

# Metasurface Coding Antenna Based on Waveguide Slot Array

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**Abstract**—This work presents a waveguide-slot metasurface programmable antenna that addresses the limitations of existing phased arrays and traditional metasurfaces. By integrating metasurfaces with waveguide slot antennas, the proposed design offers low cost, ease of integration, and high efficiency, making it suitable for large-scale deployment. The antenna utilizes a curved waveguide structure with path-dependent phase compensation to improve radiation efficiency, overcoming symmetry limitations in standing-wave arrays. With PIN diodes and FPGA programming, the concave waveguide achieves beam scanning from  $-40^\circ$  to  $30^\circ$  at 10.5 GHz, and the convex waveguide scans from  $-50^\circ$  to  $50^\circ$  with maximum gains of 15.2 dBi and 14.6 dBi, respectively. The antenna also implements 1-bit amplitude and phase modulation to achieve both far-field scanning and near-field focusing, demonstrating a scanning range from  $-40^\circ$  to  $+40^\circ$  and near-field focusing at  $z_0=12\lambda_0$ , with gain fluctuations under 2.5 dBi. This work represents a novel approach to integrated near/far-field beam control with reduced system complexity and fewer components.

**Index Terms**—Metasurface programmable antenna, waveguide slot array antenna, 1-bit reconfigurable antenna, beam scanning, near-field beam focusing

## I. INTRODUCTION

In recent years, metamaterials and metasurfaces have been widely adopted for electromagnetic (EM) wave manipulation. As 2D counterparts of metamaterials, metasurfaces enable flexible control of EM wavefronts—amplitude, phase, and polarization—thereby supporting compact and reconfigurable devices [1]. Digital (coding) metasurfaces have been actively explored as low-cost phased-array alternatives [2]; However, most implementations still require an external feed source, which increases profile and complicates integration. Metasurface antennas address this limitation by integrating the feed within the aperture.

Reconfigurable leaky-wave metasurface antennas using diodes have been reported in [3]–[5]. In [3], diode modulation is employed to tune the surface impedance and effective periodicity of a leaky-wave antenna. In [4], dual-frequency far-field scanning is achieved by controlling the on/off states of two diodes placed on both slots and patches. In [5], a sideband-free space-time-coding metasurface antenna is realized. Compared with conventional (externally fed) metasurfaces, leaky-wave metasurface antennas co-integrate the feed source, effectively reducing the overall profile while maintaining both transmit and receive capabilities.

In this project, we present waveguide-slot metasurface programmable antennas that address the limitations of existing phased arrays and traditional metasurfaces. By integrating metasurfaces with waveguide slot antennas, the proposed design offers low cost, ease of integration, and high efficiency, making it suitable for large-scale deployment.

## II. STANDING-WAVE WAVEGUIDE METASURFACE ANTENNA

To further improve radiation efficiency and reduce the design complexity of control circuits, this work proposes a standing wave waveguide metasurface antenna. A novel waveguide slot-PIN diode metasurface unit is designed, which uses only one PIN diode to achieve 1-bit phase and amplitude control of the slot metasurface unit, lowering costs and the design complexity of DC control circuits.

Furthermore, by adopting a method where a curved waveguide provides spatial path phase for each slot, the technical challenge of pattern normal symmetry in planar 1-bit standing wave beam scanning is overcome [6]. The influence of standing wave waveguide slot arrays with concave and convex curvature shapes on beam scanning is analyzed in detail. Combining the proposed slot metasurface unit, standing wave waveguide metasurface antennas with concave and convex structures are developed. As shown in Figure 1.

Simulation results show that at 10.5 GHz: the concave waveguide achieves beam scanning from  $-40^\circ$  to  $30^\circ$  with a maximum gain of 15.2 dBi; the convex waveguide achieves  $\pm 50^\circ$  beam scanning with a maximum gain of 14.6 dBi. Finally, the antenna is fabricated and tested experimentally, and the results are highly consistent with the simulation results.



Fig. 1. Fabricated prototypes of the concave and convex standing-wave metasurface antennas: (a) Convex waveguide and (b) Concave waveguide.

