Development of 2-D Generalized Tri-Focal Rotman Lens Beamforming Network to Excite Conformal Phased Arrays of Antennas for General Near/Far-Field Multi-Beam Radiations

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ABSTRACT In this paper, we present a general closed-form solution of trifocal Rotman lens beamforming network (TFRL-BFN) design to excite a conformal phased array of antennas for multibeam radiations. This TFRL-BFN is a two-dimensional (2-D) configuration and is realizable in a dielectric substrate sandwiched by a pair of metal parallel-plates. In the development, instead of employing the geometric optic (GO) ray paths external to the Rotman lens to form an equal-phase wavefront by equal path lengths for directional beam radiation, we consider the phase need of antenna array excitation as the design target of TFRL-BFN. As a result, the TFRL-BFN concept can be extended to treat conformal arrays of antennas with well-planned excitation schemes, ranging from conventional near- and far-field focus multibeam radiations, as well as multibeam with shaped patterns. Basic theoretical concepts and foundations are presented with simulation and measurement examples to demonstrate the phase production characteristics of this TFRL-BFN. When used to feed a conformal array of antennas, the resulting radiation characteristics validate this TFRL-BFN generalization concept’s feasibility.

INDEX TERMS Beamforming network, conformal antenna arrays, far-field focused radiation, multiple beam radiation, near-field focused radiation, Rotman lens.

I. INTRODUCTION

Two-dimensional (2-D) trifocal Rotman lenses [1]–[26] and its extension as multi-focal bootlace lens have been widely used as an effective beamforming network (referred to as a TFRL-BFN, hereafter) to excite planar arrays of antennas for multibeam radiations [2]–[7]. The operational mechanism [1], [2], [5]–[7], [13], [14] first builds three focal points for beam excitation. The profile is then determined by using geometric optic (GO) ray path lengths to obtain three sets of equal-path length equations via the antenna array to the directional beams pointing to three symmetric directions [1], [2], [5]–[7], [22]. The original tri-focal case has been extended to incorporate four and five focal points for bootlace lenses in [27] and [28], [29], respectively.

In practice as a beamformer, this TFRL-BFN is implemented in a dielectric substrate sandwiched by metal parallel-plates [2]–[7] with its external profile shaped to form the Rotman lens. In the past, most TFRL-BFN works considered planar arrays of antennas to achieve a linear phase progression on the array aperture for far-field focused multi-beam radiations [2]–[11], as illustrated by the scenario in Fig. 1 (a). This scenario was later extended to radiate multiple near-fields focused (NFF) beams [12]–[13] in the near-zone, as shown in Fig. 1 (b). In these scenarios, each beam’s field focus point is specified to establish an equal path length equation (or equal phase equation) between the beam selection focal point and this field focus point as the design equations. Simulations and measurements have
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FIGURE 1. The scenario of far-field focus and NFF multibeam radiations. In (a), the TFRL-BFN is conceptually illustrated by a ray path. In (b), conventional microstrips are used to realize the beam selection and excitation output ports.

The rest of this paper is organized in the following format. Section II presents the essential theoretical background of this generalized TFRL-BFN mechanism. Section III presents its applications to excite conformal periodic arrays of antennas for NFF and far-field focus multibeam radiations. Numerical examples are presented in Section IV to validate the feasibility of this new TFRL-BFN design. A realistic TFRL-BFN is examined in Section V by comparing full-wave simulation using HFSS and measurement results for NFF applications. Finally, conclusive remarks are discussed in Section V, where future works are also discussed. A time convention, $e^{j\omega t}$, is used and suppressed throughout this paper.

II. THEORETICAL TFRL-BFN OPERATIONAL MECHANISM

The application scenarios in Fig. 1 by a TFRL-BFN can be alternatively depicted in an operational mechanism with three geometrically separated functional blocks (i.e., FB-A $\sim$ FB-C) in Fig. 2 to excite a general conformal array of antennas. Particularly, FB-A describes the geometrical architecture of a conformal array of antennas and its required excitation phases for multibeam radiations. FB-C represents incorporating the desired phase distribution in the design equations. Secondly, the array configuration can have very general variations, including conformal or aperiodic arrays. Thirdly, the TFRL-BFN may produce the desired phases to excite the array for shaped beam radiation, where the excitation phases are generally available only from the numerical synthesis technique. They cannot be interpreted by GO ray paths. Fourthly, through this excitation phase creation, the TFRL-BFN may also provide multi-mode operations for conformal arrays of antennas. Besides, the realization of the TFRL-BFN can be compact because the transmission lines with constant phases in the conventional design can be replaced by a set of phase compensation circuits [15]–[17] for the same phase variations.
the 2-D Rotman lens body, including the tri-focal feeding arc of beam excitations, the 2-D external profile of the Rotman lens, and the antenna excitation output ports. A pair of metal parallel-plates sandwich this TFRL-BFN to form a metal cavity in the Rotman lens. It forms an \( M \times N \) operational mode transformer between \( M \) beam ports and \( N \) antenna excitation ports. On the other hand, FB-B is formed by a set of phase compensation circuits which were the transmission lines with constant phases in the conventional TFRL-BFN and served as a relay between the TFRL-BFN’s antenna excitation ports and that of the actual antennas. These three functional blocks can be realized separately by different means and be designed in other coordinate systems.

Among the three blocks, FB-A considered the GO ray path lengths in the original TFRL-BFN design equations. They are now the antenna excitation phases planned, in advance, by a designer to achieve a desired multibeam radiation goal in the new concept. The array can be configured in various shapes, reasonably ranging from planar, circular, elliptic arrays to other smooth ones. In FB-C, the GO ray paths inside the TFRL-BFN retain being used to set up the equal-phase wavefront equations without changing their nature in the original design equations of equal path lengths. It is noted that the GO ray paths in FB-A cannot be identified for a general excitation phase distribution.

