ROTMAN LENS TOOLKIT FOR ALTAIR FEKO

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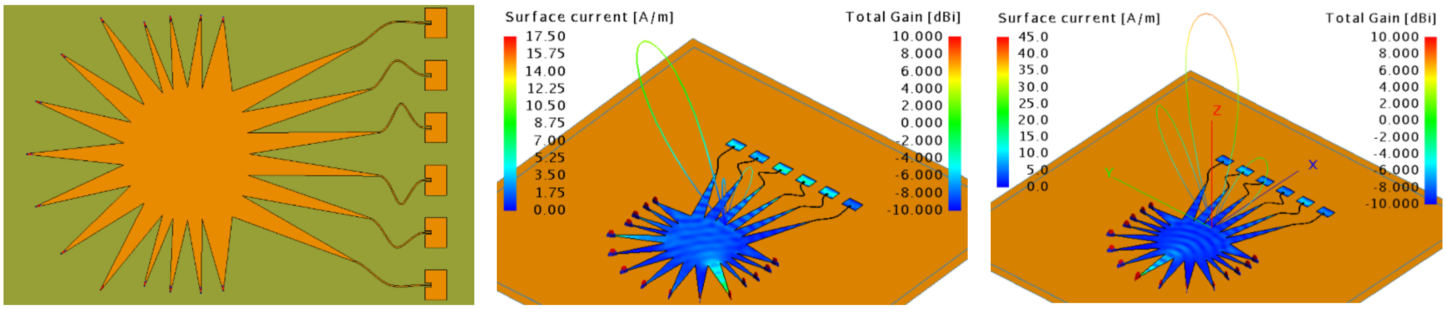

Introduction

Rotman Lens is a wide-angle, two-dimensional microwave lens that is able to steer a beam using numerous ports that would be excited individually [1-3]. The steerability is determined by the maximum angle of the input ports along a contour and the number of input ports in the design. The maximum angle of the input ports is associated with the maximum angles the beam can be steered. The number of beam ports determines the resolution of the steerability of the Rotman Lens, the more ports the finer the resolution. A benefit to this design than the normal array is the phase of the excitation does not need to be changed, only the specific port being excited determines the direction of the beam. Therefore, this means that a better radiation pattern can be observed using the Rotman Lens over conventional techniques. In this paper, we demonstrate a toolkit for the design of Rotman Lens. Calculation of the Rotman Lens contours, phase centers, and vertices are performed in Altair Compose [4] and the design implementation and simulation of the lens is performed in Altair Feko [5]. Lua scripting in Feko was performed in order to make modifications to the geometry to save time and be more efficient. This paper will discuss the Rotman Lens design in Compose, the implementation and simulation in Feko, and lastly the use of Lua scripting to integrate the toolkit into one interface.

Background

There had been previous Rotman Lens implementation in Feko specifically investigating the candidacy of Rotman Lens implementation in automotive applications [6]. In [6], a Rotman Lens was designed at 76.5 GHz with 13 Beam Ports providing 13 individual directions to steer the beam. A 2.7 x 3.1 cm design for the lens was chosen on a Rogers 3003 substrate. Figure 1 shows the Rotman Lens geometry with surface current results based on Port 7 and Port 3 being excited as well as the radiation pattern showing the results of the beam being steered due to these excitations. The array factor was plotted, Figure 2, for eight port excitations at 5 GHz comparing measurements to the Feko simulation. These results show that Rotman Lens is a suited fit for automotive applications requiring good beam steering criteria.

