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Radiation Performance Comparison and Analysis of Ku-band Microstrip Antennas with Diamond, Octagonal, and Circular Array Configurations

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ABSTRACT: Phased array antennas are essential in modern communication systems, particularly within the Ku-band, which is widely used for satellite communications and radar applications due to its high data rate capabilities. This paper explores the radiation characteristics of Ku-band microstrip antennas arranged in diamond, octagonal, and circular arrays, focusing on uniform excitation to ensure consistency across evaluations. Using CST Microwave Studio 2024 for simulations, the study found that the rectangular array provides the highest gain and narrowest beamwidth, making it suitable for applications where directional accuracy is critical. However, this configuration also resulted in higher sidelobe levels, which can be problematic in environments where minimal interference is required. The diamond array, while exhibiting lower gain, achieved superior sidelobe suppression, making it ideal for scenarios where reducing interference is prioritized over maximizing directivity. The octagonal and circular arrays provided balanced performance across all metrics, offering versatile options for various operational needs. These results provide valuable guidance for optimizing phased array designs to meet specific requirements in Ku-band applications.

KEYWORDS: Phased array; microstrip antenna; Ku-band; array configuration

1. Introduction

Phased array antennas have become integral components in modern communication systems due to their ability to electronically steer beams, offering improved performance and flexibility over traditional antenna designs. These advantages make phased array antennas particularly suitable for applications in the Ku-band, which is widely used for satellite communications, radar, and other high-frequency applications [1–3].

The Ku-band, ranging from 12 to 18 GHz, is favored for its ability to provide high data rates and for its relative immunity to atmospheric attenuation compared to higher frequency bands [4]. However, designing efficient and compact antennas for this band remains challenging, particularly when optimizing for parameters such as gain, sidelobe level (SLL), and half-power beamwidth (HPBW) [5–7]. One approach to addressing these challenges is through the use of different array geometries, which can significantly influence antenna radiation characteristics [8].

Recent research has focused extensively on improving the radiation performance of phased array antennas, particularly by increasing gain and suppressing SLL. Techniques such as array thinning, where certain elements are strategically turned off, have been explored to reduce SLL without significantly compromising the overall gain of the array [9, 10]. Moreover, implementing nonuniform excitation methods, in which elements are fed with varying amplitudes and phases, has effectively suppressed sidelobes while enhancing the directivity of the main lobe [11]. Advanced algorithms, such as genetic algorithms and particle swarm optimization, have also been applied to optimize element placement and excitation distribution, resulting in arrays with both high gain and low SLL [12, 13]. Additionally, materials science has contributed to new substrates that enhance antenna performance by reducing losses and improving impedance matching. The integration of metamaterials, which can manipulate electromagnetic waves in unconventional ways, has also been explored to improve gain and sidelobe suppression in phased array antennas [14, 15].

Furthermore, novel array geometries have been proposed to improve radiation characteristics. For example, hexagonal array configurations have been investigated for their ability to provide more uniform radiation patterns and reduce sidelobe levels compared to traditional rectangular arrays while maintaining a compact form factor [16]. These nontraditional array shapes offer unique advantages in terms of sidelobe reduction and improved beam-steering capabilities, which are critical for high-precision applications in the Ku-band [17].

This study aims to analyze and compare the radiation performance of Ku-band microstrip antennas with diamond, octagonal, and circular array configurations, using a rectangular array as a reference. The primary focus will be on evaluating key performance metrics such as gain, SLL, and HPBW. By systematically comparing these configurations, this research seeks to identify the optimal array geometry to maximize performance in Ku-band applications.

2. Research Methodology

The section outlines the design, simulation setup, and analysis approach used to evaluate the radiation performance of Ku-band microstrip antennas with various array configurations—specifically, diamond, octagonal, and circular arrays. Each configuration uses uniform excitation to ensure consistency in analyzing radiation characteristics.

