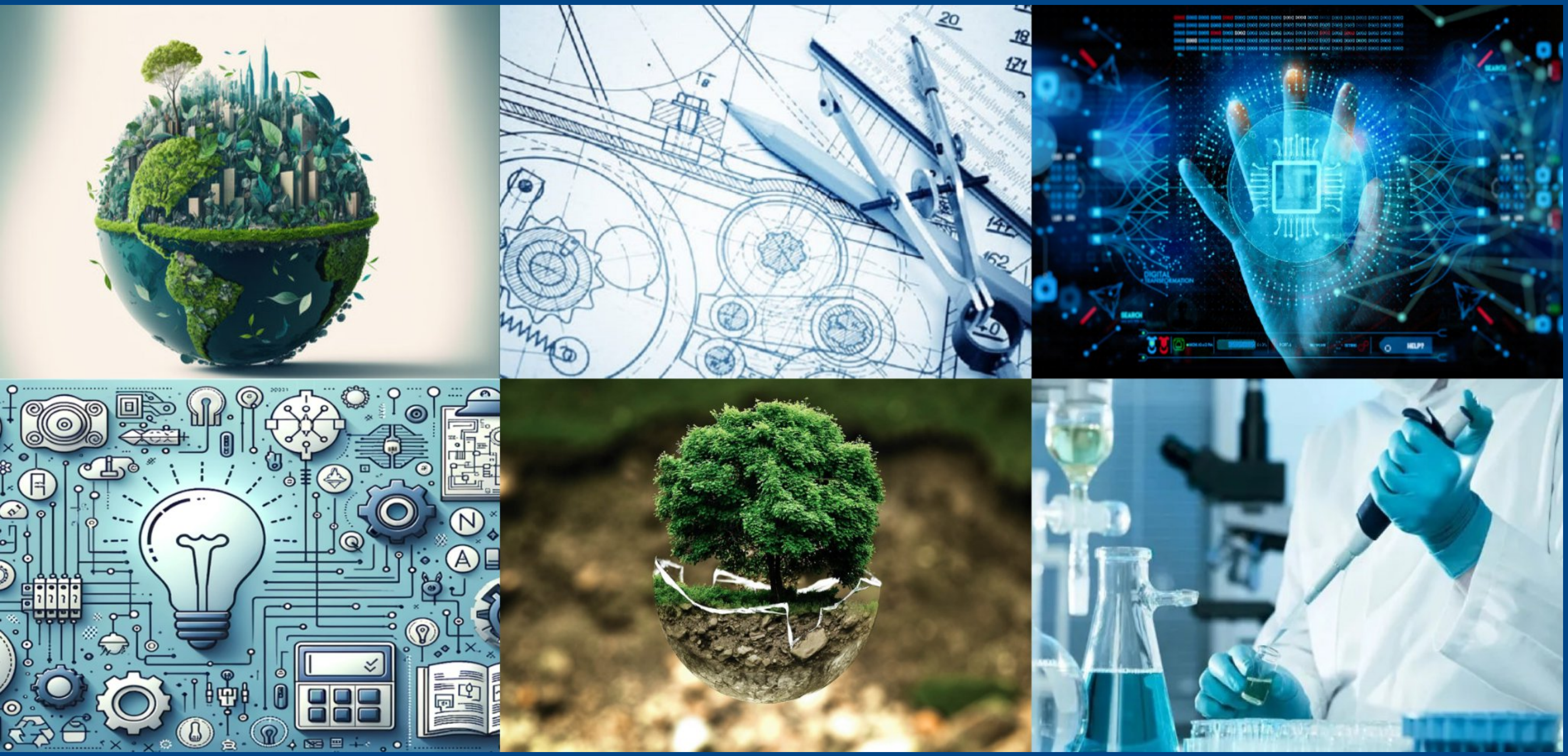

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Design and Analysis of Highly Isolated Compact UWB MIMO Antenna

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ABSTRACT: This paper is about the design and analysis of a compact ultra-wideband multiple-input multiple-output antenna intended to use for portable wireless systems. The proposed configuration combines two radiating elements with a modified ground plane, parasitic stubs, a connecting strip, and slot loading to achieve wide impedance band width and reduced mutual coupling. The antenna occupies a compact size of 26 × 40 mm² and is designed to operate over the 3.1–10.6 GHz ultra-wideband region. Structural modifications are introduced to control surface current flow, create additional resonances, and improve isolation between the two ports. Simulated results indicate satisfactory reflection coefficient performance with |S11| and |S22| below the acceptable limit over most of the operating band, while the transmission coefficients remain sufficiently low, confirming good isolation. The design also exhibits low envelope correlation coefficient, acceptable voltage standing wave ratio, stable radiation behavior, and useful diversity characteristics. Characteristic mode analysis further explains the wideband response and validates the radiating modes responsible for the antenna performance. Owing to its compact geometry and enhanced isolation, the proposed antenna is suitable for ultra-wideband MIMO applications in modern handheld and portable communication devices.

KEYWORDS: Ultra-wideband antenna, MIMO antenna, compact antenna, isolation improvement, stubs, slots, characteristic mode analysis, portable wireless devices.

I. INTRODUCTION

Wireless communication technology is getting better and better. This means we need antennas that're small do not weigh a lot and can send a lot of data quickly. When we talk about devices like the ones we carry around the antenna has to be small enough to fit inside. It also has to work electrically no matter what frequency we are using.Ultra-wideband technology is really useful here. It can send a lot of data over a range of frequencies it does not use a lot of power and it is good, for communicating over short distances very quickly. The problem is, when we try to make ultra-wideband antennas small it gets tricky. This is especially true when we put antennas close together like we do for MIMO operation, which is a way of making wireless communication faster.

In a MIMO system, the use of multiple ports improves channel capacity, link reliability, and diversity performance. At the same time, close spacing between radiating elements leads to mutual coupling, which degrades isolation and affects radiation efficiency. Poor isolation also increases the envelope correlation coefficient and reduces diversity gain, both of which are undesirable in practical systems. Therefore, an effective UWB MIMO antenna must simultaneously provide wide bandwidth, compact size, low reflection coefficient, reduced mutual coupling, and stable radiation characteristics.

The present work addresses these requirements through a compact UWB MIMO antenna in which the ground plane is carefully modified using long stubs and a short connecting strip. Additional slot loading is also considered to further improve current distribution and bandwidth behavior. The complete study includes design evolution, parametric understanding, S-parameter analysis, VSWR behavior, radiation performance, surface current interpretation, and characteristic mode analysis. The aim is to develop a compact antenna structure that is suitable for integration in modern wireless devices.

II. PROBLEM STATEMENT

Conventional single-element antennas are often unable to satisfy the demands of next-generation portable communication devices, especially when both compactness and broadband operation are required. Although ultra-wideband systems provide large bandwidth, compact UWB antennas generally suffer from performance limitations such as narrow matching regions, strong surface wave interaction, and poor isolation when more than one radiating element is employed. These limitations become more severe in MIMO configurations because the antenna elements are positioned in close proximity.

The major design challenge is therefore to realize a compact UWB MIMO antenna that offers wide impedance bandwidth together with reduced mutual coupling and acceptable diversity performance. The problem becomes more critical when the antenna must also maintain simple geometry, easy fabrication, and compatibility with portable devices. The proposed work is aimed at overcoming these difficulties by introducing structural modifications in the ground and radiating regions so that the current path is controlled more effectively and better isolation is achieved without increasing overall size.

III. LITERATURE REVIEW

The performance of recently developed UWB MIMO antennas is analyzed and compared based on different parameters such as isolation, bandwidth, and diversity performance. Various design approaches including stub-based structures, slot techniques, and compact MIMO configurations have been used by researchers to enhance antenna performance. The following table presents a comparative study of existing works based on their design methodology, platform, and performance characteristics.

Author	Year	Dataset / Platform	Performance
Kumar et al.	2018	Simulated UWB antenna model (HFSS)	Isolation ≈ -15 dB , ECC < 0.3
Sharma et al.	2019	CST simulation environment	Moderate bandwidth improvement and isolation
Reddy et al.	2020	FR4 substrate based antenna design	“Isolation ≈ -18 dB with improved coupling reduction
Singh et al.	2021	Compact UWB MIMO structure	ECC < 0.2 good diversity performance
Patel et al.	2022	Slot-based antenna configuration	Wide bandwidth with improved isolation
Verma et al.	2023	Hybrid stub-slot UWB design	High isolation (< -20 dB) stable radiation

From the above comparison, it is observed that most of the existing antenna designs achieve either good bandwidth or improved isolation, but not both simultaneously in a compact structure. Some designs provide better isolation but increase complexity, while others focus on bandwidth improvement with moderate coupling reduction. Therefore, there is a need for a compact and efficient UWB MIMO antenna that provides wide bandwidth, high isolation, and improved diversity performance. The proposed work aims to overcome these limitations by using a combination of stub and slot techniques to achieve enhanced overall performance.

