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Microwave shielding and polarization characteristics of carbon fiber reinforced plastic laminates with unidirectional materials

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Abstract: The electromagnetic shielding and polarization characteristics of carbon fiber reinforce plastics (CFRP) based on unidirectional (UD) materials are determined by experiments. The UD CFRP laminates have single direction carbon fibers, which behave the same as wire-grid structures. The measured transmission coefficient for the 1 ply UD CFRP laminate is about -2 dB, when the direction of the carbon fiber is perpendicular to the incident wave. The polarization ratio is more than 20 dB for most frequency points. In addition, it is confirmed that the transmission coefficient can be controlled by rotating the UD CFRP laminates.

Keywords: carbon fiber reinforced plastics, microwave, polarization, unidirectional prepreg, shielding effect, wire-grid
Classification: Electromagnetic compatibility (EMC)

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1 Introduction

The advantages of carbon fiber reinforced plastics (CFRP) include their very high specific strength, which means light weight as well as high strength and rigidity. The excellent physical performance of CFRP materials has lead to them replacing many conventional materials. Their electric characteristics such as conductivity and dielectric constant have been discussed of the specific CFRP materials [1, 2]. We have been investigating the shielding characteristics of CFRP laminates [3]. This paper discusses these characteristics in more detail based on the results of the latest experiments. The CFRP laminates tested employ unidirectional (UD) materials.

The purpose of the paper is to evaluate the shielding and polarization characteristics of UD CFRP laminates. This is because the UD CFRP laminate is one of the basic structures used to form the quasi-isotropic CFRP laminates employed for constructing strength members. To achieve a high shielding performance of these multi-layered CFRP laminates, it is required to obtain the characteristics of the most fundamental UD CFRP structure. In addition, the polarization characteristics of UD CFRP laminates can be utilized as polarization control structure such as used for cross polarization suppressors or polarization diversity devices.

First, the structure and the fabrication of UD CFRP laminates are discussed. The UD CFRP laminate is one of the basic structures used to form the quasi-isotropic CFRP laminates employed for constructing strength members. Our transmission coefficient measurement system, which consists of a shielding box and a compact signal generator, is introduced. Next, the transmission coefficients of UD CFRP laminates with different laminate thickness are measured in an anechoic chamber. Fundamental polarization and shielding characteristics are measured between 400 MHz and 6 GHz. Finally, the polarization characteristics are obtained by rotating the UD CFRP laminates.

2 CFRP laminates based on unidirectional materials

The CFRP laminates assessed here are made of UD carbon prepreg sheets [4]. In these unidirectional carbon materials, all carbon fibers are parallel to each other. Unlike the CFRP laminates based on woven fabrics, UD CFRP laminates have only single direction fibers. A thermosetting epoxy resin is used as the matrix. Fig. 1 (a) shows typical scanning electron microscope images of the UD carbon fiber with epoxy resin.

The diameter and conductivity of each carbon fiber are less than 10 μm and around $2 \times 10^{-3}\,\Omega \cdot \mathrm{cm}$, respectively. This means that in the direction of the fiber, the direct current (DC) conductivity is very high. On the other hand, perpendicular to the fiber the DC conductivity is basically zero due to the epoxy resin. Because of this, UD CFRPs can be modeled in same way as the wire-grid structure [5, 6]. The loss of the epoxy resin used is not zero at the high frequency region, but resin thickness is very small. The dielectric characteristics of the resin will not significantly deviate from the wire-grid characteristics. Note that the length of the carbon fiber is the same as the

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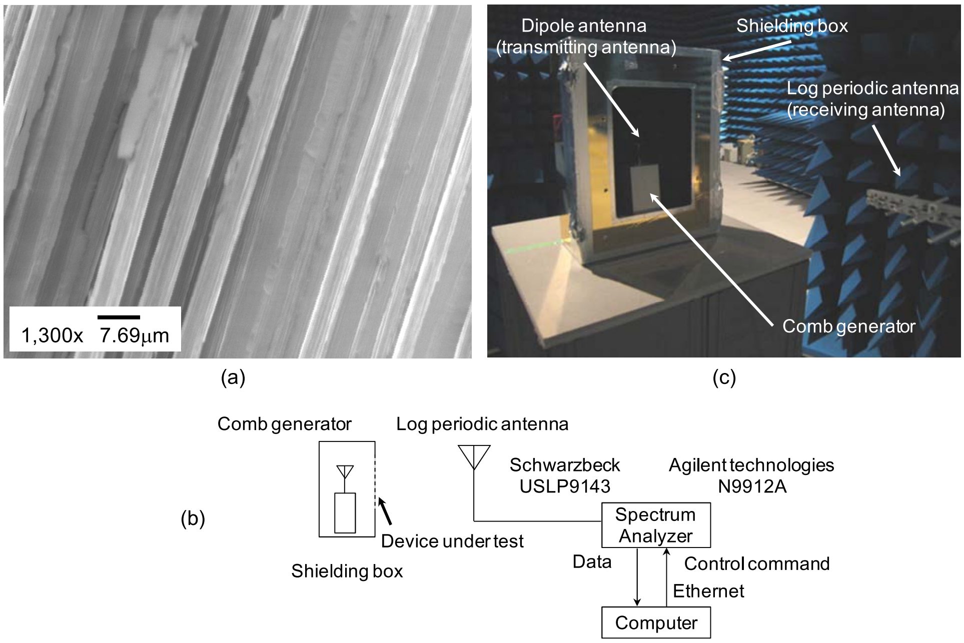

