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Research Article

Design and Experimental Validation of a High-Efficiency FR-4 Microstrip Patch Antenna Based on a Single Air-Gap Configuration for Wireless Applications

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Abstract

In this work, a low-cost FR-4 microstrip patch antenna with a single air-gap layer is proposed to achieve enhanced efficiency and gain while keeping structural simplicity and fabrication capability, which was experimentally performed as well. Unlike multilayer designs or metasurfaces, which may achieve better radiation efficiency or gain through additional orders of complexity in the design and fabrication processes, the introduced approach leverages a simple structural modification to make significant improvements while ensuring fabrication simplicity. The effect of the air-gap thickness on the performance of various antenna types is systematically studied using full-wave simulations, followed by experiments for validation. These results show an increase in realized gain from 2.29 dB to greater than 7.68 dB, and radiation efficiency exceeded 75%. Moreover, the air gap allows a change in resonant behaviour and helps to increase bandwidth. In this study, the results of both are compared and show good agreement. This simple and low-cost method improves the effectiveness of FR-4-type antennas in wireless transmission scenarios, especially for devices operating below 6 GHz.

Keywords: Microstrip patch antenna, Single air-gap antenna, FR-4 substrate, Gain enhancement, Radiation efficiency, Wireless communication systems

Introduction

Because of their low profile, light weight, ease of fabrication, and compatibility with integrated circuits, microstrip patch antennas have been focused on in current wireless communication systems[1, 2]. Due to these features, they are well-suited for applications such as wireless local area networks (WLANs), satellite communications, and mobile systems. Nevertheless, despite these merits, conventional microstrip antennas have several disadvantages, such as low bandwidth, gain and radiation efficiency (especially when inexpensive substrates like FR4 are used)[3-5].

Many methods have been included in the literature to tackle these constraints and improve antenna functionality. For these reasons, Electromagnetic Band Gap (EBG) structures have been highly used for surface wave suppression and radiation improvement[6, 7]. Based on this phenomenon, Defected Ground Structures (DGS) have been proposed to control the distribution of currents and improve impedance bandwidth and gain[8, 9]. Moreover, meta surface-based designs have shown considerable enhancements in antenna directivity and efficiency through electromagnetic wave manipulation[10, 11]. While these approaches are effective, they often add complexity to the design and increase fabrication cost.

The insertion of an air gap between the radiating patch and substrate is another effective technique to enhance the performance of the antenna which is simple as well. The air gap effectively lowers the effective dielectric constant of the structure, which can increase bandwidth, gain, and radiation efficiency[12, 13]. It helps to reduce the dielectric loss on FR4 substrates that optimizes good radiation performance, which makes this technique interesting to low-cost antenna design [14].

Various works have been performed on the application of air gaps in microstrip. For example, gain and bandwidth improvement is observed in conventional designs of stacked patch antennas such as air-spaced or even multilayered spaced arrangements[15]. In addition, some recent contributions have shown that a controlled air gap can be beneficial for such an antenna to attain enhanced total efficiency without resorting to complex topologies or extra parts[16].

Although these improvements have been made, high gain and efficiency along with low cost and easy fabrication remain hard to achieve, in particular with widely available substrates like FR4. So, this work presents a microstrip patch antenna structure with a lone air gap layer to improve performance parameters (return loss, bandwidth, gain and efficiency), while retaining compactness and a low-cost structure. The designed structure is evaluated and compared against recent research to show its efficacy and applicability in wireless applications.

In contrast with many prior air-gap or multilayer microstrip antenna designs that have resorted to elaborate structures, such as metasurfaces, stacked patches and defected ground structures (DGS), the novel proposed antenna offers an elegant single air-gap configuration set up on low-cost FR-4 substrate and experimentally validated via fabrication and measurement. By using spaced structures, it is still possible to improve radiation efficiency and gain at low complexity and fabrication cost.

2. Antenna Configuration

One air-gap-based solution is to propose an antenna; this configuration aims at the better performance of the normal microstrip patch substrate belonging to the PCB as FR-4 substrate. This design aims to enhance the efficiency and gain of the radiator while keeping structural simplicity and manufacturability.

The antenna includes a rectangular radiating patch which is printed on an FR-4 substrate that's distanced from the radio frequency ground plane through an air gap. By adding the air gap, the total height of the antenna is increased, and thus its effective permittivity is decreased, which elevates radiation performance.

Figure 1 shows the geometry of the proposed antenna. 1 where the essential parameters are the dimension of patches, thickness of substrate and height of air gap. Non-conductive spacers are used to maintain a uniform separation between the substrate and ground plane, creating an air gap.

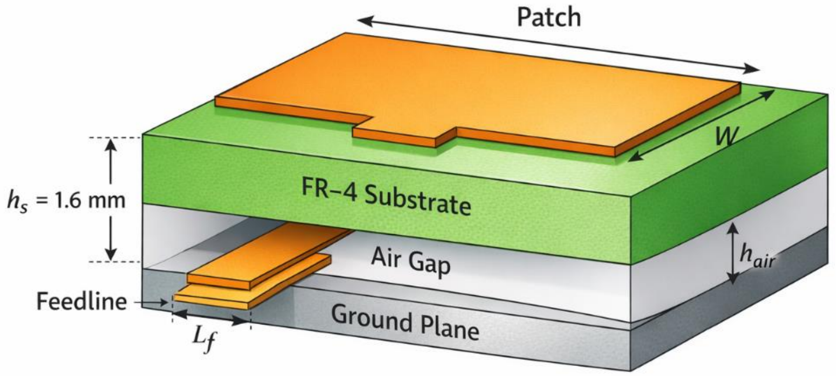


Fig. 1: Geometry of the proposed single air-gap microstrip patch antenna, showing the radiating patch, FR-4 substrate, air-gap layer, and ground plane.

