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THE EFFECT OF PLY ORIENTATION ON THE PERFORMANCE OF ANTENNAS IN OR ON CARBON FIBER COMPOSITES

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Abstract—In this paper, the anisotropic conductivity effect of quasi-isotropic carbon fiber laminates on conformal load-bearing antenna structures (CLAS) is presented. The conductivity of a quasi-isotropic IM7/977-3 CFRP laminate is measured using waveguide techniques. The results show that orientation of the surface ply relative to the polarization of the incident E-field has a major influence on the reflectivity. This difference is attributed to the fact that carbon fibres oriented parallel to the E-field plies behave as good conductors, while off-axis plies present as lossy dielectric layers with a finite conductivity. This anisotropic behavior of the ply layers is shown to have a distinctive influence on the operation of both microstrip patch and slot antennas.

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1. INTRODUCTION

The ever increasing number of Carbon Fiber Reinforced Polymer (CFRP) applications has stimulated vast interest towards the use of CFRP for antenna applications, and thus the characterization of the electromagnetic performance of CFRP composites. In particular the potential use of CFRP in conformal load-bearing antenna structure (CLAS) technology for military and commercial aircraft has gained momentum [1, 2].

Unlike any homogenous materials, CFRP has complex electromagnetic characteristics due to it intricate microstructure. The electrical characteristics of CFRP are highly dependent on the ply stacking sequence as well as the fabrication technique used. For aerospace applications, ply stacking sequences typically involve a combination of three ply angles: 0°, ±45°, and 90°, where the angles are relative to main loading direction of the applied load. The basic constitute of laminated composites is the unidirectional (UD) ply, as shown in Fig. 1(a). The carbon fibers in a single ply are oriented in one direction and the laminate has the maximum possible stiffness and strength in that direction. However, UD laminates possess very poor mechanical properties in all other directions, thus it is considered good design practice to include at least 10% of plies in each of the 45°, −45° and 90° directions. One special case is the QI laminate, referring to Fig. 1(b), where there are equal numbers of plies in each of the 0°, 45°, 90° and −45° directions.

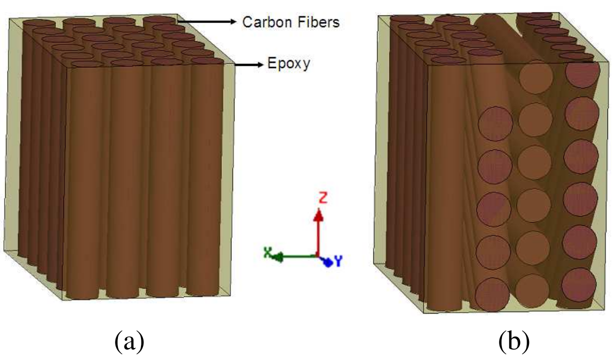


Figure 1. (a) 4 ply UD CFRP, (b) 4 ply Quasi-isotropic layup representatively showing fiber direction.

The conductivity of the UD CFRP panels has previously been discussed in the literature [3–8]. It is reported that the conductivity of UD CFRP panels (Fig. 1(a)) is high in the direction of the fibre orientation, and is low transverse to fibers where it shows lossy dielectric characteristics. These dielectric characteristics are highly dependent on the epoxy used and the fiber dimensions. In contrast to this, QI panels (Fig. 1(b)) are shown to have high conductivity in all directions [7].

In this paper, we present an experimental investigation on the electric characteristics of UD and QI laminates and the effects of ply orientation on CFRP antennas. It will be shown for the first time that despite the layup sequence the QI laminates have an anisotropic conductivity, being higher in the direction of the fibers of the first ply (Z direction in Fig. 1(b)). This phenomenon is explained by analyzing the individual plies of a QI panel as a stack of conductive and lossy dielectric layers. It is shown that UD laminates are highly conductive in the direction of the fibers (Z direction in Fig. 1(a)), and they act like a lossy dielectric transverse to fibers (Y direction in Fig. 1(a)). This anisotropic characteristic of QI laminates has a significant effect on the RF performance of antennas made out of or mounted on CFRP panels. These effects are examined, measured and explained.