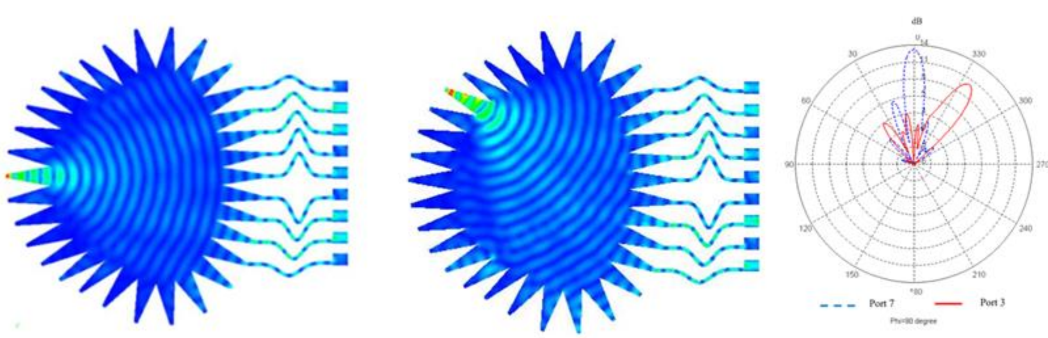

Figure 1 – Rotman Lens design and current and gain results for Port 3 and Port 7 excitation [6]

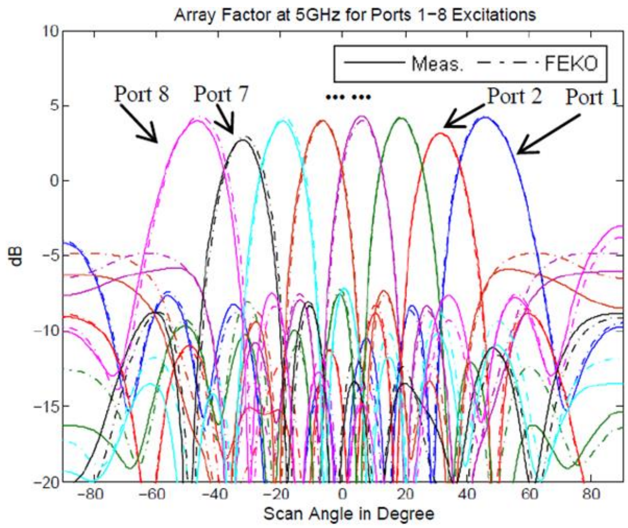

Figure 2 – Array Factor results from measurements and Feko simulation results for 8 port excitations [6]

Rotman Lens Motivation

The purpose of this paper is to expand upon the previous implementation in Feko and create a Rotman Lens design workflow to design a lens based off user input of requirements. The goal is to provide an automated approach from design to simulation results (Figure 3) using Lua scripting. This will aid users to conveniently create this complex geometry and easily simulate it to fit their application.

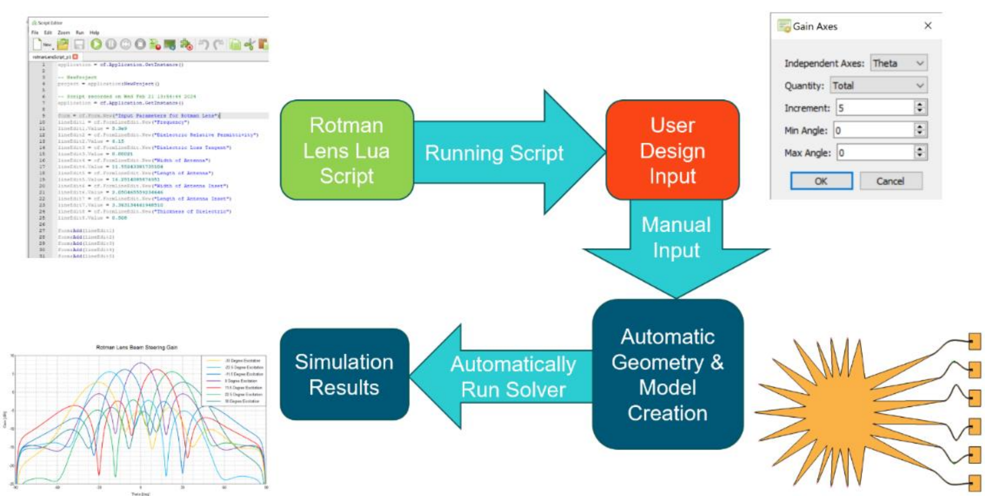

Figure 3 – Automated design process workflow, from user input to results

Rotman Lens Terminology

Rotman Lens terminology will be explained to understand various components of the Rotman Lens that will be mentioned in this paper. Figure 4 shows the Rotman Lens design and includes various terminology of components. The Beam Contour is the curve of which the Beam Port and Dummy Port phase centers lie on the lens. The Array Contour is the curve of which the Array Port phase centers lie. There are seven Beam Ports that provide individual excitation for the lens. Eight Dummy Ports which help minimize reflection that occurs in the lens. There are six Array Ports which are connected to inset-fed rectangular patch antennas via 50 ohm transmission lines.

