A High-Gain Dipole Antenna with a Modified Cross-Shaped AMC Reflector for sub-6 GHz 5G Applications

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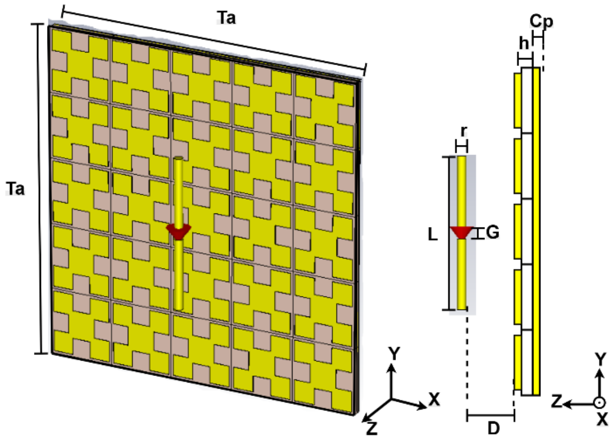
Abstract -----The research details the design and development of a high-gain, compact dipole antenna for sub-6 GHz frequencies, aimed at 5G communication systems. The design employs an Artificial Magnetic Conductor (AMC) reflector with a modified cross-shaped unit cell to improve the antenna's performance. The design was refined by comparing several unit cell geometries, reflector array dimensions, and the distance between the antenna and the reflector. Additionally, its performance was evaluated in comparison to a freestanding dipole and a dipole equipped with a typical Perfect Electric Conductor (PEC) reflector. The findings indicate that the optimized design attains a 3.7 dB gain improvement compared to the solitary dipole, yielding a realized gain of 6.2 dBi at the specified frequency of 4.3 GHz. The suggested structure is considerably more compact than the PEC-based option. This study verifies that utilizing an AMC reflector is an exceptionally efficient method for creating tiny, high-gain antennas appropriate for 5G applications.

Keywords: Artificial Magnetic Conductor (AMC), Reflector, Dipole, High Gain, Unidirectional

1. Introduction

The shift to fifth-generation (5G) wireless communications, alongside advancements for sixth-generation (6G), has transformed communications technology. Contemporary wireless networks require the swiftest and most dependable connections, with service in the sub-6 GHz bands, especially the 3.5 GHz and 4.5 GHz bands, crucial for worldwide 5G network implementations [1]. This spectrum provides an ideal balance between data transmission and signal range. Antennae have evolved into an important point and complex technical element to fulfill these performance requirements. The microstrip patch antenna is a foundational design element for wireless communication hardware[1, 2], valued for its compact dimensions, lightweight nature, and ease of manufacturing, which allows for seamless integration with the main circuit board. The reduction of antennas for small devices imposes significant physical constraints, notably a reduction in antenna gain, which negatively impacts the quality and reliability of connections in 5G networks. [3]. The main objective of this research is to design and build an antenna that attains high gain while preserving a small form suited for sub-6 GHz 5G communication systems. This study proposes utilizing an Artificial Magnetic Conductor (AMC) surface as a reflector to improve antenna performance in achieving these objectives. The primary benefit of an AMC structure is its distinctive in-phase (0° phase shift) reflection characteristic at a specified frequency. This differs significantly from a traditional metallic Perfect Electric Conductor (PEC) reflector, which inverts the phase of reflected waves and necessitates an exact separation distance for constructive interference, frequently leading to a cumbersome structure. The AMC's in-phase reflection property permits the antenna to be situated near the surface without inducing signal cancelation, facilitating a notably slimmer and more compact design suitable for contemporary wireless devices.



(I) (II)

Fig 1. Configuration of the proposed antenna: (I) Overall assembly and (II) side-view profile with design parameters.

Various techniques have been previously presented to mitigate the restricted gain of patch antennas. This basic method is to setup a metallic reflector behind the antenna. This approach exhibits significant physical constraints [4, 5], The reflector must be placed at a precise distance from the antenna element to achieve constructive interference and expand the bandwidth at the operating frequency. This requirement creates a bulky structure that is unsuitable for the streamlined design of modern network devices. A more advanced method requires setting up the antennas in an array, utilizing a greater

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quantity of antenna elements to enhance the overall gain. This method helps enhance the gain [6] [7], but it leads to significantly larger system dimensions, more intricate feed circuitry, and connectivity challenges, all of which pose significant difficulties in the design of small 5G/6G and Wi-Fi systems. Due to the constraints of current techniques, there is a distinct necessity for novel solutions that can improve antenna gain without substantially increasing the antenna's size.

