Feasibility evaluations of three-dimensional-printed high-gain reflectarray antenna for W-band applications

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Abstract: An evaluation reveals the feasibility of a high-gain and low-fabrication-cost reflectarray antenna for W-band millimeter-wave radar applications. This reflectarray antenna offers the advantage of a simple, flat structure, and can be fabricated at low cost by three-dimensional (3D) printing. This paper describes the fabrication of a 3D-printed reflectarray antenna, whose gain is more than 30 dBi in the W-band. Firstly, the reflection-signal phases of dielectric plates of different thicknesses are evaluated using finite-difference time-domain (FDTD) analysis to obtain the characteristics of the reflectarray design. Then, an eight-zone Fresnel reflectarray, in which a phase difference of 45° separated each zone, is analyzed and fabricated. The results of the FDTD analysis shows a 31.6 dBi antenna gain at 78.5 GHz. Finally, the designed reflectarray is fabricated using a 3D printer. Measurements indicate that the achieved 30.4 dBi antenna gain nearly equaled the FDTD analysis value of 31.6 dBi at 78.5 GHz.

Keywords: acrylonitrile butadiene styrene plastic, finite-difference time-domain method, millimeter-wave radar, reflectarray antenna, three-dimensional printer, W-band

Classification: Antennas and Propagation

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1 Introduction

Reflectarray antennas offer the advantages of a simple, small-volume, and flat structure [1, 2, 3]. We have been developing a millimeter-wave radar system for civil aviation uses, including helicopter collision-avoidance onboard radar [4]. A reflectarray antenna with a quasioptical approach is one of the most important options supporting high-performance radar systems usable for millimeter-wave radar applications [3]. In addition, we are interested in low-cost fabrication methods that maintain high performance [5]. Three-dimensional (3D) printers can reduce the cost of fabrication [2]. However, as far as we know, reflectarray antennas produced in this fashion difficult to demonstrate high-gain characteristics above 30 dBi in the W-band.

This paper discusses the feasibility evaluations of a high-gain reflectarray antenna for W-band millimeter-wave radar applications. Our discussion confirms that 3D-printed fabrication produces a reflectarray antenna with gains exceeding 30 dBi. Firstly, the reflection-signal phases of dielectric plates of varying thicknesses are investigated numerically in the W-band using the finite-difference time-domain (FDTD) method. Next, an eight-zone reflectarray is designed to operate at 78.5 GHz and then analyzed to evaluate the antenna characteristics. Finally, the reflectarray antenna is fabricated with a 3D printer. Then, the antenna characteristics are evaluated in an anechoic chamber.

2 Analysis of the reflection-signal phase of dielectric plates

The reflection-signal phase must be determined to finalize the design of a reflectarray antenna. The thickness of the dielectric plate is the major design parameter for a 3D-printed reflectarray antenna. An FDTD analysis of the dielectric plate is carried out to obtain the quantitative value of the phase shift of the dielectric material.

Fig. 1(a) shows the FDTD analysis model used to obtain the reflection-signal phases. These reflection-signal phases of the plane-incident wave are analyzed for different dielectric-plate thicknesses. If one assumes an infinite periodical space, the top and bottom walls each consist of perfect electric conductor (PEC). In addition, each side wall consists of a perfect magnetic conductor (PMC). Also, the PEC is attached to the back of the dielectric plate. Commercially available FDTD analysis...
software (SEMCAD X, Schmid & Partner Engineering AG, Zürich, Switzerland) is employed. Fig. 1(b) shows the FDTD analysis parameters. Fabrication of the reflectarray with a 3D printer employs the dielectric constants of acrylonitrile butadiene styrene (ABS) plastics. The relative permittivity and loss tangent are 2.3 and 0.1, respectively.

Fig. 1(c) shows the analyzed reflection-signal relative phase shift for the different dielectric-plate thicknesses at 73.5 GHz, 78.5 GHz, and 83.5 GHz. In this case, the amounts of the phase shift are relative values compared without any dielectric materials. The thickness of the 0.1 mm step is analyzed. Results confirmed that the phase shift is proportional to the frequency. Because the center frequency of the reflectarray is 78.5 GHz, a 360° phase shift is obtained at a dielectric-plate thickness of approximately 3.3 mm.

3 Design and analysis of the reflectarray antenna

The W-band reflectarray antenna is designed using the analysis results of the dielectric-plate reflection phase. The reflectarray design is derived from the Fresnel equation
\[ r_n = \sqrt{\frac{2nf\lambda}{P} + \left(\frac{n\lambda}{P}\right)^2}, \]  
where \( r_n \) and \( f \) are the \( n \)th radius and focal length, respectively. In addition, \( P \) and \( \lambda \) are the number of Fresnel zones and wavelength of the incident wave, respectively.

A comparison with the conventional reflectarray fabricated by the metallic patch on the dielectric substrate [3] shows that the number of Fresnel zones \( P \) and focal length \( f \) were 8 and 75 mm, respectively. Then, the outer diameter of the reflectarray was 154 mm. The designed center frequency was 78.5 GHz.

