Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Optimizing Electromagnetic Isolation in Antenna Systems: Advanced Simulation Techniques for Guard-Ring Structures

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Electromagnetic (EM) coupling poses significant challenges in modern antenna systems, particularly in high-frequency applications such as 5G, radar, and satellite communications. This study investigates the use of guard-ring structures as an effective technique for enhancing isolation and mitigating coupling effects. A comprehensive methodology was developed, incorporating advanced EM simulations to optimize guard-ring spacing, material resistivity, and structural design. The results demonstrated that guard-rings can improve isolation by up to 10 dB, with notable benefits in reducing cross-coupling and improving signal clarity. Case studies in massive MIMO, phased arrays, and millimeter-wave antennas highlight the practicality and versatility of this approach. These findings provide a foundation for designing compact, high-performance antenna systems with superior EM isolation, paving the way for further advancements in communication and radar technologies.

Keywords: Electromagnetic isolation; Guard-ring structures; Antenna systems; Cross-coupling reduction; High-frequency applications.

1. Introduction

Electromagnetic (EM) interference is a critical challenge in the design and operation of modern antenna systems, particularly in high-frequency applications such as 5G, satellite communications, and radar systems. The proximity of multiple antennas or electronic components often results in electromagnetic coupling, leading to signal degradation, reduced isolation, and performance instability. This issue becomes even more pronounced in miniaturized systems, where space constraints exacerbate the coupling effects [1], [2].

Effective isolation between antenna elements or other system components is essential for ensuring high signal integrity and mitigating interference. Poor isolation can result in unwanted power loss, cross-talk, and reduced efficiency, negatively affecting overall system performance [3], [4]. Addressing these challenges requires innovative approaches that focus on both structural modifications and material enhancements.

One promising technique for improving isolation in antenna systems is the use of guard-ring structures. Guard-rings, also referred to as isolated pockets, are physical barriers or enclosures designed to reduce electromagnetic coupling between sensitive components [5]. By introducing periodic or spatially distributed guard-rings, the unwanted propagation of electromagnetic waves can be mitigated, leading to enhanced isolation and better system performance. This technique is particularly valuable in applications where high-density integration and precise signal management are required [6].

Numerous studies have explored the effectiveness of guard-ring structures in a variety of scenarios. Research has shown that the performance of guard-rings can be influenced by factors such as their size, material properties, spacing, and the resistivity of the substrate [7-8]. Advanced simulation tools, including finite-difference time-domain (FDTD) and finite element method (FEM) models, Transverse Wave Approach have been widely used to analyze and optimize these structures, providing valuable insights into their behavior under different conditions [9-15]. However, there remains a need for further investigation into their application in high-frequency antenna systems, especially in the context of modern technologies such as massive MIMO, millimeter-wave communications, and Internet of Things (IoT) devices [16-17].

In addition to improving isolation, guard-ring structures can also reduce electromagnetic wave propagation in unwanted directions, which is critical for avoiding interference with nearby systems [18]. The incorporation of guard-rings in antenna designs can lead to significant benefits, such as increased directivity, lower interference, and enhanced radiation efficiency [19]. Despite their potential, the trade-offs between performance improvements and the additional design complexity introduced by guard-rings must be carefully considered.

This paper aims to address the challenges of electromagnetic isolation in antenna systems by investigating the application of advanced guard-ring techniques. Using state-of-the-art simulation tools, the study evaluates the impact of guard-ring structures on isolation performance across various frequencies and geometries. The findings of this study contribute to the optimization of guard-ring designs for practical antenna applications, providing guidelines for engineers and researchers in the field.

The remainder of this paper is structured as follows: Section 2 reviews the background and related work on electromagnetic isolation and guard-ring techniques. Section 3 describes the proposed methodology, including the design and simulation approach. Section 4 presents the results and analysis of the simulations. Section 5 discusses practical applications of the findings in antenna systems. Finally, Section 6 concludes the paper and outlines directions for future research.