IV. DESIGN METHODOLOGY AND BASIC EQUATIONS

The basic dimensions of the microstrip radiating element are initially estimated from conventional patch design relations. The patch width is selected based on the resonant frequency and dielectric properties of the substrate. The effective dielectric constant is then calculated to account for fringing fields, and the effective length is obtained accordingly. A correction term is introduced to determine the actual physical patch length. For MIMO operation, the spacing between elements must also be considered because insufficient separation directly increases mutual coupling.

To get a match the reflection coefficients |S11| and |S22| need to be low below −10 dB for the whole frequency range we want to use. We also want |S11| and |S22| to be as low as possible. For the antennas to work together the transmission coefficients |S21|. |S12| should be very low, below −15 dB for the whole range we are using. The transmission coefficients |S21|. |S12| are important. The envelope correlation coefficient is a measure that helps us see how similar the two antenna ports are. When this measure is low it means the antennas are working well together and we get results, from the antenna ports. Lower values of the envelope correlation coefficient are good because they mean the two antenna ports are not too similar.

To enhance wideband behavior and improve isolation, slot loading is incorporated in the radiating region. Slot dimensions are related to guided wavelength so that additional resonances may be introduced. The slot length, slot width, and slot position influence impedance bandwidth, resonant frequency, and coupling reduction. These theoretical considerations provide the basis for the proposed geometry and guide the subsequent design evolution.

Basic Design Equation

- **Patch Width (W)**

$$W = c/\left(2\, f_r\right) * sqrt\left(2-\left(\varepsilon_r + 1\right)\right)$$

The patch width (W) is calculated to achieve efficient radiation and wider bandwidth. It mainly depends on the operating frequency and dielectric constant of the substrate.

- **Effective Dielectric Constant (εeff)**

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} * \left(1 + \frac{12h}{W}\right)^{-\frac{1}{2}}$$

The effective dielectric constant represents the combined effect of air and substrate on the antenna. It plays an important role in determining the propagation characteristics.

- **Effective Length (Leff)**

$$L_{eff} = c/\left(2\, f_r sqrt\left(\varepsilon_{eff}\right)\right)$$

The effective length accounts for the fringing fields around the patch and helps in accurate calculation of resonant frequency.

- **Actual Length (L)**

$$L = L_{eff} - 2\Delta L$$

The actual length of the patch is obtained by subtracting the length extension due to fringing effects from the effective length.

- **ECC**

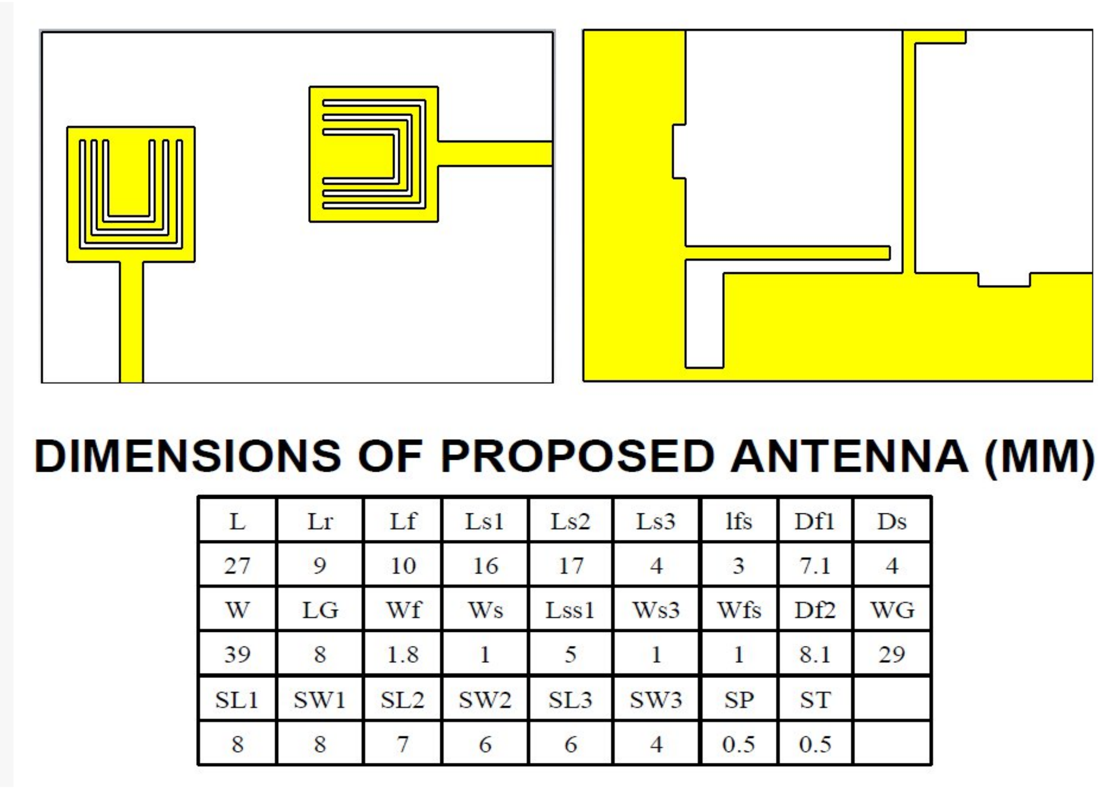
$$ECC < 0.5$$

The envelope correlation coefficient (ECC) indicates the level of correlation between antenna elements. Lower values represent better diversity performance.

V. PROPOSED ANTENNA STRUCTURE

The proposed antenna consists of two compact radiating elements arranged in a two-port MIMO configuration. Each element is excited through a microstrip feed line, and both elements share a modified ground plane. The complete antenna occupies only 26 × 40 mm², which is suitable for compact wireless hardware. The geometry is intentionally designed to remain simple while still incorporating the essential features required for high isolation and wideband response.

Two elongated ground stubs act as parasitic elements that reshape the surface current distribution. In addition, a short connecting strip is placed between the ground portions of the two antenna elements. This strip plays an important role in redistributing current and suppressing unwanted coupling paths. The combined effect of the stubs and connecting strip is to create multiple current paths and resonant mechanisms that support improved impedance matching and lower mutual coupling across the ultra-wideband region.



DIMENSIONS OF PROPOSED ANTENNA (MM)

L	Lr	Lf	Ls1	Ls2	Ls3	lfs	Df1	Ds
27	9	10	16	17	4	3	7.1	4
W	LG	Wf	Ws	Lss1	Ws3	Wfs	Df2	WG
39	8	1.8	1	5	1	1	8.1	29
SL1	SW1	SL2	SW2	SL3	SW3	SP	ST	
8	8	7	6	6	4	0.5	0.5	

Fig. 1. Proposed antenna structure with dimensions

The dimensional parameters of the antenna are selected through iterative design refinement so that the structure provides acceptable matching, isolation, and radiation characteristics. The final geometry represents a balance between compact size, ease of fabrication, and electrical performance.

VI. DESIGN EVOLUTION

The development of the final antenna is carried out in stages in order to understand the contribution of each structural feature. In the first stage, the basic PM1 element without stub modification is considered. Although the initial radiator is capable of resonance, its matching behavior is limited and it does not provide the required wideband performance.

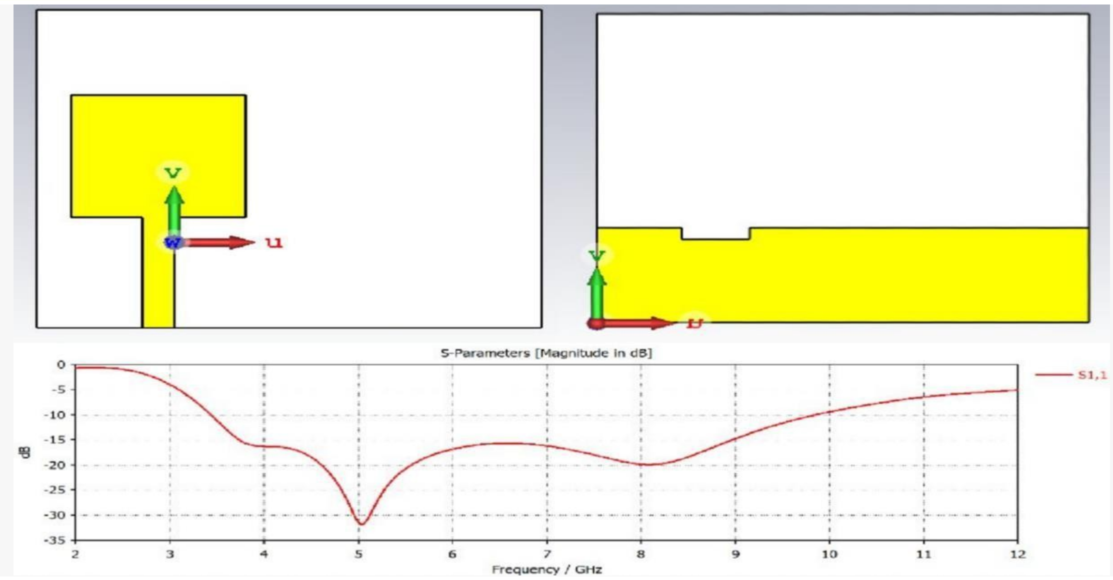


Fig. 2. PM1 without stub

In the next stage, a stub is introduced near PM1. This changes the current path and creates additional resonant behavior, leading to noticeable improvement in impedance response. The stub also begins to influence the current concentration in the ground region, which is useful for subsequent isolation enhancement.

