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An alternative approach to the design of multiple beam constrained lens antennas

Rasime UYGUROĞLU[1,*], **Abdullah Yücel ÖZTOPRAK**[2]

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Eastern Mediterranean University, Gazimağusa, North Cyprus

[2]Department of Electrical and Electronic Engineering, Faculty of Engineering, Final International University, Girne, North Cyprus

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Abstract: Rotman lenses are constrained lenses that are used as beam-forming networks to feed array antennas. Their design is based on three focal points, producing three beams with perfect phase fronts. This paper introduces an alternative constrained lens, which has phase equality at five radiating array elements for each beam position. In addition, the center point of the feed curve produces a perfect beam at broadside. The performance of this lens is analyzed and compared to the conventional Rotman lens. The analysis demonstrates that the new lens has better phase performance for wide angle designs. Our study shows that the phase errors of the proposed lens can be as low as half of those produced when using the conventional Rotman lens.

Key words: Antenna arrays, multiple beams, Rotman lens antennas, phase error, constrained lens antenna

1. Introduction

Rotman lens-fed arrays are used as multibeam-forming networks in communication, radar, and electronic warfare systems. Rotman lens-fed array antennas can produce simultaneous multiple beams. These networks can cover wide angles, and as their design is based on path length equality, they are wideband [1–4].

Rotman lenses are two-dimensional devices that have three radiated beams with no phase errors. These beams correspond to three feed elements placed on focal points on the feed curve (Figure 1). The beams that correspond to nonfocal points on the feed curve have phase errors. These errors may be large for Rotman lenses designed for wide angle coverage and may cause deterioration in the radiation pattern. The x and y variables of the inner lens curve and the transmission line lengths (w) between the radiating array elements and the Rotman lens are the variables to be determined. Radiating arrays are usually linear arrays and are uniformly spaced. Three simultaneous equations are obtained for the three focal points and are solved for (x, y, w) [5,6]. This is repeated so that each point on the radiating array obtains the inner array curve (x, y) and the associated w values.

The proposed lens uses the available three degrees of freedom to obtain path length equality for the three radiating array points and for each feed position of the lens. In this paper, we show that, in addition to the three variables (x, y, w) mentioned above, we can use the coordinates of the feed curve (x_f, y_f) as design parameters (Figure 1). The additional degrees of freedom enable us to achieve two additional path length equalities, making five points in total for each feed position. Furthermore, the proposed lens has a perfect focal point at the center of the feed curve.

*Correspondence: rasime.uyguroglu@emu.edu.tr

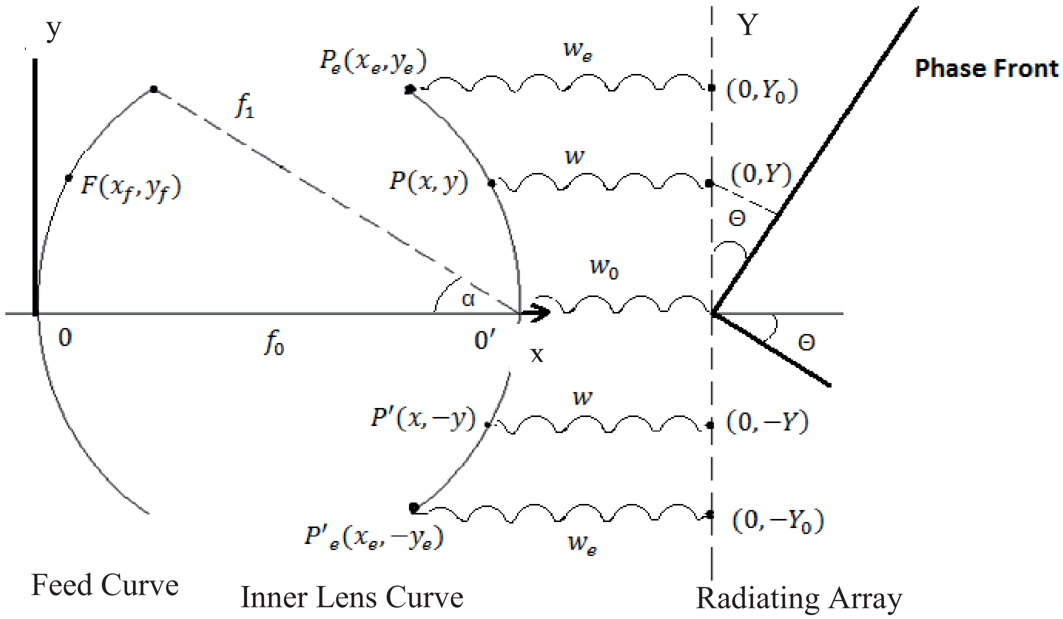

Figure 1. Lens geometry.