2.1. Antenna design and array configurations.

The microstrip antennas in this study were designed to operate at a central frequency of 14 GHz within the Ku-band. The array configurations analyzed included diamond, octagonal, and circular, with a rectangular array serving as a reference. These configurations are illustrated in Figure 1. Each array was selected to assess its impact on key performance metrics such as gain, sidelobe level (SLL), and half-power beamwidth (HPBW).

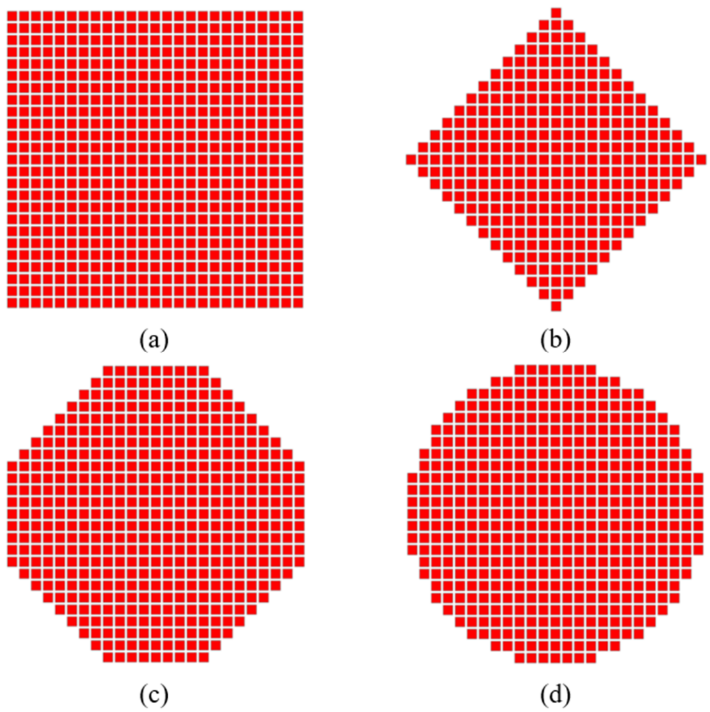

Figure 1. Illustration of the antenna array configurations: (a) Rectangular, (b) Diamond, (c) Octagon, (d) Circular.

The reference configuration comprises 625 elements, while the analyzed configurations contain slightly fewer elements due to geometric constraints. Element spacing is fixed at 0.5λ to ensure compactness and prevent grating lobes and mutual coupling effects. Each antenna element is a coaxial probe-fed microstrip patch, designed on a Rogers RT5880 substrate with a dielectric constant (ϵ_r) of 2.2. The patch dimensions are 6.82 mm × 5.98 mm, optimized to resonate at 14 GHz. The maximum gain for a single element is approximately 7.13 dBi, with an HPBW of 82.3° in the φ = 0° plane.

2.2. Array factor calculation.

All arrays in this study use uniform excitation, which means that each antenna element is fed with the same amplitude and phase. This uniformity ensures that the observed differences in performance are attributed solely to the array's geometry. The Array Factor (AF), which governs the radiation pattern of an antenna array, can be defined as Equation 1.

$$AF(\theta,\phi) = \sum_{m=1}^{M}\sum_{n=1}^{N} I_{mn} e^{j\vec{k}\cdot\vec{r_{mn}}} \tag{1}$$

Here, θ and ϕ are the elevation and azimuth angles, respectively, I_{mn} is the excitation current of the *mn*-th element, $\vec{k}$ is the wave vector, and $\overrightarrow{r_{mn}}$ is the position vector of the mn-th element [18]. For uniformly excited arrays, I_{mn} remains constant, making the AF primarily dependent only on the geometry of the array and the position of the elements [19].

