Single-Feed Quad-Beam Transmitarray Antenna Design

Ahmed H. Abdelrahman, Member, IEEE, Payam Nayeri, Member, IEEE, Atef Z. Elsherbeni, Fellow, IEEE, and Fan Yang, Senior Member, IEEE

Abstract—We present a design methodology for single-feed multibeam transmitarray antennas through case studies of quad-beam designs. Different far-field pattern masks and fitness functions are studied for multibeam designs, and the particle swarm optimization (PSO) technique is implemented for aperture phase synthesis. A quad-layer configuration of double square loops is used for the transmitarray elements, and a quad-beam transmitarray prototype is fabricated and tested. The effects of various approximations in unit-cell analysis are also investigated in detail. The Ku-band prototype generates four symmetric beams with 50° elevation separation between the beams and gains around 23 dB.

Index Terms—Multibeam, particle swarm optimization (PSO), phase synthesis, transmitarray antenna.

I. INTRODUCTION

Planar transmitarray antennas have attracted a growing interest in the area of high-gain antennas due to their numerous advantages [1], [2]. They combine the favorable features of optical lens and array antennas leading to a low-profile aperture and light weight design, which is well appropriate for long distance communications and space applications [3]. One of the main advantages of transmitarray antennas compared to dielectric lens is the individual phase control of each transmitarray element, which provides flexibility in array phase synthesis, and hence is suitable for various applications that require radiation pattern control [4]–[6].

Multibeam antennas receive considerable attention in space [7]–[8], radar [9]–[10], SAR [11], millimeter wave [12], and MIMO [13] applications. High-gain antennas with multiple simultaneous beams are usually implemented using reflectors or lenses with feed-horn clusters, or large phased arrays. The main disadvantages of these structures are cost, size, and weight, mainly for space applications. Similar to reflectarray antennas [14], [15], a transmitarray antenna with a single feed can achieve multiple simultaneous beams with the added advantages of light weight and low-profile aperture [16], [17]. In comparison to a multibeam reflectarray, the main advantage of a multibeam transmitarray is the inherent ability to avoid feed blockage, which is typically a concern for simultaneous multibeam patterns [15].

In this paper, we present a general design methodology for multibeam transmitarray antennas using a single source feed, through case studies of several quad-beam designs. It should be noted that since all beam are generated with a single source, they carry the same signal. The particle swarm optimization (PSO) technique is implemented to synthesize the transmission phase of the transmitarray elements [18], and various pattern masks and fitness functions are implemented for multibeam designs. A Ku-band quad-beam transmitarray prototype is fabricated and tested using quad-layer double square loop (QLDSL) elements. Effects of oblique incidence and local periodicity approximation in the element design are also investigated in detail to determine their impacts on the element transmission coefficients and the overall antenna radiation pattern.

II. DESIGN OF SINGLE-FEED MULTIBEAM TRANSMITARRAY ANTENNAS

A. Design Methodologies

In transmitarray antennas, the element amplitudes are fixed by the properties of the feed and the element locations. However, the elements of a transmitarray antenna have the flexibility to achieve any value of phase shift. Utilizing this direct control of phase shift for every element, the phase distribution on the array aperture can be synthesized to achieve any desired pattern shape, such as multibeam patterns. Accordingly, the design procedure of the proposed transmitarray antenna starts with synthesis of the transmission phase distribution of the array aperture using PSO technique. Once the required transmission phase is determined for each element, the corresponding element dimension is obtained using the transmission phase versus element dimension curve, which is usually obtained from the unit-cell full EM wave analysis.

Two different synthesis approaches are available for single-feed multibeam space-fed arrays, i.e., direct analytical solutions or optimization methods. While analytical solutions are typically simple to implement, recent studies [14] have shown that the performance of these methods is not satisfactory in many cases. Optimization methods on the other hand have the
The periodicity of the unit-cell element is $P = 11$. The separation between the four beams is designed to be 50°.

In this study, we use the PSO global search method to synthesize the aperture phase distribution of transmitarray antennas for multibeam performance. Far-field pattern masks are defined based on the design requirements, and different fitness functions are studied to achieve optimal beam performance and sidelobe level. Pattern computation is conducted efficiently using an in-house code, which is based on the array theory formulation with spectral transformations for computational speedup [19].