2.1. Design Concept

The antenna is based on the basic operation of microstrip patch antennas, in which the resonant frequency is mainly linked to the effective length of the patch and substrate effective permittivity[5 ,1]. For the dominant $TM10$ mode, the resonant frequency can be approximated as

$$f_r = \frac{c}{2L_{eff}\sqrt{\epsilon_{eef}}} \quad (1)$$

where (c) is the speed of light, (L_{eff}) is the effective length of the patch and (ϵ_{eef}) the effective permittivity.

The effective permittivity remains high compared with conventional designs as a consequence of the dielectric substrate, which affects both strong field confinement and higher dielectric losses. The effective permittivity is reduced when an air gap (($\varepsilon_r \approx 1$)) is added, which obviously increases the fringing fields and improves radiation efficiency [17].

Redesigning the antenna to have a greater effective height allows us to reduce the Q-factor and hence increase impedance bandwidth[1] .

2.2. Effect of the Air-Gap Layer

An air-gap layer is a layer whose dielectric property alters the electromagnetic characteristic of an antenna. Visually, the structure can be compared to a composite dielectric, while its effective permittivity is determined by the certain ratio of air thickness and permittivity of dielectric in between.

Decreased effective permittivity results in:

1. More pronounced fringing fields at the edges of patches
2. Suppression of surface-wave propagation
3. Improved radiation efficiency
4. Enhanced gain

Similar effects have been demonstrated in several different studies on air-gap structures, with improvements found [18].

Additionally, the air gap provides more design freedom for optimizing antenna characteristics such as gain, bandwidth, and resonance frequency."

2.3. Feeding Technique

A microstrip line feed printed on the FR-4 substrate is used to excite the antenna. Using standard transmission line equations[5], the feedline is designed to realize a 50 Ω characteristic impedance.

The feedline is connected to an inset-fed configuration for better impedance matching with the radiating patch. By choosing the inset depth properly, we can minimize the reflection coefficient at the desired frequency of operation.

2.4. Parametric Design and Optimization

In this work, the air-gap height, which has a significant impact on antenna performance, is perceived as the primary design component, as it influences various parameters, including gain and impedance characteristics. Thus, for parametric analysis, the air-gap thickness is varied, and the remaining parameters are kept constant.

The optimization is conducted through iterative simulations using CST Microwave Studio. The objective is to achieve:

- Maximum realized gain
- High radiation efficiency
- Good Impedance matching ($S_{11} < -10\ dB$)
- Acceptable bandwidth

Table 1 summarizes the optimized antenna parameters.

Table 1: Optimized Parameters of the Proposed Antenna

Parameter	Description	Value
L	Patch length	14.2 mm
W	Patch width	18.43 mm
h_s	Substrate thickness	1.6 mm
h_air	Air-gap height	(varied)
εr	Substrate permittivity	4.3
tanδ	Loss tangent	0.02
Wf	Feedline width	1.945 mm
Lf	Feedline length	13.833 mm

3. Theoretical Analysis

The fundamental electromagnetic principles help explain the performance enhancement of the proposed antenna. Using a single air-gap layer improves the effective permittivity of the antenna medium, lowers dielectric losses and suppresses surface-wave propagation. The combination of these mechanisms leads to enhancements in gain, radiation efficiency, and bandwidth.

3.1. Effective Permittivity Reduction

The configured model could be estimated around a two-layer medium that is created of the layers with an FR-4 dielectric and air. Based on a simple quasi-static approximation, the effective permittivity of the composite structure reads[1, 5] :

$$\epsilon_{eff} = \frac{\epsilon_r h_s + \epsilon_{air} h_{air}}{h_s + h_{air}} \qquad (2)$$

where $\boldsymbol{h_s}$ is the substrate thickness, $\boldsymbol{h_{air}}$ is the air-gap thickness, $\in_{\boldsymbol{r}}$ is FR-4 relative permittivity and $\in_{\boldsymbol{air}} \approx 1$. According to Eq. (2), as the air-gap thickness is increased, it reduces the effective permittivity of the entire structure, which promotes fringing fields and leads to gain improvement and radiation efficiency enhancement.

3.2. Surface Wave Suppression

A high percentage of the electromagnetic energy in conventional microstrip antennas is trapped in the dielectric substrate as surface waves. Those waves travel along the interface formed between the substrate and air, with the energy eventually lost at edges, causing low-radiation efficiency[17].

This surface wave excitation relies heavily on the dielectric constant of the substrate. Higher permittivity leads to stronger electromagnetic field confinement and surface-wave modes.

This provides an extra increase in the cutoff frequency of the surface-wave modes, due to a decrease in permittivity of the effective structure caused by the introduction of air gap. This leads to the suppression of surface-wave excitation, allowing a greater fraction of the input power to be radiated into free space. This may directly explain the increased radiation efficiency of the proposed design.

3.3. Effect on Bandwidth and Quality Factor

The impedance bandwidth of a microstrip antenna is inversely related to its quality factor (Q-factor), as stated in[1] :

$$\mathbf{BW} \propto \frac{\mathbf{1}}{\mathbf{Q}} \qquad (3)$$

“Antennas and propagation: Isolated antennas” The Q-factor of the antenna is determined with respect to the effective height of the structure in question and, hence also by its permittivity. Increasing the air-gap thickness is equivalent to making the overall height of the antenna bigger, thus reducing the Q-factor and giving a wider impedance bandwidth.

Moreover, the decrease in dielectric losses also helps improve bandwidth. The introduction of an air-gap layer is a simple and helpful strategy to achieve wide bandwidth.

