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REGULAR ARTICLE

Wideband Gear-Shaped Slot Quad-Port MIMO Antenna on ITO Substrate with Parasitic-Assisted Isolation Enhancement for Sub-6 GHz 5G/WLAN Applications

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This study introduces a compact, wideband quad-port MIMO antenna featuring a gear-shaped slot radiator integrated onto a 40 × 50 mm² ITO-based dielectric substrate, engineered for 5G and WLAN applications below 6 GHz. The antenna is created through a series of design steps that start with a simple circular monopole, move on to partial ground modification, add multilayer slotting, and end with a gear-shaped form based on fractals. The optimized geometry, along with the ITO substrate's transparency and low loss properties, improves the flow of electrical current, making it easier to excite multiple modes and giving the system a wide range of impedance. The single-element prototype works in the frequency range of 2.1 to 5.9 GHz and has clear resonances at 3.2 and 4.5 GHz. The device has a peak gain of 3.1 to 4.2 dBi and a radiation efficiency of 86 to 91%. This means that it works well with a lot of different frequencies. To make the MIMO setup more isolated, corner parasitic patches are added. These patches stop surface-wave coupling without making the antenna footprint bigger. The suggested 2 × 2 MIMO architecture shows an isolation level of more than 18 dB and an envelope correlation coefficient (ECC) of less than 0.02, which guarantees better diversity performance. The proposed antenna is a strong candidate for next-generation portable 5G and WLAN communication systems owing to its compact dimensions, ITO composition, extensive frequency range, high efficiency, and superior isolation.

Keywords: ITO substrate, Quad-Port MIMO, Isolation enhancement, Sub-6 GHz.

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1. INTRODUCTION

The rapid increase in wireless data traffic from UHD streaming, AR/VR, and large-scale IoT systems has intensified the need for compact, high-performance antenna solutions. Multiple-input multiple-output (MIMO) technology is now fundamental in modern wireless standards because it enhances spectral efficiency, capacity, and link reliability [1, 2]. The sub-6 GHz 5G and WLAN bands are especially attractive for wide-area and high-throughput communication [3]. Integrating MIMO antennas into portable devices remains difficult due to strong mutual coupling, high ECC, bandwidth reduction, and pattern distortion that occur when elements are closely spaced [4, 5, 16]. Numerous isolation-enhancement methods neutralization lines, parasitic elements, DGS, EBG structures, meta surfaces, and CMA-based techniques have been explored, though many increase design complexity or size [6-9]. Slot-based radiators have recently gained attention for achieving compact multiresonant wideband operation, with modified shapes such as hexagonal, gear-shaped, and E-slot configurations demonstrating stable multimode performance [10-12]. Flexible and CPW-fed slot MIMO designs are also emerging for wearable and IoT platforms due to their robustness and compactness [13, 15]. Despite extensive research on compact MIMO antennas, achieving an optimal combination of small size, wide impedance bandwidth, low ECC, and high isolation in the sub-6 GHz range remains a major design challenge. The proposed work addresses this gap by introducing a novel gear-shaped slot radiator configured in a 2 × 2 MIMO layout on a compact 40 × 50 mm² substrate. The unique gear-shaped geometry enables efficient multimode excitation, resulting in wideband performance without increasing antenna size. Furthermore, the inclusion of corner parasitic patches enhances isolation and bandwidth by acting as passive decoupling elements. The proposed design is a practical and effective solution for next generation 5G and WLAN systems that work below 6 GHz. It has isolation levels higher than 18 dB, ECC below 0.02, and high radiation efficiency. This combination of compactness, simplicity, and strong electromagnetic performance establishes the significance and novelty of the presented antenna.

2. DESIGN METHODOLGY

During the design process, an ITO substrate material that could be changed and had great performance was chosen. The antenna design goes through several stages of development, starting with Iteration (a), which is a

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simple circular ring monopole with basic resonance and a narrow bandwidth. The feed line acts as the first radiator. In (b), a rectangular partial ground plane is added to control return loss, improve impedance matching, and increase bandwidth. In iteration (c), slots are added to the circular patch. This makes the current channel longer and lets it respond to multiple bands and lower resonant frequencies. In iteration (d), a more complex star-shaped slot structure is added. This makes gain and radiation efficiency better and works with more than one frequency band. Iteration (e) does more fractal iterations with smaller slots inside the star to make the effective electrical length as long as possible while keeping the same compact shape. This allows for wideband or multiband operation with much better gain and efficiency.

