Characteristic Mode–Enabled Hexagonal Ring Patch Antenna for 5.5 GHz IoT/Wi-Fi Sensing

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Abstract

The design and analysis of a small hexagonal ring microstrip antenna optimized at 5.5 GHz are presented in this work. The FR4 substrate, which has a dielectric constant of 4.3 and a thickness of 1.6 mm, is used to fabricate the antenna because it is inexpensive and compatible with printed circuit board technology. By extending the effective current path and allowing for multiple resonant modes, the hexagonal ring geometry improves radiation performance and impedance bandwidth when compared to traditional rectangular patches. Using CST Microwave Studio, Characteristic Mode Analysis (CMA) is used to analyze the antenna's modal behavior. According to the CMA results, higher-order modes aid in stability, but the dominant resonant mode around 5.5 GHz largely controls the radiation mechanism. With an impedance bandwidth of 126 MHz (5.392–5.518 GHz), the simulated response exhibits a resonance of –20 dB at 5.5 GHz. The antenna produces strong current distribution along the hexagonal edges, broadside radiation, and a steady gain of 6.11 dBi. The design is appropriate for WLAN and Wi-Fi 5 (IEEE 802.11ac) applications because of these features. The hexagonal ring structure is an efficient technique for increasing bandwidth and performance in wireless systems, as demonstrated by the combination of CMA and full-wave simulations.

Keywords- Microstrip antenna, Hexagonal ring, Characteristic Mode Analysis (CMA), WLAN, Modal significance, Bandwidth enhancement, CST Microwave Studio.

I. INTRODUCTION

The antenna of portable devices and access points are in demand of small size, effective and wideband because of the rapid growth of wireless communication systems [1-3] The use of microstrip patch antennas is very common because it does not occupy space and is very easy to manufacture besides being easily integrated with printed circuit boards [4-5] Significant the antennas in the 5 GHz band to support the application of the WLAN and Wi-Fi 5 (IEEE 802.11ac) interface that needs high data rates, and stable connectivity [7-9]

The conventional microstrip antennas have narrow bandwidths of impedances and low efficiency on realistic substrates [10-13]. A number of improvement methods have been explored which include slots, defected ground structures (DGS) [14], parasitic patches [15], and resonant ring geometries [16], [17]. These methods, however, are usually based on parameter sweeps or blind optimisation in full-wave simulators, which are computationally expensive and give little physical information [18-21].

Characteristic Mode Analysis (CMA) is a method which provides a definite framework by breaking down the currents on the antenna surface into orthogonal modes. Using modal significance, eigenvalues, and current distributions, CMA allows one to determine which modes are important to the radiation, and which are selectively [22-24]. This method minimizes brute force optimization and offers physical insight into the nature of radiations. Recent publications have used CMA to enhance bandwidth, polarization and MIMO performance [25-27].

This paper presents a hexagonal ring microstrip antenna that is optimized at 5.5 GHz. The geometry lengthens current path length, sustains multiple resonances and augments radiation stability. The proposed antenna, which is developed with the help of CMA, as opposed to traditional designs, relates to finding out the dominant radiation mode at 5.5 GHz. The last prototype has a resonance of -20 dB at bandwidth 126 MHz, which is suitable in the application of WLAN and Wi-Fi 5.

Although there have been a number of documented microstrip antenna designs for WLAN, the majority rely on black-box optimization or trial-and-error, which makes it difficult to physically evaluate the radiation mechanism. By showing how CMA offers direct physical insight into modal behavior and directs the design process of a compact hexagonal ring antenna, this research fills that gap. With a bandwidth of 126 MHz and a deep resonance of -20 dB at 5.5 GHz, the suggested antenna is appropriate for WLAN and Wi-Fi 5 applications.

The remainder of this paper is organized as follows. Section two presents the theoretical background. Section three describes the antenna design methodology of Characteristic Mode Analysis (CMA) for identifying the dominant resonant modes. Section four discusses the simulation results, including return loss, impedance bandwidth, radiation pattern, and gain performance. Finally, Section five concludes the work with key findings and future perspectives.