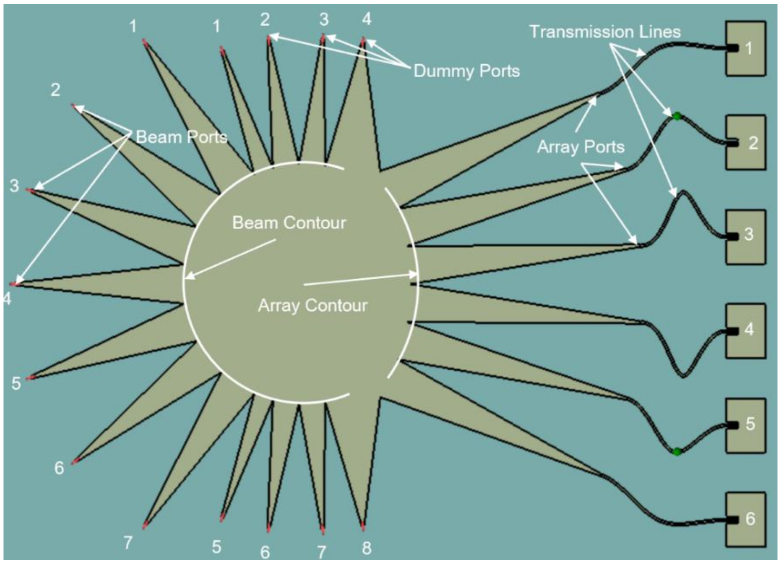

Figure 4 – Components and terminology of the Rotman Lens design

Rotman Lens Design

For the first part of the toolkit, the design of the Rotman Lens there are many parameters that are predefined. Such parameters are: the thickness of the substrate (d), width of 50Ω transmission line (W_t), substrate permittivity (epsr), frequency (freq), Beam Contour focal distance (G), off focal angle (α), number of beam ports (numBeam), number of array ports (arrayPorts), and number of dummy ports (dummyPorts). From these predefined parameters the complete design of the Rotman Lens can be performed. Table 1 shows the input parameters and their values. The Rotman Lens Beam and Array Contours were designed to resemble Figure 5 [1].

Table 1: Input Parameters for Rotman Lens Design

Parameter	Value
d	0.508 mm
W_t	0.715 mm
epsr	6.15
freq	5.3 GHz
G	3λ
α	30°
numBeam	7

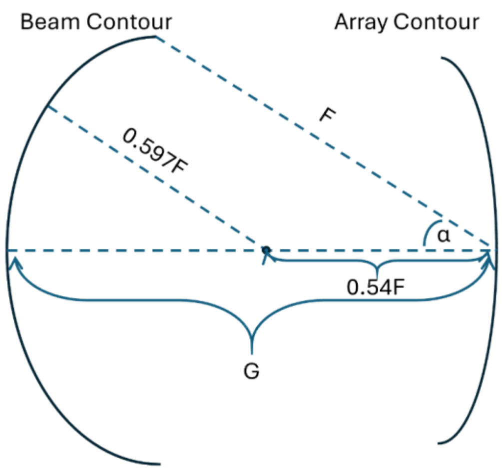

Figure 5 – Rotman Lens contours and dimensions for the design

Using the thickness of the substrate, width of the 50Ω transmission line, and the relative permittivity of the dielectric the effective permittivity was calculated below.

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\sqrt{1 + 12\frac{d}{W\_t}}$$

This helps in the computation of the impedances of the apertures of the Rotman Lens to determine the taper length, which will be discussed further into this paper.

Rotman Lens Design – Beam Contour

The design of the Beam Contour was focused on the parameters α and G. Equations 1 and 2 below are the Beam Contour design equations that will define the off focal distance (F) [1].

