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Design of a Rotman Lens Operating in the Full K/K$_a$ Band Using Ridge Waveguide Technology

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***Abstract*— Several services associated with satellite on the move and 5G applications are populating the K and K$_a$ frequency bands. Beam forming networks are crucial components for achieving the necessary beam flexibility and agility of these systems. The Rotman lens is being widely investigate as a cost-effective solution for overcoming the main limitations of other types of beam forming networks, namely bandwidth, complexity, and size. One of the main design challenges is obtaining broadband transitions for the array and beam ports. In this work, we used a standard K/K$_a$ double ridge (WRD180) for interfacing with the Rotman Lens. The main motivation for this choice is the wide bandwidth, compatible with the K/K$_a$ satcom frequency bands, and the use of air/vacuum propagation medium in the parallel plate waveguide section to avoid dielectric losses associated with microstrip implementations. We present a design capable of fully exploiting the ridge waveguide bandwidth with wide beam scanning, outperforming previous works. The presented design consists of a 13×7 Rotman Lens with a scanning range of ±50 degrees operating between 16 and 40 GHz, validated through full-wave simulations.**

***Index Terms*—5G, Satellite on the move, Beam forming networks, Rotman Lens, Double Ridge Waveguide, K/K$_a$ Band**

I. INTRODUCTION

The demand for ubiquitous broadband internet access is pushing forward the development of new mobile terrestrial and space communication infrastructures. K and K$_a$ frequency bands are expected to become a common place in a near future of 5G and satellite communications [1]. There is an intense research effort on the development of broadband (multi)beam antennas [2], [3]. The design of the corresponding beam forming networks (BFNs) is particularly challenging for millimetre-waves, as they become more inefficient and complex with the increase of the operation frequency and aperture size relative to the wavelength in order to compensate for higher propagation losses. For these reasons, quasi-optical beamforming solutions are considered well suited for higher frequencies [4]. In particular, the Rotman lens (RL) [5], as a true time delay BFN, offers a combination of broadband operation with low-cost, compactness and wide-angle beam steering. Continuous improvements and variation on this classic topic are still being put forward [6]-[10]. This work presents a Rotman Lens design with wide-angle (±50º) and ultra-wide band (16-40 GHz) using standard double ridgewaveguides (WRD180) as array and beam ports. In fact, the combination of the large operation bandwidth of ridge waveguides and of the Rotman lens has been previously reported [6], [9]-[11]. Specifically, an exhaustive comparison between different feeding port designs was provided in [10], which confirmed the superior performance of ridged waveguide designs. In [6], ultrawideband was achieved but only for a limited scanning range and small number of array and beam ports (5×5). The impact on the operating bandwidth of the transitions between the array and beam ports to the central parallel plate waveguide (PPW) was investigated in [11], indicating a careful design is required to achieve an ultrawideband response with waveguide ports, even when ridged waveguides are implemented.

In this paper, a novel transition design is proposed which demonstrates superior performance compared to previously reported ones. Specifically, the sidewalls of the ridged waveguides are not connected as in previously reported designs. Instead, a longitudinal corrugation is implemented between each feeding ports, which has a positive impact on the return loss and port-to-port coupling at the expense of a moderate increase in the distance between adjacent ports. A standard WRD180 double ridge waveguide (18-40 GHz) is used as the input and output ports of a 13×7 Rotman lens with a scanning range of ±50 degrees. Bézier curves is applied in the design of the Rotman lens transmission lines (TLs). This method provides smooth curvature, which is particularly important when aiming for ultrawideband operation, as is the case in this work. The results were validated by full-wave simulations using CST microwave studio [12]. The return losses of the presented design are better than 10 dB even beyond the K/K$_a$ bands of interest for satcom applications (16-40 GHz). The proposed design outperforms previous works when comparing return loss, wide angle scanning and bandwidth. The work paves the way for a future experimental validation that is being planned.

