Design and Simulation of a Power Efficient Waveguide Rotman Lens

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Abstract—Rotman lens is a true-time-delay beam forming network with parallel plate structure. Owing to its frequency-independency and wide-band operation, it has gained vast applications as feeding element of linear array antennas. However, the lens suffers from high intrinsic power loss and the problem worsens in microstrip structures by their inevitable dielectric loss. On the other hand, waveguides experience extremely lower loss and also have higher power capacity. Thus, waveguides can be advantageously utilized in Rotman lens structure. Here, a waveguide Rotman lens for the frequency range of 8 to 12 GHz is designed and simulated in CST Microwave Studio. Phase error and power efficiency of the proposed structure are satisfactory.

Index Terms—Rotman lens, waveguide, phase error, phased array antenna.

I. INTRODUCTION

Rotman lens, a beam forming network with parallel-plate structure, has attracted much attention from the early days of introduction [1-7]. Frequency-independency of beam-steering, easy and low cost fabrication, light weight, and simultaneous availability of many beams are the advantages that make it an excellent candidate to be used in various applications, especially in satellite-based radiating arrays [4]. The parallel-plate structure of Rotman lens is based on TEM mode propagation; therefore, it has a theoretical wide bandwidth. Although, propagation of higher modes in the connected transmission lines limits the ultimate frequency bandwidth [2, 8, 9].

Rotman lens suffers from inherent power losses to the extent that, in some cases, more than half of the power dissipates within the lens [10]. This power loss in microstrip Rotman lens can be aggravated by ohmic and dielectric losses. These inevitable losses in microstrips cause adverse heating and can eventually lead to dielectric breakdown. Consequently, their maximum power capacity is strictly limited [11]. Also, in microstrip Rotman lens, designing a structure for matching the microstrip lines to the parallel plates is vital. On the other hand, waveguides experience considerably reduced dielectric and radiation losses. High power handling capacity and unnecessity of designing a matching structure are other advantages of waveguides over microstrips.

Unlike waveguide Rotman lens, the microstrip type has been subject of numerous past studies [4, 5, 12, and 13]. In this research work, for maximum scan angle of ±20° and the frequency range of 8-12 GHz, designing a Rotman lens with WR90 waveguides is accomplished. Ports coupling, spill-over loss and phase errors are considerably influenced by the shape of the lens [1]. Here, a lens shape is achieved which has minimum phase error and its power efficiency is improved in comparison to the reported microstrip one.

II. DESIGN PARAMETERS

Fig.1 shows the schematic diagram of a typical Rotman lens. F₀ is the on-axis focal point with (G, 0) coordinates. Off-axis focal points of F₁ and F₂ have (-Fcos α, Fsin α) and (-Fcos α, -Fsin α) coordinates, respectively. The off-axis focal points correspond to the maximum scan angle, ±θ₀. For obtaining smaller scan angles, non-focal points can be placed between the focal ones. The array points on the Σ₁ curve, Pᵢ, are connected to the antenna elements with transmission lines of electrical length, Wᵢ [1, 2].

For a set of design parameters, array ports positions and lengths of transmission lines can be calculated using equations derived by Rotman and Turner [2]. These equations have few degrees of freedom whose connections with the lens shape are not explicit. Each set of these freedom degrees lead to different lens shapes with different spill-over losses and phase errors. Compact lens have less spill-over loss, but slight differences in curve heights cause unequal optical path-lengths and consequently, serious phase errors [1]. So a trade-off between the spill-over loss and the phase error must be made. The effects of these parameters on the shape of the lens are demonstrated below.

![Fig. 1](image-url) Schematic diagram of a typical Rotman lens.
The design parameters are focal angle, $\alpha$, focal length, $F$, array element spacing, $d$, and focal ratio, $g$ that is defined as [1]:

$$g = \frac{G}{F}$$  \hfill (1)

In order to obtain minimum phase errors, the optimum focal ratio must be a function of focal angle as [2]:

$$g = 1 + \frac{\alpha^2}{2}$$  \hfill (2)

Also array element spacing is influential on the shape of the lens. There is a maximum value for the element spacing as it affects the grating lobes [1]:

$$d \leq \frac{\lambda}{2}\left(2 + \sin \theta_n \right)$$  \hfill (3)

With all other parameters fixed, increasing focal angle opens the beam curve, closes the array curve and changes the beam and array points positions. With the focal length fixed, the effect of increasing focal ratio on the curvatures is similar to increasing the focal angle but the beam and array points positions remain approximately unchanged. Both increasing the array elements spacing and the focal length, cause an increase in the array ports spacing [1]. Considering all above, the parameters have to be properly chosen so that the heights of the two curves are similar, the off-axis focal points are inside the array ports curve, and the width of the proposed lens is moderate.