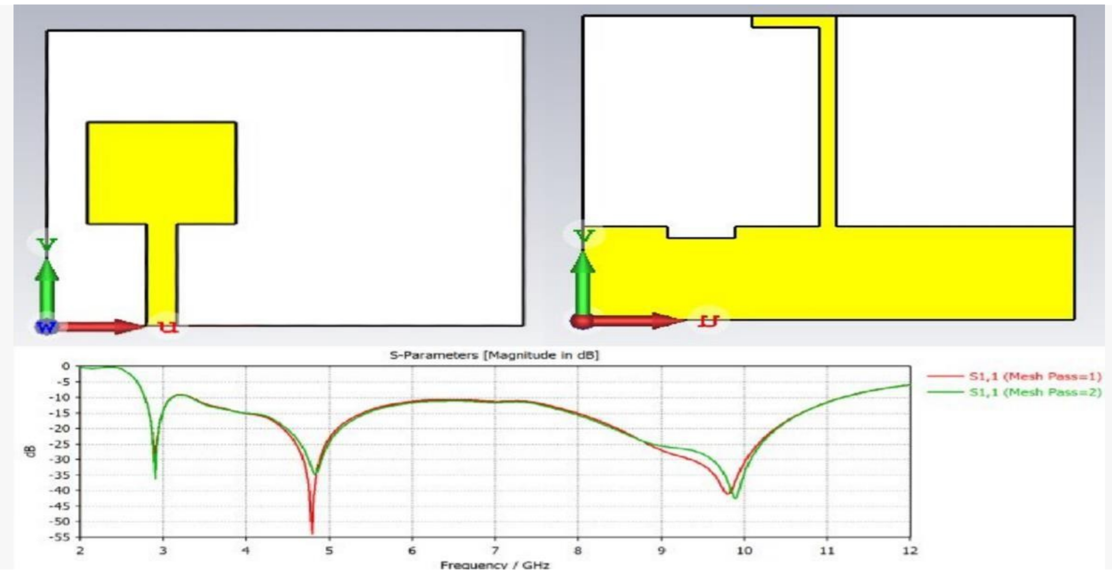


Fig. 3. PM1 with stub

A similar step-by-step approach is followed for PM2. The element without stub shows a narrower operating response and insufficient current control. After the introduction of the corresponding stub, the resonant behavior improves and the element becomes better suited for integration into the two-port arrangement.

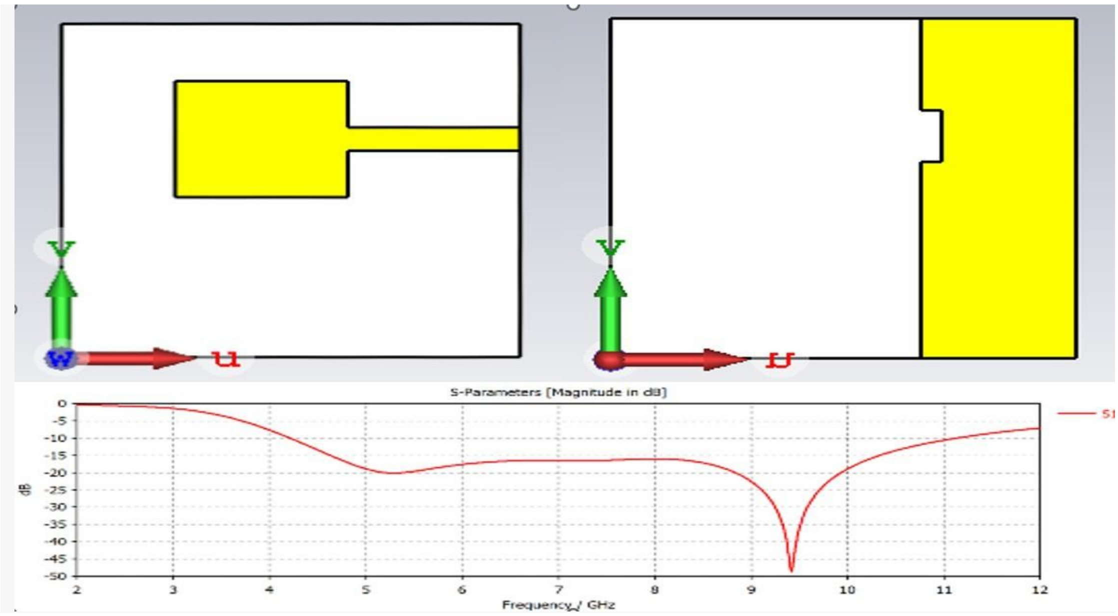


Fig. 4. PM2 without stub

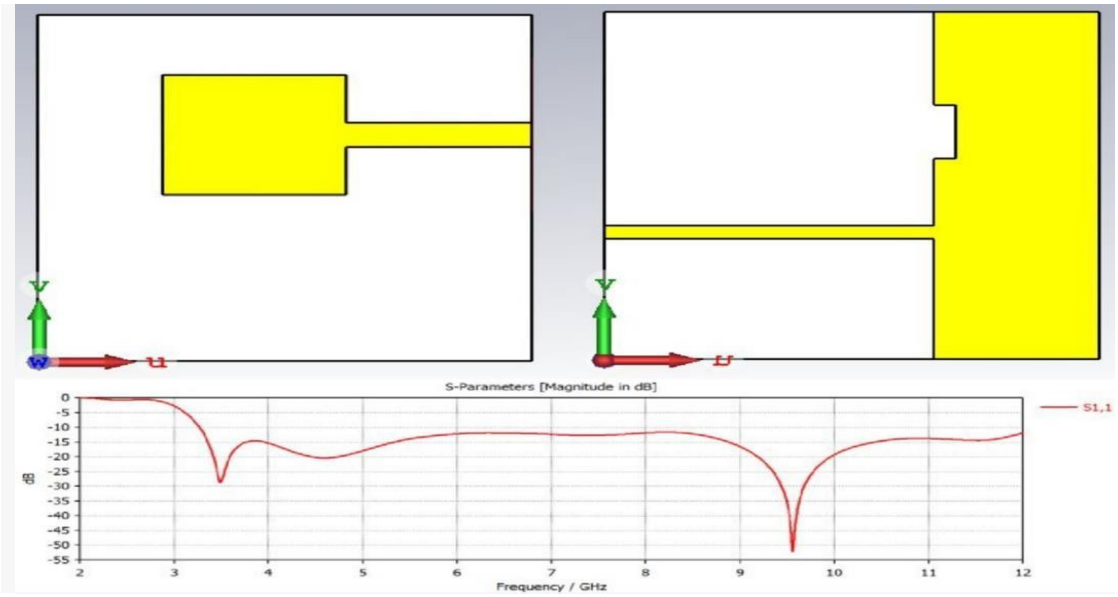


Fig. 5. PM2 with stub

After both radiating elements are individually improved, they are combined into the final MIMO arrangement. A short strip is then added between the ground regions to further reduce coupling and improve port interaction. This stage marks the transition from individual element optimization to system-level MIMO optimization.

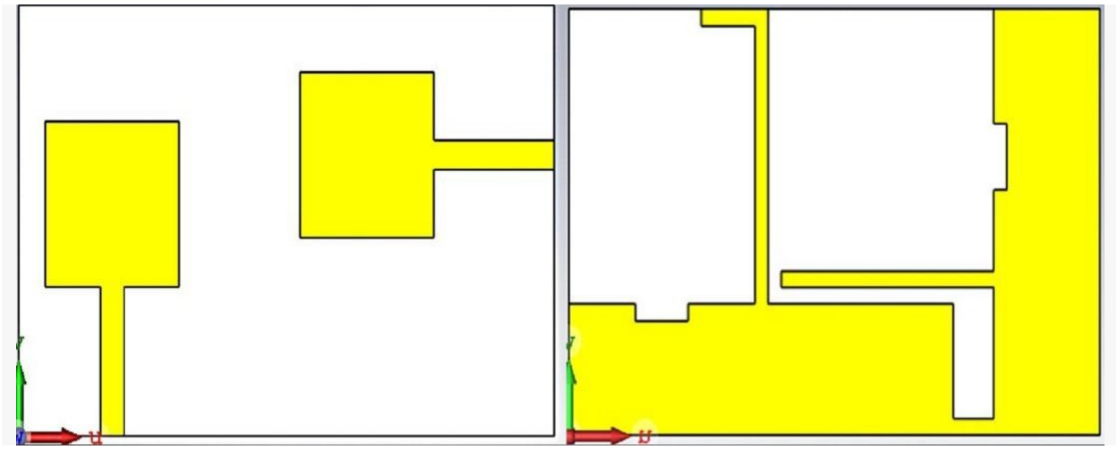


Fig. 6. PM1 and PM2 with short strip

The design evolution clearly shows that the final performance is not due to a single geometric feature. Rather, it results from the combined effect of the two radiators, ground stubs, and short strip, all of which contribute to wideband impedance performance and isolation improvement.