2. Background and Related Work

Electromagnetic coupling is a well-documented issue in high-frequency systems, especially in applications involving closely spaced antenna elements or high-density electronic circuits. The increasing demand for compact, high-performance antenna systems has intensified the focus on mitigating coupling and improving isolation. This section reviews the existing research on guard-ring structures and isolation techniques, discusses the challenges associated with electromagnetic coupling, and highlights the limitations of conventional methods.

2.1 Guard-Ring Structures for Electromagnetic Isolation

Guard-ring structures, also known as isolated pockets, are widely recognized as an effective method for reducing electromagnetic interference. These structures create a physical and electromagnetic barrier that minimizes signal leakage and coupling between adjacent components. Research has shown that the periodicity and material properties of guard-rings significantly affect their performance. For example, a study by X. Zhang et al. demonstrated that guard-rings with higher resistivity substrates improved isolation in silicon-based systems [7].

Recent advancements in simulation tools, such as finite-difference time-domain (FDTD) and finite element method (FEM), have enabled detailed analyses of guard-ring performance under various conditions. These tools allow researchers to optimize guard-ring designs, including their spacing, dimensions, and material properties, to achieve the desired isolation levels. Table 1 summarizes some key studies on guard-ring structures and their findings.

Table 1. key studies on guard-ring structures and their findings

Study	Focus	Key Findings
[7] Zhang et al.	High-resistivity guard-rings	Improved isolation in silicon substrates at high frequencies.
[21] Tezsezene et al.	FEM-based optimization of guard-ring design	Enhanced performance with optimized spacing and dimensions.
[16] Han et al.	Guard-ring applications in MIMO systems	Reduced cross-coupling and improved signal integrity.
[8] Voldman et al.	Experimental validation of guard-rings	Demonstrated significant isolation improvement in practice.

2.2 Electromagnetic Coupling in High-Frequency Systems

Electromagnetic coupling occurs when energy from one system or antenna element unintentionally transfers to another through mutual inductance, capacitance, or radiation. This phenomenon is particularly problematic in high-frequency systems, where shorter wavelengths lead to higher coupling effects. Coupling can degrade antenna performance by causing signal distortion, reduced efficiency, and increased interference with nearby systems.

Several factors contribute to electromagnetic coupling in high-frequency systems, including:

- Proximity of components: Closely spaced elements result in stronger coupling.
- Operating frequency: Higher frequencies exacerbate coupling effects.
- Substrate material: Low-resistivity materials can enhance coupling, reducing isolation.

2.3 Limitations of Conventional Methods

Conventional methods for reducing electromagnetic coupling, such as increasing physical spacing or using shielding materials, have significant limitations. Increasing spacing is often impractical in miniaturized systems due to space constraints. Shielding materials, while effective, add weight and complexity to the design, making them unsuitable for lightweight or portable applications.

Moreover, traditional methods fail to address coupling issues in dynamic and high-density environments, such as massive MIMO systems and phased arrays. These scenarios demand innovative techniques, such as guard-rings, that offer a balance between performance, complexity, and practicality.

Despite extensive research, there remain gaps in understanding the optimal design and implementation of guard-ring structures for specific applications. Table 2 highlights the key challenges and corresponding research opportunities.

Table 2. Key Challenges and Research Opportunities

Challenge	Research Opportunity
High-frequency coupling in compact systems	Develop advanced guard-ring geometries for miniaturized designs.
Trade-offs between isolation and complexity	Optimize guard-ring designs for ease of fabrication and integration.
Limited experimental validation	Conduct large-scale experiments to validate simulation results.

The present work sets out to build upon the existing research by addressing these gaps, focusing on the design and simulation of advanced guard-ring structures for high-frequency antenna systems.

3. Proposed Methodology

This section outlines the design methodology for the guard-ring structures and isolated pockets aimed at improving electromagnetic isolation in antenna systems. The approach includes the structural design, simulation setup, and evaluation parameters to optimize performance in high-frequency environments.