The FDTD analysis results described in the previous section support determining the thickness of each zone to configure an 8-zone reflectarray in which phase shifts were 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° at 78.5 GHz. The required thickness of the dielectric plate is obtained from Fig. 1(a). For example, the dielectric thicknesses for phase shifts of 0°, 90°, and 180° are 3.3 mm, 2.8 mm, and 1.7 mm, respectively. The dimensions of the reflectarray are 154 mm × 154 mm × 3.3 mm.

Fig. 2(a) shows the numerical model of the designed eight-zone reflectarray antenna with a WR-10 waveguide antenna serving as a primary source. Then, the antenna characteristics are analyzed by FDTD analysis. The constants of the
reflectarray dielectric material are the same as in Fig. 1(b). In addition, a PEC is attached behind the reflectarray. Fig. 2(b) and 2(c) show the analyzed yz-plane electric-field strength and radiation patterns of the reflectarray antenna at 78.5 GHz. The radiation conditions for the reflectarray surface are confirmed by the electric-field strength. In addition, the maximum antenna gain is found to be 31.6 dBi. The half-power beamwidth (HPBW) measures for azimuth and elevation are 1.8° and 1.6°, respectively.

4 Fabrication and measurement of the reflectarray antenna

The designed reflectarray antenna was fabricated using a commercially available 3D printer (Afinia H800 3D Printer, Afinia 3D, Chanhassen, MN). Fig. 3(a) shows the printing process of the eight-zone reflectarray. The printing resolution of the vertical axis is 0.1 mm using an ABS plastics filament. In addition, the total printing time is 9 hours for the designed 3.3-mm-thick reflectarray. Because the ABS plastics filament is one of the most common materials for 3D printing, the cost of the used filament is less than a few US dollars.

Then, Fig. 3(b) shows the measurement setup of the fabricated reflectarray antenna for the W-band. The surface of the reflectarray do not receive any processing, such as smoothing or other postprinting corrections. The 0.1 mm aluminum tape is attached to the back of the reflectarray. The primary source of
the antenna is the WR-10 open-ended waveguide, which is the same used in the analysis. In addition, the focal length of the antenna can be adjusted at the micrometer level to clarify the sensitivity depending on the radiation point.

Fig. 3(c) shows the analyzed and measured radiation patterns for the azimuth plane at 78.5 GHz. The measured radiation characteristics at focal lengths of 75 mm and 77 mm are shown. The focal length of the original design is 75 mm. In addition, the 77 mm focal length produce the maximum measured antenna gain. The measured antenna gains for different focal lengths appear in Fig. 3(d). The antenna gain increased as the focal length increased. The maximum antenna gain is obtained at a 77 mm focal length. The FDTD analysis shows a 31.6 dBi antenna gain; the measured antenna gains of the 75 mm and 77 mm focal lengths are 27.9 dBi and 30.4 dBi, respectively. This 2 mm difference in focal lengths is attributable mainly to the differences in the material constant across the reflectarray. The 2.3 dielectric constant of the ABS plastics in the analysis is slightly higher than the dielectric constant of the ABS plastics filament employed in the fabrication. The HPBW of the measured azimuth radiation patterns is 1.7° for the focal lengths of 75 mm and 77 mm. On the other hand, the analyzed HPBW was 1.6°. The demonstrated antenna characteristics of the fabricated reflectarray antenna agree well with the FDTD analysis results. In addition, the effectiveness and validity of the analysis are confirmed by the measurement.

The reflectarray antenna based on the printed substrate showed a maximum gain of 33 dBi at 72 GHz, which is shifted from the gain at 78.5 GHz [3]. The proposed 3D-printed reflectarray antenna also achieved a maximum antenna gain greater than 30 dBi. These measurements confirm the feasibility of the 3D-printed millimeter wave antenna exhibiting both high gain and low cost.

5 Conclusion

3D printing of a W-band reflectarray antenna was proposed and demonstrated to be a practical method for producing a high-gain and low-cost millimeter-wave antenna that could be used in radar systems.

Firstly, the reflection-signal phase shifts, attributable to different dielectric-plate thicknesses, were investigated using FDTD analysis that assumed the use of ABS plastics. Secondly, a 154-mm-diameter eight-zone reflectarray antenna was designed using the analysis results of the reflection phase. The results of the reflectarray antenna analysis showed an antenna gain greater than 30 dBi at 78.5 GHz. Then, the reflectarray antenna was fabricated using a commercially available 3D printer and common ABS plastic filaments. Finally, the measured antenna characteristics showed a 30.4 dBi antenna gain at 78.5 GHz. The feasibility of producing high-gain performance above 30 dBi with low-cost fabrication was confirmed by these results.

A conformal antenna, produced by a 3D printer at 0.1 mm resolution, will be investigated next to obtain additional high-gain characteristics.