According to the FB-C illustration in Fig. 2, one specifies three-beam focal points \( A_1 \sim A_3 \) of equal angular separation \( \alpha \) on a circular arc. This beam port arc is centered at the origin of a cylindrical coordinate system \((x', z')\), on the \( y' = 0 \) plane to express \( A_1 \sim A_3 \) by \([1], [2], [13], [14], [22]\)

\[
\begin{align*}
A_1 &= (F \sin \alpha, -F \cos \alpha) \\
A_2 &= (-F \sin \alpha, -F \cos \alpha) \\
A_3 &= (0, -F),
\end{align*}
\tag{1}
\]

where \( F \) is the beam focal length and is also the radius of the circular arc. The profile of this TFRL-BFN, \( z' = f(x') \), is built in this coordinate system. On the other hand, the antenna array configuration in the FB-A is specified in a \((x'', z'')\) coordinate system. Let the array element be located at \( Q, \tilde{r}_a = (x_a, z_a) \), in the \((x'', z'')\) coordinate system via the transmission line in the FB-B with a constant phase. It connects a pair of \( Q \) and \( P \) in the FB-B to excite an antenna element by a phase, \(-\phi (\phi = -k_wW\text{ with } W \text{ being the length of the transmission line with } k_w \text{ being its wavenumber})\). All these elements in the FB-A \( \sim \) FB-C select a reference point by the \((x', z')\) coordinate system’s origin in FB-C, a reference element at \( \tilde{r}_{ref} = (x_{ref}, z_{ref}) \) in FB-A, and the transmission line phase, \(-\phi_{0}\), between these two points in FB-B.

As illustrated in Fig. 2, let the excitation phases provided by the TFRL-BFN in FB-C and the transmission lines in FB-B be denoted by \( \Phi_q(\tilde{r}_{ref}) \). \( \Phi_q(\tilde{r}_a) \) should be equal or have constant offsets to the desired phase distribution, \( \tilde{B}_q(\tilde{r}_a) \), for the three shaped beams when they are compared to the case of the selected references. Thus, the following three equations can be built by pairing \( A_1 \sim A_3 \) with the beams, \( B_1 \sim B_3 \), respectively:

\[
\Phi_q(\tilde{r}_a) - \tilde{B}_q(\tilde{r}_a) = \Phi_q(\tilde{r}_{ref}) - \tilde{B}_q(\tilde{r}_{ref}),
\tag{2a}
\]

where \( q = 1 \sim 3 \) indicate the three beams excited by the beam ports \( A_1 \sim A_3 \). Let \( k_w \) and \( k_0 \) be the wavenumbers of PCB substrate and free space, respectively. The excitation phases produced in FB-C and FB-B to excite the array are given by

\[
\Phi_q(\tilde{r}_a) = -k_w\bar{A}_qP - \phi; \Phi_q(\tilde{r}_{ref}) = -k_F - \phi_{0},
\tag{2b};(2c)
\]

where \( A_qP \) are given by

\[
\begin{align*}
A_1P &= \sqrt{(x_b - F \sin \alpha)^2 + (z_b + F \cos \alpha)^2} \\
A_2P &= \sqrt{(x_b + F \sin \alpha)^2 + (z_b + F \cos \alpha)^2} \\
A_3P &= \sqrt{(x_b)^2 + (z_b + F)^2}.
\end{align*}
\tag{3a} -(3c)
\]

Next, (2) is normalized by \( k_F \) to give

\[
\bar{A}_qP = w_a + \bar{B}_q(\tilde{r}_a); \quad q = 1 \sim 3,
\tag{4}
\]

where

\[
w_a = 1 - w; \quad w = \frac{\phi - \phi_{0}}{k_F},
\tag{5a};(5b)
\]

\[
\bar{B}_q(\tilde{r}_a) = \frac{(\bar{B}_q(\tilde{r}_{ref}) - \bar{B}_q(\tilde{r}_a))}{k_F}.
\tag{6}
\]

The normalized distance parameters, \( \bar{A}_qP \), are now given by

\[
\begin{align*}
A_1P &= \sqrt{(x_b - \sin \alpha)^2 + (z_b + \cos \alpha)^2} \\
A_2P &= \sqrt{(x_b + \sin \alpha)^2 + (z_b + \cos \alpha)^2} \\
A_3P &= \sqrt{(x_b)^2 + (z_b + 1)^2},
\end{align*}
\tag{7a} -(7c)
\]

where \( (x_b, z_b) = (x_b, z_b)/F \). The three equations in (4) can be thus solved for \( (x_b, z_b) \) and \( w_a \) to determine the TFRL-BFN’s external profile and the constant phases required in the compensation circuits in FB-B.

One first square (4) to generate three polynomial equations for solving the solutions. The difference between the squared equations of \( q = 2 \) and 1 in (4) results in the solution of \( x_b \), by

\[
\tilde{x}_b = y_1w_a + y_2; \quad \begin{cases}
y_1 = \frac{\bar{B}^2q(\tilde{r}_a) - \bar{B}_q^2(\tilde{r}_a)}{2b} \\
y_2 = \frac{[\bar{B}^2q(\tilde{r}_a)]^2 - [\bar{B}^2q(\tilde{r}_a)]^2}{4b}.
\end{cases}
\tag{8a};(8b)
\]

where \( b = \sin \alpha \). It is seen that \( x_b \) is linear of \( w_a \) and is a function of antenna array excitations. Similarly, the difference by the squared equations of \( q = 3 \) and 2, in conjunction with substituting (8) for \( x_b \) in (4), gives

\[
\tilde{z}_b = \zeta_1w_a + \zeta_2; \quad \begin{cases}
\zeta_1 = \frac{2\bar{B}^2q_3(\tilde{r}_a) - \bar{B}_3^2(\tilde{r}_a) - \bar{B}_q^2(\tilde{r}_a)}{2(1 - a)} \\
\zeta_2 = \frac{2[\bar{B}^2q_3(\tilde{r}_a)]^2 - [\bar{B}_q^2(\tilde{r}_a)]^2}{4(1 - a)}.
\end{cases}
\tag{9a}
\]

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It is noted that (10) has real solutions when \( \tau \) distance values in (4) for all three equations. The solutions should also fulfill the conditions of positive elements with complex solutions in (10) should be avoided.

The design’s effectiveness highly relies on a proper selection of \( F \). Those antenna elements with complex solutions in (10) should be avoided. The solutions should also fulfill the conditions of positive distance values in (4) for all three equations.

