Insensitivity Characteristics in the Dual Polarization of Deployable CFRP Reflector Antennas for SAR

Seong Sik Yoon, Jae W. Lee, *Member, IEEE*, Taek-Kyung Lee, *Member, IEEE*, and Jin Ho Roh

***Abstract*— A large deployable reflector antenna is considered and designed for the application of a synthetic aperture radar system requiring high gain for the high resolution of a detected image within a distance of a few hundred kilometers. For its lightweight and strong characteristics, carbon fiber reinforced polymer (CFRP) is introduced as a composite material and fabricated for conductivity evaluation. Effective electrical characteristics are obtained as a function of carbon fiber direction, using measured S-parameters in a rectangular waveguide. By taking into account the changes of the effective electrical characteristics that depend on the fiber direction of reflector antenna, the radiation pattern is investigated at X-band in terms of gain and polarization variation effects. The proposed reflector antenna made of quasi-isotropic CFRP panel can realize the insensitive characteristics depending on the incident polarization.**

***Index Terms*— Carbon fiber reinforced polymer (CFRP), deployable reflector antenna, effective electrical conductivity, synthetic aperture radar (SAR).**

I. Introduction

THE importance of synthetic aperture radar (SAR) reflector antennas to satellite payload has been considerably increased due to the abundance of applications for image detection and sensing in all weather conditions. In order to improve the specified observation swath and satisfy the need for a clear image resolution within a certain orbit, the reflector-type satellite antenna, which is required for high gain, is proposed but it is limited in terms of its physical dimensions [1], [2].

On the other aspect, the weight of a reflector antenna is directly related to launching cost. As the possible candidates overcoming this problem, new composite materials are suggested for a stable, lightweight model. To improve the quality of image resolution and data accuracy, the polarization effects of dual polarization or quad polarization on SAR images should also be considered [3].

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In general, composite materials combined with two or more constituents are electrically modelled as an effective homogeneous medium even if they have characteristics of nonperfect conductivity and inhomogeneity. Among these proposed composite materials, CFRP composites are desirable in terms of high strength, high stiffness, low coefficients of thermal expansion, and insusceptibility to corrosion [4].

As a candidate for a lightweight material to replace alloyed materials, CFRP has gathered much attention regarding its electrical performance in the areas of shipbuilding, aerospace, and aeronautical devices as well as shielding enclosures [5].

Before applying the CFRP-based antenna to the space program, its effective conductivity characteristics should be taken into account because of the effect on the antenna's gain and radiation patterns. Since CFRP fibers are measured in nanometers and the array/alignment of fibers and resins is irregular [6], [7], it is difficult to effectively evaluate and consistently predict conductivity by using a simulation tool.

Proper CFRP modeling, as a nonuniform and inhomogeneous material, is required to gain an accurate prediction of the electrical performance in the operating frequency range. To extract electrical properties of material, several material-modeling techniques, such as open resonators, air-filled waveguides, and surface impedance, have been considered and well-established theoretically by Holloway *et al.* [8] and Wasselynck *et al.* [9]. An application of a simple modification of waveguides as well as an extraction algorithm of electrical complex permittivity and conductivity will be discussed.

However, considering the importance of reliability and experience in the space environments, there are few studies on CFRP electrical performance for satellite antennas, to the best of our knowledge. To enhance the conductivity characteristics of CFRP materials in reflector antennas, researchers have focused on the quasi-isotropic-layered structure of laminating carbon fibers with different directions, or they have studied coating techniques on the surfaces of reflector antennas with the aim of activating a perfect conductor.

In this paper, we propose an analytical procedure for a deployable CFRP reflector antenna using the proposed composite material without any coating material on the surface. Section II describes the measurement method and calculating algorithm for deriving the effective electrical characteristics of the proposed composite material, CFRP, with nonhomogeneous and anisotropic properties. In Section III, the electrical performance of the deployable antenna is analyzed using

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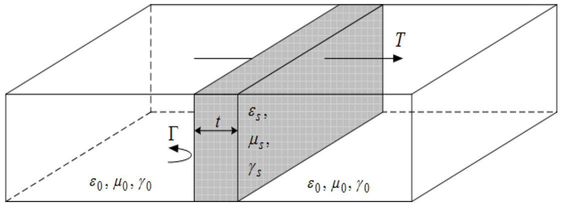


Fig. 1. Description of a CFRP specimen in a rectangular waveguide.

commercially available software GRASP based on the ray-tracing method, including the effects of the composite material CFRP.

II. Evaluation of the Proposed CFRP Material

As the main parameters for the electromagnetic properties of the reflector material (electrical conductivity), complex permittivity and permeability are considered and calculated from data related to the reflection and transmission of the target specimen. Especially for a high-frequency regime, the air-filled waveguide method using transmission line theory has been adopted primarily [10], [11]. This method has been used here to determine the electrical properties of composite materials, such as CFRP, that share characteristics with anisotropic materials, depending on the array direction and orientation of the layered fiber.

