Design of High Performance Wide Band Rotman Lens In X-Band

Alireza Bayat*1, Shayan Kajbaf Vala*2, Ashkan Soleimani*3
*Department of communication engineering
Imam Khomeini international university, Iran

Abstract—In this paper a Rotman lens consisting of 13 beamports and 10 array ports offers a phase shift from -50 degree to +50 degree with 7.5 degree step in X band is presented. The structure of lens has been simulated using MATLAB and optimized with help of Genetic Algorithm then results have been imported to CST Microwave Studio and simulated. For reducing phase error, path-lengths have been optimized using Advanced Design System (ADS). By this way the magnitude error of different frequency is limited within 3 dB.

Keywords—rotman lens; beamforming network; x-band; wide scanning.

I. INTRODUCTION

Application of Rotman lens as a feed structure for phased array antennas particularly in military applications has been increased recently. Rotman lens is a cost effective RF beam-former network which provides simultaneous wide scanning. The Rotman lens has been implemented in waveguide, microstrip, stripline and using surface wave transmission lines [1]. Rotman lens applys path delay mechanism to form the desired phase front at the array input. The path-length design mechanism in the microwave lens in independent of frequency thus it is typically considered as true-time delay (TTD) device.

In 1950, Ruze introduced the concept and design equations for microwave lenses that can provide the capability of wide-angle electronic scanning of narrow multiple beam [2]. In 1963 first microstrip lens with parallel-plate was introduced by Rotman[3]. Many kinds of Rotman lens has been studied in the past decades, including printed Rotman lens [4-6], graded dielectric substrate Rotman lens [7], and SIW Rotman lens [8].

Rotman lens consists of beam ports (input ports), array ports (output ports), dummy ports, and the transmission line connected to them (Shown in Fig. 1) [9]. Dummy ports are necessary in order to reduce the side wall reflections as well as to increase the adjacent beam port isolations [10]. By increasing number of beam ports, 3dB beam width would decrease thus coverage the space improves but by doing so phase error will be increased. Minimizing the phase error level could be challenging. In this work phase error is minimized by Genetic Algorithm using MATLAB in first place then optimized by using ADS for obtaining the shape of transmission lines.
\[ F_1 \sqrt{e_r} + W_1 \sqrt{e_e} + N \sqrt{e_r} \sin(\psi_a) = F \sqrt{e_r} + W_0 \sqrt{e_e} \quad (1) \]

\[ F_2 \sqrt{e_r} + W_2 \sqrt{e_e} - N \sqrt{e_r} \sin(\psi_a) = F \sqrt{e_r} + W_0 \sqrt{e_e} \quad (2) \]

\[ GP \sqrt{e_r} + W_0 \sqrt{e_e} = G \sqrt{e_r} + W_0 \quad (3) \]

From Fig. 2 we know the following equations hold true for locus of inner receiver:

\[ (GP)^2 = (G + X)^2 + Y^2 \quad (4) \]

\[ (F_1 P)^2 = (-F \cos(\alpha) - X)^2 + (-F \sin(\alpha) + Y)^2 \quad (5) \]

\[ (F_2 P)^2 = (-F \cos(\alpha) - X)^2 + (-F \sin(\alpha) - Y)^2 \quad (6) \]

Divide both sides of equations (1)-(3) by \(G \sqrt{e_r}\) and the equations change into

\[ F_1 P \left( \frac{W - W_0 \sqrt{e_e}}{e_e} \right) - N \sin(\psi_a) \sqrt{e_i} = \frac{F}{G} \sqrt{e_r} \quad (7) \]

\[ F_2 P \left( \frac{W - W_0 \sqrt{e_e}}{e_e} \right) + N \sin(\psi_a) \sqrt{e_i} = \frac{F}{G} \sqrt{e_r} \quad (8) \]

\[ \frac{GP}{G} = 1 - \frac{W - W_0 \sqrt{e_e}}{e_e} \quad (9) \]

Let

\[ w = \frac{W - W_0}{G}, \beta = \frac{F}{G}, \xi = D \sin(\psi_a), x = \frac{X}{G}, y = \frac{Y}{G}. \]

Square (7)-(9) and equate with (4)-(6). After obtaining these equations, the simplified simultaneous equations are shown blow

\[ W^2 \frac{e_e}{e_e} + \left( \frac{N \sin(\psi_a)}{G} \right)^2 \frac{e_i}{e_i} - 2 \beta W \frac{\sqrt{e_e e_i}}{e_r} = x^2 + y^2 + 2 \beta x \cos(\alpha) \quad (10) \]

\[ \beta N \sin(\psi_a) \sqrt{e_i} \left( \frac{\sqrt{e_e e_i}}{G} \right) = \frac{\beta \sqrt{e_r}}{G} \quad (11) \]

\[ 2x + x^2 + y^2 = W \frac{e_i}{e_r} - 2W \frac{\sqrt{e_e}}{e_r} \quad (12) \]