After \( w \) in (10) is solved, (5a) and (5b) can be used to solve \( \phi \) as a function of \( \tilde{r}_a \), to construct the phase compensation circuits in FB-B. This \( w \) is also used to find \((\tilde{x}_b, \tilde{z}_b)\) in (8a) and (9a) to build up the Rotman lens’s external profile by \( (x_b, z_b) = F(\tilde{x}_b, \tilde{z}_b) \). Based on this general derivation, it is seen that when three reasonable beam excitation phases, \( \tilde{B}_q(\tilde{r}_a) \), are specified, then a TFRL-BFN can be determined appropriately to provide the array excitations. In the mathematic derivation, the solutions are exact without causing phase aberrations in focal point beam excitations. The design’s effectiveness highly relies on a proper selection of \( \tilde{B}_q(\tilde{r}_a) \) as the mathematically exact profile may not be physically realizable for a BFN with reasonable effectiveness. However, the solutions have opened the possibility to design a TFRL-BFN for a wide range of multiple shaped beam applications. It is also noted that the realization of the phase compensation circuits in FB-B is not limited to microstrip transmission lines [15]–[17], [30]. It is conveniently built to bridge the TFRL-BFN and the conformal antenna arrays of various configurations.

III. TYPICAL SCENARIOS OF CONFORMAL PHASED ARRAYS OF ANTENNAS FOR NFF AND FAR-FIELD RADIATIONS

The solution is demonstrated by designing TFRL-BFNs to excite a conformal array of antennas for NFF or far-field multibeam radiations. It is assumed that the one-dimensional (1-D) conformal antenna elements are placed on a virtual curved surface in free space, i.e., the field points of multibeam directions are in the lit region to the antenna elements for line-of-sight (LOS) radiations without curvature effects. Note that a mechanical structure may be used to implement the antenna elements, which may cause creeping waves from some antenna elements in the shadow region to the field points for wide-angle beams. These shadowing effects can also be included in the proposed conformal multibeam TFRL-BFN design by planning proper excitation schemes if necessary. The geometrical theory of diffraction (GTD) based ray-tracing method [31] can be used to incorporate the creeping/surface wave effects.

A. FAR-FIELD FOCUS SCENARIO BY A CONFORMAL ARRAY OF ANTENNAS

One considers a far-field scenario of multibeam radiations by conformal phased arrays of antennas [33], as illustrated in Fig. 3 (a). In this configuration, \( z_a \) is a function of \( x_a \). The excitation phases of the antenna to produce a directional beam in the \( \theta = \vartheta_q \) (\( q = 1 \sim 3 \)) direction linearly and are given by

\[
\tilde{B}_q(\tilde{r}_a) = -k(x_a \sin \vartheta_q + z_a \cos \vartheta_q)
\]
In this example, we assume that \( \vartheta_{1,2} = \mp \alpha \) and \( \vartheta_3 = 0 \), which is not required in a general situation. For easy demonstration, one selects a reference position at \( \tilde{r}_{\text{ref}} = (x_a = 0, z_a = 0) \), which results in reference phases by

\[
\tilde{B}_q(\tilde{r}_{\text{ref}}) = 0.
\]

Thus, the normalized relative phases in (6) are given by

\[
\tilde{\bar{\Phi}}_q(\tilde{r}_a) = \left( \frac{\delta_z \sin \theta_q + \delta_x \cos \theta_q}{\sqrt{\varepsilon_r}} \right),
\]

where \((\delta_x, \delta_z) = (x_a, z_a)/F\), and \( \varepsilon_r \) is the dielectric constant of the Rotman lens’s dielectric substrate.

To design the TFRL-BFN, one first finds the coefficients in (8), (9), and (10), which are used to determine \((x_b, z_b)\) and the parameter, \(w_s\). Thus, using (8b) gives

\[
(\gamma_1, \gamma_2) = \left( \frac{\delta_z}{\sqrt{\varepsilon_r}}, \frac{\delta_x a}{\varepsilon_r} \right),
\]

and the coefficients in (9b) are found by

\[
(\zeta_1, \zeta_2) = \left( \frac{\delta_z}{\sqrt{\varepsilon_r}}, \frac{(1 + a)(\delta_z^2 - \delta_x^2)}{\varepsilon_r} \right).
\]

Finally, the coefficients in (11) are given by

\[
\tau_1 = \left( \frac{\delta_z^2 + \delta_x^2}{\varepsilon_r} \right)^{1/2} - 1,
\]

\[
\tau_2 = \frac{\delta_z^2}{\varepsilon_r} \left( a - 1 \right) \delta_x^2 + \left( a + 1 \right) \delta_z^2 \right)^{1/2},
\]

\[
\tau_3 = \left( a + \frac{1 + a}{2\varepsilon_r} (\delta_z^2 - \delta_x^2) \right)^{1/2} + b^2 \left( 1 + \frac{\delta_z^2 - \delta_x^2}{\varepsilon_r} \right)
- \frac{\delta_x^2}{\varepsilon_r} \left( 1 - \frac{a^2 \delta_z^2}{\varepsilon_r} \right).
\]

These coefficients are functions of antenna element positions, where (17) is used to find \(w_s\) for phase compensation circuits. Afterward, (15) and (16) are used with \(w_s\) to determine the TFRL-BFN’s external profile, \((x_b, z_b)\), by (8a) and (9a). This solution is very general and reduces to the derivation in [22] for a circularly cylindrical conformal array without performing any approximation [22] or using four beam focal points [27].

The above solution reduces exactly to the solutions of a planar phased array of antennas in [2] by making \(z_a = 0\). In this case, \(\delta_z = 0\) reduces (15)-(17) to

\[
(\eta_1, \eta_2) = \left( \frac{\delta_x}{\varepsilon_r}, 0 \right),
(\xi_1, \xi_2) = \left( 0, -\frac{\delta_x^2(1 + a)}{2\varepsilon_r} \right),
\]

\[
(\tau_1, \tau_2, \tau_3) = \left( \frac{\delta_x^2}{\varepsilon_r} - 1, 0, b^2 \left( 1 - \frac{\delta_x^2}{\varepsilon_r} \right) \right)
+ \left( a - \frac{\delta_x^2(1 + a)}{2\varepsilon_r} \right)^{1/2}.
\]

This result is consistent with the results in [1], [2].