A. Electrical Properties of CFRP

In order to derive the electrical characteristics of our samples, we employed the two-port vector network analyzer (VNA) used for measuring S-parameters from an air-filled rectangular waveguide, as shown in Fig. 1. For easy fabrication and measurement, WR90 standard waveguides suitable for X-bands were employed to measure S-parameters. For this research, the electrical properties of the target specimens were modelled as uniformly effective bulk materials, represented by effective complex permittivity ε_s or effective permeability μ_s. The effective values ε_s and μ_s can be obtained by applying the measured S-parameters to the Nicolson-Ross theory. Fig. 1 shows the measurement concept of the experimental configuration using a rectangular waveguide. The reflection coefficient Γ of a given specimen with thickness t, which is relatively small compared to the wavelength, can be obtained as a function of the propagation constant inside the waveguide by applying the appropriate boundary conditions.

Taking into account the multiple reflections inside the waveguide, the total reflection and transmitted coefficients can be represented as the closed-form expressions shown in the following equations:

$$S_{11}(\omega) = \frac{V_A}{V_{\text{inc}}} = \frac{(1 - e^{-2\gamma_s t})\Gamma}{1 - \Gamma^2 e^{-2\gamma_s t}} \tag{1}$$

$$S_{21}(\omega) = \frac{V_B}{V_{\text{inc}}} = \frac{(1 - \Gamma^2)e^{-\gamma_s t}}{1 - \Gamma^2 e^{-2\gamma_s t}}. \tag{2}$$

Effective complex permittivity and permeability can be derived from the mathematical manipulations of the relationship between the scattering parameters and reflection or transmission coefficients, as follows:

$$\mu_s = \frac{(1+\Gamma)\left[\sqrt{-\left\{\left(\frac{1}{2\pi t}\right)\ln(e^{\gamma_s t})\right\}^2}\right]}{(1-\Gamma)\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \tag{3}$$

$$\varepsilon_s = \frac{\lambda_0^2}{\mu_s}\left(\frac{1}{\lambda_c^2} - \left\{\left(\frac{1}{2\pi t}\right)\ln(e^{\gamma_s t})\right\}^2\right) \tag{4}$$

where λ_0 and λ_c are the wavelengths in the free-space and in the cutoff frequencies, respectively, of the TE_{10}-mode in the rectangular waveguide.

In contrast, in the case where the imaginary part of complex permittivity is high, a target material with a high reflection coefficient leads to significant fluctuation in the phase variation of the measured transmission coefficient, providing insufficient information. Hence, the derivation of conductivity can be represented as a relationship between the measured S-parameters and the surface impedance of the composite material considered in this paper

$$\sigma = 4\pi\mu_0 f \frac{(1 - |S_{11}|^2)^2}{Z_w^2[(1 + |S_{11}|^2) - \sqrt{-|S_{11}|^4 + 6|S_{11}|^2 - 1}]^2}. \tag{5}$$

B. Characteristic of Dependence on Fiber Orientation

In this section, the CFRP characteristics for the application of the reflector antenna are investigated under the operation of an X-band frequency range. At the center frequency, calibration using a thru-reflect-line has been carried out at the reference planes at the end of the waveguide. A measurement setup that included the rotation stage was assembled, as shown in Fig. 2, using a VNA from Agilent Technologies (N5230 PNA). A process involving an autoclave and oven has been employed for the lamination of the proposed CFRP, namely, M55J/RS3 prepreg material.