3.4. Resonance Behavior

The resonance frequency of a rectangular microstrip patch antenna is a function of the effective length and effective permittivity, which can be approximated as [1, 5] (as eq. (1)):

The effective permittivity decrease with increasing air-gap thickness results in a resonance frequency shift. The reason for this difference is that we are also using rotation in our simulation; hence the variation in resonance frequency from what we got in simulation results.

Fundamental resonance frequency-wise equivalent circuit parameters are extracted from CST simulation results. An agreement between the circuit model and full-wave simulation confirms a successful implementation of the proposed design approach.

3.5 Radiation Efficiency Improvement

Microstrip antenna radiation efficiency is deteriorated due to dielectric and conductor losses. Due to the relatively high loss tangent, dielectric losses dominate for antennas based on FR-4.

The air gap reduces the fraction of electromagnetic energy consumed in the lossy dielectric, allowing more energy content to be distributed throughout the air area. Given that air is a lossless medium, this translates to a huge decrease in dielectric losses.

As a result, the antenna's radiation efficiency is enhanced, which does agree with the measured results in Section 4.

4. Results and Discussion

This section provides a detailed validation of the suggested single air-gap antenna using full-wave simulations and experimental measurements. The effect of the air-gap thickness on antenna performance (resonance behavior, gain, radiation efficiency, and impedance bandwidth) is analyzed.

These results are analyzed according to the theoretical analysis in Sec. 3, especially with respect to effective permittivity reduction and surface-wave propagation suppression.

4.1. Effect of Air-Gap Thickness on Resonance Behavior

The simulated reflection coefficient (S_{11}) of the proposed antenna at various gaps is shown in Figure 2. As the air-gap height increases, a clear resonance shift occurs, as would be expected from the reduction is effective permittivity explained in Section 3.1. For optimized case, dual resonances are at around 4.541 GHz and 7.306 GHz with reflection coefficients of lower than −10 dB, which indicates the impedance matching condition is satisfactory in two operating band as well

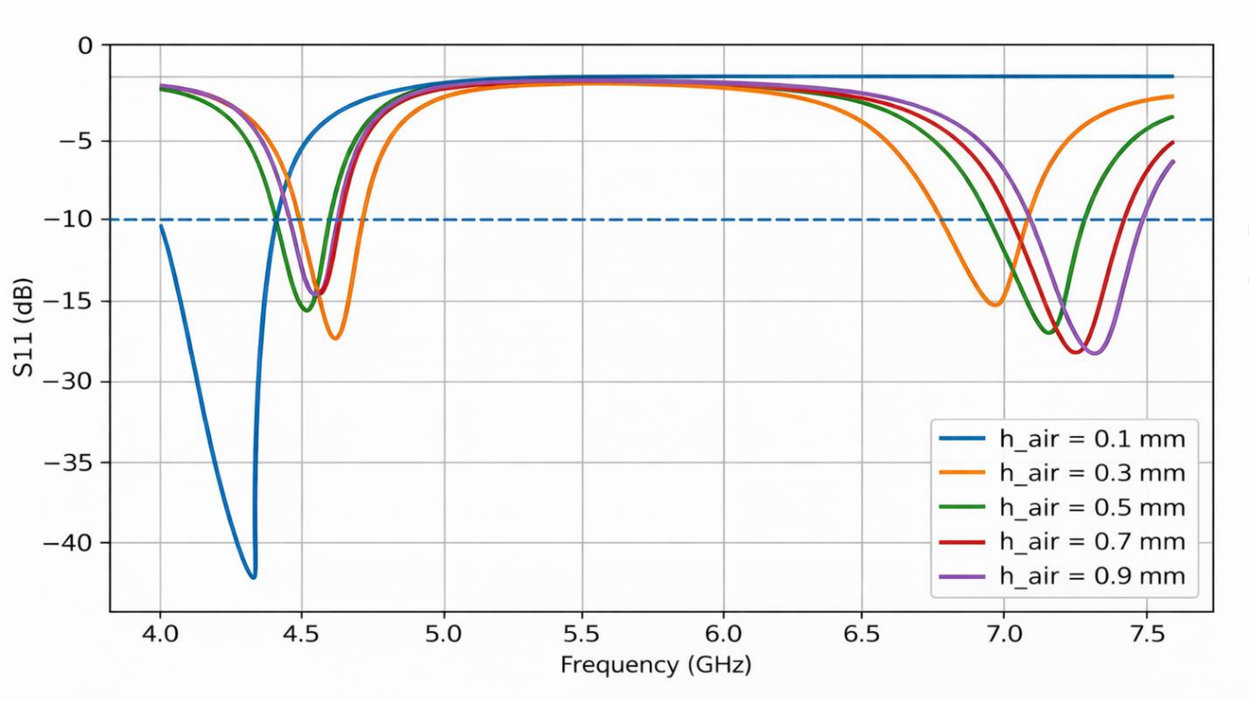


Fig. 2: Simulated reflection coefficient (S_{11}) for varied air gap thicknesses.

This behavior relates to reduced effect permittivity as mentioned in Section 3.1. The effective permittivity decreases with an increase in air-gap thickness, and thus the resonant frequency shifts.

In the best configuration, this dual resonance is observed at around 4.541 GHz and 7.306 GHz, showing the excitation of higher-order modes in the antenna structure.

The emergence of the second resonance can be understood as a result of the increase of the antenna structure's effective height due to the air-gap layer introduction. The introduction of an air gap alters the distribution of the electromagnetic fields and encourages higher-order resonant modes to be excited in the patch. Consequently, the antenna shows dual-band characteristics without resorting to more parasitic elements or complex multilayer configurations.

Moreover, the reflection coefficient is lower than −10 dB at both resonances, verifying good impedance matching.

4.2. Gain Enhancement

Figure 3 shows the variation of realized gain as a function of air-gap thickness. . These results show that with increasing air-gap height, a drastic improvement in gain is achieved.

