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Carbon Fiber Reinforced Polymer with Isotropic 60 GHz Reflectivity

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Abstract—Carbon fiber reinforced polymer (CFRP) is measured as reflector material for millimeter waves at 60 GHz. Reflectivity is measured to characterize material anisotropy in a mono-static setup. Disc shaped material samples are rotated in steps of one degree. Four commonly employed CFRP are investigated: unidirectional fibers, plain-weave, twill-weave and fiber shreds. Results show that the unidirectional CFRP and twill-weave CFRP are anisotropic, while the remaining materials are isotropic within measurement accuracy.

1. INTRODUCTION

Carbon fiber reinforced polymer (CFRP) consists of a polymer matrix that is reinforced with carbon fibers. Antennas are built from CFRP [1, 2], but more commonly large CFRP parts are applied as antenna ground planes [3–7], reflectors [8] or panels for slot antennas [9–11]. Airplanes, boats, car chassis and sports equipment are today built with CFRP. There, CFRP are widely utilized in lightweight construction, where they are built as laminates. From a mechanical engineering viewpoint CFRP laminates with unidirectional (UD) fiber and ply alignment offer a large Young's modulus relative to material density, but they are orthotropic and high material strength is only obtained in fiber direction. Woven fabrics are used to get more smoothed mechanical and electrical properties, but Young's modulus is then greatly reduced. Plain-weave and twill-weave CFRP are among these fabrics. Plain-weave CFRP are widely applied in large laminate panels, but suffer from a poor drapability. Therefore, twill-weaves are often applied in parts with more complex shapes. CFRP with fiber-shreds are typically built with compression molding and spray-up techniques. They are often brought in when the application of recycled fibers is beneficial.

1.1. Related and Prior Work

Measurements of anisotropic conductivity of UD-CFRP of up to 12 GHz are found in [12, 13]. Those of twill-weave CFRP and shred-CFRP are found in [14]. In most practical applications isotropic materials, which have little influence on reflectivity and antenna patterns are preferred. Only, in specialized applications the anisotropy of CFRP can be utilized, e.g., as mode filters for reconfigurable antennas [15] or as polarization filtering reflectors [16]. Measurements of UD-, twill- and shred- CFRP as ground plane materials for monopole antennas show, that twill- and shred-CFRP behave as isotropic ground planes up to at least 10 GHz, while the UD-CFRP ground plane has a large influence on the antenna's gain pattern and efficiency [5].

Millimeter waves are increasingly used for radar applications [17, 18] and for wireless communications [19, 20]. Especially the 60 GHz band has attracted attention recently. The IEEE

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802.11ad standard is subject to investigation as possible vehicular communications standard [21] and for joint radar-communications [22]. CFRP reflectors are applicable at millimeter wavelengths, as demonstrated in [23], where a parabolic millimeter wave reflector is built from UD-CFRP as part of an autonomous unmanned helicopter's radar system [24]. The gain of the CFRP reflector antenna is found to be close to that of a chrome plated version at 96 GHz [23]. Above 100 GHz the anisotropic reflectivity of UD-CFRP is measured in [25, 26], but material orientation is only considered in fiber direction and perpendicular to fiber direction. Reflectivity measurements in two directions are sufficient to characterize UD-CFRP, but woven fabrics have a more complex geometry and therefore require a finer angular resolution. Mono-static reflectivity measurements are important for radar applications and antenna reflectors.

In many applications isotropic reflectivity is desirable. As is well known, UD-CFRP are unsuitable due to their anisotropy. Woven materials are frequently used instead. Recently, it was shown that the application of the commonly used twill-weave CFRP is limited at millimeter waves, because the wavelength is then close to the size of their weave pattern, and grating effects possibly cause anisotropic reflectivity in bi-static setups [27]. It is therefore necessary to identify CFRP that have isotropic reflectivity at 60 GHz.

1.2. Contribution

The isotropy of four different CFRP laminates at 60 GHz is investigated. This closes the gap of CFRP investigation in the V- and E-band. Isotropy is determined by measuring the angle dependent relative reflectivity. All samples are cut to disc shapes and rotated in steps of one degree. Our material samples have unidirectional, plain-weave, twill-weave and shredded fibers ply geometries. We emphasize, that mono-static reflectivity is measured in this work.

