

# Spillover Mitigation Method in Rotman Lens-Based Retrodirective Arrays

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**Abstract**—This paper presents a new method to compensate for spillover loss in Rotman lens-based retrodirective arrays. The proposed approach aims to minimize the radar cross section (RCS) variation across the full field-of-view (FoV) of  $\pm 30^\circ$  and the operating bandwidth of 24–24.25 GHz. By proper phase correction transmission line (TL) design at the array side and compensating for phase errors between adjacent beamports, the method significantly reduces the initial RCS variation from 25 dB to 3.2 dB over the  $30^\circ$  scan angle. The results demonstrate improved performance in maintaining a more uniform RCS across the entire FoV, contributing to enhanced retrodirective array functionality.

**Index Terms**—Rotman Lens, Retrodirective Array, Backscatter communication, RCS variation.

## I. INTRODUCTION

As wireless communications continue to evolve towards 6G, billions of small communication devices are expected to be deployed across various applications [1], [2]. Current technologies for these devices often require complex components, leading to higher costs and energy consumption, as they must generate their own radio signals. In contrast, ambient backscatter communications offers a new approach by using existing ambient Radio Frequency (RF) signals as carriers, significantly reducing both the size and power needs of these low-cost devices [3]. This makes it an attractive solution for the massive IoT ecosystem, especially in low data-rate applications.

Retrodirective arrays have the potential to be strong candidates for backscatter technology, offering promising solutions for real-world implementation. These arrays reflect signals back in the direction of arrival without requiring active electronic components or complex signal processing. For instance, the Van Atta array achieves passive retro-directivity by pairwise connecting antenna elements using either equal-length [4] or equal-phase (multiple of wavelength) [5] transmission lines (TLs). However, the former approach is constrained by narrowband operation, whereas the equal-length TLs become increasingly complex and exhibit greater loss as additional antennas are incorporated.

To address the bandwidth requirements of the retrodirective array, the Rotman lens beamforming network incorporates

a true time delay (TTD) mechanism [6]. This configuration utilizes open-circuited beamports along with the reciprocity principle to enable retro-directivity. However, the incoming signal, even from the primary beam direction, does not focus on a single beamport. The simultaneous reflection of spillover energy along with the primary reflection can introduce additional variations in the radar cross-section (RCS) [7].

In this paper, we propose a method to mitigate the spillover effect, by maximizing the gain in transmit mode through extending the TL length at beamports. In Section II, we briefly explain the principles of the Rotman lens, along with initial design and simulation results. Section III discusses the spillover issue and its effect on retro-directivity. We also outline the proposed method to mitigate the spillover effect and reduce the final RCS variation. Conclusions are presented in Section IV.

## II. ROTMAN LENS-BASED RETRODIRECTIVE ARRAY

The Rotman lens, as a wide-band wide-angle passive beamforming network, was first introduced in [8]. It consists of  $M$  beam ports that serve as input ports, a parallel plate waveguide functioning as a true time delay (TTD) network, and  $N$  array ports that are intended to feed  $N$  antenna elements. As a beamforming network, the Rotman lens generates a specific phase taper at the output ports that feed the array. The antenna array is connected to the lens's array ports through phase correction transmission lines, which are typically configured in a meandered layout.

The initial microstrip Rotman lens in this work is designed using Antenna Magus [9] on Rogers RO4350B substrate with  $\epsilon_r = 3.66$  and thickness of 0.34 mm, which employs a trifocal design principle to minimize phase error across all beam ports. It consists of a lens body, tapered line impedance transformers, and extended transmission lines towards the substrate edges for waveguide port definition. The lens features seven beam ports and eight array ports. To utilize the lens in retrodirective mode, the extended transmission lines on the beam side have been removed, resulting in open-circuited beam ports. The initial design is then further analyzed and adjusted in CST Microwave Studio [10].

To investigate the retrodirectivity performance, we also designed a printed linear tapered slot antenna, as shown in Fig. 1. Rogers RO4003 with  $\epsilon_r = 3.55$  and thickness of 0.13 mm with loss tangent around 0.0037, is used as the substrate. The antenna has excellent impedance matching over a wide bandwidth and end-fire radiation pattern with less than 0.18 dB gain variation over  $\pm 30^\circ$  FoV, as illustrated in Fig. 2. Afterwards, the antenna elements are integrated with the Rotman lens, as shown in Fig. 3. The monostatic RCS is simulated in CST by defining a plane wave excitation with varying incident angles. A significant RCS variation of 25 dB is observed in Fig. 4 for the initial lens-based retrodirective array. The reason for this is that Antenna Magus defines different reference planes on the antenna side for waveguide ports, whereas a direct connection to the antenna does not account for this. Therefore, we designed modified curved TLs that properly account for phase tapering in the antenna array, as shown in Fig. 3b. This reduces the RCS variation to 4.5 dB, as can be observed in Fig. 5.

