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Phase Management for Extended Scan Range Antenna Arrays Based on Rotman Lens

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***Abstract*— This paper presents an implementation of a technique aimed to double the scanning range of a 24 GHz array antenna system based on Rotman lens beamforming. The new concept of the enhanced beam forming network consists of a combination of Rotman lens and 1-bit phase shifters, positioned in a peculiar way on the array side of the lens, and together with a particular beam arrangement allows to overcome the scan limitations which is typical of the standalone Rotman lens solution. Simulations will demonstrate that a Rotman lens, designed to steer the beam up to ±30°, when arranged in combination with properly designed Ratrace based phase shifters, allows to increase the scan range up to ±60°.**

Index Terms— ***Rotman lens, phased array, beamforming network.***

I. INTRODUCTION

Modern communication systems and radars require high performance, efficient and low cost beam steering devices. In this context increasing interest is gaining the Rotman lens, because of its planar structure, that is easy to manufacture and for its low weight, low cost and reliability represent a good solution for array systems. Moreover, this particular lens provides phase shifting in a wide frequency range in true-time delay (TTD) mode to a linear antenna array, and this made it attractive in many applications.

Despite the easy integration of this beam forming device and its reliable performance, Rotman lens has shown to lead to critical solutions when very wide scanning angles are meant to be achieved. In these cases the design of the lens exhibits high beam pointing errors and low levels of the beams, mostly due to internal reflections. Many attempts for improving the Rotman lens have been investigated: in literature can be found different solutions ranging from refinement of design equations for the definition of the lens geometry [1] - [4], to the exploitation of innovative technologies (e.g. the use of Substrate Integrated Waveguide, LTCC or Liquid Cristal Polymer substrates) for incrementing the performance of the overall lens [5] - [7].

However, in this paper a new concept for enhancing the scan range of the Rotman lens by introducing 1-bit Reflective Phase Shifters (RPS) will be described and numerically verified.

II. DESIGN CONCEPT

As discussed in the previous paragraph, the Rotman lens is an attractive solution for antenna array beamforming due to its good performances and easy manufacturing. In Fig. 1 an example of phased array realized with Rotman lens is illustrated.

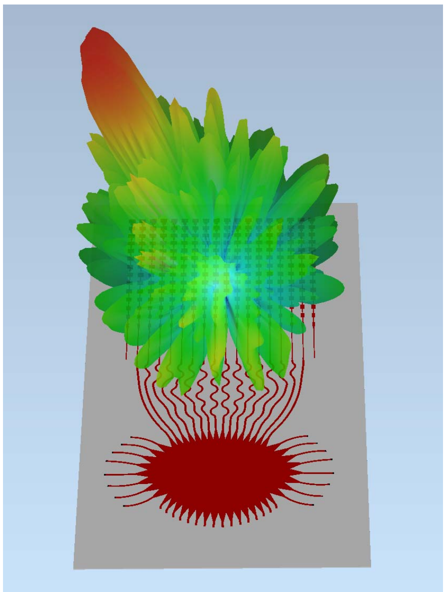

Fig. 1. Standard approach for antenna array beamforming employing Rotman Lens.

This work is based on the concept recently described in [8], where the main purpose was to develop a concept that allows to use the Rotman lens beamforming in Short Range Radar (SRR) systems for automotive application. In fact, a new method aimed to widen the scan range of the Rotman lens was necessary for making it usable in automotive radar applications, and thus exploiting its low cost and compact structure. Moreover, it was demonstrated that by adding a phase management stage between the antenna array and the Rotman Lens an extended scan range can be achieved, as represented in Fig. 2. Furthermore, in the concept development only ideal components were used in order to provide the necessary phase shifting.

Besides, in this paper the innovative phase management model is realized by a proper design of 1-bit phase shifters that incorporate the 2 basic operations for the broadening of the scan angle, named “beams mirroring” and “complete beams shifting”. In fact, the phase management block, inserted between the antenna array and the Rotman lens, is characterized by a particular pattern and it produces the two effects already mentioned, that will be described separately.