Notice that the maximal realized gain of 7.68 dBi achieved for this antenna is significantly larger than corresponding values for FR-4-based antennas.

This improvement results primarily from the decreased effective permittivity and enhanced fringing fields, where an increase in radiation efficiency occurs. Such observations are in agreement with the theoretical interpretation provided in Section 3.1.

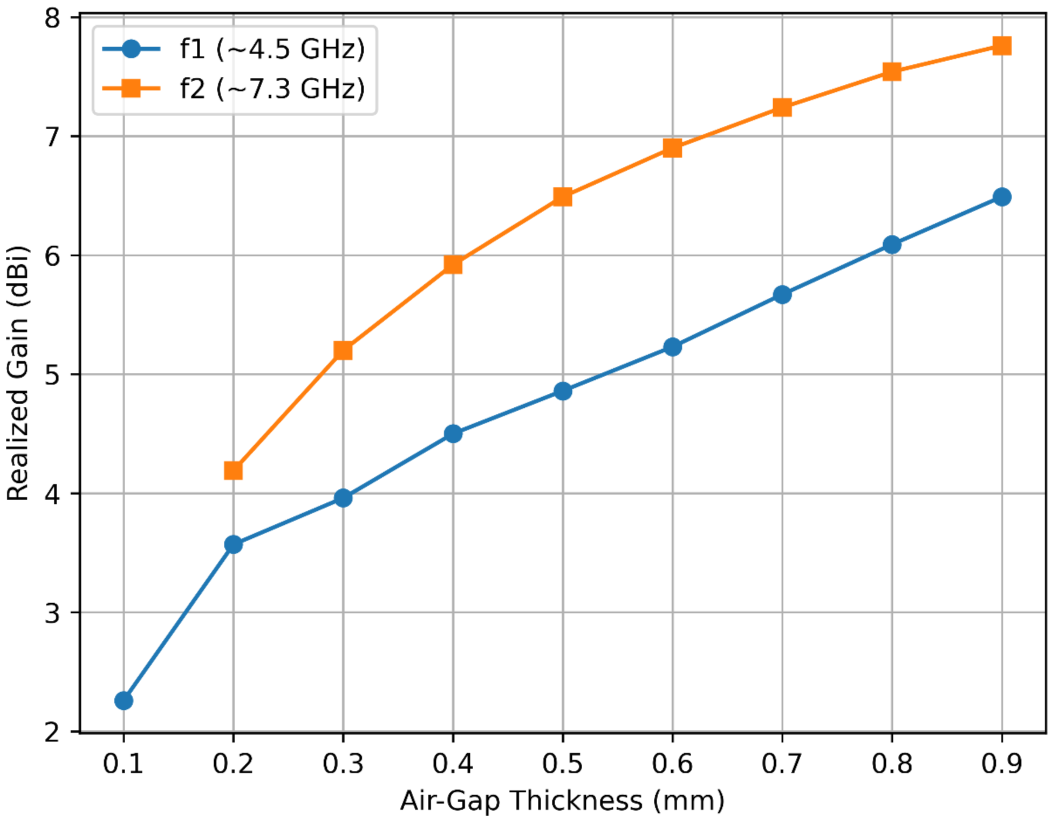


Fig. 3 : Variation of the realized gain as a function of air-gap thickness for the proposed antenna at the two resonance frequencies (≈4.5 GHz and ≈7.3 GHz).

4.3 Radiation Efficiency

Table 2 summarizes radiation efficiency of the antenna for different air-gap configurations.

The analysis shows that the radiation efficiency increases from about 36% with conventional design to above 75% with a single air-gap optimized structure.

The changes in dielectric losses and suppression of surface waves, which are elaborated on in Section 3.2, contribute to this improvement.

Table 2: Simulated Radiation Efficiency for Different Configurations

Configuration	Efficiency (%)
Conventional (No Air Gap)	36%
Single Air Gap	> 75%

The methodology used to extract these efficiency values is clarified in the following section.

4.4 Radiation Efficiency Evaluation

Important to note is that the reported values of radiation efficiency were derived from full-wave simulations using CST Microwave Studio rather than actual data measurements. The radiation efficiency was then assessed in the simulation environment considering conductor and dielectric loss within the antenna structure. However, direct efficiency measurement would need dedicated facilities like an anechoic chamber or gain-comparison techniques, whereas the experimental validation was limited to only $S11$ measurements, which were performed with a vector network analyzer (VNA).

4.5. Bandwidth Performance

The impedance bandwidth of the antenna is derived from the S11 response, and it is defined for ($S_{11} < -10$) dB. The bandwidth of the optimized design shows a significant increase over the conventional antenna.

This improvement also relates to a smaller Q-factor, which is a result of the larger effective height of the antenna, as explained in Section 3.3.