### B. Design of Single-Feed Quad-Beam Transmitarray Antennas at Ku-Band

To demonstrate the feasibility of the proposed design technique for single-feed multibeam transmitarray antennas, we study a symmetric quad-beam system. The elevation separation between the four beams is designed to be 50°, such that the four beams are pointing at $\vartheta_1 = 25°$, $\varphi_1 = 0°$, $\varphi_2 = 90°$, $\varphi_3 = 180°$, and $\varphi_4 = 270°$. The transmitarray is designed for the center operating frequency of 13.5 GHz.

A linearly polarized corrugated conical horn with a gain equal to 16.3 dB at 13.5 GHz is used as the feed antenna. The phase center of the horn is placed at a distance of 275 mm from the transmitarray antenna aperture. For the simulation model, the radiation pattern of this feed is approximated with a $\cos^q (\theta)$ model with $q = 9.25$.

The array has a circular aperture with a diameter of 311 mm consisting of 648 elements. The elements are QLDSL as described in [20]. The element configuration and design parameters are shown in Fig. 1.

The unit-cell simulations were carried out using CST Microwave Studio software [21]. The optimum dimensions of the separation between the two loops (S) and the loop width (W) were determined through parametric analysis aiming to achieve an optimal linear slope of the transmission phase, under normal incidence excitation. These dimensions were determined to be $S = 0.2\ L_1$ and $W = 4.2$ mm, and phase tuning is achieved by varying the length $L_1$ from 6.6 to 10.4 mm. $L_1$ is the only variable parameter, $S$ and $L_2$ are dependent parameters of $L_1$. The four-layers of the unit-cell are identical. The elements are printed on a Taconic TLX-8 dielectric substrate with permittivity $\epsilon_r = 2.574$ and thickness $T = 0.5$ mm. The periodicity of the unit-cell element is $P = 11.1$ mm, and the separation between layers is equal to $H = 5$ mm, which can achieve a 360° transmission phase range with transmission magnitudes better than −1.2 dB at 13.5 GHz [2], as shown in Fig. 2.

Three different design models are investigated for quad-beam transmitarray antennas. First, we consider two different pattern masks: a constant sidelobe level of $-30$ dB (Design 1), and a tapered mask with $-25$ dB SLL at the first sidelobe to $-40$ dB at $\vartheta = 90°$ (Design 2). A two term fitness function is defined, which evaluates the radiation performance of the array in terms of the peak gain for each beam and sidelobe level in the entire angular space based on the mask requirements as described in [15]. The fitness function to be minimized is

$$\text{Cost} = W_1 \sum_{(u,v) \in \text{mainbeam} \ and \ |F(u,v)| > M_U(u,v)} \sum_{|F(u,v)| > M_L(u,v)} (|F(u,v)| - M_U(u,v))^2$$

$$+ W_2 \sum_{(u,v) \in \text{mainbeam} \ and \ |F(u,v)| < M_U(u,v)} (|F(u,v)| - M_U(u,v))^2.$$

Here, $M_U$ and $M_L$ are the upper and lower bounds of the radiation pattern mask, respectively, and $F$ is the far-field radiation pattern of the antenna, as described in [14] and [15].

A swarm population of 150 particles is selected for the PSO and two symmetry planes are defined to reduce the size of the solution hyperspace. It is worthwhile to mention that, PSO is only applied to the design of aperture phase distribution, and not applied to the optimization of element dimensions. Experimental studies showed that with the tapered mask, the penalty for the main-beam fitness term had to be increased, in comparison with the penalty of the pattern mask for the case of constant sidelobe level, to achieve a better performance. Thus in the next stage, a third design with double penalty for main-beam fitness was also studied (Design 3). The double penalty relates to the weights associated with the terms in the fitness function. For double penalty in the main beam area $W_2 = 2W_1$.

Table I summarizes the gain performances of these three designs, where the transmission loss of the QLDSL elements is considered in the right column.

