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3D Printed Millimeter-Wave High-Gain Wideband Antenna Arrays

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Abstract

Millimeter-wave high-gain wideband antenna arrays realized by employing the commercial metallic three dimensional (3D) printing facilities are summarized in this paper. Two types of wideband antennas fed by an air-filled waveguide, i.e. the horn and the magneto-electric (ME) dipole, are designed as the radiating elements of the arrays. The full-corporate feed network consisting of air-filled waveguides are employed due to the wideband and low-loss characteristics. In order to improve the operating bandwidth and shorten the printing duration of the arrays, novel wideband power dividers composed of stepped waveguides and the array with a self-supporting geometry are investigated as well. Three array designs are fulfilled and measured to demonstrate the superiority of the 3D printed arrays, which are valuable to the emerging wireless applications at millimeter-wave frequencies.

1 Introduction

Planar antenna arrays with high gain characteristics is of great significance for millimeter-wave communications because of their compact configurations easy to integrate with the circuits and the ability to meet the required link budget [1]. The millimeter-wave arrays implemented in dielectric laminates have been persistently studied in the last decade, but it was found that the achievable radiation efficiency of the substrate integrated array was limited by the undesirable dielectric loss [2, 3]. The ultra-high gain above 34 dBi that is demanded by the wireless backhaul system was not easy to achieve even though the low-loss dielectric material has been utilized.

Compared with the substrate integrated arrays, the arrays with air-filled waveguide feed network has the superiority in radiation efficiency due to the absence of the dielectric loss. Nevertheless, the multi-layered metallic array geometry should be divided into several portions in the fabrication process based on the conventional milling technology. As a result, the power leakage attributed to the air gap between the portions was difficult to prevent entirely after the assembling, which affected the radiation efficiency and gain of the arrays [4]. In order to cope with the challenge, the millimeter-wave antenna array fed by the air-filled laminated waveguides was fabricated by utilizing the diffusion bonding technology [5]. Moreover, the air-filled gap waveguide has also been introduced to improve the radiation efficiency of the large-size arrays [6]. Unfortunately, the complicated fabrication procedure of these designs was not desirable for cost-effective large-scale applications.

The three dimensional (3D) printing is a technique to build sliced 3D models layer by layer, which is able to realize the complex 3D structures in a whole piece. Therefore, it would be an attractive means for the investigation on millimeter-wave high-gain wideband arrays without the need of complex fabrication processes. 3D printed planar antenna arrays have been analyzed at the microwave frequencies of about 10 GHz [7]. However, the 3D millimeter-wave antenna array with satisfying performance is still seldom addressed in the literature. Three novel 3D printed high-gain wideband antenna arrays are summarized in the Ka-band in this paper, which verifies both the high gain and the improved bandwidth. It is believed that the proposed work can find possible application in future millimeter-wave wireless communications.

2 High-Gain Horn Antenna Array

A Ka-band air-filled waveguide fed horn antenna array with a large size of 16 × 16 is realized by employing a commercial direct metal laser sintering (DMLS) facility, whose configuration is illustrated in Fig. 1. The pyramidal E-plane horn antennas with a side length of less than an operating wavelength are arranged in the top layer as the radiating elements. The full-corporate waveguide feed network is divided into two parts. The major portion is deployed in the bottom layer, while the feed cavities acting as the feed of sub-arrays are assigned in the middle layer. The two portions are linked with the help of a series of the vertical waveguides with a short length.

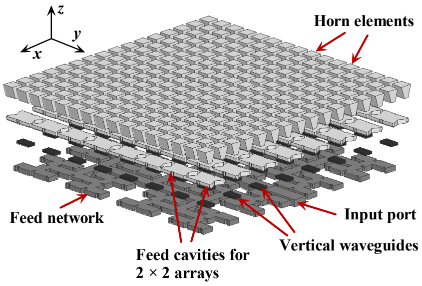

Figure 1. Geometry of the 3D printed millimeter-wave high-gain horn antenna array with the full-corporate air-filled waveguide feed network.

