論　　文　　要　　旨

申請者氏名　刘　文博

申 請 学 位　　博士（工学）

主論文題目

A Study of Alternating Phase Fed Single-Layer Slotted Waveguide Array Antenna at 38 GHz

for Low Grating Lobes with Reflection Canceling Stairs

主論文要旨（邦文は４，０００字以内　外国語は２，０００語以内）

This paper presents a simulation and experimental study of a 10 × 10 alternating phase-fed single-layer waveguide slot array antenna with reflection-canceling stairs (RCSs) at 38 GHz. The aim of the study was to improve the aperture efficiency of the antenna. Two optimization methods were employed: 1) RCSs for each slot were proposed and optimized for height and position to minimize reflection, and 2) the broad wall width and slot offset were optimized to suppress grating lobes. A design procedure for the feed part was also presented. The characterization of the proposed antenna was found to be in good agreement with simulation results, with a measured S11 of less than −20 dB and a gain of more than 27.71 dBi at 38 GHz (corresponding to an aperture efficiency of 85.6%). The results of this study demonstrate the feasibility of using the proposed antenna in millimeter-wave communication systems.Besides, we also derive the underlying physic mechanism of slotted rectangular waveguide antenna in chapter II, discuss the further issues of the devices in chapter VI and present the prospective work in the final chapter VII.

In chapter 2, we have briefly introduced the fundamental physics of the propagation nature of electromagnetic wave in rectangular waveguide and the radiation nature of a narrow rectangular slot along longitude direction. All the equations are derived from four basic Maxwell equations. The cutoff wavelength means that the wavelength longer than this value is invalid to propagate through the rectangular waveguide. The rectangular waveguide size to determine the single mode condition are obtained from the Maxwell equations. The wavelength inside the rectangular waveguide is determined by the single mode condition. (Notice: related basic knowledges can be found in several textbook of slotted antenna array.)

Chapter 3 is a pivotal segment offering a detailed exploration of the Finite Element Method (FEM) and the specialized simulation software, Femtet, focusing on its application in high-frequency electromagnetic wave analysis through harmonic analysis. 3.1 is introduction to FEM. The chapter commences with a comprehensive introduction to the Finite Element Method (FEM), an indispensable numerical approach for solving complex engineering challenges. FEM's fundamental principles are laid out, illustrating its versatility in problem-solving by discretizing structures into manageable elements. This section underscores the adaptability of FEM across diverse engineering domains, underscoring its efficacy in structural mechanics, thermal analysis, and electromagnetic simulations.

Section 3.2 is introduction to Femtet. Building on the FEM foundation, Section 3.2 provides an in-depth overview of Femtet, a robust simulation software developed by Murata Software. The discussion underscores Femtet's user-friendly interface and its ability to handle multi physics simulations with finesse. Noteworthy is Femtet's prowess in electromagnetic analysis, thermal simulations, and structural mechanics, positioning it as a versatile solution applicable across a spectrum of engineering disciplines.

Section 3.3 is introduction to Harmonic Analysis in Femtet for High-Frequency Electromagnetic Wave Simulation:A focal point of the chapter, Section 3.3 introduces the application of Femtet in simulating high-frequency electromagnetic waves through harmonic analysis. Harmonic analysis, explained asa technique for studying system behavior under sinusoidal excitations, is particularly relevant in high-frequency scenarios.The section elucidates the core principles of harmonic analysis and demonstrates how Femtet streamlines precise and efficient simulations. Femtet's role in providing insights into electromagnetic compatibility, antenna design, and other high-frequency wave scenarios is underscored.Finally, we make a conclusion of this chapter as follows.

Chapter 3 serves as a comprehensive guide to both the theoretical underpinnings of FEM and the practical application of Femtet. The emphasis on harmonic analysis within Femtet positions it as an invaluable tool for engineers and researchers navigating the intricacies of high-frequency electromagnetic wave simulations. As technology progresses, users are encouraged to refer to the latest documentation from Murata Software for updates, advanced features, and real-world applications of Femtet in the dynamic field of electromagnetic analysis.

In chapter 4, we have numerically demonstrated a high-efficiency single-layer slotted waveguide array antenna. Furthermore, only a 0.4 dB power penalty by adding the feeding part indicates that this design is feasible for fabrication.In the feeding part design, we successfully demonstrate an input aperture with > 800-MHz bandwidth and < -30 dB S11. In addition, we realize alternative-phase (deviation < 1 degree for the first four ports and < 10 degree for the end port) uniform-power (deviation < 0.43 dBi) feeding for ten radiating waveguides through two 1x5 feed waveguides. In the radiating waveguide design part, we successfully suppress the reflection of a single waveguide < -14.5 dB by employing reflection canceling stairs. Simultaneously, the power compensation effect of stair makes it possible to use constant offset for ten slots.For the waveguide array design, we minimize the offset and the $|O_1O_2|$ to effectively eliminate the grating side lobes. As a result, we realize a remarkable high aperture efficiency of 89.4% with a 5 mm broad wall width.

