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Design of an All-Metal Broadband Rotman Lens for Satellite Communications at K/Ka-band

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***Abstract*— In this work an all-metal Rotman lens antenna design is presented. Ridge waveguides are used for the input and output ports of the lens to achieve broadband behavior in the K/KA bands of the new generation of satellite communications (17 GHz to 30 GHz). The Rotman lens is composed by 5 input and 5 outputs ports, with a maximum beam scanning of 30 degrees. The connection between the input and output ports is done through a parallel plate waveguide (PPW) in the TEM regime. This simple configuration allows to have an initial assessment of the antenna port isolation and return losses, for the designed ridge to parallel plate waveguide transitions. This preliminary work shows promising results which pave the way for future improvements in terms of bandwidth and scanning performance.**

Keywords — All-metal antennas, 5G and Satellite Communications, K/Ka Band, Rotman Lens, Beam forming networks (BFN)

I. INTRODUCTION

The Rotman Lens Antenna is one of the most popular types of constrained lens. The combination of broadband operation, compactness and wide-angle beam steering makes this type of antenna an appealing solution for a wide range of applications related with 5G and satellite communications [1]. This classical antenna [1], [2][1][2] is still being widely researched for continuous improvements and adaptions to currently technology developments [3]-[5]. As a beam forming network (BFN), the radiation of each antenna input port is channeled to multiple output beam ports that collectively form the collimated beam. The direction of the beam shifts as different input ports are used. The connection between the input and output ports is done through a parallel plate waveguide (PPW) in the TEM regime, which explains the intrinsic broadband behavior of the lens. Moreover, the radiating elements of the antenna are connected to the beam ports by transmission lines with specific lengths (as depicted in Figure 1). The positions of the input and output ports are readily obtained from geometric optics analysis. However, a careful design is required for the feeding network, which will limit the lens performance. The first design aspect is related with the number of input and output ports of the lens, which depend on the intended application. There is a trade-off between the feed spacing and port isolation. On the one hand, closer feeding ports correspond to a higher beam density. On the other hand, closer feeding ports will increase the coupling between adjacent ports. Moreover, the physical aperture of the feeding elements will further constrain the array spacing. Another crucial step for this design is the bandwidth of the transmission lines and the transition to the PPW. In the context of satellite communications, Rotman lens are particularly appealing for the space segments, being currently investigate as viable solution for the emergent mega-constellations in low and medium Earth orbit (LEO/MEO) [3]. In this case, an all-metal design is best suitable to survive the harsh environment of space. In this work we will focus on the design of this type of antenna aiming for a broadband behavior starting in the satellite Rx K band (17 GHz) until the Tx Ka band (30 GHz). Ridge wave technology emerges as a natural option for achieving such a wideband using only metal. In fact, several recent works have explored this configuration [3], [5], however, not in this bandwidth. Herein, we present a simple preliminary design of a Rotman lens with 5 input and output ports fed by ridge waveguides. The goal is to assess the viability of using this type of waveguide and transitions to cover the entire bandwidth. We should stress that this study will be used to set the baseline for future improvements. Preliminary results points that is indeed possible to operate from 17 GHz to 40 GHz with this type of technology.

The paper is organized as follows. In Section II, the design of the Rotman based on PO is shown. In Section III we present the full-wave analysis of the ridge waveguide to PPW transition. In section IV, the numerical results for the complete Rotman lens are shown. Finally, the conclusions are draw in Section V.

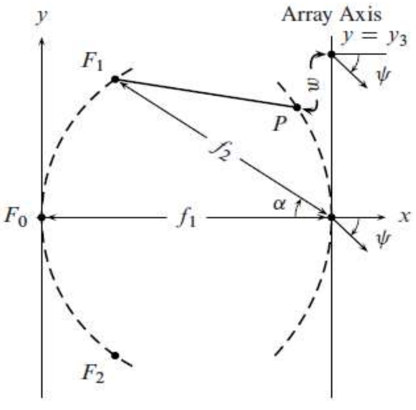

Figure 1: Ray Geometry of the Rotman Lens (After Hansen) [3]