This article presents the Artificial Magnetic Conductor (AMC) as a complex solution to the gain enhancement issue in antennas for wireless networks. An AMC is an engineered surface with electromagnetic wave reflection characteristics that are fundamentally different from those of conventional materials. In contrast to a conventional metallic reflector, which inverts the phase of reflected waves and requires a certain spacing [8] distance to prevent signal cancellation[9], an AMC structure is designed to reflect waves in-phase (0° phase shift) at a target frequency[10],[11]. This unique characteristic removes the thickness limitation, enabling the antenna to be positioned near the AMC surface while still attaining constructive signal interference. Several conventional techniques are employed to enhance antenna gain, each with distinct advantages and disadvantages. Traditional reflectors, for instance, can effectively direct waves into a single direction. Nonetheless, their dimensions, often around 48 mm, render them unsuitable for tiny devices. Maximum of 96 mm. [5] It possesses the capability to create complex structures. Array antennas, capable of improving gain by as much as 6 dBi, represent another common technique. The primary disadvantages of arrays are the size and intricacy, which often demand multi-tiered configurations with distinct layers, therefore complicating the development process. These constraints contradict the necessity to advance more efficient signal amplification methods while keeping the compact design of the antenna. The primary advantage of AMC compared to the antenna array method is its ability to significantly improve gain without increasing antenna size or complicating the system[12]. Furthermore, the unique properties of the AMC surface diminish the transmission of surface waves, which mostly result in energy dissipation at the source. Thus, the application of AMC constitutes an effective approach for developing compact[13] and highly efficient antennas to meet the demands of 5G and 6G communication networks.

A structure was designed for measuring the model unit cell of the AMC, determining the number of arrays, and finding the distance between the antenna and the AMC to identify the optimal configuration that maximizes gain while maintaining a compact size. Electromagnetic simulations were performed using CST Studio Suite. A dipole antenna operating in the 3.8-4.3 GHz frequency range was used as a reference prototype and was subsequently integrated with an artificial magnetic conductor (AMC) surface designed to exhibit in-phase reflection characteristics at the same frequency. Both components were designed on a common printed circuit board with a dielectric constant (ε_r) of 4.3 and a thickness of 1.6 mm. The primary performance parameters, including the reflection coefficient (S_{11}), gain, and radiation pattern, were simulated and compared with those of a reference antenna at the designated frequency to demonstrate the significant improvements achieved by the AMC substrate.

2. Antenna design

This article delineates the design of a high-gain, flat-profile antenna system operating at 4.3 GHz, employing the previously discussed characteristics of artificial magnetic conductor (AMC). An AMC reflector, specifically built, is incorporated with a dipole antenna system to form a directed antenna. The AMC is constructed on commonly accessible and cost-effective FR-4 substrate. The waves reflected from the AMC surface must constructively interfere with the waves from the original dipole in the forward direction, as the surface possesses the possibility for same-phase reflection. This stage efficiently redirects energy, augmenting the antenna's gain and directivity.

2.1 Dipole Radiator

The primary radiating element is a half-wavelength ($\lambda_0/2$) dipole antenna, designed to resonate at 4.3 GHz with a 50-ohm impedance feed. Show in Fig. 1. (I), The radiator is constructed from copper with the following specifications: a total length (L) of 28 mm, an arm radius (r) of 1.6 mm, and a central feed gap (G) of 2 mm. In its standalone configuration, the dipole shows a conventional omnidirectional radiation pattern with a baseline gain of approximately 2.1 dBi. This serves as the reference against which the gain enhancement provided by the AMC reflector is measured.

