Progress In Electromagnetics Research C, Vol. 25, 107–118, 2012

A FREQUENCY SELECTIVE POLARIZER USING CARBON FIBRE REINFORCED POLYMER COMPOSITES

A. Galehdar[1, *], W. S. T. Rowe[1], K. Ghorbani[1], P. J. Callus[2], S. John[3], and C. H. Wang[3]

[1]School of Electrical and Computer Engineering, RMIT University, Melbourne 3001, Australia

[2]Defence Science and Technology Organisation, Air Vehicles Division (DSTO-AVD), Melbourne 3207, Australia

[3]School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne 3001, Australia

Abstract—Unidirectional carbon/epoxy composite laminates are highly orthotropic, with their conductivity and permittivity being strongly dependent on the incident angle relative to the fibre orientation. This paper presents a novel frequency selective polarizing subreflector manufactured from unidirectional carbon fibre reinforced polymer (CFRP), placed a certain distance from a conducting ground also made from CFRP laminate. Theoretical analysis, computational simulation, and experimental measurements are conducted to investigate the effects of separation offset, laminate thickness and incident angle on the performance of a reflector manufactured from a unidirectional IM7/977-3 CFRP. The results show that this new reflector reduces the cross polarization at S-band by 13 dB while remaining a good reflector at X-band and the incident angle has minimal effect on the frequency response of the polarizer. The single reflector can support two orthogonal polarized frequencies, unlike traditional wire grid polarizer screens.

Received 26 September 2011, Accepted 3 November 2011, Scheduled 10 November 2011
* Corresponding author: Amir Galehdar (amir.galehdar@rmit.edu.au).

1. INTRODUCTION

Reflector antennas have become one of the most commonly known radiators since their application in deep space communication, and moon explorations in the 1960's [1]. Subsequent demand for reflectors in radio astronomy, microwave communication, and satellite tracking has resulted in significant development of sophisticated analytical and experimental techniques in shaping reflector surfaces and optimizing illumination over their aperture. In recent years, advances in materials technology and increasing demand for weight reduction in space communication applications has led to the development of a new generation of light composite reflector antennas. Carbon fibre reinforced plastic (CFRP) was used as a reflector antenna for satellite communication. It was shown that the CFRP dish exhibited similar RF performance to that for a metallic dish [2].

Dual frequency feeding of a reflector antenna can maximize the communication capacity of the link. However, the cross polarization level of the feed can cause crosstalk and reduce the quality of the link, especially in offset feeds with sub-reflectors [3]. The smallest misalignment can cause a significant depolarization and increase in crosstalk. In [4], a grid polarizer was found to have the same field radiation as an offset curved reflector. Broadband cross polarization cancelation can be achieved by using two orthogonal grid polarizers with parallel spaced elements for different frequencies. Hence, two separate feeds are required for different frequency bands [4].

More recently, periodic surfaces have been used to design dichroic subreflectors which are transparent at one frequency and reflective at another. This enables one feed to be placed at the focal point of the main reflector, and another at the Cassegrain focal point [5]. In [6], a dichroic subreflector was designed for a dual frequency reflector antenna. Crossed dipoles were printed on a dielectric sheet to create a Frequency Selective Surface (FSS) subreflector which was highly reflective at Ku-band and transparent at S-band. In [7], circular rings were used to design a FSS dichroic subreflector for S-band and X-band. However, FSS subreflectors present two major issues for dual band reflector design. Firstly, the angle of incidence has a significant influence on the frequency response of the dichroic subreflectors, which complicates the design of offset feed antennas. Secondly, the FSS subreflectors increase cross polarization, and consequently the crosstalk in the dual frequency antennas. In [8], the full wave analysis of circular ring FSS elements embedded in a multilayer spherical supporting structure was presented. The FSS radome showed a stable intensity of the resonant frequency over a range of incidence angles.