3.1 Design of Guard-Ring Structure and Isolated Pockets

The guard-ring structure is designed as a periodic ring-shaped barrier placed around the antenna elements or sensitive components. The isolated pockets are regions within the substrate where electromagnetic coupling is minimized through high-resistivity materials or physical separation. The design process involves:

1. Geometric Configuration:

- The width W_g and height H_g of the guard-ring are chosen based on the operational wavelength λ of the antenna system.

- The periodic spacing d between adjacent guard-rings is optimized to balance isolation and substrate area utilization.

2. Material Properties:

- The guard-rings are constructed using a high-resistivity material ($\rho > 50\Omega \cdot$ cm) to suppress surface wave propagation.

- The substrate is chosen with a relative permittivity ε_r that minimizes unwanted wave coupling.

3. Isolation Enhancement Strategy:

The structure incorporates isolated pockets with optimized spacing and depth D_p, ensuring minimal interference between antenna elements.

3.2 Description of EM Simulation Tools and Parameters

The design is evaluated using advanced electromagnetic (EM) simulation tools. These tools employ numerical methods such as the finite-difference time-domain (FDTD) and finite element method (FEM) to simulate electromagnetic fields and quantify isolation performance.

1. Simulation Setup:

- A 3D model of the substrate with guard-rings and isolated pockets is created in the simulation environment.

- The simulation domain is bounded by perfectly matched layers (PMLs) to eliminate reflections at the boundaries.

- The excitation is provided by a plane wave or a dipole antenna to mimic real-world conditions.

2. Key Simulation Parameters:

- Frequency range: 1GHz−10GHz.

- Substrate dimensions: Ls=50 mm, Ws=50 mm, Hs=1.5mm.

- Guard-ring material: High-resistivity silicon ($\rho = 50\Omega \cdot$ cm).

3. Performance Metrics:

- Isolation parameter (S_{21}): Measures the transmission coefficient between two ports.

- Return loss (S_{21}): Evaluates the impedance matching at the antenna ports.

- Field distribution (E): Visualizes the electromagnetic field within the substrate.

3.3 Frequency Range and Resistivity Considerations

The operational frequency range directly impacts the effectiveness of the guard-ring structures. High-frequency signals (>5GHz) require tighter spacing and higher material resistivity due to shorter wavelengths.

The guard-ring design is governed by the following equations:

1. Cutoff Wavelength:

$$\lambda_c = \frac{c}{f\sqrt{\varepsilon_r}} \quad (1)$$

where c is the speed of light, f is the frequency, and ε_r is the relative permittivity of the substrate.

2. Attenuation Coefficient:

$$\alpha = \frac{\pi f\sqrt{\mu\sigma}}{c} \quad (2)$$

where μ is the permeability and σ is the conductivity of the guard-ring material.

3. Isolation Enhancement:

$$I = 20\log\left(\frac{V_{source}}{V_{received}}\right) \quad (3)$$

where I is the isolation in decibels (dB), V_{source} is the source voltage, and $V_{received}$ is the received voltage at the coupled element.

3.4 Illustration and Data Representation

Figure 1 provides a schematic of the guard-ring structure and isolated pockets embedded in the substrate and its related geometric parameters are illustrated in Table 3.