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

$$F = \frac{G}{g}$$

The off focal distance defines two outside points of the Beam Contour F_1 and F_2. These two points are the outside phase centers on the Beam Contour. As defined by the input parameters, numBeam, there needs to be five more phase centers defined on the Beam Contour. For these additional phase centers, incrementing an even angle from the radius of the Beam Contour will define them. First, because numBeam is odd there will be one phase center along the x-axis a distance G from the origin. As shown in Figure 5, the remaining four phase centers depend on the angle the radius $R = 0.5974F$ makes with the Beam Curve offset by -$0.540F$ on the x-axis.

With the phase centers on the Beam Contour defined, the vertices for the tapers from the lens to the 50Ω transmission lines are next computed. The vertices on the Beam Contour were taken as half the distance between one phase center and another along the Beam Contour. The vertices are the points on the Beam Contour where the port line tapers will meet with each other. Figure 6 shows the Beam Contour's Phase Centers (In Blue) and Vertices (In Green).

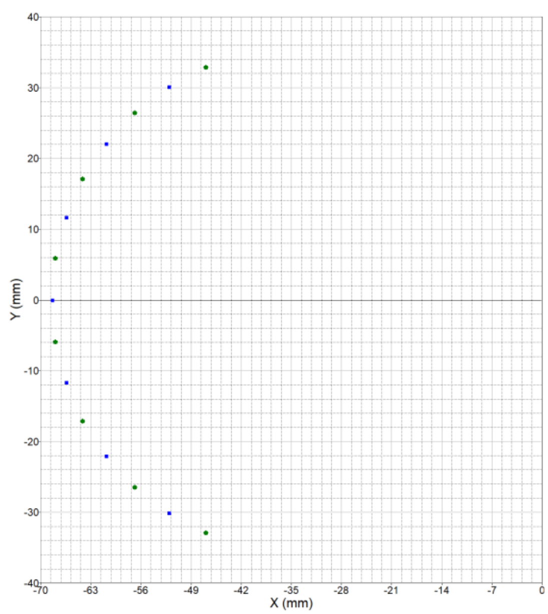

Figure 6 – Beam Contour Phase Centers and Vertices

Rotman Lens Design – Array Contour

For the design of the array contour, the main parameter used to define the contour was the transmission line length from the lens to the antenna array. The design of the contour was modeled from [7]. From [7], the normalized transmission line lengths are of the quadratic form:

$$aw^2 + bw + c = 0$$

Where the normalized transmission line length is:

$$w = \frac{W-W_0}{F},\ W_0 \text{ is the length of the center element.}$$

The coefficients in the quadratic equation are:

$$a = \frac{\epsilon_{eff}}{\epsilon_r}(1 - \left(\frac{g-1}{g-a_0}\right)^2 - \frac{\eta^2}{\epsilon_r})$$

$$b = \sqrt{\frac{\epsilon_{eff}}{\epsilon_r}}(2g\left(\frac{g-1}{g-a_0} - 1\right) - \frac{g-1}{(g-a_0)^2} b_0^2 \frac{\eta^2}{\epsilon_r} + 2\frac{\eta^2}{\epsilon_r})$$

$$c = \frac{g(b_0^2\eta^2)}{(g-a_0)\epsilon_r} - \frac{b_0^4\eta^4}{4\epsilon_r^2(g-a_0)^2} - \frac{\eta^2}{\epsilon_r}$$

Using the quadratic equation and plugging a, b, and c to solve for w. With w now known, the actual transmission line length is obtained by solving for W for a pre-defined W_0. With the normalized w known, the normalized x and y components of the Array Contour then can be solved by using the equations:

$$x = w\sqrt{\frac{\epsilon_e}{\epsilon_r}}\frac{1-g}{g-a_0} + \frac{\eta^2 b_0^2}{2(g-a_0)\epsilon_r}$$

$$y = \frac{\eta}{\sqrt{\epsilon_r}}\left(1 - w\sqrt{\frac{\epsilon_e}{\epsilon_r}}\right)$$

The unnormalized X and Y positions are determined by multiplying x and y by F. X also is required to be mirrored across the Y axis in order to be applicable to the application at hand.

$$X = -xF$$

$$Y = yF$$

X and Y are the coordinates of the phase centers of the Antenna Array for the Rotman Lens.