In summary, all quad-beam transmitarrays studied here achieved a good performance, which demonstrates the effectiveness of the proposed multibeam design approach. In comparison among the designs, Design 3 achieves the highest gain, with the best overall radiation performance in the entire angular.
### TABLE I
**COMPARISON OF THREE DIFFERENT DESIGN MODELS FOR SINGLE-FEED QUAD-BEAM TRANSMITARRAY ANTENNAS**

<table>
<thead>
<tr>
<th>Transmitarray</th>
<th>Gain (ideal elements) (dB)</th>
<th>Gain (QLDSL elements) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1</td>
<td>25.19</td>
<td>24.56</td>
</tr>
<tr>
<td>Design 2</td>
<td>24.95</td>
<td>24.15</td>
</tr>
<tr>
<td>Design 3</td>
<td>25.35</td>
<td>24.77</td>
</tr>
</tbody>
</table>

space, and thus was selected for fabrication. The synthesized phase distribution on the aperture, the pattern mask, and the radiation patterns for this design are given in Fig. 3.

### III. PROTOTYPE FABRICATION AND MEASUREMENTS

The optimized quad-beam prototype is fabricated using a commercial PCB etching process. The mask and photograph of one layer of the fabricated array with 648 QLDSL elements are shown in Fig. 4. The fabricated prototype is tested using the NSI planar near-field measurement system at the University of Mississippi. An image of the test setup is shown in Fig. 5.

The far-field radiation patterns for y-polarized feed-horn are depicted in Fig. 6, which show a good quad-beam performance. The four beams are located at elevation angle $\theta_{1,2,3,4} = 25^\circ$, except a $1^\circ$ shift in one beam, and azimuth angles $\phi_1 = 0^\circ$, $\phi_2 = 90^\circ$, $\phi_3 = 180^\circ$, and $\phi_4 = 270^\circ$ as desired. The measured gain of the two beams along the yz-plane are the same and equal to 23.8 dB, and those along the xz-plane are equal to 22.3 dB and 22.6 dB. Note that the simulated gain is 24.77 dB for each beam. The sidelobe and cross polarized levels are less than $-14$ dB and $-30$ dB, respectively.

---

Fig. 3. (a) Synthesized phase distribution. (b) Radiation pattern mask. (c) Simulated radiation patterns for the quad-beam transmitarray antenna at 13.5 GHz.

Fig. 4. One layer of the fabricated quad-beam transmitarray prototype. (a) Mask. (b) Photograph.

Fig. 5. Measurement setup of the quad-beam transmitarray antenna in the NSI planar near-field system.

Fig. 6. Far-field patterns. (a) xz-plane. (b) yz-plane. (c) 3-D pattern.
The gain reduction of 1.5 and 1.2 dB observed for the two beams along the xz-plane in comparison with the other two beams along the yz-plane is primarily attributed to polarization effects [3]. Additionally, the higher sidelobe levels observed in the measured results are attributed to fabrication tolerances, and approximation errors in the unit-cell analysis, which include normal incidence and local periodicity approximations. Detailed investigations on these sources of error are conducted and presented in the following sections.

IV. EFFECTS OF VARIOUS APPROXIMATIONS

A. Oblique Incidence Effects on the Element Performance

In this section, we study the transmission performance of the phasing elements under oblique incidence excitation. The aim of this study is to investigate the potential errors due to normal incidence approximation in the element design. Fig. 7 depicts the variations in the transmission magnitude and phase of the QLDSL element at different oblique incidence angles and for y-polarized incidence wave. The parameters $\theta$ and $\varphi$ are the elevation and azimuth angles of the incident wave, respectively.

The results shown here indicate that despite some minor differences, the transmission magnitude and phase of the elements do not differ significantly with the normal incidence case for elevation angles up to $30^\circ$. It should be noted, however, that for the case of $L_1 = 9.4$ mm, when placed along the x-axis ($\varphi = 0^\circ$), the element does exhibit a resonance for oblique excitation angles that significantly degrades its performance. However, the fabricated prototype only has four elements with this dimension, which are not along the x-axis, and are close to the aperture edge, thus they also exhibit a weaker taper. In summary, the errors arising from the normal incident approximation are relatively small, and the discrepancies between measured and simulated results are not attributed to this approximation.