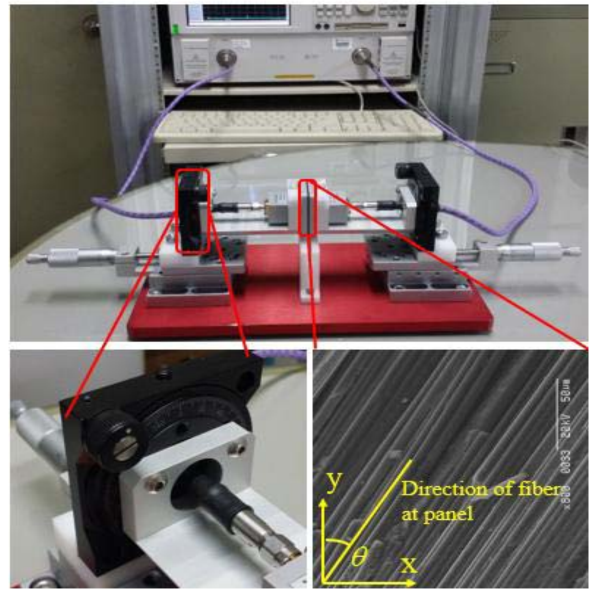
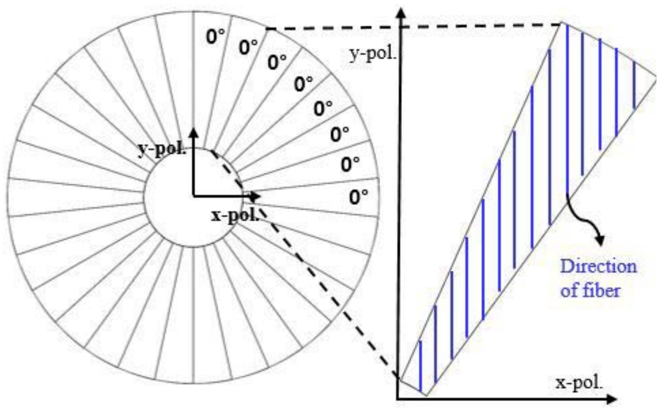
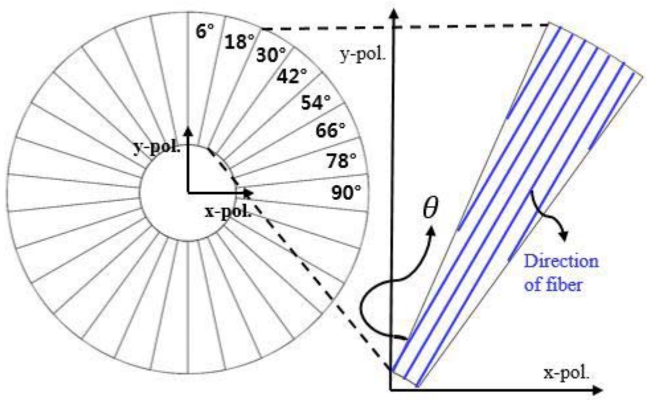


Fig. 2. Conductivity measurement setup of the proposed composite material.



(a)



(b)

Fig. 3. Fiber directions at each panel in two cases. (a) In parallel with the y-axis in all panels. (b) In parallel with the rotation angle of each panel.

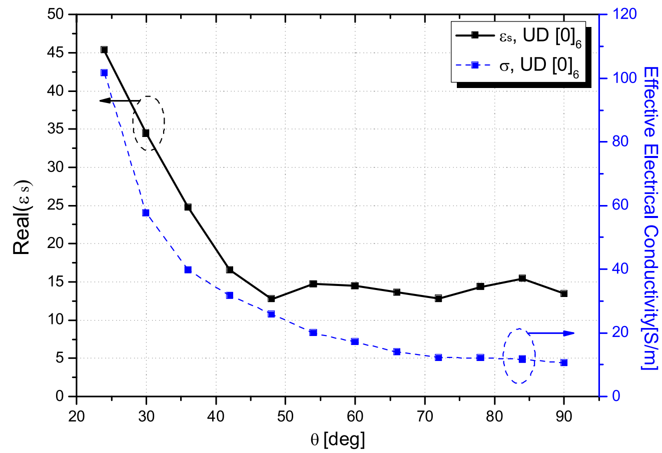


Fig. 4. Complex permittivity of a unidirectional CFRP.

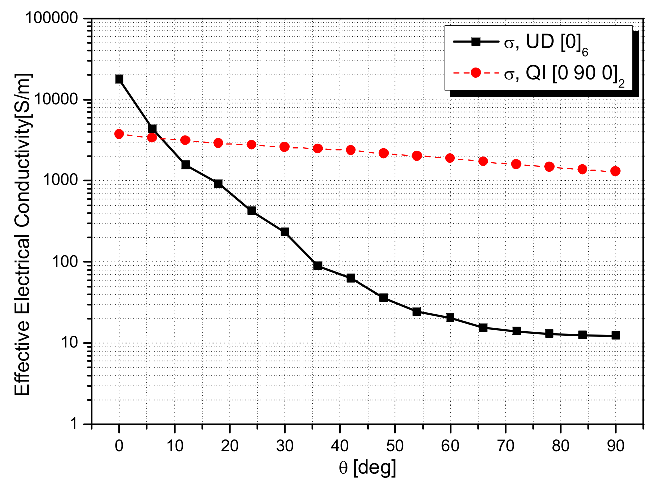


Fig. 5. Comparison of effective electrical conductivity in unidirectional and quasi-isotropic CFRPs.