2.2 AMC Reflector Design

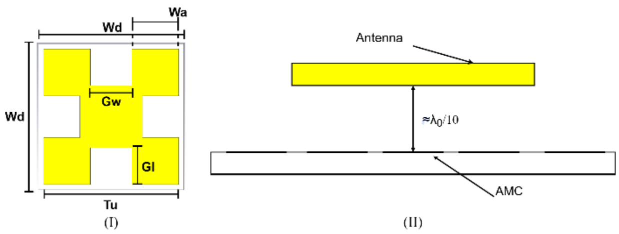

Fig 2. (I) Proposed dimensions of unit cell AMC, (II)Reflection of unit cell AMC.

$$L = \mu_0 \times h \quad (1)$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

The core of the gain enhancement mechanism is the AMC reflector, which is composed of a 5x5 array of the unit cell shown in Fig 1. (II). The total dimension of the reflector (Ta) is 61.25 mm. The unit cell is designed on a low-cost and widely available FR-4 substrate, which has a dielectric constant (ε_r) of 4.3, a thickness (h) of 1.6 mm, and a copper cladding thickness (Cp) of 0.035 mm. The unit cell has dimensions of 12.25 mm x 12.25 mm, corresponding to an electrical size of approximately 0.175λ_0 at the target frequency. The behavior of this via-less AMC can be modeled as a parallel LC resonant circuit.

The inductance (**L**) is primarily determined by the substrate thickness and is calculated to be approximately 2.01 nH using the formula (1). To achieve resonance at the target frequency (f_0) of 4.3 GHz, the required equivalent capacitance (C) is calculated from the resonance formula (2), result in a target capacitance of approximately 0.68 pF. The physical geometry of the unit cell shown in Fig. 2(I), a modified cross-shape with parameters Wd = 12.25 mm, Tu = 11.38 mm, Wa = 3.94 mm, Gw = 3.5 mm, and Gl = 3.06 mm, was optimized to achieve this required capacitance and provide a 0° phase reflection. By placing the dipole radiator at a close proximity of D = 7 mm (should not exceed $\lambda_0/10$), the AMC surface acts as an artificial magnetic ground plane, ensuring that the reflected waves are in phase with the source waves, thus significantly increasing the antenna's forward gain, as shown in Fig. 2(II).

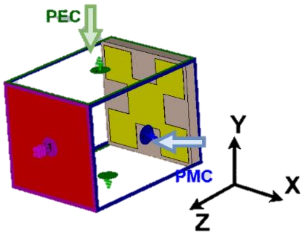

Fig 3. Simulation setup for the AMC unit cell, illustrating the use of PEC and PMC boundary conditions for reflection phase analysis.

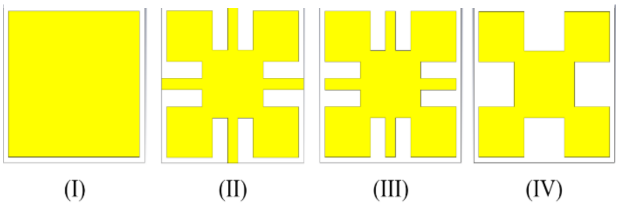

Fig 4 The design evolution of the AMC unit cell: (I) a conventional square patch, (II) an inter-connected slotted-cross structure, (II) an isolated slotted-cross structure with gaps between cells , and (IV) the modified cross-shaped structure.

A simulation using the commercial electromagnetic software CST Studio Suite was performed based on the analysis of the reflection phase characteristics of the unit cell shown in Fig. 3. The simulation was set up using periodic boundary conditions to model an array, with a Perfect Magnetic Conductor (PMC) boundary along the x-axis and a Perfect Electric Conductor (PEC) boundary along the y-axis. Waveguide ports were placed along the z-axis to launch a plane wave towards the AMC surface and measure the reflection coefficient, from which the reflection phase is determined.

To find the optimal reflector geometry, four unit cell designs (I, II, III, and IV) were simulated, as shown in Fig. 4. The primary selection criterion was the reflection phase characteristic of the standalone unit cell, with the objective of achieving a 0° phase crossing at the target frequency of 4.3 GHz.

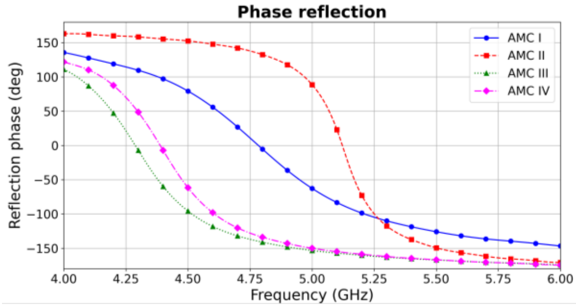

Fig 5. Simulated reflection phase of the four different AMC unit cell geometries (I-IV), showing the resonant frequency at the zero-degree phase crossing.