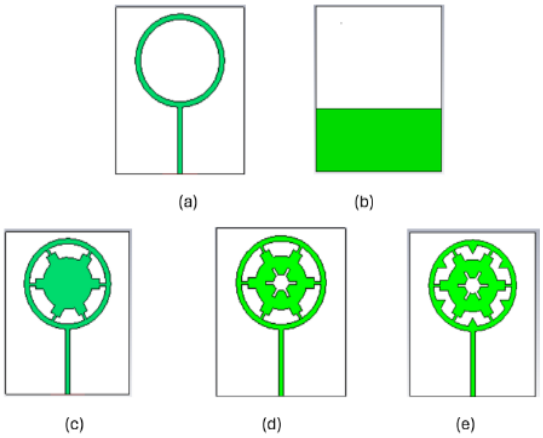


Fig. 1 – Evolution of antenna design across different iterations. a) Basic circular monopole, (b) partial ground plane, (c) slotted patch, (d) fractal-inspired slotting, (e) proposed optimized configuration

The antenna design methodology entails a systematic evolution of radiator geometry, corroborated by the reflection coefficient analysis of successive iterations. In Iteration 1, the basic structure has shallow resonant dips and high reflection levels, which means that the impedance matching is not good. Iteration 2 adds geometric changes that make resonances deeper below –10 dB around 3 GHz and 6-8 GHz. This shows better matching and a wider bandwidth. Iteration 3 makes more resonant paths possible, which results in stronger dips below – 15 dB across 2.5-5 GHz and 8-9 GHz. This improves multiband behaviour. The last Proposed Model has optimized gear-shaped slots that make stable resonances at 2.4, 3.5, 5.5, and 8.8 GHz, all of which are below – 10 dB. This optimized configuration delivers the best impedance performance and the widest operational bandwidth among all stages. Overall, the iterative geometric enhancement approach effectively improves resonance strength, matching quality, and wideband characteristics suitable for sub-6 GHz and UWB applications.

The single element consists of a circular patch with iterative slotting, where the fractal geometry increases the effective current path, enhancing radiation efficiency, bandwidth, and multiresonant behavior within a compact size. This enables multiband or UWB operations suitable for small wireless devices.

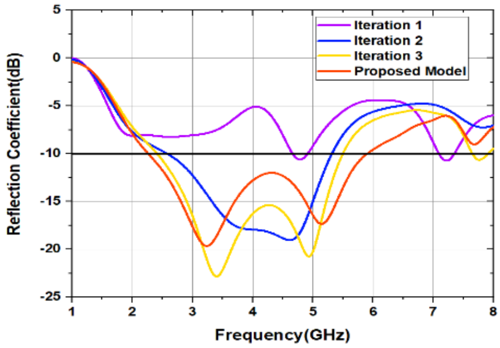


Fig. 2 – S_{11} for all iterations

Two identical elements are then combined through a feeding network to improve gain and radiation coverage, though mutual coupling becomes a key consideration. Extending the design to a four-element array further enhances directivity, gain, and diversity for higher data-rate sub-6 GHz and UWB applications. Overall, each array stage strengthens performance, making the structure scalable for modern wireless systems including advanced UWB and IoT applications.

The antenna's circular-slot radius has been computed as

$$a = \lambda / (4 \times \Pi \times \sqrt{(\varepsilon r)}) \quad (1)$$

where 'εr' is the 'relative permittivity' of the substrate 'λ' is the Wavelength.

The antenna's hexagonal-slot side length is measured as [16]:

$$s = 2 \times a \times \sin(60) \quad (2)$$

The calculated height of the monopole is

$$h = \lambda / (4 \times \sqrt{(\varepsilon r)}) \quad (3)$$

Using the equation given below, the ground plane dimensions in terms of the wavelength can be obtained

$$Lg = 2 \times \lambda, Wg = \lambda \quad (4)$$

The resonant frequency can be calculated as

$$f = c / (2 \times \sqrt{(\varepsilon r)} \times (h + s)) \quad (5)$$

where 'εr' corresponds to the substrate relative permittivity, 'c' is the speed of light [16].

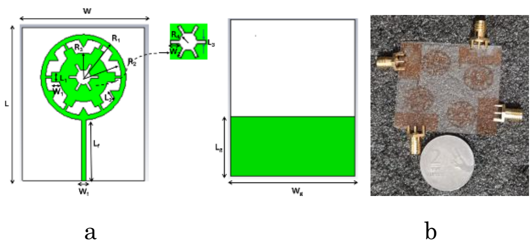


Fig. 3 – (a)Circular hexagonal slot monopole antenna with DGS, (b)Fabricated antenna

This study performs a parametric analysis of L_g, W_f, and R_1, followed by antenna fabrication and testing using a radiation measurement setup and VNA. The antenna achieves a wide impedance bandwidth of 2.1-5.9 GHz with $|S_{11}| < -10$ dB, covering sub-6 GHz, 5G, and WLAN bands. Measured and simulated results align closely, confirming stable wideband performance with resonances near 3.2 GHz and 4.5 GHz.

