Analysis of Transmission Properties of Sludge Biochar Composites in the C-Band

Muhammad Yasir and Patrizia Savi

Abstract – In order to pave the way for the widespread use of eco-friendly materials for novel applications, there is a growing need for morphological, mechanical and electrical, and microwave characterization techniques. The measurement of scattering parameters is an accurate technique for the microwave characterization of novel materials, but it requires a number of components, including waveguides, adapters, and so on. The band of measurements is also limited to the working band of the waveguide used. A method of retrieving waveguide scattering parameters from permittivity values is devised. The method is validated with measurements of the scattering parameters in a waveguide. The method is tested with composites based on biochar derived from sewage sludge and a standard epoxy sample. The addition of biochar considerably reduces transmission scattering and is found to be a suitable candidate for filling composite materials.

1. Introduction

There is a high demand for an increase in the data rate and the available spectrum for realizing 5G cellular technology [1], making the use of higher frequencies inevitable [2, 3]. At micromillimeter and millimeter wave frequencies, transmission mediums, such as coaxial and microstrip lines, bear high insertion loss [4, 5]. Waveguide technology is an attractive alternative for use at higher frequencies since it possesses lower insertion loss (see, e.g., [6]). The growing interest in the use of waveguide technology calls for an increased use of the technology in various applications, such as wireless communications (see, e.g., [7]), power transfer (see, e.g., [8]), and the characterization of materials and films [9, 10].

With an increased interest in the use of eco-friendly materials, novel methods of characterization are required for the accurate detection of material properties and the proposal of relevant applications. The use of eco-friendly materials has been growing due to the excess production of pollutants that has aggravated the problems of climate change and global warming (see, e.g., [11]). The treatment of wastewater produces sewage sludge, which contains a number of pollutants, including heavy metals and pathogens. With the rapid increase of the human population, there has been a considerable increase in the creation of sewage [12, 13]. Sludge derived from sewage is used in agricultural applications, such as manure. Due to the ever-increasing production of sewage sludge and the limited opportunities for disposal and productive use, there is an imminent need for using it in innovative applications. This will result in value being added to the product and also help recycle unwanted and environmentally damaging material. The use of carbon-negative materials in innovative applications can be effective in reducing the carbon footprint [14]. A number of studies have been performed on the use of carbon-based materials (see, e.g., [15] and [16]), specifically biochar, in applications on the effectiveness of electromagnetic interference/shielding [16].

Formerly, sewage sludge–based biochar composites have been characterized by measurements of scattering parameters in a waveguide structure [16]. In this article, an alternative method of retrieving scattering parameters is proposed. The method is based on the measurements of the values of complex permittivity with the help of an open-ended coaxial probe and using these values to simulate composite samples in a waveguide structure. Samples of standard epoxy and sewage sludge biochar composites are fabricated and measured in a waveguide structure. The values of scattering parameters retrieved from the simulations are compared with measured values.

2. Methodology

A flowchart describing the proposed method, validation of the method, and the individual steps is shown in Figure 1. The method consists of measurements of complex permittivity of cylindrical samples with adequate thickness and full-wave simulations of the samples in the waveguide for the extraction of scattering parameter values. For validation of the proposed method, samples of adequate dimensions to fit in the waveguide cross section are fabricated. The measurements of the scattering parameters are performed in WR137 waveguide (5 GHz to 8 GHz), and a comparison of the measured and simulated values is carried out.

A commercial FEM [18] software (Ansys HFSS) was used to simulate the waveguide structure with a reference sample and biochar samples. Values of relative permittivity and dielectric loss tangent are calculated from the measured complex permittivity. The values of relative permittivity and dielectric loss tangent at each frequency are loaded as a data set in the simulator. Piecewise linear functions are created based

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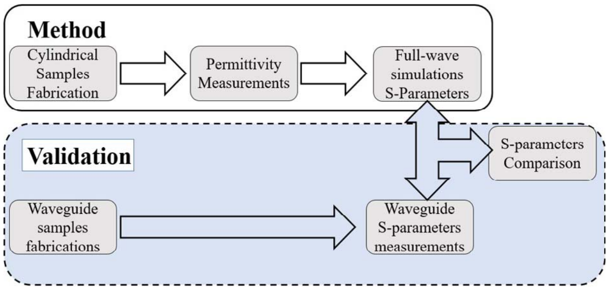

Figure 1. Process flow for scattering parameter acquisition in waveguide technology.

on the data sets and the simulation frequency. These linear functions are loaded in the creation of a custom material representing the samples. In this way, the behavior of the dielectric materials (kept constant for standard materials) is retained over the frequency band. The simulated structure of the waveguide is shown in Figure 2. The analysis of the waveguide is performed with discrete sweep type in order to perform the simulations for each point in frequency, taking into account the variation of the material properties with frequency.

3. Experimental Validation

In order to make composites of the sewage sludge biochar (Bioforcetech Corporation), a preweighed quantity of the biochar was mechanically mixed in an epoxy resin (Hexion, Infusion Resin RIMR-135). A hardener (RIMR-134) was then added to polymerize the mixture. The mixture of the biochar, epoxy resin, and hardener was then shifted to molds of a specific shape. A detailed procedure of the composite preparation is described in [16] and [17].