To select the most suitable shape, four different unit cell structures were simulated, as shown in Fig. 5. The reflection range was from 90 degrees to -90 degrees[7] The analysis results showed that the simple square patch (I) and the connected structure (II) had higher resonant frequencies, approximately 4.4 to 5.1 GHz and 5 to 5.3 GHz, respectively. Conversely, the separated structures (III and IV) resonated at lower frequencies. It was observed that although structures II and III looked similar, increasing the gap between cells in structure III increased the electrical length of the surface current path, significantly reducing the resonant frequency to 4.1 to 4.5 GHz. Therefore, an increase in electrical length results in a decrease in frequency, consequently influencing the overall size of the reflector. Based on this analysis, the AMC structure IV was selected as the most interesting option because its resonant frequency of approximately 4.2 to 4.55 GHz was closest to the target frequency of 4.3 GHz, making it the best choice for the final design.

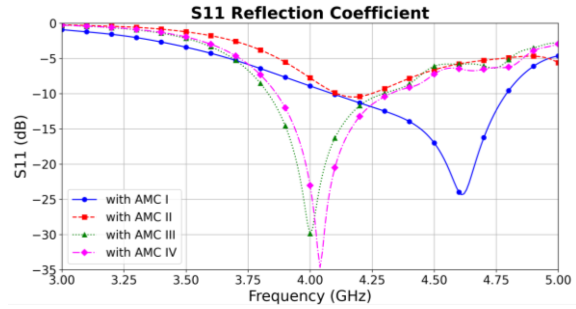

Fig6. Comparison of the simulated reflection coefficient (S_{11}) for the dipole antenna when integrated with the four different arrays 5x5 AMC reflector geometries (I-IV).

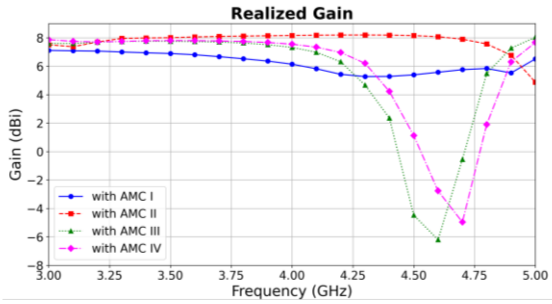

Fig 7. Comparison of the simulated realized gain for the dipole antenna when integrated with the four different arrays 5x5 AMC reflector geometries (I-IV).

After theoretically selecting based on the phase response of the unit cells, the performance of the entire antenna system was simulated by integrating the dipole with the four types of AMC to confirm the best option. The results for the reflection coefficient (S_{11}) and actual gain values were analyzed. From Fig. 6, S11 is unsuitable for the AMC II structure because the impedance was slightly low, exactly -10 dB. While AMC I showed acceptable matching, its resonant frequency was shifted to 4.6 GHz. In contrast, both AMC III and IV provided excellent impedance matching, with S_{11} values below -30 dB, but the optimal resonant points of both models were consistently shifted down to 4.0 GHz. This frequency shift was caused by the strong near-field coupling between the dipole and the complex geometry of these cells. The gain graphs provided clear information for selection, as shown in Fig. 7. The AMC IV structure had a maximum gain of almost 8 dBi. Despite reaching its peak at 4.0 GHz, the AMC IV structure maintained a gain of 4.3 GHz at the target frequency. It still outperforms other configurations, even though it's less than AMC II. However, AMC II has too low impedance, and although AMC I has consistent gain, its focus gain range is less than AMC IV. In final analysis, despite the shift in the frequency of the peak performance, the AMC IV structure was definitively chosen for the final design due to its superior impedance matching properties and maximum gain at the desired operating frequency.

This analysis compares the performance of the dipole antenna when integrated with the proposed Artificial Magnetic Conductor (AMC) reflector versus a conventional Perfect Electric Conductor (PEC) reflector. The AMC configuration consists of a 5x5 unit cell array (61.25 x 61.25 mm) placed at a distance of 7 mm from the dipole, while the PEC reflector has dimensions of 70 x 70 mm and is positioned 17 mm away. The provided graph illustrates the simulated reflection coefficient (S_{11}) and realized gain for both configurations. As shown in Fig. 8.