II. THEORETICAL BACKGROUND

Microstrip patch antennas have found extensive application in wireless communication system mainly because they are easy to build since they are planar and work well with the integrated circuits as well [1]. An antenna that has a conventional microstrip is made of a metallic patch on a dielectric substrate with a ground plane behind it. The effective electrical length of the patch and dielectric properties of the substrate are the main factors that determine the resonant frequency of the antenna. In the case of a ring or circular geometry, the basic resonance can be given by approximation as [28]:

$$f_r = \frac{c}{2\pi R_{eff}\sqrt{\varepsilon_{eff}}} \quad (1)$$

In which c is the speed of light in free space, Reff is the effective radius of the ring, and ε_{eff} is the effective dielectric constant, as [29]:

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

Where ε_r is the substrate permittivity, h is the substrate thickness, and the width of the microstrip line is W.

Even though these equations give preliminary values, in the real world, designs are highly coupled, higher order effects, and substrate losses, which make it hard to predict accurately. Conventional design methods are based on trial and error trial sweeps in simulation packages, in many cases without any physical understanding of the reasons why some designs are more successful than others. This shortcoming encourages the use of Characteristic Mode Analysis (CMA).

CMA is a physics based model of antenna analysis and design. The approach breaks down the existing distribution on a conductor body into a collection of orthogonal characteristic distributions by solving the eigenvalue problem [30]:

$$[X]J_n = \lambda_n[R]J_n \quad (3)$$

In which [R]and [X] are the real and complex components of the Method of Moments (MoM) impedance matrix, J n is the eigen current of the n th mode, and 3 n is the eigens value of the n th mode. The modal significance (MS) is the critical parameter that shows the strength of the mode contribution to radiation [30]:

$$MS_n = \frac{1}{|1+j\lambda_n|} \quad (4)$$

When $\lambda_n = 0$n=0, the mode is at resonance, and $MS_n = 1$.
When Modes have $MS >$0.707 are considered effectively radiating.
Through modal significance, eigen current distribution, and characteristic angles, the designers can ascertain which modes prevail at the target frequency (frequency) and how they can be induced by the feed structuremodes dominate at the desired frequency and how they can be excited through the feed structure.
In this way, CMA removes the uninformed process of optimization because it puts the behavior of the modes into perspective and allows selective excitation of the modes that are desirable and deactivation of the ones that are undesirable. In the example of the suggested hexagonal ring antenna, CMA finds the strongest resonant mode at approximately 5.5 GHz, leading to optimization of the design in terms of better impedance bandwidth and radiation stability.

III. ANTENNA DESIGN METHODOLOGY BASED ON CMA

In order to design and optimize the proposed antenna systematically, a systematic technique is used in terms of Characteristic Mode Analysis (CMA). CMA, in comparison to traditional trial-and-error approaches, offers a physics-based framework that determines the resonant modes that cause radiation and informs the positioning of the feeding structure. This process leads to a simpler design, less blind optimization, and a faster approach to the desirable performance.
The general process of the overall approach can be described as a step-by-step approach which begins with defining the design specifications, the extraction and interpretation of characteristic modes, feed placement to excite dominant modes, and validation by full-wave simulation. Figure 1 below represents the process of design adopted and shows how CMA would be incorporated in the development of the antenna.

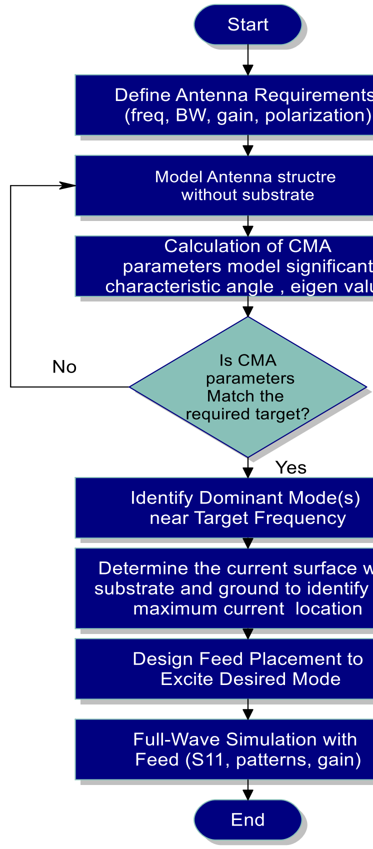

Figure 1. Flow chart of design process based on CMA..