### B. NFF SCENARIO BY A CONFORMAL PHASED ARRAY OF ANTENNAS

The scenario of NFF multibeam radiations by a conformal periodic array of antennas is illustrated in Fig. 3(b). Again, the reference element is at \(\tilde{r}_{\text{ref}} = 0\). The field focal lengths of the three NFF beams are different by \(L_q (q = 1 \sim 3)\) measured from \(\tilde{r}_{\text{ref}} = 0\), which is much more general than the previous studies in [13] with the same field focal lengths. Besides, the angular separations are further different in contrast to the case in [13]. They are specified by \(\beta_1\) between \(B_1\) and \(B_3\), and by \(\beta_2\) between \(B_2\) and \(B_3\), respectively, to make the NFF field focal points at \(B_{1,2} = L_{1,2}(\mp \sin \beta_{1,2} \cdot \cos \beta_{1,2})\) and \(B_3 = (0, L_3)\), respectively. Thus, the required excitation phases are given by

\[
\begin{align*}
\tilde{B}_1(\tilde{r}_a) &= k \ell_1 = k \sqrt{(x_a + L_1 \sin \beta_1)^2 + (z_a - L_1 \cos \beta_1)^2}, \\
\tilde{B}_2(\tilde{r}_a) &= k \ell_2 = k \sqrt{(x_a - L_2 \sin \beta_2)^2 + (z_a - L_2 \cos \beta_2)^2}, \\
\tilde{B}_3(\tilde{r}_a) &= k \ell_3 = k \sqrt{x_a^2 + (z_a - L_3)^2}.
\end{align*}
\]

At \(\tilde{r}_{\text{ref}} = 0\), the reference phases are given by

\[
\tilde{B}_q(\tilde{r}_{\text{ref}}) = kl_q, \quad q = 1 \sim 3.
\]

One thus defines the following normalized parameters:

\[
(L_{q,F}, \ell_{q,F}) = \frac{k \ell_q}{F}; \quad k = k_0/k_e
\]

(23a);(23b)

to make

\[
\tilde{\bar{\Phi}}_q(\tilde{r}_a) = -\ell_{q,F}^s; \quad \ell_{q,F}^s = \ell_{q,F} - L_{q,F}.
\]

(24a);(24b)

By using same definitions in [13] for the following parameters:

\[
\Delta_{pq}^s = \ell_{p,F}^s - \ell_{q,F}^s; \quad \Sigma_{pq} = \ell_{p,F}^s + \ell_{q,F}^s
\]

(25a);(25b)

\[
\Delta_{pq}^{sq} = (\ell_{p,F}^s)^2 - (\ell_{q,F}^s)^2 = \Delta_{pq} \Sigma_{pq},
\]

the coefficients in (8b) and (9b) can be found by

\[
(\gamma_1, \gamma_2) = \left( \frac{-\Delta_{21}}{2b}; \frac{-\Delta_{21}^{sq}}{4b} \right),
(\zeta_1, \zeta_2) = \left( \frac{\Omega}{2(1-a)}; \frac{\Pi}{4(1-a)} \right),
\]

(27);(28)

where \(\Omega \equiv \Delta_{21} + 2\Delta_{32}\) and \(\Pi \equiv \Delta_{21}^{sq} + 2\Delta_{32}^{sq}\). Besides, the coefficients of (10) can be found by

\[
\tau_1 = \left( \frac{\Delta_{21}}{2b} \right)^2 + \left( \frac{\Omega}{2(1-a)} \right)^2 - 1,
\]

(29a)

\[
\tau_2 = -\Sigma_{21} \left( \frac{\Delta_{21}}{2b} \right)^2 - \frac{\Omega}{1-a} - \frac{\Omega \Pi}{4(1-a)} \sqrt{1 + 2\ell_{3,F}^s},
\]

(29b)

\[
\tau_3 = \left( \frac{\Delta_{21}^{sq}}{4b} \right)^2 + \left( \frac{\Pi}{4(1-a)} \right)^2 - (\ell_{3,F}^s)^2.
\]

(29c)

Similar to the procedure in Section III.A, (29) is used to solve \(w_s\), and together with (27) and (28) to determine \((x_b, z_b)\).
It is noted that when $L_q = L$ and $z_a = 0$, the solutions reduce to the case in [13] in the same format. Moreover, if $z_a = 0$ and $\beta_{1,2} = 0$, then the beams point to the axial direction with different FFLs to axially shift beams. In this case, (24b) becomes
\begin{equation}
\ell_{q,F}^s = \sqrt{\frac{\delta^2}{\epsilon_r}} + L_q^2 - L_q,F,
\end{equation}
where $\delta_x = x_a/F$, as previously defined in (14).

### C. DUAL NFF AND FAR-FIELD FOCUS HYBRID MODE OPERATION

The TFRL-BFN is used to provide the excitation phases for dual-mode operations of a conformal array of antennas between NFF and far-field radiations. In this case, the beam ports become mode selection ports. In particular, $A_3$ is selected to produce a far-field focus directional beam, $B_3$, pointing toward the $\theta = 0^\circ$ direction. In contrast, the two lateral beam ports, $A_{1,2}$, are used to have two NFF beams, $B_{1,2}$, in the $\theta = \pm \alpha$ directions with a field focal length, $L$. For simplicity, one lets $z_a = 0$ for a planar array of antennas. As a result, $\tilde{B}_q(\tilde{r}_a)$ in (2) becomes
\begin{align}
\begin{cases}
\tilde{B}_1(\tilde{r}_a) = k\ell_1 = k\sqrt{(x_a + L_1b)^2 + (L_1a)^2} \\
\tilde{B}_2(\tilde{r}_a) = k\ell_2 = k\sqrt{(x_a - L_2b)^2 + (L_2a)^2} \\
\tilde{B}_3(\tilde{r}_a) = k\ell_3 = 0.
\end{cases}
\end{align}
In this case, the phases at $\tilde{r}_{ref} = 0$ are given by
\begin{equation}
(\tilde{B}_1(\tilde{r}_{ref}), \tilde{B}_2(\tilde{r}_{ref}), \tilde{B}_3(\tilde{r}_{ref})) = (k(L, L, 0)).
\end{equation}
In this case, $\tilde{B}_q^s(\tilde{r}_a)$ in (6) are given in (24) for $q = 1, 2$ with a focal length replacement by (31) and (32), and $\tilde{B}_q^s(\tilde{r}_a) = 0$. As a result, the coefficients, $\gamma_{1,2}$, in (8b) are identical in form to (27). On the other hand, the coefficients, $\xi_{1,2}$, in (9b) become
\begin{equation}
(\xi_1, \xi_2) = \left(\frac{\Sigma_{21}}{2(1-a)} - \frac{\Sigma_{sq}^{a}}{4(1-a)}\right),
\end{equation}
where $\Sigma_{pq}^{a} = [\ell^s_{p,F}]^2 + [\ell^s_{q,F}]^2$. $\tau_{1-3}$ in (11) are found by
\begin{align}
\tau_1 &= \frac{\Delta^2_{21}}{4b^2} + \frac{\Sigma^2_{21}}{4(1-a)^2} - 1, \\
\tau_2 &= -\frac{\Delta_{21}\Delta_{sq}^{a}}{4b^2} + \frac{\Sigma_{21}}{(1-a)} \left(1 - \frac{\Sigma_{sq}^{a}}{4(1-a)}\right), \\
\tau_3 &= \left(\frac{\Delta_{sq}^{a}}{4b}\right)^2 + \left(1 - \frac{\Sigma_{sq}^{a}}{4(1-a)}\right)^2.
\end{align}

