

Development of a Compact 4×4 Ultra-Wideband (UWB) MIMO Antenna Featuring Quadra Band-Notch Attributes on FR-4 Substrate for Wireless Communication Applications

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Abstract— Advancements in wireless communication technology require devices with high bandwidth, swift speeds, and superior communication reliability. Ultra-Wideband (UWB) technology operates within the frequency spectrum of 3.1–10.6 GHz, facilitating swift data transmission with minimal power usage. UWB is susceptible to interference from several systems, including WiMAX (3.3–3.8 GHz), C-Band (4.0–4.9 GHz), and WLAN (5.1–5.8 GHz), which may reduce antenna efficiency. This study designs a microstrip antenna featuring 4×4 MIMO and UWB capabilities, integrating quad-band notch capability with a FR-4 substrate to mitigate interference problems. The design was systematically implemented, involving specification identification, design and simulation using CST Studio Suite 2019, parametric analyses for optimizing the dimensions of the U-shaped slot and C-shaped stub, prototype fabrication through PCB etching, and measurements with a Vector Network Analyzer (VNA). The performance evaluation included essential antenna metrics such as return loss, Voltage Standing Wave Ratio (VSWR), and gain, alongside MIMO metrics including Envelope Correlation Coefficient (ECC), Diversity Gain (DG), Total Active Reflection Coefficient (TARC), and Channel Capacity Loss (CCL). The test results demonstrated that the antenna operated within the frequency spectrum of 3 to 14 GHz, displaying four significant band notches at 3.4 GHz, 4.0 GHz, 4.6 GHz, and 5.7 GHz. Return loss values < -10 dB, VSWR < 2 , maximum gain 4.8 dBi, ECC < 0.03 , DG ≈ 10 dB, TARC < -10 dB, and CCL < 0.35 bps/Hz indicate outstanding performance. This design is proven to be feasible for high-speed wireless communication systems with effective multi-band interference reduction needs.

Keywords— Band notch, U-slot, C-stub, UWB MIMO.

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I. INTRODUCTION

Recent improvements in wireless communication technology require devices with substantial capacity, high transmission rates, and strong communication dependability [1]. Antennas are vital elements of modern communication systems, serving as a link between electronic devices and electromagnetic transmission media [3][4]. The microstrip antenna is a common form of antenna known for its compact size, lightweight design, low profile, and ease of manufacturing [7].

The Federal Communications Commission (FCC) has permitted Ultra-Wideband (UWB) technology to operate inside the 3.1–10.6 GHz frequency range. This technology facilitates the transfer of high-speed data with little power consumption and a broad bandwidth. UWB is susceptible to interference from adjacent communication systems operating in similar frequency ranges, such as WiMAX (3.3–3.8 GHz), C-Band (4.0–4.9 GHz), and WLAN (5.1–5.8 GHz). This interference may reduce antenna efficiency and overall communication quality [11].

The band-notch approach has been widely employed in the design of UWB antennas to mitigate this problem. This

approach can be implemented by integrating slots, stubs, resonators, or Electromagnetic Band Gap (EBG) structures, allowing the antenna to reject or attenuate specific frequencies while maintaining performance over other broad bands [12].

Many previous studies have successfully developed antennas with dual-notch or triple-notch capabilities. Creating a UWB antenna including a multi-band notch while yet guaranteeing superior isolation in MIMO systems is a considerable challenge [14]. MIMO technology has proven effective in increasing channel capacity, improving signal diversity, and reducing the effects of multipath fading in wireless communication systems.

However, the deployment of MIMO technology in tiny devices occasionally faces obstacles due to reciprocal coupling or electromagnetic interference among antenna components. Therefore, a UWB MIMO antenna design is necessary that is compact, offers large bandwidth, ensures great isolation between elements, exhibits high efficiency, and demonstrates effective band-notch capabilities to reduce interference from other systems. This study aims to design a 4×4 UWB MIMO microstrip antenna featuring quad-band notch functionality by the integration of U-shaped slots and C-shaped stubs. This antenna is engineered to operate across the 3–14 GHz

frequency spectrum, guaranteeing optimal MIMO performance distinguished by elevated isolation among elements, minimal envelope correlation, and significant channel capacity.

