Millimetre-Wave Multi-Beam Shaped Transmitarray with A Wide Beam Coverage

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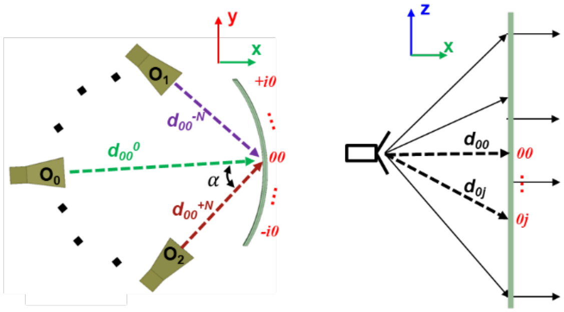
***Abstract*— A millimeter-wave (mm-wave) shaped transmitarray for wide-angle multi-beam radiations is proposed at 70.5 GHz in this paper. The transmitting surface shows a three-dimensional (3-D) elliptical cylindrical configuration. With desired maximal beam radiation angles, the elliptical curvature of the transmitarray and its phase compensations are jointly designed. A new focal arc is developed with different focal lengths for different radiation beams. Comparing to other reported works, it is demonstrated that the developed transmitarray can provide a wider beam coverage with a less gain drop at the maximal beam angle. Finally, the transmitarray prototype is fabricated and measured, achieving a continuous beam scanning between ±43° with a 2.7-dB scanning loss.**

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

I. INTRODUCTION

Millimeter-wave (mm-wave) antennas have attracted substantial attention as a key technology for the fifth generation (5G) and beyond wireless communications. They can provide high directivities with narrow beamwidths, thereby compensating for the high path loss at high frequency bands. To serve multi-point-to-multi-point communications with a wide beam coverage, mm-wave multi-beam antennas are desperately desired. To date, significant research efforts have been devoted to develop passive mm-wave multi-beam antennas, e.g., lens antennas [1], reflectarray/ transmitarray antennas [2-3] and beamforming networks [4]. Among them, transmitarrays can achieve high gains without bulky and lossy transmission-line-based feeding networks. Besides, they do not have issues of feed blockages compared to the reflectarrays.

To date, various design techniques have been advocated to develop mm-wave multi-beam transmitarrays. In [3], a circular-polarized transmitarray is designed at 26 GHz based on a bifocal phase compensation method. It can radiate multiple beams between ±33° with a 1.2-dB scanning loss. In [5], a transparent transmitarray is designed at 28.5 GHz, achieving seven beams between ± 30° with a scanning loss of 3.5 dB. In [6], a metamaterial-based transmitarray is proposed at 28 GHz, resulting in multi-beam radiations between ±27° with a scanning loss of 3.7 dB. Besides, in [7], by sliding the transmitting surface or the feeding source relatively to each other, a mechanical beam-steering transmitarray is obtained at Ka-band. An asymmetric beam coverage between 0°-50° is realized with an about 4-dB scanning loss. Multiple beams can be radiated by applying multiple feeding sources simultaneously.



(a) (b)

Fig. 1. Proposed transmitarray configuration with multiple feeds. (a) Top view. (b) Front view.

Based on the aforementioned advances on multi-beam transmitarrays, it is noteworthy that most of them provide up-to-60° (or ±30°) beam coverages. This limits their applications in wide-angle multi-point-to-multi-point communications. Furthermore, all of those transmitarrays are designed at lower mm-wave bands. Owing to the large available spectrum of higher mm-wave bands, multi-beam transmitarrays operating at above 50 GHz are highly demanded to support future high-speed wireless networks.

In this paper, we proposed a mm-wave wide-angle multi-beam transmitarray with an elliptical cylindrical shape for the first time. The shape of the transmitting surface is taken as an extra degree of freedom, along with a new phase compensation method. The feed positions for different radiation beams are optimized to achieve a wider beam coverage and a less scanning loss. A transmitarray prototype is simulated, fabricated and measured at 70.5 GHz, yielding a wide beam coverage of ±43° with a scanning loss of 2.7 dB.

II. MULTI-BEAN TRANSMITARRAY DESIGN

As illustrated in Fig. 1, the developed multi-beam transmitarray shows a 3-D elliptical cylindrical shape. Along *xoy* (horizontal) plane, it has an elliptical contour as shown in Fig. 1(a). Along *xoz* (vertical) plane in Fig. 1(b), the cross section shows a straight contour.