The design procedure for the proposed lens is presented in Section 2 and the phase error performance analysis of the new lens is provided in Section 3. The implications of the new lens are discussed in the conclusion in Section 4.

2. Lens design

The parameters of the lens are given in Figure 1. The midpoint of the feed curve, O, is the origin of the coordinate system, O' is the midpoint of the inner lens curve, and f_0 is the distance between O and O'. The length of the transmission line that joins O to O' is ω_0. All curves are symmetric about the OO' axis. $P_e\,(x_e, y_e)$ and $P'_e\,(x_e, -y_e)$, the end points of the inner lens curve, are predetermined. As the midpoint of the inner lens curve is also determined by the choice of f_o, three of the lens points are determined in advance. This is an advantage when compared to the Rotman lens, as the approximate shape of the inner lens curve can be predetermined by the designer. This makes the new lens more widely applicable. The end points of the inner lens curve are connected to the end points of the radiating array by the transmission lines of length ω_e. The elements of the radiating array are positioned uniformly on a line of length $2Y_0$.

The proposed lens will have a single focal point at the center of the feed curve with a corresponding perfect beam at the broadside ($\theta = 0^o$); this can be used to obtain the transmission line length ω_e. By equating the path lengths from the focal point to the phase front for center and end elements, the following equation is obtained:

$$OP_e + \omega_e = f_0 + \omega_0 \quad , \tag{1}$$

where $OP_e = \left(x_e^2 + y_e^2\right)^{\frac{1}{2}}$.

By solving Eq. (1), ω_e is obtained. We then proceed to obtain the coordinates x_f and y_f of the feed array curve. For each point on the feed curve, the path lengths to the phase front at θ through the end and center elements are equal. Each feed curve point has an associated θ value, which is related to a Y coordinate of the radiating array. This relationship is necessary to obtain the (x,y) coordinates of the inner lens curve for the designated Y and θ. We formulated the relationship between Y and θ as follows:

$$\theta = sin^{-1}\left(k\frac{Y}{f_0}\right),$$

where $k = \frac{f_0}{Y_0}\sin\theta_0$ and θ_0 is the maximum coverage angle.

Other alternative relationships may also be selected as appropriate.

The path lengths from a general point F on the feed curve, with coordinates x_f and y_f, to the related phase front at θ through the center point and the two end points of the inner lens curve are made equal. These path length equality equations are given below:

$$FP_e + \omega_e + Y_0 \sin\theta = FO' + \omega_0, \tag{2}$$

$$FP_e' + \omega_e - Y_0 \sin\theta = FO' + \omega_0, \tag{3}$$

where

$$FP_e = \left[(x_f - x_e)^2 + (y_f - y_e)^2\right]^{\frac{1}{2}},$$

$$FP_e' = \left[(x_f - x_e)^2 + (y_f + y_e)^2\right]^{\frac{1}{2}},$$

$$FO' = \left[(x_f - f_0)^2 + y_f^2\right]^{\frac{1}{2}}.$$

Eqs. (2) and (3) are solved for x_f and y_f for the required range of θ values to obtain the feed curve. With this process, it is assured that we have at least three equal paths to the phase front for each point on the feed curve.

We then proceed to obtain a point P on the inner lens curve such that the path length from point F to the associated phase front at θ through points $P(x,y)$ and $P'(x,-y)$ are equal to the path length through center point O' to the same phase front. The path length equality equations are given below:

$$FP + \omega + Y\sin\theta = FO' + \omega_0, \tag{4}$$

$$FP' + \omega - Y\sin\theta = FO' + \omega_0, \tag{5}$$

where

$$FP = \left[(x_f - x)^2 + (y_f - y)^2\right]^{\frac{1}{2}},$$

$$FP' = \left[(x_f - x)^2 + (y_f + y)^2\right]^{\frac{1}{2}}.$$

As we have already obtained the values of x_f and y_f, we have three variables (x, y, w) to be determined.