2. CONDUCTIVITY MEASUREMENTS OF CFRP

There are many methods of measuring the electromagnetic (EM) characteristics of a material [7–13]. A common method for measuring the conductivity is the electrode plates method. In this method the resistance of a sample held between two electrode plates is measured then divided by the sample cross-sectional area. For this method to be effective for CFRP a perfect physical connection is required between the electrode plates and the fibers [6, 11]. This means that the epoxy should be removed from the electrode area. This would introduce an error in the measurements because the epoxy is a lossy dielectric and the effects of its losses on the conductivity should be considered. Here, the waveguide technique is used to measure the EM characteristics of CFRP [8, 9]. Because the EM field is linearly polarized in the waveguide the anisotropic characteristics of the material can be measured. Two 15 cm lengths of WR-90 waveguide are connected together, then to a Wiltron 360B vector network analyzer (VNA) and the setup is calibrated with an LRL calibration procedure over X-band.

The carbon fiber under test is the Cytec IM7/977-3 prepreg tape [14] which was cured in an autoclave in accordance with the manufacturers recommended conditions (177°C @ 586 kPa for 6 hours). The fibers are around 5 μm in diameter (Fig. 2(a)). For a fiber volume fraction of 60% each ply will contain 25–30 fibers (see Fig. 2(b)) with a gap between the fibers of 1–3 μm. Due to the small fiber

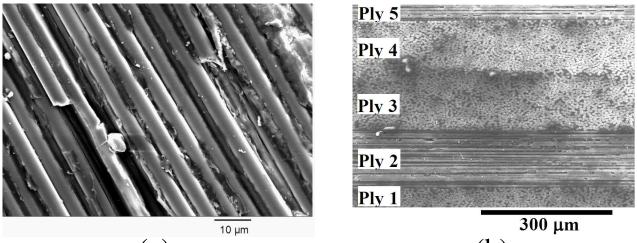


Figure 2. (a) Top view of unidirectional carbon-fibers in epoxy. (b) Side view of a QI laminate.

dimensions numerical analysis at the fiber scale would be extremely computationally intensive. Hence this investigation was conducted purely using analytical and experimental techniques.

A UD CFRP panel was measured when the fibers were perpendicular and 45° to the E-field and the losses of the material were determined by analyzing the S_{11} and S_{12} using the Nicolson-Ross-Weir (NRW) method [12, 13]. Then the anisotropic conductivity of QI laminates was measured in the waveguide setup when the E-field was both parallel, and perpendicular, to the first ply. Differences in the results are explained using the measured losses from the UD laminate tests.

2.1. Waveguide Measurement of UD CFRP

It is well established that the conductivity of UD CFRP laminates is higher in the 0° fibre direction than the transverse 90° direction [4–8]. In this work we assume that when the E-field of the dominate mode (TE_{10}) is perpendicular or 45° to the fibers in the UD CFRP laminate, the material behaves as a lossy dielectric. The waveguide method is a common method of measuring the transmission and reflection signal of a material under test (MUT). Using the NRW equations, the permittivity (ε) and permeability (μ) can be separated into their real and imaginary components. The reflection coefficient can be defined by Eq. (1) [12, 13].

$$\Gamma = x \pm \sqrt{x^2 - 1} \tag{1}$$

where x can be found from Eq. (2),

$$x = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{2}$$

The propagation factor is given by Eq. (3),

$$\frac{1}{\Lambda^2} = -\left(\frac{1}{2\pi d}\ln\left(\frac{1}{P}\right)\right)^2 \tag{3}$$

where P can be found from Eq. (4).

$$P = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{4}$$

Finally, the complex permittivity and permeability can be calculated from Eqs. (5) and 6 respectively.

$$\mu_r = \frac{1+\Gamma}{\Lambda(1-\Gamma)\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \tag{5}$$

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left(\frac{1}{\lambda_c^2} + \frac{1}{\Lambda^2}\right) \tag{6}$$

where d is the sample thickness, λ_c is waveguide cut-off frequency (6.55731 GHz for WR-90) and λ_0 is the wavelength in free space at the measurement frequency.