Although the AF is crucial in determining the overall radiation pattern, the Element Factor (EF) also plays a significant role, especially when the antenna elements are not isotropic radiators. The total radiation pattern F(θ, ϕ) of an array is the product of AF and EF, as described in Equation 2 where EF(θ, ϕ) represents the radiation pattern of a single element in the matrix and AF(θ, ϕ) accounts for the geometric configuration of the matrix and the positions of the elements [20].

$$F(\theta, \phi) = EF(\theta, \phi) \times AF(\theta, \phi) \tag{2}$$

2.3. Simulation setup.

The simulations were conducted using CST Microwave Studio 2024, focusing on evaluating the arrays' radiation performance at a central frequency of 14 GHz within the Ku-band. Open boundary conditions were used to replicate free-space conditions, and a fine mesh was used to ensure high precision in the results. The primary metrics analyzed included gain, SLL, and HPBW, with data extracted from 1D and 2D radiation patterns for a complete comparison.

2.4. Performance metrics analysis.

The simulation data were analyzed to compare the radiation performance of the four array configurations. The rectangular array served as the reference, and the diamond, octagonal, and circular arrays were evaluated on the basis of their ability to achieve high gain, reduced sidelobe levels, and narrow beam widths. The goal was to identify the optimal array configuration for Ku-band applications, focusing on balanced performance across all key metrics.

3. Results and Discussion

The radiation performance of Ku-band microstrip antennas was evaluated for all array configurations illustrated in Figure 1. The results are presented in a comparative framework to highlight the strengths and weaknesses of each configuration of the array, as seen in Table 1.

Table 1. Simulated results of array radiation patterns.

Configuration	Number of Elements	Simulated Results		
		Gain	SLL	HPBW
Rectangular	625	33.1 dBi	-13.3 dB	4°
Diamond	313	30.0 dBi	-26.7 dB	5.8°
Octagon	481	31.9 dBi	-20.3 dB	4.8°
Circular	489	32.0 dBi	-18.2 dB	4.7°

3.1. Gain analysis.

The Gain of each array configuration was assessed to determine the directivity and efficiency. The rectangular array, with the highest number of elements, achieved a maximum gain of 33.1

dBi. The circular array followed closely with 32 dBi, while the octagonal array had 31.9 dBi. The diamond array, with the fewest elements, recorded the lowest gain at 30 dBi. The reduced gain in the diamond and octagonal arrays is largely due to their fewer elements, which limits their ability to concentrate power, resulting in lower directivity compared to the rectangular and circular arrays.

3.2. Sidelobe level analysis.

SLL is a critical parameter for phased array antennas, especially in high-precision applications where minimizing interference from undesired directions is paramount. The radiation patterns shown in Figure 2, Figure 3, and Figure 4 reveal notable differences in SLL in the various array configurations, significantly impacting overall antenna performance. The rectangular array, which serves as a reference, exhibits relatively higher sidelobe levels, particularly in directions perpendicular to the main lobe. Although this configuration effectively focuses energy in the desired direction, it also radiates a considerable amount of energy in unintended directions, leading to increased interference and reduced efficiency in scenarios requiring low interference. The SLL of the rectangular array stands at -13.3 dB, indicating less effective sidelobe suppression compared to the other configurations.