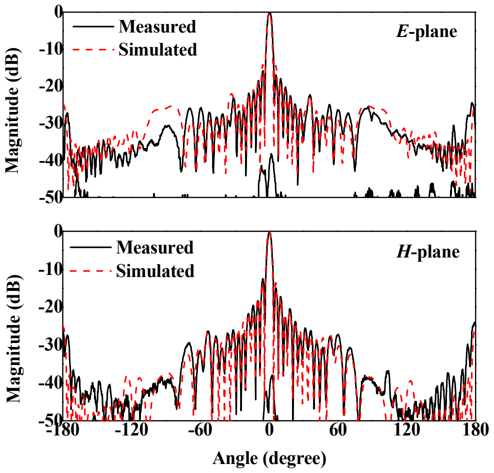

Figure 2. Measured and simulated radiation patterns of the 3D printed 16 × 16 horn antenna array.

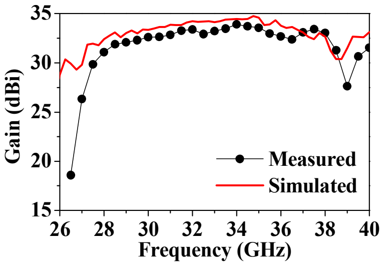

Figure 3. Measured and simulated gain results of the 3D printed 16 × 16 horn antenna array.

The fabricated prototype confirms a measured impedance bandwidth of 23.8% (from 28.2 to 35.8 GHz) for $|S_{11}| < -10$ dB, which agrees well with the simulated one of 23.2% (from 27.1 to 34.2 GHz). Furthermore, the measured and simulated radiation patterns of the array at 32 GHz are compared in Fig. 2. The unidirectional radiation pattern is symmetrical in both the E- and H- planes. The first sidelobe is about -13 dB, which is close to the theoretical value for the array with a uniform in-phase aperture field distribution. Besides, the measured backward radiation and cross polarization are less than -25 and -39 dB, respectively. As depicted in Fig. 3, the measured gain of the 3D printed 16 × 16 array is up to 33.8 dBi. The variation of the gain is less than 1.5 dB throughout the operating band. By comparing the measured gain with the simulated directivity, it is seen that the estimated radiation efficiency is around 80%, which demonstrates the excellent performance of the 3D printed millimeter-wave antenna array with a large size. More detailed results and discussions can be found in [8].

3 Wideband ME-Dipole Antenna Array

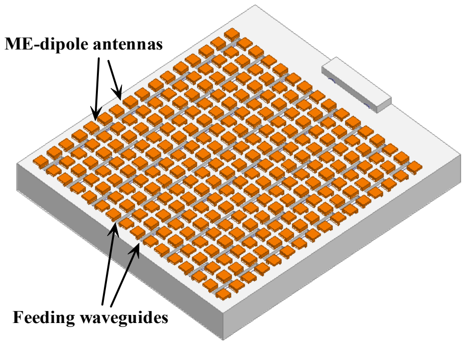

Figure 4. Geometry of the 3D printed millimeter-wave wideband stepped waveguide fed ME-dipole antenna array.

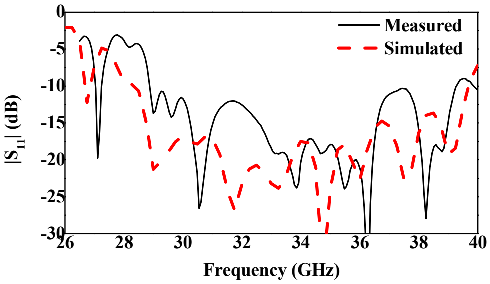

Figure 5. Measured and simulated $|S_{11}|$ results of the 3D printed millimeter-wave wideband stepped waveguide fed ME-dipole antenna array.

Good radiation characteristics have been obtained by the 3D printed horn array, but its bandwidth can still be improved. To this end, a 3D printed wideband ME-dipole antenna array with a novel stepped waveguide feed network is then investigated as shown in Fig. 4. The overall geometry is similar with that of the horn array, but the wideband ME-dipoles with a lower profile are adopted as the radiating structures. More importantly, taking the advantage of the 3D printing, H-plane rectangular waveguide T-junctions with stepped heights are designed, which significantly improves the impedance matching features of the feed network over a wide bandwidth. As exhibited in Fig. 5, an enhanced impedance bandwidth of 31% is confirmed experimentally by an 8 × 8 ME-dipole array. At the same time, the good radiation performance, including the stable unidirectional radiation pattern with the cross polarization below -35 dB and low backward radiation, the gain vary from 25.5 to 28.5 dBi, and the radiation efficiency of around 89% are maintained. The detailed design process and related studies have been described in [9].

