Low-Profile High-Gain and Wide-Angle Beam Scanning Phased Transmitarray Antennas

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This work was supported by the Natural Science Foundation of China Project under Grants 61622104 and 61721001, and the Fundamental Research Funds for the Central Universities (ZYGX2019Z005).

ABSTRACT Combining the inherent multiple beam capabilities of transmitarray antennas (TAAs) and the flexible fields launched by phased array antennas (PAAs), PAA-fed TAAs are proposed in this paper for high-gain and wide-angle beam scanning in millimeter-wave (MMW) band. After thoroughly analyzing the operating mechanisms of the PAA-fed TAAs, a divisionally multi-focal method is proposed to deploy the TAA elements, which can be better adapted to the PAA feed whereby the scanning performances are improved. Subsequently, two PAA-fed TAAs with feeding distance-to-diameter ratios (H/Ds) of mere 0.28 are numerically demonstrated at 39 GHz, wherein both TAAs are composed of the square subwavelength low-pass elements and the cavity-backed bowtie patch antenna is identified as the PAA feed element. Simulated results show that the first design example achieves a conical beam steering over ±30° with a 30.9 dBi peak gain and gain drop below 2.1 dB. The second design can scan across ±50°/±10° along the E/H planes, respectively, together with the gain losses of 3.3 and 1.6 dB from the peak value of 31.1 dBi. Finally, the first design case is fabricated and measured for experimental verification purpose, whose measured results agree reasonably well with the simulated ones.

INDEX TERMS Beam scanning, high gain, low profile, millimeter wave, periodic structures, phased array antennas, transmitarray antennas.

I. INTRODUCTION

Millimeter-wave (MMW) communication systems have attracted growing research attention due to their wide available frequency spectrum. However, the link budget for highly integrated MMW systems is rather limited because of the restricted transmitting power and the high propagation loss. Therefore, highly directional array antennas with beam scanning capabilities are urgently required at MMW frequencies. One of the most popular solution is the phased array antennas (PAAs), whereby the pencil-shaped beams with high gain can be quickly steered across a wide angular scope [1]. Nevertheless, masses of active modules employed in large-scale PAAs would cause unaffordably high cost. Combining the space-fed mechanism of traditional lens antennas and the operations of PAAs, transmitarray antennas (TAAs) are now emerging as an attractively low-cost candidate of high-gain beam scanning MMW array antennas. In recent years, numerous TAAs with different operating mechanisms have been developed to pursue higher efficiency and more compact volume, primarily including TAAs with the receiving-transmitting scheme [2], [3], TAAs composed of multilayer frequency-selective surface (FSS) elements [4], [5], and those with polarization-conversion property [6], [7], etc. Albeit great merits like low mass and ease of fabrication, beam steering of the reported TAAs is mainly implemented by mechanical scan [8], [9] or switched beam [10], [11] techniques, which are both associated with notable and intrinsic drawbacks. The mechanically scanning TAAs with feed antenna displacement suffer from slow scan speed and low system reliability, which are hard to fulfill the practical demands. Meanwhile, the number of the beams generated by the switched beam TAAs is equivalent to that of the feed elements, suggesting that densely arranging the feed elements is unavoidable for high-gain beam scanning applications. Importantly, besides high profiles, both aforementioned techniques are with the concentrated energy distribution over the focal area, inevitably causing some unexpected issues at the radio frequency (RF) sub-system level, e.g., limited effective isotropic radiated power (EIRP) in the transmitting mode.
To conquer these difficulties, combining the adjustable fields launched by the PAA and the inherent multi-beam capabilities of the TAA is a promising technical solution.

Some earlier studies on PAA-fed lens antennas are presented in [12]–[14], where numerical analyses of lens-enhanced PAA are implemented in [12] but with low aperture efficiency as well as huge scan loss. In [13], a modular PAA is adopted to illuminate a dielectric lens thus realizing a peak gain of 29 dBi and an azimuth scan sector across ±45°. Nevertheless, the extremely bulky and heavy dielectric lens remarkably increases the inconvenience of the system integration. Furthermore, a phased TAA for one-dimensional (1-D) beam scanning is proposed in [14], achieving a scanning coverage of ±30°. However, because the TAA phase distribution in [14] is determined by traditional single-focal method, obvious scan loss up to 3.7 dB is suffered according to the measured results.