The Rotman lens designed with the chosen parameters is schematically illustrated in Fig. 2. To achieve minimum phase errors, the value of focal ratio is calculated based on equation 2. The lens is designed for the frequency range of 8 to 12 GHz, has a maximum scan angle of $\pm 20^\circ$ with $10^\circ$ steps, and feeds an array of 7 antenna elements. WR90 waveguides are utilized as ports of the proposed lens. The operating frequency band of the waveguide is 8.2 to 12.4 GHz so that propagation of higher modes is avoided. The waveguide dimensions are 22.86 $\times$ 10.16 mm$^2$ (w$\times$h). For a dispersionless parallel plate medium, the electrical field has to be perpendicular to the parallel plates. Therefore, the waveguides have to be horizontally oriented with the wide sides parallel to the plates and thus, array points spacings have to be at least equal to waveguide width. In conventional Rotman lenses, the beam curve was circular. In order to reduce the phase error, Katagi et al. proposed an elliptical beam curve [14]. So in this paper, beam curve is chosen to be part of an ellipse passing through the focal points. In order to reduce the sidelobe levels, triangle sidewalls are designed so that most of the reflections take place within the triangle sidewall region [15].

III. SIMULATION RESULTS

Fig. 3 shows the top view of the proposed lens simulated in CST Microwave Studio. The input and output ports are fed by WR90 waveguides numbered from 1-5 for the input and 6-12 for the output ones. Waveguides placed along each sidewall are terminated with waveguide ports to avoid any reflection into the structure. Using lens equations [2], Output waveguides lengths are calculated with respect to $W_0$, the central output waveguide length which is arbitrarily chosen to be 40 mm. Since the waveguide ports are not aligned with Cartesian coordinate planes, CST frequency domain solver with tetrahedral mesh is used to calculate the scattering parameters.

Simulation results of scattering parameters magnitudes in case of exciting the on-axis focal beam port are exhibited in Fig. 4. As expected, without designing a matching structure, the reflection coefficient magnitude is below -10 dB in the operating frequency range (Fig. 4.a). Also from the isolation coefficients shown in Fig. 4.a, it can be perceived that the input waveguides are quite isolated from each other. Fig. 4.b
represents the transmission coefficients magnitudes for all the 7 output waveguide ports. The insertion loss for exciting the on-axis focal beam port is calculated to be 2.06 dB at 8 GHz, 2.92 dB at 10 GHz, and 2.74 dB at 12 GHz. These results show significant improvement in comparison to the insertion losses reported for a microstrip Rotman lens designed in the same frequency range [16]. Fig. 5 shows simulation results of electric field propagation at 10 GHz frequency in case of exciting off-axis and on-axis focal beam ports. Generation of a linear phase front at the end of the output waveguides is clear from the figure.

Rotman lens equations are derived based on equality of wave path-lengths, and thus, phase errors are expected to be zero in case of focal beam ports excitation. Although, reflections of electromagnetic waves from the sidewalls of the lens result in non-zero phase errors, even for focal beam ports. Phase error values for exciting focal and non-focal beam ports are calculated from the simulation results and the average value in the operating frequency range is shown in Table 1. Owing to the elliptical beam curve, triangular sidewalls, and chosen design parameters, the obtained phase errors are believed to be the minimum ones.

![Fig. 4. Simulation results of scattering parameters for the proposed Rotman lens in case of exciting on-axis focal beam ports. Reflection and isolation scatter coefficients (a) and transmission scatter coefficients (b).](image)

![Fig. 5. Simulation results of electrical field at 10 GHz frequency in the proposed Rotman lens in case of exciting off-axis (a) and on-axis (b) focal beam ports.](image)

| Output waveguide number | Phase error corresponding to 0° scan angle | Phase error corresponding to 20° scan angle | Phase error corresponding to 30° scan angle |
|-------------------------|-------------------------------------------|-------------------------------------------|------------------------------------------|
| 7                       | 4.3°                                      | 13.6°                                     | 8.0°                                      |
| 8                       | 4.3°                                      | 11.7°                                     | 4.8°                                      |
| 9                       | 5.2°                                      | 12.6°                                     | 8.8°                                      |
| 10                      | 5.2°                                      | 11.2°                                     | 4.7°                                      |
| 11                      | 6.3°                                      | 13.2°                                     | 6.2°                                      |
| 12                      | 6.3°                                      | 10.9°                                     | 6.4°                                      |