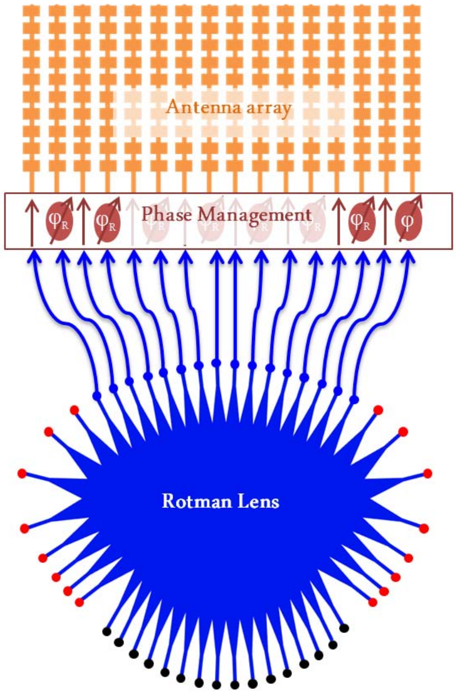

Fig. 2. Drawing of the extended scan range Rotman Lens antenna array, in which the 3 main components are highlighted.

The first phase adjustment introduces a shifting of all the beams towards positive scan angles (or equivalently to negative scan angles). In Fig. 3 the “beam shifting” application´s result is shown: it can be noticed that starting from the typical array scan distribution given by a Rotman lens, in which the beams are ranging from ±Ψ, a complete shifting of the beams is performed through the application of an additional phase contribution to the beamforming network. In this way, the array scan produced with the combination of Rotman lens and beam shifting ranges from 0° to 2*Ψ.

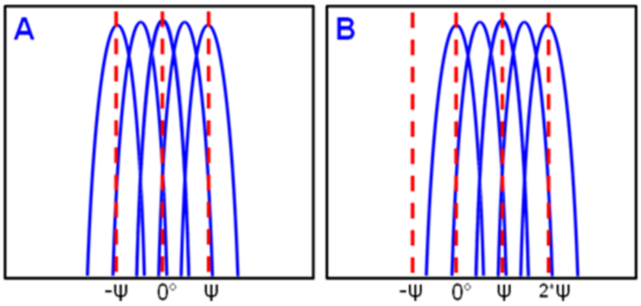

Fig. 3. Working principle of the complete beam shifting effect. In picture A) the beams are related to the antenna array only, while in B) the beams are shifted towards positive scan angles by appliying the beam shifting.

The second effect, which is the keynote for the enhanced scan range of the Rotman lens, exploits the so called “mirroring effect” that is depicted in Fig. 4.

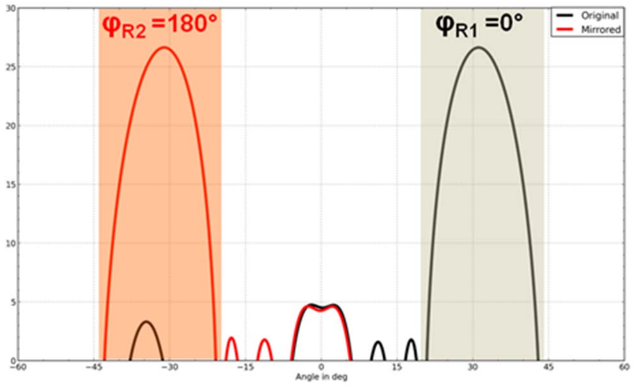

Fig. 4. Beam mirroring functionality: the beam is mirrored by setting the phase shift value φ_R to 0° or 180°.

In fact, the variable phase shifters pattern that can be noticed in Fig. 2, in which the phase is changed every second line that is feeding the antenna array, is composed by 1-bit phase shifter that corresponds to two states setting $\varphi_{R1} = 0°$ and $\varphi_{R2} = 180°$.

In particular, when the antenna array is excited by the Rotman lens and the additional 180° phase inversion is active in the described order, the beam selected by a specific beam port of the Rotman lens is mirrored with respect to broadside.