Since we have two equations (Eqs. (4) and (5)) but three degrees of freedom, we are in a position to formulate a further equation. This will be based on a perfect focal point at the feed curve center O. In this third equation, the path length from O through point P is equated to the path length from O through point $O,'$ to the phase front at $\theta = 0^{\circ}$:

$$OP + \omega = f_0 + \omega_0, \tag{6}$$

where $OP = \left[x^2 + y^2\right]^{\frac{1}{2}}$.

Thus, Eqs. (4)–(6) are solved for x, y, and ω. This process is carried out for all Y values of the radiating array, and the inner lens curve is obtained.

Eq. (6) thereby provides a focal point for a beam at the broadside, and Eqs. (2)–(5) ensure that, for each point on the feed curve, there are 5 points on the radiating array that have phase equality.

3. Performance analysis and discussion

In this section, the phase error performance of the proposed new lens is compared to the conventional Rotman lens. Path length error $\Delta\ell$ can be defined as the difference in path length from a general point F on the feed curve to the phase front at the associated θ angle, through a general point P and through the center point O of the inner lens curve. Path length error is expressed as:

$$\Delta\ell = FP + \omega + Y\sin\theta - FO^{'} - \omega_0. \tag{7}$$

Path length errors determine the phase errors at the phase fronts. Large phase errors cause deterioration in the radiation patterns.

Figures 2 and 3 show the path length errors for both designs when the maximum beam angle is 65°. The design parameters of the new lens are $f_0 = 10,\ Y_0 = 6.4,\ x_e = 5.83,\ y_e = 6.14,\ \omega_0 = 0,\ \theta_0 = 65^{\circ}$.

The feed and the inner lens curves for the new lens and the Rotman lens are shown in Figures 4 and 5, respectively.

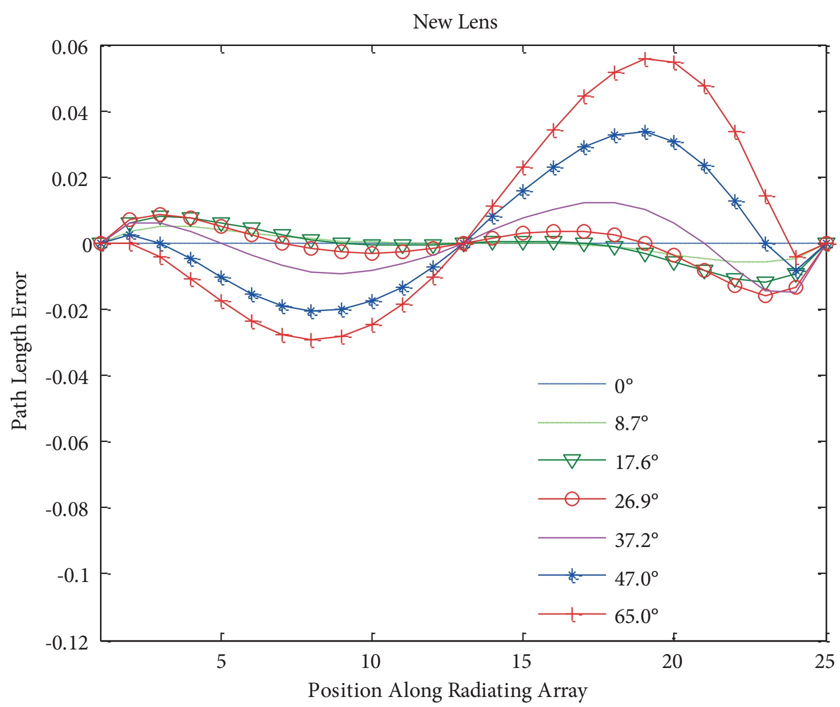

Figure 2. Path length error curves for the new lens.

The design parameters of the Rotman lens were selected to have the same size of radiating array, the same focal length, the same angular coverage, and the same end point coordinates for the feed curve and inner lens curves, so that the two lenses could be compared under the same conditions. We can observe from Figures 4 and 5 that the shapes of the two curves are very similar to each other, as intended.