II. METHOD

A. Antenna Design Stages

The antenna design process is conducted in phases, beginning with specification determination, followed by design and simulation with CST Studio Suite 2019 software, parametric analysis, fabrication, and measurement. This systematic methodology is frequently employed in microstrip antenna research to guarantee that the design outcomes align with the anticipated performance objectives [2]. The entire design process is illustrated in the flowchart presented in Figure 1.

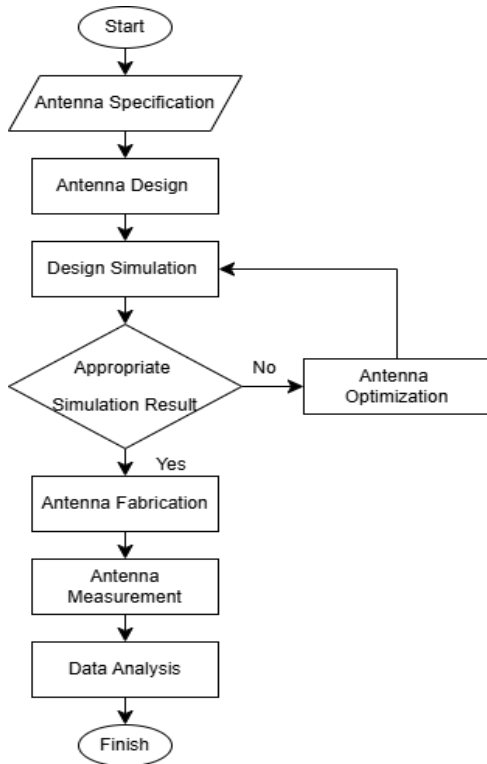


Figure 1. Antenna Design Flowchart

B. Antenna Specifications

The antenna was constructed using a lossy FR-4 substrate with a dielectric constant $\epsilon_r = 4.3$, a thickness of $h = 1.6$ mm, and dimensions of 40×40 mm². The choice of FR-4 material was based on its cost-effectiveness and widespread availability, despite its higher dielectric losses compared to specialized antenna substrates such as Rogers RT/Duroid [5]. The utilization of FR-4 substrate in antenna research is warranted due to its balance of performance and cost, leading to its

widespread implementation in practical antenna investigations [6].

The antenna is engineered to function within a frequency spectrum of 3–14 GHz, incorporating four band notches at 3.4 GHz, 4.0 GHz, 4.6 GHz, and 5.7 GHz. The objective of these band notches is to reduce interference from WiMAX, C-band, and WLAN systems. The detailed antenna design parameters are shown in Table 1..

TABLE I
ANTENNA DESIGN PARAMETERS

Variable	Dimension (mm)	Description
Ps	40	Substrate Length
Ls	40	Substrate Width
PP	19	Patch Length
LP	14.5	Patch Width
PP2	14	Patch 2 Length
Lp2	3	Patch 2 Width
Lf	3	Feedline Width
Pf	11	Feedline Length
Lg	10.5	Ground Width
Pg1	3	Ground 1 Length
Lg1	2	Ground 1 Width
H	1.6	Substrate Thickness
T	0.035	Patch Thickness
Up	9.5	U-slot Outer Length
UI	11	U-slot Outer Width
Up1	8.5	U-slot Inner Length
UI1	8	U-slot Inner Length
Up2	8.2	U-slot Outer Length
UI2	6	U-slot Outer Width
Cp	9.6	C-stub Length
Cl	3.63	C-stub Width
Lu	0.5	U-slot Gap
Lc	0.2	C-stub Gap
Lc1	0.5	C-stub Gap 1
Pg	40	Ground Length

C. Antenna Design and Simulation

The antenna design features square radiating elements (patches) complemented by U-shaped slots and C-shaped stubs to attain band-notch characteristics. The slot and stub technique is acknowledged for its effectiveness in producing rejection bands while preserving the antenna's operational bandwidth [10].