It is now easy to recognize that, by putting together the “complete beam shifting” with the “beam mirroring” effect, a double scan range for the Rotman lens based beamforming can be achieved: in fact considering first the state $\varphi_{R1} = 0°$ for an initial ±Ψ scan range system by shifting all the beam for having the span from 0° to 2*Ψ, and consequently switching to $\varphi_{R2} = 180°$ all the beams can be mirrored covering the range from 0° to -2*Ψ. This description is summarized in Fig. 5, where it is also shown that the final scanning range is ±2*Ψ, that is equivalent to double the one provided by the Rotman lens only.

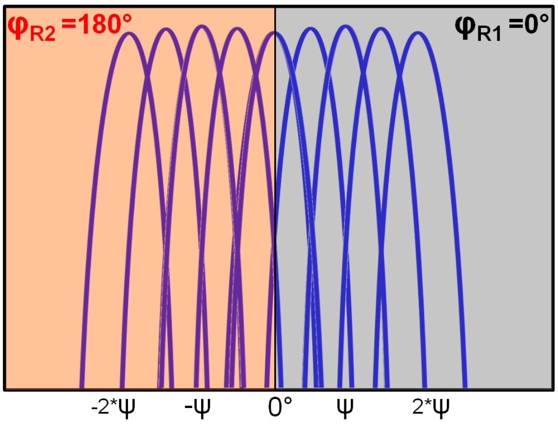

Fig. 5. Combination of “complete beam shifting” and “beam mirroring” for scanning range extension of Rotman lenses.

III. PHASED ARRAY DESIGN

The described concept will be verified by designing the complete phased array, whose main elements are the

Rotman lens, the 1-bit phase shifters and the antenna array. The phased array has been modeled and simulated by Empire XPU [9].

A. Rotman Lens Design

Rotman lens is the key part of the beamforming network: ideally it provides the right phase and equal amplitude at all the antenna array inputs.

In order to prove the extended scan range concept, a 24 GHz tri-focal Rotman lens enabling scanning angles of ±30° (identified as $\Psi = 30°$, mentioned in previous paragraph) and constituted by 16 beam ports, 16 array ports and 8 dummy ports on each side, has been calculated and simulated according to the formulation described in [10] and [11].

The simulated model of the lens, including the TEM delay lines used for connecting it with the antenna array, is depicted in Fig. 6.

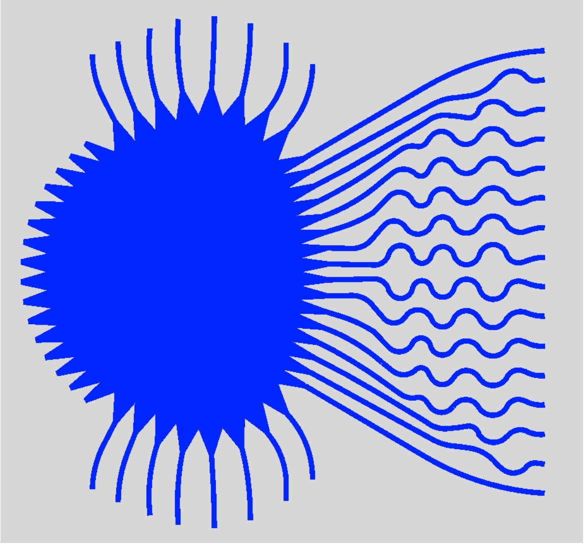

Fig. 6. Complete model of the Rotman lens designed in Empire XPU.

B. Phase Shifters Design

In order to fulfill the widening scan range of the Rotman lens beamforming, 8 digital phase shifters (corresponding to half of the Rotman lens array ports, which number is 16) have to be designed. Moreover, a proper phase adjust is needed for providing the complete beam shifting, as already discussed. From array theory, it is known that, for achieving the complete beam shifting depicted in Fig. 3, a n X 90° phase shift (with n=1, 2,..,16 number of array ports) has to be applied at the antenna array.