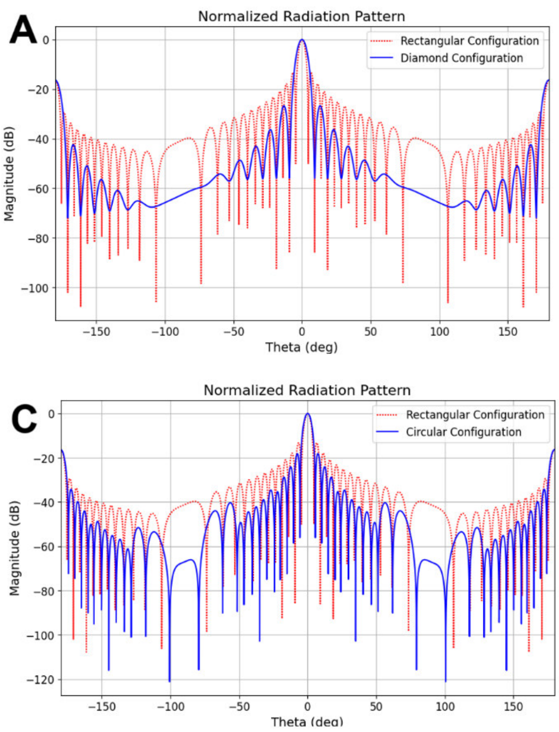

Figure 2. Comparison of normalized 1D radiation pattern results of various array. configurations at ϕ = 0◦ to the reference array for (a) Diamond configuration, (b) Octagon configuration, and (c) Circular configuration.

In contrast, the diamond array excels in sidelobe suppression, achieving a significant reduction with an SLL of -26.7 dB in directions perpendicular to the main lobe. This improvement can be attributed to the diamond shape's ability to disrupt the coherence of sidelobes, making it highly suitable for applications where minimizing interference is crucial.

The octagonal and circular arrays also show improved sidelobe performance compared to the rectangular array. The octagonal array, with an SLL of -20.3 dB, strikes a balance between gain and sidelobe suppression, offering a versatile solution that reduces interference while maintaining adequate directivity. The circular array, although less effective in sidelobe reduction with an SLL of -18.2 dB, provides a uniform and symmetric sidelobe distribution, advantageous for applications requiring consistent radiation patterns in multiple directions. These findings underscore the importance of the geometry of the array in determining the effectiveness of phased array antennas in various applications.

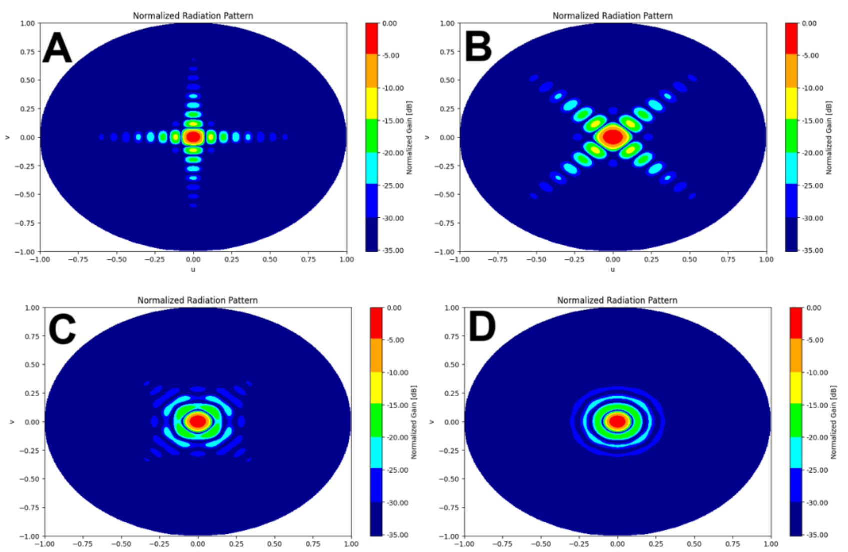

Figure 3. Comparison of normalized 2D radiation pattern results of various array configurations of (a) Rectangular configuration, (b) Diamond configuration, (c) Octagon configuration, and (d) circular configuration.

