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Waveguide Method for Surface Impedance Measurements on Composite Material Substrates

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***Abstract* — A novel method has been introduced for measuring the surface impedance of composite material sheets at microwave frequencies. A length of circular waveguide is manufactured using the fibre-reinforced composite material and its scattering parameters are measured with the use of a network analyser (VNA). An iterative simulation method is subsequently used for the derivation of the surface impedance of the composite based on altering the impedance boundary condition on the walls of a precise model of the waveguide, as manufactured, until the simulation results for its scattering parameters match the experimental values.**

***Index Terms* — microwaves, measurement techniques, waveguides, surface impedance, dielectrics, composite materials, carbon fibre composites, modelling, simulation, digital twin.**

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I. Introduction

By definition, composite materials consist of at least two different phases/components. Fibre-reinforced composites (FRC) consist of fibres embedded in and bonded to a matrix with distinct boundaries between them. Fibre-reinforced composites combine low weight with impressive mechanical properties and are often used as structural parts in the aircraft, spacecraft, automotive and marine industry, but also in infrastructure and for sports performance equipment. Due to this ever-increasing usage the characterisation of their electrical properties is essential for a wide range of applications. This includes conformal antennas for communication and radars, microwave non-destructive testing techniques for detection of defects and composite absorbing surfaces for radar-cross section reduction.

The full characterization of composite materials in terms of dielectric properties is inherently a challenging task due to their complicated microstructure. The constituent phases of the material retain their physical properties, affecting the overall properties of the composite. Specifically, for fibre-reinforced composites, the basic components are the reinforcement, typically glass, aramid or carbon fibres and the matrix material, which can either be a thermoplastic polymer or a thermoset (such as epoxies, polyesters, vinyl esters). Additional fillers, such as carbon black particles and graphene flakes can be added to adjust its mechanical, electrical and thermal properties of the material.

The electrical properties of composites are defined not only by the electrical properties of their components but also from their microstructure, as the reinforcement material is available in different forms (single fibers, unidirectional fiber sheets or various types of "weaves" which are similar to textiles). These layers often form a stack-up called a "laminate". The length, orientation and volume fraction of the fibres in a composite have a significant impact on its electrical properties [1]. The matrix material is usually a low loss dielectric, either a resin or a polymer; therefore, a composite could be described as a low loss dielectric as well when dielectric material fibres are used. An example of such a material is FR4, widely used in circuit board manufacturing, which is a type of glass fibre-reinforced epoxy composite. On the contrary, a composite material performs as a lossy dielectric when conductive fibres are used which is the case for most carbon-fibre reinforced composites.

The dielectric properties of a lossy material are represented by its complex permittivity value.

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 \varepsilon_r' (1 - j tan\delta) \quad (1)$$

where ε_r is the relative complex permittivity, ε_0 is the permittivity of vacuum and $tan\delta$ is the dielectric loss tangent, the losses being result of both dielectric loss mechanisms and conductivity. The complex permittivity of low dielectric loss composites can generally be approximated as a scalar value, while composite materials with conductive fibre reinforcement can be characterized as an anisotropic medium due to fiber orientation. In this case their complex permittivity is formulated as a tensor.

$$\overleftrightarrow{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} \quad (2)$$

Several frequency-domain methods have been introduced for the measurement of dielectric properties at microwave frequencies. For lossy materials such as carbon composites, the open-ended probe and free-space measurement methods are considered the most accurate [2]. By implementing these methods, the surface impedance and skin depth of a composite substrate can be derived [2,3,4]. The surface impedance Z_s of the substrate is defined as follows [5].

$$Z_s = -E_z / H_x \quad (3)$$

Where Z_s the complex surface impedance, E_z the electric field component that is perpendicular to the boundary and H_x the magnetic field component on the boundary that is perpendicular to the propagation direction $\hat{z}$[6].

Nonetheless, there is an evident inconsistency about the results that are reported in literature for the dielectric properties of composite materials, especially in the case of carbon-fiber reinforced composites. [4,7-10]. These can be attributed to the evidently significant effects of the composition and microstructure of a carbon composite to its properties as a dielectric [8,11]. It is therefore necessary, due to the numerous variations of composite materials in terms of composition and manufacturing methods, to provide a detailed and precise description of each composite substrate sample so that the measurements are replicable and the results comparable. A novel method for characterization of composite substrates is therefore proposed and the first results for a specific type of carbon-fiber/epoxy composite are presented.

II. Circular Waveguide Method for Surface Impedance Measurements

A. Method Description

The method introduced in this work utilises the structural properties of composites to manufacture samples with optimum characteristics for surface impedance measurements. Each sample that is thus manufactured is an aluminium circular waveguide with the entirety of its inner wall coated with the composite material substrate to-be-measured. Appropriate waveguide dimensions are selected depending on the frequency range at which the surface impedance will be measured.