This paper presents a new polarizing screen, consisting of a unidirectional (UD) CFRP panel placed at a certain distance from a perfect conductor. The high orthotropic conductivity and permittivity of a unidirectional CFRP enables the new FSS reflector to significantly reduce cross polarization of the reflected wave at one frequency, whilst reflecting the orthogonal polarization at another frequency. So unlike traditional wire grid polarizers, one screen can support two orthogonally polarized frequencies and consequently one feed can be used for both frequencies. One of the most significant advantages of this screen over traditional FSS's is that its performance and bandwidth are not dependent on the angle of incidence, making it a good candidate for the design of offset feed polarizing subreflectors. The theory, design and performance evaluation of CFRP FSS polarizer screens are presented in this paper.

2. THEORETICAL ANALYSIS

The design aim of a frequency selective polarizer is to match the impedance of free space to that of the polarizer, consisting of plies of unidirectional CFRP. This concept is similar to the Salisbury screen approach of placing a resistive sheet at an odd multiple of wavelengths over a highly conducting ground, usually separated by an air gap [9]. However, the proposed frequency selective polarizer differs from the conventional Salisbury screen in that the frontal layer, made of UD CFRP, is strongly orthotropic in its conductivity and dielectric properties, making it possible to reflect or absorb depending on the polarization and frequency of the incident wave.

To design such an absorber, the effective impedance of the screen should match the impedance of the incident medium. The characteristic impedance of CFRP layer can be determined using:

$$Z_{\mathrm{CFRP}} = Z_0 \sqrt{\frac{\mu_{\mathrm{CFRP}}}{\varepsilon_{\mathrm{CFRP}}}} \tag{1}$$

where the Z_0 is the free space impedance, and μ_{CFRP} and $\varepsilon_{\mathrm{CFRP}}$ are the permeability and permittivity of the CFRP. For an absorbing structure with a panel made of UD CFRP placed at a certain distance from a perfectly conductive surface, the effective input impedance at the front panel is given by:

$$Z_{in} = Z_{\mathrm{CFRP}} \times \left[\frac{Z_{is} + Z_{\mathrm{CFRP}} \tanh(j\theta_{\mathrm{CFRP}})}{Z_{\mathrm{CFRP}} + Z_{is} \tanh(j\theta_{\mathrm{CFRP}})}\right] \tag{2}$$

where

$$\theta_{\mathrm{CFRP}} = 2\pi t_{\mathrm{CFRP}} \left(\frac{f}{c}\right) \sqrt{\mu_{\mathrm{CFRP}}\varepsilon_{\mathrm{CFRP}}} \tag{3}$$

$$Z_{is} = jZ_0 \tan \beta_0 l_{is} \tag{4}$$

with Z_{CFRP} and t_{CFRP} denoting the characteristic impedance and thickness of the CFRP panel (Equation (1)), Z_{is} the input impedance of the short, l_{is} the distance between the CFRP panel and the conducting ground, θ_{CFRP} is a phase shift in the composite panel, and β_0 the wave number in free space. The reflection by this panel-ground structure can be calculated using:

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{5}$$

Using this theory and the characteristics of UD CFRP laminates, the impedance of free space can be matched to the CFRP in the polarization transverse to the fibre orientation, whilst maintaining high reflectivity in the fibre direction. This means:

$$\varphi = 0 \Rightarrow \Gamma(\text{across all bands}) = -1 \text{ or } 0\,\text{dB}$$
$$\varphi = 90 \Rightarrow \Gamma(\text{absorbing band}) = 0 \text{ or } -\infty\,\text{dB}$$

The theoretical, simulated and measured absorption characteristics of a CFRP Polarizer will be presented and compared in the following subsection.