IV. SUGGESTED ANTENNA DESIGN BASED ON CMA

To gain deeper physical insight into the radiation behaviour of the proposed Hexagonal Ring Microstrip Antenna, Characteristic Mode Analysis (CMA) is performed using CST Microwave Studio. Unlike conventional parameter sweeping, CMA enables the designer to investigate the inherent resonant modes of the antenna structure without exciting it through a specific feed. This provides a clear understanding of which modes contribute effectively to radiation near the desired operating band of 5.5 GHz. The suggested antenna CST model is explained in Figure 2.

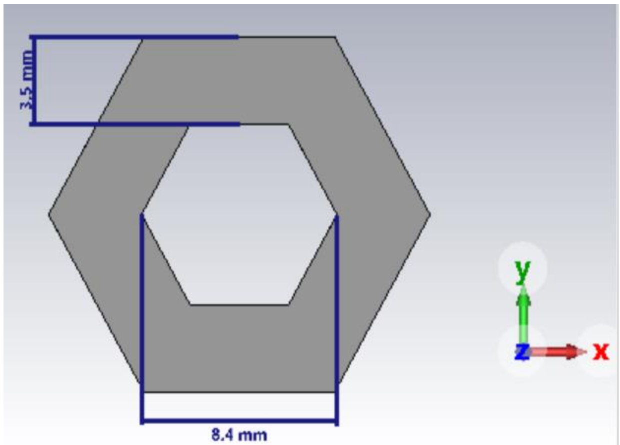

Figure 2. Flow chart of design process based on CMA

As shown in Figure 3, the CMA study starts with the extraction of the hexagonal ring's eigenvalue spectrum and then computes the Modal Significance (MS).

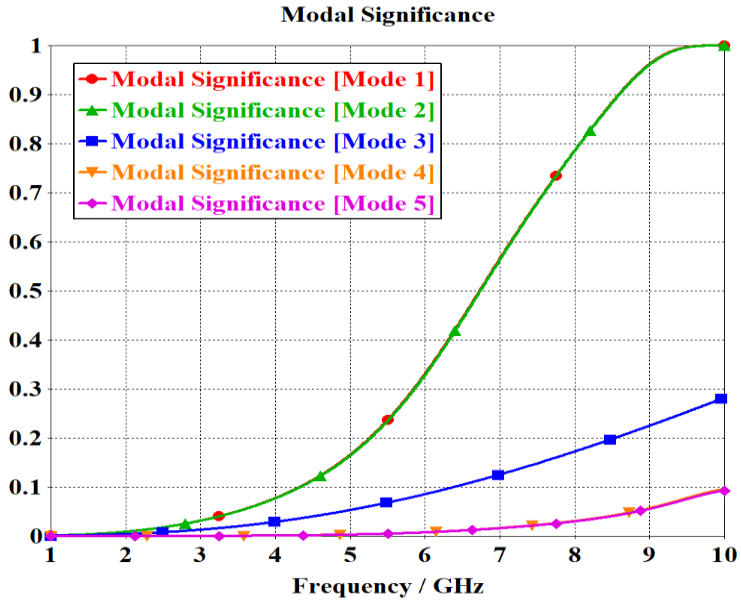

Figure 3. Calculated MS for proposed antenna structure

Figure 3 shows that two different modes have MS values that are close to unity in the frequency range of 7–10 GHz. This suggests that both modes can radiate efficiently in this band and are highly resonant. These resonances' close proximity indicates that the structure naturally supports a number of radiating modes, which could be used for wideband or multiband applications if desired.