### III. SPILLOVER MITIGATION METHOD

To further enhance the retrodirectivity performance of the proposed structure, it is critical to ensure that the lens operates effectively in both transmit and receive modes. Surface current plots provide a visualization of wave propagation within the lens. Fig. 6 demonstrates the surface currents in receive mode for incident angles of  $0^\circ$  and  $20^\circ$ . As can be observed, even for the primary beams, the incoming wave does not converge on a single beam and also leaks into other beam ports. Fig. 7 quantifies the leakage to other ports and indicates that the spillover is more pronounced in the adjacent ports of the desired beamport. Upon reflection, these do not necessarily add constructively to the primary beam reflection.

To account for spillover reflections from adjacent beamports, while assuming that leakage to other beamports is negligible, we can consider the simultaneous excitation of two adjacent beamports in the TX mode. By modifying the length of the TL at the adjacent beamport, we identify the maximum realized gain at the intermediate beam angle (the midpoint between the two primary beams) where these two ports become phase coherent. For instance, when beamports 4 and 3 are excited simultaneously, the realized gain is monitored at  $5^\circ$  while adjusting the TL length at beamport 3. This method is then applied sequentially to beamports 3 and 2, and subsequently to beamports 2 and 1. Since the structure is symmetric, the beamports on either side of beamport 4 have corresponding counterparts, so we modify their TL lengths accordingly. Fig. 8, shows the maximum realized gain and the corresponding TL length at other beam ports while the beam port 4 is considered as a reference.

Finally, the monostatic RCS variation of the modified Rotman lens-based retrodirective array is demonstrated in Fig. 9, where the variation is reduced to 3.2 dB over the entire FoV. Furthermore, the maximum 1.46 dB difference among multiple frequency components in Fig. 5 is reduced to 0.64 dB in Fig. 9, which is critical for the signal integrity.

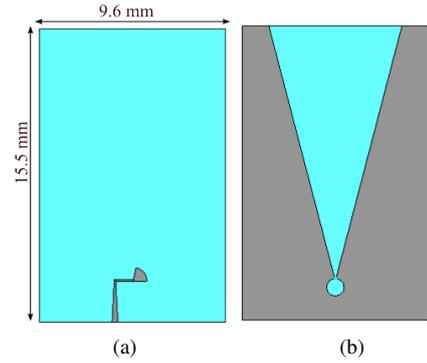


Fig. 1. Slot taper antenna: (a) Back side; (b) Front side

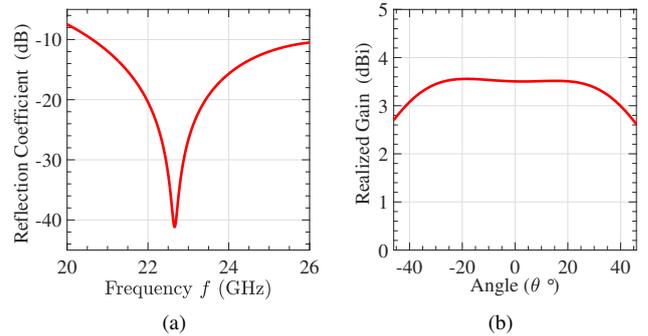


Fig. 2. Slot taper antenna parameters: (a) Reflection coefficient; (b) E-plane pattern

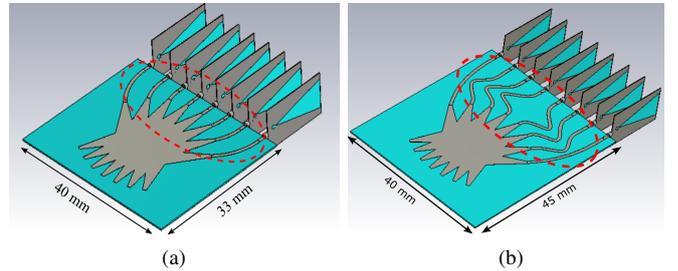


Fig. 3. Rotman lens-based retrodirective array with: (a) Initial TLs designed by Antenna Magus; (b) Modified curved TLs.