The simulation was executed using CST Studio Suite 2019 software. The antenna was initially constructed without a band-notch structure; later, slots and stubs were integrated to enable quad-band notch functionality. Figure 2 depicts the

antenna geometry, whereas Figure 3 compares antenna designs with and without band-notch capabilities.

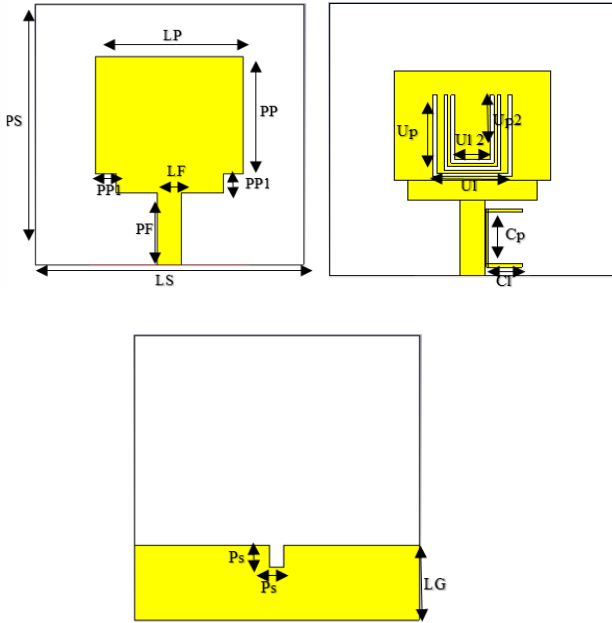


Figure 2. UWB antenna geometry with U-slots and C-stubs

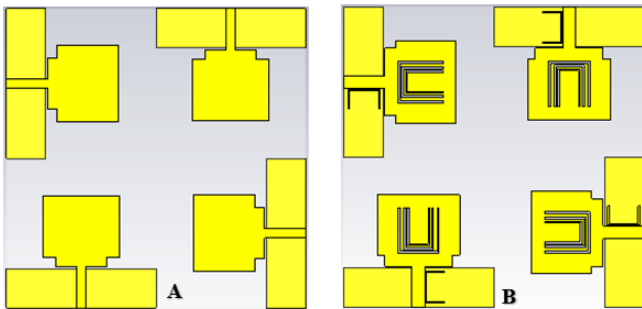


Figure 3. MIMO antenna design: (a) without band-notch, (b) with band-notch

D. Parametric Study and Optimization

To attain optimal outcomes, alterations were made to the dimensions of the slots and stubs. The lengths of the U-slot and C-stub were systematically modified, and their effect on the notched frequency was observed. The findings of the parametric analysis demonstrate that an increase in slot dimensions is associated with a reduction in the resultant notch frequency. The stub-C concurrently affects the rejection bandwidth (notched bandwidth). This technique has been utilized in previous studies to fabricate antennas with multi-notch characteristics [13].

E. Fabrication

Subsequent to obtaining the optimal design from the simulation results, the antenna was fabricated using the PCB etching method. The manufacturing process was executed using a FR-4 substrate in accordance with the simulation design. Figure 4

presents the assembled antenna prototype, showcasing both the forward and posterior perspectives, along with the attached SMA connector.