In the CFRP specimen, the volume ratios for fibers and resins are 60% and 40%, respectively, and the thickness of the 1-ply prepreg is 0.125 mm. As shown in Fig. 3, depending on the fabrication procedure of each panel while building the final reflector antenna, the polarized direction of the incident electric field from the feeding structure to the main reflector will be different from the laminating directions of the CFRP. At that time, the inclined direction of the carbon fiber relative to the y-axis is defined as θ (see Fig. 2). As shown in Fig. 3(a), the fiber direction is in parallel with the y-axis in all panels, comprising the total antenna reflectors so that the polarization of the incident electric field coming from the feed horn is in parallel with the fiber direction at all points on the reflector antenna. Fig. 3(b) shows that the fiber direction is in parallel with the rotation angle of each panel, which determines the angle between the polarization of the incoming electric field and the fiber direction. To analyze the electromagnetic performance of CFRP panels for reflector antennas, the effective electrical conductivity has been approximated, depending on the rotation angle, using measurements and numerical simulation formulas in the practical application of an anisotropic and inhomogeneous medium.

For the validation of our measurement and simulation approaches, dielectric specimens that have well-known material data, such as FR-4 and RO3010, have been tested and compared with the predicted data in [10]. To measure the effective permittivity of multilayered and laminated CFRP specimens, six-layered and uniformly directed fibers in a certain direction ($\theta = 0°$) are introduced and named $UD[0]_6$. In Fig. 4, it is apparent that the real line shows real part of effectively relative complex permittivity, and the blue-dashed line represents the effective electrical conductivity resulting from the imaginary aspect of effective complex permittivity. For a comparison of effective conductivity, depending on the assigned direction of the laminated fiber, Fig. 5 shows the effective conductivity of quasi-isotropic CFRP named $QI[0\ 90\ 0]_2$, which indicates that the fiber direction in each layer of the laminated CFRP is sequentially rotated (0°, 90°, 0°, 0°, 90°, and 0°) in a symmetrical structure from the bottom layer to the top layer. As shown in Fig. 5, it can be conjectured that the variation of effective conductivity in $QI[0\ 90\ 0]_2$ is relatively insensitive according to the rotation angle as compared to $UD[0]_6$ under the same conditions with the same number of layers.

III. Applications of CFRP to Antenna Systems

In the case of reflector antennas for satellite SAR, high gain characteristics are required to obtain a noise equivalent

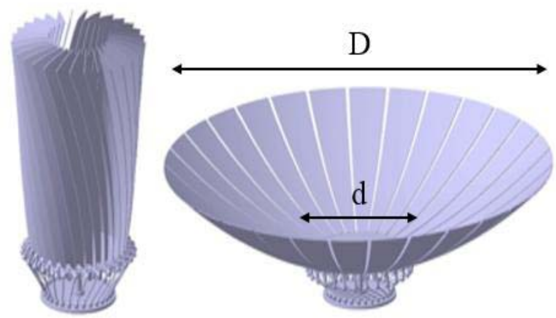


Fig. 6. Geometry of stowed and deployed reflector antennas.

sigma zero capable of detecting target images and smart beamforming technology, depending on the selected operating mode. As the candidates for satellite SAR antennas, many researchers have proposed waveguide-type slot arrays, planar arrays, and reflector antennas. In this paper, a solid-type reflector antenna with high electrical conductivity has been recommended and designed for the application of passive electronically scanned array radar with the help of relatively straightforward implementation and data processing of SAR data. In addition, to reduce the stowed volume during the launching of the satellite and enhance the stowed packing efficiency, antenna structures that consider deployment characteristics are recommended. In this section, the radiation patterns of reflector antenna based on CFRP will be briefly investigated using effective electrical characteristics on each panel according to the rotation angle.

A. Geometrical Structure of Reflector Antennas

As a key metric for the design of deployable reflector antennas, the number of panels should be determined and optimized from an electrical and mechanical standpoint, taking into account the deployable mechanism and the dimensions of the central dish located at the center of the antenna. It is generally known that as the number of panels decreases, the diameter ratio (d/D) between the central and main dish becomes larger, and stowed packing efficiency is reduced in the passive and active deployable equipment driven by mechanical systems. Conversely, if the number of panels increases, the amount of deployable driving equipment increases, and the concern for surface accuracy and electrical performance degradation due to deployment error will increase as well—even though a compact payload can be achieved—because of the reduced diameter ratio. As shown in Fig. 6, a central dish is required for the perfect deployment of each panel. However, the existence of this central dish may cause a phase difference at the aperture and increase the sidelobe level. In a real application of SAR, the sidelobe level of the reflector antenna is directly related to the ambiguity parameter. In [12], the optimization process for the diameter of a central dish and the number of panels were carried out by considering mechanical and electrical characteristics. The optimized values for the diameter of the main reflector, the diameter of the planar central dish, the focal length, and the total number of panels were determined to be 3, 0.8, 1.1, and 30, respectively.