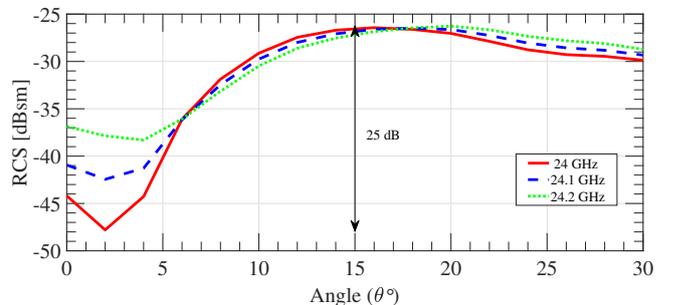


Fig. 4. Monostatic RCS of initial lens-based retrodirective array

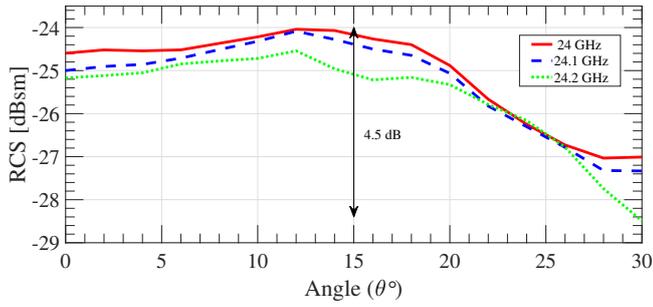


Fig. 5. Monostatic RCS of the lens-based retrodirective array with modified TLs at the array ports.

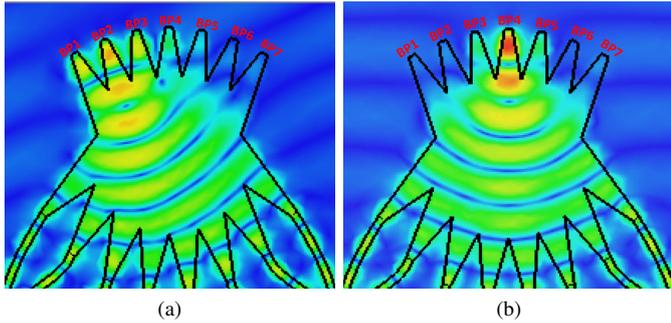


Fig. 6. Surface current of the Rotman lens-based retrodirective array at incident angle of: (a) 20°; (b) 0°

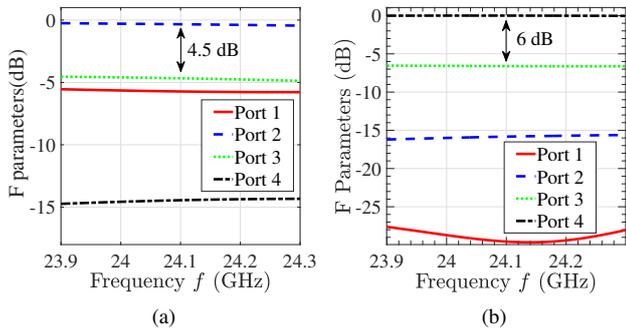


Fig. 7. F parameters of the Rotman lens-based retrodirective array at incident angle of: (a) 20°; (b) 0°

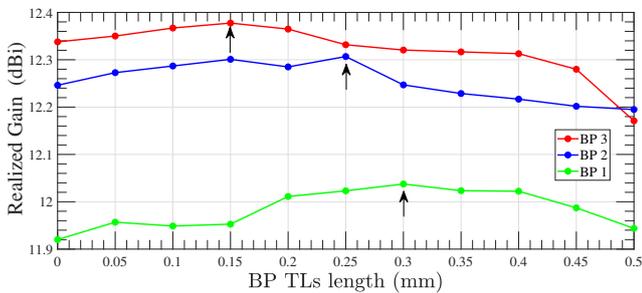


Fig. 8. Simulation of realized gain over different lengths of TLs at beam ports.

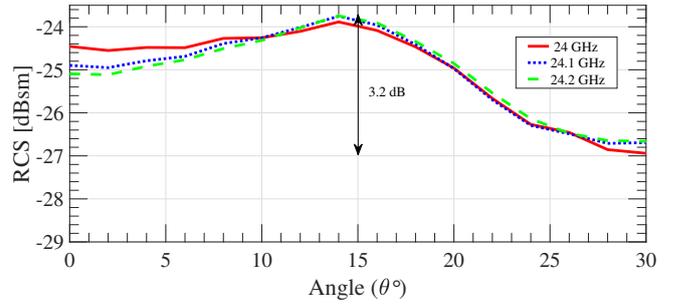


Fig. 9. Monostatic RCS of the lens-based retrodirective array with modified TLs at both beam and array ports.

#### IV. CONCLUSION

In this study, we propose a method to address spillover loss in Rotman lens-based retrodirective arrays. The work investigates the initial lens design from Antenna Magus and details the sequential steps taken to enhance its retrodirectivity performance. It has been demonstrated that spillover is more pronounced in the adjacent ports of the desired beamport. Thus, we propose the simultaneous excitation of two adjacent beamports, varying the TL at one of them, as a method to maximize the achievable realized gain, in the transmit mode, at the intermediate beam direction. Using this technique, the 25 dB monostatic RCS variation of the initial lens has been reduced to 3.2 dB over the entire  $\pm 30^\circ$  FoV.

#### V. ACKNOWLEDGMENT

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