II. ROTMAN LENSES DESIGN

A. Geometry

The general design rules of a RL are well establish [13], which are based on Geometrical Optics for the definition of the paths from the Beam Ports (BPs), through the Array Ports (APs) and ending at the Radiating Elements (RE) (Figure 1). However, these initial values need to be adjusted considering the real structure of the beam and array ports (in our case standard ridges WRD180) and corresponding transitions to the PPW. The design parameters are shown in Table 1. These values followed from an iterative optimization using preliminary full-wave tests. We adopt a 13×7 configuration with a ±50 degrees scanning range, which is a representative example of a RL design for 5G and satellite-on-the-move (SOTM) applications. We limit the number of ports to keep the associated computational effort manageable, which is required for full-wave optimizations. A practical design may be adapted in size to meet given requirements. The focal length f_1 was kept as low as possible ensuring low reflections and good illuminations of the array ports according to full-wave results. The value of β, that controls the shape of the focal arc, was adjusted to minimize the coupling between adjacent ports. The profile of the focal arc and inner lens contour are shown in Figure 2.

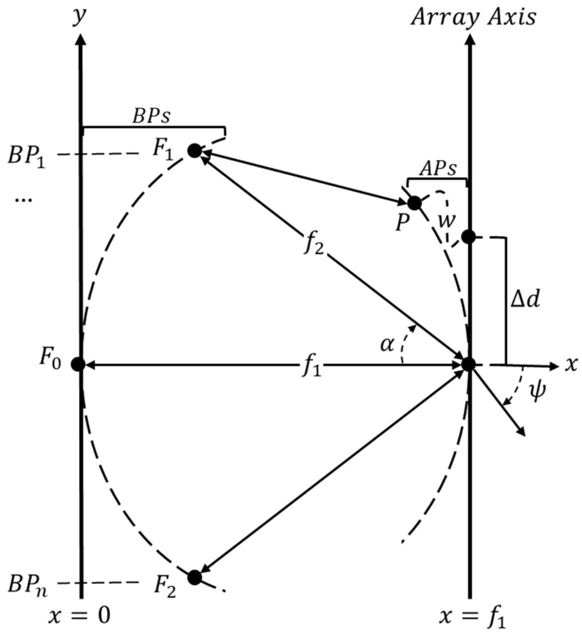


Figure 1. Rotman lens schematics [13].

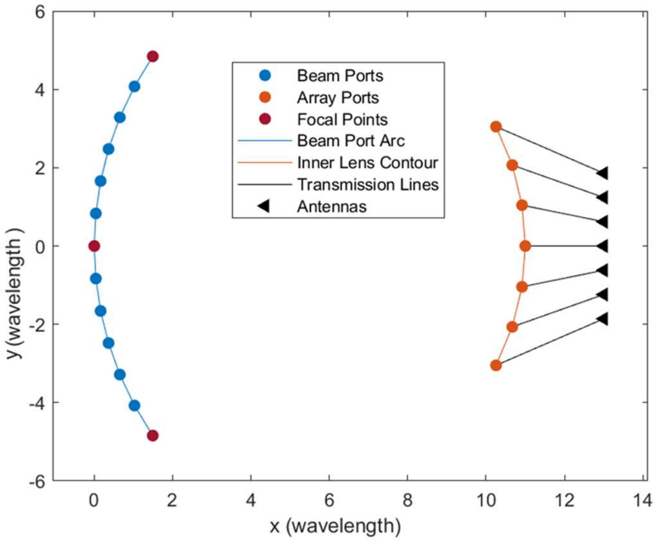


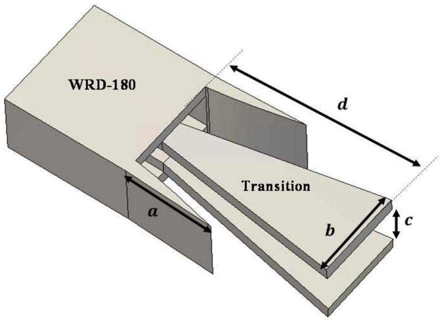
Figure 2. Profile of the designed Rotman lens .

Table 1 – Design parameter of the Rotman Lens.