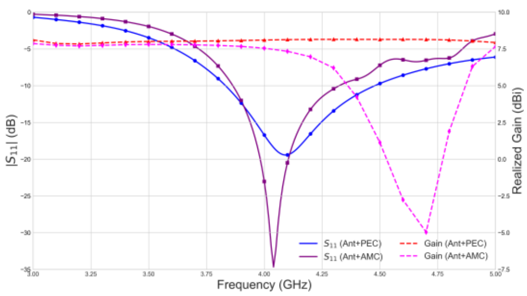

Fig 8 Comparison of the simulated reflection coefficient (S_{11}) and realized gain for the dipole antenna with the proposed AMC reflector versus a conventional PEC reflector.

A comparative investigation indicates that the proposed AMC reflector demonstrates enhanced performance for the intended application relative to a standard PEC reflector. The AMC has significantly superior impedance matching, achieving a reflection coefficient (S11) below -30 dB, greatly surpassing the PEC's -19 dB at the 4.05 GHz resonance. The PEC reflector provides a wider gain bandwidth, whilst the AMC attains a similar peak gain of around 8 dBi within the designated band. The primary advantage of the AMC is its inconspicuous nature. It allows for a markedly decreased antenna separation distance of merely 7 mm, in contrast to the 17 mm mandated by the PEC. The significant decrease in total thickness is essential for compact 5G devices, rendering the AMC the optimal selection that corresponds with the key aims of this research.

3. Experimental and Result

To validate the performance and determine the optimal size of the AMC reflector, CST Studio Suite.was employed for the simulations, and the FieldFox N9923A was utilized to measure S11 and S21 parameters, which were subsequently used for the calculations. The antenna system was simulated in four configurations: the dipole antenna alone (without AMC) and the dipole backed by 4x4, 5x5, and 6x6 arrays of the selected AMC IV unit cell. The performance was evaluated based on the reflection coefficient (S11) and the realized gain, as shown in Fig. 9 and Fig. 10, respectively.

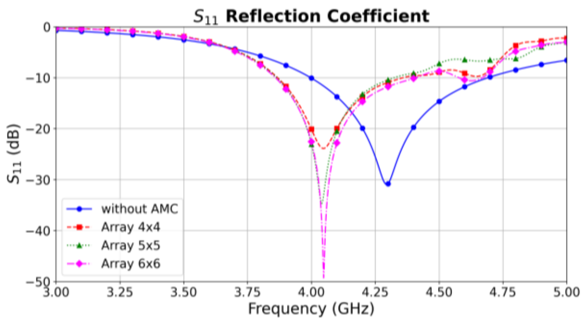

Fig 9 Comparison of the simulated realized gain for the standalone dipole versus the dipole integrated with 4x4, 5x5, and 6x6 AMC reflectors.

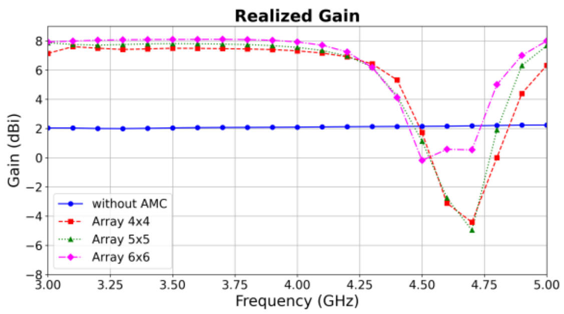

Fig 10 Comparison of the simulated realized gain for the standalone dipole versus the dipole integrated with 4x4, 5x5, and 6x6 AMC reflectors.

The analysis of the reflection coefficient in Fig. 9 reveals that the standalone dipole is well-matched at the target frequency of 4.3 GHz. However, the introduction of the AMC reflector shifts the resonant frequency of the system down to approximately 4.05 GHz due to near-field coupling. While the 6x6 array provides the best impedance match at this new frequency, the 5x5 array also shows acceptable matching. Notably, the 4x4 array results in a poorer match compared to the standalone dipole at the target frequency. All three AMC array configurations achieve a fractional bandwidth of approximately 12%, representing a significant enhancement compared to the 3–4% bandwidth obtained without the AMC.

The gain performance, shown in Fig. 10, demonstrates the effectiveness of the AMC reflector. All array designs provide significant gains over the only dipole's 2.5 dBi gain. The 6x6 array achieves the highest peak gain, but the gain of the 5x5 array is only marginally lower. The 5x5 array was chosen as the optimum arrangement, balancing performance and physical dimensions. It offers an advantageous combination of high gain, effective impedance matching, and a more compact design relative to the 6x6 array, rendering it the most pragmatic option for the application.