### IV. NUMERICAL DEMONSTRATION EXAMPLES AND CHARACTERISTIC EXAMINATION

Examples by numerical computations and simulations are presented to demonstrate the characteristics of this generalized TFRL-BFN for conformal arrays of antennas. The output phase characteristics are first examined, and the radiation patterns are afterward shown to explore the multibeam characteristics. For simplicity, a $\alpha$-polarized cosine taper is employed to model the antenna radiation pattern as previously used in [32].

#### A. FAR-FIELD FOCUS SCENARIO BY A CONFORMAL PHASED ARRAY OF ANTENNAS

The conformal array of antennas is implemented on a convex circular boundary of a radius, $\rho = 5\lambda$, where the position vectors to place the antennas are given by [18], [20], [22]
\begin{equation}
(x_a, z_a) = \rho(\sin \phi_a, -1 + \cos \phi_a),
\end{equation}
where, as illustrated in Fig. 5, $\phi_a$ is the angular variable to discretize the circular boundary. The antenna elements are...
periodical with an angular separation, $\Delta \phi$. For comparison, a planar array of the same antennas at $z_a = 0$ is also examined to justify the phase production behavior of TFRL-BFN. In both cases, the antenna elements point outward from their array apertures. In particular, $F = 30$ cm and $\alpha = 30^\circ$ are selected to specify $A_1 \sim A_3$ on the beam port arc, operated at 2.4 GHz. The three beams, $B_1 \sim B_3$, are angularly separated by $\alpha$. The period of the antenna array is $0.5\lambda$ with an angular period of $\Delta \phi = 0.5\lambda / \rho$. The realization of phase compensation circuits in FB-B of Fig. 2 is not specified. They only provide constant phases between the paired antenna ports of TFRL-BFN and the antenna array. In this case, the range of $\bar{r}_a = -\rho \leq x_a \leq \rho$ and $-\rho \leq z_a \leq 0$, where the maximum array size is $\pi \rho$.

Section III.A’s derivations first compute the phases produced by this TFRL-BFN on the circular array aperture for directional beam radiations to the ideal excitations. Afterward, the extra feeds are placed on the beam port arc every $10^\circ$ to produce 13 beams. The phase discrepancies [9]–[11] are shown in Fig. 6(a), where only seven beams are shown owing to the symmetric structure of antennas. It is seen that the computed phases by (2b) for beams $B_1 \sim B_3$ exactly match the theoretical values by (12) to result in zero phase discrepancy in Fig. 6(a). On the other hand, the computed phases show deviations for the five defocused beams in Fig. 6(a), where wide-angle beams show larger phase discrepancies. However, in the central region of the aperture, the phase discrepancies are small. These large phase discrepancies will cause beam squints to be seen in the multibeam radiation patterns in Fig. 6(b).

These seven beams’ radiation patterns are shown in Fig. 6(b) to demonstrate the multibeam overlapping, where the array has 21 elements. In this examination, the amplitudes of excitations are assuming uniform for simplification because the solutions of the TFRL-BFN do not provide amplitude information. It is noted that the amplitude tapers are highly dependent on the feeding structures of beam and antenna excitation output ports, where the Friis equation can be used for simple estimation if the feeding structures are determined [10], [34].

The multibeam radiation patterns from a planar antenna array are also shown in Fig. 6(b). In both arrays, the excitation phases of antennas are all produced by their associated TFRL-BFNs for comparison. In this case, it is seen that the multibeam directions by the planar antenna array align very well to the desired directions of beams by every 10 degrees. Beam squints are observed on the multi beams by the conformal array of antennas. This beam squint behavior is also exhibited from the large phase discrepancy in Fig. 6(a). It is seen that the planar array has severer gain drops of more than 8 dB for the beam at $60^\circ$. On the other hand, the gain drops are less than 4 dB for the conformal array of antennas. It is noted that the beams near the planar array broadside direction have smaller gains for the circular array because the antenna elements’ broadsides, which have the largest gain, are gradually tilted away from this direction. Besides, the planar array has a larger projected aperture than the circular array.

To justify the phase discrepancy, we define a mean phase estimation discrepancy (MPED) per beam by

$$MPED = \frac{1}{N} \sum_{n=1}^{N} \left| \Phi_q(x_n, z_n) - \tilde{B}_q(x_n, z_n) \right|,$$  (38)

where $N = 21$ is the number of antenna elements. It is noted that a smaller MPED indicates a better excitation phase production with a zero value for a perfect match between the TFRL-BFN and the theoretical requirement in (12). The antenna array is placed on various radii’s circular boundaries to exhibit this behavior, where the array becomes planar when the radius is very large. The results of MPED to beam feed’s angular position, $\alpha_b$, on the beam port arc are shown.
FIGURE 7. Estimation of average excitation phase discrepancy produced by the TFRL-BFN for various circular boundaries to implement the conformal array of antennas in the far-field focus scenario.

in Fig. 7(a). It is seen that the phases produced by the TFRL-BFN are more stable for $|\alpha_b| < 30^\circ$, i.e., the feed is between $A_1$ and $A_2$. For the beam ports external to this region, the average phase discrepancy becomes large to cause beam squints and pattern distortions, as earlier shown in Fig. 6(b). In this case, it is also seen that a flatter planar array with a larger radius for the circular boundary may decrease the phase discrepancy.