The anisotropic or orthotropic conductivity of UD CFRP has been discussed at length in the literature [10, 11]. It has been shown that the conductivity is high in the direction carbon fibres (Z direction in Figure 1), which are highly conductive, and low transverse to the fibers (X Direction in Figure 1). In [11], the characteristics of UD

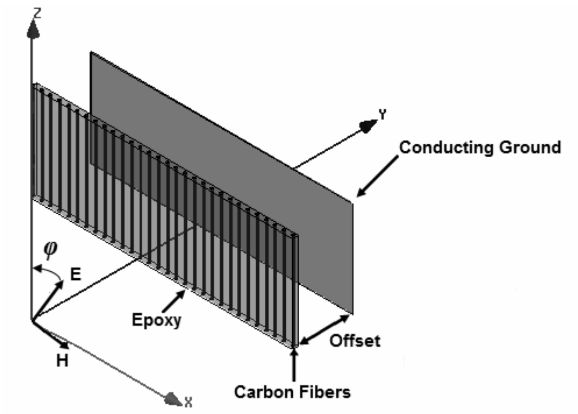


Figure 1. A novel frequency selective polarizer using carbon fiber composites.

CFRP laminates transverse to the fibers ($\varphi = 90$) were classified as a lossy dielectric, primarily due to the finite conductivity of the carbon fiber composites in the transverse direction, and the loss tangent was measured using a waveguide technique. This lossy dielectric characteristics is exploited here to minimize the reflection for the polarization transverse to fibers.

3. MEASUREMENTS AND SIMULATION RESULTS

In [11], it was shown that transverse to fibres the IM7/977-3 $[90]_8$ laminate can be considered as a homogenous dielectric layer with a relative permittivity ε_r of approximately 30 and loss tangent of about 0.24 ($\varepsilon_r = 30 - 7.4j$). These values are now used to design a frequency selective polariser. The theory, simulated and measured performance of the IM7/977-3 CFRP polarizer is evaluated, and the effects of material thickness and the incident angle are discussed.

3.1. Proof of Concept

A $50 \times 50\,\text{cm}^2$ 4-ply UD CFRP, i.e., the ply stacking sequence is $[0]_4$, IM7/977-3 laminate was laid up and cured in an autoclave in accordance with the manufacturers recommended conditions (177°C @ 586 kPa for 6 hours). The carbon fibers are around 5 μm in diameter. Each ply contains around 25–30 fibers through its thickness and the gap between the fibers is approximately 1–3 μm, which equates to a fiber volume fraction of 60% [12]. The cured thickness of the laminate was 0.59 mm. The laminate was cut into a 40 cm diameter disc and suspended above a 40 cm diameter Aluminium disc with a 1.0 mm air gap. The structure was placed in the free space test

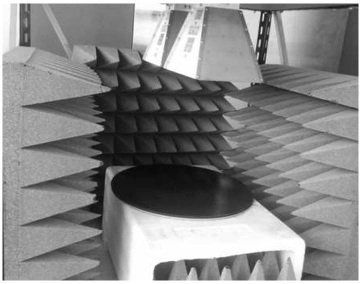


Figure 2. The free space test setup used for practical measurements. The horn antennas are 25 cm apart and the sample is 40 cm away from the aperture of the horns.

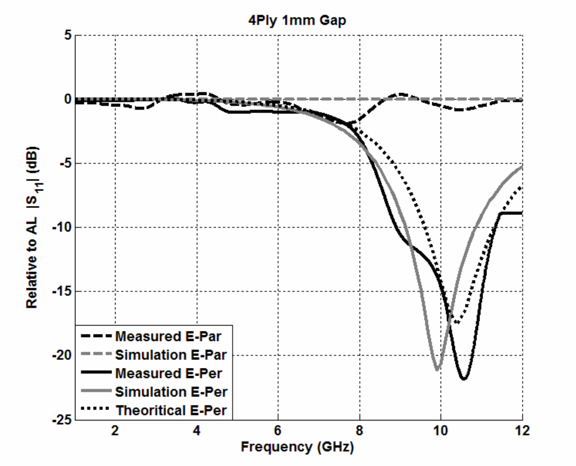


Figure 3. Measured and simulated E-Par reflection, and theoretical, simulated and measured E-Per reflection of a 4 Ply UD CFRP polarizer with 1 mm air gap.