B. Variations in Dimensions of Neighbor Elements

In multibeam space-fed arrays, the aperture phase distribution is considerably different than traditional single-beam designs. For the latter, the elements exhibit a smooth phase variation between their neighboring elements and phase wraps (element dimension jumping from a maximum to minimum or vice versa) are only observed at the edge of the Fresnel zones. As such, local periodicity is generally considered to be a reasonable approximation. For multibeam designs, however, the phase distribution on the aperture is quite complex and significant differences between each element and its surrounding neighbor elements are observed (see Fig. 4). Accordingly, the approximations in the traditional unit-cell analysis, which consider all elements to be identical, could lead to noticeable error in the transmission coefficient values.

In order to investigate the accuracy of the unit-cell element approximations, a large unit-cell consisting of nine neighbor elements is studied, which is known as the surrounded element approach [22]. Three different cases, as shown in Fig. 8, are simulated using CST Microwave Studio software [21]. The dimensions $L_1$ of the center element for the three cases are 7.2, 7.75, and 8.85 mm, respectively. The dimensions of the other neighbor elements are selected according to their actual dimensions in the designed quad-beam transmitarray prototype.

The transmission coefficients of the three cases are compared with those of the conventional unit-cell element in Fig. 9. Due to the asymmetry of the large unit-cell, the transmission coefficients for both perpendicular (TE) and parallel (TM) polarizations are considered [3]. It can be seen that Case 1) and Case 2) both show large phase error and magnitude loss when compared with the conventional unit-cell element. Case 3) on the other hand shows almost no significant change in the transmission coefficient values. This is due to the fact that the dimensional difference between the elements in this case is small compared to the other two cases. This study shows that the local periodicity approximation appears to be the primary reason for the transmission coefficient errors of the elements.
C. Impact of Element Phase Error and Magnitude Loss on Antenna Radiation Pattern

The potential sources of error were investigated in the previous two sections and it was shown that approximation of local periodicity led to significant inaccuracies in the transmission coefficients values of the elements. Here, we study the effect of both transmission phase error and loss of the elements on the radiation pattern of the quad-beam transmitarray prototype. For phase error analysis, a random phase is added to the actual phase of each element using a normal distribution with mean value of $0^\circ$. The standard deviation for this normal distribution ranges from 0 to $60^\circ$. For each standard deviation value, the average normalized radiation pattern of 20 trials is demonstrated, and tested at 13.5 GHz by using QLDSL elements. The measured gains of four beams are 23.8, 23.8, 22.3, and 22.6 dB, respectively. Furthermore, the impact of unit-cell approximations during simulation process is studied, and then the effects of phase error and magnitude loss of the unit-cell element on the antenna patterns are demonstrated.

V. Conclusion

The feasibility of designing single-feed multibeam transmitarray antennas is demonstrated through the design of quad-beam patterns. The PSO method is used to synthesize the aperture phase distribution of the transmitarray, and various pattern masks and fitness functions are studied for multibeam designs. A Ku-band single-feed quad-beam transmitarray antenna with $50^\circ$ elevation separation between the beams is designed, fabricated, and tested at 13.5 GHz by using QLDSL elements. The array has a circular aperture with a diameter of 311 mm. The measured gains of four beams are 23.8, 23.8, 22.3, and 22.6 dB, respectively.

References


Ahmed H. Abdeldrahman (S’13–M’15) received the B.S. degree in electrical engineering and the M.S. degree in electronics and communications from Ain Shams University, Cairo, Egypt, and the Ph.D. degree in engineering sciences from the University of Mississippi, University, MS, USA, in 2001, 2010, and 2014, respectively.

He is currently a Postdoctoral Research Associate with the Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, USA. He also possesses over eight years of experience in Satellite Communications industry. He worked as a RF Design Engineer and a Communication System Engineer in building the low earth orbit satellite Egyptsat-1. His research interests include transmitarray/reflectarray antennas, mobile antennas, 3-D printed antennas, and thermoacoustic and millimeter-wave imaging.

Dr. Abdeldrahman was the recipient of the several prestigious awards, including the third place Winner Student Paper Competition at the 2014 IEEE AP-S International Symposium on Antennas and Propagation.