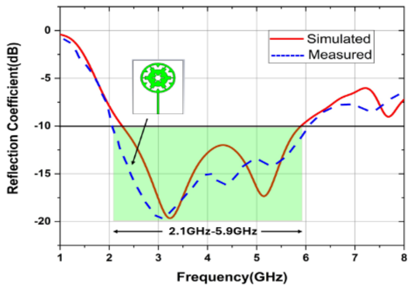


Fig. 4 – S_{11} response of single-element antenna

Quad Port MIMO Antenna

Geometry: Substrate: dielectric ($\varepsilon_r \approx 0.02$, $h = 0.01$ mm). Dimensions: 40×50 mm². **Radiators:** Four gear-shaped slots arranged symmetrically. **Feeding:** Microstrip line feed at each corner. Corner parasitic patches act as decoupling elements.

The gear slot increases effective current path length, enabling multiband response. The corner parasitic help reduce coupling by disturbing surface currents, improving isolation without additional ground modifications.

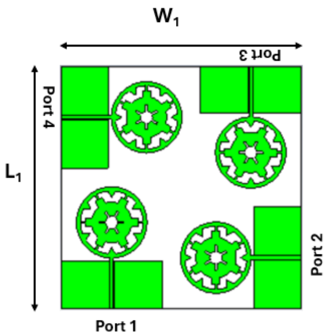


Fig. 5 – Geometry of the proposed quad-port gear-shaped MIMO antenna

3. RESULTS AND DISCUSSION

The two curves are very similar, showing a wide impedance range of about 2.1 to 5.8 GHz, where $|S_{11}|$ stays below -10 dB. The close match between the measured and simulated responses shows that the device can work stably and over a wide range of frequencies, making it suitable for applications below 6 GHz.

The graph shows the quad-port MIMO antenna's transmission coefficients (S_{12}, S_{23}, S_{34}, and S_{41}). All of these stay below -18 dB across the main operating band. This means that the ports don't connect much with each other, which shows that the corner parasitic patches work. The consistent curves across different port combinations show that MIMO performance is stable and symmetrical.

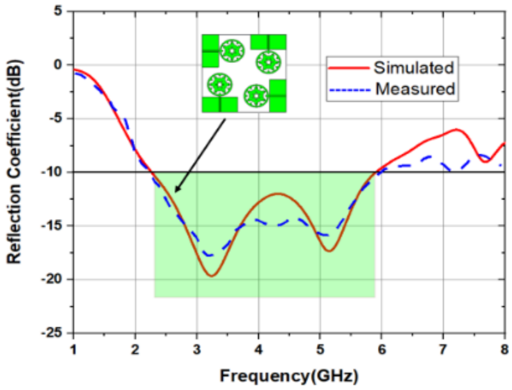


Fig. 6 – S_{11} response of four-element MIMO antenna

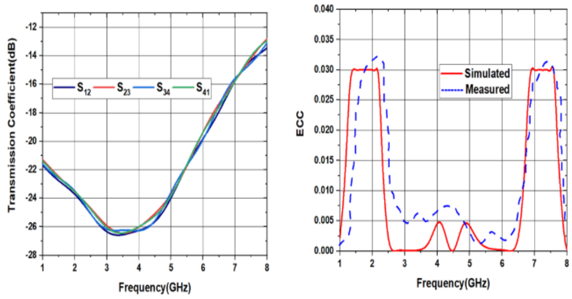
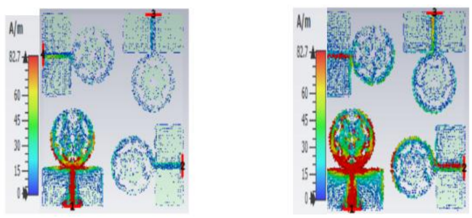


Fig. 7 – S-Parameters (Transmission Coefficients S_{12}, S_{23}, S_{34}, S_{41}) of Quad-Port MIMO Antenna abn Envelope Correlation Coefficient (ECC) — Simulated vs Measured

The ECC plot shows that both the measured and simulated values stay well below 0.02 across the antenna's operating band. This means that the antenna has great diversity performance. The fact that the two curves are so close together shows that the MIMO design is stable. These low ECC values show that there is very little correlation between ports, which makes the antenna perfect for high-capacity sub-6 GHz communication systems. The surface current distributions at 3.3 GHz and 5.2 GHz show that a lot of current is flowing around the excited gear-shaped slot and its feedline. This confirms that both frequencies are resonating well. The parasitic patches are shown to be effective at suppressing coupling because there is only a small amount of current on the neighboring elements. The well-contained current flow confirms stable multiband behavior and enhances the antenna's wideband MIMO performance.



a b

Fig. 8 – (a) Surface Current Distribution at 3.3 GHz, (b) 5.2 GHz

The gain characteristics show that the proposed antenna maintains a stable gain of 3.5-6.8 dBi across the entire operating band, with simulated and measured