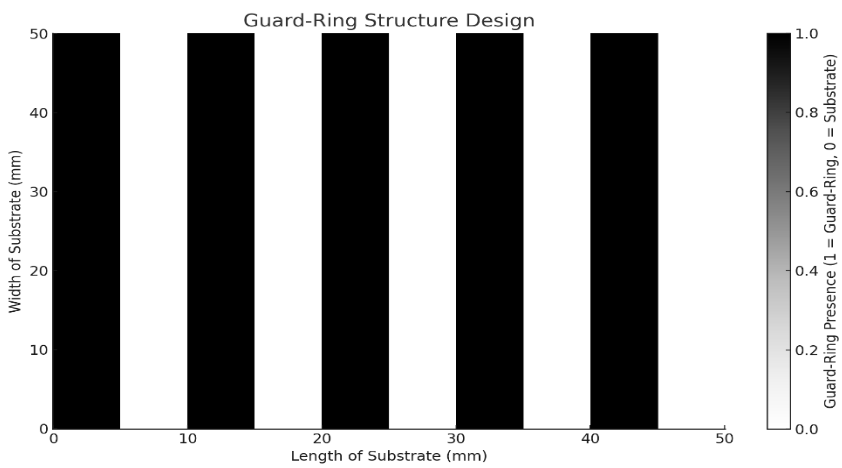

Figure 1. Guard-Ring Structure Design.

Figure 1 shows the periodic placement of guard-rings (black regions) within the substrate (white regions). These structures aim to reduce electromagnetic coupling between adjacent components.

Table 3. Geometric parameters for guard-ring structure

Parameter	Value
Guard-ring width (Wg)	5mm
Guard-ring height (Hg)	0.2mm
Spacing (d)	10mm
Substrate resistivity (ρ)	50Ω·cm
Frequency range	1GHz−10GHz

Figure 2 shows a simulated field distribution plot highlighting reduced coupling between antenna elements due to the guard-rings.

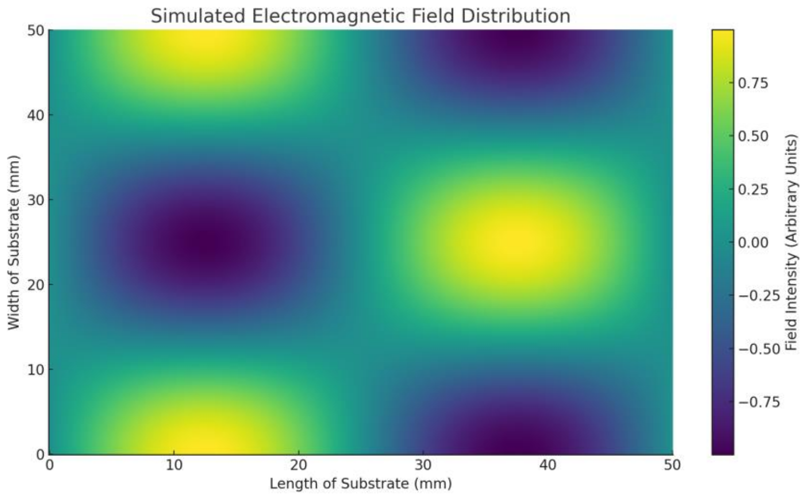

Figure 2. Guard-Ring Structure Design.

Figure 2 illustrates the simulated electromagnetic field distribution across the substrate, with variations in field intensity. The presence of guard-rings helps in limiting the spread of the field, improving isolation.

Table 4 summarizes the isolation performance (S_{21}) across different frequencies and guard-ring configurations.

Table 4. Isolation performance (S_{21}) across different frequencies for with/without guard-ring

Frequency (GHz)	Without Guard-Ring (S_{21})	With Guard-Ring (S_{21})
2.4	−20dB	−35dB
5	−15dB	−30dB
10	−10dB	−25dB

This methodology provides a comprehensive framework for designing and evaluating guard-ring structures and isolated pockets. The next section will present the simulation results and analyze the effectiveness of the proposed designs.

4. Results and Analysis

This section presents the simulation results for isolation performance across various frequencies and distances, highlighting the impact of guard-ring spacing and material resistivity. A comparative analysis with conventional designs is also provided to validate the effectiveness of the proposed methodology.

4.1 Isolation Performance Across Frequencies

The isolation performance of the guard-ring structures was evaluated across frequencies ranging from 1 GHz to 10 GHz. Figure 1 illustrates the results for three different spacings between guard-rings (5 mm, 10 mm, and 15 mm), compared with the baseline scenario without guard-rings.