II. ROTMAN LENS DESIGN

Figure 1 depicts a schematic of the lens design. The beam port arc is located at the left, and the array port at the right. The six basic design parameters defined by Hansen [6]: Focal angle (α), focal ratio(β), Beam angle to ray angle ratio(γ), maximum beam angle (ψ), focal length (f_1) and array element spacing (d). The position of the input and output ports as well as the size of transmission lines follows from the traditional design rule of this lens [6][7]. For a design frequency of 28 GHz, the adopted numerical values of the lens are given in Table 1. To confirm our calculations, the position of the input and out ports were also obtained using the software developed by Simon, P. S. [8], resulting the beam and array contour plotted in Figure 2. As mentioned previously, this is a preliminary test to assess if the adopted ridge waveguide ports and transitions can operate in the intended bandwidth with good port isolation and insertion losses when placed along the focal arcs.

Table 1 – Design parameters for the Rotman lens

Number of input ports, N	5
Number of output ports, *M*	5
Focal angle, α	±35º
Focal ratio, β	0.9
Maximum beam angle, ψ	±30º
Focal length, f_1	5.5λ
Array element spacing, *d*	λ

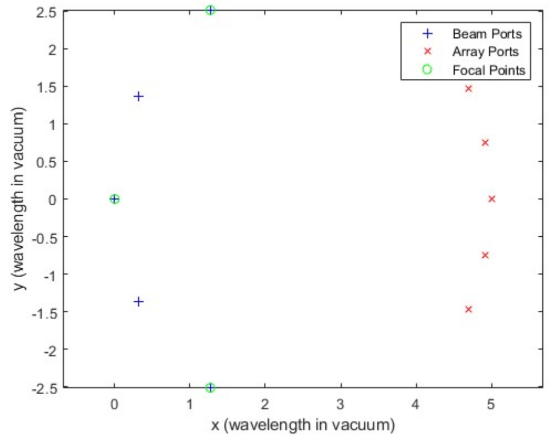

Figure 2: Beam and array contour phase centers [MATLAB], adapted from Simon, P.S. [8]

III. FEEDING NETWORK

The performance of the antenna will depend on the type of transmission lines that will connect to the input and output port as well as the corresponding transitions. In the present work, we use a double ridged waveguide, inspired in the design presented in [5] and adapted to operate in the bandwidth between 20 a 30 GHz. Although the feed reported in [5] shows smooth transitions on the lateral, upper and bottom flares, in this work we follow an approach resembling [3]. The upper and bottom flares or transitions into the lens have a straight profile. For the lateral flares we used the same equations as [3]. With the values (in mm): $a = 6.5$, $b = 3, l_1 = 7, l_2 = 5, m = 1.23, n = 1, r_1 = 2.5, r_2$ =5.5 and $b_r = 0.7$. The transition design is presented in Figure 3. The S11 parameter in a single feed, all full wave analyses were made using CST Microwave Studio (Figure 4). As Figure 4 depicts, around 21GHz the S11 results start to go below -10 dB, presenting good results up to 40GHz. In future work, we will focus on obtaining the best possible values between 20 and 30 GHz, so that this decrease does not start at 21 GHz, but rather at a lower frequency.

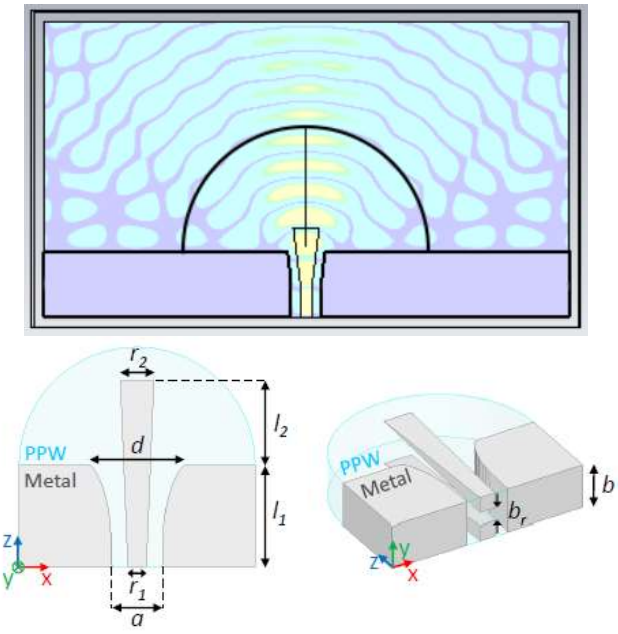

Figure 3: Single Feeding Port (adapted from [3])