VII. S-PARAMETER ANALYSIS OF THE PROPOSED ANTENNA

The S-parameter response is one of the most important indicators of antenna performance. The reflection coefficients S11 and S22 describe how effectively each port is matched to the input, while S21 and S12 quantify the coupling between the two ports. For the proposed antenna, the matching behavior remains favorable across the ultra-wideband region, with the reflection coefficients falling below −10 dB over most of the useful operating band. This confirms that the antenna is capable of efficient power transfer.

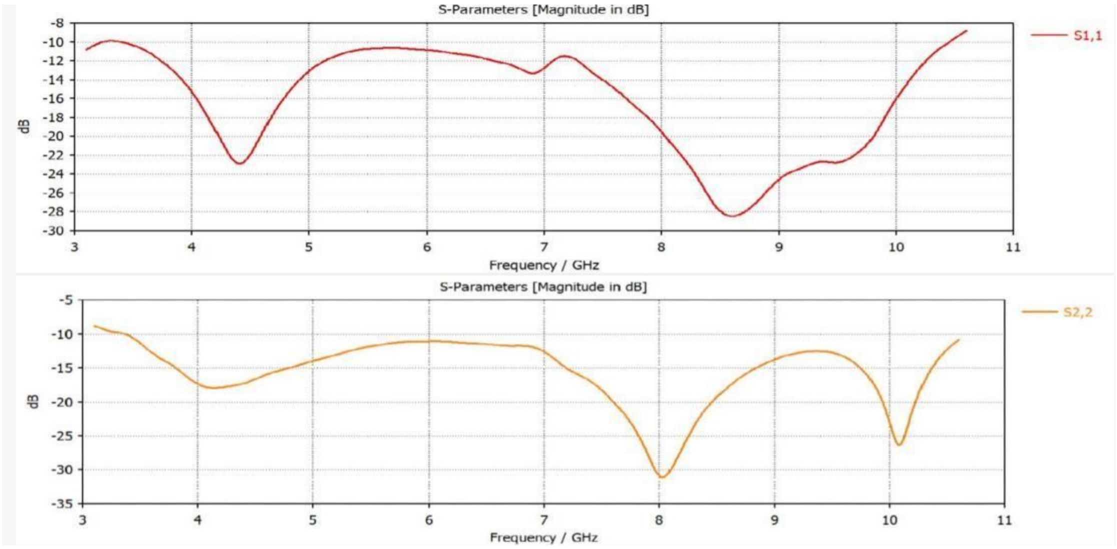


Fig. 7. Simulated reflection coefficients S11 and S22

The transmission characteristics indicate that mutual coupling is significantly reduced by the adopted ground modification technique. The long stubs and short strip alter the distribution of induced current between the two ports and suppress direct interaction between the elements. As a result, the isolation remains sufficiently high, with transmission coefficients generally below the preferred limit for compact UWB MIMO operation.

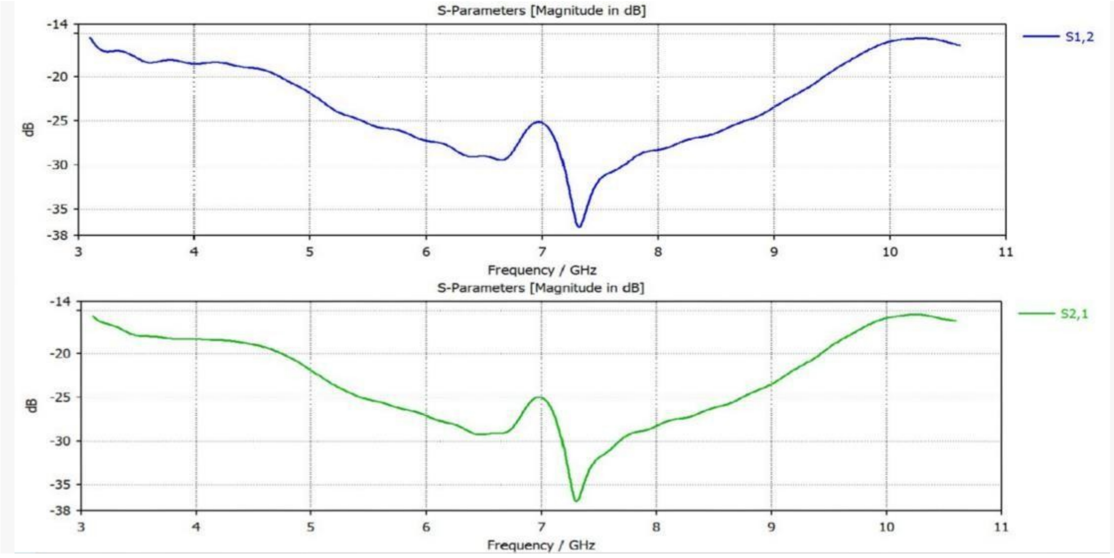


Fig. 8. Simulated transmission coefficients S12 and S21

These results verify that the proposed geometry satisfies the basic performance requirements of a compact UWB MIMO antenna. The S-parameter behavior also supports the claim that the design is suitable for applications where both bandwidth and isolation are critical.

VIII. VSWR ANALYSIS

Voltage standing wave ratio provides another useful measure of matching quality. A VSWR value close to 1 indicates very good impedance matching, while a value below 2 is generally considered acceptable for practical antenna operation. The proposed antenna exhibits VSWR values within the acceptable range over most of the intended UWB spectrum, confirming that the antenna effectively radiates the supplied power instead of reflecting it back to the source.

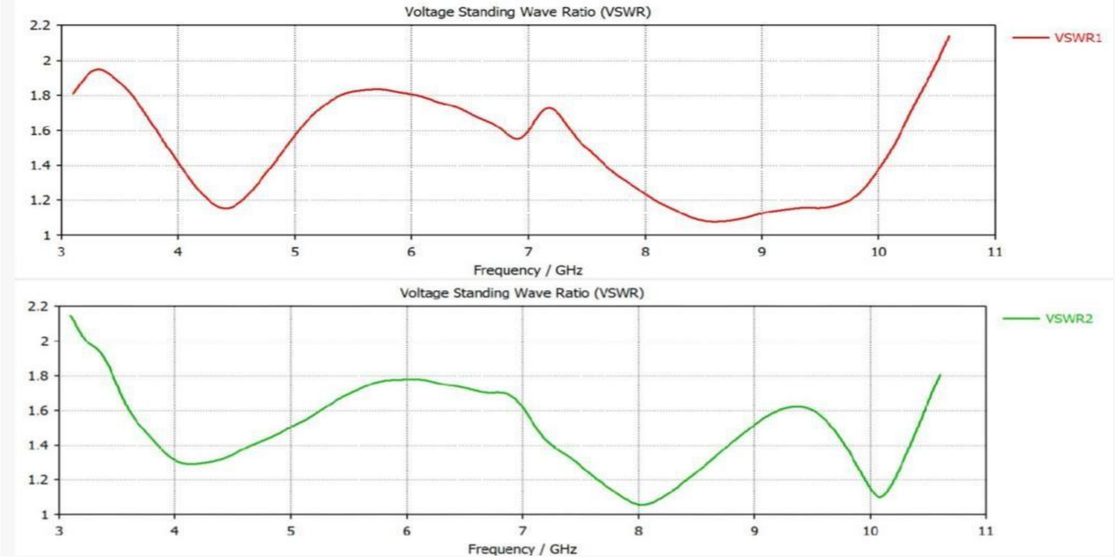


Fig. 9. VSWR characteristics for both ports

The observed VSWR trend follows the matching behavior seen in the S-parameter plots. At frequencies where the reflection coefficient improves, the VSWR also approaches lower values. This consistency demonstrates that the antenna is properly tuned over the desired frequency range and supports stable ultra-wideband operation.

IX. RADIATION CHARACTERISTICS

Radiation pattern analysis is essential for understanding how the antenna distributes energy in space at different frequencies. The radiation behavior of the proposed antenna is evaluated at representative frequencies within the UWB band. The obtained patterns show that the antenna maintains useful radiation characteristics over the operating range and exhibits acceptable main lobe direction, beam width, and side lobe behavior.