Multiple beams are expected to be radiated along the middle horizontal plane. With expected maximal beam radiation angles of α=±45°, two symmetrical focal points are determined at O_1 and O_2 with their offset angles equal to the related beam angles. The focal length $d_{00}^{\pm N}$ is decided by considering the aperture size and the radiation properties of feeding sources. In order to obtain good oblique radiation beams, element phase distributions along the *xoy* plane are calculated to compensate for spatial phase delays from both O_1 and O_2. According to the theory from a constrained metal plate lens [8], the transmitarray shape and its corresponding phase compensations $\Delta\varphi_e$ are obtained from (1)-(2).

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

$$\Delta\varphi_e=-k_0 x\cos\alpha, \tag{2}$$

where k_0 is the propagation constant in free space. From (1), it is noticed that the transmitarray cross section along the *xoy* plane has an elliptical contour, which is related to the maximal beam radiation angles.

Since it is obtained based on the maximal radiation angles at $\alpha=\pm45°$ rather than 0°, phase errors exist for the feed O_0 generating a beam towards 0°. In order to mitigate this error, a refocusing arc is introduced from –[9]for a two-dimensional (2-D) lens. However, for a 3-D transmitarray design, phase compensations along *xoy* plane and *xoz* plane should be considered together for an optimal radiation performance.

Along the vertical plane, all beams will point to boresight. As illustrated in Fig. 1(b), along the middle column (*z* axis), phase compensations can be derived from (3).

$$\Delta\varphi_s=k_0(d_{0j}-d_{00}), \tag{3}$$

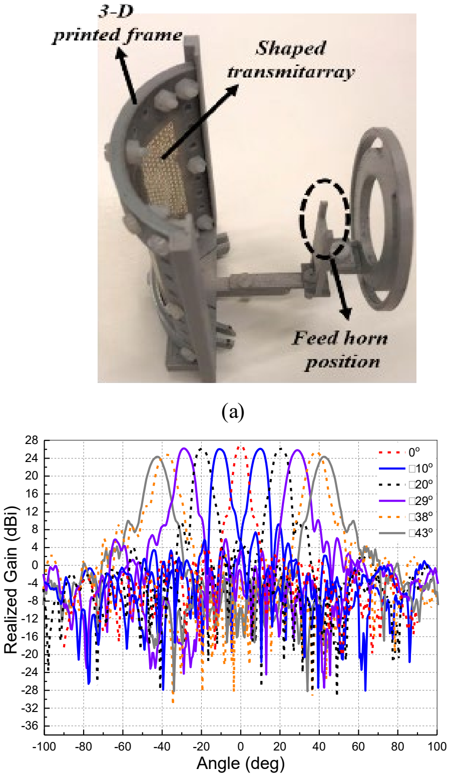
where d_{00} represents the focal length of the feeding source, and d_{0j} is the distance from the focal point to the *j-th* element. The same phase calculation principle can be applied to other non-middle columns. However, as seen from Fig. 1(a), along the refocusing arc, different feeding sources correspond to different focal lengths from d_{00}^{-N} to d_{00}^{+N}. To avoid confusions in phase calculations, a virtual focal point is defined with a virtual focal length for a compromise.

Moreover, the previous refocusing arc is developed from the 2-D lens, further optimizations are required to balance beam properties along *xoy* and *xoz* planes for a 3-D transmitarray.The details for designing the final focal arc can be found in [9]. By placing the feeding source at a random point O_n along the final focal arc, an oblique radiation beam can be achieved. If applying multiple feeds simultaneously, multi-beam radiations will be realized.

In this method, different focal lengths are introduced for different beam directions. It is distinct to other reported multi-beam transmitarray designs, where constant focal lengths for all beams are usually applied. The detailed analysis will be presented in conference.

III. PROTOTYPE SIMULATION AND MEASUREMENT

A shaped transmitarray prototype is constructed for the desired maximal beam angles of ±45° at 70.5 GHz. A three-layer square-slot element is used for the array [9].. For an easier and cost-effective fabrication, the unfolded transmitting surface is fabricated with a standard PCB technology. Then it is attached onto a 3-D printed elliptical cylindrical frame. A picture of the practical configuration is given in Fig. 2 (a). For measurements, eleven desired beams are chosen between ±45°, i.e., 0°, ±10°, ±20°, ±30°, ±40° and ±45°, and their corresponding feed positions are calculated along the final focal arc. The measured radiation patterns are plotted in Fig. 2 (b), showing a peak gain of 27 dBi at boresight. The multi-beam range is between ±43° with a 2.7-dB scanning loss. The measured peak aperture efficiency 34%. More measured results will be provided in conference.



(a)

(b)

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

IV. CONCLUSION

A mm-wave wide-angle multi-beam transmitarray is proposed with a 3-D elliptical cylindrical configuration. A prototype is fabricated and measured at 70.5 GHz, achieving a wide beam coverage of ±43° with a 2.7-dB scanning loss. The developed multi-beam transmitarray is expected to find wide applications in 5G wireless systems and beyond.

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