setup as shown in Figure 2. Two identical linearly polarised double-ridged waveguide horn antennas were placed 25 cm apart surrounded by pyramidal absorbers and connected to a Wiltron 360B vector network analyzer (VNA). The system was calibrated with full 12 term calibration procedure to eliminate the cable losses. The free space setup was not calibrated, as the measurements taken are to be made relative to the Aluminium sheet. The CFRP structure was placed 40 cm away from the aperture of the horns. Reflections were measured for the cases where the incident E-field was perpendicular (E-Per) and parallel (E-Par) to the fibres in the UD laminate. The reflections were normalized to the reflection from the 40 cm diameter aluminium disc in order to show the relative reflection, and the results are presented in Figure 3.

Figure 3 shows that the E-Par orientation has a high reflection over the 1 to 12 GHz band due to its high conductivity. The measured reflection of CFRP was very slightly higher than that of aluminium at 4 and 9 GHz. This was expected to be an accuracy related consequence of the test setup, which was approximately 2 dB. This could have caused by close proximity of the horns or a multi path refection from the environment. In the E-Per orientation there was an absorption characteristic observed around 10 GHz due to the designed polarizer characteristics.

The theoretical reflection coefficient can be estimated using

Equations (1) to (5) by substituting the relative permittivity of the UD IM7/977-3 laminates in the E-Per direction ($\varepsilon_r = 30 - 7.4j$) and the air gap dimension (1 mm). The results are plotted in Figure 3.

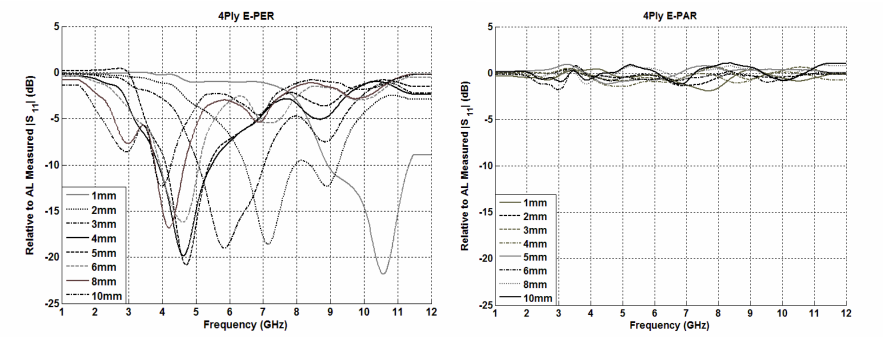
An HFSS [13] unit cell simulation with periodic boundary condition (Master-Slave) was also conducted to help validate the theoretical and measured results. The unit cell consisted of a 0.59 mm thick (thickness of 4-ply UD CFRP) anisotropic dielectric material ($\varepsilon_r = 30 - 7.4j$) with 35,000 S/m conductivity [11] in one direction (E-Par) and zero in the orthogonal direction (E-Per), suspended 1 mm above a conductive ground. The dielectric characteristics are dominated by the conductivity in the fibre direction, whilst remaining a lossy dielectric in the orthogonal direction [11]. The theoretical and simulated absorption characteristics correlate well with the measured results. The slight discrepancy could be a result of the close proximity of the horns and screen, or the slight curvature of the UD CFRP laminate, which could have caused by the lack of off-axis fibres. This curvature can be eliminated by including glass-fibre composites. In the theory and simulation a plane wave was assumed to be incident on an infinite screen, while in the measurement the separation of the screen and horns was not far enough for the plane wave assumption to apply. The feeds in the reflector antennas were placed in close proximity to the subreflector, so the test setup was representative of a subreflector arrangement.