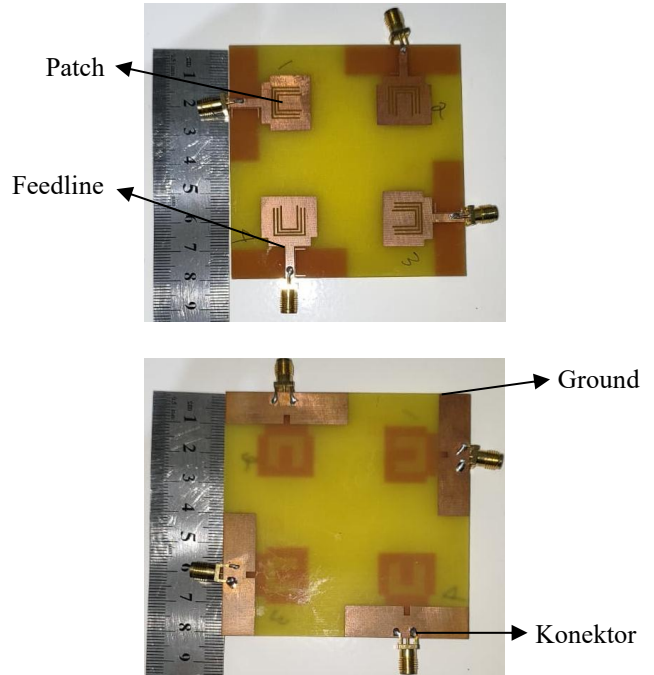


Figure 4. Fabricated prototype of the proposed 4x4 UWB MIMO antenna

F. Measurement

Testing employed a Vector Network Analyzer (VNA) to evaluate return loss (S_{11}), Voltage Standing Wave Ratio (VSWR), and isolation among antenna elements (S_{21}). Additionally, MIMO attributes such as Envelope Correlation Coefficient (ECC), Diversity Gain (DG), Total Active Reflection Coefficient (TARC), and Channel Capacity Loss (CCL) were calculated using MATLAB software. Key parameters for evaluating MIMO performance include $ECC < 0.5$, DG around 10 dB, $TARC < -10$ dB, and $CCL < 0.5$ bps/Hz, indicating advantageous MIMO performance [16].

III. RESULT AND DISCUSSION

A. Return Loss and VSWR

The antenna modeling and test results demonstrate essentially comparable curve patterns for the Return Loss (S_{11}) parameter. The return loss values are predominantly below -10 dB over the operational band, indicating that the antenna demonstrates sufficient impedance matching. Figure 5 presents a comparison of the simulated results and the measured outcomes, indicating a slight variation in the notched frequency due to fabrication tolerances and discrepancies in the dielectric constant of the FR-4 substrate. This criterion indicates that the optimized simulation results demonstrate a high level of accuracy concerning the actual antenna conditions [5][13][17].

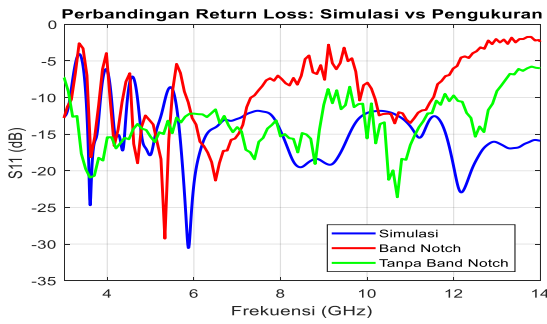


Figure 5. Comparison of simulation results and Return Loss (S_{11}) measurements of UWB MIMO antennas.

Figure 6 displays a comparative examination of the Voltage Standing Wave Ratio (VSWR) data obtained from both simulation and measurement. The VSWR values from both trials demonstrate a consistent pattern, remaining under 2 in the primary operational band and markedly rising in the notched band, indicating the efficient operation of the band rejection mechanism [18][19]. Both outcomes suggest that we can attain an antenna design whose performance closely corresponds with the simulation results.

