2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI) | 978-1-7281-4670-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/APS/URSI47566.2021.9704612

Optimizing Rotmen Lens Topologies for 5G Wireless Grids

Aline Eid, Jimmy Hester, and Manos M. Tentzeris
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA.

Abstract— **The design of high-gain, orientation-agnostic systems capable of efficiently capturing the high transmitted EIRPs by the 5G base stations is key to enabling the 5G infrastructure as a Wireless Power Grid (WPG). In this effort, the authors present a framework for the design of fully-printed, planar, and highly-customizable mm-wave Rotman-lens-based rectennas. A scalability study evaluates the performance of the lens with different numbers of antenna and beam ports, resulting in a successful architecture offering a combination of high gain and wide angular coverage. A structure, involving eight antenna ports and six beam ports, was then inkjet-printed on a thin, flexible substrate and its S-parameters were measured. This structure, breaking the trade-off between high gain and large angular coverage, is at the core of the realization of Rotman lens-based mm-wave rectenna and backscattering mmID tags for the 5G WPG.**

Keywords— **5G, IoT, wireless power transfer, millimeter-waves.**

I. Introduction

WITH the boost in the Equivalent Isotropic Radiated Powers (EIRPs) allowable by the FCC in the mm-wave bands, it has been recognized that 5G base-stations could—in addition to providing the ultra-low-latency and ultra-high-bandwidth data coverage that they are intended for—form a WPG that could wirelessly distribute power to IoT devices [1]. The rise of affordable mm-wave systems——catalyzed and exemplified by 5G—has made accessible reasonably-sized high-gain radiators, capable of focalizing their electromagnetic energy to create highly efficient wireless links. However, the beneficial high-gain feature of such systems is also a curse for large-aperture low-cost passive receivers requiring a direction-agnostic operation. It has been shown that Beamforming Networks (BFNs) provide a practical solution to the (at first glance) impossible problem of providing combined high gains and large angular coverages to passive—and therefore non-actively-steered—rectenna systems [2]. Two widely-known examples of circuit-based networks are the Butler Matrix and the Blass Matrix. However, these two circuit-based systems suffer from beam squint [3], and are relatively complex, especially at higher frequencies where the design parameters become extremely critical and difficult to manufacture within tolerances. Other approaches can control the relative phase values at the array elements using microwave lens structures, achieving the desired progressive phase shifts through time delays. The Rotman lens constitutes a planar instantiation of such a strategy and one of the most cost-effective designs for BFNs. It is commonly utilized in the transmission mode to enable multibeam phased array system and wide-band operation. This paper presents a framework that can be used to properly dimension Rotman lenses to achieve the desired properties for the efficient and angle-agnostic reception of the mm-wave energy delivered by the 5G WPG.

Table 1. Scalability Study

(Na,Nb) \ Parameter	Maximum Array Factor	Angular Coverage
(4,3)	1.2 dB	180°
(8,6)	5.95 dB	120°
(16,12)	7.8 dB	100°
(32,24)	7.6 dB	83°
(64,48)	5.2 dB	80°

II. Planar MM-Wave Rotman Lens Design

The Rotman lens, a passive type of BFN, is composed of an electrically large parallel plate region with antenna ports on one side and beam/feed ports on the other side. A significant advantage of this structure is its ultra-wideband operation [4] and frequency-invariant beamforming ability, due to its introduction of true-time-delays (TTDs). In transmission mode, a signal generated at a beam port radiates across the parallel plate region and couples into the antenna ports. Depending on the location of the beam port in reference to the antenna ports, the beam is steered in a specific direction based on the phase gradient created at the array aperture. In the receiving mode, the plane waves impinging on the antenna side are focalized to the focal points corresponding to their angle of incidence on the beam ports side [5]. The design of the lens, including the shape of the plate, number of antennas and beam ports, and transmission line lengths play a critical role in the proper operation of the structure, its losses, side lobes, maximum array factor, and angular coverage. In applications such as mm-wave energy harvesting and backscattering communications [1], [2], [6], the lens is used as a receiver and is incorporated as an intermediate element between the antennas and the rectifiers/switches. For such applications, the gain and angular coverage of the receiver are the most critical performance metrics, controlling the ability of the structure to efficiently receive power from all directions while displaying a high gain. In order to assess the effect of varying the number of antenna ports Na and beam ports Nb in the Rotman lens on its maximum array factor and angular coverage, a scalability study was conducted. Structures of varying sizes—(4,3), (8,6), (16,12), (32,24) and (64,48)—were first designed using Antenna Magus and then imported into CST STUDIO SUITE for simulation. Matlab was used to process the simulated data and output the array factors created by the respective lens structures using the following equation:

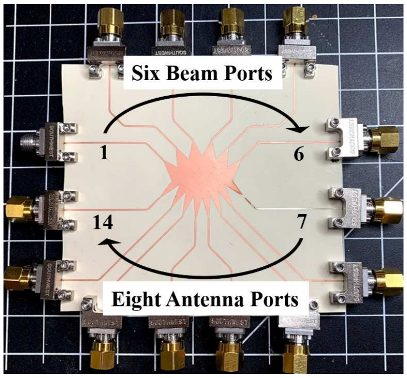

Fig. 1. Picture of the fabricated Rotman lens structure on thin LCP substrate.