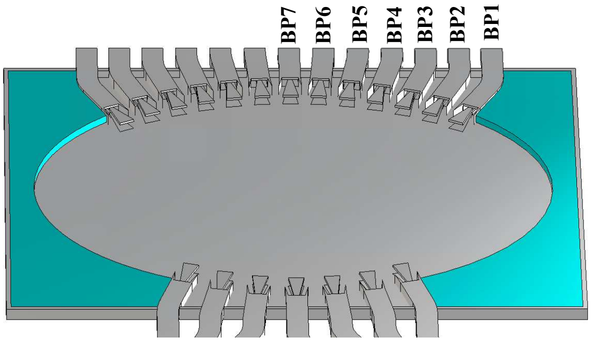
Variable	Value
Number of input ports	13
Number of output ports	7
Focal angle, α	±27º
Focal ratio, $\beta = f_2/f_1$	0.97
Maximum beam angle, $\psi_{\text{máx}}$	±50º
Focal length, f_1 (mm)	137
Array element spacing, Δd (mm)	9.7

B. Double Ridge to PPW Transition

A proper design of a transition is required to ensure a wideband behaviour of the lens. The design proposed in [10] was adapted and optimized to operate between 16 and 40 GHz. The final dimensions are shown in Figure 3, which also contains a representation of the positioning of these transitions along the focal arc, illustrating the longitudinal corrugation introduced between adjacent ports (Figure 2b).



(a)



(b)

Figure 3. (a) Geometry of the design Ridge to PPW transitions with $a = 7\ mm$, $b = 6.8\ mm$, $c = 3.4\ mm$, $d = 14.9\ mm$. (b) Transitions in the Rotman lens.

C. Assembling the Rotman lens

After positioning all the lens components in the previously calculated locations, the lens is closed. The PPW takes a rectangular shape filled with absorbing material (ECCOSORB NA 77) on the sides so that reflections due to spillover are minimized. In fact, absorbing material was also included originally between each feeding ports within the rectangular cavity. It was found that removing them would not affect notably the performance, thus simplifying the design and assembly. This also introduces new design parameters with the length of these longitudinal corrugations, which may be further investigated in the future. The remaining absorbing material on the sides of the cavity can be removed as well, by adding new ports (including dummy ports) which would allow achieving an all-metal design. Finally, the TLs, designed using Bézier curves, are added, completing the RL beamformer. Figure 4 shows the final design of the lens.

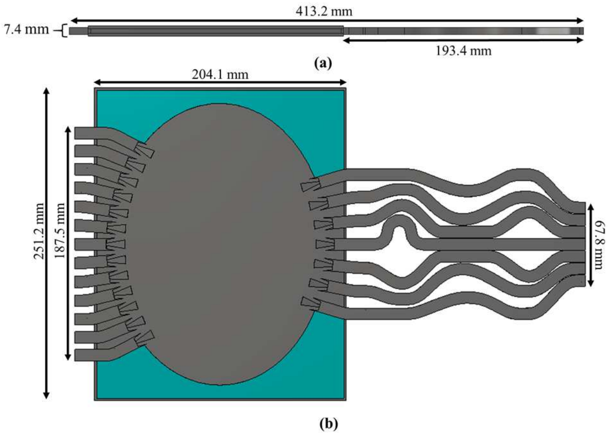


Figure 4. 3D Model representation [CST]: (a) side view; (b) top view.

III. NUMERICAL RESULTS AND DISCUSSION

This section shows the full-wave simulation results of the model presented in Figure 4. The model was simulated from 16 to 40 GHz using the FDTD solver of CST Microwave Studio. In Figure 5 it is shown that all the scattering parameters between the beam ports are well below -10 dB over the entire analysed band.

