Three-dimensional-printed W-band high-gain reflector Fresnel lens antenna based on acrylonitrile butadiene styrene plastic

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Abstract: A high-gain three-dimensional (3D) printed W-band reflector Fresnel lens antenna based on acrylonitrile butadiene styrene (ABS) is proposed for practical solution to achieve a low-cost and a high-gain antenna for a millimeter-wave radar system. Firstly, a 250-mm-diameter thin reflector Fresnel lens antenna are designed at center frequency of 76.5 GHz, based on a thick conventional reflector lens antenna. Then, assuming fabrication using high dielectric-loss materials, such as ABS plastics, the antenna characteristics difference of the two types of antennas are discussed using finite-difference time-domain (FDTD) analysis. Finally, a reflector Fresnel lens antenna is fabricated using commercially available 3D printer with a low-cost ABS filament. The measured gain and the azimuth half-power beamwidth are 36.0 dBi and 1.1°, respectively. These results agree well with the FDTD analysis result of 37.2 dBi.

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

Classification: Antennas and Propagation

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1 Introduction

Three-dimensional (3D) printing technology enables low-cost construction of millimeter-wave antennas [1, 2]. However, it is difficult to realize a high-gain antenna using relatively high dielectric-loss materials, such as acrylonitrile butadiene styrene (ABS) plastics, which are commonly used for 3D printing. Our aim is to fabricate a 3D printed high-gain antenna for millimeter-wave radar systems [2]. The regulations of the millimeter-wave radar system having low-power transmission (not requiring a radio license) allow an antenna gain of 40 dBi [3]. We have been demonstrated that the reflectarray antenna has more than 30 dBi in W-band [2].

This paper describes a low-cost 3D printed reflector Fresnel lens antenna having high gain for use in 76-GHz millimeter-wave radar systems. Firstly, to mitigate antenna gain reduction caused by dielectric losses of the lens, a thin reflector Fresnel antenna is designed using a thick reflector lens antenna. Then, the antenna characteristics, which is assumed to be fabricated by low-cost ABS plastic are discussed using finite-difference time-domain (FDTD) analysis. Finally, the designed 250-mm-diameter reflector Fresnel lens antenna is fabricated by the 3D printer and measured in anechoic chamber to confirm the analysis results.

2 Design of W-band reflector Fresnel lens antenna

ABS plastic is the typical filament material for 3D printers. However, a problem with the ABS plastic is the relatively high loss tangent than other dielectric materials for the millimeter-wave antennas, such as Teflon (i.e., polytetrafluoroethylene) and TPX (i.e., polymethylpentene). The tan δ of the ABS plastic is between $2 \times 10^{-2}$ and $4 \times 10^{-2}$ in the millimeter-wave region [1]. On the other hand, typical tan δ of Teflon and TPX are $5 \times 10^{-4}$ and $1 \times 10^{-3}$, respectively, at the same frequency. The effect on the antenna characteristics due to the dielectric loss are investigated using the FDTD analysis.

Fig. 1(a) shows the structure of the reflector lens antenna and the reflector Fresnel lens antenna. The lens curve of the conventional reflector lens antenna is as follows [4]:

$$R = \frac{(n - 1)2F}{(2n - 1)\cos \theta - 1}, \quad (1)$$

where $n$ and $R$ are the index of the refraction and the distance between any point on the lens surface and the focal point, respectively. In addition, $\theta$ and $F$ are the ray angle and the focal length, respectively.

Then, integral multiplication of the wavelength inside the dielectric lens is subtracted from the lens curve described in Eq. (1) to achieve the Fresnel lens. Fig. 1(b) shows the design parameters and FDTD analysis parameters. The design frequency is 76.5 GHz, which is the center frequency of the millimeter-wave radar.
system having low transmitting power, and the focal length $F$ is 125 mm. In addition, the diameter of the reflector lens is 250 mm. The relative permittivity is 2.3, assuming that the fabrication using the ABS plastic filament. Then, $\tan \delta$ is varied between 0 and $5 \times 10^{-2}$. The thickness of the conventional reflector lens and the reflector Fresnel lens are 41.0 mm and 4.3 mm, respectively.

Fig. 1(c) shows the designed reflector Fresnel lens antenna analysis model having a diameter of 250 mm. The perfect electric conductor is attached behind the dielectric lens. In addition, the primary source is the WR-10 open-ended waveguide.

### 3 Analysis of W-band reflector Fresnel lens antenna

The antenna characteristics of the designed reflector lens are investigated using FDTD analysis. The commercially available FDTD analysis software (SEMCAD X, Schmid & Partner Engineering AG, Zürich, Switzerland) is employed [5]. Fig. 2(a) shows the maximum antenna gains of the reflector lens antenna and the reflector Fresnel lens antenna against the loss tangent of the lens. For lossless material, the gains of the reflector lens antenna and the reflector Fresnel lens antenna are 40.6 dBi and 39.2 dBi, respectively. The antenna gain of the reflector Fresnel lens antenna is slightly lower than that of the reflector lens antenna. The small difference occurred mainly due to the shadows of the step Fresnel structure. However, the antenna gains of the reflector lens antenna decrease rapidly with
increase in loss tangent values. The reduction of the antenna gain of the reflector Fresnel lens antenna is much slower than that of the reflector lens antenna.