Broadband waveguide adapters have been designed and manufactured in the form of bow-tie monopole antennas mounted perpendicularly on copper-clad printed circuit boards as in Fig.1. The adapters have been designed as such to be non-intrusive to the walls of the waveguide samples but also modular so that they can be fixed and properly aligned on the ends of any circular waveguide with a diameter ranging from 50 to 150 mm.

The full scattering matrix between the two ports is subsequently measured with the use of a network analyser and the surface impedance of the walls is calculated from the perceived waveguide losses. The surface impedance, complex permittivity and skin depth of the composite substrate can also be subsequently derived.

The advantages of this method in comparison to aforementioned measurement methods for the complex permittivity of composites can be described up as follows:

- Open-ended probe: The surface area of the interaction between the propagating wave and the composite substrate is many times larger compared to the “sensing” part of an open-ended probe, resulting in improved accuracy. To support this and compare the open-waveguide method to the proposed one, a sensitivity analysis was conducted on models of both experimental set-ups with the use of the ANSYS Electromagnetics Suite. The measured signal in the form of scattering parameters was found to be be significantly more affected by changes in the surface impedance of the composite substrate when the circular waveguide method was simulated. Furthermore, using a transmission and reflection methods (full scattering matrix of a 2-port network) yields additional information compared to reflection-only methods (only S11) which can be used for a more accurate determination of the electrical properties of the substrate.
- Free-space method: The waveguide method that is proposed does not require the use of an anechoic chamber for the measurement. This greatly simplifies the experimental setup and reduces the requirements in terms of facilities. Additional errors due to non-perfectly absorbing walls of an anechoic chamber are also avoided.

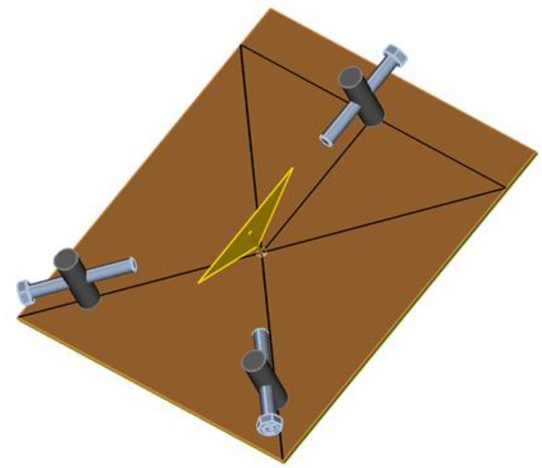

Fig. 1. CAD model of a circular waveguide adapter with details of the monopole antenna at the centre (yellow), the copper ground plane (brown) and the waveguide fixing and aligning bolts (grey).

B. Manufacturing of Circular Waveguide Samples

The circular waveguide samples are prepared by wrapping an uncured epoxy resin pre-pregnated carbon-fiber sheet on a cylindrical mandrel. This single-sheet layer constitutes the carbon-fiber substrate, the surface impedance of which will be subsequently measured. A mandrel with a diameter of 100 mm was used for the measurements presented in this work, and unidirectional carbon-fiber sheets pre-pregnated with epoxy resin were used as the composite substrate samples.

A metal cladding was subsequently introduced on top of the substrate in the form of a 0.1mm thick aluminum sheet which was tightly wrapped around the carbon-fiber sheet. The thickness of the aluminum sheet was selected as such so that it would be flexible enough to be formed into a cylinder while maintaining a smooth surface. It is also significantly thicker than the skin depth of aluminum at the frequency range used for these measurements to properly shield the walls of the waveguide.

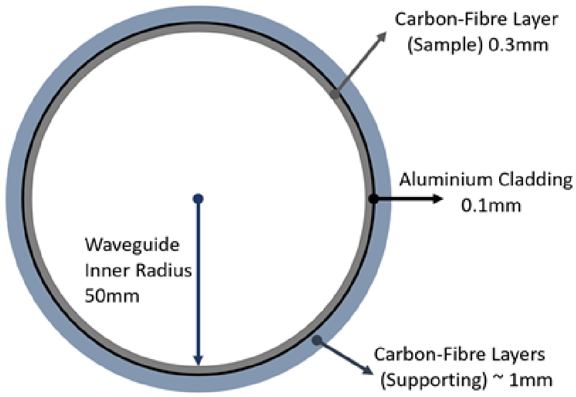

Fig. 2. Cross-section schematic of a circular waveguide sample (not to scale).