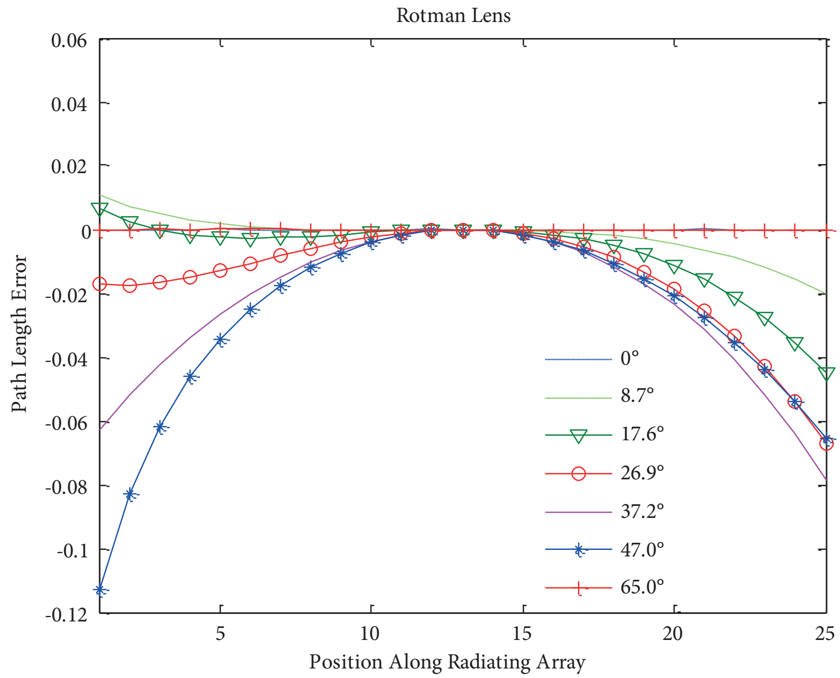

Figure 3. Path length error curves for the Rotman lens.

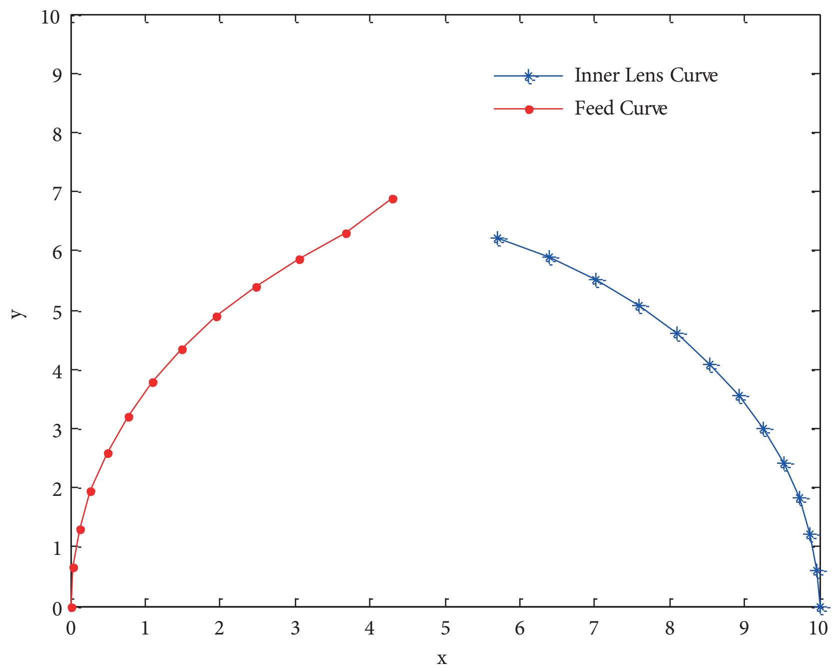

Figure 4. Feed curve and inner lens curves of the new lens.

We can also observe from the path length error curves, illustrated in Figures 2 and 3, that the maximum path length errors of the new lens are about half those of the Rotman lens.

Larger path length errors cause larger phase errors, which, in turn, cause further degradation in the radiation patterns, manifesting in lower gain, higher side lobes, and beam squinting [7,8]. Reducing these errors by half will alleviate these performance deficiencies.