Similarly, to examine gain performance, a quantity “mean radiation gain uniformity (MRGU)” is also investigated to the radius of the circular boundary in Fig. 7(b). It is computed by the following for average gain discrepancy:

$$\text{MRGU} = \frac{1}{M} \sum_{m=1}^{M} |G_m(dB) - G_{av}(dB)|,$$  \hfill (39)

where $G_{av}(dB)$ is the average gain of the $M$ beams defined by

$$G_{av} = \frac{1}{M} \sum_{m=1}^{M} G_m(dB).$$  \hfill (40)

Apparently, a smaller MRGU indicates a better gain uniformity, where each beam’s gain performance is close to $G_{av}$. It is noted that in Fig. 7(b), the computations of MRGU consider two angular ranges on the beam port arc for comparison to produce directional beams by shifting their feeds with one degree per step of shifting in these two angular ranges. Thus, 61 and 121 feed shiftings are performed to compute the MRGUs in (39) for these two cases. It is seen that when a wide angular range of beam implementation is required, it will result in a large gain fluctuation, which is caused by the large beam squints and distortions due to the feeds placed external to the beam port arc. In this case, a conformal array may reduce gain discrepancies for outer beams. Thus, when the outer beams are not considered in the computation of (39), the gain discrepancy is smaller and remains stable. The black curve’s averages show a minimum of roughly 0.4 dB, which are even stabler when the radii are between $25\lambda$ and $50\lambda$. This MRGU analysis assists one in determining a proper radius of circular boundary to implement the antenna array.

B. NFF SCENARIO BY A CONCAVE CONFORMAL ARRAY OF ANTENNAS

The investigation of NFF multibeam radiations follows the same procedure in Section IV.A to compare the output phases with the theoretical requirement in (21). In this case, $21 \times 31$ antenna elements by a period of 0.5$\lambda$ are considered along the

FIGURE 8. A concave conformal array of antennas for NFF multibeam applications by using TFRL-BFN to produce excitation phases.
concave circular surface with the antenna boresights pointing inward for NFF radiations, as illustrated in Fig. 8. Again, the circular boundary has a radius of 5\(\lambda\). Each column subarray along the y-dimension has 31 elements whose excitations are first phased to radiate NFF fields at \(L = 120\) cm from the column subarrays at its boresight axis. Afterward, the TFRL-BFN is designed for the multibeam radiations on the x-z plane. In this case, the NFF field points of \(B_1 \sim B_3\) are selected on a circular arc of a radius, \(L = 120\) cm, with the same angular separations of \(\alpha = 30^\circ\).

Following the similar discussion in Section IV.A, Fig. 9(a) shows the excitation phase discrepancies while Fig. 9(b) shows the normalized multibeam radiation patterns, where the -6dB contours are plotted for easy comparison. Fig. 9(a) shows that the phase discrepancies are small for the NFF beams within the \(\pm 30^\circ\) range. The excitation phase discrepancies by the TFRL-BFN increase significantly for the beams outside the \(\pm 30^\circ\) range. The normalized NFF radiation patterns in Fig. 9(b) are compared between the concave circular array and a planar array case with the same antenna periods of 0.5\(\lambda\). Owing to their symmetric array configurations, only one-half beams of both arrays are shown for easy figure demonstration. In this case, the planar array has a larger projection aperture along its boresight direction. It is first observed that the maximum field points of the NFF beams are at similar distances for both array radiations because they are highly dependent on the field focal lengths. In this examination, the field focal length, \(L = 120\) cm, is used for all multibeam cases, explaining the similar distances of maximum field strengths. However, the concave circular array results in narrower beamwidths in the -6dB contours, which indicates a better field focusing in the near-zone.

The MPED behaviors are shown in Fig. 10, analogous to the analysis in Fig. 7(a) to consider the phase discrepancy between the TFRL-BFN and theoretical requirements (21). In contrast to the case in Fig. 7(a), where a flatter planar array results in less average phase discrepancy for the feeds placed inside the beam port arc within \(\pm 30^\circ\), the phase discrepancy of NFF radiations is smaller for a conformal array. The conformal array on the circular boundary of 5\(\lambda\) in radius has the least phase discrepancy in excitations, where the average discrepancy is less than 4\(^\circ\). For the beams outside \(\pm 30^\circ\), phase discrepancy increases for wide-angle beams to cause distortions.

C. DUAL NFF AND FAR-FIELD FOCUS HYBRID MODE OPERATION

Finally, the dual NFF and far-field focus mode operations, as discussed in Section III.C, are examined. The antenna
array configuration is the same as that in Section IV.B in Fig. 8 for simplification. In this example, the two lateral beams at $\alpha = \pm 30^\circ$ are implemented for NFF radiation as in Section IV.B, while the central beam at $\alpha = 0^\circ$ has far-field focus radiation as considered in Section IV.A. This hybrid design allows the beam focusing to switch from near zone to far zone by changing the feeds’ positions on the beam port arc. Thus, the vicinity of $A_1$ and $A_2$ are used to specify the NFF radiation modes while the vicinity area of $A_3$ is used to select the far-field focus radiation mode. The excitation phase discrepancies to (21) and (12), when the TFRL-BFN is used in a standing-alone fashion for the NFF and far-field focus radiations, respectively, are shown in Fig. 11(a). The dash lines show phase discrepancies of NFF multi beams, while the solid lines show that of far-field focus multi beams. Again, owing to the symmetric array structure, only a half beams are shown. Without surprise, at $\alpha = 0^\circ$ and $\pm 30^\circ$ the excitation phase discrepancies are zeros. The NFF contoured and far-field focus beam patterns by these three-beam selection focal point feeds are shown in Fig. 11(b) and (c), respectively, where good beam behaviors are seen.

It is noted that the excitation phase discrepancies increase as the feeds shift away from these three-beam selection focal points, as shown in Fig. 11(a). In this case, the far-field focus case has a focused beam at $\alpha = 0^\circ$, and then gradually results in defocus beams when the feed is away from this far-field beam focal point ($A_3$), where the first three beams are still well focused. The beams defocus when the feed is close to the two outer beam selection focal points at $\alpha = \pm 30^\circ (A_{1,2})$, which validates the far-field focus beam functionality by this TFRL-BFN. In this case, the radiation becomes NFF beams as expected in the design.

On the other hand, the two contoured NFF beams in Fig. 11(b) also have good behaviors. To further explore
FIGURE 13. Measurement setup and the beam ports’ reflection coefficients.

FIGURE 14. Amplitude taper and phase distributions produced by the TFRL-BFN for NFF multibeam radiation.