$$AF_j = \sum_{i=1}^{N} S_{ij} e^{-jkr} \tag{1}$$

where AF_j, N, S_{ij}, k and r are, respectively, the array factor for beam port j, the number of antenna elements, the S parameters corresponding to ports i and j, the wave vector and the direction, respectively. The maximum value of the array factors as well as their total $3\,\mathrm{dB}$ beamwidths (accounting for the aggregated coverage of all ports) where then tabulated. It can be seen from table 1 that the increase in antenna ports leads to an increase in the maximum array factor until reaching a peak of around $7.8\,\mathrm{dB}$ with 16 antenna arrays and 12 beam ports connected to the lens. The remaining larger simulated lenses seem to be accompanied with increased losses as the lens grows in electrical size, leading to a drop in the array factor down to $5.2\,\mathrm{dB}$ for a 64 antenna arrays structure with 48 beam ports. The same table shows that the angular coverage decreases with the increase of antenna and beam ports with a coverage of $180°$ with 4 antenna arrays down to $80°$ with 64 antenna arrays. As mentioned earlier, for the applications of interest, a combination of a good array factor and relatively wide angular coverage are desired in the receiving mode. It was then concluded that a lens composed of eight antenna arrays and six beam ports offers a nearly optimal compromise between a high array factor of $5.95\,\mathrm{dB}$ and a $120°$ total angular coverage, while maintaining an acceptable number of antenna arrays and beam ports.

III. Experimental characterization

After setting the number of antenna and beam ports based on the scalability study, the design was completed by adding tapered transmission lines on both sides of the lens. The structure was then inkjet printed on a $180\,\mu\mathrm{m}$ thin liquid crystal polymer (LCP) substrate, resulting in the prototype shown in Fig. 1. The S parameters of the structure were then measured and compared to the simulated performance as shown in Fig. 2. The results show a good agreement between the simulated and measured structures, over a wide frequency range from $10\,\mathrm{GHz}$ to $43\,\mathrm{GHz}$. A good matching under $-10\,\mathrm{dB}$ is observed in Fig. 2a for the reflection coefficients results at beam port 2. In addition, a good transmission

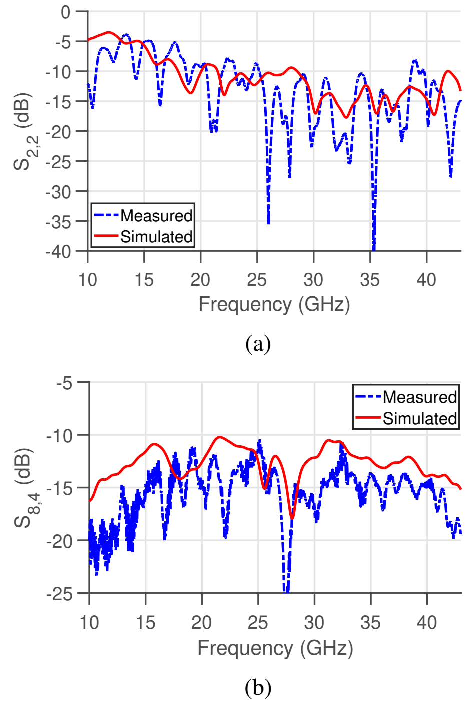

Fig. 2. (a) Plot of the simulated and measured reflection coefficient at beam port 2 and (b) Plot of the simulated and measured transmission coefficient at antenna port 8 when beam port 4 is excited.

coefficient (in the most challenging case) at antenna port 8– when beam port 4 is excited–is realized with this structure, as shown in Fig. 2b. Taking into consideration that the power is divided over eight antenna ports, resulting in $9\,\mathrm{dB}$ loss in power in perfect lossless conditions, a loss of $10\,\mathrm{dB}$ to $15\,\mathrm{dB}$ is quite good.

IV. Conclusion

The work presented in this paper serves as a guide for the proper design of Rotman-lens-based wide beamwidth, large bandwidth, and high gain mm-wave antenna systems used to power IoT devices through the 5G WPG. This scalable implementation sets a robust basis for the advent of orientation-agnostic, long-range and efficient receivers for energy harvesting and RFID systems for IoT, smart cities and smart agriculture applications.

References

[1] A. Eid, J. G. Hester, and M. M. Tentzeris, "5g as a wireless power grid," *Scientific Reports*, vol. 11, no. 1, pp. 1–9, 2021.

[2] A. Eid, J. Hester, and M. M. Tentzeris, "A scalable high-gain and large-beamwidth mm-wave harvesting approach for 5g-powered iot," in *2019 IEEE MTT-S International Microwave Symposium (IMS)*, June 2019, pp. 1309–1312.

[3] R. L. Haupt, *Timed arrays: wideband and time varying antenna arrays*. John Wiley & Sons, 2015.

[4] R. Rotman, M. Tur, and L. Yaron, "True time delay in phased arrays," *Proceedings of the IEEE*, vol. 104, no. 3, pp. 504–518, 2016.

[5] W. Rotman and R. Turner, "Wide-angle microwave lens for line source applications," *IEEE Transactions on antennas and propagation*, vol. 11, no. 6, pp. 623–632, 1963.

[6] A. Eid, J. G. D. Hester, and M. M. Tentzeris, "Rotman lens-based wide angular coverage and high-gain semipassive architecture for ultralong range mm-wave rfids," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 11, pp. 1943–1947, 2020.