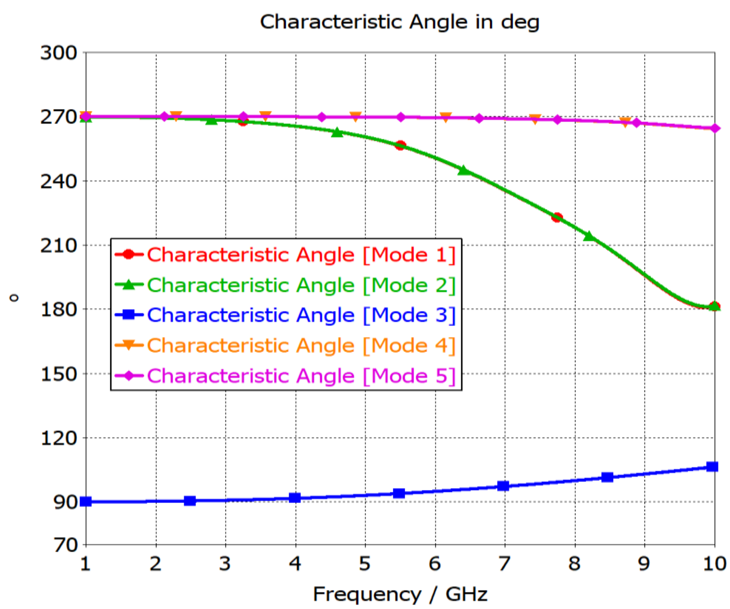

Figure 4. Calculated CA for proposed antenna structre

The dominant resonant behavior is not concentrated around the intended 5.5 GHz band, but rather becomes significant in the higher frequency range, according to the CMA investigation of the hexagonal ring structure without substrate. The Modal Significance (MS) and Characteristic Angle (CA) plots show that the most prominent resonance indicators appear between 9.5 and 10 GHz.

In particular, Modes 1 and 2 show significant resonance in this band, with CA values close to 180° at 9.5 GHz and 10 GHz, respectively. This indicates that these modes are actually radiating at higher frequencies. The modal significance (MS) plots, which display values close to unity in this range, validate the significance of the dominant modes. In the absence of a substrate, the modal resonances are shifted to higher frequencies. After the substrate and feeding structure are integrated, the resonant frequencies move downward toward the target band of 5.5 GHz, enabling the proposed antenna to function as intended.

In this study, the initial Characteristic Mode Analysis (CMA) of the hexagonal ring antenna is performed without the substrate or feed. This approach is widely used in CMA-based design because characteristic modes are intrinsic to the metallic geometry and unaffected by external excitation.. By removing the substrate in the first stage, the intrinsic resonant behavior of the conducting structure is revealed, providing a clear understanding of the supported modes. The hexagonal ring's dominant modes are located between 9.5 and 10 GHz. Modes 1 and 2 exhibit characteristic angles close to 180°, suggesting that they are strongly radiating. After the substrate is added, the effective dielectric constant reduces the resonant frequencies, bringing these modes closer to the intended operating band of 5.5 GHz.

By avoiding the blind optimization process that is usually necessary in traditional full-wave antenna design, this procedure guarantees that the feed can subsequently be positioned to effectively excite the dominant mode. Therefore, carrying out CMA without the substrate is a crucial first step to direct the design toward the intended operating frequency band.

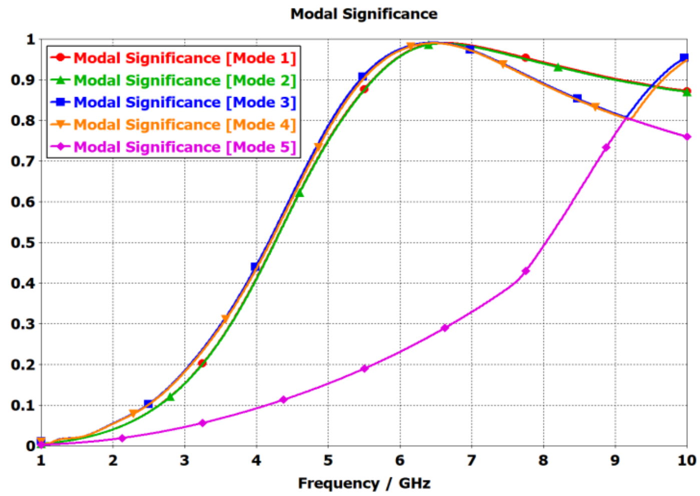

Figure 5. Calculated MS for proposed antenna structre including substrate

In comparison to the results obtained without the substrate, the Modal Significance (MS) of the suggested hexagonal ring antenna shifts significantly after the FR-4 substrate is added to the structure where it has been selected due it is availability and cost. as depicted in Figure 5. In order to resonate close to the target frequency band of 5.5 GHz, or 0.91, the dominant modes that previously appeared around 9.5–10 GHz are now pulled down. This frequency shift is explained by the substrate's effective dielectric constant, which reduces the supported modes' resonant frequency.