2. MATERIALS UNDER TEST

Four different CFRP laminates with different ply structures are investigated: unidirectional, plain-weave, twill-weave and fiber shreds. These materials are shown in Fig. 1 and are referred to as UD-CFRP,

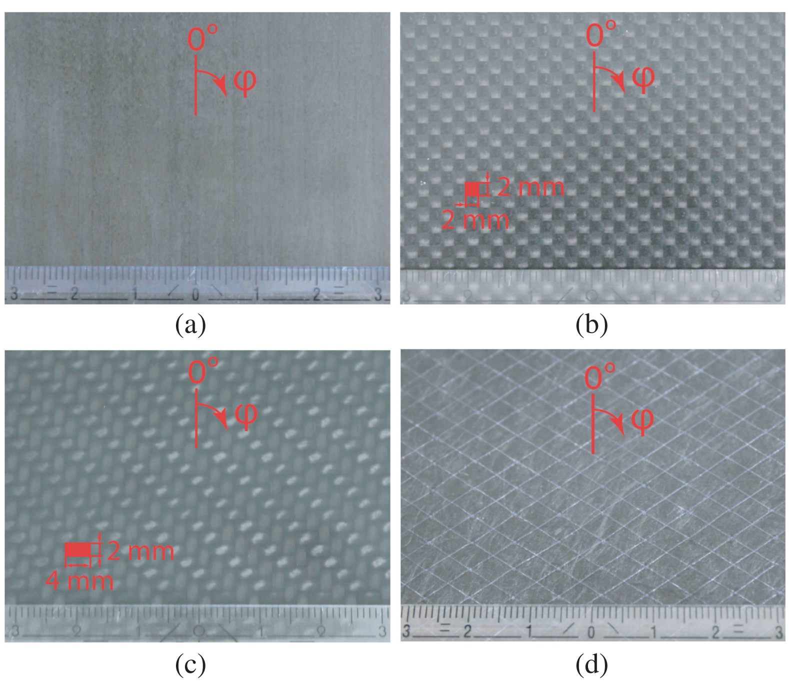


Figure 1. Photographs of the investigated CFRP: (a) unidirectional fiber alignment, (b) plain weave, (c) twill weave and (d) fiber shreds in random alignment on top. All ruler dimensions are in centimeter.

plain-CFRP, twill-CFRP and shred-CFRP, respectively. As reference, measurements are repeated with an aluminum sheet and an FR4 laminate with a copper layer. Aluminum without surface treatment is used. The FR4 material is a Panasonic 104 laminate that is usually used for printed circuit board production. Its copper plating has a thickness of 17 µm. All materials under test (MUT) are cut to discs of 280 mm diameter by water-jet.

The UD-CFRP has all fibers aligned towards $\varphi = 0°$. The plain-CFRP has an elementary cell size of its characteristic checker-board pattern of about $2 \times 2\,\mathrm{mm}^2$. The twill-CFRP is a 2/2 twill-weave with a pattern size of about $2 \times 4\,\mathrm{mm}^2$. The geometries of the plain- and twill-CFRP are within the same order of magnitude as the free space wavelength of approximately 5 mm. The laminate's plies are stacked as [0 90]. For the plain- and twill-CFRP a zero direction $\varphi = 0°$ is defined according to Figs. 1(b)–1(c). The shred-CFRP has shredded fiber strands of about 10 mm length in random alignment on its top layer. For shred-CFRP $\varphi = 0°$ is arbitrarily defined. The UD-CFRP, plain-CFRP and twill-CFRP are commercially available.

3. MEASUREMENT SETUP

The reflectivity of CFRP is measured at 60 GHz. For this purpose, the MUT is illuminated by a conical horn antenna. The electromagnetic wave is reflected by the MUT, and received by an identical horn antenna. Both horn antennas are co-aligned perpendicular to the MUT surface as a mono-static setup. The horn antennas' orientation is chosen such that the electric field vector coincides with MUT orientation $\varphi = 90°$. In order to measure the angle dependency of the MUT's reflectivity, the MUT is rotated in φ, indicated in Fig. 2(a).

As transmit and receive antennas, conical horn antennas with a narrow 3 dB opening angle of approximately 18° are used. The distance between the antennas and the MUT is chosen as 55 cm; the MUT is then in the far-field. Due to the horn antenna's opening angle, the energy is focused on the disc at this distance. The MUT disc is placed on a polymeric fixture and backed by pyramidal absorbers, see Figs. 2(b) and 2(c). Undesired reflections with the surrounding environment are thereby avoided.