Therefore, each waveguide sample manufactured with this process is essentially an aluminium circular waveguide that is internally coated with a single epoxy pre-pregnated carbon-fibre sheet as in Fig.2. A precisely machined (<0.5% tolerance) PTFE mandrel for manufacturing composite pipes was used to minimize the roughness of the composite substrate on the inner wall of the waveguide. The pre-pregnated carbon-fiber sheet that was used for coating the interior wall of the cylindrical waveguide (XPREG® XC130 Prepreg Carbon, 300g, UD) [12] has a uniform thickness of approximately 0.3 mm post curing.

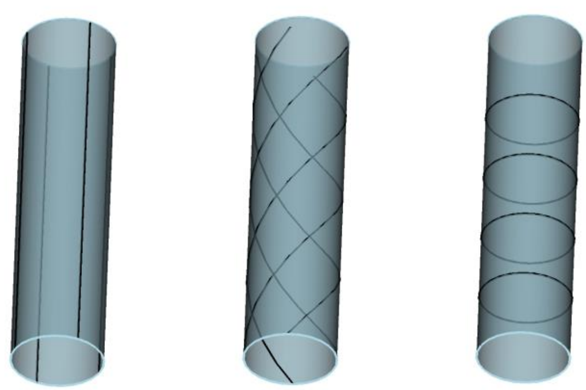

Fig. 3. CAD illustration of different fiber angles for coating the interior walls of the waveguide with a unidirectional carbon fiber sheet. The fibers on the left are wrapped along the axis of the waveguide (0º angle), at an 55º angle in the centre and for the waveguide on the right they are wrapped the circumference of the cylinder (90º angle).

Additional layers of carbon-fibre sheet were added on top of this structure to provide mechanical support so that the waveguide samples stay rigid and maintain their shape during the measurements. Each sample was covered with a sleeve of constricting "heat-shrink" tape to ensure good compaction and bonding between all layers and then oven-cured according to the instructions on the datasheet of the carbon-fibre sheet manufacturer.

A number of circular waveguide samples were thus manufactured with different fibre orientation (angle) towards the waveguide axis to investigate the effect of the increased conductivity along the length of individual carbon fibers to the derived surface impedance values for the carbon-fibre sheet. An un-coated cylindrical waveguide of the same dimensions with aluminum walls was also manufactured for benchmarking, to test the accuracy of the surface impedance results.

III. Surface Impedance Calculation

A. Measurement of the Scattering Matrix

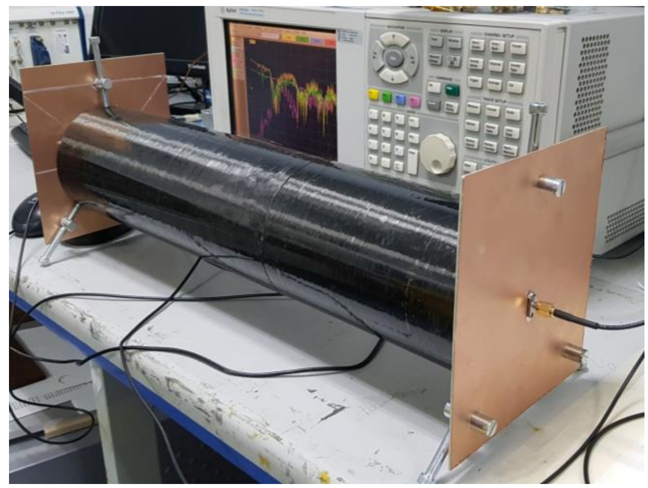

Fig. 4. Photograph of the experimental setup; details: the network analyzer, circular waveguide (sample) and waveguide adapters.

The adapters were mounted on each waveguide sample as in Fig.4 and full scattering parameter matrices were extracted at 4-8GHz (C-Band) with the use of a VNA (Agilent E8358A). The measured signals were parsed and processed with a Chebyshev filter for noise reduction.

B. Simulation and Iterative Method

The High Frequency Structure Simulator (HFSS) [13] of the ANSYS Electronics Suite (2017.0) was used to model the waveguide and simulate the propagating mode. Each circular waveguide was modelled as a cylinder with the same dimensions as the manufactured sample (diameter: 100mm, length: ~400mm). Slight variations in length between samples were measured and the dimensions of the models were altered accordingly. A complex impedance boundary condition was applied on the curved face of the cylinder with its real and imaginary parts set as variables. Waveguide adapters were imported from a CAD file as shown on Fig.2 to seal both ends of the waveguide. Lumped ports were used for both adapters to excite a TEM mode on the coaxial feed of each monopole. A symmetry plane was introduced along the axis of the cylinder to reduce solving time. An iterative method was then implemented using the "optimization", Quasi-Newton method option of HFSS for the calculation of the surface impedance, as described in the following flowchart [Fig. 6].