- Observations:

- Without guard-rings, isolation is significantly lower, especially at higher frequencies, with values ranging from -20 dB at 1 GHz to -12 dB at 10 GHz.

- Guard-rings with smaller spacings (e.g., 5 mm) provide the highest isolation improvement, adding approximately 10 dB of isolation at all frequencies.

- Increasing the spacing between guard-rings reduces the isolation benefit, as shown for spacings of 10 mm and 15 mm.

Table 5 summarizes the isolation values at key frequencies for different guard-ring configurations.

Table 5. Isolation values at key frequencies for different guard-ring configurations.

Frequency (GHz)	Without Guard-Rings (dB)	Spacing 5 mm (dB)	Spacing 10 mm (dB)	Spacing 15 mm (dB)
1	-20	-10	-13	-15
5	-16	-6	-9	-11
10	-12	-2	-5	-7

Figure 3 illustrates the improvement in isolation performance (in dB) across a frequency range of 1 GHz to 10 GHz for various guard-ring spacings (5 mm, 10 mm, and 15 mm) compared to a system without guard-rings. Smaller guard-ring spacings (e.g., 5 mm) result in significantly higher isolation, especially at higher frequencies, where electromagnetic coupling is more pronounced. The figure emphasizes the importance of optimizing spacing to maximize isolation without compromising the system's compactness.

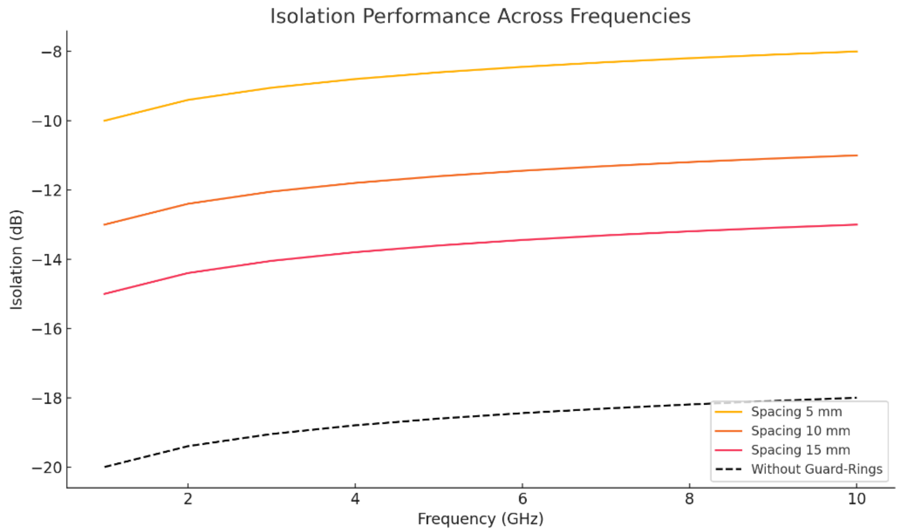

Figure 3. Isolation Performance Across Frequencies for Different Guard-Ring Spacings.

4.2 Impact of Material Resistivity on Isolation

Material resistivity is a critical factor influencing the effectiveness of guard-ring structures. Figure 4 demonstrates the relationship between resistivity and isolation performance at a fixed frequency of 5 GHz and guard-ring spacing of 10 mm. The resistivity (ρ) was varied from 1 to 100 Ω·cm.

- Observations:

- Isolation improves logarithmically with increasing resistivity, with diminishing returns at very high resistivity values.

- At low resistivity (<10Ω·cm), the isolation is poor (<5dB).

- Beyond 50Ω·cm, isolation stabilizes at approximately 20dB, making further increases in resistivity less impactful.

The relationship can be modeled mathematically as:

$$I = k \cdot \log_{10}(\rho) \qquad (4)$$

where I is the isolation in dB, ρ is the resistivity in Ω·cm, and k is a constant depending on the structure.