Payam Nayeri (S’09–M’12) received the B.Sc. degree in applied physics from Shahid Beheshti University, Tehran, Iran, the M.Sc. degree in electrical engineering from Iran University of Science and Technology, Tehran, Iran, and the Ph.D. degree in electrical engineering from the University of Mississippi, University, MS, USA, in 2004, 2007, and 2012, respectively.

From 2008 to 2013, he was with the Center for Applied Electromagnetic Systems Research (CAESR), University of Mississippi. Prior to this, he was a Visiting Researcher at the University of Queensland, Brisbane, QLD, Australia. From August 2012 to December 2013, he was a Postdoctoral Research Associate and an Instructor with the Department of Electrical Engineering, University of Mississippi. From January 2014 to June 2015, he was a Postdoctoral Fellow with the Department of Electrical Engineering and Computer Science, Colorado School of Mines, as an Assistant Professor in July 2015. He has authored over sixty journal articles and conference papers. His research interests include antennas, arrays, and RF/microwave devices and systems, with applications in deep space communications, microwave imaging, and remote sensing.

Dr. Nayeri is a member of Sigma Xi, and Phi Kappa Phi. He was the recipient of several prestigious awards, including the IEEE Antennas and Propagation Society Doctoral Research Award in 2010, the University of Mississippi Graduate Achievement Award in Electrical Engineering in 2011, and the Best Student Paper Award of the 29th International Review of Progress in Antennas and Propagation (ISAP), Oct. 2013, pp. 484–487.

He is currently a Postdoctoral Research Associate with the Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, USA. He also possesses over eight years of experience in Satellite Communications industry. He worked as a RF Design Engineer and a Communication System Engineer in building the low earth orbit satellite Egyptsat-1. His research interests include transmitarray/reflectarray antennas, mobile antennas, 3-D printed antennas, and thermoacoustic and millimeter-wave imaging.

Dr. Abdeldrahman was the recipient of the several prestigious awards, including the third place Winner Student Paper Competition at the 2014 IEEE AP-S International Symposium on Antennas and Propagation.
Fan Yang (S’96–M’03–SM’08) received the B.S. and M.S. degrees from Tsinghua University, Beijing, China, and the Ph.D. degree from the University of California at Los Angeles (UCLA), Los Angeles, CA, USA, in 1997, 1999, and 2002, respectively.

From 1994 to 1999, he was a Research Assistant with the State Key Laboratory of Microwave and Digital Communications, Tsinghua University. From 1999 to 2002, he was a Graduate Student Researcher with the Antenna Laboratory, UCLA. From 2002 to 2004, he was a Postdoctoral Research Engineer and Instructor with the Electrical Engineering Department, UCLA. In 2004, he joined the Department of Electrical Engineering, University of Mississippi, University, MS, USA, as an Assistant Professor, and was promoted to an Associate Professor. In 2011, he joined the Department of Electronic Engineering, Tsinghua University, Beijing, China, as a Professor, and has served as the Director of the Microwave and Antenna Institute since then. He has authored over 200 journal articles and conference papers, five book chapters, and three books entitled *Scattering Analysis of Periodic Structures Using Finite-Difference Time-Domain Method* (Morgan & Claypool, 2012), *Electromagnetic Band Gap Structures in Antenna Engineering* (Cambridge Univ. Press, 2009), and *Electromagnetics and Antenna Optimization Using Taguchi’s Method* (Morgan & Claypool, 2007). His research interests include antennas, periodic structures, computational electromagnetics, and applied electromagnetic systems.

Dr. Yang served as an Associate Editor of the *IEEE Transactions on Antennas and Propagation* (2010–2013) and an Associate Editor-in-Chief of *Applied Computational Electromagnetics Society (ACES) Journal* (2008–2014). He was the Technical Program Committee (TPC) Chair of the 2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting. He was the recipient of several prestigious awards and recognitions, including the Young Scientist Award of the 2005 URSI General Assembly and the 2007 International Symposium on Electromagnetic Theory, the 2008 Junior Faculty Research Award of the University of Mississippi, the 2009 inaugural IEEE Donald G. Dudley Jr. Undergraduate Teaching Award, and the 2011 Recipient of Global Experts Program of China.