TABLE I
SURFACE IMPEDANCE RESULTS FOR A UNIDIRECTIONAL CARBON FIBER SUBSTRATE[12]

Frequency [GHz]	Complex Surface Impedance (Zs) [Ohm]		
	0º angle	55º angle	90º angle
4	4.325+25.21j	4.853+25.74j	5.791+26.59j
5	3.893+25.64j	3.704+14.18j	7.4+28.54j
7	2.183+27.79j	3.182+17.74j	9.24+46.14j

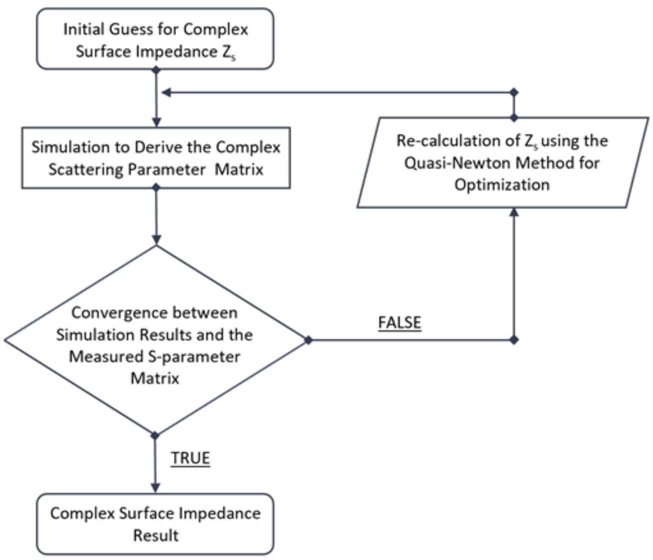

Fig. 6. Flowchart of the iterative process for complex surface Impedance (Zs) calculation.

The number of simulations required for the convergence of the iterative method depends on the accuracy of the initial guess and the convergence criterion that is set, while the overall calculation time depends on the solution time of each simulation as well. Increased mesh resolution is nonetheless required for the regions of the model that are close to the waveguide walls as they are critical for the accuracy of the result. Once the first values for the complex surface impedance of a composite substrate are calculated the accuracy of the initial guess can be improved, and the number of required iterations can be drastically reduced for calculations at other frequencies. Furthermore, each iteration loop is independent, allowing for the calculation of the surface impedance of a substrate over an entire frequency band with the use of parallel computing.

C. Results

The surface impedance values that were derived from the measured data by using this iterative method are available in Table. 1. These results indicate that the real part of the surface impedance, which is the resistivity of the substrate, is lower when the conductive carbon fibers are parallel to the axis of the cylinder. This can be attributed to the fact that, according to the simulation results, the propagating TM modes at the selected frequencies induce surface current oscillations on the waveguide walls which are parallel to the waveguide axis. Results for an un-coated waveguide of the same dimensions were also derived for verification and the value of complex surface impedance was found to be close to the one of aluminum, as expected, with an error of approximately 4%.

Furthermore, the sign of the imaginary part of the measured surface impedance for these carbon fiber sheets is positive, meaning that the substrate has inductive characteristics in terms of reactance and it is, therefore, suitable for the propagation of TM0 surface wave modes [5,14]. This is a result of great interest since surface modes can significantly affect the performance of conformal antennas mounted on the surfaces of carbon composite structural parts, as often happens in aerospace applications [9].

D. Future Work

It is important to mention that the thickness of the carbon fibre sheet that was measured is significantly lower than the skin depth for carbon-fibre epoxy composites at these frequencies [4]. Therefore, the derived values for surface impedance are for an aluminium-coated carbon composite substrate. The surface impedance of aluminium can be easily calculated and the surface impedance of individual sheets of composite material can thus be analytically derived using the impedance calculation formulation known from the transmission line theory [16]. Future work will focus on the full dielectric characterisation of individual composite material layers in the form of complex permittivity tensors $\overleftrightarrow{\varepsilon}$ and the implementation of a multi-layer dielectric model to predict the surface impedance of composite material laminates consisting of multiple such sheets. An analytical solution for anisotropic dielectric-coated circular waveguides will also be derived to compare the results with the presented iterative method.

IV. CONCLUSION

A novel method for measuring complex surface impedance of composite material substrates has been developed and experimentally verified. The novelty of this method lies in the use of the composite material as an integral part of a waveguide wall to allow for an accurate surface impedance measurement without the use of an anechoic chamber and in the use of simulations to process the measurement results and derive surface impedance values. Appropriate dimensions and high manufacturing quality of the samples, along with strict convergence criteria for both individual simulations and the iterative algorithm are critical for the accuracy of surface impedance measurements by applying this method. Further calculations on the surface impedance results can yield additional information about the composite material such as the complex permittivity and skin depth of the substrate [16].

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