The vertices of the Array Contour were calculated differently than the Beam Contour. The phase centers of each element were not on a ideal contour of a circle, therefore a radius assumption was required to be made. Because of this, I assumed that the Array Contour had an identical radius (R) that was equal to G. Therefore, the Array Contour vertices were calculated. First, the angle (θ) was determined for each given phase center coordinate.

$$\theta = \sin^{-1}\left(\frac{Y}{R}\right)$$

The difference of angles between each θ was computed. The vertex coordinates were calculated by taking the midpoint between two phase centers and using the radius R.

$$X_{av} = R\cos\left(\theta - \frac{\theta_{diff}}{2}\right) - R$$

$$Y_{av} = R\sin\left(\theta - \frac{\theta_{diff}}{2}\right)$$

The coordinates of both the Array Contour phase centers and vertices are shown in Figure 7.

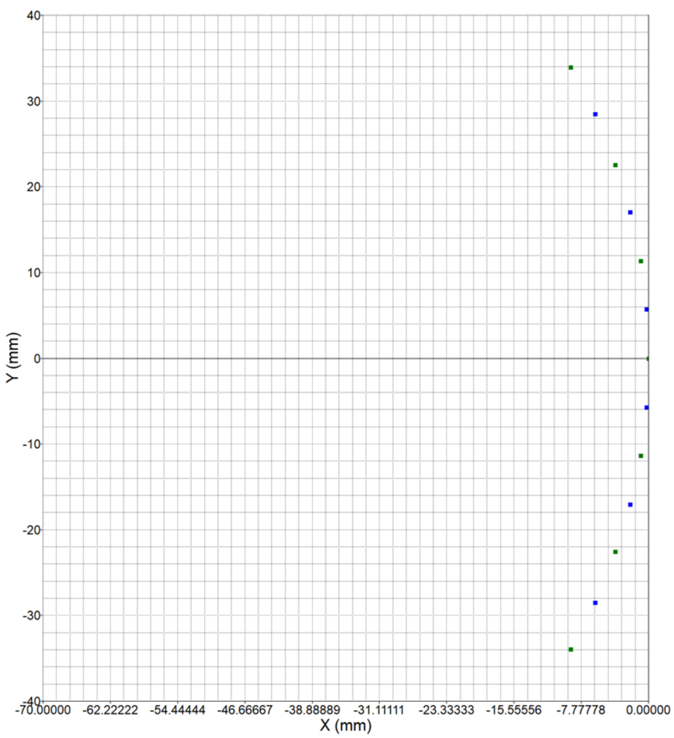

Figure 7 – Array Contour Phase Centers and Vertices

Dummy Ports

The dummy ports were defined by continuing the Beam Contour. The phase centers of the dummy ports were placed likewise to the Beam Contour phase centers. The spacing between phase centers was determined differently as the location of them does not specifically matter. The Dummy Port phase centers occur after the Off Focal point, which is the last Beam Contour Phase Center. Therefore, the Dummy Ports phase centers were computed by:

$$X_D = -\left(R\cos\left(\theta_r + \frac{i}{5\theta_r}\right) + 0.54F\right)$$

$$Y_D = R\sin\left(\theta_r + \frac{i}{5\theta_r}\right)$$

Next, the Dummy Port aperture vertices were computed. The vertex for the dummy port next to the Beam Contour used that Beam Contours vertex. Similarly, the vertex of the dummy port next to the Array Contour used that Array Contour vertex. In this design, four dummy ports were chosen to be created on both sides of the Rotman Lens. Using these formulas, the locations of the dummy ports are shown in Figure 8.