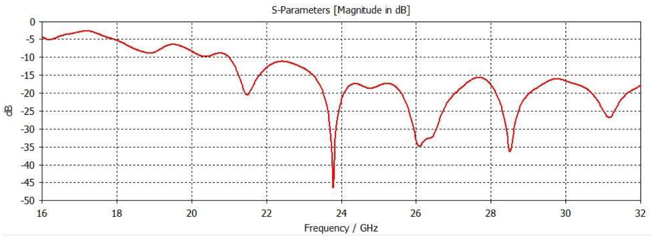

Figure 4: Simulated S11 for a single feed port

To evaluate the coupling between adjacent ports, and the transmission of these ports from beam port to array port, we reproduced a simple model with 3 ports side by side with the lateral sides open. The feed ports are spaced from each other by 3/2 of the aperture value "d", counting from the phase center Figure 5).In Figure 6 we verify that the isolation between ports is relatively low in a very wide bandwidth, expect near 24 GHz and 26 GHz. Further improvements can be made to ensure that isolation is below -10 dB from 17 GHz to 30 GHz.

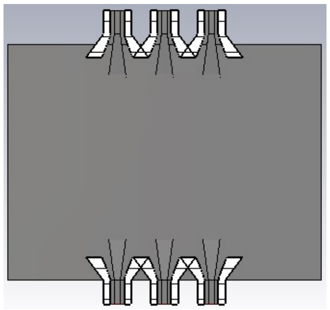

Figure 5: Model to evaluate mutual coupling between adjacent ports

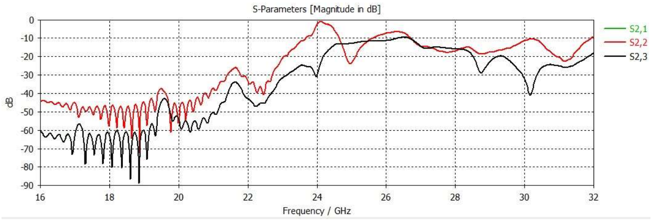

Figure 6: Simulated S parameters of the 3 adjacent feeds

IV. ROTMAN LENS FULL-WAVE SIMULATION

In this section we reveal a final design of the lens with the feeds embedded and rightly positioned. This prototype is a 5x5 lens as displayed in Figure 7. The final Rotman lens design was simulated from 17 to 30 GHz and promising results were obtained. The E-Field for 3 ports at 20, 22, 28 and 30 GHz are shown in Figure 7, Figure 8, Figure 9 and Figure 10, respectively. The corresponding S-parameters are shown Figure 11, Figure 12 and Figure 13 for each beam port.

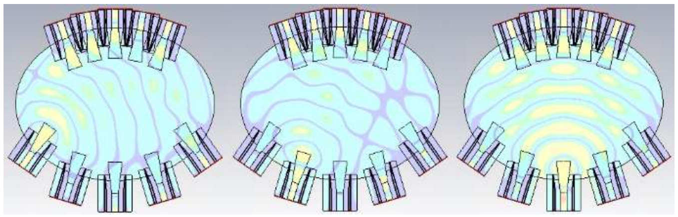

Figure 7: Simulated E-Fields at 20 GHz for beam port 1 (left), beam port 2 (middle), and port 3 (right)

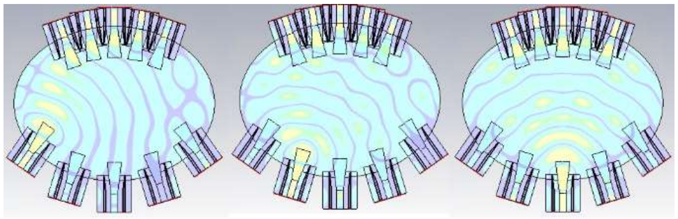

Figure 8: Simulated E-Fields at 22 GHz for beam port 1 (left), beam port 2 (middle), and port 3 (right)