These two functions can be easily combined by using just one component for providing a constant phase shifting, and in addition, a controlled phase inversion state. One of the best structures to be used for such an operation is the Rat-race coupler, that together with PIN diodes placed in antiparallel position, can realize a 1-bit Reflective Phase Shifter.

In fact, the PIN diodes are meant to command the loading of two terminations that presents high reflecting coefficient, and are 180° out of phase with respect to each other.

With the same structure it is easy to realize also a static phase shifter by simply ensuring the latter condition, as can be also recognize by Fig. 7.

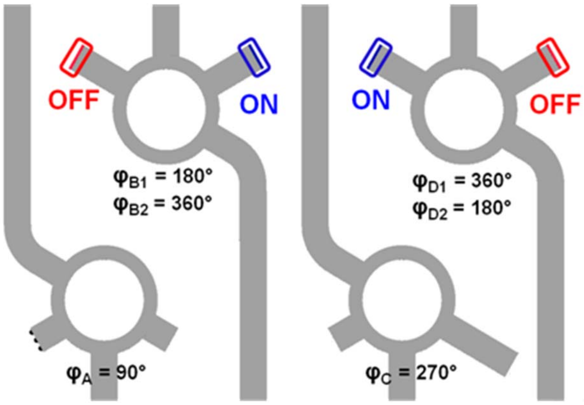

Fig. 7. Circuit model realization for the phase management block. In the picture the state φ_{R1}, corresponding to 0° phase shifting is depicted. The state φ_{R2} =180° can be achieved by swapping the state of the pin diodes, highlighten in blue and red boxes.

With reference to Fig. 7, it is shown how the phase management block has been practically designed. In particular the first and third Rat-race based RPS provide the 90° and 270° constant phase shifting, while the other two are loaded with ideal PIN diodes (i.e. ON state is realized by direct connection to ground, while OFF state produce an open in the line termination) whose states gives the 0° and 180° condition, due to the exploitation of the selection of open and short terminations.

As an example, the S-parameters for the lines providing φ_A and φ_B are reported in Fig. 8, showing also a quite broadband performance of this solution. It is important to make notice that a good return loss ensure that no power is coming back in the Rotman lens, thus interfering with the proper wave distribution inside the lens.

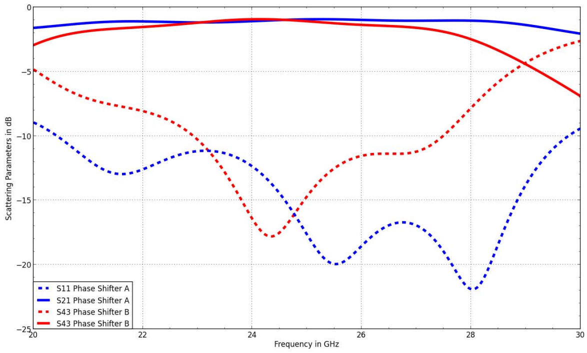

Fig. 8. S-parameters of the phase management lines providing 90° (blue) and 180° (red).

C. Antenna Array Design

The antenna array is an fundamental part of the system, and its performance influences the final operation of the scanning array. In this research study an array of 14 patches and 16 columns (for each of the 16 channels of the Rotman lens) have been implemented in a 0.508 mm thickness Roger

RO4350 material, as well as the beamforming network already described. Furthermore, for reducing the sidelobes level, a Taylor amplitude tapering has been applied, together with 2 passive antenna array columns inserted for reducing the edge effects of the finite PCB and thus increasing the overall performance of the array. Fig. 9 provides the image of the simulated model, in which the described phase management block, composed by active and passive Ratrace based phase shifters, has been included. In addition, from the figure the two passive antenna columns can be recognized.