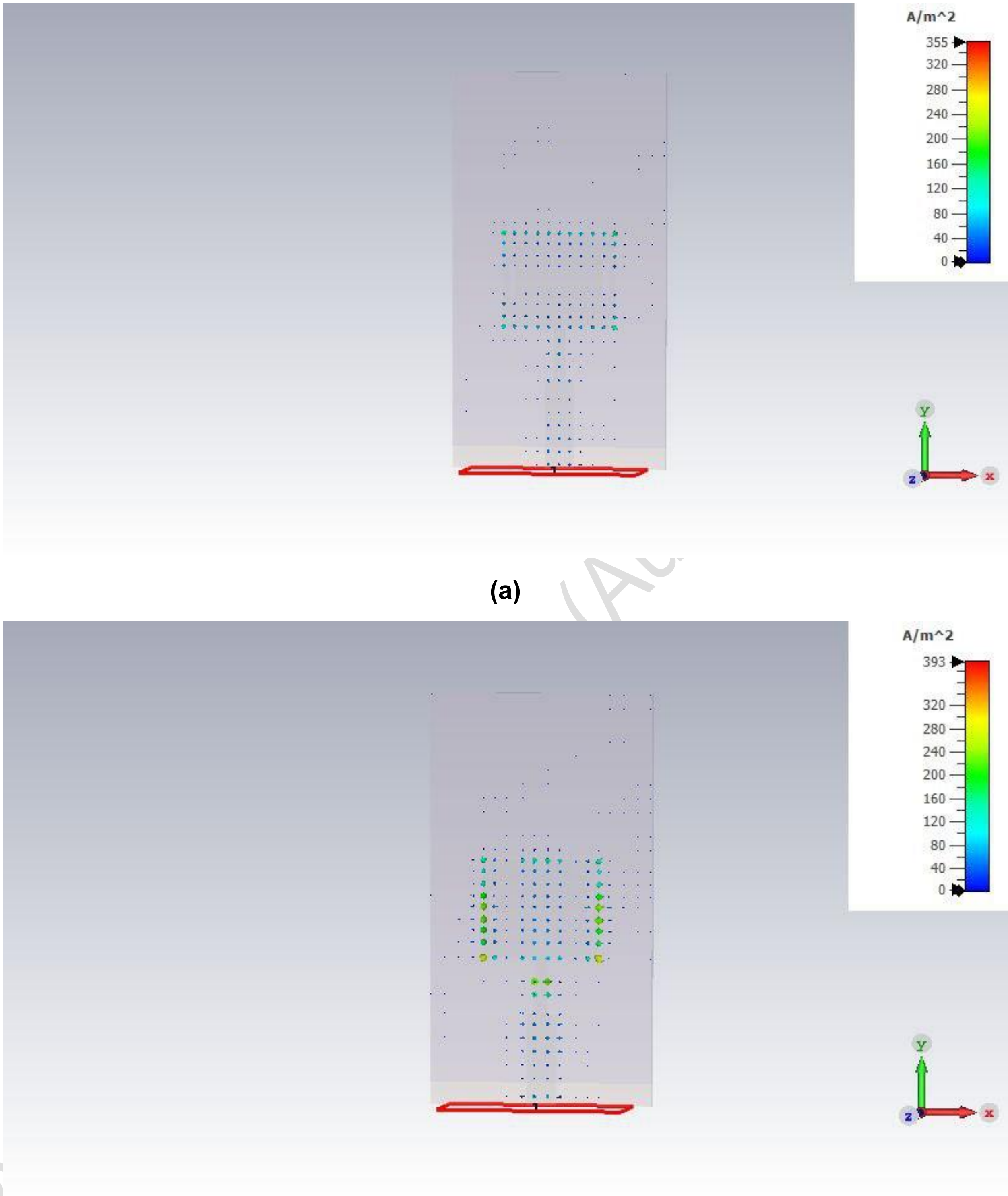
4.6. Surface Current Distribution

In order to better analyze the improved performance, we investigate the surface current distributions at resonance frequencies in Fig. 4.

As expected, efficient radiation occurs at the fundamental resonance frequency (4.541 GHz), where current distribution is mainly along the edges of the patch.

For the second resonance frequency (7.306 GHz), a different current distribution is established, which represents higher orders of modes. This accounts for the behavior of the antenna as dual band.

These observations affirm that the incorporation of an air gap alters electromagnetic field distribution and significantly improves radiation performance.



(a)

(b)

Fig. 4: Surface current distribution at **a)** 4.541 GHz and **b)** 7.306 GHz of a single air-gap antenna

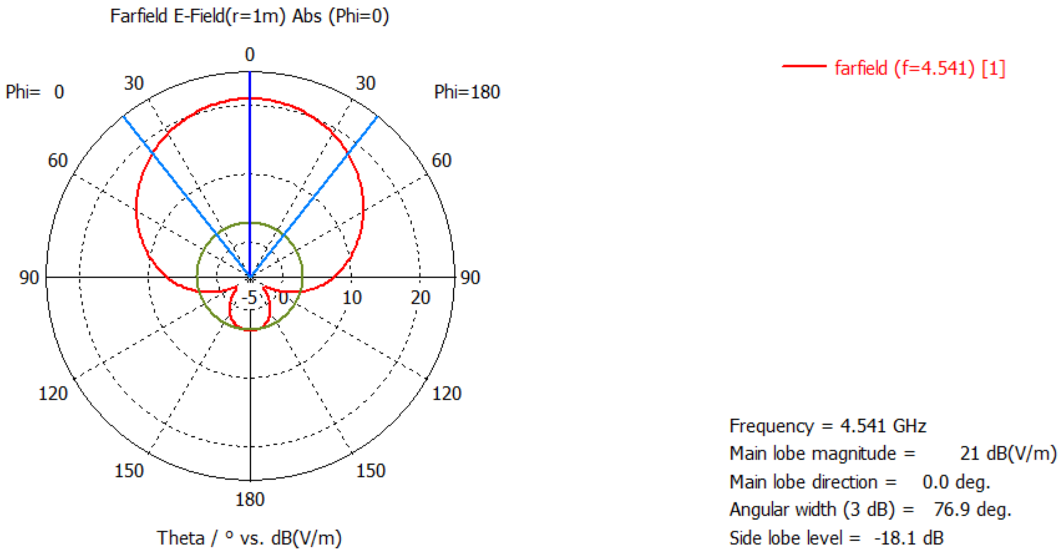
4.7 Radiation Patterns

In order to gain additional insight into the radiation characteristics of the proposed antenna, we present it in Fig. 5.