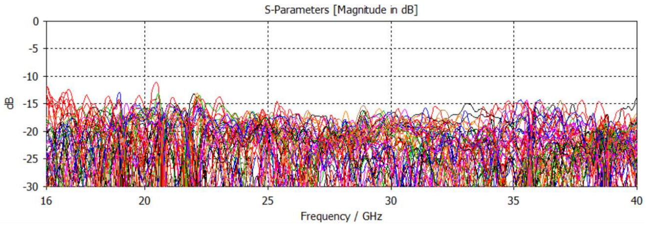
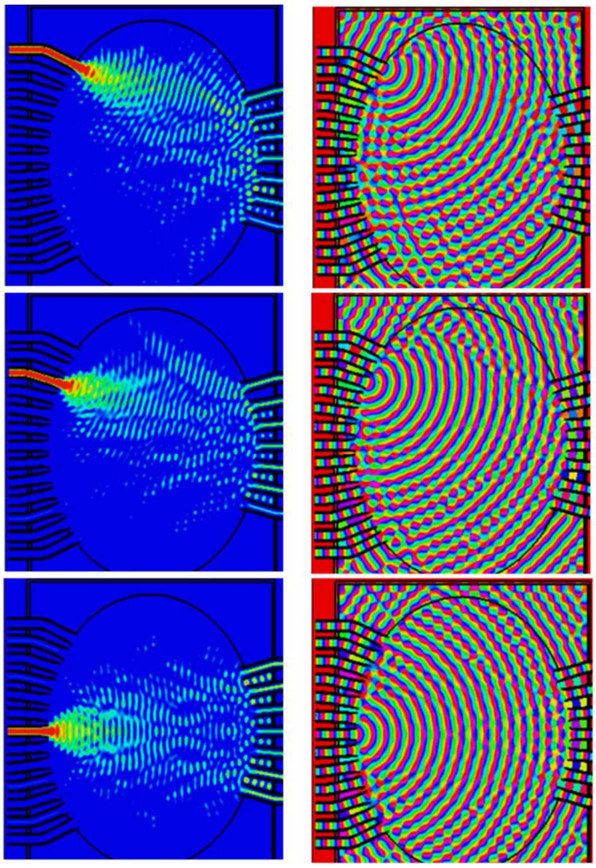


Figure 5. S-parameters between all beam ports 16 to 40 GHz.

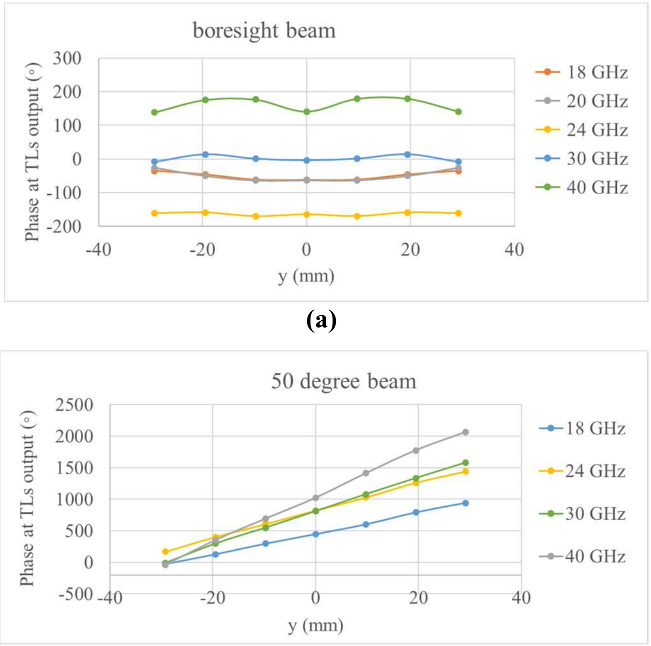
The field amplitude and phase representation inside the lens is shown in Figure 6 for different beam ports at 30 GHz. This representation highlights the role of the cavities between the arrays ports on reducing reflections back to the beam ports. As expected, a significant spill over is observed due to the small size of the array contour. This may be mitigated adding more array ports; however, it would increase the numerical complexity of the analysis. The presented design is sufficient for showing the broadband potential of this approach.



(a) **(b)**

Figure 6. Amplitude (a) and phase (b) field distribution inside RL for 30 GHz for three different beam port excitations.