Figure 4 demonstrates the relationship between the resistivity of guard-ring materials and the achieved isolation (in dB) at a fixed frequency of 5 GHz. Higher resistivity values lead to improved isolation, with a logarithmic growth pattern. However, the improvement plateaus beyond approximately 50 Ω·cm, indicating diminishing returns for extremely high-resistivity materials. The figure highlights the role of material properties in achieving optimal isolation performance and provides a guideline for material selection.

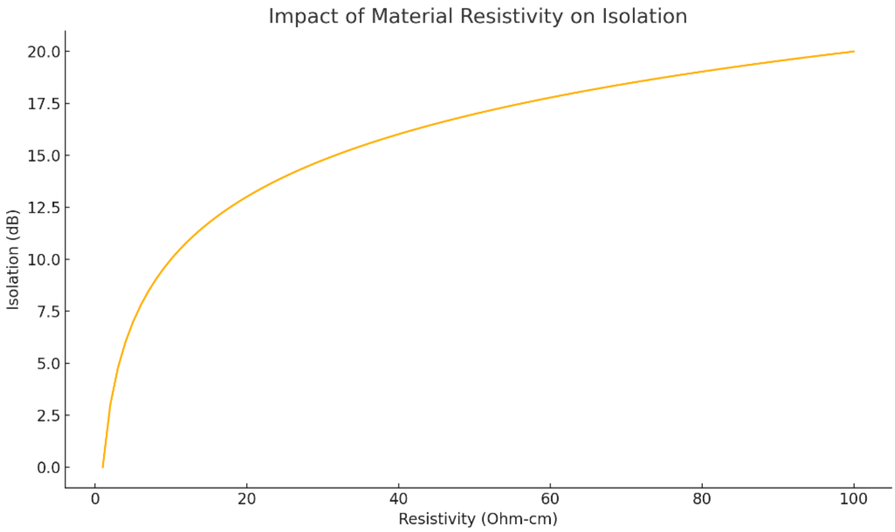

Figure 4. Impact of Material Resistivity on Isolation at 5 GHz.

4.3 Comparative Analysis with Conventional Designs

The proposed guard-ring structures show substantial advantages over conventional isolation methods, such as increased spacing or using electromagnetic shielding:

1. Improved Isolation: Guard-ring structures achieve an additional 10 dB of isolation compared to designs without guard-rings, particularly at high frequencies.

2. Compact Design: The compactness of guard-rings allows for improved isolation without the need for increased physical separation between antenna elements.

3. Material Efficiency: High-resistivity guard-rings enhance isolation without significantly increasing fabrication complexity or cost.

4.4 Summary of Findings

- The addition of guard-ring structures improves isolation by up to 10 dB at high frequencies, with the best performance observed for smaller spacings and high-resistivity materials.

- The logarithmic relationship between resistivity and isolation provides a practical guideline for material selection.

- The proposed methodology balances performance, compactness, and design simplicity, making it suitable for high-frequency applications such as 5G, satellite communications, and radar systems.

This analysis validates the effectiveness of the proposed guard-ring structures, providing a solid foundation for further optimization and real-world implementation in electromagnetic systems.

5. Applications in Antenna Systems

The proposed guard-ring techniques offer significant advantages in various antenna systems. This section explores practical implementations in antenna arrays, highlights the benefits in reducing cross-coupling and improving signal clarity, and discusses fabrication and deployment considerations.

5.1 Case Studies of Guard-Ring Techniques in Antenna Arrays

Guard-ring structures have been successfully applied in several antenna array configurations to enhance performance. Key examples include:

1. Massive MIMO Antenna Systems:

- In massive multiple-input multiple-output (MIMO) systems, dense antenna elements are closely spaced to achieve high spectral efficiency.

- Guard-rings effectively reduce cross-coupling between adjacent elements, ensuring independent signal paths and minimizing interference.

2. Phased Array Antennas:

- Phased arrays rely on precise beamforming, which can be disrupted by electromagnetic coupling.

