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Innovative Rotman Lens Setup for Extended Scan Range Array Antennas

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***Abstract* – The aim of this work is to design a smart and cost effective 24 GHz Short Range Radar (SRR) array antenna system for automotive applications. The beam forming network consists of a hybrid solution including an analog phase shifter, realized with a Rotman lens, and an additional digital phase shifting stage on array side allowing to select between two states, and consequently to enhance the scan angle. This paper will demonstrate that this new concept allows to double the scanning capability of the array with respect to a design employing only the Rotman lens.**

1 INTRODUCTION

The continuous increase of technology in cars for improving security is setting demanding requirements to the automotive suppliers to design compact and low cost solutions to fulfill this needs.

Short Range Radars (SRR) and Long Range Radars (LRR) are one of the key technologies used to increase intelligent security and comfort systems in vehicles. In fact SRR operates around a vehicle to prevent possible impacts by detecting obstacles or even other cars, so that safety measures can be triggered automatically.

Rotman lenses are planar structure, so they are easy to manufacture and for its low weight, low cost and reliability represent a good solution for array systems in the automotive market.

This particular lens represents the key element of the antenna system, and it provides phase shifting in a wide frequency range in true-time delay (TTD) mode to a linear antenna array.

Despite the easy integration of this beam forming device and its good performance, it is critical to achieve wide scanning angles while maintaining a good level of the beams in correspondence of the higher scanning angles without remarkably increasing design complexity.

Many attempts for improving the Rotman lens have been made in past years: in literature can be found different solutions ranging from refinement of design equations for improving the phase error [1] - [4], to the exploitation of new technologies (e.g. the use of Substrate Integrated Waveguide) for incrementing the performance of the overall lens [5] - [8].

However in this research activity a new concept to double the scan angle of the Rotman lens without introducing complexity in the design, along with typical trade-offs to achieve a wide scan range will be described and verified.

2 DESIGN PRINCIPLE

This study will not focus just on the Rotman lens design, attempting to develop a wide scan angle lens, but instead it proposes a new concept that combines this particular lens and an appropriate pattern of digital phase shifters.

The design concept is depicted in *Figure 1*, where the three main components of the antenna system and their connections are displayed.

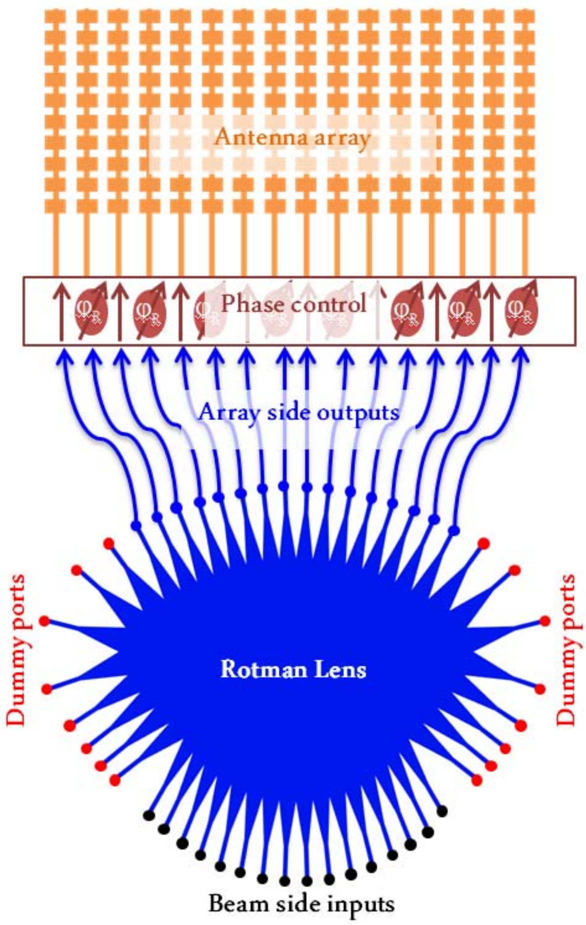

Figure 1: Illustration of the extended scan range Rotman lens concept for automotive SRR including all main components.

It is clear from the picture that the innovation is the use of phase shifters with two possible states on every second line of the linear array side of the Rotman lens. These states correspond to $\varphi_R = 0°$ for the first one and $\varphi_R = 180°$ for the second one.

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It will be pointed out that this peculiar arrangement of phase shifters providing φ_R = 180° introduces a phase distribution on the array whose effect causes a "mirroring" of the beam respect to the broadside position. However, in order to exploit this technique, a further crucial keynote has to be implemented.

In fact, calling ±Ψ the steering angles of the Rotman lens, in order to achieve a correct mirroring effect an appropriate phase translation has to be applied for setting the broadside beam to Ψ position. In this way the Rotman lens will introduce a phase distribution (in the case of φ_R = 0°) that performers an array scan from 0° to 2*Ψ.