In chapter 5, we described details the fabrication and performance evaluation of an antenna design with reflection canceling structures (RCSs) and a traditional antenna array without RCSs for reference. Utilizing the proposed design parameters, the antenna features a compact single-layer configuration and a standard WR-28 aperture, ensuring ease of use. Measurement and simulation results of the reflection coefficient S11, depicted in Figure 10, validate the accuracy of the finite-element method (FEM) simulations. The RCS antenna array exhibits reduced reflection losses (< 15 dB at 38 GHz), showcasing superior performance within the specified frequency range.

Relative radiation patterns (Figures 11 and 12) confirm successful fabrication of devices with both configurations, emphasizing a remarkable reduction in sidelobes near $\theta = \pm 60°$ on the $\phi = 45$-degree plane with RCSs. This reduction suggests the potential of RCSs in enhancing antenna efficiency by mitigating sidelobes.

Comparisons with a standard gain horn antenna demonstrate higher gains and aperture efficiency (> 80%) at 38 GHz for the proposed antenna compared to the traditional one. Future work could explore further optimizations beyond the specified frequency range, addressing limitations in the design of the feeding component and extending the efficiency gains observed within the current parameters. The results affirm the effectiveness of the proposed RCS design in enhancing antenna performance, providing a promising foundation for future advancements in antenna technology.

Chapter 6 delves into a comprehensive investigation of slotted waveguide applications through three distinctive case studies, each contributing valuable insights to the advancement of this technology.

1. Inclined Stair for Enhanced Tolerance: The first case study explores the application of inclined stairs in slotted waveguide design. This innovative approach serves to elevate processing tolerance, addressing challenges associated with fabrication precision. By incorporating inclined stairs, the study demonstrates a notable improvement in processing tolerance, showcasing the potential for this technique to enhance manufacturing feasibility.

2. Circular Array Performance: The second case study focuses on the performance of circular slotted waveguide arrays. Comparing these arrays to their rectangular counterparts, the study highlights the superior symmetry inherent in circular arrays. This inherent symmetry proves advantageous in mitigating side lobes, particularly when compared to rectangular configurations. The findings underscore the potential of circular slotted waveguide arrays in achieving enhanced performance through improved radiation characteristics.

3. Perturbated Boundary Conditions for Transmission Loss Analysis: The third case study employs perturbated boundary conditions to scrutinize transmission losses in slotted waveguides.

Specifically, the study investigates the transmission loss in a 5-mm copper waveguide at 38 GHz. Conclusive results indicate that, within this frequency domain, the transmission loss for the specified waveguide size is negligible. The study establishes the viability of perturbated boundary conditions for accurately assessing transmission losses in slotted waveguides operating at 38 GHz.

Collectively, these case studies contribute to a nuanced understanding of slotted waveguide applications. The exploration of inclined stairs for improved tolerance, the performance evaluation of circular arrays, and the analysis of transmission losses through perturbated boundary conditions collectively advance our comprehension of slotted waveguide intricacies. These insights are crucial for enhancing the design, fabrication, and performance of slotted waveguides, particularly in the context of applications operating at 38 GHz.

Chapter 7 is for conclusion.

7.1 Conclusion of this work

In conclusion, this paper presented a simulation and experimental study on a waveguide slotted array antenna with RCSs for sidelobe suppression at 38 GHz. The main objective of the study was to improve the aperture efficiency of the antenna. Two optimization methods were employed: the use of RCSs to minimize reflection and the optimization of the broad wall width and slot offset to suppress grating lobes. The design procedure for the feed part of the antenna was also presented.

The proposed antenna design experimentally achieved a measured S11 of less than -20 dB and a gain of more than 27.71 dBi at 38 GHz, corresponding to an aperture efficiency of 85.6%. These results were in good agreement with the simulation results, confirming the feasibility of using the proposed antenna in millimeter-wave communication systems.

7.2 Prospective research

As we conclude this doctoral research on slotted waveguide antenna arrays, it is essential to look ahead and identify key factors that will drive and enhance the impact of this study in the future. Three major factors are poised to significantly influence and propel further advancements in the field of slotted waveguide antennas.