The broadside radiation patterns of the antenna in both planes are performed at 4.541 GHz with a stable beam width and low side-lobe levels, in agreement with those characteristic of conventional microstrip patch antennas, as illustrated in Fig.

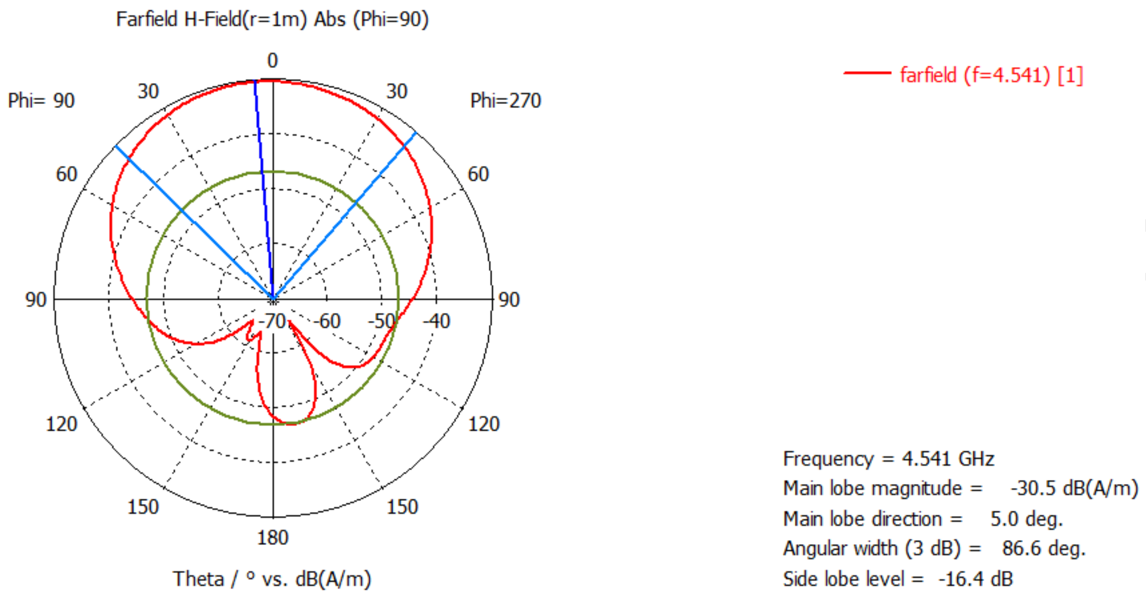
The radiation becomes more directional at higher frequency, with a marked increase in directivity, as shown by the decrease in beam width, especially at 7.306 GHz . Although both planes still show the fraction vector pointing toward the main lobe, side lobes appear at higher frequencies on each plane, indicating a more complex radiation mechanism.

The antenna maintains acceptable radiation performance for this behavior, and the observed increase in gain with increased directivity at the higher resonance is a reasonable result. The slight asymmetry of the radiation patterns is due to the air-gap layer feeding configuration and structure effects.



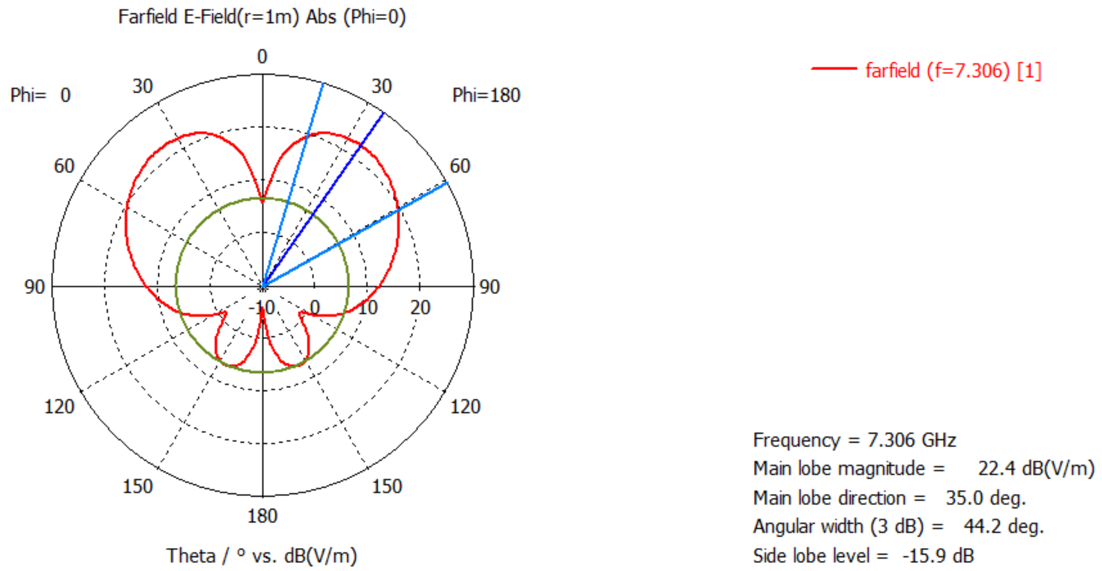
Frequency = 4.541 GHz
Main lobe magnitude = 21 dB(V/m)
Main lobe direction = 0.0 deg.
Angular width (3 dB) = 76.9 deg.
Side lobe level = -18.1 dB

(a)