Then these beams can be then easily mirrored by setting φ_R = 180°: the feeding network including the phase distribution of the Rotman lens and the half wavelength phase shifting organized in the described pattern creates beams with same property and control as the previous case (scanning is driven by Rotman lens in the same way as φ_R = 0°) but in the range from 0° to -2*Ψ.

3 SYSTEM DESIGN

In order to prove the innovative concept described in the last paragraph a phased array composed by a Rotman lens, phase shifters and an antenna array has been designed and simulated.

3.1 ROTMAN LENS DESIGN

The key element of this Radar array is the TTD phase distribution given by the Rotman lens. In this research a 24 GHz tri-focal Rotman lens enabling scanning angles of ±30° (Ψ = 30° according to previous notation) and composed by 16 beam ports, 16 array ports and 8 dummy ports in both sides has been designed according to the formulation described in [9] and [10]. Moreover the calculated lens contour has been optimized through full wave simulation by employing Empire XPU [11].

The simulated model of the lens is depicted in *Figure 2*.

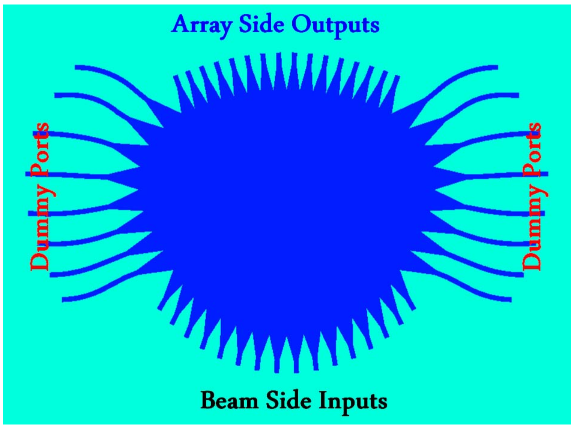

Figure 2: EMPIRE XPU model of the Rotman Lens.

The lens has been designed on a 0.508 mm Roger RO4350 substrate material, characterized by ε_r = 3.66 and *tan*δ = 0.004. This structure allows measurement accuracy better than 0.5° in azimuth field of view, if the amplitude imbalance between adjacent beams is taken into account.

3.2 PHASE SHIFTERS

The digital phase shifters (φ_R equal to 0° or 180°) have been considered ideal for the development of this concept design, and practically they have been inserted as concentrated components on every second line connecting the Rotman lens to the antenna array (i.e. in this design only 8 phase shifters are needed for providing the "beam mirror" effect).

As already discussed in the second paragraph, the main beam has to be translated to 30° for the correct function of the mirroring effect.

This reshaping of the center beam is shown in *Figure 3*, where a beam is initially tilted at 30° and by setting a phase delay φ_R = 180° in every second line of the array feeding network the beam is then tilted to -30°.

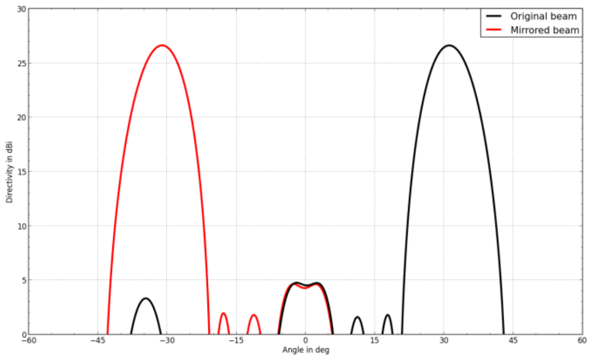

Figure 3: Simulated functionality of the beam mirror principle: setting the main beam to Ψ and by applying φ_R = 180° the beam is mirrored with respect to broadside position.

3.3 ANTENNA ARRAY DESIGN

The antenna array is an important part of an automotive radar system, and it must ensure a high directivity, a small Half Power Beam Width (HPBW) and low sidelobes levels.

Dimensions of the antenna system is also to be considered for best integration in the vehicle: in this work an array of 14 patches for each of the 16 channels have been implemented in a 115 x 120 mm^2 Roger RO4350 substrate with thickness of 0.508 mm (same thickness as the Rotman lens, according to the research study described in [12]) in which also 2 passive antenna array columns were inserted in order to reduce edge effects of the finite PCB and thus improving the overall performance of the array.

A Taylor amplitude tapering has been applied in order to reduce sidelobes, as can be noticed form *Figure 4*, where the complete antenna array is reported.

