E-band Wide-Angle Multi-Beam Shaped Transmitarray

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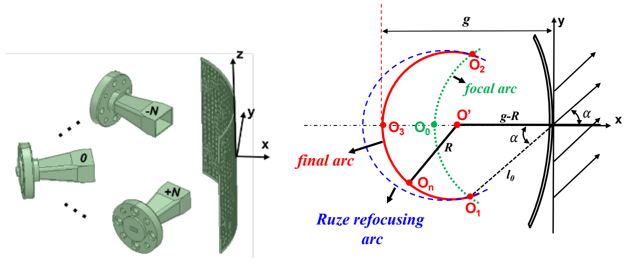
***Abstract*— A millimeter-wave (mm-wave) E-band multi-beam transmitarray with a wide beam coverage is developed in this paper. The transmitarray has a three-dimensional (3D) elliptical cylindrical shape. This aperture shape and phase compensation are jointly designed according to the desired maximum beam direction, leading to different focal lengths for different beams. This way, the proposed transmitarray can achieve a larger beam scanning range with a low scanning loss compared to many other reported designs. A transmitarray prototype is simulated, fabricated and measured at 70.5 GHz, which can provide a continuous beam coverage between ±43° with a 2.7-dB gain drop at the maximum radiation angle.**

Keywords—millimeter wave antenna, multi-beam antenna, transmitarray.

I. INTRODUCTION

Millimeter-wave (mm-wave) antennas are poised to play a key role in the fifth generation (5G) and beyond wireless communication systems. They usually have a high directivity with a narrow beamwidth to compensate for the path loss at high frequencies. In order to provide a wide beam coverage to serve a number of distributed users, mm-wave multi-beam antennas have attracted considerable attention from both academia and industry. To date, passive mm-wave multi-beam technologies have been extensively developed based on lens antennas [1], reflectarray/ transmitarray [2-3] and beamforming networks [4]. Transmitarrays show unique advantages of high realized gains without lossy transmission-line-based feeding networks and they do not have feed blockage issues as in reflectarrays. Consequently, significant research efforts have been devoted to mm-wave multi-beam transmitarrays. In [3], a bifocal phase compensation method is employed in a circular-polarized transmitarray at 26 GHz, which can support a multi-beam radiation between ±33°. In [5], a transparent transmitarray is presented at 28.5 GHz, realizing seven beams between ± 30° with a scanning loss of 3.5 dB. Besides, a metamaterial-based multi-beam transmitarray at 28 GHz is developed in [6], showing a beam coverage of ±27° with a 3.7-dB scanning loss. Moreover, by sliding the transmitting aperture or the feeing source [7], a mechanical beam scanning transmitarray is realized at Ka-band, providing an asymmetric beam coverage from 0° to 50° with an about 4-dB scanning loss. This mechanical beam scanning can be extended to a multi-beam design if multiple feed sources are utilized at the same time.



(a) (b)

Fig. 1. Proposed multi-beam transmitarray configuration. (a) 3-D view. (b) Top view.

Referring to the abovementioned advances on multi-beam transmitarrays, it is noticeable that most of them provide a beam coverage of around 60° (or ±30°), which may limit their applications for wide angle point-to-multi-point/multi-point-to-multi-point communications. Second, all of these designs operate at lower mm-wave bands. Since mm-wave bands above 50 GHz offer a large spectrum and has a great potential to support future high-speed wireless networks, multi-beam transmitarrays operating at higher mm-wave bands are highly desired.

In this work, we proposed an elliptical cylindrical shaped transmitarray for wide-angle multi-beam applications for the first time. The shape of the transmitting surface is employed as an extra degree of freedom for the multi-beam design, together with an optimization method on multiple feed positions. A prototype at 70.5 GHz is constructed achieving a beam coverage of ±43° with a 2.7-dB scanning loss. To the best of the authors' knowledge, this represents one of the most advanced mm-wave multi-beam transmitarrays with a wide beam coverage and a small scanning loss.

II. MULTI-BEAN TRANSMITARRAY DESIGN METHODOLOGY

As shown in Fig. 1, the proposed wide-angle multi-beam transmitarray has an elliptical cylindrical shaped radiating aperture, i.e., it has an elliptical-arc cross section along xoy plane and a straight contour along xoz plane.

As indicated in Fig. 1(b), O_1 and O_2 are chosen as two symmetrical focal points for the largest beam radiation angles at $\alpha=\pm 45°$, and the feed offset angles at these two points are equal to the beam radiation angles. To satisfy the beam radiations at these two directions, element phase distributions on the aperture are designed to compensate for the spatial phase delay from both O_1 and O_2. Then, the transmitarray profile along xoy plane and its phase compensation values $\Delta\varphi_e$ are derived based on the constrained metal plate lens [8], which are given in (1)-(2).

$$\left(\frac{x}{l_0\cos\alpha}+1\right)^2+\left(\frac{y}{l_0}\right)^2=1 \quad (1)$$

$$\Delta\varphi_e=-k_0x\cos\alpha \quad (2)$$

where l_0 is the focal length at O_1/O_2, and k_0 is the propagation constant in free space. From (1), it is shown that the contour of transmitarray along xoy plane has an elliptical shape, which is related to the maximum beam scanning angles.