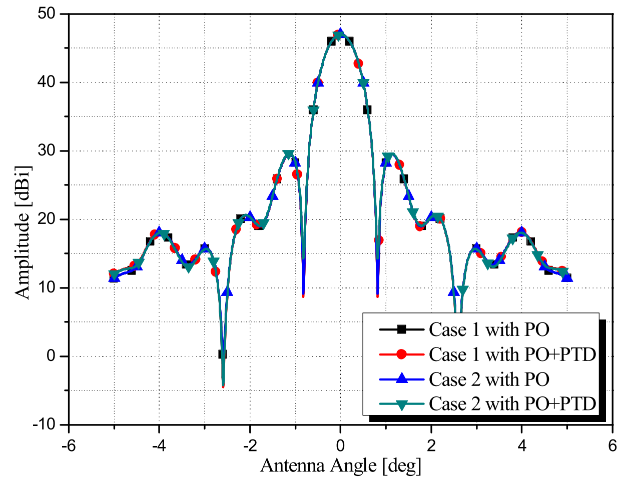


Fig. 7. Comparison of radiation patterns, depending on the analysis methods and considered structures.

B. Antenna Analysis Assuming Infinite Conductivity

In this section, the effects of the main reflector on the radiation pattern will be described with the validity check of numerical simulation technology. The edge illumination is assumed to be -11.9 dB for the optimum radiation efficiency under the assumption of a Gaussian beam pattern as an input signal generated from a conical feeding horn. At both end points from the center, the beam angle of the antenna corresponds to $\pm 68.57°$. To verify the accuracy of the numerical simulation technology in this antenna analysis, several cases of reflector antennas are considered for improved simulation accuracy.

1) *Case 1:* The main reflector is represented as a single panel in a unified structure.
2) *Case 2:* The main reflector is divided into many panels.

The electrical performance of these structures has been analyzed using TICRA commercially available software, GRASP, based on physical optics (PO). Case 1 involves a main reflector made of a single scatterer during a numerical simulation, while case 2 describes a main reflector composed of 30 panels and a central dish. From the results shown in Fig. 7, it is established that according to the analysis methods and structures considered (case 1 and case 2), the radiation patterns are in agreement in terms of the co-polarization level, irrespective of the inclusion of the diffraction effects on panel edges.

C. Antenna Analysis Assuming the Finite Conductivity of CFRP

In this section, a dual-polarized wave will be considered as an input signal of the main CFRP reflector, which has finite conductivity in real situations. By using two kinds of polarizations (x-polarization and y-polarization) and replacing the main reflector with effective complex permittivity and conductivity that depend on the rotation angle, the radiation pattern and gain deviation, according to the two different laminating processes (unidirectional [UD] and quasi-isotropic [QI]) and panel constitution (case1 and case2), have been investigated and summarized in Figs. 8–11. For the numerical evaluations, PO analysis has been carried out.

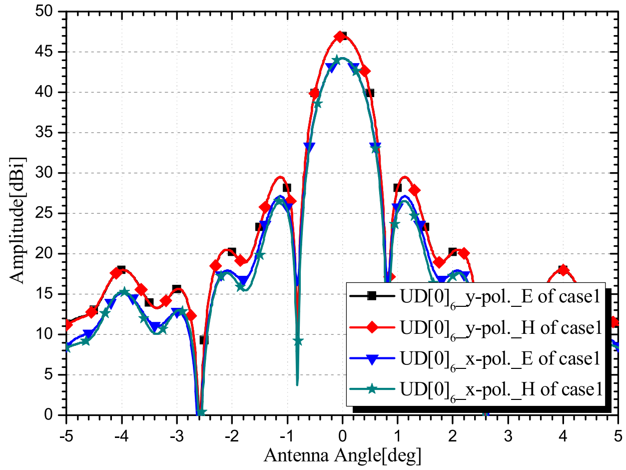


Fig. 8. Radiation patterns when applying unidirectional CFRP to case 1.

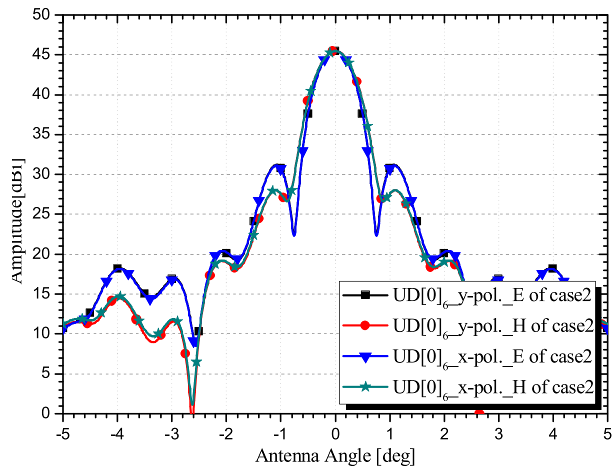


Fig. 9. Radiation patterns when applying unidirectional CFRP to case 2.