Inspired by these works, PAA-fed TAAs aiming at high-gain and wide-angle two-dimensional (2-D) beam scanning are proposed in this paper in MMW band. Firstly, a divisionally multi–focal method based on ray-tracing theory is proposed to determine the phase distribution on the TAA aperture, which possesses smaller phase errors at different scan angles against those calculated by traditional single-focal method, and hence obviously improves the scanning performances. Subsequently, the subwavelength square low-pass FSS unit cell and the cavity-backed patch antenna are identified as the TAA and PAA feed elements, respectively, because the miniaturized TAA elements can alleviate the quantization error of phase discretization and such a PAA feed is easily integrated with the planar control circuits. After optimizing the TAA element deployments and the PAA feed excitation coefficients, two PAA-fed TAAs with the feeding distance-to-diameter ratios (H/Ds) of mere 0.28 are designed at 39 GHz. The first one features a conical beam scanning over ±30° with a peak gain of 30.9 dBi and a scanning gain drop of 2.1 dB. The second one covers ±50° and ±10° in the E and H planes, respectively, along with gain drops of 3.3 and 1.6 dB from the maximum value of 31.1 dBi. For experimental demonstration, the first PAA-fed TAA is fabricated and examined by the measurements, showing reasonable agreements with the simulated results.

II. OPERATIONS OF WIDE-ANGLE BEAM SCANNING PAA-FED TAAS

A. IMPROVED FEEDING MECHANISM

The schematic of the proposed PAA-fed TAA for launching the broadside beam is shown in Fig. 1(a), where D, H and F represent the aperture diameter, the feeding distance and the designed focal length of the TAA, respectively. The TAA and the PAA feed are parallel to each other, and each PAA feed element is integrated with an active transmitting/receiving (T/R) module, including a phase shifter, a power amplifier, or an attenuator, etc. Different from traditional near-field focusing PAAAs concentrating the electromagnetic power in the near-field region [15], virtual focal spot, denoted by O in Fig. 1(a), is created by the PAA feed at back of its ground plane. By carefully matching it with the real focal spot of the TAA, the PAA feed can effectively excite the TAA with an obviously smaller feeding distance against traditional single feed antenna, but without gain degradation or even with higher efficiency. Importantly, as depicted in Fig. 1(b), the virtual focal spot can be moved via tuning the PAA feed excitation coefficients to match the real ones of the TAA at different scan angles, thus realizing highly overlapped scanning beams. Here, the number of the beams generated by the proposed PAA-fed TAA is primarily dominated by the precision of the employed T/R module, which is much more than that of the feed elements in general.

Besides the superiorities such as more compact volume and higher scanning precision, the proposed PAA-fed TAA also features some significant merits at the RF sub-system level. Since the PAA feed is located between the TAA and its real focal spot, dispersed energy distributions are produced across the PAA feed aperture, thus successfully activating more feed elements simultaneously for any given desired scan direction. Such a phenomenon enables remarkable EIRP enhancements against traditional switched beam TAA in the transmitting mode. Furthermore, sharing the transmitting power over the PAA feed aperture makes it realizable to replace power amplifiers necessarily with high output power in traditional single feed mechanism by more low-cost ones with smaller output power but higher efficiency, which also alleviates the stress on cooling designs. Meanwhile in the receiving mode, the PAA-fed TAA with dispersed incident RF power is inherently
B. DIVISIONALLY MULTI-FOCAL METHOD