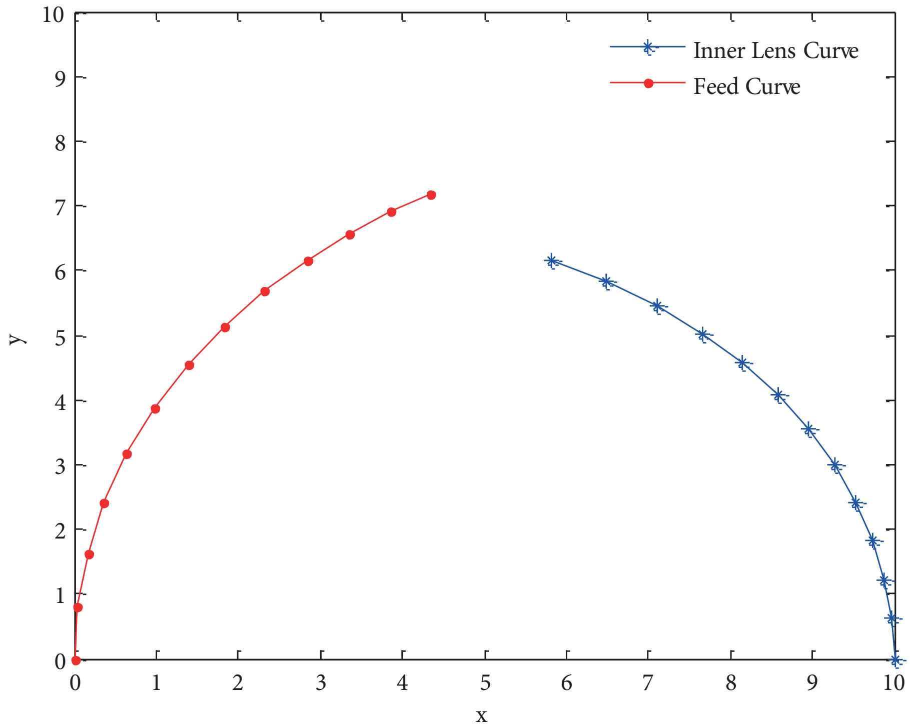

Figure 5. Feed curve and inner lens curves of the Rotman lens.

Figures 6 and 7 show the path length errors for the new lens and the Rotman lens, for a smaller maximum beam angle. The design parameters for the new lens were $f_0 = 10,\ Y_0 = 6,\ x_e = 7.74,\ y_e = 5.38,\ \omega_0 = 0,\ \theta_0 = 40^{\circ}$. The same parameters were chosen for the Rotman lens. The lens curves of these two lenses are very similar in shape, and for the sake of brevity are not included.

We can observe from the path length errors shown in Figures 6 and 7 that for half of the elements (1 to 13) there is an improvement in the phase performance, but for the other half, the maximum phase error is about the same. These results indicate that the use of the new lens is preferable for wider angle lenses.

As explained in Section 1, the conventional Rotman lens has three degrees of freedom. As the new lens uses the feed curve coordinates as design variables, the number of degrees of freedom is increased to five. This increase is the main reason for having better phase performance, especially for wide angle lenses for which the path length errors are larger.

In previous studies of Rotman lenses, such as [3] and [9], it was observed that the shapes of the inner lens curves are unrealizable for some parameters. As the edge points of the new lens are chosen in advance, we have better control over the shape of this curve and unrealizable lens designs can be avoided.

Due to the large number of design parameters, no attempt was made to optimize the performance of the lenses.

4. Conclusion

This study has introduced a new method for the design of multiple beam constrained, lens-fed array antennas. The main purpose was to provide a better performance for wide angular coverage than that provided to date by the Rotman lens.