Two modes' strong radiation capability in the targeted band is confirmed by the MS plot, which shows values near unity around 5.5 GHz. These overlapping modes are advantageous for improving bandwidth and attaining impedance matching. Additionally, by directing the radiated energy and suppressing unwanted surface waves, the ground plane helps to stabilize the radiation performance.

When choosing the ideal feeding location for the suggested hexagonal ring antenna, the surface current distribution derived from CMA offers crucial guidance [31]. The current distribution explained in Figure 6 shows areas of maximum current density along the hexagonal ring's edges at the target resonant frequency of 5.5 GHz. These locations match strong modal excitation points, which are the best places for a feed to couple energy into the dominant mode.

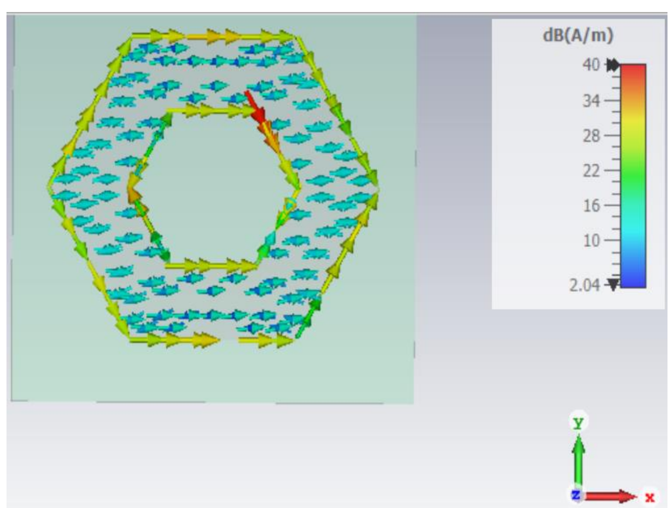

Figure 6. Calculated MS for proposed antenna structre including substrate

Figure 6 displays the suggested hexagonal ring antenna's surface current distribution at 5.5 GHz. Instead of being concentrated at a single location, the current is seen to be evenly distributed throughout the hexagonal ring's perimeter. This suggests that the dominant mode can be successfully excited at several points along the ring circumference.

The hexagonal ring antenna is completed by adding a feeding line and two slots after gaining understanding from the CMA results. As shown in Figure 7, the feeding line is used to supply energy to the structure, and the two slots etched next to it act as coupling elements to increase the resonant mode's excitation.

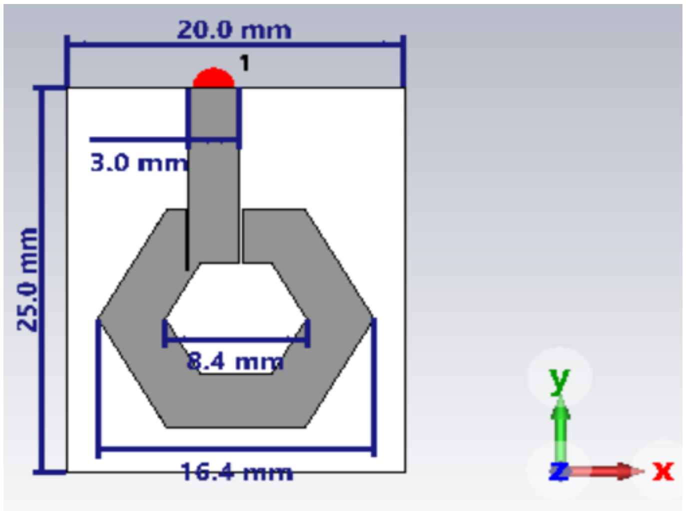

Figure 7. Proposed Antenna CST model

In order to ensure effective energy transfer from the feed into the ring structure, the slots are placed next to the feeding line, where the surface current distribution is comparatively strong. The antenna attains better impedance matching and stronger coupling at the target frequency of 5.5 GHz by carefully adjusting the slot width of 0.2 mm and placement.