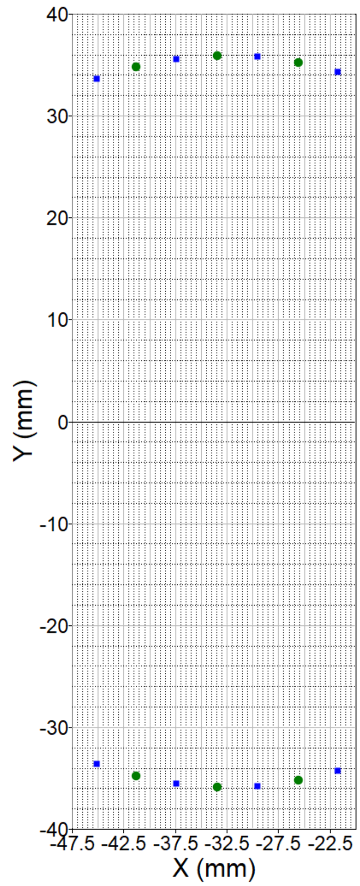

Figure 8 – Dummy Port phase centers and vertices

Transmission Line Tapers

The transmission line tapers provide the ability for the 50 Ω transmission line port width to enlarge to the different impedance of the Beam Contour aperture widths. These taper lengths were determined by providing, at most, a -10dB reflection at these ports. For this computation a taper calculator designed by Northwest Engineering Solutions [8], tapercalc.xls, was used. In the spreadsheet, the thickness of the substrate, the frequency for the design, and the width to thickness ratio of the aperture and the substrate. The calculated lengths that provided good, minimized reflection for the Beam Ports, Array Ports, and Dummy Ports were 0.0508 m, 0.06985 m, and 0.0381 m respectively. The results of all the vertex points calculated for the design are shown in Figure 9.

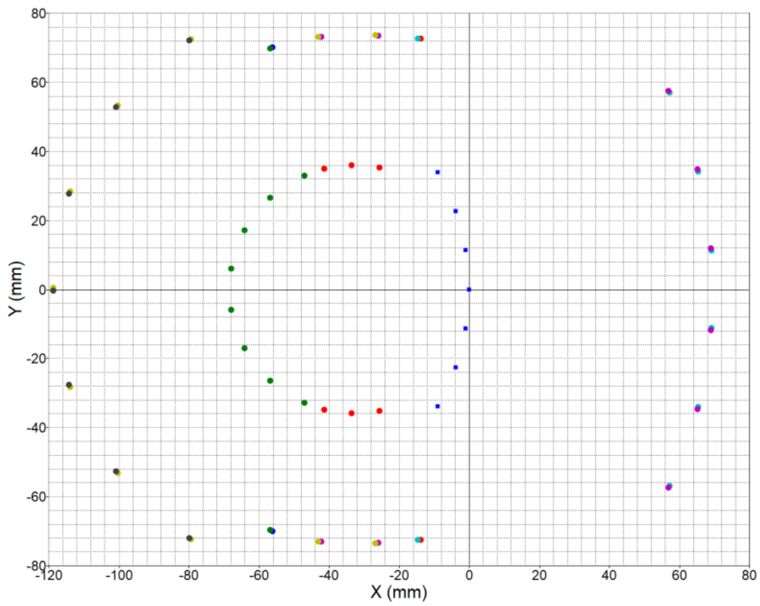

Figure 9 – Vertices of all points in Rotman Lens Design

Rotman Lens Antenna Array

A microstrip inset-fed rectangular patch antenna was used for the antenna array for the Rotman Lens. For the desired frequency of interest, 5.3 GHz, the dimensions are shown in Table 2. The relative permittivity is that of the Rotman Lens (epsr). The substrate has a dimension of substrateHeight, substrateLengthX, and substrateLengthY. The patch's dimensions are lengthX and lengthY, with the inset gap width and depth of gap and yo respectively. The feedline to the microstrip patch is feedline_width. Optimization was performed on the patch antenna to ensure good resonance at 5.3 GHz, the frequency of design for the Rotman Lens.

Table 2: Input Parameters for Rotman Lens Design

Parameter	Value
epsr	6.15
feedline_width	0.715 mm
gap	2.050466 mm
lengthX	11.552434 mm
lengthY	16.251408 mm
substrateHeight	0.508 mm
substrateLengthX	50 mm
substrateLengthY	80 mm
yo	3.363134 mm

Rotman Lens Implementation

The location of all the vertices, phase centers, and ports were calculated, Figure 9, and then transferred over into Feko. A Lua script was written to design the Rotman Lens in a quick and efficient manner. A Polyline was used to connect all points above the x-axis together. This polyline was then mirrored and filled in with PEC material. This required knowledge of which points connected to each other for using the Polyline tool.