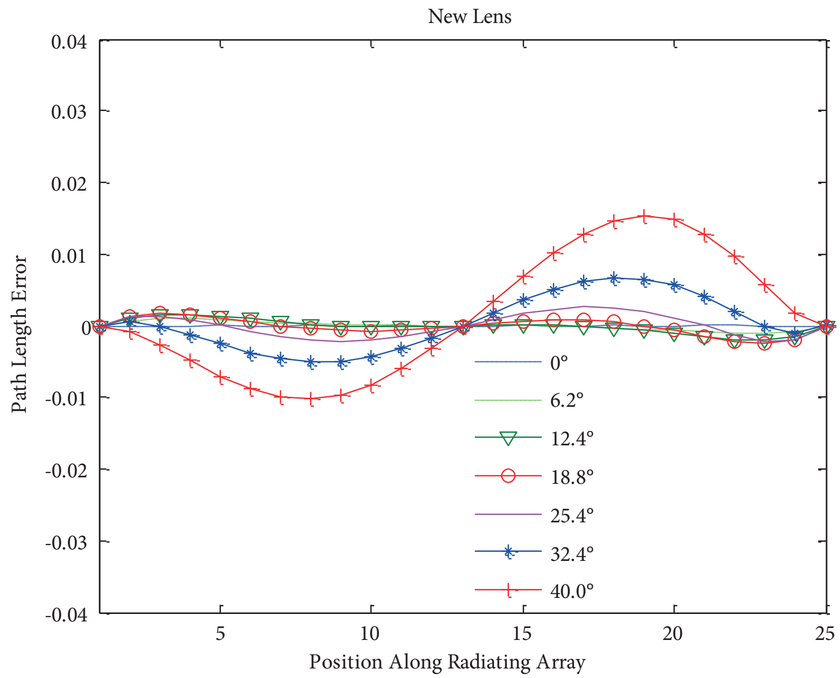

Figure 6. Path length error curves for the new lens.

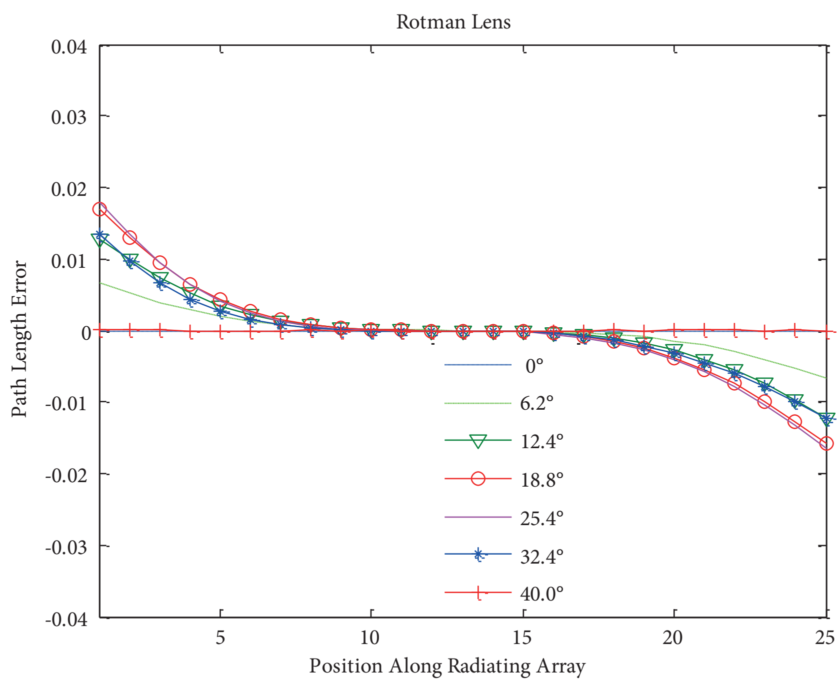

Figure 7. Path length error curves for the Rotman lens.

The Rotman lens has three focal points, producing three beams with perfect phase fronts. However, it has no designed phase equality for other beams. The proposed lens has one focal point only, but has phase equality for five points for all beams. The relevant equations for the design of the new lens have been presented in this paper.

A path length error study of the two lenses, incorporating similar design parameters with a maximum beam angle of 65°, has shown that the new lens approximately halves the maximum phase error. Beams with lower phase errors have higher gain and lower side lobes. Furthermore, a parallel study using a maximum angle of 40° shows that there is a better phase performance in one half of the array antenna.

Since the end points of the inner lens curve have been selected as design parameters, there is better control over the shape of the inner lens curve of the new lens. This is important because we can use the new design method to obtain lenses with larger radiating arrays to produce higher gain beams.

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