3.2. The Influence of CFRP Thickness and Air Gap

The CFRP structure behaved as an absorbing screen when the E-field is perpendicular to the fibers of UD laminate, as can be seen from the results presented in Figure 4. The theoretical and simulation results further confirm the permittivity of the IM7/977-3 UD laminates.

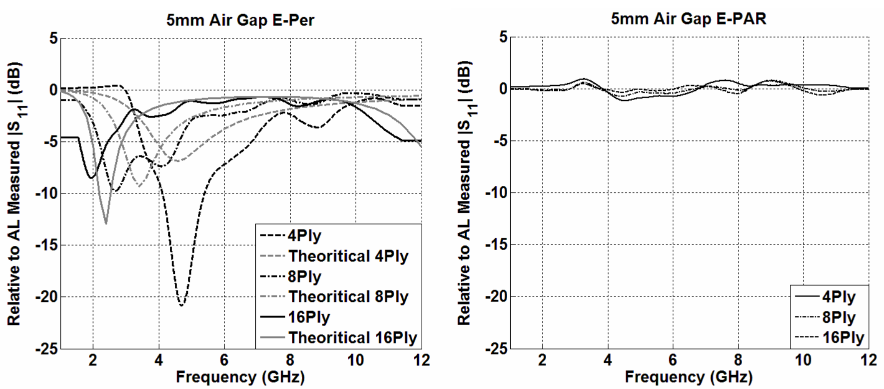
Unlike other Salisbury screens, the proposed structure maintains excellent reflection at frequencies away from its resonance and the other polarization. The effect of the air gap on the resonant frequency was studied and results are presented in Figure 4. The results indicate that the frequency of absorption in E-Per depends on the air gap dimensions while the E-Par polarization maintains a high reflection regardless of the air gap.

The effects of the laminate thickness on the performance of the structure are presented in Figure 5. One and two-ply laminates are too fragile to be made for measurement so measurements were only carried out for 4-ply (0.59 mm thick), 8-ply (1.05 mm thick) and 16-ply (2.1 mm thick) UD laminates with a 5 mm air gap from an aluminium ground plane. Good agreement between the theoretical and measured frequency response can be observed in Figure 5(a). The absorption



(a) (b)

Figure 4. Experimental results of (a) E-Per and (b) E-Par reflection of a 4-ply UD CFRP polarizer with different air gaps.



(a) (b)

Figure 5. Experimental results of (a) E-Per and (b) E-Par reflection of a 4, 8, and 16 ply UD CFRP polarizer.

Table 1. Measured reflection for E-Per polarization.

AirGap / Plies	1 mm	2 mm	3 mm	4 mm	5 mm	
4 ply (0.59 mm)	−21.5	−18.6	−18.9	−19.2	−20.3	$\lvert S_{11}\rvert$ dB
	10.5	7.1	5.9	4.6	4.7	Freq. (GHz)
8 ply (1.05 mm)	−14.7	−11.4	−8	−7.5	−6.4	$\lvert S_{11}\rvert$ dB
	7.8	4.7	3.9	3.7	3.4	Freq. (GHz)
16 ply (2.1 mm)	−7.5	−5.9	−7.1	−7.8	−8.4	$\lvert S_{11}\rvert$ dB
	4.2	2.8	2.6	1.9	1.9	Freq. (GHz)

characteristics and bandwidth of the structure generally appeared to improve as the UD laminate thickness decreased.

The results for all the analysed air gaps and CFRP thicknesses are summarized in Table 1. For the same air gap, thicker samples perform well at lower frequencies while the thinner laminates perform better at higher frequencies. In addition, thinner laminates showed better reduction in the cross-polarisation. This can be explained by a higher level of signal that penetrates the thinner laminates and undergoes a 180 degree phase shift at the conducting ground, inducing higher absorption. On the basis of these findings a thin (4 ply) laminate was selected as a screen with a high absorption in the S-band and good reflection in the X-band.