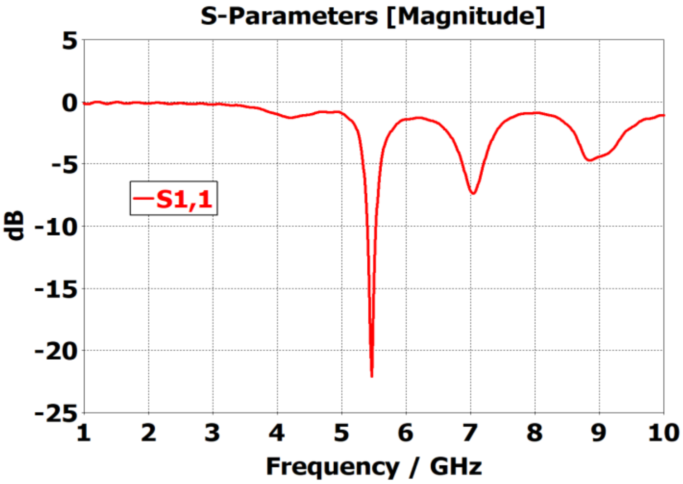

Figure 8. Calculated S11 for the proposed antenna

Figure 8 shows the simulated return loss of the suggested hexagonal ring antenna with two slots and a feeding line. The antenna achieves a minimum return loss of about –20 dB by precisely resonating at the design frequency of 5.5 GHz. This shows that the antenna and feeding structure have good impedance matching, which guarantees effective power transfer. Additionally, the simulated –10 dB bandwidth spans from 5.401 GHz to 5.527 GHz, resulting in a total bandwidth of roughly 126 MHz. This operational range confirms that the suggested antenna is appropriate for wireless communication applications since it completely covers the WLAN 5.5 GHz band.

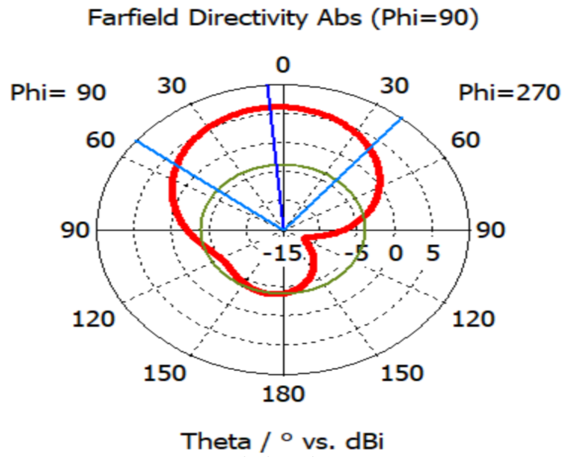

Figure 9. Determined farfield for the proposed antenna

Figure 9 shows the suggested hexagonal ring antenna's far-field radiation performance at 5.5 GHz. The antenna's main lobe magnitude of roughly 6.1 dBi confirms a moderate gain appropriate for WLAN applications. Stable directional radiation with little tilt is indicated by the main lobe's direction of 5°, which is extremely near broadside.

For practical wireless communication systems that need reliable connectivity over a wide angular range, the antenna's 3 dB angular beamwidth of 91.3° offers a comparatively large coverage area. The side lobe level (SLL), which is roughly –9.9 dB, shows good suppression of undesired radiation and less sidelobe interference.

Since the dominant mode found by CMA successfully couples into the far-field radiation pattern, the radiation characteristics are in good agreement with the modal analysis. The findings verify that the antenna radiates with adequate gain, wide coverage, and controlled sidelobes in addition to resonating effectively at 5.5 GHz. This demonstrates how well the slot-assisted feed structure and CMA-guided design work to create a well-matched and effective radiating antenna.

The suggested hexagonal ring microstrip antenna was created using conventional PCB manufacturing methods in order to verify the simulation results. According to the methodology, the design was implemented on a dielectric substrate, feeding line, and two slots. The manufactured antenna prototype's front view (radiating surface) and rear view (ground plane with slots) are photographed in Figure 10.

Figure 10. Fabricated proposed antenna

A Vector Network Analyzer (VNA) was used to experimentally characterize the antenna by measuring the reflection coefficient |S11|. The robustness of the design is confirmed in Figure 11 by the measured results, which closely match the simulated data and confirm a strong resonance at 5.5 GHz.