The transmit signal is generated as shown Fig. 2(a). An arbitrary waveform generator (Keysight M8195A) produces a 1 GHz wide baseband sequence. The baseband sequence is a low crest factor multi-tone signal with Newman phases [28]. This baseband signal is up-converted with an external module (Pasternack PEM001) that includes a synthesizer phase-locked loop (PLL) and uses a 285.714 MHz reference signal. The transmitted signal is centered at $7/4 \cdot 120 \cdot 285.714\,\mathrm{MHz} = 59999.94\,\mathrm{MHz} \approx 60\,\mathrm{GHz}$, where $7/4 \cdot 120$ is the scaling factor of the PLL counters.

A spectrum analyzer (R&S FSW67) is employed as receiver. It obtains and stores IQ samples from the received signal. Multiple, consecutive received multi-tone signals, for fixed φ, are coherently averaged to achieve a processing gain of 33 dB [28]. The receive power $P(\varphi)$ is the sum power of all tones. The arbitrary waveform generator and the reference clock for the PLL are all synchronized to the 10 MHz reference of the FSW67.

4. MEASUREMENT RESULTS

The transmit power is 7 dBm, which results in a received power of about −25 dBm depending on the used material. To allow comparison of all materials in one plot, the receive power is normalized to the mean received power for each MUT, i.e., $P(\varphi)/\mathbb{E}\{P(\varphi)\}$, where $\mathbb{E}\{\cdot\}$ denotes the expectation operator. Losses in the MUTs are therefore not visible in the results. For measurements of losses in the composite other methods are at hand, for example [25].

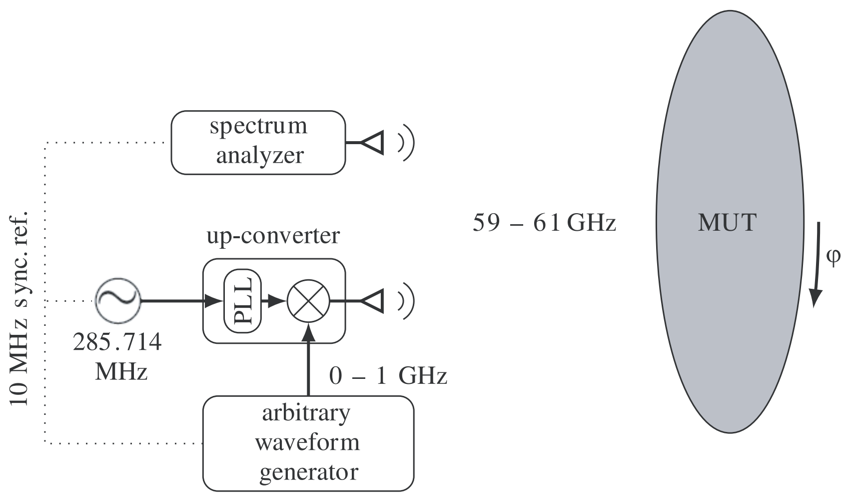
The normalized reflected power is shown in Fig. 3 as a function of MUT orientation. Reflectivity of the four investigated CFRP is shown together with the reflectivity of the aluminum and the FR4 reference material. Two full rotations of the MUT discs are performed as an estimate for angular positional precision; the second rotations are shown in lighter shades. The total measurement precision is 0.6 dB, as described in Section 5.

As a measure of anisotropy we take the difference between the maximum relative receive power and minimum relative receive power over both rotations.

The first observation from the measurement results in Fig. 3 is that the UD-CFRP is anisotropic. With the electric field vector in fiber direction (90° and 270°) the reflectivity is 4.8 ± 0.6 dB higher than perpendicular to fiber direction (0° and 180°). This finding is aligned with previous measurements [12, 13, 25, 26]. The anisotropy of CFRP with unidirectional fiber alignment is well known and described for the frequency ranges 10 kHz–10 GHz in [12], 8–12 GHz in [13] and 110–200 GHz in [25, 26]. Note, all prior works measured only in fiber direction and perpendicular to fiber direction. This contribution confirms the anisotropy of UD-CFRP for 60 GHz millimeter wave transmission in steps of 1°.