The scanning range and gain drop are the most pivotal criteria to gauge the performances of wide-angle beam scanning TAAs, which are mainly determined by the phase mismatching between the required phase compensations and those provided by the available TAA elements at each scan angle. In traditional beam scanning TAAs with mechanisms of mechanically steering or electrically switching, single-focal configurations with parabolic-type aperture phase distribution are commonly employed. The desired phase shift of each TAA element at different scan angles can be computed as follows:

$$
\phi_{mn}^{\text{desired}}(i) = k_0 \left[ R_{mn}^i (\theta_b^i) - \sin \theta_b^i (x_{mn} \cos \varphi_{b}^i \sin \varphi_{b}^i + y_{mn} \sin \varphi_{b}^i) \right] + \Delta \phi(i) \quad i = 1, 2, \ldots, I
$$

(1)

where $i$ denotes the $i^{th}$ considered scan angle with a total number of $I$. $(x_{mn}, y_{mn})$ are the coordinates of the $mn^{th}$ TAA element, and its spatial distance from the feed antenna with respect to the $i^{th}$ scan angle is expressed by $R_{mn}^i$. $(\theta_b^i, \varphi_b^i)$ represent the spherical angles of the $i^{th}$ scanning beam direction. Meanwhile, $\theta_b^i$ is the feed offset angle, and $\Delta \phi(i)$ is the constant reference phase. Assuming that the single focal spot is along a circular-arc path to guarantee a fixed $F/D$ of 0.28, and $\theta_b^i = \theta_f$ with $\varphi_b^i = 0^\circ$, the desired phase distributions on the TAA aperture as scan to $0^\circ$ and $-30^\circ$ are presented in Figs. 2(a) and (b), respectively. Nevertheless, if the angle sensitivity characteristic of the employed TAA element is ignored, the realized phase shifts on the TAA aperture are almost unchanged versus the scan angle, indicating that mere one scan angle can be ideally compensated but huge phase errors will be suffered at other directions, e.g., the phase error across the TAA aperture in Fig. 2(c) as scan to $-30^\circ$. Therefore, the single-focal TAAs can only scan in a limited angular range of a few beam widths also with obvious scanning gain losses.

By averaging the spatial phase delays associated with two or multiple focal spots on the whole TAA aperture, bifocal [16] or multi-focal [17]–[19] design methods were later suggested as effective approaches to realize better scanning performances against the single-focal configurations. Based on these works, a divisionally multi-focal method is proposed in this paper to determine the TAA element arrangement, which is expected to be more appropriately adapted to the PAA feed thus improving the scanning performance. Considering that the concentric phase distribution is employed on the TAA aperture, general design concept is described in terms of a 1-D linear TAA, which can be directly extended to the 2-D planar case without requiring further development. As depicted in Fig. 3, the linear 1-D TAA is divided into three subarrays, i.e., $T_1$, $T_2$, and $T_3$. The central subarray $T_2$ owns the focal spot located at $F_2$, and its outgoing beam is assigned along the broadside direction. Two edge subarrays $T_1$ and $T_3$ are with the focal spots at $F_1$ and $F_3$, respectively, together with the beam offset angles of $\theta_2$ and $-\theta_2$. According to Formula (1), the phase distributions in subarrays $T_1 \sim T_3$ can be obtained. Importantly, to avoid the phase discontinuities at the junctions of $T_1 \sim T_3$, i.e., $B$ and $B'$ as marked in Fig. 3, the constant reference phase $\Delta \phi$ in each subarray should be carefully tuned to guarantee the continuous phase distribution on the whole TAA aperture. Since $T_1$ and $T_3$ are mainly excited as scan to large angles while $T_2$ has stronger illumination around the normal direction, the proposed divisional phase distribution features less pronounced phase mismatching across the entire scanning scope. Also benefiting from the flexible and controllable fields launched by the PAA feed, the phase error suffered at each scan angle can be further compensated, making it realizable to scan to larger angles but with smaller gain drops against those traditional designs.