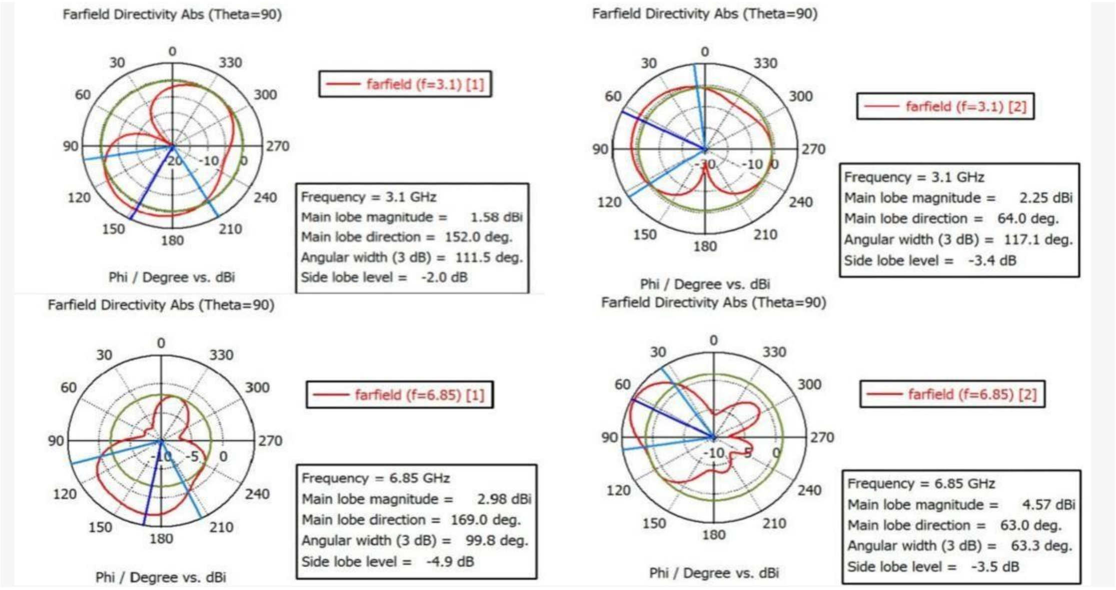


Fig. 10. Radiation patterns at 3.1 GHz and 6.85 GHz

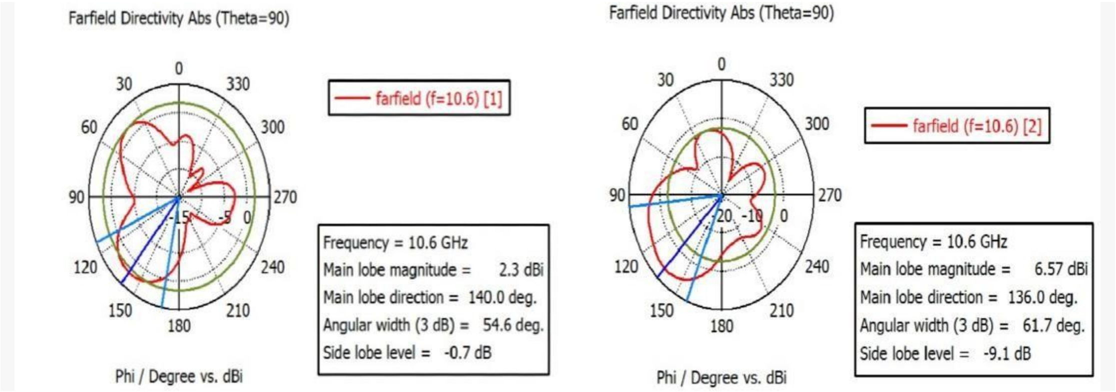


Fig. 11. Radiation patterns at 10.6 GHz

The radiation response remains sufficiently stable despite the compact configuration and the presence of isolation-improving structures. This is an important observation because the introduction of stubs and slots should not significantly degrade the radiating capability of the antenna. The presented results indicate that the proposed design achieves a good compromise between isolation enhancement and radiation quality.

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X. SURFACE CURRENT DISTRIBUTION

Surface current analysis offers physical insight into the coupling mechanism and the role of the ground modifications. In the proposed antenna, the current is strongly concentrated near the excited port and then redistributed by the stubs and strip so that less current reaches the adjacent element. This behavior is especially important in compact MIMO systems, where uncontrolled current flow can greatly increase mutual coupling.

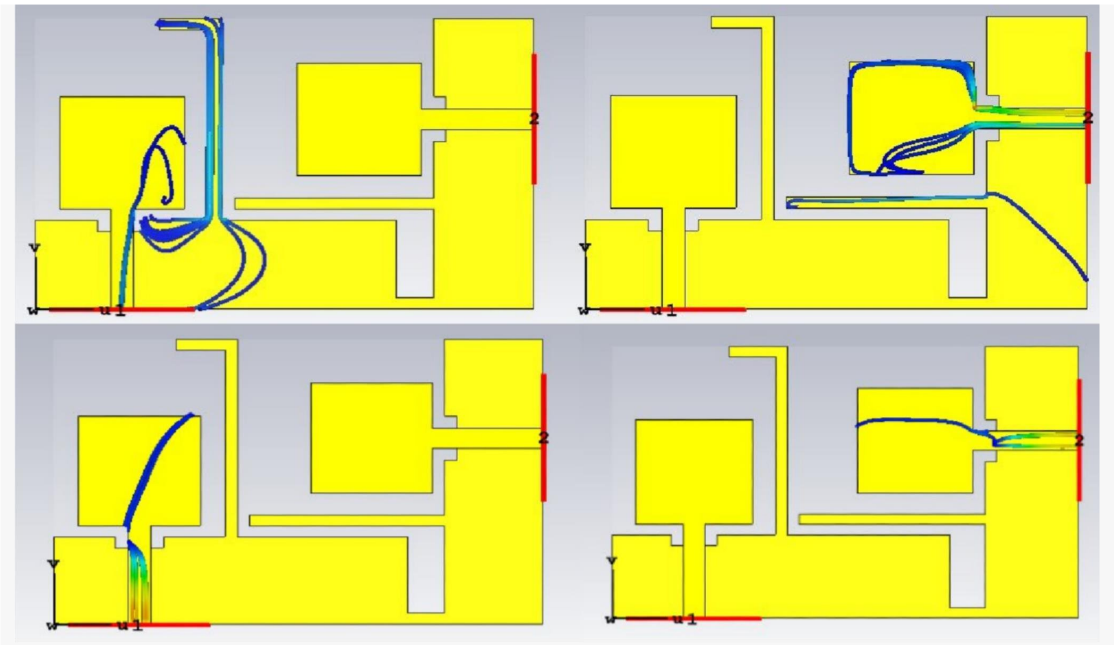


Fig. 12. Surface current distribution at selected frequencies

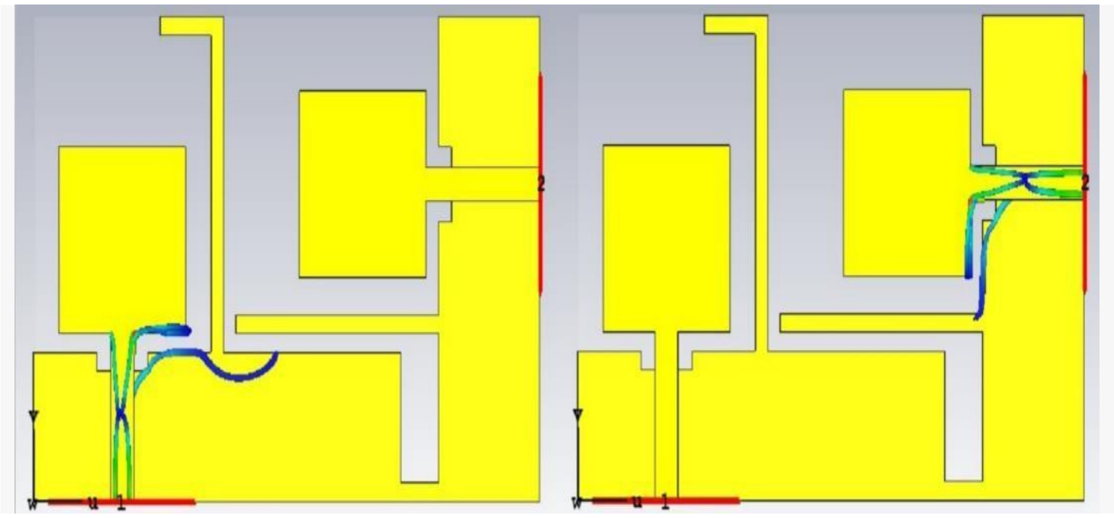


Fig. 13. Additional surface current views

The current plots demonstrate that the added structures serve as intentional current-guiding features. Instead of allowing the current to directly spread toward the neighboring port, the geometry forces it to follow longer and more controlled paths. This current redirection is one of the principal reasons for the improved isolation achieved by the design.

XI. SLOT INCORPORATION AND ITS EFFECT

To further enhance the antenna performance, slots are introduced into the radiating structure. Slot loading is a widely used technique in microstrip antenna design because it increases the effective current path length without requiring a larger physical footprint. As a result, the antenna can support additional resonances and wider impedance bandwidth within a compact area.

The slot dimensions are guided by the effective wavelength within the substrate, and their position is chosen so that they have a strong influence on current distribution and impedance characteristics. In the present design, the slots also contribute to coupling reduction because they disturb the natural current flow that would otherwise strengthen interaction between the radiating elements.