The distance D that exists between the dipole radiator and the 5x5 AMC reflector is an essential variable influencing both impedance matching and gain. The antenna system was simulated to determine the best spacing with spacing distances of D = 4 mm, 7 mm, and 10 mm.

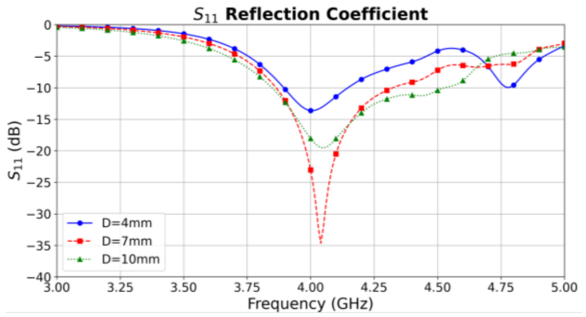

Fig 11. Comparison of the simulated reflection coefficient (S_{11}) for the proposed antenna with different separation distances (D) of 4 mm, 7 mm, and 10 mm.

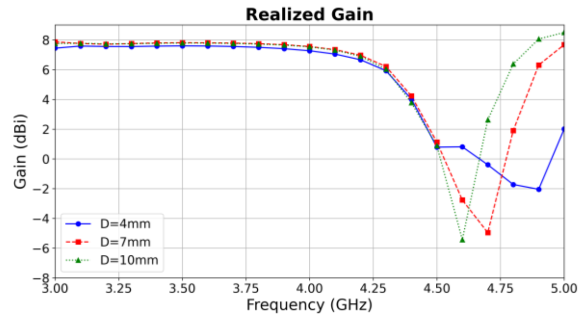

Fig 12. Comparison of the simulated realized gain for the proposed antenna with different separation distances (D) of 4 mm, 7 mm, and 10 mm.

The S_{11} in Fig. 11 shows the effect of separation distance on the antenna's impedance matching. The resonant frequency consistently centers about 4.05 GHz across all instances, although the quality of the matching exhibits considerable variation. The D = 7 mm design fulfills optimal performance, attaining a profound resonance of under -30 dB. At the designated frequency of 4.3 GHz, this case sustains an adequate match of approximately -11 dB. In Fig. 12, the gain plot shows the efficacy of each setup at the designated frequency. At 4.3 GHz, the D=7 mm arrangement results in the maximum gain of approximately 6.2 dBi, whereas the D=10 mm configuration exhibits a gain of 6.0 dBi. According to this data, a separation distance of D = 7 mm is determined to be the ideal selection. It provides not only the best impedance match but also the highest realized gain of 6.2 dBi at the target frequency of 4.3 GHz. This represents a 3.7 dB improvement over the standalone dipole and successfully meets all design requirements.

The ideal antenna comprises a dipole antenna fixed on a 5x5 array of AMC IV unit cells, with a separation distance of 7 mm. This configuration achieves a realized gain of 6.2 dBi and a satisfactory impedance match at the target frequency of 4.3 GHz, indicating a significant 3.7 dB enhancement compared to the dipole antenna alone.

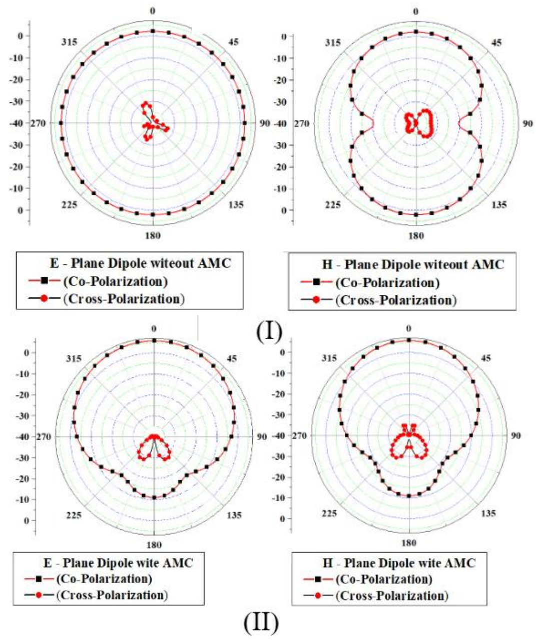

Fig 13. Simulated radiation patterns at 4.3 GHz, illustrating the transformation from an omnidirectional pattern (I) for the standalone dipole to a unidirectional pattern (II) with the addition of the AMC reflector.