A planar multilayer substrate was used for the dielectric material, and microstrip ports were utilized on each of the Beam and Dummy port locations. Depending on whether the number of excitation ports or antenna elements is odd, an additional line(s) must be created to connect the two polylines. This is due to the finite 50Ω taper width for the input ports and transmission lines.

Optimization was performed by altering the transmission line curvatures for the antenna array. The goal of optimization is to maximize the gain in all the beam-steered directions. The parameters of the optimization are the antenna array transmission line bend heights; nH1, nH2, and nH3. These bend heights are relative to the antenna element Y coordinates for one half of the Rotman Lens, N1 (14.14115 mm), N2 (42.42346 mm), and N3 (70.70577 mm). The optimized values for nH1, nH2, and nH3 were 13.3785 mm, 8.0254 mm, and 0.6509 mm respectively. Figure 10 shows the geometry implementation in Feko from the calculated points and final optimization of the transmission lines for the antenna array.

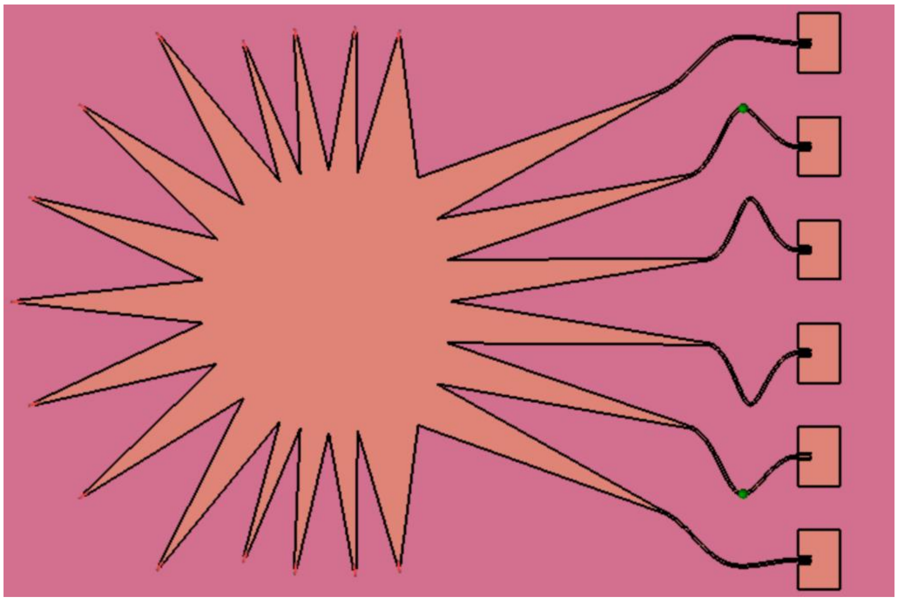

Figure 10 – Geometry implementation of Rotman Lens in Feko

Rotman Lens Results

The designed Rotman Lens was able to achieve beam-steering in $\pm30°$ directions. This resolution is identical to the off focal angle, α, that was defined in the construction of the Rotman Lens. Figure 11 show the directivity and resolution of the designed example of the Rotman Lens. The maximum directivity ranges from about 8.5 dB at 0-degrees Theta to just under 2.5 dB at $\pm$30-degrees Theta. Good gain patterns can be observed of the Rotman Lens for the whole resolution of the design. Figure 12 shows the surface currents from the various port excitations of the Rotman Lens.