V. MEASUREMENT VALIDATION

Measurement validation considers a TFRL-BFN design for NFF multibeam radiation as previously considered in [13] at 2.45 GHz. The BFN is realized on an FR4 substrate ($\varepsilon_r = 4.46$ and 1.6mm in thickness), with seven beam ports and eight antenna ports, respectively, for examination. Three NFF equal-phase focal points are specified to angularly distribute on a circular arc of 120cm in radius by 30 degrees. The Rotman lens’s focal length is $F = 23$ cm with the same angular separation of 30 degrees for the three focal beam ports. After the Rotman lens was built, additional beam ports were constructed for the overlapped multibeam radiations. Dummy ports of 50 $\Omega$ termination were also created for impedance matching.

This TFRL-BFN is measured using a network analyzer, as shown by the measurement setup photo in Fig. 13 (a). The beam and antenna excitation ports are labeled on the prototype photo in Fig. 14 (b). The measured reflection coefficients for three beam-ports $b_2 \sim b_5$ are shown in Fig. 13 (b) by the solid lines compared to HFSS full-wave simulations by the

the defocus beams of NFF radiations, the feeds are placed on the beam port arc between $A_1 \sim A_2$ to examine the NFF radiation patterns. It is noted that the beam port arcs between $A_1$ and $A_3$, and between $A_2$ and $A_3$ are the mode transition areas as the feed placed at the positions $A_1$ and $A_2$ results in an NFF beam while it results in a far-field focus beam when the feed is moved to $A_3$. As a result, the field focal point shifts between far- and near-zone when the feed is placed between these three-beam focal points. To examine the beam focus transition from NFF to far-field beam radiations, the normalized near field patterns are plotted by the $-6$ dB contours in Fig. 12, where the maximum field strength points are also labeled to indicate the beam shifting from near zone to far zone. It is seen that the outer two NFF beams near $\alpha = -30^\circ$ have a better focusing behavior with a narrower $-6$ dB contour beamwidth. On the other hand, the inner two beams near $\alpha = 0^\circ$ have broader beamwidths. In this case, the far-field focus beams in Fig. 11 (c) show good FF radiation patterns. This comparison validates the dual NFF and far-field focus mode mechanism by this TFRL-BFN design.
dashed lines. Excellent agreements have been observed with a very broad bandwidth of operational frequencies.

The transmission coefficients of the TFRL-BFN between the beam and antenna output ports are obtained and compared by simulation and measurement. Particularly, Fig. 14 (a) and (b) show the amplitude taper and phase distributions at different antenna output ports on the TFRL-BFN when the central beam and the outer beam are excited. The phase compensation circuits in the FB-B of Fig. 2 were not considered in the comparison because full-wave simulations on the transmission lines are difficult to perform.

The results in Fig. 14 (a) show relatively uniform amplitude tapers for two selected central and outer beams, which are less than 1 dB for the central beam by the blue curves, while they are larger for the outer beam by the red curves. The differences between simulation and measurement results are similar by roughly 0.8dB. The RF connectors cause these amplitude drops to build the ports for measurements, where each connector causes approximately 0.4dB power loss. Moreover, the phase variations between the measurement and simulation results are similar, with almost a constant offset caused by the RF connectors. The central beam’s symmetric phase variations result in an NFF beam along the central direction. The outer beam’s phase variations show progress variations to produce a deviated beam from the central beam. The consistency of amplitude tapers and phase variations between full-wave simulation and experimental measurement results further validate this paper’s design concept.

VI. CONCLUSION

The theoretical foundation of a general TFRL-BFN has been developed for the excitations of conformal arrays of antennas to radiate NFF/far-field shaped multi beams, ranging from NFF to far-field focus radiations. The three sets of provided exact phases of excitations by the TFRL-BFN may also allow the conformal phased array of antennas to operate at different modes of interest in the multi-mode operations. The mode selection capability has also been demonstrated for the antenna array to work in both NFF simultaneously and far-field focus radiation modes, an important feature to enhance power reception in wireless power transfer. Numerical simulations have validated the feasibility of the theoretical foundation. A TFRL-BFN is further examined by comparing the results of full-wave simulation and measurement. Potential new realistic implementations of the various applications discussed in this paper will be subsequently examined by experiments, which will be reported in the near future to continue this multibeam antenna work.

REFERENCES

[1] W. Rotman and R. Turner, “Wide-angle microwave lens for line source applications,” IEEE Trans. Antennas Propag., vol. AP-11, no. 6, pp. 623–632, Nov. 1963.

[2] Y. J. Cheng, W. Hong, K. Wu, Z. Q. Kuai, C. Yu, J. X. Chen, J. Y. Zhou, and H. J. Tang, “Substrate integrated waveguide (SIW) Rotman lens and its Ka-band multibeam antenna array applications,” IEEE Trans. Antennas Propag., vol. 56, no. 8, pp. 2504–2513, Aug. 2008.

[3] W. Zongxin, X. Bo, and Y. Fei, “A multibeam antenna array based on printed Rotman lens,” Int. J. Antennas Propag., vol. 2013, pp. 1–6, Jan. 2013.

[4] J.-W. Lian, Y.-L. Ban, H. Zhu, and Y. J. Guo, “Reduced-sidelobe multibeam array antenna based on SIW Rotman lens,” IEEE Antennas Wireless Propag. Lett., vol. 19, no. 1, pp. 188–192, Jan. 2020.

[5] T. Katagi, S. Mano, and S. Sato, “An improved design method of Rotman lens antennas,” IEEE Trans. Antennas Propag., vol. AP-32, no. 5, pp. 524–527, May 1984.

[6] W. Lee, 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.

[7] L. Schulwitz and 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.

[8] J. Hunt, N. Kundniz, N. Landy, A. Starr, T. Perfam, and D. R. Smith, “Transformation optics compressed Rotman lens implemented with complementary metamaterials,” Proc. SPIE, vol. 8021, Jun. 2011, Art. no. 802100.

[9] J. Dong, A. I. Zaghoul, and R. Rotman, “Phase-error performance of multi-focal and non-focal two-dimensional Rotman lens designs,” IET Microw. Antennas Propag., vol. 4, no. 12, pp. 2097–2103, Dec. 2010.

[10] R. C. Hansen, “Design trades for Rotman lenses,” IEEE Trans. Antennas Propag., vol. 39, no. 4, pp. 464–472, Apr. 1991.