To efficiently evaluate the scanning performances of the PAA-fed TAAs, their far-field radiation patterns need to be calculated based on the array-summation method [6]. The key point herein is that the passive TAA scatters the primary fields from each PAA feed element into secondary fields, which are further superposed in the far-field region utilizing the PAA feed excitation coefficients as the weight vectors. Specifically, each PAA feed element can be modeled by an ideal feeding point source to calculate its incident fields impinging on the TAA aperture, which also can be directly extracted from full-wave simulations for higher accuracy. After modeling the PAA-fed TAAs, the TAA element deployment and the excitation coefficient of the $pq^{th}$ PAA feed
element, termed as $I_{pq}$, need to be decided simultaneously to realize the desired wide-angle beam scanning, where $I_{pq}$ is further distinguished by $I_{pq}(\alpha)$, i.e., the PAA feed excitation coefficients for steering the beam to a desired scan angle $\alpha$. Because the phase distribution on the TAA aperture is determined by $F_1$, $F_2$, $B$ and $\theta_d$ simultaneously ($T_1$ and $T_2$ are ideally symmetric), all of these four parameters as well as $I_{pq}(\alpha)$ are set as the variables, which can be further solved to maximize the weighted summation of the integral gains of the whole PAA-fed TAA at multiple scan angles.

### III. DESIGN EXAMPLES AND NUMERICAL RESULTS

#### A. ELEMENT DESIGNS

Fig. 4 presents the topology of the employed TAA element, which possesses a subwavelength structure as well as a low-pass frequency response [20]. Such a miniaturized TAA element, which is with the volume of $0.21 \times 0.21 \times 0.26\lambda_0^3$ ($\lambda_0$ is the free-space wavelength at the center operating frequency $f_0 = 39$ GHz), can mitigate the quantization error of phase discretization, therefore emerging as a promising candidate for the beam steering design. The whole element consists of multiple square metallic patches and thin dielectric substrates that are cascaded sequentially. After each layer is individually fabricated, all of the five PCBs are bonded together by four bonding films. Following the equivalent procedures as described in [21], the metallic patches and dielectric substrates can be modeled with the parallel capacitors and series inductors, respectively, thus forming the low-pass circuit model. Subsequently, under the guidance of the filter theory, the component values of the equivalent circuit are elaborately tuned to adjust the cut-off frequency of the passband, which should be further mapped to the geometrical parameters of the FSS element.

Under the periodic boundary conditions, the employed low-pass FSS element is numerically simulated in 36–42 GHz for different incident angles. The transmission magnitudes, termed as $|S_{21}|$, of some representative TAA elements are given in Fig. 5(a). As observed, the majority of $|S_{21}|$ are higher than $-1$ dB in the whole investigated band at normal incidence, suggesting a desired low transmission loss. Furthermore, Fig. 5(b) illustrates the transmission phases, i.e., $\angle S_{21}$, of these elements versus frequency, wherein a full $2\pi$ coverage is obtained at $f_0$. For oblique incidences up to $60^\circ$, acceptable transmission loss increments and phase discrepancies are suffered by both the transverse electric (TE) and transverse magnetic (TM) polarizations, showing that the employed TAA element features a modest sensitivity to oblique incidence.

In view of the prominent merits such as lightweight, low cost, ease of fabrication and integration, the cavity-backed patch antenna as shown in Figs. 6(a) and (b) is identified as the PAA feed element. Here, a bowtie metallic patch is printed on the upper surface of the top substrate acting as the radiator, which is with the thickness of 0.127 mm and dielectric constant of 2.2. Between two substrate layers, a 0.5 mm-thick metallic cavity is placed to serve as a supporter, which also can suppress the surface waves and enhance the inter-element isolations. Meanwhile, a ground plane with an I-shaped coupling slot is etched at the top side of the bottom substrate, along with a microstrip feeding line on the other side. Specifically, all of the feeding structures are shielded by the metallic via holes to reduce the energy leakage. The simulated active reflection magnitude, represented by $|S_{ii}|$, of the employed cavity-backed patch antenna in an infinite array is depicted in Fig. 6(c). Benefiting from both resonances of the bowtie metallic patch and the coupling slot, $|S_{ii}| \leq -10$ dB is realized from 34.4 to 43.1 GHz, corresponding to a fractional bandwidth of $\sim 22.5\%$. 