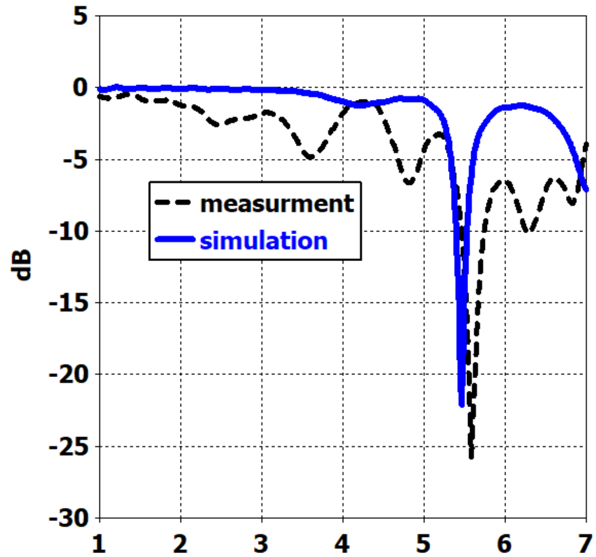

Figure 11. Measured and simulated return loss

The performance of the hexagonal ring microstrip antenna was compared with previously reported antennas in the 5 GHz WLAN band to demonstrate the efficacy of the suggested design. Key parameters such as operating frequency, bandwidth, peak gain, return loss, and design methodology are summarized in Table 1.

The findings unequivocally show that the suggested antenna achieves a return loss of –20 dB at 5.5 GHz, which is better than the majority of reported designs, which usually achieve between –10 dB and –15 dB. While keeping small dimensions, the 127 MHz (5.401–5.527 GHz) bandwidth is competitive with other designs. With a peak gain of 6.1 dBi and sidelobe suppression of roughly –10 dB, the radiation pattern is clearly defined and appropriate for WLAN applications. While the differences between the simulated result and the achieved measured return loss due to the fabrication process and connecters cable specifications. The suggested design was methodically developed using Characteristic Mode Analysis (CMA), overcoming the blind optimization process and offering deeper physical insight into the modal behavior of the antenna, whereas the majority of earlier works relied on iterative parametric optimization.

TABLE 1. COMPARISON OF THE SUGGESTED ANTENNA WITH PUBLISHED RELATED WORKS

Ref.	Operation Band (GHz)	Gain(dBi)	Design Approach
[32]	(5.58–5.83)	-	CMA
[33]	(3.4-3.6)	7	Optimization
[34]	(3.4-3.6)	1.2	Equivalent circuit
This work	(5.401- 5.527)	6.1	CMA

Table 1 compares the proposed hexagonal ring antenna with three representative works. The proposed antenna operates in the 5.401–5.527 GHz band with a peak gain of 6.1 dBi and was developed using a CMA-guided design process. Compared to [32], which uses CMA but reports a slightly different center band (5.58–5.83 GHz), our design achieves a comparable gain in the targeted 5.5 GHz WLAN band. Reference [33] demonstrates high gain (7 dBi) through optimization at 3.4–3.6 GHz, while [34] uses an equivalent-circuit approach and shows lower gain at the same band; these entries show a variety of design methodologies and performance trade-offs. The primary advantage of the present work is the combination of competitive gain and controlled matching in the WLAN band using a physics-driven (CMA) design flow, avoiding blind optimization.

V. CONCLUSIONS

In this work, a hexagonal ring microstrip antenna operating at 5.5 GHz has been designed, analyzed, and validated using the Characteristic Mode Analysis (CMA) approach. The CMA provided significant physical insight into the dominant modes and their behavior by eliminating the need for blind parametric optimization. By carefully assessing the modal significance and characteristic angle, this methodology made it possible to identify suitable resonant modes and optimal feeding locations. The antenna structure was then completed with the addition of a microstrip feed line with two slots, which enhanced bandwidth performance and produced strong impedance matching. The simulated results show a resonant band between 5.401 and 5.527 GHz with a reflection coefficient of less than –20 dB at the center frequency of 5.5 GHz. Radiation analysis reveals a broadside main lobe with a 3 dB beamwidth of 91°, a peak gain of 6.1 dBi, and sidelobe levels suppressed to –9.9 dB.

The simulations were validated by testing a manufactured prototype, which showed good agreement in radiation patterns and impedance bandwidth. Variations in material properties and fabrication tolerances were blamed for small disparities. The suggested antenna benefits from a methodical CMA-driven design approach while achieving competitive gain, adequate bandwidth, and stable matching when compared to previously published designs. This physics-based method validates the hexagonal ring design's appropriateness for WLAN/Wi-Fi applications in the 5.5 GHz band and offers a solid framework for antenna development.

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