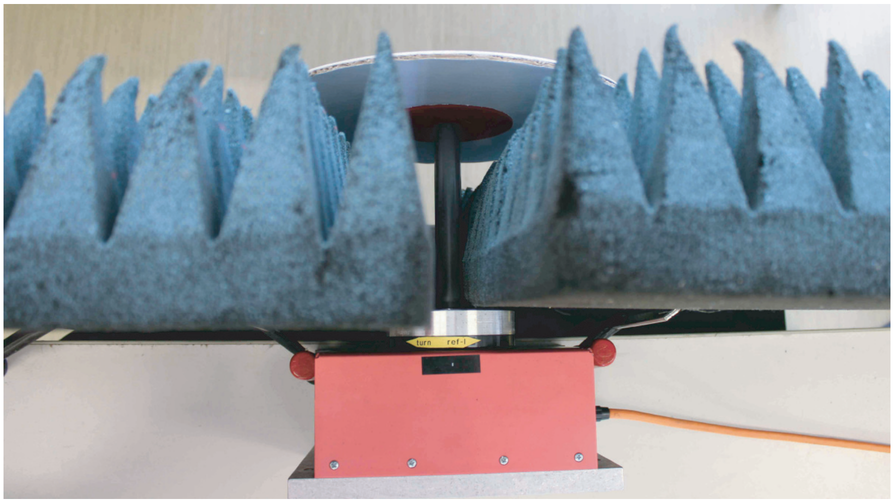
The second observation is that the twill-CFRP and the copper-plated FR4 show slight variations of reflectivity over turn angle. The maximum deviation of the received power is 1.2 dB for the FR4 and 1.5 dB for the twill-CFRP. Both values are significant as they are larger than the measurement precision. We characterize the twill-weave CFRP as anisotropic at 60 GHz and estimate the anisotropy as 1.5 ± 0.6 dB for mono-static setups. This classification is further motivated by grating effects of twill-weave CFRP at 60 GHz in bi-static setups [27].

On the contrary, the plain-weave CFRP and the CFRP with fiber shreds are identified as isotropic reflector materials at 60 GHz. The variations in reflectivity of the plain-CFRP and shred-CFRP are 0.8 ± 0.6 dB and 0.6 ± 0.6 dB, respectively. The isotropic reflectivity of shred-CFRP is aligned with the isotropic conductivity at 6 GHz [14]. Reference measurements with aluminum show a variation in receive power of 0.6 ± 0.6 dB.



(a)

(b)



(c)

Figure 2. Schematic and photograph of the measurement setup. (a) Schematic: The transmitter is built with an arbitrary waveform generator as baseband signal generator and an external up-converter module. A spectrum analyzer is used as receiver. All units are synchronized. (b) Photograph: The transmit horn antenna is aligned to the turning MUT disc, which reflects the wave back to an aligned receive horn. The MUT disc is backed by absorbers. (c) Close-up of polymeric disc fixture and rotation table (top view).

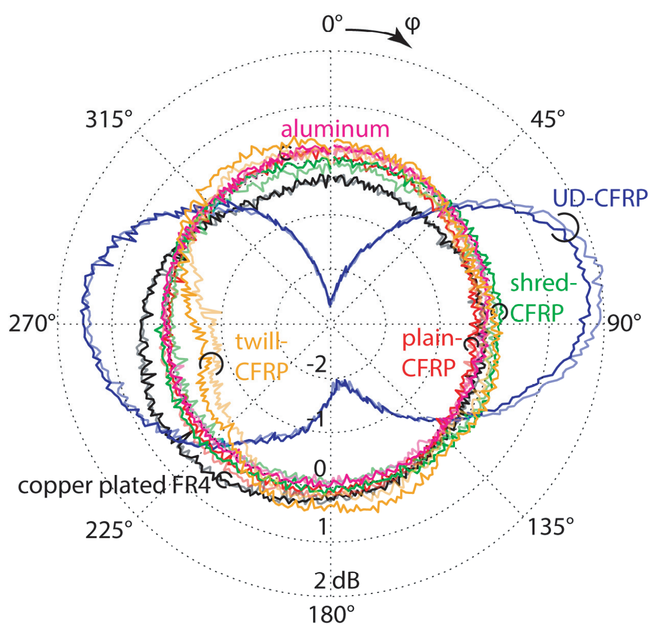


Figure 3. Measured reflectivity of MUTs dependent on φ at $f = 60\,\text{GHz}$. The curves' mean received powers are normalized.