Eight 10 cm × 10 cm plies of Cytec IM7/977-3 prepreg tape were laid-up with a UD $[90]_{8s}$ stacking sequence, vacuum bagged then cured [14]. The final panel thickness was 1.04 mm. This panel was then cut to 1.016 cm × 2.286 cm rectangle test coupons to fit inside the WR-90 waveguide. One specimen had fibers perpendicular to the short wall and one had fibers at 45° to the short wall. These were denoted E-Per and E-45 respectively. Measurements were not made in the E-Par (fibers parallel to the short wall) orientation because this illumination produced an almost perfect reflection ($|S_{11}| = 1.00$, $|S_{21}| = 0.00$). The magnitude and phase of S_{11} and S_{21} in the E-Per and E-45 orientations are shown in Fig. 3(a) and Fig. 3(b) respectively. The material exhibits a partial reflection, so it can be considered to be a lossy dielectric with the imaginary component of ε (ε_r'') representing the losses. These tests were repeated on UD laminates of different thicknesses and the reflection coefficients found to be independent of specimen thickness.

Using the NRW equations, the permittivity (ε) and permeability (μ) were separated into their real and imaginary components. As there are no magnetic components in the material, the relative permeability is approximately 1 + 0j for E-Per. The real and imaginary components of ε_r were calculated and are shown in Fig. 3. The results show that the IM7/977-3 $[90]_8$ laminate in E-Per orientation may be considered

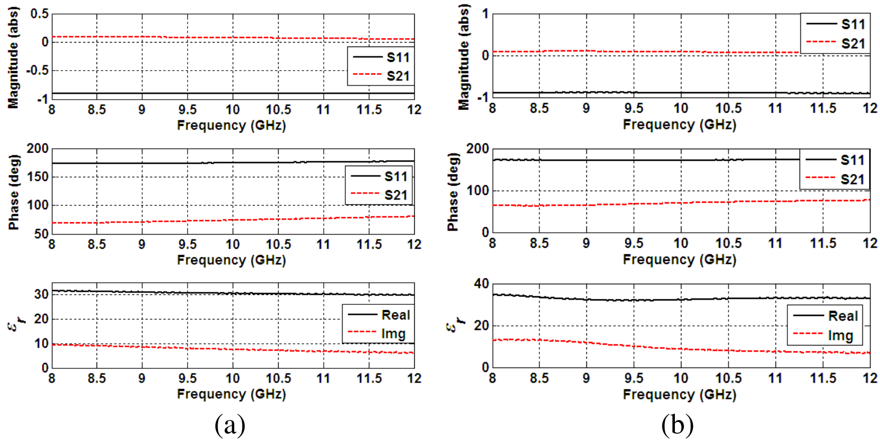


Figure 3. Electrical behavior of a 8 ply UD IM7/977-3 CFRP laminate (a) E-Per, (b) E-45.

to be a homogenous dielectric layer with a relative permittivity ε_r of approximately 30 (varies between 31.4 to 29.7) and loss tangent of about 0.24 ($\varepsilon_r = 30 + 7.4\text{j}$) over the X-band. For the E-45 orientation the ε_r was approximately 33 (varies between 34.4 to 31.7) with a loss tangent of about 0.3 ($\varepsilon_r = 33 + 9.84\text{j}$). This observation will be used to explain the anisotropic characteristics of QI laminates in the next section.

2.2. Waveguide Measurement of QI CFRP

The conductivity of the QI laminates was measured in two orientations to the incident E-field, parallel to the fibers in the first ply (E-Par) and perpendicular to the first ply fibers (E-Per). Eight 35 cm × 35 cm plies of Cytec IM7/977-3 prepreg tape were laid-up with a QI $[0\ 45\ 90\ {-45}]_{2s}$ stacking sequence, vacuum bagged then cured, achieving a final panel thickness of 1.04 mm. The panel was then cut with a water cooled diamond saw to 6 cm × 6 cm square test specimens.