[11] A. Attaran, R. Rashidzadeh, and A. Kouki, “60 GHz low phase error Rotman lens combined with wideband microstrip antenna array using LTCC technology,” IEEE Trans. Antennas Propag., vol. 64, no. 12, pp. 5172–5180, Dec. 2016.

[12] M. Yu, D. Zhao, Y. Jin, and B.-Z. Wang, “Near-field image restoration for Rotman lens by localized angle-time spread function-based filtering method,” IEEE Trans. Antennas Propag., vol. 63, no. 5, pp. 2353–2358, May 2015.

[13] H.-T. Chou and Z.-C. Tsai, “Near-field focus radiation of multibeam phased array of antennas realized by using modified Rotman lens beamformer,” IEEE Trans. Antennas Propag., vol. 66, no. 12, pp. 6618–6628, Dec. 2018.

[14] Y. F. Wu, Y. J. Cheng, and Z. X. Huang, “Ka-band near-field-focused 2-D steering antenna array with a focused Rotman lens,” IEEE Trans. Antennas Propag., vol. 66, no. 10, pp. 5204–5213, Oct. 2018.

[15] K. Tekkouk, M. Ettorre, and R. Sauleau, “SIW Rotman lens antenna with ridged delay lines and reduced footprint,” IEEE Trans. Microw. Theory Techn., vol. 66, no. 6, pp. 3136–3144, Jun. 2018.

[16] T. K. Vo Dai, T. Nguyen, and O. Kilic, “Compact multi-layer microstrip Rotman lens design using coupling slots to support millimetre wave devices,” IET Microw., Antennas Propag., vol. 12, no. 8, pp. 1260–1265, Jul. 2018.

[17] Q. Liang, B. Sun, G. Zhou, J. Zhao, and G. Zhang, “Design of compact Rotman lens using truncated ports with energy distribution slots,” IEEE Access, vol. 7, pp. 120766–120773, 2019.

[18] A. Rahimian, “Comments on ‘a multibeam cylindrically conformal slot array antenna based on a modified Rotman lens,’” IEEE Trans. Antennas Propag., vol. 67, no. 3, pp. 2034, Mar. 2019.

[19] F. K. M. A. Hosseini, N. Hamzeh, and A. J. Beall, “A conformal Rotman lens,” in Proc. IEEE Int. Symp. Antennas Propag., USNC/URSI Nat. Radio Sci. Meeting, Jul. 2017, pp. 2245–2246.

[20] T. K. Vo Dai, T. Nguyen, and O. Kilic, “A non-focal Rotman lens design to support cylindrically conformal array antenna,” Appl. Comput. Electromagn. Soc. J., vol. 33, no. 2, pp. 240–243, Feb. 2018.

[21] A. Mahmoodi and A. Pirhadi, “Enhancement of scan angle using a Rotman lens feeding network for a conformal array antenna configuration,” Appl. Comput. Electromagn. Soc. J., vol. 30, no. 9, pp. 959–966, Sep. 2015.

[22] Y. Liu, H. Yang, Z. Jin, F. Zhao, and J. Zhu, “A multibeam cylindrically conformal slot array antenna based on a modified Rotman lens,” IEEE Trans. Antennas Propag., vol. 66, no. 7, pp. 3441–3452, Jul. 2018.

[23] Y. Liu, H. Yang, Z. Jin, and J. Zhu, “Circumferentially conformal slot array antenna and its Ka-band multibeam applications,” IET Microw., Antennas Propag., vol. 12, no. 15, pp. 2307–2312, Dec. 2018.

[24] R. Uyguroglu and A. Y. Ozturak, “A wide angle multiple beam lens for convex conformal arrays,” Turkish J. Elect. Eng. Comput. Sci., vol. 28, no. 1, pp. 423–431, 2020.

[25] N. Herscovici, L. Griffiths, R. Chilton, J. Da’Angelo, and M. Champion, “A conformal Rotman lens,” in Proc. IEEE Int. Symp. Antennas Propag., USNC/URSI Nat. Radio Sci. Meeting, Jul. 2017, pp. 2245–2246.
[26] J.-R. Park and D.-C. Park, “Design of Rotman lens for curved array antenna with minimal phase error,” J. Korean Inst. Electromagn. Eng. Sci., vol. 25, no. 10, pp. 1077–1086, Oct. 2014.

[27] C. M. Rappaport and A. I. Zaghoul, “Multi-focal boottlace lens design concepts: A review,” in Proc. IEEE AP-S Int. Symp., Jul. 2005, pp. 39–42.

[28] R. P. S. Kushwah and P. K. Singhal, “Design of 2D-boottlace lens with five focal feed for multiple beam forming,” J. Electromagn. Anal. Appl., vol. 3, no. 2, pp. 39–42, 2011.

[29] C. M. Rappaport and J. Mason, “A five focal point three-dimensional boottlace lens with scanning in two planes,” in IEEE Antennas Propag. Soc. Int. Symp. Dig., Jul. 1992, pp. 1340–1343.

[30] H.-T. Chou, Z.-C. Tsai, and S. Panigrahi, “Tri-focal configuration of three-dimensional metallic waveguide-array lens antennas of Rotman lens concept for multi-beam applications,” IEEE Access, vol. 7, pp. 144524–144535, 2019.

[31] P. Pathak, N. Wang, W. Burnside, and R. Kouyoumjan, “A uniform GTD solution for the radiation from sources on a convex surface,” IEEE Trans. Antennas Propag., vol. AP-29, no. 4, pp. 609–622, Jul. 1981.

[32] Y. Rahmat-Samii and S.-W. Lee, “Directivity of planar array feeds for satellite reflector applications,” IEEE Trans. Antennas Propag., vol. AP-31, no. 3, pp. 463–470, May 1983.

[33] H.-T. Chou, S.-C. Chang, and H.-J. Huang, “Multibeam radiations from circular periodic array of Vivaldi antennas excited by an integrated 2-D Luneburg lens beamforming network,” IEEE Antennas Wireless Propag. Lett., vol. 19, no. 9, pp. 1486–1490, Sep. 2020.

[34] M. S. Smith and A. K. S. Fong, “Amplitude performance of Ruze and Rotman lenses,” Radio Electron. Eng., vol. 53, no. 9, pp. 329–336, 1983.

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