Fig. 1. (a) Scanning electron microscope image of the UD carbon fiber with epoxy resin. (b) Block diagram of the UD CFRP laminates shielding and polarization characteristics measurement. The transmitting antenna is a dipole antenna in the shielding box. (c) Overview of the measurement set-up in an anechoic chamber. During the measurement, the device under test is attached to the window of the shielding box.

length of UD CFRP laminates. This is because the series of UD prepreg sheets are employed for the fabrication.

To measure the dependence of the shielding and polarization characteristics on laminate thickness, three different thickness DUTs, single-layer (1 ply), triple-layer (3 ply) and quintuple-layer (5 ply) UD CFRP laminates, are fabricated. The thickness of the prepreg sheet is 0.12 mm prior to setting. To shape the UD CFRP laminates, the prepreg sheets are baked in an autoclave under pressure. Each layer uses the same carbon fiber direction. The 1 ply CFRP laminate is 0.1 mm as set. The thicknesses of the 3 ply and 5 ply laminates are 0.3 mm and 0.4 mm, respectively.

3 Measurement system

To obtain the shielding and polarization characteristics of the UD CFRP laminates, we constructed a measurement system consisting of an aluminum shielding box and a compact signal generator, see Fig. 1 (b). To simplify the signal transmission system inside the shielding box, a compact comb generator is employed as the signal source. It is installed inside the box along with the dipole transmission antenna. The receiving system consists of a log periodic antenna (Schwarzbeck USLP9143) and a spectrum analyzer (Agilent Technologies N9912A). Data acquisition is automatically controlled

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by the external computer through an Ethernet connection. Overview of the measurement set-up in the anechoic chamber is shown in Fig. 1 (c). To obtain the maximum measurement dynamic range, the distance between the surface of the shielding box and the receiving antenna is determined at 50 cm. This distance is the shortest structural distance of the system.

As shown in Fig. 1 (c), the shielding box has an aperture whose size is 280 mm × 190 mm (height × width). This aperture size is determined by the maximum fabrication size of the UD CFRP laminates. To suppress multiple reflections, which may affect the measurement results, ferrite wave absorbers are attached to the inside of the box. The transmitting signal frequency of the comb generator is fixed at values between 400 MHz and 6 GHz. Four types of frequency dipole antennas are employed as the transmitting antenna. Each antenna is used in the frequency band to transmit high radiated power. Note that the transmitted signal is a horizontal polarized wave.

The UD CFRP laminates are attached to the aperture of the box with aluminum tape. The tape is overlapped 10 mm on each side to prevent signal leakage from the edges. The transmission coefficient, $|T|$ (dB), is calculated by the difference in received signal power with and without the DUT as follows:

$$|T| = |P_{without\ DUT}| - |P_{with\ DUT}| \quad (1)$$

where $|P_{with\ DUT}|$ (dBm) and $|P_{without\ DUT}|$ (dBm) are received power with and without DUT on the aperture, respectively.

4 Measurement results

4.1 Fundamental shielding and polarization characteristics

As a first step, the orientation of the UD CFRP laminates is fixed so that the direction of the carbon fiber is perpendicular or parallel to the polarization plane of the incident wave. Fig. 2 shows the measured transmission coefficients of the CFRP UD laminates and a dummy aluminum plate. The closed circle plots the result of the 1.0 mm thickness aluminum plate. The transmission coefficient lies between −50 dB and −70 dB in the frequency band. This results stands for the measurement system dynamic range, which include the leakage from the shielding box or the minute gap between the DUT and the shielding box. Since the leakage is mainly due to the very fine structure of the system, these characteristics depend on frequency. This lead to fluctuation of the measurement result at the very small transmission coefficient value. However, it is clear that this measurement system has sufficient dynamic range performance to evaluate the shielding and polarization characteristics of the UD CFRP laminates. The closed box, open box, and open circle plot the result of the 1 ply, 3 ply, and 5 ply UD CFRP laminates, respectively.