Assuming that for ABS plastics, \( \tan \delta = 3 \times 10^{-2} \), the gain for the reflector lens antenna and the reflector Fresnel lens antenna are 30.1 dBi and 37.6 dBi, respectively. The gain reduction of the reflector Fresnel lens antenna is only 1.6 dB due to the dielectric loss. The maximum thickness of the reflector Fresnel lens antenna is 4.3 mm. The lens thickness is reduced by one tenth, hence, the path length inside the dielectric materials reduced; this lessened the gain reduction. Fig. 2(b) and Fig. 2(c) show the analyzed \( yz \)-plane electric-field strength and the analyzed radiation patterns of the reflector Fresnel lens antenna (\( \tan \delta = 3 \times 10^{-2} \)) at 76.5 GHz. The relative electric field shows the reflection conditions on the reflector Fresnel lens surface and the construction of the plane wave. The clear main lobe is obtained with the WR-10 open-ended waveguide illumination. In addition, the half-power beamwidth (HPBW) for the azimuth and the elevation are both 1.0°. A high-gain lens antenna with a large aperture size requires a thick lens for conventional lens structure. Therefore, the Fresnel structure is required to realize a 3D printed high-gain millimeter-wave lens antenna using the ABS materials because the thickness of this structure is independent of the aperture size or the target gain value.

![Fig. 2. Analysis of the 3D printed reflector Fresnel lens antenna in the W-band. (a) Maximum antenna gains of the reflector lens antenna and the reflector Fresnel lens antenna against the loss tangent. (b) Analyzed \( yz \)-plane electric-field strength at 76.5 GHz. (c) Analyzed radiation patterns at 76.5 GHz. Note that \( \tan \delta = 3 \times 10^{-2} \) in (b) and (c).](image)
4 Fabrication and measurement of W-band 250-mm-diameter reflector Fresnel lens antenna

The designed reflector Fresnel lens antenna having a diameter of 250 mm is fabricated using a 3D printer. A commercially available 3D printer (Afinia H800 3D Printer, Afinia 3D, Chanhassen, MN) is employed for the fabrication. The printing resolution for the vertical axis is 0.1 mm. Fig. 3(a) shows the overview of the printed reflector Fresnel lens using white ABS filament. The maximum fabrication size of the 3D printer is $200 \times 200 \times 200$ mm (width $\times$ depth); therefore, the lens having a diameter of 250 mm is fabricated in five sections consisting of a center section and four edge sections. The total printing time is about 14 hours. In addition, no post processing is performed on the lens surface. Then, a 0.1-mm-thick aluminum tape is attached behind the lens as a bottom reflector.

Fig. 3(b) shows the setup for the measurement of the antenna. The primary source is vertical polarized WR-10 open-ended waveguide, which is the same as that in the numerical analysis described in previous section. In addition, the focal length can be adjusted using the micrometer stage at the bottom of the reflector. Fig. 3(c) and Fig. 3(d) show the analyzed (focal length = 125 mm) and measured (focal length = 137 mm) radiation patterns for azimuth and elevation, respectively, at 76.5 GHz. The maximum antenna gain is measured at a focal length of 137 mm. On the other hand, the designed focal length is 125 mm. The 12-mm difference is
mainly due to the relative permittivity difference in the dielectric material of the lens. The relative permittivity of the ABS plastics is approximately 2.32; however, the relative permittivity of the fabricated solids is not the same as the plastic itself. The filling factor of the printed solids is not 100%; therefore, the effective relative permittivity is less than 2.3. This is also observed in the millimeter-wave 3D printed reflectarray antenna [2].

Antenna characteristics other than the focal length agreed well with the analysis results. The antenna gain is 36.0 dBi; this value is less than the analysis result by 1.6 dB. In addition, the HPBW for the azimuth and the elevation are 1.1° and 1.0°, respectively. These results confirm the feasibility of the high-gain millimeter-wave antenna fabricated using the low-cost 3D printer.

5 Conclusion

A 3D-printed reflector Fresnel lens antenna, which has a gain close to 40 dBi at the W-band are demonstrated for the millimeter-wave radar application. The thin Fresnel structure and fabrication using the 3D printer with ABS plastics enables both a low-cost construction and a high-gain performance.

Firstly, the 250 mm-diameter reflector Fresnel lens having a thickness of 4.3 mm, was designed based on the 41.0 mm thick reflector lens antenna. The loss of the dielectric materials directly affected the antenna gain, especially for the thick lens structure. The thin Fresnel structure enabled to mitigate the effect of the high-loss tangent ABS plastic. Then, the antenna characteristics of the reflector Fresnel lens antenna and the reflector lens antenna were compared and discussed by using the FDTD analysis. Finally, the designed reflector Fresnel lens was fabricated using the 3D printer with the ABS filament. The measured results indicated 36.0 dBi gain which is nearly equaled the FDTD analysis value of 37.2 dBi at 76.5 GHz.