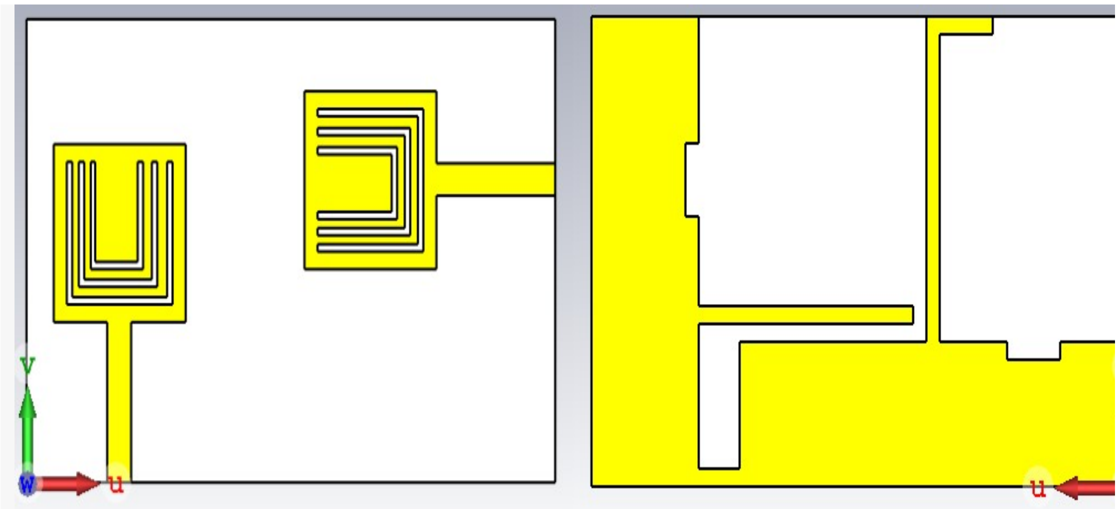
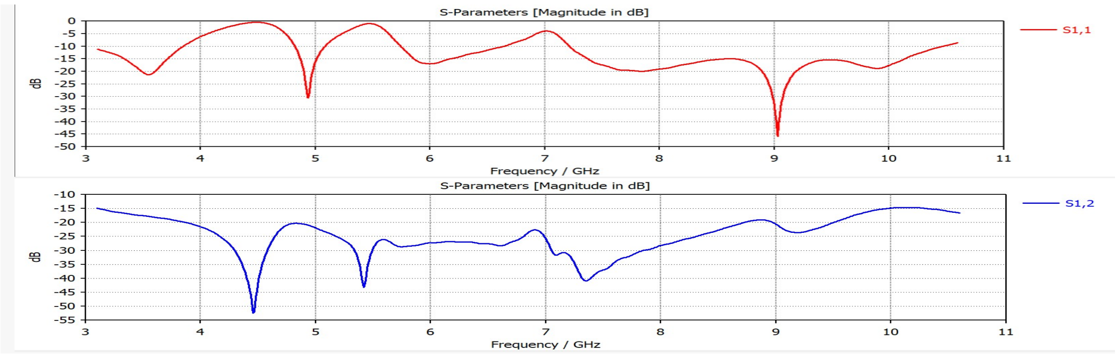


Fig. 14. Slot-loaded antenna geometry

The modified slot-loaded structure shows noticeable improvement in resonance formation and isolation performance. Therefore, slot loading works in combination with the stubs and short strip to produce a more effective compact UWB MIMO antenna.

XII. S-PARAMETERS OF THE SLOT-LOADED ANTENNA

After slot incorporation, the S-parameter response is re-evaluated to study the influence of the added resonant paths. The reflection coefficients reveal improved matching at several points in the band, while the transmission coefficients show that the disturbed current paths also support further coupling reduction. This confirms that slot loading is not merely a size-adjustment technique but an active contributor to wideband and isolation performance.



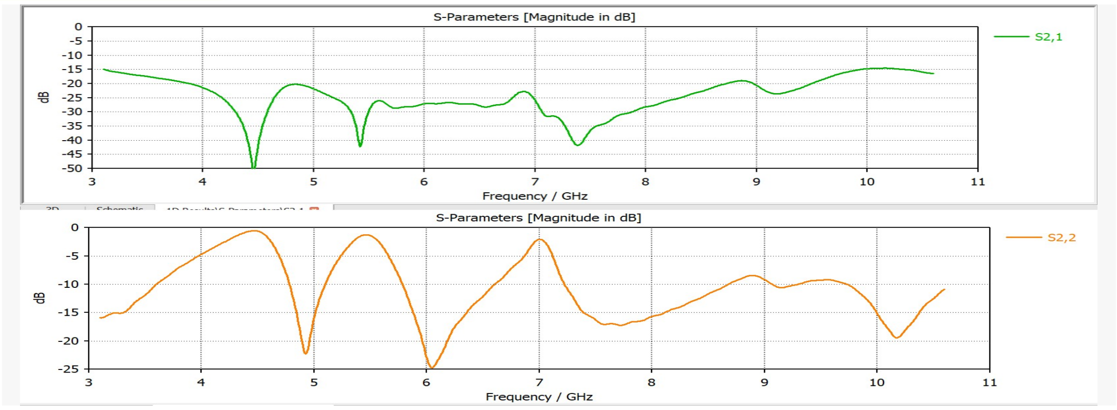


Fig. 15. Reflection and transmission coefficients of the slot-loaded antenna

The slot-loaded response demonstrates that structural optimization through current-path engineering is a practical and effective strategy for compact UWB MIMO antenna design. These observations strengthen the overall design methodology adopted in the work.

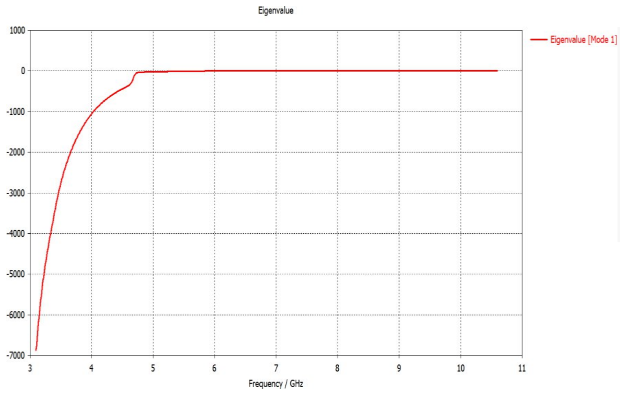
XIII. CHARACTERISTIC MODE ANALYSIS

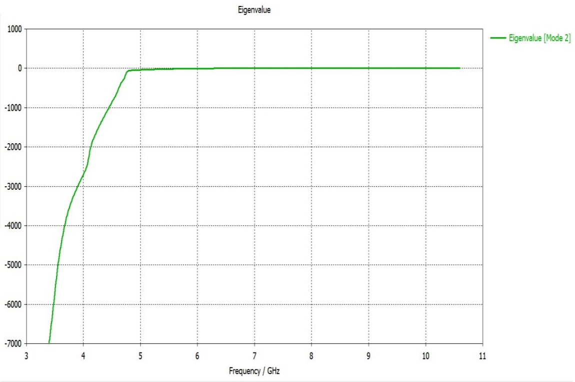
Characteristic mode analysis is used to provide deeper physical understanding of the antenna operation. Unlike direct feed-based analysis, CMA studies the natural resonant modes of the conducting structure itself. This makes it easier to identify which modes are responsible for useful radiation and which frequency regions support effective operation.

For the proposed antenna, characteristic mode analysis confirms that multiple resonant modes exist within the ultra-wideband range. These modes contribute to the broad impedance bandwidth and help explain the radiation and isolation behavior of the antenna. CMA therefore serves as a strong supporting tool for validating the performance of the proposed geometry.

Eigenvalue Analysis

In eigenvalue analysis, a mode is considered to be in resonance when its eigenvalue approaches zero. The plotted eigenvalue curves for the considered modes indicate that several modes resonate within the operating band. This is one of the reasons the antenna is capable of supporting wideband performance rather than a single narrow resonance.