**IV. CONCLUSIONS**

In this paper, a waveguide Rotman lens in the frequency range of 8 to 12 GHz was designed and simulated in CST Microwave Studio. For exciting 7 antenna elements and maximum scan angle of 20°, optimum design parameters
were chosen so that minimum phase errors were attained. The proposed lens shows significantly reduced insertion loss in comparison to the vastly studied microstrip Rotman lenses.

REFERENCES

[1] R. C. Hansen, “Design trades for Rotman lenses,” IEEE Trans. Antennas Propag., vol. 39, no. 4, pp. 464-472, Apr. 1991.
[2] W. Rotman, and R. F. Turner, “Wide-angle microwave lens for line source applications,” IEEE Trans. Antennas Propag., vol. 11, no. 6, pp. 623-632, Nov. 1963.
[3] A. Lambrecht, S. Beer, and T. Zwick, “True-Time-Delay Beamforming With a Rotman-Lens for Ultrawideband Antenna Systems,” IEEE Trans. Antennas Propag., vol. 58, no. 10, pp. 3189-3195, Oct. 2010.
[4] Z. X. Wang, D. P. Fan and L. Z. You, “A design of microstrip Rotman lens,” Proc. International Microwave and Millimeter Wave Technology Conf., Shenzhen, 2012, pp. 1-4.
[5] W. Lee, and J. Kim, and Y. J. Yoon, “Compact two-layer Rotman lens-fed microstrip antenna array at 24 GHz,” IEEE Trans. Antennas Propag., vol. 59, no. 2, pp. 460-466, Feb. 2011.
[6] N. Jastram, and D. S. Filipovic, “Design of a Wideband Millimeter Wave Micromachined Rotman Lens,” IEEE Trans. Antennas Propag., vol. 63, no. 6, pp. 2790-2796, June 2015.
[7] C. Rusch, J. Schäfer, H. Guian, and T. Zwick, “2D-scanning holographic antenna system with Rotman-lens at 60 GHz,” 8th European Conf. on Antenna and Propagation, The Hague, 2014, pp. 196-199.
[8] A. F. Peterson, “Scattering matrix integral equation analysis for the design of a waveguide Rotman lens,” IEEE Trans. Antennas propag., vol. 47, no. 5, pp. 870-878, May 1999.
[9] P. S. Simon, “Analysis and synthesis of Rotman lenses,” 22nd AIAA International Communications Satellite Systems Conf. and Exhib., Monterey, 2004, pp. 9-12.
[10] L. Schulwitz, A. Mortazawi, “A new low loss Rotman lens design using a graded dielectric substrate,” IEEE Trans. Microw. Theory Techn., vol. 56, no. 12, pp. 2734-2741, Dec. 2008.
[11] R. Garg et al., “Design of planar transmission lines and discontinuities,” in Microstrip Antenna Design Handbook, 1st ed. Norwood, Artech House, 2001, pp 777.
[12] B. Carlegrim, and L. Pettersson, “Rotman lens in microstrip technology,” 22nd European Microwave Conf., Helsinki, 1992, pp. 882-887.
[13] J. Dong, and R. Cheung, “A computer synthesized 2~8 GHz printed rotman Lens with 9×8 input-to-output configuration,” 2011 IEEE Antenna and Propagation International Symp., Spokane, 2011, pp. 616-619.
[14] T. Katagi, S. Mano, and S. I. Sato, “An improved design method of Rotman lens antennas,” IEEE Trans. Antennas Propag., vol. 32, no. 5, pp. 524-527, May 1984.
[15] E.O. Rausch, and A.F. Peterson, “Rotman lens design issues,” IEEE Antenna and Propagation Society International Symp., Washington DC, 2005, pp. 35-38.
[16] C. Steven, C. Robert, and N. Buchanan, “Rotman lens-based retrodirective array,” IEEE Trans. Antennas Propag., vol. 60, no. 3, pp. 1343-1351, Mar. 2012.