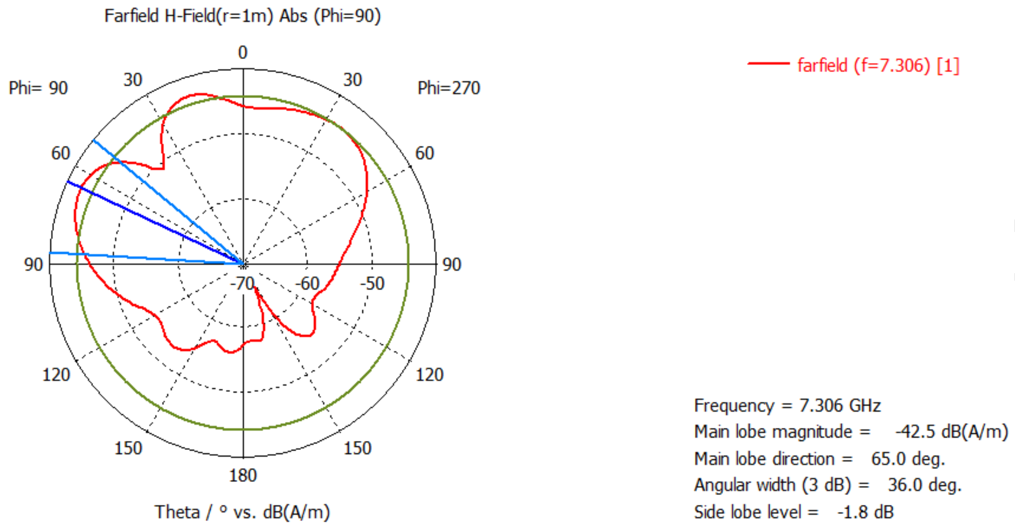
Frequency = 4.541 GHz
Main lobe magnitude = -30.5 dB(A/m)
Main lobe direction = 5.0 deg.
Angular width (3 dB) = 86.6 deg.
Side lobe level = -16.4 dB

(b)



Frequency = 7.306 GHz
Main lobe magnitude = 22.4 dB(V/m)
Main lobe direction = 35.0 deg.
Angular width (3 dB) = 44.2 deg.
Side lobe level = -15.9 dB

(c)



(d)

Fig. 5: Simulated E-plane and H-plane normalized radiation patterns of the proposed antenna plotted at (a, b) 4.541 GHz, and (c, d) 7.306 GHz.

4.8 Experimental Validation

The antenna was fabricated and measured to validate the simulation results. As illustrated in Fig. 6, a comparison between the measured reflection coefficient and the simulated results is given in Fig. 7.

The acceptable correlation of the corresponding S11 results for comparison, both simulated (red) and measured (blue), implies the accurate engineering of the proposed design.

Small differences between the simulated and measured S parameters can be explained by fabrication tolerances, connector losses, or uncertainties in the height of the air gap.

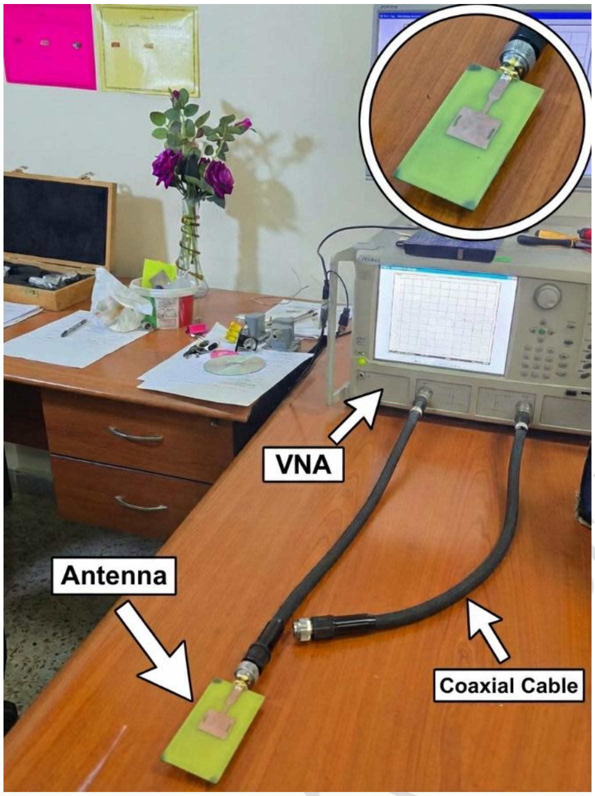


Figure 6: Fabricated antenna prototype and measurement setup using a vector network analyzer (VNA).

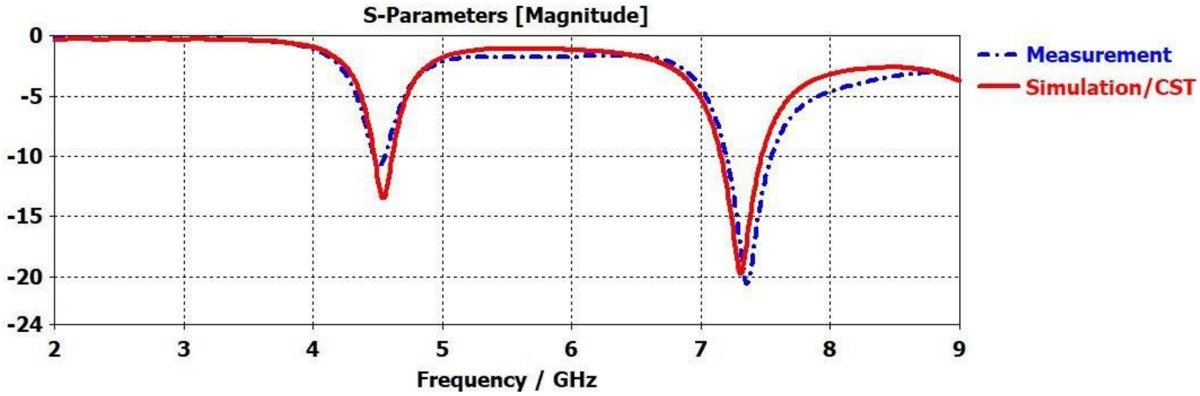


Fig. 7: Measured vs simulated S11

4.9 Comparison with Recent Gain-Enhancement Approaches

In order to put the proposed layout in a more perspective position relative to the existing literature, the performance of the current antenna is compared not only with traditional (FR-4) microstrip patch antennas but also with different recent gain-improvement methods such as defected ground structures (DGS), slot-loaded and parasitic-assisted layouts.