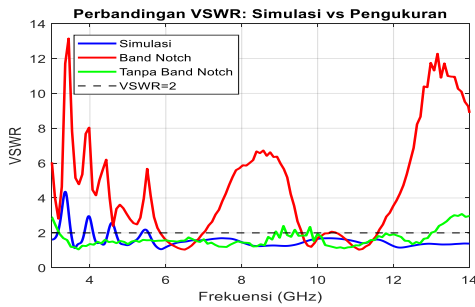


Figure 6. Comparison of simulation results and VSWR measurements of UWB MIMO antennas.

B. Antenna Gain

The U-slot and C-stub in alleviating interference. Figure 7 depicts the gain characteristics of the antenna. The simulation findings demonstrate a maximum gain of 4.8 dBi; however, the measured values are slightly diminished due to connector losses and manufacturing defects. A decrease in gain is clearly seen at the rejection band frequency (notched frequency), indicating the effectiveness of the.

The results correspond with previous studies [8][18], demonstrating that the application of slot techniques in UWB antennas resulted in a significant decrease in gain inside the notched region, while preserving gain stability in the core operational band. Attaining stability in the UWB working band is crucial for guaranteeing good signal transmission quality.

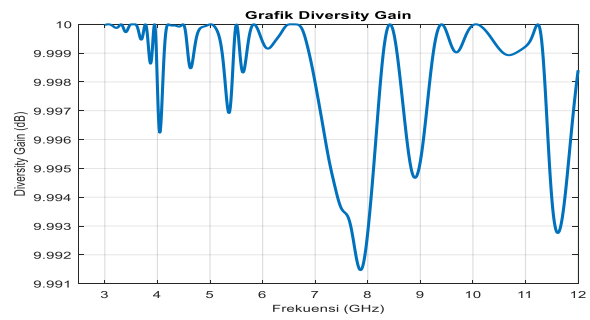


Figure 7. Gain characteristics of the simulated and measured antenna

Figure 8 illustrates the radiation pattern of the simulated antenna, showcasing its omnidirectional radiation features in horizontal, vertical, and three-dimensional views. This pattern illustrates that the antenna can transmit energy consistently in all directions, hence enhancing wireless communication systems with broad and dependable coverage. The radiation performance is consistent with previous studies [13][17][20], demonstrating that UWB antennas with omnidirectional properties exhibit strong propagation capabilities and are suitable for MIMO applications..

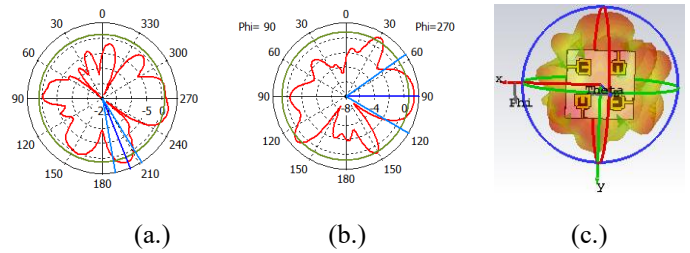


Figure 8. Radiation patterns resulting from the simulation of UWB MIMO antennas in (a) horizontal, (b) vertical, and (c) 3D planes.

C. MIMO Performance

In addition to the fundamental antenna parameters, it is crucial to assess MIMO performance owing to the antenna's configuration of four elements. The results of the MIMO parameter evaluation indicate:

- The Envelope Correlation Coefficient (ECC) is less than 0.03 in both models and tests, signifying exceptional isolation between antenna parts (refer to Figure 8).
- Diversity Gain (DG) approaches 10 dB, aligning with the specifications of an optimal MIMO system [19].
- The Total Active Reflection Coefficient (TARC) is less than -10 dB, signifying minimal power reflection.
- The Total Active Reflection Coefficient (TARC) is less than -10 dB, signifying minimal power reflection.

The results indicate that the engineered antenna fulfills the performance criteria for UWB MIMO antennas, exhibiting strong isolation, low correlation, and substantial channel capacity [21].