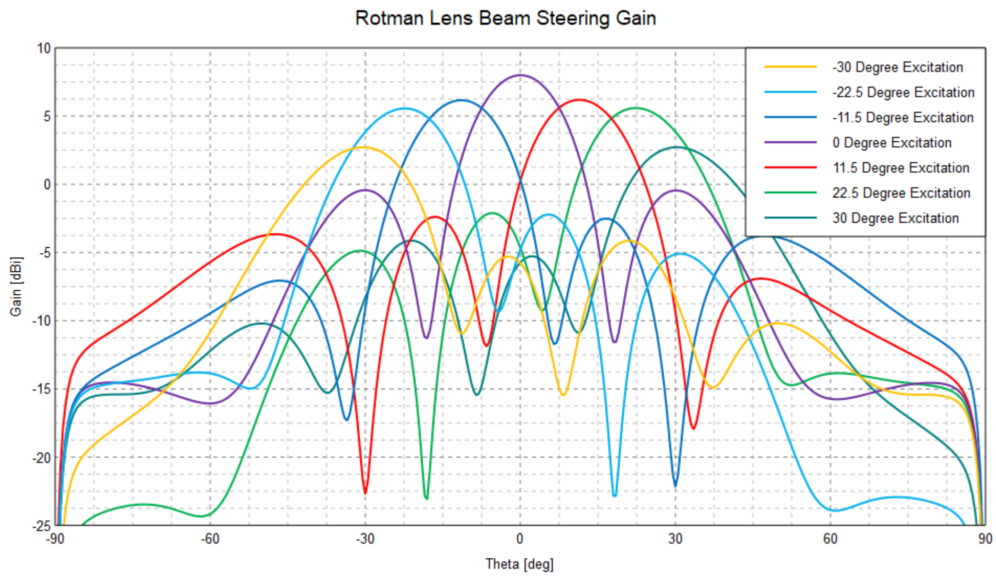

Figure 11 – Gain patterns of the Rotman Lens for each port excitation

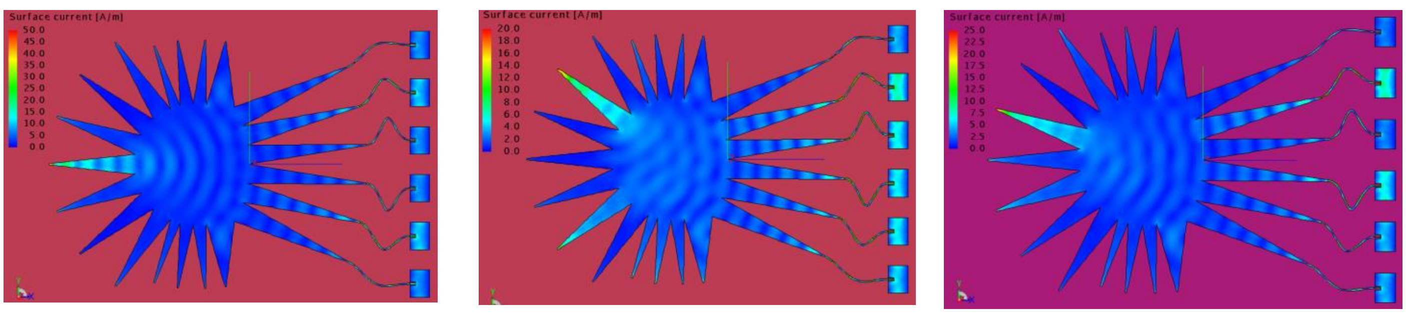

Figure 12 – Surface current of Rotman Lens for various port excitations

Rotman Lens Lua Scripting

The final part of the Toolkit is the Lua script to interface Compose and Feko into one program to create a more efficient method to construct the Rotman Lens. To get a script, Feko's Record Macro feature is used, first construction of the lens to obtain the construction written to Lua script. After the script is written, minor changes and edits were made to fine tune the design appropriately. As of right now the script uses hardcoded points that were obtained through the design in Compose. To obtain a better toolkit, the design of the Rotman Lens will need to be implemented in the Lua script from Compose so the full design and construction take place all in one program.

Conclusion

The Rotman Lens has been successfully designed in Compose and implemented in Feko. The gain results show successful beam-steering over the designed scan angle dependent upon individual port excitation. Optimization was performed to enhance these results and obtain the best transmission line orientation for the antenna array from the Rotman Lens. Further improvements can be made to this toolkit to provide more options for a user to design a Rotman Lens based off of their own criteria of design.

References

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