3.3. FSS CFRP Subreflector Design

A 15 mm thick honeycomb material was used to mount a 4-ply UD outer skin above an 8-ply [0 45 90 −45]2s Quasi-Isotropic (QI) laminate inner skin. The QI laminate is a special case where there are an equal number of plies in each of the 0, 45, 90 and −45° directions. In [11], the conductivity of the QI laminates was shown to be very high in every direction. Hence a QI laminate was used as a ground plane in the final FSS subreflector design. This would be lighter than an equivalent aluminium design. The measured results are shown in Figure 6.

The structure exhibited almost perfect reflection at 2.2 GHz in the E-Par orientation whilst reducing the cross polarization (E-Per) by 13 dB, and has very good reflection at 8.2 GHz in both E-Per and

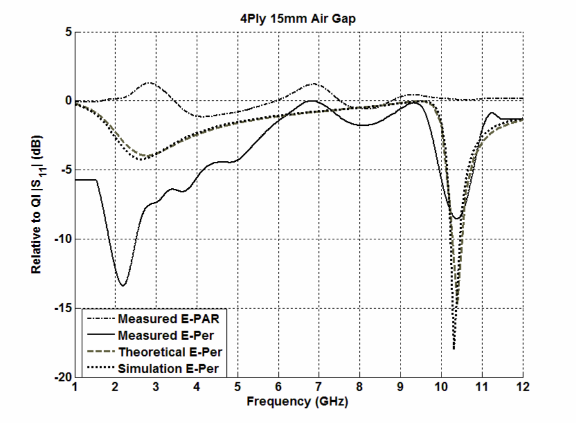
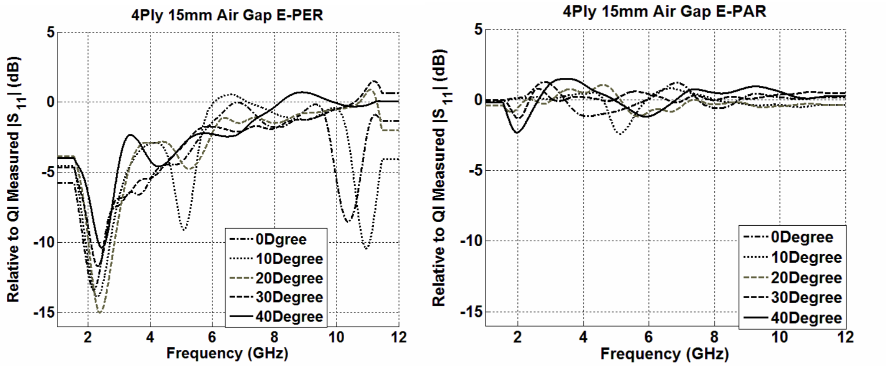


Figure 6. Experimental results of E-Per and E-Par reflection of 4 ply UD CFRP polarizer with 15 mm air gap.



(a) (b)

Figure 7. Experimental results of reflection by 4 ply UD laminate placed in front of a quasi-isotropic carbon laminate with a 15 mm air gap: (a) E-Per and (b) E-Par orientations.

E-Par polarizations. The designed subreflector supported orthogonal polarizations at different frequencies while reducing the crosstalk between the two frequencies by 13 dB.

3.4. Dependence on Angle of Incidence

The angle of incidence has a considerable effect on the frequency response of a traditional FSS. This issue becomes more significant in FSS subreflectors, due to the extremely narrow bandwidth operation of the reflector antennas [6]. The effect of incident angle on the performance of the proposed polarizing subreflector is presented in Figure 7. The test setup in Figure 2 is used where the angle of incidence was changed from 0 to 40°. It can be seen in Figure 7(b) that the reflection remains high regardless of the incidence angle in the E-Par orientation.