5. MEASUREMENT ACCURACY

The measurement accuracy of our setup is determined by two experiments.

Firstly, the reflectivity at a fixed orientation was measured over a long time ($> 12\,\text{h}$). This reveals the RF setup's temperature dependence. Although the room temperature is controlled by air-conditioning, the temperature swings within a range of 1.5 K. The measured variation in the

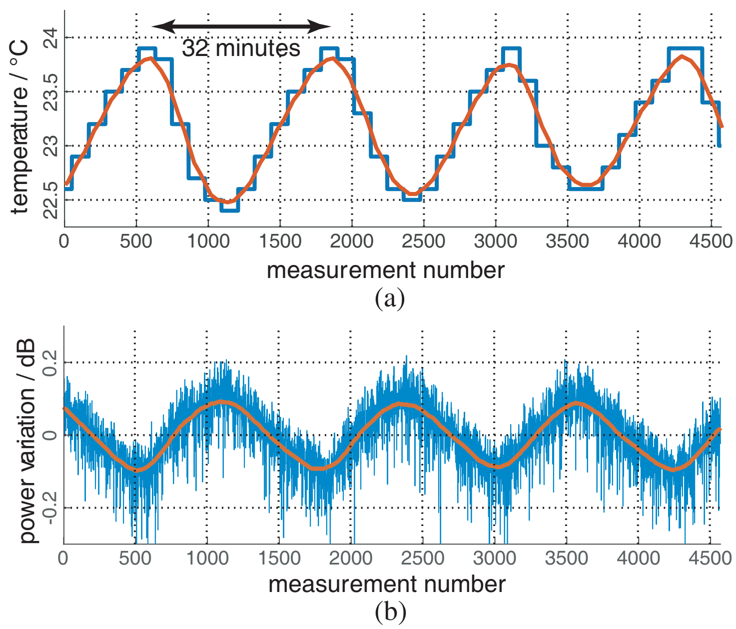


Figure 4. Measurements of room temperature influence on the measurement setup. Blue curves show raw measured quantities, while red curves show a sliding average over 300 measurement points. (a) Room temperature deviation. (b) Measured received power at fixed angle.

room temperature, over a period of about two hours, is shown in Fig. 4(a). The air-conditioning unit's controller results in a temperature cycle of about 32 minutes duration. Measurements show a deterministic relationship between room temperature and variation in received signal power, see Fig. 4(b). With our setup it takes 20 minutes to measure two full turns of one MUT, which is in the same order of magnitude as the temperature cycle duration. Therefore, room temperature variations cause measurement uncertainties in the received power of ± 0.1 dB, see red curve in Fig. 4(b). Additionally to the slow change in received power due to room temperature variation, we observe an uncertainty due to receiver noise of approximately ± 0.1 dB (Fig. 4(b) shows all temperature effects simultaneously).

Secondly, to determine the mechanical precision, i.e., the effect of sample placement and tilt, the disc was removed and again attached between measurements. Mechanical precision of the setup adds ± 0.1 dB uncertainty.

Each measured point has thus an uncertainty of ± 0.3 dB. Our definition of anisotropy as difference leads to a worst case inaccuracy of ± 0.6 dB.

6. CONCLUSION

We have determined anisotropy values for different carbon fiber reinforced polymer (CFRP) laminates at 60 GHz. The unidirectional CFRP shows 4.8 dB higher reflectivity in fiber direction than perpendicular to the fibers. The anisotropy of twill-weave CFRP is 1.5 dB, and twill-CFRP is classified to be anisotropic as well. Both, plain-weave CFRP and CFRP with about 10 mm long fiber shreds in random alignment on the top layer, show isotropic reflectivity within measurement accuracy.

For most applications, such as antenna reflectors, isotropic reflectivity is desired. Among the investigated laminates, shred-CFRP and plain-weave CFRP are identified as suitable materials. The performed measurements highlight shred-CFRP as reflector material for millimeter wave applications. Shred-CFRP has both the least measured anisotropic reflectivity and the shredded fibers are obtainable from recycling [29].

The isotropic characteristics of CFRP for millimeter waves also motivate their application outside of mechanical engineering for antenna applications and waveguides. Alignment of anisotropic CFRP car parts influences the radar cross section for millimeter wave automotive radar.

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