Figure 7 shows the phase variation at the output of the TLs for two beam positions, the central one and the most scanned one, confirming the stable design of the complete beamformer over the analysed frequency range. In Table 2 the beam direction and corresponding phase errors are also presented. The corresponding array factors for port 1, 3 and 7 for 18 and 30 GHz are represented in Figure 8. A good agreement of the full-wave results with the reference case of ideal linear phase variation and constant amplitude is obtained. Finally, in Table 3 the presented design is compared with other broadband RL designs in terms of lens size, TL technology, scanning range, frequency range and 10 dB return loss bandwidth. This comparison clearly highlights the benefits of presented design.



(a)

(b)

Figure 7. Phase at the output ports of the TLs (each dot corresponds to a different TL) considering multiple frequencies for the central port (a) and most scanned one (b).

Table 2 –Beam direction and average phase error for sequential beam port excitation (see Figure 3b), at 18 GHz, 30 GHz, 40 GHz.

BP (#)	18 GHZ		30 GHZ		40 GHZ	
	ψ (°)	Average Error(°)	ψ (°)	Average Error(°)	ψ (°)	Average Error(°)
1	50.6	7.1	48.9	12.0	49.0	19.9
2	40.2	9.8	39.9	10.0	39.1	19.7
3	30.8	5.6	30.7	11.2	30.1	13.6
4	23.0	9.5	22.6	15.0	22.0	19.7
5	14.9	9.8	14.0	12.7	14.3	28.0
6	7.7	9.3	7.5	15.7	7.0	20.8
7	0.0	10.2	0.0	7.0	0.0	18.5

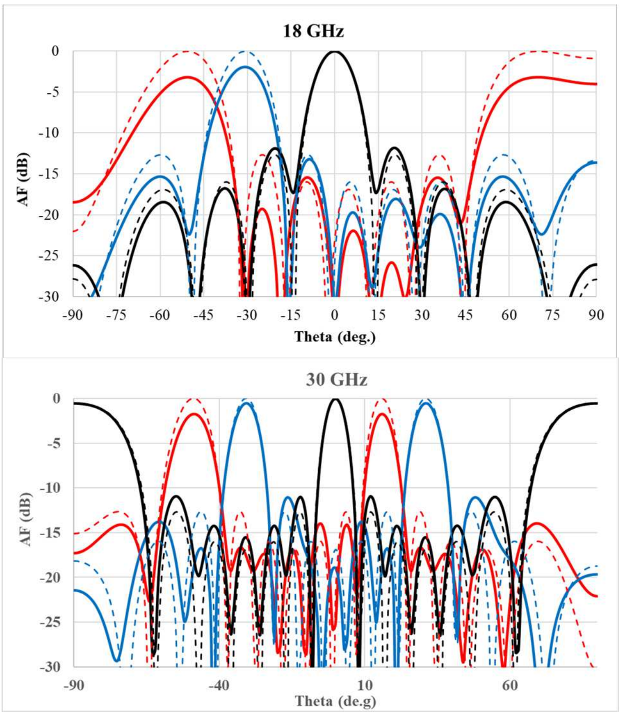


Figure 8. Array factors for ports 1,3 and 7 at 18 GHz and 30 GHz. Comparison of the full-wave simulations (solid lines) with the case of ideal linear phase variations and constant amplitude (dashed lines).

Table 3 – Comparing different broadband Rotman lens designs.

	Size	**Tech.**	**Scan**	**Freq. (GHz)**	**10 dB Bandwidth**
[6]	5×5	Ridge	±30 º	6-18	100%
[8]	18×16	Microstrip + PMU	±30º RL ±60º RL+PMU	20-25	23%
[10]	13×11	Ridge	±15 º	37-43	15%
This work	13×7	Ridge	±50 º	16-40	86%

IV. CONCLUSION

This work presented a Rotman lens design with ultrawide band operation and wide angular scanning range. The bandwidth potential of WRD180 double ridge waveguides was fully exploited thanks to a novel design of transitions between the beam/array ports and the PPW section. This work confirms the potential of ridge waveguide technology for millimeter wave applications. Future works will include investigations on the design of the proposed longitudinal corrugations, as well as experimental validation.

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