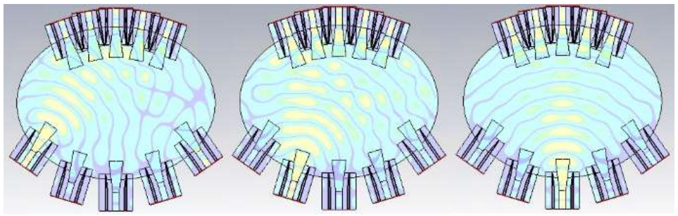

Figure 9: Simulated E-Fields at 28 GHz for beam port 1 (left), beam port 2 (middle), and port 3 (right)

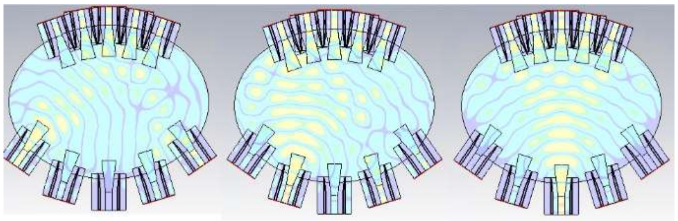

Figure 10: Simulated E-Fields at 30 GHz for beam port 1 (left), beam port 2 (middle), and port 3 (right)

As expected, the end ports, that are the ports from the extremities present the worst performances (see S_{11} and S_{51} in Figure 11. This preliminary study shows that the S-parameters can be below 10 dB in wide frequency range, however, further optimization must be done to reach the goal of a ultrawideband from 17 GHz to 30 GHz. Furthermore, as Figure 6 suggests, as the feeds are placed closer the coupling between adjacent ports can degrade this response.

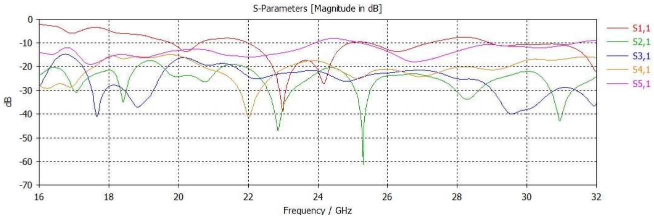

Figure 11: Simulated S11 from 16GHz to 32 GHz, for Beam Port 1

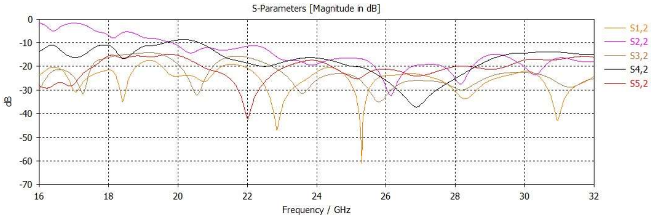

Figure 12: Simulated S11 from 16GHz to 32 GHz, for Beam Port 2

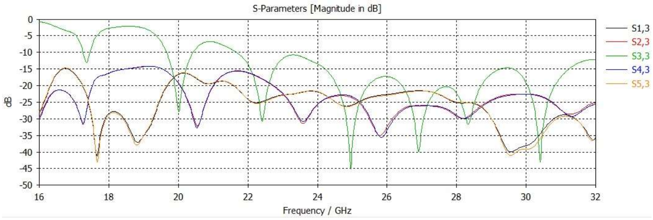

Figure 13: Simulated S11 from 16GHz to 32 GHz, for Beam Port 3

V. CONCLUSIONS

This works presents a Rotman lens design based on ridge waveguide technology to operate in the Rx and Tx K/Ka bands of satellite communications. The preliminary design shows promising results. However, further optimization will be required to achieve the entire operating band. As future work, new strategy to mitigate the coupling between ports will also be researched in the context of a master program. We expect to be able to present future develops during the conference.

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