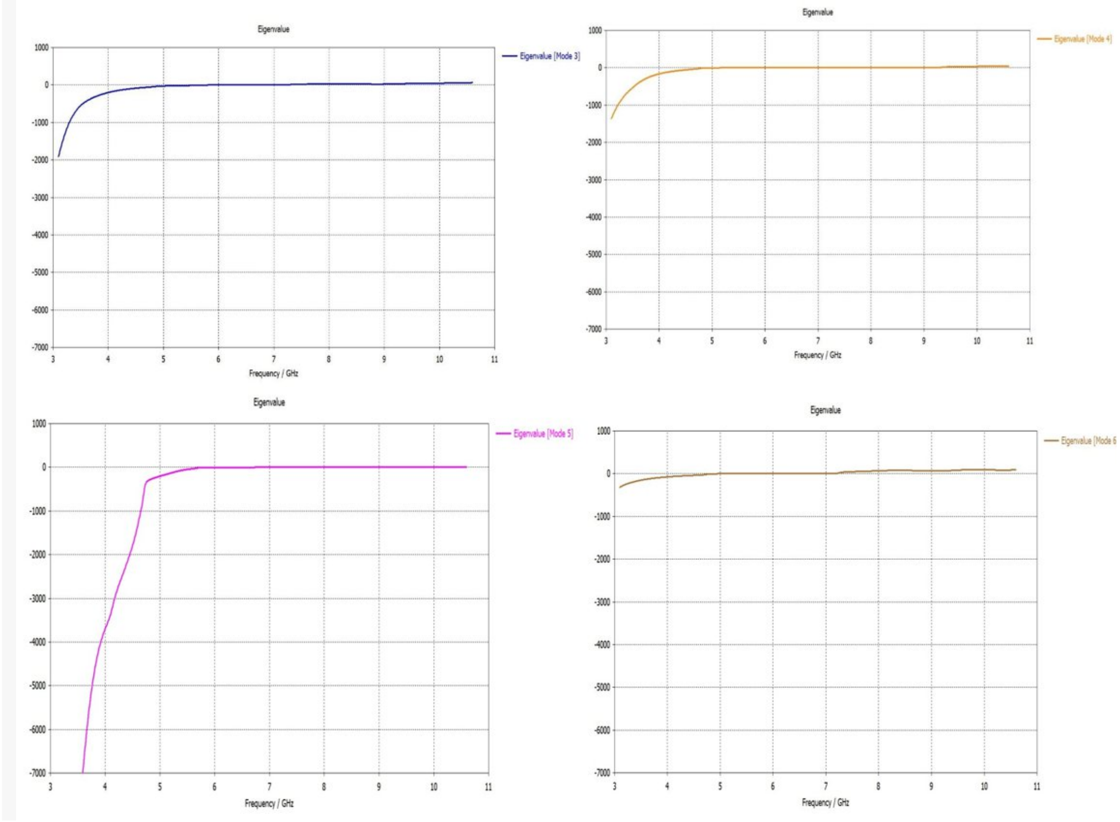
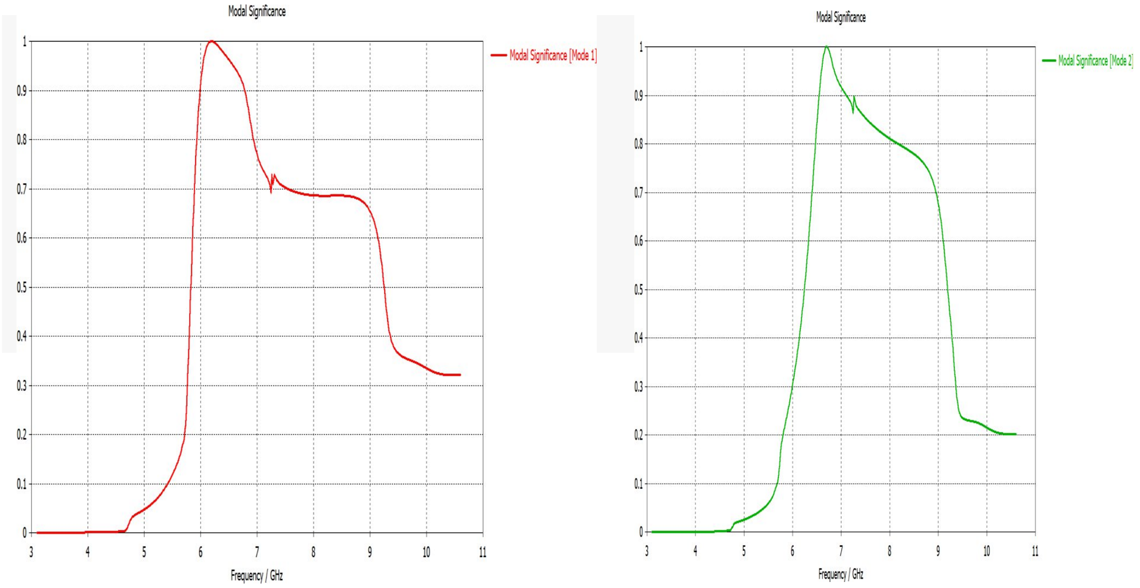


Fig. 16. Eigenvalue analysis for characteristic modes

Modal Significance Analysis

Modal significance indicates how strongly each characteristic mode radiates. A value near unity denotes effective radiation, while modes with lower values are less significant. The modal significance plots of the proposed antenna show that multiple modes remain strong over the UWB region, which supports the observed wideband and diversity performance.



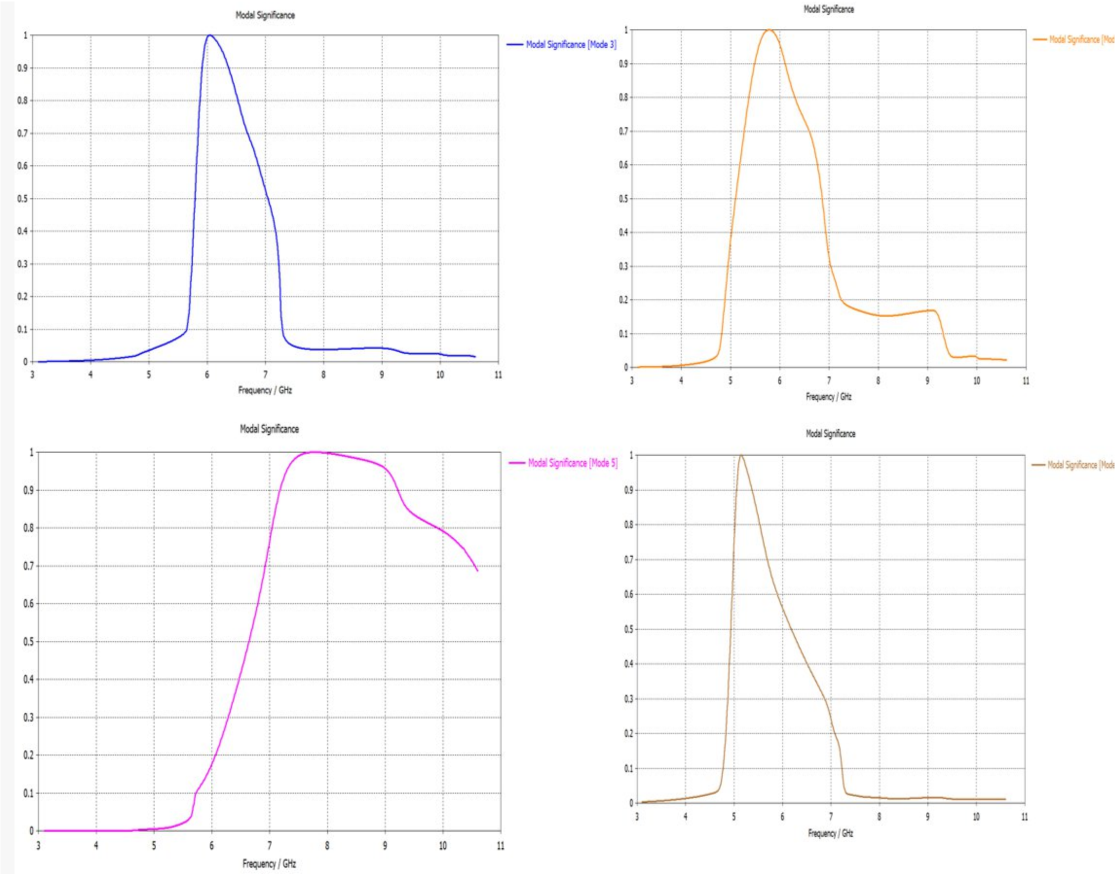
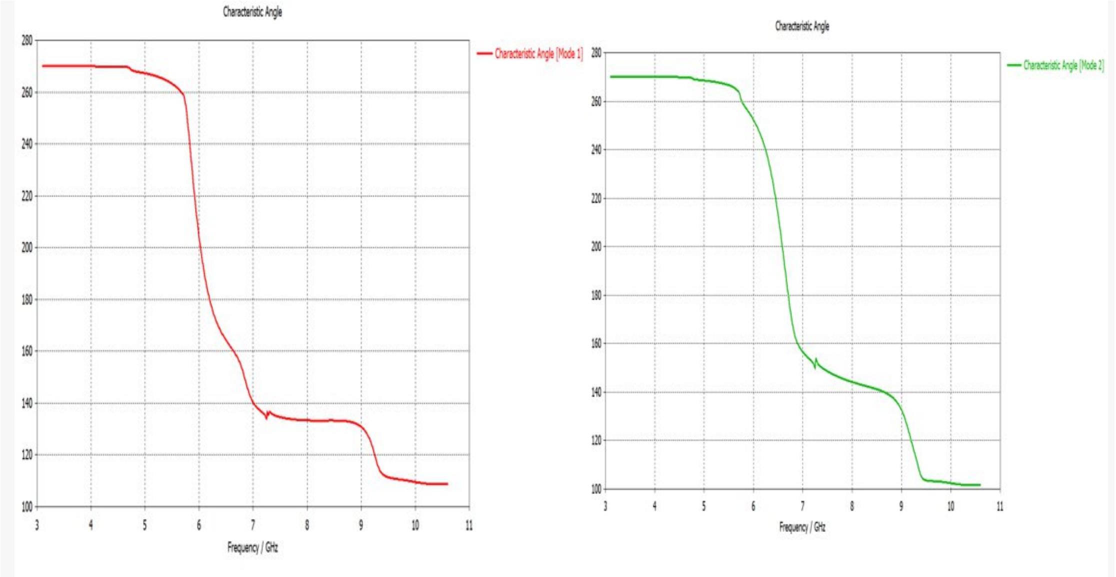


Fig. 17. Modal significance for characteristic modes

Characteristic Angle Analysis

Characteristic angle describes the phase behavior of the current associated with each mode. Efficient radiation occurs when the characteristic angle approaches 180 degrees. The characteristic angle results confirm that the major modes cross or approach this condition within the UWB range, validating the radiating nature of the selected modes.