\[ \frac{36 \text{ to } 42 \text{ GHz}}{\text{Frequency}} \]
FIGURE 6. (a) 3-D view of the employed PAA element. (b) Geometry of the feeding layer. (c) Simulated active reflection magnitudes versus frequency. $p_0 = 5.6$, $p_1 = 2.5$, $p_2 = 2.5$, $l_1 = 0.127$, $l_2 = 0.5$, $l_3 = 0.254$, $a_1 = 0.34$, $a_2 = 0.8$, $a_3 = 0.45$, $a_4 = 0.15$, and $a_5 = 1.38$ in mm. Employed substrates are with $\varepsilon_r = 2.2$.

FIGURE 7. Schematics of the (a) octagonal 64-element PAA feed employed in the first design example and (b) 4×16-element rectangular array in the second design example. Optimal TAA phase distributions of the (c) first design case and (d) the second design case.

FIGURE 8. Magnitudes/phases of the PAA feed excitation coefficients corresponding to some representative scan angles in the first design example.

B. PAA-FED TAA FOR ±30° CONICAL BEAM SCANNING

To fully examine the feasibility of the introduced method in Section II-B, two PAA-fed TAAs are designed at $f_0$ for high-gain and wide-angle beam scanning applications. In two design examples, the TAAs are with the identical aperture diameter $D$ of 123.2 mm ($\sim 16\lambda_0$), i.e., 77×77-element TAAs, and both illuminated by the 64-element PAA feeds with the feeding distance $H$ of 35 mm ($\sim 4.55\lambda_0$), except for the different TAA element deployments or PAA feed configurations.

The first design example aims at steering the beam over a ±30° conical scope with the peak gain higher than 30 dBi. To improve the illuminations on the TAA aperture, the total of 64 PAA feed elements are arranged according to Fig. 7(a) thus forming an octagonal structure. After extracting the incident fields from each PAA feed element on the TAA aperture, the optimal phase distribution of the first TAA is determined as presented in Fig. 7(c), followed by the normalized magnitudes and phases of $I_{pq}(\alpha)$ at scan angles over $0°\sim30°$ with a step of $10°$ along both principle planes given in Fig. 8. Here, it can be noticed that the excitation coefficients of the PAA feed are greatly different from those of traditional PAAs, which is because that the far-field energy is the summation of the scattered fields from the TAA, rather
TABLE 1. Simulated gains of transmitarrays with different phase distributions at 39 GHz in the first design example.

| Scan angle Methods | α=0° | α=10° | α=20° | α=30° | ΔG |
|--------------------|------|-------|-------|-------|----|
| Single-focal       | 32.7dBi | 31.3dBi | 28.6dBi | 25.4dBi | 6.9dB |
| TAA-1°             | 30.9dBi | 30.2dBi | 29.4dBi | 28.8dBi | 2.1dB |

than direct superposition of the primary fields launched by the PAA feed elements. Moreover, against traditional single feed antenna, dispersed energy distributions are created over the PAA feed aperture, which are more obvious around the normal direction but less pronounced as scan to large angles.

The simulated scanning radiation patterns of the first PAA-fed TAA at $f_0$ along the E and H planes are given in Figs. 9(a) and (b), respectively, where good main beam shapes and reasonable side lobe levels (SLLs) are realized across the entire scanning scope. Moreover, the peak gain of 30.9 dBi is realized at the normal direction, together with the scan losses less than 1.6 or 2.1 dB along the E or H planes. Specifically, an acceptable beam crossover can be easily achieved with 4-bit attenuators and phase shifters, proving good beam scanning performance of our proposed design. Fig. 9(c) shows the simulated gains versus frequency of the first PAA-fed TAA as scan over $0° \sim 30°$ with a step of 15° in both principle planes, where the 1 dB gain bandwidths larger than 11.5% are obtained over the whole scanning range. To better illustrate the improvement by the proposed dimensionally multi-focal method, an equal-scale TAA with traditional single-focal phase distribution is also fed by the octagonal 64-element PAA feed as a comparison. The simulated gains versus scan angle at $f_0$ of these two designs are summarized in Table 1, where $ΔG$ indicates the maximum gain loss suffered over the whole scanning scope. It can be observed that the single-focal TAA features higher gains around the broadside direction, but suffers from gain drops up to 4.1 or 6.9 dB as scan to 20° or 30°, which are much more remarkable than the first proposed design example.