Fig. 13(I) shows the pattern of the standalone dipole at 4.3 GHz, which demonstrates a classic omnidirectional characteristic, radiating energy equally in all directions perpendicular to its axis. In contrast, Fig. 13(II) shows the radiation pattern of the dipole integrated with the 5x5 AMC reflector. The pattern is converted into a highly directed, unidirectional beam, with the primary lobe focused in the forward direction (0°). The backward radiation (at 180°) is markedly diminished, validating that the AMC surface functions efficiently as a reflector, redirecting energy that would have been emitted backward into the primary beam. This transformation from an omnidirectional to a unidirectional pattern is the primary reason for the significant gain enhancement observed. Based on the iterative design process and experimental validation, the antenna parameters were optimized to achieve the desired performance characteristics. A physical prototype was subsequently

Fig 14. A prototype proposed of antenna

fabricated to conduct empirical measurements, which were then compared against the simulated results to assess the accuracy of the computational model, as shows in Fig. 14. During the practical installation, in order to avoid deviations in the air gap, either foam or 3D-printed material with a dielectric constant (ε_r) of approximately 1 will be employed, corresponding to a thickness of 7 mm to closely match that of air.

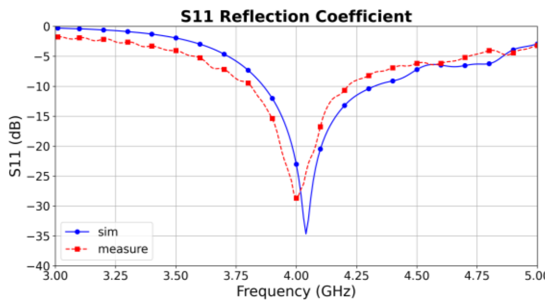

Fig 15. Comparison between the simulated and measured reflection coefficient (S_{11}) of the proposed antenna.

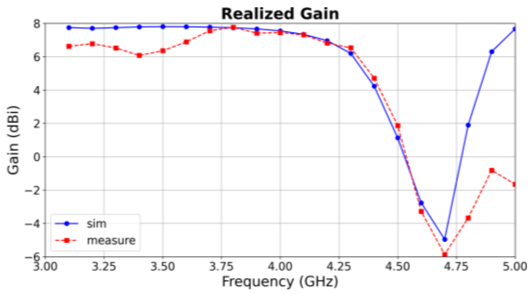

Fig 16. Comparison between the simulated and measured realized gain of the proposed antenna.

From Fig. 15 and Fig. 16. The measured results show a strong agreement with the simulated data. Both curves exhibit very similar trends and reach a peak gain of approximately 8 dBi. Although the measured values donot exactly match the simulated results, the overall outcome confirms that the simulation model is highly accurate, and the designed antenna performs as expected.

4. Conclusion

This research has effectively demonstrated the design, development, and optimization of a high-gain antenna for the 4.3 GHz band utilizing an Artificial Magnetic Conductor (AMC) reflector. A methodical design method was executed, encompassing the comparison of four unique AMC unit cell shapes, the optimization of the reflector array dimensions, and the adjustment of the separation distance. The ultimate optimum arrangement comprises a dipole antenna supported by a 5x5 array of the proposed modified cross-shaped (AMC IV) unit cells, positioned at a separation distance of 7 mm.

The results validate the efficacy of the suggested design. The final antenna attains a notable 3.7 dB gain improvement over the independent dipole radiator, yielding an average realized gain of 7.24 dBi across the working frequency range of 3.8 GHz to 4.3 GHz. It achieves a bandwidth of approximately 12%The examination of the radiation patterns clearly illustrates the efficacy of the AMC reflector, which adeptly converts the dipole's inherent omnidirectional pattern into a highly directed, unidirectional beam with improved backward radiation suppression. This study confirms that employing an AMC reflector is a viable and efficient approach for creating tiny, high-performance antennas that satisfy the stringent demands of 5G and available wireless communication systems. Future work will be directed towards the development of a high-gain multiband antenna.

5. Acknowledgments

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