The CFRP specimens were clamped between the two WR-90 waveguide sections in the E-Par and E-Per orientations and the reflection/transmission measured across the X-band. This method in combination with a trial-and-error based Microwave Studio software simulation is used in [8] to determine the conductivity of carbon nanotube impregnated carbon fiber composites. In this paper, surface resistance theory is used to calculate the conductivity instead of estimation via simulation software. The results for $|S_{11}|$ are shown

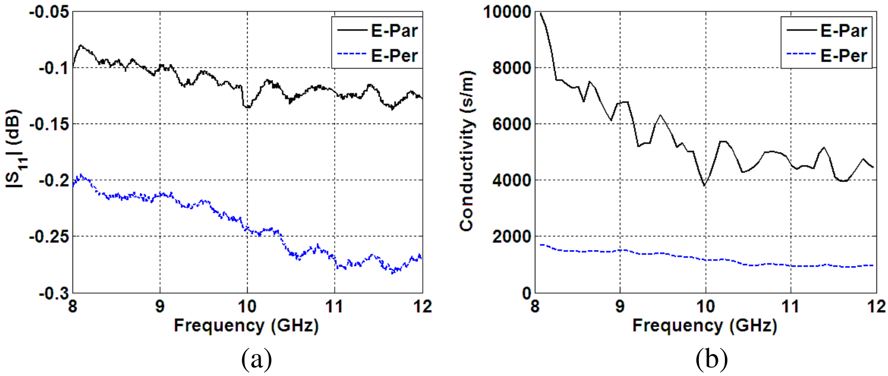


Figure 4. Effect of frequency on (a) S_{11} and (b) conductivity derived from $|S_{11}|$ using [16], for an IM7/977-3 $[0\ 45\ 90\ -45]_{2s}$ laminate.

in Fig. 4(a). Although the results are very close to 0 dB, there was a detectable difference in $|S_{11}|$ for the two orientations[†]. $|S_{21}|$ is not shown because it was less than the sensitivity of the test equipment.

The measurements ($|S_{11}| \approx 1.00$ and $|S_{21}| \approx 0.00$) represent almost total reflection. This occurs when the thickness of the MUT is larger than skin depth and it is considered to be a good conductor rather than a lossy dielectric. In this case, the imaginary part of permittivity ($\varepsilon = \varepsilon' - \mathrm{j}(\varepsilon'' + \sigma/\omega)$) is dominated by the conductivity term. The NRW equations cannot be used due to a lack of transmission, so the relationship between conductivity (σ) and reflection coefficient is derived from the surface resistance [9], as given by Eq. (7),

$$\sigma = 4\pi\mu_0 f \frac{\left(1-|S_{11}|^2\right)^2}{Z_0^2\left(\left(1+|S_{11}|^2\right)-\sqrt{-|S_{11}|^4+6|S_{11}|^2-1}\right)^2} \tag{7}$$

where μ_0 is the permeability of free space, f is the frequency and Z_0 is the intrinsic impedance of free space.

The measurements in Fig. 4(a) were processed using Eq. (7) and the resulting conductivity is presented in Fig. 4(b). The reasonably low conductivity measured could be due to the $|S_{11}|$ measurement accuracy the VNA equipment. Theoretically, the difference in $|S_{11}|$ for conductivities obtained by Eq. (7) of 50,000 S/m and 10,000 S/m at 8 GHz is less than 0.04 dB (see Fig. 5(a)), which is approximately

† The accuracy of the VNA is to two decimal places (in dB).

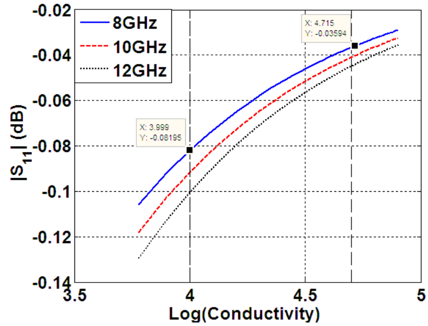


Figure 5. The theoretical relation between $|S_{11}|$ and conductivity according to Eq. (7).

the accuracy of the VNA [15]. This limitation applies for waveguide conductivity measurements, but waveguide techniques are still the most suitable method for evaluating conductivity of anisotropic materials.