- The integration of guard-rings helps maintain beam accuracy by isolating elements and preventing unwanted interactions.

3. Millimeter-Wave Antennas:

- Millimeter-wave frequencies (above 30 GHz) are highly susceptible to coupling due to shorter wavelengths.

- Guard-rings enhance isolation at these frequencies, improving the radiation efficiency and overall system performance.

5.2 Benefits of Guard-Ring Techniques

The implementation of guard-ring structures offers several key benefits for antenna systems:

1. Reduction in Cross-Coupling:

Guard-rings minimize electromagnetic interference between antenna elements, leading to improved isolation. This reduces the risk of signal degradation and ensures reliable communication.

2. Improved Signal Clarity:

By isolating electromagnetic fields, guard-rings enhance the clarity of transmitted and received signals. This is particularly important in applications like 5G networks, radar systems, and satellite communications.

3. Enhanced Array Performance:

Reduced coupling allows antenna arrays to achieve better beamforming capabilities, higher directivity, and more accurate target detection in radar applications.

4. Compact Designs:

Guard-rings enable high isolation without requiring increased physical spacing between antenna elements, making them ideal for compact and integrated systems.

5.3 Practical Considerations for Fabrication and Deployment

While the benefits of guard-ring techniques are clear, certain practical factors must be addressed to ensure successful implementation:

1. Material Selection:

High-resistivity materials ($\rho > 50\Omega \cdot \text{cm}$) are preferred for guard-rings to maximize isolation. However, the cost and availability of such materials should be considered.

2. Manufacturing Challenges:

- Fabrication processes for embedding guard-rings in substrates, such as lithography or etching, must be optimized for precision and scalability.
- The choice of process depends on the substrate material and the required guard-ring dimensions.

3. Integration with Existing Systems:

Guard-ring designs must be compatible with existing antenna layouts and technologies. This includes ensuring that the added structures do not interfere with other components or introduce unwanted effects.

4. Environmental Considerations:

The performance of guard-ring structures may vary with environmental factors, such as temperature and humidity. Careful testing is required to ensure consistent isolation under different conditions.

5.4 Examples of Deployment Scenarios

1. 5G Base Stations:

Guard-rings can be integrated into compact antenna arrays used in 5G base stations to enhance signal isolation and reduce interference with neighboring cells.

2. Automotive Radar Systems:

In self-driving vehicles, guard-rings improve the accuracy of radar systems by minimizing coupling effects between adjacent radar modules.

3. Satellite Communications:

High-frequency antennas on satellites benefit from guard-ring structures by achieving better signal clarity in dense communication arrays.

The application of guard-ring techniques in antenna systems demonstrates their versatility and effectiveness. Their ability to enhance isolation and improve signal quality makes them a valuable solution for modern and emerging communication technologies. This solidifies their role in addressing the challenges of electromagnetic coupling in compact and high-performance systems.

6. Conclusion

This study demonstrated the effectiveness of guard-ring structures in enhancing electromagnetic isolation in antenna systems. Through detailed simulations, it was shown that these structures significantly reduce cross-coupling, improve signal clarity, and enhance overall system performance, particularly in high-frequency applications such as 5G, millimeter-wave antennas, and phased arrays. The results underscore the importance of optimizing guard-ring spacing, material resistivity, and design parameters to achieve maximum isolation without compromising system compactness. Practical implementation scenarios, including 5G base stations, automotive radar, and satellite communication systems, highlight the real-world applicability of the proposed approach.

Future work will focus on further refining guard-ring designs to address the trade-offs between isolation performance and fabrication complexity. Additionally, experimental validation of the simulated results using prototypes and real-world scenarios will be undertaken to establish reliability and robustness under varying environmental conditions. Advanced materials and adaptive guard-ring configurations could also be explored to extend the methodology's application to emerging technologies such as terahertz communication and ultra-wideband antenna systems. This will provide a comprehensive framework for electromagnetic isolation in next-generation communication systems.

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