C. PAA-FED TAA FOR ±50° E-PLANE BEAM SCANNING AND ±10° H-PLANE BEAM SCANNING

To extend the scanning scope of the PAA-fed TAA, the second design example is investigated for scanning over ±50° and ±10° in the E and H planes, respectively. Specifically, the octagonal 64-element PAA feed of the first design is re-arranged to form a 4 × 16-element rectangular array as given in Fig. 7(b), followed by the re-optimized TAA phase distribution and PAA feed excitation coefficients in Fig. 7(d) and Fig. 10. The simulated scanning radiation patterns of the second design case at 39 GHz are presented in Fig. 11, where a peak gain of 31.1 dBi is reached at the normal direction, along with gain losses less than 3.3 or 1.6 dB in the E or H planes, respectively. Albeit such a small $H/D$ of mere 0.28, a maximum aperture efficiency of 40% is successfully realized, showing the advantages of the PAA feed mechanism. Fig. 12 gives the simulated TAA insertion losses versus scan angle for both design examples at 39 GHz, which are relatively flat as scan angles less than 30°, but gradually grow pronounced as scan from 30° to 50°. Moreover,
as compared with other relevant studies on beam scanning TAA's in Table 2, it can be clearly observed that the second proposed PAA-fed TAA exhibits a higher gain, a wider scanning coverage, a more compact volume but with smaller gain losses.

IV. EXPERIMENTAL DEMONSTRATION AND ERROR ANALYSES

A. EXPERIMENTAL DEMONSTRATION

To validate the effectiveness of the proposed designs, the first PAA-fed TAA for ±30° conical beam scanning is fabricated and tested. However, directly measuring the scanning performances of the whole PAA-fed TAA is very complicated and expensive, because multiple T/R modules and a complete power divider network are required. Therefore, to facilitate the experiments, three microstrip line feed networks are designed to provide the required excitation amplitudes and phases of the PAA feed elements for broadside radiating and scanning to +30° in both principle planes. Specifically, the PAA feed elements with normalized excitation magnitudes less than 0.2 are set as dummy elements or directly omitted to simplify the design. The circuit layers of the three designed feed networks are presented in Figs. 13(a)-(c), followed by their prototypes in Figs. 13(d)-(f). Meanwhile, Fig. 14 depicts the simulated and measured reflection magnitudes of the three array feeds integrated with these feed networks in 36~40 GHz since the upper frequency limit of the available vector network analyzer is 40 GHz. To reuse the detachable 2.92 mm-connector, the inner conductor is
FIGURE 13. Schematics and prototypes of the designed feed networks. (a) 0°, (b) 30°/E plane, (c) 30°/H plane, (d) 0°, (e) 30°/E plane, and (f) 30°/H plane.

FIGURE 14. Simulated and measured reflection magnitudes of the different array feeds integrated with feed networks.

Based on the multilayer PCB fabrication technology, the TAA in the first design case is developed as shown in Fig. 15(a), together with the whole array-fed TAA with the 0° feed network in Fig. 15(b). Subsequently, Figs. 16(a)-(c) compare the simulated and measured normalized radiation patterns of the TAA excited by the three different array feeds at $f_0$, where reasonable agreements between them can be observed. Meanwhile, the simulated and measured gains of the TAA excited by the three different array feeds with feed networks are presented in Fig. 17. Partly affected by the high measured reflection magnitudes of the array feeds integrated with feed networks (see Fig. 14), the measured gains are relatively lower than the simulated ones, also due to the fabrication errors of the multilayer PCBs.
TABLE 3. Loss analyses of the first design example at 39 GHz.