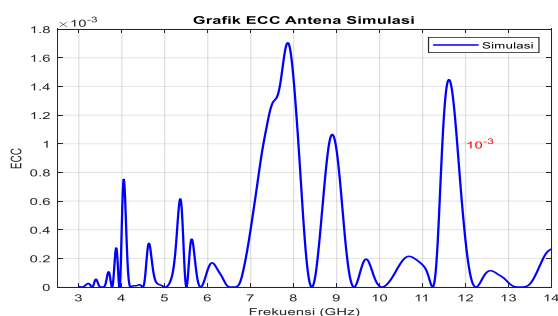


Figure 9. Simulation and measurement results of ECC values

D. Comparison of Simulation and Measurement

The experimental results demonstrate remarkable consistency with the simulated results across all antenna settings. The frequency shift mostly results from manufacture tolerances, changes in patch dimensions, and dielectric constant inhomogeneities inside the FR-4 substrate [13]. Minor discrepancies may also be affected by conductive losses in the SMA connector and flaws in the soldering process during the antenna fabrication phase.

The recorded Return Loss (S_{11}) and VSWR values exhibit a comparable pattern to the simulation outcomes, indicating successful attainment of the primary operating band and effective operation of the band-notch mechanism as intended [5][17][18]. The gain and radiation pattern results demonstrate that the antenna efficiently transmits power with an omnidirectional pattern, facilitating signal transmission across diverse antenna orientations [13][20].

The performance of MIMO parameters, including ECC, DG, TARC, and CCL, demonstrates consistency between simulation and measurement, with values remaining within the optimal bounds for UWB MIMO wireless communication systems [19][21]. Consequently, it can be inferred that the measurement outcomes not only corroborate the modeling results but also demonstrate the feasibility of implementing the design of this 4x4 UWB MIMO antenna with a quad-band notch in practice. The antenna design demonstrates stable and efficient performance, aligning with the findings of other investigations on analogous subjects [10][18][20].

IV. CONCLUSION

This research successfully created a 4x4 UWB MIMO antenna including quad-band notch capability, fabricated on a FR-4 substrate, utilizing a combination of U-shaped slots and C-shaped stubs to provide efficient band-rejection characteristics. Simulation and measurement results exhibit significant alignment, with numerous key discoveries summarized as follows:

1. The antenna functions within a frequency spectrum of 3–14 GHz, incorporating four effective band-notch frequencies at 3.4 GHz, 4.0 GHz, 4.6 GHz, and 5.7 GHz. The four bands operate to reduce interference from WiMAX, C-Band, and WLAN systems, in accordance with the design objectives.
2. The return loss value of less than -10 dB and a VSWR of less than 2 across practically the entire operating band

indicate that the antenna displays excellent impedance matching, as confirmed by both simulation results and tests.

3. The antenna gain remains rather steady, peaking at 4.8 dBi, but undergoes a substantial decline within the notched band. This demonstrates that the U-slot and stub-C methods effectively mitigate interference while maintaining performance in the primary working band..
4. MIMO parameters, including Envelope Correlation Coefficient (ECC) < 0.03 , Diversity Gain (DG) ≈ 10 dB, Total Active Reflection Coefficient (TARC) < -10 dB, and Channel Capacity Loss (CCL) < 0.35 bps/Hz, demonstrate that the antenna exhibits high isolation, low correlation, and sufficient channel capacity, thereby enhancing the performance of wireless communication systems.
5. The minor discrepancies between the simulation results and the observations are mainly due to fabrication tolerances, SMA connector losses, and variations in the properties of the FR-4 substrate; however, these differences do not significantly affect the antenna's overall performance.

Consequently, it can be inferred that the UWB MIMO 4x4 quad-band notch antenna created in this research is appropriate for deployment in high-speed wireless communication systems. This design serves as a viable remedy for mitigating multi-band interference inside the UWB frequency spectrum, while ensuring robust MIMO performance stability for prospective applications.

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