The results in Fig. 4(b) confirm the difference between conductivity of QI CFRP in E-Par and E-Per orientations is noticeable. In the E-Per orientation the first two plies (90° and 45°) act as lossy dielectrics with loss tangent of 0.24 and 0.3 respectively, while the third ply presented a reflective surface to the incident wave. In the E-Par orientation the first ply primarily reflected the incident wave, and hence suffered less losses caused by the lossy dielectric layers. The effect of this anisotropic behavior on antennas will be examined in the next section.

3. THE EFFECT OF A CFRP GROUND PLANE ON AN ANTENNA

The effects of multilayer composites on patch antenna performance have been investigated previously (for example, [16, 17]). In this section, the influence of the anisotropic properties of QI CFRP laminates on antennas will be investigated for the first time. Initially, the behavior of a patch antenna with a CFRP ground plane will be examined. Then the effects of carbon fiber ply orientation on the performance of slot antennas cut into CFRP will be investigated.

3.1. Patch Antennas on CFRP Ground Planes

Two rectangular microstrip patch antennas with a length (L) of 10.98 mm and width (W) of 13.18 mm were made on a 0.254 mm

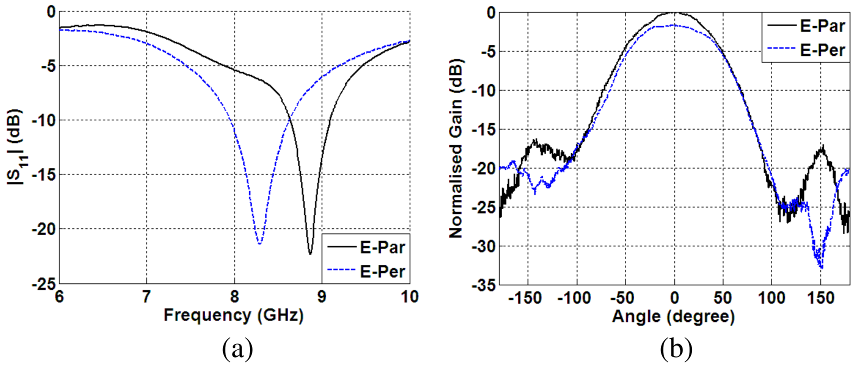


Figure 6. (a) $|S_{11}|$ of microstrip patches on CFRP and (b) the normalised radiation patterns in both the E-Par and E-Per configurations.

thick Rogers RT/duroid 5880 substrate. The patches were fed with a microstrip line of width 1.55 mm which was inset 2.98 mm into the patch. The conductor was removed from the reverse side of the substrate, and the patches were mounted on a QI CFRP panel, which acts as the ground plane. One patch was placed with its polarization in line with the fibres of the first ply (E-Par) of the CFRP ground, and the other was orthogonal (E-Per). The S_{11} was measured between 8 and 12 GHz for both patch antennas (Fig. 6(a)), and the radiation patterns were measured at the resonant frequency of the patch (Fig. 6(b)). The gain was also calculated in comparison to a known horn antenna. The S_{11} measurements of Fig. 6(a) show that there is an approximately 800 MHz (or just under 10%) shift in the resonant frequencies of the two antennas. This is consistent with the theoretical predictions, since an increase in both the relative dielectric constant and height of a substrate in the E-Per case (as the first two layers appear to be a high permittivity lossy substrate) would result in a lower resonant frequency of a microstrip patch. This frequency shift could be very beneficial as it would allow the patch dimensions to be reduced by almost 10% aligning the patches in the E-Per configuration. However, the antenna gain for the E-Per orientation is also lower than the E-Par case.