| Parameter                          | 0°  | +30°/E | +30°/H |
|-----------------------------------|-----|--------|--------|
| -α-Measured Gain (dBi)            | 24.1| 24.3   | 23.0   |
| -α-Return Loss Discrepancy        | 0.28| 0.69   | 0.31   |
| Simu. & Meas. (dBi) (see Fig. 15) |     |        |        |
| -α-Fabrication & Assembling errors|  -1 |  -0.9  |  -0.4  |
| -α-Simulated Gain (dBi)           | 25.4| 25.9   | 23.7   |
| -α-Feed Network Loss (dB)         | 4.6 | 2.6    | 4.0    |
| -α-Excitation Error Loss (dB)     | 0.9 | 0.6    | 0.7    |
| -α-Theoretical Gain (dBi)         | 30.9| 29.1   | 28.4   |
| *β-Simulated Gain (dBi)           | 30.9| 29.3   | 28.8   |

*α: TAA excited by the array feed integrated with feed network  
*β: TAA excited by the PAA feed at ideal feed conditions

FIGURE 17. Simulated and measured gains versus frequency of the TAA excited by the different array feeds integrated with feed networks in the first design example. (upper) 0°, (middle) 30°/E plane, and (bottom) 30°/H plane.

B. ERROR ANALYSES

It can be noticed that the measured gains of the TAA excited by the array feeds integrated with feed networks (as given in Fig. 17) are lower than those ideally expected values of the TAA excited by the PAA feed at ideal feed conditions (as given in Fig. 9), which are mainly caused by those loss factors as precisely summarized in Table 3.

As discussed in Section IV-A, the discrepancies between the simulated and measured gains of the TAA excited by the array feed integrated with feed network primarily result from the following two factors:

1) The higher measured return loss of the array feed with feed network against the simulated ones.

2) The fabrication and assembling errors.

Subsequently, the simulated gain discrepancies between two cases, i.e., the TAA excited by the array feed with feed network, and the TAA excited by the PAA feed at ideal feed conditions, are further attributed to the following loss terms:

3) The huge losses of the microstrip feed networks in MMW band, due to the increasing losses versus frequency and line lengths as well as the undesired radiations. Here, the simulated losses of the feed networks in Figs. 13(d)-(f) are ~4.6, 2.6 and 4 dB, respectively.

4) The excitation errors of the feed networks, which include two parts. The first part is attributed to the fact that the feed elements with excitation magnitudes less than 0.2 are ignored in the feed network designs. The second one is that excitation coefficients offered by the feed networks are slightly different from those ideally optimized values in Fig. 8, where the absolute errors between them at different scan angles are depicted in Fig. 18.

After considering the aforementioned loss factors, the theoretical gains are in good agreements with those simulated values in Fig. 9, validating the proposed design.

V. CONCLUSION

This paper demonstrates the design concepts of low-profile PAA-fed TAAs for 2-D high-gain and wide-angle beam scanning at MMW frequencies. By identifying the miniaturized FSS structure and the cavity-backed bowtie patch antenna as the TAA and PAA feed elements, respectively, two PAA-fed TAAs are designed at 39 GHz to numerically verify the operating mechanism and divisionally multi-focal method as discussed in Section II. The first design case for ±30° conical scanning is selected for experimental examination, where three microstrip feed networks are designed to facilitate the experiments. After comprehensively analyzing the losses mainly introduced by the feed networks, the measured results show reasonable agreements with the simulated ones, validating that our proposed designs provide a promising technical solution for MMW beam scanning applications.

Compared with traditional 64-element PAAs usually with gain of ~23 dBi (5 dBi element gain along with 18 dBi array factor) and 2-D scanning coverage of ±60°, obviously higher gains can be realized by the proposed PAA-fed TAAs also utilizing 64 T/R modules, but with narrower scanning scopes. It is also noted that the PAA-fed TAAs can scan to larger angles by enlarging the scale of the PAA feed, reducing the feeding distance \( H \), or re-deploying the TAA phase distribution, therefore these parameters should be elaborately tuned by designers to fulfill the practical demands.

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