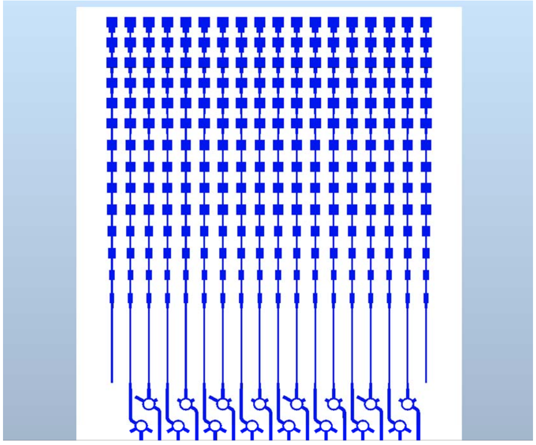

Fig. 9. Empire XPU model of the designed antenna array, in which also the phase management stage is inserted.

IV. SIMULATED RESULTS

As previously explained, the operative conditions of the 24GHz extended scan range beamforming network based on Rotman lens can be divided in two separate parts: the first is characterized by $\varphi_{R1} = 0°$, while the second one is characterized by the state providing $\varphi_{R2} = 180°$.

The radiation pattern resulting from the combination of the Rotman lens phase distribution and the phase management in the first state (Rat-race based phase shifters adding 0° to the complete beam shifting condition) is shown in Fig. 10, while the case in which the RPS provide extra 180° phase shifting is reported in Fig. 11.

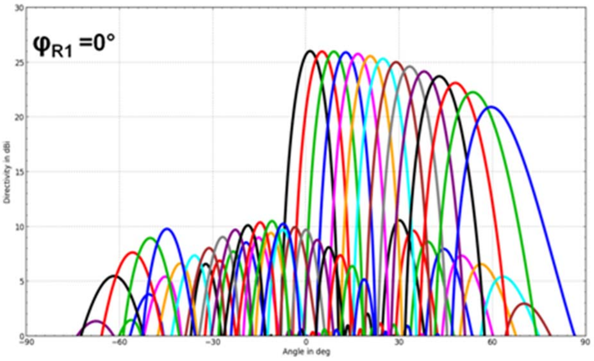

Fig. 10. Simulated directivity of the extended scan range Rotman lens based phased array with φ_{R1} =0°

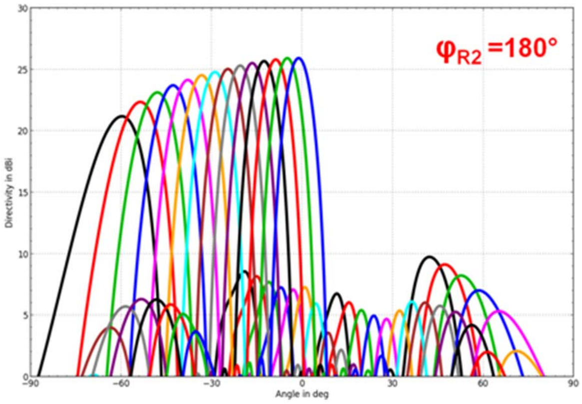

Fig. 11. Simulated directivity of the extended scan range Rotman lens based phased array with φ_{R2} =180°

From the simulated co-polar directivity radiation pattern it can be noticed that beams are steered for ±60°, instead of the initial ±30° given by the lens alone, with good performance in terms of radiation. Furthermore, it can be seen that the "beam mirror" effect works as expected, and the beams are symmetric in all the azimutal angles.

In both Fig. 10 and Fig. 11 the simulated directivity shows its maximum at broadside, with the value of 26 dBi, while the lowest value is 21 dBi in correspondence of a beam tilted at 60°. It can also be noticed that there is a slightly increase of sidelobes in the state $\varphi_{R1} = 0°$: this is probably due to the slightly different performance of each phase shifter, whose effect depends on the position and the state of the PIN diodes. 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.

V. CONCLUSION AND PERSPECTIVES

In this work, the novel concept for a phased array based on a smart combination of Rotman lens and reflective type phase shifters based on Rat-race couplers has been presented and validated through simulations. The scan range of the phased array has been doubled with respect to the use of only the lens as beamformer. The designed phase shifters show good performance and straightforward integration on the antenna array system. The choice of using PIN diodes as switching device allows to have only one control voltage for controlling the direction of the beam towards positive or negative angles.

Finally, as next step of this project it is planned to fabricate and measure the designed system, including also the integration of the active components.

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