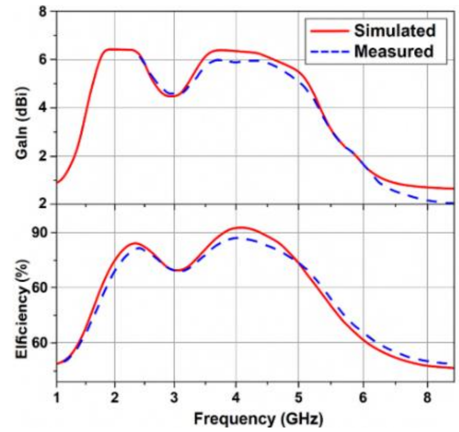


Fig. 9 – Gain and efficiency Comparison

results closely matching. The higher mid-band gain shows that the gear-shaped slot does improve radiation performance, which makes the design good for WLAN and sub-6 GHz 5G systems. The radiation efficiency stays high, reaching almost 85% at its highest point. This means that there are very few losses and a strong ability to radiate. This high efficiency over a wide range of frequencies confirms that the slot geometry works well. The combined gain–efficiency behavior shows that the ITO-based antenna is very good for wideband communication applications below 6 GHz.

4. COMPARING PERFORMANCE TO THE SATATE-OF-THE- ART

Table 1 – Comparison of present work with existing Research

Ref	Dimen-sions	Subst-rate	Frequency Band (GHz)	Isolation (dB)	ECC	Gain (dBi)
[2]	80 × 80 mm²	FR4	3.3-3.8	> 20	< 0.02	4.2
[8]	15 × 29 mm² per element	Rogers RT5880	3.5-5.5	> 22	< 0.01	5.0
[9]	25 × 25 mm²	Textile	4.8-6.0	> 18	< 0.05	4.6
[10]	70 × 70 mm²	FR4	3.0-6.0	> 20	< 0.015	5.8
Propo-sed	40 × 50 mm²	ITO	2.1 to 5.8	− 16 dB to − 26 dB	0.001 – 0.03	6.8

5. CONCLUSION

The proposed gear-shaped quad-port MIMO antenna on an ITO substrate operates efficiently across 2.1-5.8 GHz, covering sub-6 GHz 5G and WLAN bands. Its iterative slot geometry enables effective multimode excitation, achieving up to 6.8 dBi gain and 85 % peak radiation efficiency. Corner parasitic patches enhance MIMO isolation, maintaining values above 18 dB with an ECC below 0.02. Simulated and measured results show close agreement, confirming the robustness of the design. The antenna's compact size, wide bandwidth, strong isolation, and stable performance make it well suited for next-generation portable wireless systems.

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Широкосмугова шестернеподібна щілинна чотирипортова MIMO-антена на підкладці ITO з покращеною ізоляцією за допомогою паразитних впливів для застосувань 5G/WLAN у діапазоні менше 6 ГГц

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У цьому дослідженні представлено компактну широкосмугову чотирипортову MIMO-антену з шестернеподібним щілинним випромінювачем, інтегрованим на діелектричну підкладку на основі ITO площею 40 × 50 мм², розроблену для застосувань 5G та WLAN нижче 6 ГГц. Антена створюється за допомогою серії етапів проектування, які починаються з простого круглого монополя, переходять до часткової модифікації заземлення, додавання багатошарового щілинного розміщення та закінчуються шестернеподібною формою на основі фракталів. Оптимізована геометрія, разом із прозорістю та низькими втратами підкладки ITO, покращує потік електричного струму, полегшуючи збудження кількох мод та надаючи системі широкий діапазон імпедансу. Одноелементний прототип працює в діапазоні частот від 2,1 до 5,9 ГГц та має чіткі резонанси на частотах 3,2 та 4,5 ГГц. Пристрій має піковий коефіцієнт посилення від 3,1 до 4,2 дБі та ефективність випромінювання від 86 до 91 %. Це означає, що він добре працює з багатьма різними частотами. Щоб зробити MIMO-конфігурацію більш ізольованою, додаються кутові паразитні ділянки. Ці виправлення запобігають зв'язку поверхневих хвиль, не збільшуючи займану площу антени. Запропонована архітектура 2 × 2 MIMO демонструє рівень ізоляції понад 18 дБ та коефіцієнт кореляції обвідної (ECC) менше 0,02, що гарантує кращу продуктивність рознесення. Запропонована антена є сильним кандидатом для портативних систем зв'язку 5G та WLAN наступного покоління завдяки своїм компактним розмірам, складу ITO, широкому діапазону частот, високій ефективності та чудовій ізоляції.

Ключові слова: Підкладка ITO, Чотирипортовий MIMO, Покращена ізоляція, Частота нижче 6 ГГц.