Note we are looking for the locus of point \(P(X, Y)\), which actually forms the receiving element port counter, \(x, y, \) and \(w\) are variables. Solving equations (10)-(12) lead us to finding \(x\) and \(y\) as follows

\[ y = \frac{\xi \sqrt{e_i} \left( 1 - \frac{W \sqrt{e_e}}{\beta \sqrt{e_r}} \right)}{e_r} \quad (13) \]

\[ x = \frac{\xi e_2 N^2 \sin(\psi_a)^2}{2 e_r (\beta \cos(\alpha) - 1)} + \frac{(1 - \beta) W \sqrt{e_e}}{e_r} \quad (14) \]

\[ w \] is formulated from (10)-(12) into an standard equation show in (13)

\[ \frac{\alpha e_i}{e_r} W^2 + b \frac{e_i}{e_r} W + c = 0 \quad (15) \]

\[ W = \frac{\sqrt{e_r} - b \pm \sqrt{b^2 - 4ac}}{2a} \quad (16) \]

Where

\[ a = 1 - \left( \frac{1 - \beta}{1 - \beta \cos(\alpha)} \right)^2 \]

\[ b = -2 + \frac{2 \xi^2}{\beta} \frac{e_i}{e_r} + 2 \left( \frac{1 - \beta}{1 - \beta \cos(\alpha)} \right) \frac{e_i}{e_r} \]

\[ c = -\frac{\xi^2 \sin(\alpha)^2}{1 - \beta \cos(\alpha)} - \frac{\xi^2 \sin(\alpha)^4}{4 (1 - \beta \cos(\alpha))^2} \frac{e_i}{e_r} \quad (19) \]

Now with help of \(x, y\) and winner receiver contour and the transmission lines will be obtain.

These equations have been based on 3 focal but in fact more than 3 focal is needed. To determine their locations the beam contour has been assumed as acircular shape that has all the three focal points. Beam port coordinates are given as follows

\[ y_b = -x_b \tan(\theta) \quad (20) \]

\[ x_b = \frac{1}{2} \frac{a - 2a + 2ab \sqrt{a^2 + 2b^2 \tan^2(\theta) + 2b^2 \tan^2(\theta)}}{a^2 + b^2 \tan^2(\theta)} \quad (21) \]

Where \(\theta\) is the beam subtended angle.
III. SIMULATION AND OPTIMIZATION

After obtaining the lens formula, for minimizing phase error as much as possible, a proper MATLAB code is used and the optimized locus of beam contour is obtained. Results of MATLAB have been imported to CST Microwave Studio to draw the shape of lens. Finally, results of CST Microwave Studio have been imported to ADS and the final shape of the lens for obtaining least phase error are specified.

These simulations and optimizations will be discussed in detail in the following subsections.

A. MATLAB simulation

By using equations (13)–(20) we designed a unique MATLAB code to produce coordinates of beam ports and array ports as shown in Fig. 3.

Many parameters affect the phase error but $G/N$, $\beta$, and $\gamma$, where $\gamma$ is equal as follows

$$\gamma = \frac{\sin(\psi_{s})}{\sin(\alpha)}$$

These parameters are optimized by Genetic Algorithm for reducing phase error as shown in Fig. 4.

B. CST Microwave Studio and ADS simulation

Results of MATLAB simulation imported to CST Microwave Studio to shape the lens. The model is constructed on Rogers 4003 substrate with permittivity of 3.55 and the thickness of 0.8 mm as shown in Fig. 5.

Ports 1 to 13 are beam ports and ports 14 to 23 are array ports while other ports are dummy ports.

The final model of the lens for optimizing the shape of the transmission lines is imported to ADS. By defining proper goals in ADS, the best shape of transmission lines is obtained.

C. Analysis

The reflection and isolation characteristics of the beam ports and array ports of the microstrip Rotman lens are measured and shown in Fig. 6 and Fig. 7.
Fig. 7. VSWR parameters of array ports of the lens

S parameters of output ports (array ports) are shown in Fig. 8 to Fig. 13. Note that because of high number of input and output ports just 3 outputs and 3 inputs are shown.

As you can see in Fig. 8 to Fig. 10, the phase of s-parameters is linear in X band frequency. It shows that a linear phase shift across the aperture is obtained so phase error is least. The magnitude of these s-parameters are shown in Fig. 11 to Fig. 13.

As you can see in Fig. 11 to Fig. 13, the received energy with fluctuation to output ports are below 3dB and the coupling effect is below -20dB. This feature indicates that and acceptable amplitude distribution is obtained and this lens can be applied to phase array antennas.

Fig. 14 shows electric field distribution on the lens if port 4 is excited. As you can see most of electric field propagates to output ports, backscattered waves are absorbed in dummy ports and coupling effect between input ports is nearly zero.

The normalized pattern of the lens is shown in Fig. 15. This figure shows that this lens has the ability to scan -50 degree to 50 degree with step of 7.5 degree.
IV. CONCLUSIONS

In this work, design formulations for microstrip Rotman lens was formed. The lens is designed on Rogers RT4003 substrate and can be applied for phase array antennas with ability to scan -50 degree to 50 degree with step of 7.5 degree.

The output characteristic of simulations indicates that the results fit perfectly well with theory in the x-band frequency.

REFERENCES