4 ME-Dipole Antenna Array with a Self-Supporting Geometry

Apart from the good operating characteristics, the fabrication duration is also of importance to the practical large-scale applications. It was found in the study that the printing duration of the previous millimeter-wave antenna arrays wass time-consuming, which can be attributed to the not self-supporting array geometry. Actually, in order to prevent the use of additional internal supporting structures that cannot be removed from the air-filled

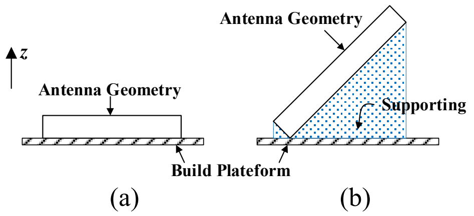

Figure 6. Printing schemes of the planar antenna arrays. (a) Proposed timesaving scheme, (b) traditional time-consuming scheme with an inclined angle.

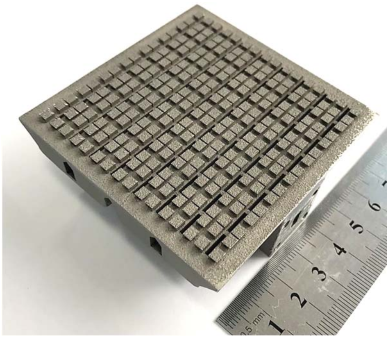

Figure 7. 3D printed prototype of the millimeter-wave wideband ME-dipole antenna array with the self-supporting geometry.

Table I
A COMPARISON OF THE PROPOSED 3D PRINTED MILLIMETER-WAVE ANTENNA ARRAYS

Radiator	Array Size	BW	Max. gain (dBi)	Printing Duration (hours)
Horn	16 × 16	23.8%	33.8	38
Horn	8 × 8	25.8%	27.5	21
ME-dipole	8 × 8	31%	28.5	19
ME-dipole (Self-supporting)	8 × 8	32.4%	27.1	16
ME-dipole (Self-supporting)	16 × 16	-	-	22

channels in the array geometry in the post-processing, the conventional printing scheme with an inclined angle as indicated in Fig. 6 (b) has to be employed. As a result, the dimension of the printed array in *z*-direction shown in the figure is increased, which means that more printing layers are required in the printing process. Considering the time used for spreading a layer of printing powder is fixed, the total printing time is increased with the number of layers.

For the purpose of shortening the printing duration, a 3D printed millimeter-wave ME-dipole array composed of novel radiating and feeding devices with self-supporting configurations is analyzed. By this means, the entire array can be realized by applying the timesaving printing scheme shown in Fig. 6 (a). A printed prototype of the designed array is illustrated in Fig. 7, whose operating performance and required printing duration are summarized in Table for comparing with the counterparts of the previous two arrays. Clearly, both the bandwidth and the maximum gain of the array with the self-supporting geometry is comparable with the other two arrays. However, a 15% reduction in the printing time can be saved by the new 8 × 8 array, and the reduction can be further enhanced to 40% for the 16 × 16 array, which demonstrates the effectiveness of this method.

5 Conclusion

Three millimeter-wave high-gain wideband antenna arrays fabricated by applying the commercial metallic 3D printing technology have been summarized in this paper. Both the horn and the magneto-electric dipole antennas with wide operating bands and stable radiation features have been introduced as the radiating elements. The air-filled stepped waveguide feed network has been designed to improve the bandwidth of the array with a large size. The array with self-supporting configurations has also been explored to reduce the required printing duration. The excellent operating results, including a bandwidth of 32.4% and a gain up to 33.8 dBi, verify that the 3D printed high-gain wideband antenna array is an attractive candidate for various millimeter-wave applications.

6 Acknowledgements

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