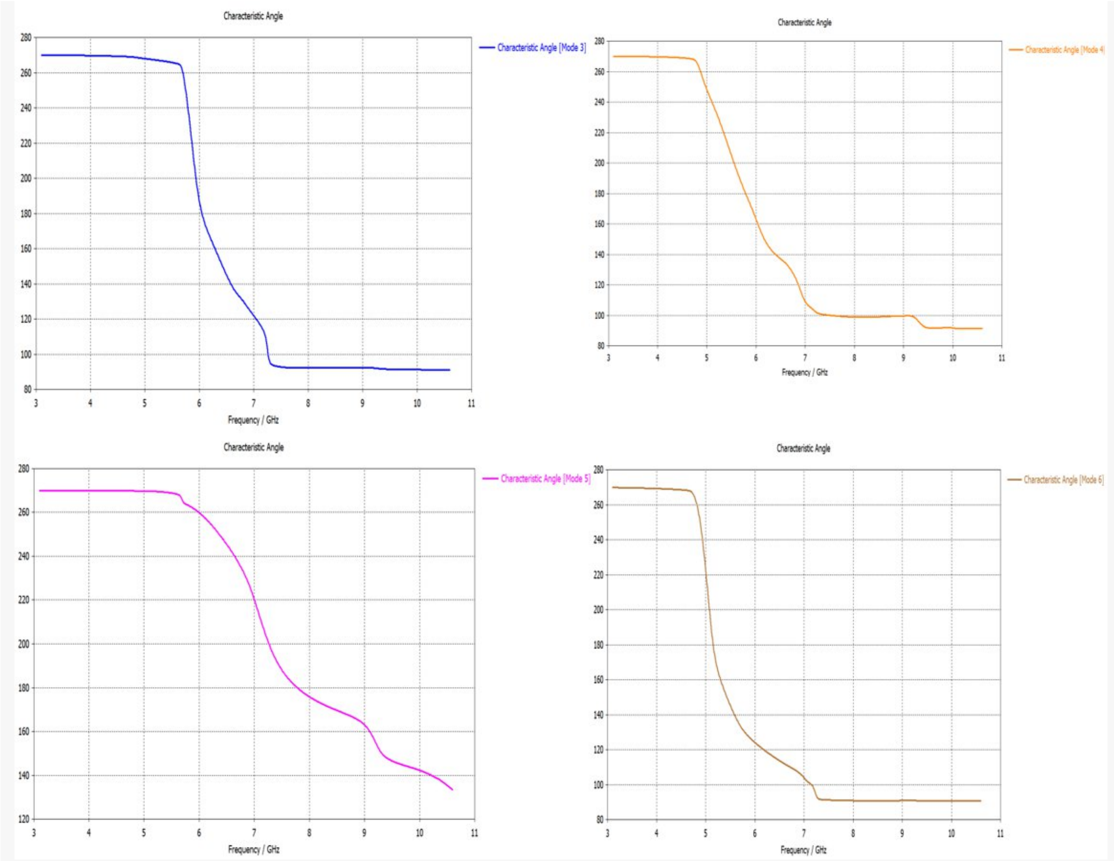


Fig. 18. Characteristic angle analysis for characteristic modes

XIV. RESULTS AND DISCUSSION

The overall results indicate that the proposed compact UWB MIMO design achieves a useful combination of compact size, broad operating bandwidth, and improved isolation. The return loss characteristics show satisfactory matching for both ports, while the isolation performance remains adequate despite close spacing between the radiating elements. The voltage standing wave ratio stays within acceptable bounds over most of the operating spectrum, confirming efficient power delivery.

Radiation patterns at representative frequencies demonstrate stable radiating behavior, and the current distribution plots provide a clear explanation of how the stubs, strip, and slots suppress coupling. In addition, characteristic mode analysis confirms that multiple natural resonances are available in the target band, which supports the wideband behavior observed in the conventional simulation results.

Taken together, these observations prove that the antenna design is not based on isolated performance improvements but on a coordinated set of structural mechanisms. The long stubs improve current control, the short strip modifies ground interaction, and the slots introduce additional resonant effects. Their combined action leads to a compact and effective UWB MIMO solution suitable for practical wireless systems.

XV. CONCLUSION

A highly isolated compact UWB MIMO antenna has been designed and analyzed for portable wireless applications. The antenna employs two radiating elements together with an improved ground plane, long parasitic stubs, a short connecting strip, and slot loading to achieve broad impedance bandwidth and reduced mutual coupling. The proposed

26 × 40 mm² structure covers the ultra-wideband region and demonstrates acceptable matching, good isolation, low envelope correlation coefficient, stable VSWR, and useful radiation behavior.

The design evolution and characteristic mode analysis provide strong physical justification for the observed performance. The results confirm that careful control of current distribution is highly effective in improving MIMO antenna behavior without increasing the antenna size. Therefore, the proposed design can be considered a suitable candidate for compact UWB MIMO integration in next-generation handheld and portable communication devices.

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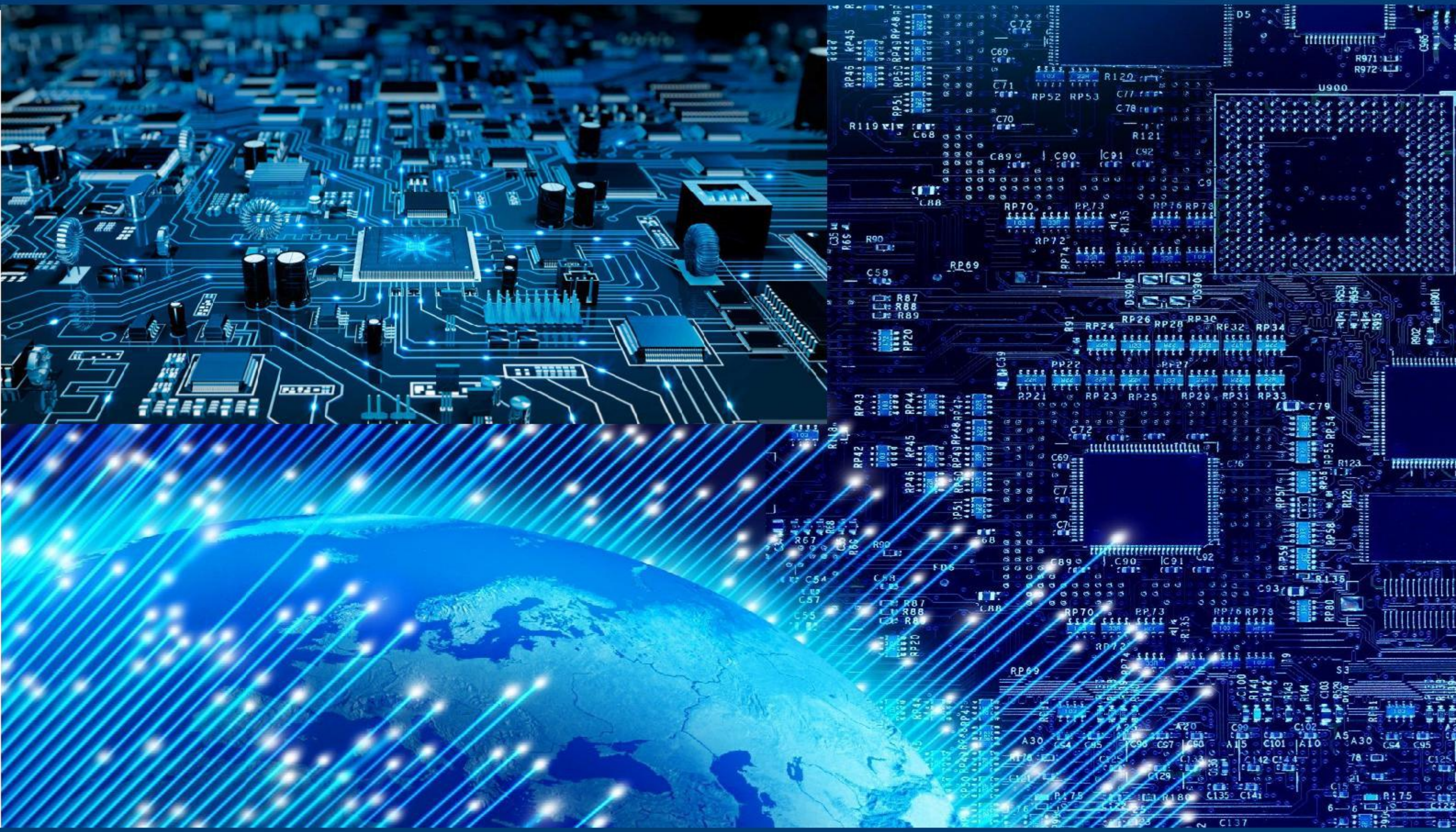

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