The subreflector also maintains good absorption characteristics at S-band (2.2 GHz) while remaining reflective at X-band (8.2 GHz) when considering an E-Per polarized wave. However, the level of measured absorption drops slightly with an increase in the incidence angle, which can be attributed to an increase in mutual coupling between the two horns. A time gating was not applied to minimize this mutual coupling so the results would remain comparable to previous measurements. The results indicate that the frequency response of proposed subreflector does not change greatly with the incidence angle, which provides a significant advantage over traditional dichroic subreflectors.

4. CONCLUSION

The highly anisotropic or orthotropic characteristics of UD IM7/977-3 CFRP laminates have been utilized to design a novel FSS CFRP subreflector. The UD CFRP laminate was placed above a highly reflective ground to create a polarizing screen in one polarization, whilst maintaining an almost perfect reflection in other polarization. A theoretical analysis is presented for determining the appropriate offset distance for a given bandwidth requirement.

A FSS polarizing subreflector for satellite communications was designed using this technique. The subreflector exhibited good reflection at both S-band (2.2 GHz) and X-band (8.2 GHz), while reducing crosstalk by around 13 dB. It was shown that unlike traditional FSS subreflectors, the proposed design maintained its frequency response over a range of incidence angles. However, the most significant advantage of the proposed polarizing subreflector is that it can support two orthogonal polarizations at different frequencies, where a traditional wire grid polarizer would require two grids for the two frequencies.

ACKNOWLEDGMENT

This research was partly conducted within the Defence Materials Technology Center, which was established and is supported by the Australian Government's Defence Future Capability Technology Center (DFCTC) initiative.

REFERENCES

1. Balanis, C. A., *Antenna Theory*, 3rd edition, Wiley, Hoboken, NJ, 2005.
2. Datashvili, L., H. Baier, J. Antonio, and H. Legay, "Mechanical investigation of a multi-layer reflectarray for Ku-band space antennas," *Aerospace Science and Technology*, Vol. 10, 618–627, 2006.
3. Chu, T.-S. and R. H. Turrin, "Depolarization properties of offset reflector antennas," *IEEE Trans. on Antennas and Propagation*, Vol. 21, No. 3, 339–345, May 1973.
4. Chu, T.-S. and N. J. Lincroft, "Method and apparatus for substantially reducing cross polarized radiation in offset reflector antennas," U.S. Patent 4 109 253, Aug. 22, 1978.

5. Munk, B. A., *Frequency Selective Surfaces Theory and Design*, John Wiley & Sons, 2000.
6. Agrawal, V. D. and W. A. Imbriale, "Design of a dichroic Cassegrain subreflector," *IEEE Trans. on Antennas and Propagation*, Vol. 27, No. 4, 466–473, Jul. 1979.
7. Tienda, C., P. Otero, and M. P. Garcia, "Design of a dichroic subreflector for an antenna operating at S and X bands," *EuCAP 2007*, 1–5, Feb. 2008.
8. Sipus, Z., M. Bosiljevac, and S. Skokic, "Analysis of curved frequency selective surfaces," *EuCAP 2007*, 1–5, Feb. 2008.
9. Salisbury, W. W., "Absorber body for electromagnetic wave," United States Patent 2 599 944, Jun. 10, 1952.
10. Galehdar, A., K. J. Nicholson, W. S. T. Rowe, and K. Ghorbani, "The conductivity of unidirectional and quasi-isotropic carbon fibre composites," *EUMC 2010*, 882–885, Nov. 2010.
11. Galehdar, A., W. S. T. Rowe, K. Ghorbani, P. J. Callus, S. John, and C. H. Wang, "The effect of ply orientation on the performance of antennas in or on carbon fiber composites," *Progress In Electromagnetics Research*, Vol. 116, 123–136, 2011.
12. Cytec Engineering Materials, HMF 977-3 Carbon Prepreg data sheet.
13. HFSS 13 HFSS Online help Ansys, Inc. (Undated).