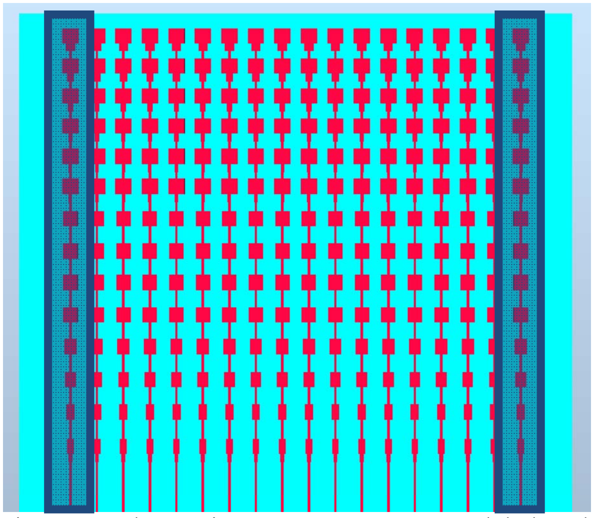

Figure 4: The 16 input antenna array modeled and simulated in EMPIRE XPU. Parasitic antennas columns are highlighted in the shaded box.

4 SIMULATION RESULTS

For showing the effectiveness of the concept it is interesting to evaluate the radiation pattern of the array with the contribution of the Rotman lens alone, without the phase arrangement described.

The result of the simulation including only the designed Rotman lens and antenna array is shown in *Figure 5*.

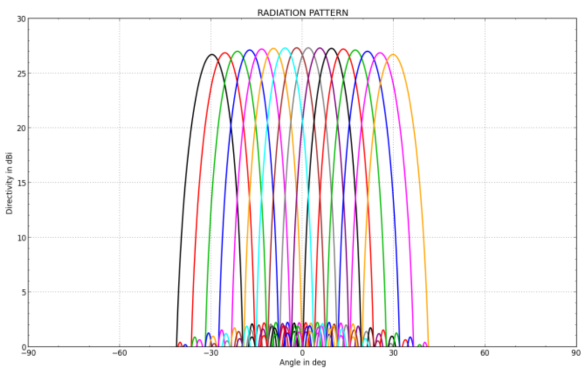

Figure 5: Simulated directivity of the antenna array driven by the Rotman lens without employing the new concept.

In *Figure 6* the simulated co-polar directivity radiation pattern of the new concept designed for the 24 GHz automotive radar are shown: it can be noticed that the beam are steered from more than ±60° with good performances in terms of radiation.

From the picture it is also clear that the “beam mirror” effect described works as expected, and the beams are symmetric in all the azimutal angles.

By comparing results depicted in *Figure 5* and *Figure 6* it is evident that the scan range is effectively doubled, without degradation of the radiation patterns in the initial scan range of ±30°.

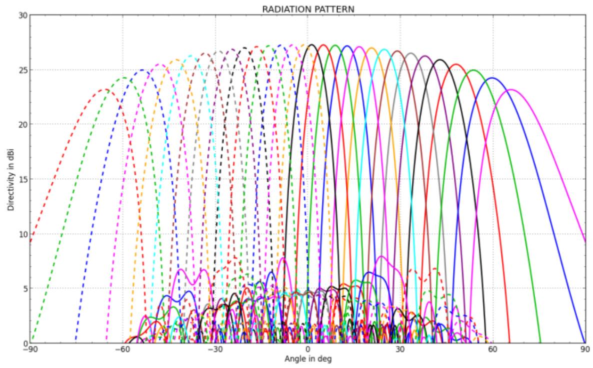

Figure 6: Simulated directivity of the SRR system. Solid lines refer to the φ_R=0° scan operation; dashed lines refer to φ_R=180° scan.

The simulated directivity shows its maximum at broadside, with the value of 27 dBi, while the lowest value is of 23 dBi in correspondence of a beam tilted at 65°.

For sake of completeness it will be reminded to the reader that in this proof of concept the phase shifters were considered ideal, so no contributions to radiation performance have been introduced by these components. In addition, especially for wide scanning angles, the active impedance of each antenna column will change. This will introduce an additional mismatch loss for wide scanning angles.

5 CONCLUSION and PERSPECTIVES

In this paper a novel concept for a phased array based on a smart combination of a Rotman lens and a digital phase shifting stage has been presented and validated through simulation. The scan range of the radar has been doubled with respect to the use of only the lens as phase distribution device. This wide angular range has been achieved by exploiting a peculiar phase shifter pattern in only half of the ports on array side.

This new concept for phase distribution allows to avoid complicates and sub-optimal designs of the lens, as well as the increase of complexity on the beam side of the lens (e.g. by increasing the number of input ports and consequently all the electronics behind). As final remark it will be noticed that no degradation of the performance of the radiation pattern was observed.

For these reasons the presented design is particularly suitable for high performance automotive radar applications, where size, dimensions and costs are key factors, especially in the case of SRR radars that are placed in many position along the vehicle.

The next step of this research activity is the physical realization of the proposed concept, including a compact and suitable implementation of the φ_R variation along the feeding lines.

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