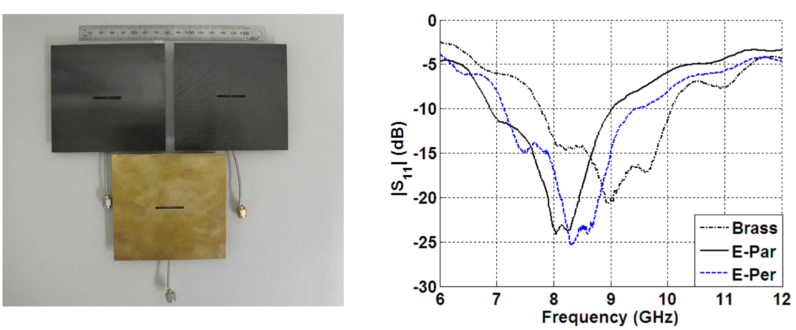
The radiation patterns of both antennas (Fig. 6(b)) display the characteristic shape of a standard rectangular patch showing that the CFRP panel is acting as a ground plane in establishing a transmission cavity, and to direct and block the back radiation. The measured results show that there is a 1.7 dB difference between the gain of the E-Par and the E-Per oriented antennas. These results confirm the anisotropic evaluation of QI CFRP from Section 2.

3.2. CLAS CFRP Slot Antenna

Two 10 cm × 10 cm panels of CFRP were cut from a Cytec IM7/977-3 laminate with a QI $[0\ 45\ 90\ -45]_{2s}$ stacking sequence. A 2 mm wide × 25 mm long slot was cut in the middle of both these panels. One of the antennas had the slot E-field (across the short axis of the slot) parallel to fibres in the surface ply (E-Par), while the other was perpendicular (E-Per). A slot antenna with the same dimensions cut into a 0.52 mm thick (larger than skin depth) brass ground plane was also manufactured for comparison (see Fig. 7(a) for a picture of the three slot antennas).

The measured $|S_{11}|$ results for the three antennas are shown in Fig. 7(b). The resonant frequency of both CFRP antennas was lower than that of the brass antenna because the highly conductive carbon fibers are covered by a thin layer of epoxy dielectric ($\varepsilon_r = 3.2$ [14]). This layer of dielectric reduces the resonant frequency in CFRP slot antennas. Fig. 7(b) also shows that the resonant frequency in E-Par orientation is lower than for E-Per. This appears to contradict the results of the patch antennas on a CFRP ground plane.

It is anticipated that the outer two plies in the E-Per orientation would act as a lossy dielectric and so this orientation should have lowered resonant frequency. This is not observed. The reason for this apparent contradiction lies in the way that slots radiate. Fig. 8 shows the current and E field differences between a slot antenna and dipole antenna. In slot antennas, a magnetic current is excited. Therefore, the accompanying current is perpendicular to the E-field produced in the slot, whereas in the free space permittivity test the E-field and



(a) (b)

Figure 7. (a) A photograph of the slot antennas (brass and both orientations of CFRP). (b) The $|S_{11}|$ of all three antennas.

Table 1. Slot antenna results.

Antenna	Frequency (GHz)	Normalized 0°	Gain (dB) 180°	Weight (g)
Brass	8.5	0	−0.5	48.3
E-Par	8.5	−4	−2.8	20.8
E-Per	8.5	−0.5	−1.9	20.8

induced current are in the same direction. So, the current in the slot antennas with the E-field perpendicular to the first ply is actually parallel to the fibers. Consequently it does not significantly experience the lossy dielectric. This means we should also expect more loss in the E-Par oriented slot than the E-Per slot.

The measured H-plane radiation patterns of the E-Par and E-per slot antennas at 8.5 GHz are plotted in Fig. 9 in comparison to the brass slot antenna. It is observed that the gain of the slot antenna in the E-Par orientation is 3.5 dB lower than the E-Per orientation slot in the 0° (broadside) direction, and 0.9 dB lower in the 180° direction. The discrepancy between front and back radiation indicated in Fig. 9(a), is due to presence of the feeding cable on the back side of antenna. For the E-Per case, the broadside gain is much closer to level of the brass slot (Fig. 9(b)). A summary of the gain results is presented in Table 1. The excitation efficiency and radiation efficiency can be evaluated by considering the $|S_{11}|$ and gain results. The input impedance of an antenna at resonance consists of radiation resistance and loss resistance. The $|S_{11}|$ results show that all antennas are matched (SWR < 2) to the transmission line at 8.5 GHz, therefore, 83% (or better) of energy has been transferred from cable to the antennas. The radiation efficiency of an antenna is the ratio of gain to directivity. The same physical dimensions of the antennas and similarity in radiation pattern shape in Fig. 9 indicate that the directivity of the antennas is similar, so the change in gain provides a good indicator of the radiation efficiency of the slot antennas, and consequently the losses.