Fig. 2 (a) shows the results under the perpendicular arrangement. The transmission coefficients of the 1 ply UD CFRP laminate is -2.4 ± 0.9 dB. The transmission coefficient is reduced as the laminate thickness is increased. In addition, the average transmission coefficient with the perpendicular con-

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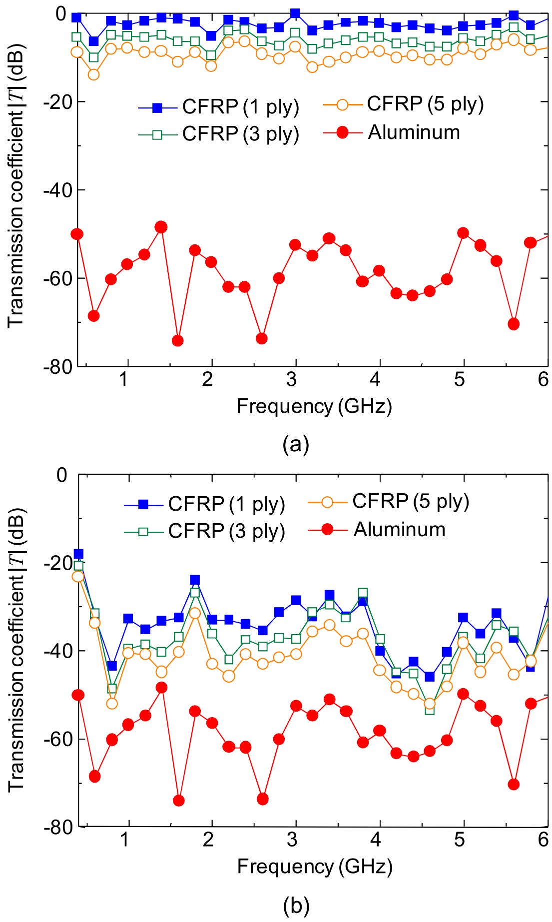

Fig. 2. Measured shield attenuation of the CFRP UD laminates and the aluminum plate. (a) The direction of the carbon fiber and polarization of the incident wave (E-plane) are perpendicular. (b) The direction of the carbon fiber and polarization of the incident wave (E-plane) are parallel.

dition is about −2 dB per laminate. On the other hand, when the carbon fiber and the incident wave polarization are parallel, the transmission coefficient is drastically decreased for all measurement conditions as shown in Fig. 2 (b). The transmission coefficients of the 1 ply UD CFRP laminate varied between −18 dB and −48 dB.

The difference in the transmission characteristics is caused by the wire-grid structure of the UD CFRP laminates. The very fine spacing of the carbon fibers creates slits which induce magnetic currents, when irradiated by the perpendicular incident wave. Because of this, the UD CFRP laminates can be used as electromagnetic wave polarizing materials. The measurement results show that the polarization ratio is more than 20 dB at most frequencies.

4.2 Polarization characteristics obtained with rotation of CFRP laminates

Fig. 3 shows the measured transmission coefficient of the 1 ply UD CFRP laminate as a function of rotation angle. 0 degrees indicates the perpendicular

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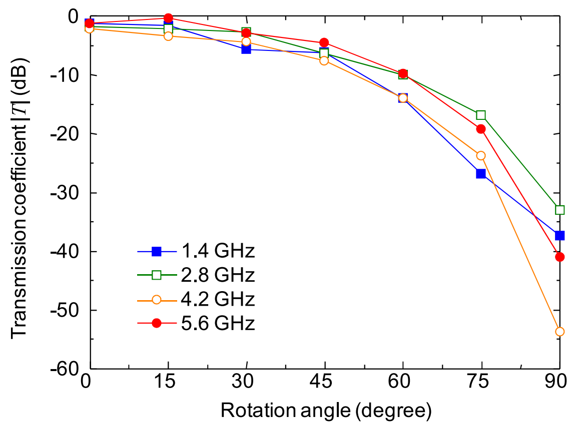

Fig. 3. Measured shield attenuation of the UD CFRP laminates as a function of rotation angle of UD CFRP laminates. In term of the rotation angle, 0 degree stands for the direction of the carbon fiber and polarization of the incident wave (E-plane) are perpendicular. In addition, 90 degree stands for the direction of the carbon fiber and polarization of the incident wave are parallel.

arrangement. The closed box, open box, open circle, and closed circle are the results at 1.4 GHz, 2.8 GHz, 4.2 GHz, and 5.6 GHz, respectively.

These results confirm that the transmission coefficient is monotonically reduced as the rotation angle approaches 90 degrees (parallel condition). At 1.4 GHz, the transmission coefficient is about −1 dB at 0 degrees and is reduced to −37 dB at 90 degrees. Small variations are seen in the small transmission coefficient region, however, the same attenuation trend is also observed at the other frequencies. By using UD CFRP laminates as a polarizing device, we can control the value of the transmission coefficient over a large fractional bandwidth.

5 Conclusion

The shielding and polarizing characteristics of UD CFRP laminates were experimentally obtained between 400 MHz and 6 GHz. The CFRP laminates tested were based single directional carbon fibers. Three UD CFRP laminates of different thicknesses were fabricated. The transmission coefficient was evaluated by a measurement system consisting of an aluminum shielding box and a compact signal generator. The measured results show the significant impact of the direction of the carbon fibers on the transmission coefficient of the laminates. The transmission coefficient for the 1 ply UD CFRP (0.1 mm thick) was about −2 dB, when the direction of the carbon fiber was perpendicular to the incident wave. The polarization ratio was more than 20 dB for most frequency points. In addition, it was experimentally confirmed that the transmission coefficient can be controlled by rotating the UD CFRP laminate. These results confirm that UD CFRP laminates can be utilized as both shielding and polarizing materials for a broad frequency band.

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