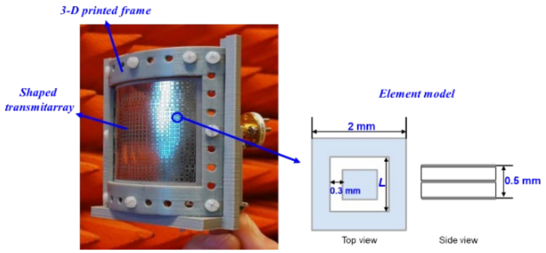
The initial focal arc, with a radius of l_0 to the origin shown in the green curve in Fig. 1 (b), is decided by the maximal radiation angles at $\alpha=\pm45°$ rather than 0°, resulting in a phase error for the feed located at O_0 generating a beam towards 0°. In order to mitigate this error, a refocusing arc is found as shown in blue-dash line. Furthermore, in a 3-D transmitarray design, both phase distributions along xoy plane and xoz plane should be considered together. Therefore, optimizations on the feed positions are required to reduce the phase errors between different radiation angles, leading to the final focal arc as marked with a red solid line in Fig. 1(b), which shows the radius *R* with respect to the centre at O'. It can be seen that the proposed method leads to different focal lengths for different beam directions. This is different from other reported work using a constant focal length for all the beams. The detailed analysis will be presented in conference.

By positioning the feed source at a random point O_n along the final focal arc, an oblique radiation beam can be obtained. Therefore, with multiple feeds working simultaneously, multiple beams can be achieved.

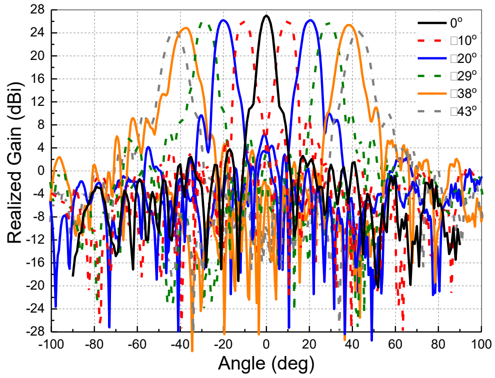
III. SIMULATION AND MEASUREMENT

A transmitarray prototype composed of 25×23=575 elements is designed with the maximal beam directions at ±45° at 70.5 GHz. Although the proposed multi-beam design method can be applied to any type of transmitarray element, here we use a three-layer square-slot element for verification, and its dimensions are shown in Fig. 2(a) with variable slot length *L* for phase tuning. The array cross-sectional size is 46.4 mm×46 mm=$10.9\lambda_0\times10.8\lambda_0$. As an example, we chose 11 desired beam angles in the range of ±45°, i.e., 0°, ±10°, ±20°, ±30°, ±40° and ±45°, and calculated their feed positions along the final focal arc. A photo of the prototype is shown in Fig. 2(a). Considering the overall cost and available measurement conditions, one feed horn is moved along the final focal arc for different beams. The measured radiation patterns are plotted in Fig. 2(b), realizing a multi-beam range between ±43° with a 2.7-dB scanning loss. More measurement results will be provided in conference.

Table I provides the performance comparison of the presented transmitarray to other reported works. It is noticed that this work can realize a wider beam coverage with a small scanning loss at a higher mm-wave band. Meanwhile, its aperture efficiency is still comparable to others.



(a)



(b)

Fig. 2. (a) Fabricated prototype (b) Multi-beam radiation patterns

TABLE I

PERFORMANCE COMPARISON WITH OTHER WORKS

Ref. No.	**Frequency**	**Maximal beam coverage**	**Peak gain /dBi**	**Aperture efficiency**	**Scanning loss /dB**
[3]	26 GHz	66° (-33°~ +33°)	22.2	35.7%	1.2
[5]	28.5 GHz	60° (-30°~ +30°)	25	32.3%	3.5
[6]	28 GHz	54° (-27°~ +27°)	24.2	24.5%	3.7
[7]	20/30 GHz	50° (0°~ +50°)	24.7/27.2	37.3%/29.5%	4.4/3.7
This work	70.5 GHz	86° (-43°~ +43°)	27	34%	2.7

IV. CONCLUSION

A mm-wave wide-angle multi-beam transmitarray is developed with an elliptical cylindrical profile. The fabricated prototype shows a wide beam coverage of ±43° with a 2.7-dB scanning loss, which is expected to find wide applications in 5G wireless systems and beyond.

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