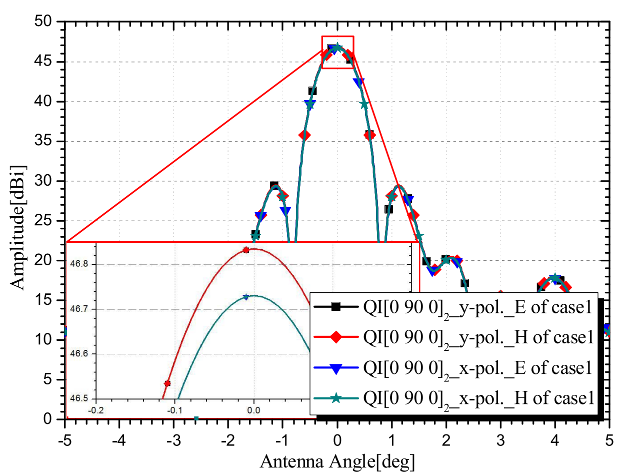


Fig. 10. Radiation patterns when applying quasi-isotropic CFRP to case 1.

The interested beam angle is limited to a range within ±5° from the center because the effects of the peak values on SAR performance are larger than those of accumulated values in the sidelobe level. In Figs. 8 and 9, unidirectional CFRPs with six layers are applied to case 1 and case 2 (see Section III-B), respectively, and the radiation patterns are plotted according to the input polarization from the feeding structure. The case

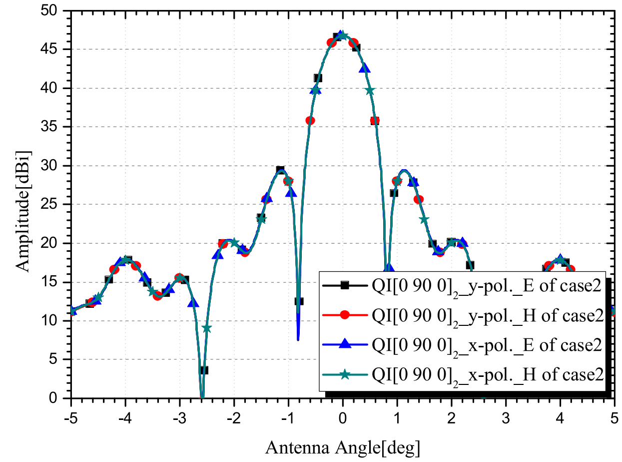


Fig. 11. Radiation patterns when applying quasi-isotropic CFRP to case 2.

TABLE I

Performance of Reflector Antennas Depending on Fiber Direction

Direction of Fiber	Pol.[a]	Performance		
		Gain (dBi)	SLL[b] (dB)	BW[c] (°)
UD Case 1	x-pol.	44.18	-17.08	0.68°
	y-pol.	46.92	-17.43	0.68°
UD Case 2 (E/H)	x-pol. (E/H)	45.46 / 45.46	-14.37 dB/ -17.45 dB	0.65°/ 0.7°
	y-pol. (E/H)	45.46 / 45.46	-14.28 dB/ -17.5 dB	0.65°/ 0.7°
QI Case 1	x-pol.	46.72	-17.44 dB	0.68°
	y-pol.	46.83	-17.43 dB	0.68°
QI Case 2	x-pol.	46.79	-17.37 dB	0.68°
	y-pol.	46.79	-17.37 dB	0.68°

[a] pol.: Polarization, [b] SLL: Side Lobe Level, [c] BW: Beam Width

of a unidirectional CFRP laminating sequence that is parallel to all positions on the reflector antenna (explained in Fig. 3) shows a gain difference that depends on the polarization of the incident wave. Fig. 9, which shows a unidirectional CFRP laminating sequence that is parallel relative to each panel, depicts a negligible gain difference, but a difference between sidelobe levels still exists depending on the cutting plane. In a similar manner, a quasi-isotropic laminating sequence has been applied to the same structure as case 1 and case 2. As a result, there is nearly no variation in terms of radiation pattern and gain magnitude in the case where quasi-isotropic lamination is used, as shown in Figs. 10 and 11. In particular, it is notable that the radiation patterns using a quasi-isotropic laminating sequence are independent and insensitive to the dual polarization propagated by the feeding horn. Finally, the performance values of beam patterns are quantitatively listed and summarized in Table I, according to the laminating sequence and polarization.

D. Fabrication and Measurement of Small-Scaled Antenna

In order to verify the accuracy of our analysis and conductivity modeling of the proposed CFRP-based reflector antenna, the small-scaled reflector antenna with a dimension

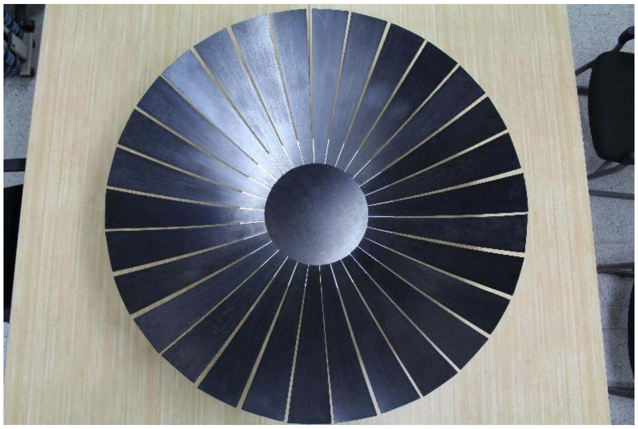


Fig. 12. Top view of the fabricated deployed CFRP reflector antenna.