## III. LEAKY-WAVE WAVEGUIDE METASURFACE ANTENNA

To address the requirement that antennas need to simultaneously possess near-field and far-field beam manipulation capabilities, this chapter proposes a leaky-wave waveguide slot array metasurface antenna [7]. It introduces the far-field scanning and near-field focusing principles of the 1-bit

leaky-wave array. A staggered slot arrangement method is adopted to increase the number of array elements and element density. By combining the waveguide slot metasurface unit proposed in Chapter 3, the waveguide metasurface antenna is enabled to have both near-field and far-field beam manipulation capabilities. As shown in Figure 2.

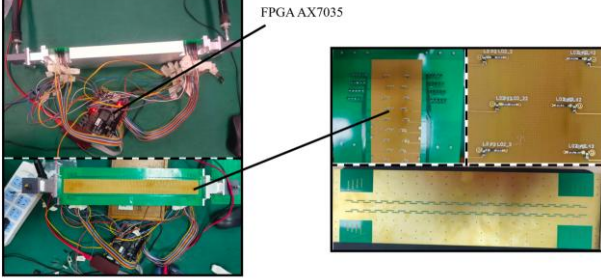


Fig. 2. Photograph of the fabricated and assembled antenna prototype.

Far-field scanning simulation results show that at 9.5 GHz, beam scanning from  $-40^\circ$  to  $+40^\circ$  is achieved, with a maximum gain of 16.2 dBi and a gain attenuation of less than 2 dB within the scanning range. For near-field beam focusing, at 9.5 GHz, near-field beam focusing on a planar surface is realized, where the difference in sidelobe focal level is controlled within -9 dB. Meanwhile, scanning of the focal point by approximately  $10^\circ$  on the plane is achieved, enabling beam focusing at  $-10^\circ$ ,  $0^\circ$ , and  $10^\circ$ , with the difference in the peak electric field value of the focal points being less than 2 dB.

The model was finally fabricated and tested. S-parameter test results confirm that the PIN diodes in the fabricated prototype have the ability to control the slots. Radiation pattern test results demonstrate that the antenna achieves beam scanning from  $-40^\circ$  to  $+40^\circ$  at 9.6 GHz. Simultaneously, three focal points at different angles on the planar surface were observed at 9.6 GHz, with the sidelobe level controlled within -6 dB. Ultimately, the leaky-wave metasurface antenna platform possesses both far-field beam scanning and near-field beam focusing capabilities, demonstrating high flexibility in beam control.

#### IV. CONCLUSION

We presented two programmable waveguide-slot metasurface antennas with internal feeds: a standing-wave design that boosts radiation efficiency and, via curved routing, suppresses symmetric grating lobes to enable 1-bit beam scanning; and a leaky-wave design that combines binary amplitude/phase control with interleaved slots to realize unified far-/near-field manipulation, including far-field scanning with low gain ripple and near-field focusing at  $z_0 = 12\lambda_0$ . Prototypes at 10.6 and 9.6 GHz validate high gain with fewer elements and simpler circuitry. Overall, the results demonstrate compact, scalable, and low-cost metasurface antennas well suited for large-area indoor deployment.

#### V. IMPACT STATEMENT AND FUTURE PLAN

Receiving the MTT-S Graduate Student Scholarship is a double blessing for me. Financially, it reduces the pressure of research costs, allowing me to purchase experimental equipment and books. Mentally, this recognition strengthens my motivation to focus on RF technology and participate in international forums. Most importantly, it deepens my determination in microwave engineering, encouraging me to hold higher standards in future research and career.

In the future, I plan to refine the theoretical framework for selecting the pre-phase function in 1-bit reflectarray antennas. Although the concept is well established, the mechanism by which the pre-phase enables scanning with half-wavelength unit spacing requires deeper exploration. More comprehensive theoretical models will be developed, and potential optimizations in curved waveguide shapes derived from reflectarray inversion will be investigated.

I will also focus on improving array layouts. While a staggered slot arrangement meets the minimum unit spacing requirement, the current analysis does not account for coupling effects between slots. Future work will optimize slot positioning while considering mutual interactions.

Finally, I plan to address issues in practical implementation. The large PCB area used in the prototype resulted in inefficient utilization of the antenna's lateral width. Optimizing PCB design to reduce wasted space will improve both efficiency and manufacturability, making metasurface antennas more suitable for real-world applications.

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