The cross polarization level is similar between CFRP and brass slot antennas. Finally, the similar gain/efficiency for the brass and CFRP antennas (in E-Per orientation) indicates that at high frequencies (such as X-band) the conductivity of CFRP is sufficient for CLAS antennas with reasonable efficiency. The density of brass is 8.4–8.7 $\text{kg}\,\text{m}^{-3}$ while CFRP is in the order of 1.2–1.6 $\text{kg}\,\text{m}^{-3}$. Clearly producing antennas from CFRP would result in massive weight savings. Also bonding issues between a CFRP aircraft body and traditional metallic antennas can be avoided by using fully CFRP antennas.

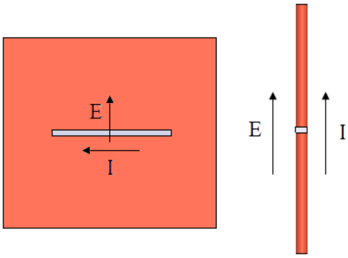


Figure 8. The current and *E*-field in a slot and dipole antenna.

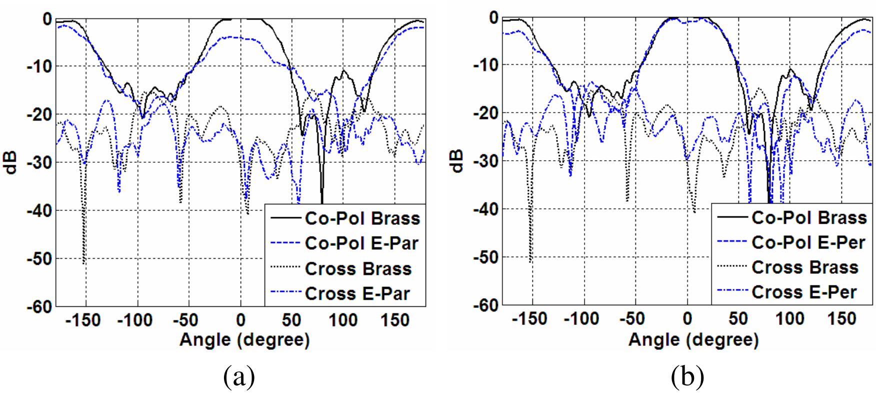


Figure 9. The normalised *E*-plane radiation patterns of the (a) E-Par and (b) E-Per CFRP slot configurations compared to the brass slot antenna.

4. CONCLUSION

The anisotropic electromagnetic properties of quasi-isotropic carbon fibre reinforced polymer have been measured and presented. It was shown that QI laminates are more conductive in the direction of the fibers of the first ply than in the transverse direction. The conductivity was measured using waveguide techniques and surface resistance theory. The anisotropic conductivity is explained by measuring the losses in UD laminates when the fibers are 90° and 45° to the incident wave. It was shown that the UD laminates act as lossy dielectrics with permittivities of 30 + 7.4j in the 90° and 32 + 9.4j in the 45° directions. Then the influence of this anisotropic characteristic on patch and slot antennas was evaluated. A 10% variation in the resonant frequency and 1.7 dB difference in gain was observed from two identical patch antennas simply by changing the orientation of the

QI CFRP ground plane. Slot antennas cut into a QI CFRP laminate also displayed significant dependence on the orientation of the carbon fibers in the surface ply. Despite the lower conductivity measurement of QI CFRP when the incident E-field is perpendicular to the fibers in the first ply, a slot antenna in this orientation has a higher gain (up to 3.5 dB higher) than the parallel orientation. This phenomenon is explained by the current distribution in a slot antenna relative to the fiber stacking sequence. It is also concluded that the conductivity of a QI CFRP laminate in E-Per is high enough to produce a similar radiation efficiency to a brass slot antenna.

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