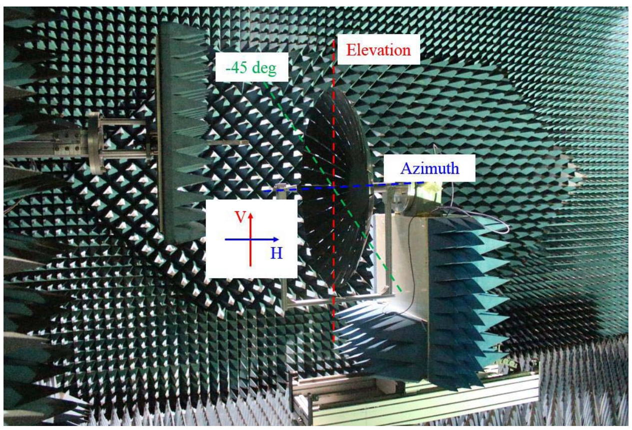


Fig. 13. Near-field measurement of CFRP reflector antenna.

of radius 50 cm has been fabricated and the photograph is shown in Fig. 12 with unfolded panels and central disc. The layered sequence of the proposed scale-down model was extended to QI[0 90 0 90 0]$_2$ by considering the mechanical characteristics and electrical performance. Each panel has been fabricated by employing the appropriate curing process of autoclave under the high temperature and high pressure. By taking the maximum size of autoclave into consideration in fabrication and simulation, a small-scaled antenna having a ratio ($F/D = 0.37$), between the focal length (F) and the diameter of reflector antenna (D) has been proposed and fabricated.

From the comparison between the simulated and measured patterns, it is considered that the electrical characteristics of the full-scaled CFRP antenna can be easily estimated and predicted by employing our analysis approach and simulation.

Fig. 12 shows the top view of the unfolded structure of the fabricated CFRP antenna without feeding network and struts. The gap between the panels is equally assumed to be 1° and the resin was used for a tight adhesion between the central disc and each panel. For a near-field measurement, CFRP reflector antenna with rectangular horn antenna as a feeding network and the grooved struts has been set up, as shown in Fig. 13. After applying the effective electrical properties on each CFRP panel and importing the radiation pattern of feed network obtained from electromagnetic simulation into the

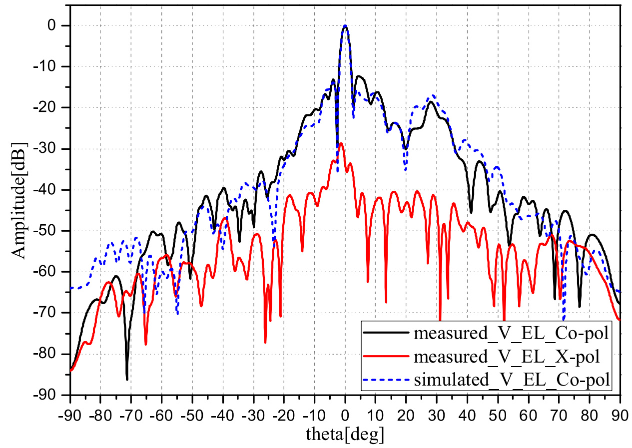


Fig. 14. Normalized radiation patterns of vertically polarized incident wave in the elevation plane.

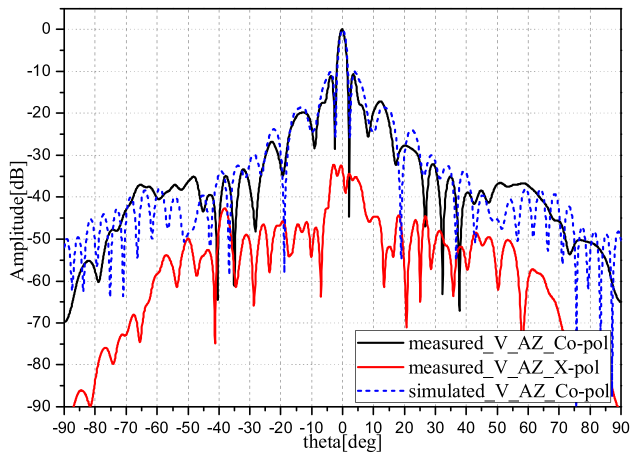


Fig. 15. Normalized radiation patterns of vertically polarized incident wave in the azimuth plane.