High dielectric losses inherent in polymeric substrates lead to low gain and efficiency of traditionally fabricated single patch antennas on the FR-4 substrate, for which reason this fact is well known. Maximum gain for a typical single patch antenna can be in the range of 6- 9 dBi [7], although some implementations on other substrates such as FR-4 are not as efficient.

Recently, apart from the air-gap techniques, other gain-enhancement methods like high-slotting, structural optimization and low-profile design modifications have been studied for improvement in radiation characteristics of microstrip antennas. Such approaches are a testament to sustained interest in high gain and efficiency with sidelobe performance amidst constraints on compactness, form factors, and ease of fabrication[19-21].

Therefore, the proposed design achieves a competitive performance while maintaining significantly lower structural complexity compared to many existing approaches.

As an example, one design of microstrip patch antenna with DGS reported in [19] demonstrated a measured gain of about 4.4 dBi at 5.8 GHz, indicating modest improvement when ground plane changes are applied. Multiband designs using slot loading and partial ground structures, e.g., the antenna introduced in [20], provided simulated gains of 2.2 dB, 4.9 dB and 4.6 dB at frequencies of 2:4, 3:6, and 5:57 GHz, respectively. These findings suggest that while multiband operation is possible, it still has limited improvement in terms of gain.

Also, features such as parasitic elements are used to improve the antenna performance. As another scenario, in [21], a simulation of gains of 3.83 dB and 0.57 dB at 3.45 GHz and 5.9 GHz were applied with about 59% efficiency. Although small in size and operating on both bands, the radiation performance is still quite mediocre.

Also, a standard microstrip patch antenna for 5G devices with FR-4 substrate was simulated to have approximately 6.94 dBi gain at the operating frequency of 3.5 GHz [22]; this result is near the theoretical maximum of one patch antenna. But such performance is often hard-fought for through careful optimization, and still suffers from decreased efficiency due to substrate losses.

In contrast, the suggested antenna achieves a realized gain of 7.68 dBi and radiation efficiency exceeding 75% with only one air-gap layer employing inexpensive FR-4 substrate. The enhancement is due to the effective permittivity reduction and surface-wave loss suppression through the introduced air-gap structure. The improvement in gain and efficiency with respect to prior work comes at the cost of structural complexities; thus, its potential implementation does not rely on complicated geometries, such as metasurfaces, multilayer systems, or antenna arrays.

Thus, the proposed antenna offers a trade-off between performance improvements, cost, and ease of fabrication, which is practical in wireless communication applications.

Table 3: Performance comparison of the proposed antenna with recent gain-enhancement techniques

Ref.	Frequency (GHz)	Substrate	Technique	Gain (dB)	Efficiency (%)	Complexity
[22]	5.8	FR4	Patch with DGS	4.4 (meas.)	—	Moderate
[23]	2.4 / 3.6 / 5.57	FR4	Slot + partial ground	2.2 / 4.9 / 4.6 (sim.)	—	Moderate
[24]	3.45 / 5.9	FR4	Parasitic strips	3.83 / 0.57 (sim.)	~59	High
[25]	3.5	FR4	Conventional patch	6.94 (sim,)	—	Moderate
This work	4.54 / 7.30	FR4	Single air-gap	7.68 (meas,)	>75	Simple

Conclusion

A single air-gap setup is proposed in this work that can upgrade the performance of a low-cost FR-4 microstrip patch antenna. This design minimizes complexity while still allowing for improved radiation features, making it easy to manufacture.

Systematic full-wave simulations have explored the effect of air-gap thickness on antenna performance. The results show that increasing the air-gap thickness effectively leads to a decrease of permittivity, due to enhancement in fringing fields at edges and suppression of surface-wave propagation. This results directly in the improvements of the gain, radiation efficiency and bandwidth.

The prototyped dual-band antenna has resonance frequencies of about 4.541 GHz and 7.306 GHz, confirming that this antenna can operate in different frequency bands. Good impedance matching is apparent, as the reflection coefficient is under −10 dB for full operating bands.

The air-gap layer increases the antenna performance noticeably. The gain realisation is that for air-gap thickness greater than 0.1 mm, the realized gain increases from a minimum value of 2.26 dBi at an air gap thickness of 0.1 mm to a maximum value of 6.49 dBi at the lower resonance frequency, and in between this variation towards maximum values changes from 4.19 dBi to 7.68 dB for the higher resonance frequency. The antenna's radiation efficiency also rises, from 35% to 75.8%, showing a considerably low dielectric loss.

Moreover, the quality factor is reduced with increasing air-gap thickness, leading to improved impedance bandwidth and overall performance of the antenna.

Indented, more complicated designs such as multilayer structures or metasurface-based implementations have been developed in the literature, whereas our proposed antenna shows a competitive performance with just one air-gap layer built on a low-cost FR-4 substrate. That offers the usable answer for uses with a combination of low cost, simple fabrication and better radiation traits.

Overall, it can be confirmed from the results obtained that this single air-gap approach would provide a better trade-off of performance improvement and structural simplicity, making them suitable to sub-6 GHz and C-band wireless communication systems.

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Author Contributions (CRediT):

Muayyed Jabar Zoory: Conceptualization, Methodology, Investigation, Writing – original draft.
Sarah Kareem Mohammed: Data analysis, Validation, Writing – review & editing.

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Declaration of competing interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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