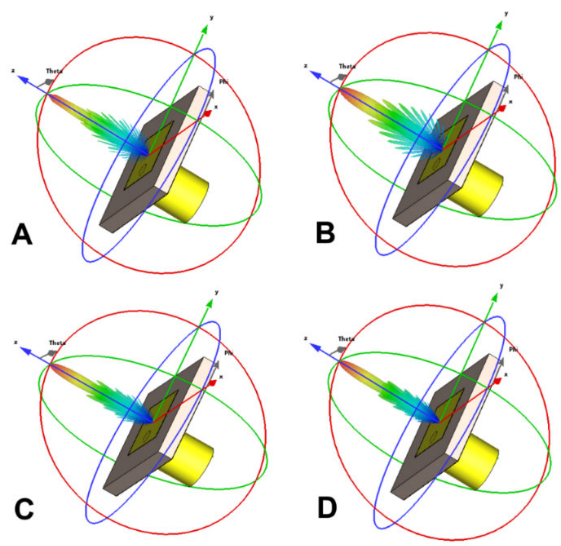

Figure 4. Comparison of 3D radiation pattern results of various array configurations of (a) Rectangular configuration, (b) Diamond configuration, (c) Octagon configuration, and (d) Circular configuration.

3.3. Half-power beamwidth analysis.

HPBW is a measure of the beamwidth of the antenna's main lobe, and a narrower beamwidth is generally desirable for applications requiring focused directional beams. The rectangular array, as expected, exhibited the narrowest HPBW at 4^{o}, due to its linear and symmetric structure. The circular array was followed by an HPBW of 4.7^{o} , which is slightly wider but still within an acceptable range for high-precision applications. The octagonal array had a marginally wider HPBW of 4.8^{o}, while the diamond array showed the widest beamwidth of 5.8^{o}. The broader beamwidth in the diamond array can be attributed to its nonlinear edges, which likely caused the main lobe to spread more, reducing its focus.

3.4. Comparative performance.

The comparative analysis reveals that each array configuration offers distinct trade-offs. The rectangular array, while providing the highest gain and narrowest beamwidth, exhibits higher sidelobe levels. Although the diamond array has the lowest gain and widest beamwidth, it excels in sidelobe suppression, making it ideal for applications where minimizing interference is crucial. The octagonal and circular arrays offer a balance between these extremes, with the circular array showing more uniform performance across all metrics, and the octagonal array providing a compromise between gain and sidelobe suppression. In practical applications, the choice of array configuration will depend on the system's specific requirements. For instance, in satellite communications where gain and focused beams are essential, the rectangular array may be preferred. However, in radar systems where sidelobe suppression is critical, diamond, octagonal, or circular arrays might be more suitable.

3.5. Limitations and future work.

This study utilized uniform excitation across the three arrays to enable a controlled comparison, though it did not explore the potential benefits of nonuniform excitation techniques. Future research could investigate advanced optimization methods, such as genetic algorithms, particle swarm optimization, or machine learning-based approaches, to identify optimal array configurations for enhanced performance. These methods could dynamically optimize gain and sidelobe suppression while potentially improving design efficiency. Such investigations could significantly advance the field, leading to more efficient and adaptable phased array antenna designs suitable for diverse applications.

4. Conclusions

This study systematically analyzed the radiation performance of Ku-band microstrip antennas with rectangular, diamond, octagonal, and circular array configurations. The rectangular array demonstrated the highest gain and narrowest beamwidth, though at the cost of higher sidelobe levels, making it suitable for applications requiring focused directional beams but less ideal for environments where minimizing interference is crucial. The diamond array, despite its lower gain, excelled in sidelobe suppression, making it particularly suitable for high-precision applications where interference reduction is paramount. The octagonal and circular arrays offered balanced performance, with the circular array producing uniform radiation patterns, advantageous in applications requiring consistent coverage. These findings provide valuable insights for optimizing array design based on specific application requirements, emphasizing the importance of selecting the appropriate array geometry to meet the unique demands of various communication systems.

Author Contribution

Conceptualization: Catur Apriono; Methodology: Muhammad Athallah Adriansyah, Aditya Inzani Wahdiyat; Data Collection: Muhammad Athallah Adriansyah; Data Analysis: Muhammad Athallah Adriansyah, Aditya Inzani Wahdiyat, Catur Apriono; Writing: Muhammad Athallah Adriansyah, Catur Apriono; Supervision: Catur Apriono; Funding: Catur Apriono

Competing Interest

The authors declare that there are no conflicts of interest in this research.

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