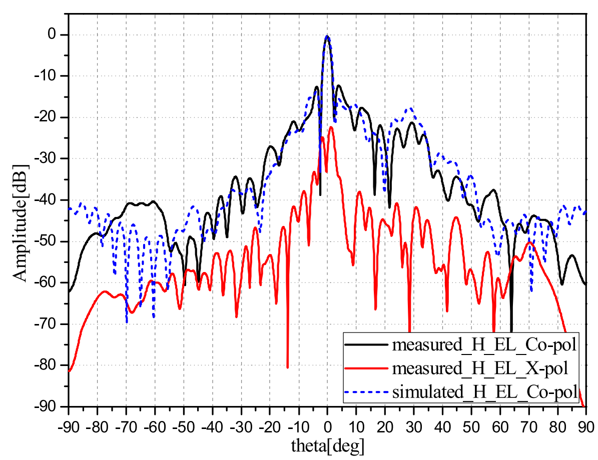


Fig. 16. Normalized radiation patterns of horizontally polarized incident wave in the elevation plane.

incident field of the main reflector antenna, the total radiation patterns of CFRP reflector antenna have been estimated and predicted with the strut effects resulting in the blockage, the increase of sidelobe level, and scattering loss. Figs. 14–17 show the radiation patterns in the elevation (*yz* plane) and

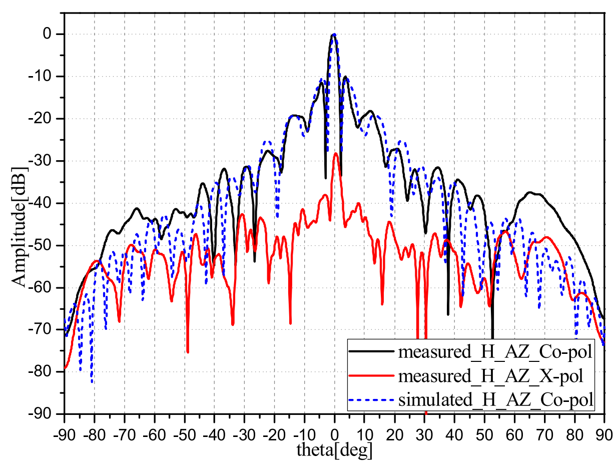


Fig. 17. Normalized radiation patterns of horizontally polarized incident wave in the azimuth plane.

azimuth plane (*xz* plane) according to the polarization of the incident fields. The simulated gains of the proposed reflector antenna according to V-polarization and H-polarization are 33 and 32.8 dBi, respectively, with each measured gains of 32.6 and 32.4 dBi. As can be seen from Figs. 14–17, reasonably good agreements between the simulation and measurement according to the polarization have been obtained.

IV. Conclusion

First of all we suggest that the proposed CFRP material is a good candidate for satellite SAR reflector antenna systems. For SAR antennas in space environments, the characteristics of high gain, stability, lightweight, and excellent mechanical performance are essential. Stowed packing efficiency and weight are so important and closely related to the development costs of reflector antennas that a variety of materials for space antennas should be studied, which would provide recommendations for weight reduction and low-loss characteristics.

In this paper, a newly proposed CFRP material has been used to design a deployable, solid, reflector antenna while considering surface accuracy and stable deployment mechanisms. The optimized parameter values that satisfy the requirements of electrical and mechanical performance have been provided regarding the diameters of the main reflector and the central dish, the proper focal length, and the total number of panels comprising the entire reflector antenna. In order to extract the effective complex permittivity of the employed carbon materials, waveguide fixtures and laminated CFRPs that were equivalently modelled as an isotropic homogeneous structure have been employed with the measurement of reflection and transmission coefficients. The effects of the rotation angle of fiber direction have been included in the incident polarization in the numerical simulation; according to laminating sequences such as $UD[0]_6$ and $QI[0\ 90\ 0]_2$, the radiation patterns have been obtained and investigated in terms of polarization aspects.

From the simulation results, it is confirmed that $QI[0\ 90\ 0]_2$, which is the suggested laminating sequence with a total of six layers in a symmetrical structure from the bottom layer to the top layer, produces gain and radiation patterns that are insensitive to dual polarization. $QI[0\ 90\ 0]_2$ is preferred over $UD[0]_6$, which is directed according to the assigned fiber direction in all six layers. Hence, it is ensured that the proposed quasi-isotropic laminating sequence for the CFRP panel, as an element of the main reflector, is a good candidate as a dual-polarized deployable SAR antenna, which satisfies the requirements of a high gain of 46.8 dBi and a sidelobe level of −17.4 dB. In order to increase the reliability of our analysis and simulations, a small-scaled CFRP-based reflector antenna made of $QI[0\ 90\ 0\ 90\ 0]_2$ sequence has been proposed, fabricated, and measured through the near-field measurement system with comparison data in a good agreement.

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