The measurement of complex permittivity was performed by an Agilent 85070D open-ended coaxial probe, which requires flat samples with specified dimensions, as shown in Figure 4. The thickness of the samples should be chosen in order to consider the sample as “infinite.” In this way, there is no influence on the measurements coming from the thickness of the material. The probe works in the frequency band of 200 MHz to 20 GHz. Details of the measurements performed with this setup can be found in [14]. To measure the complex permittivity of the composites, the

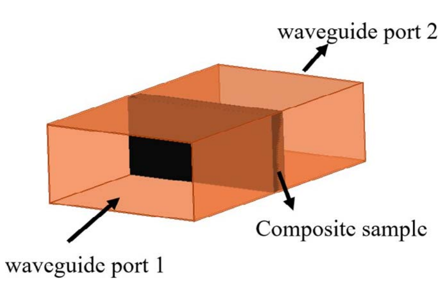

Figure 2. Simulated waveguide structure.

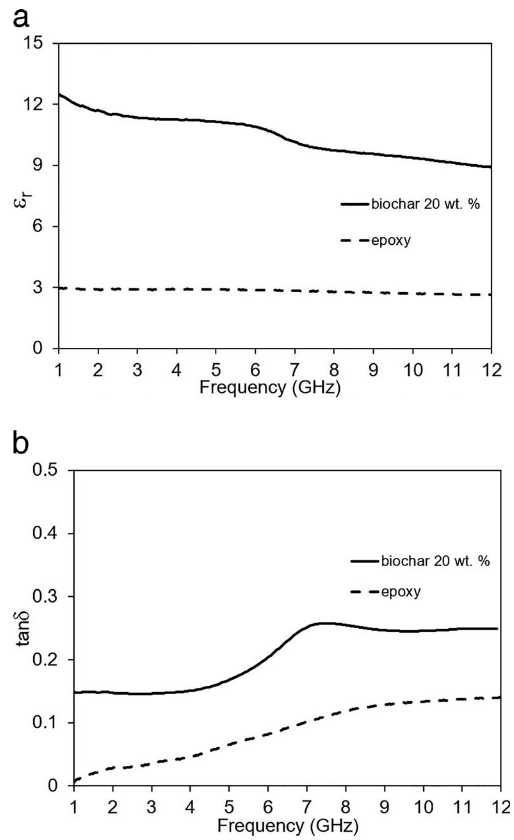

Figure 3. Permittivity and loss tangent values of the samples. (a) Relative permittivity of biochar (solid line) and epoxy sample (dashed line) and (b) loss tangent of biochar (solid line) and epoxy sample (dashed line).

probe was calibrated using the required calibration procedure with air, short, and water. Air corresponds to leaving the probe open in the air, short is a calibration standard provided by the manufacturer, and water is the measurement of deionized water. The relative permittivity and loss tangent of standard epoxy and sewage sludge biochar composite with 20wt% filler are shown in Figure 3(a) and Figure 3(b), respectively.

It can be seen that the values of the relative permittivity and loss tangent of the sample with 20wt% biochar are high compared to those of the standard epoxy sample. This shows that biochar is a good contender for filling composite samples for increasing electrical properties.

Scattering parameters in the C-band are measured in a waveguide that requires cuboid-shaped samples to fill the interior of the waveguide. In order to fabricate samples of precise dimensions, a master mold was 3D printed. Liquid silicone was used to fabricate reusable molds. The shape and size of the 3D-printed master molds and the silicone molds can be varied according to the shape of waveguides of different dimensions working in different frequency bands. The thickness of the samples was chosen as 4 mm. The value of thickness does not affect the calculation of the

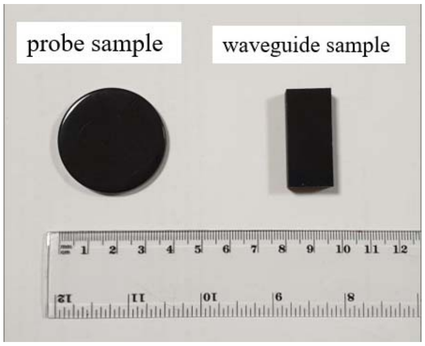

Figure 4. Fabricated biochar samples for the dielectric probe and waveguide measurements.

permittivity, but it is an input parameter for the simulations of the S parameters. The elasticity of silicone facilitates easy extraction of the biochar samples once they have polymerized. An example of the fabricated sample is shown in Figure 4.

Measurements of the transmission and reflection scattering performed in a WR137 waveguide show a transmission loss of almost –10 dB for a composite sample with 20wt% sewage sludge biochar. A comparison of the measured and simulated values of the scattering parameters for the standard epoxy sample and a sample with 20wt% biochar is shown in Figure 5. The simulated and measured values are in good agreement with each other. The simulated values of the transmission scattering (S_{21}) are slightly higher than the measured values for both samples, while the simulated values of the reflection scattering (S_{11}) are slightly lower than the measured values for both samples. This is an indication of additional losses in the measured values that are not taken into account in the simulated values. There is also a small difference in the simulated and measured scattering parameters throughout the frequency range that is due to error in measurement of the dielectric constant by the coaxial probe that is propagated into the simulated results. For the sample with biochar, the difference in measured and simulated values increases with frequency. It can be due to the particle size of the filler, which becomes more significant in terms of the wavelength at higher frequencies.

Measurements of the scattering parameters were performed with the help of a vector network analyzer (Agilent E8361A). The ports of the analyzer are connected to the waveguide with the help of coaxial-to-waveguide adapters. Calibration of the waveguide is performed by a standard waveguide calibration kit with short-load-through standards.

4. Conclusions

The method of retrieval of the scattering parameters proposed here is based on the knowledge of the complex permittivity of samples (easily measured or computed for a wide band) as a function of frequency.

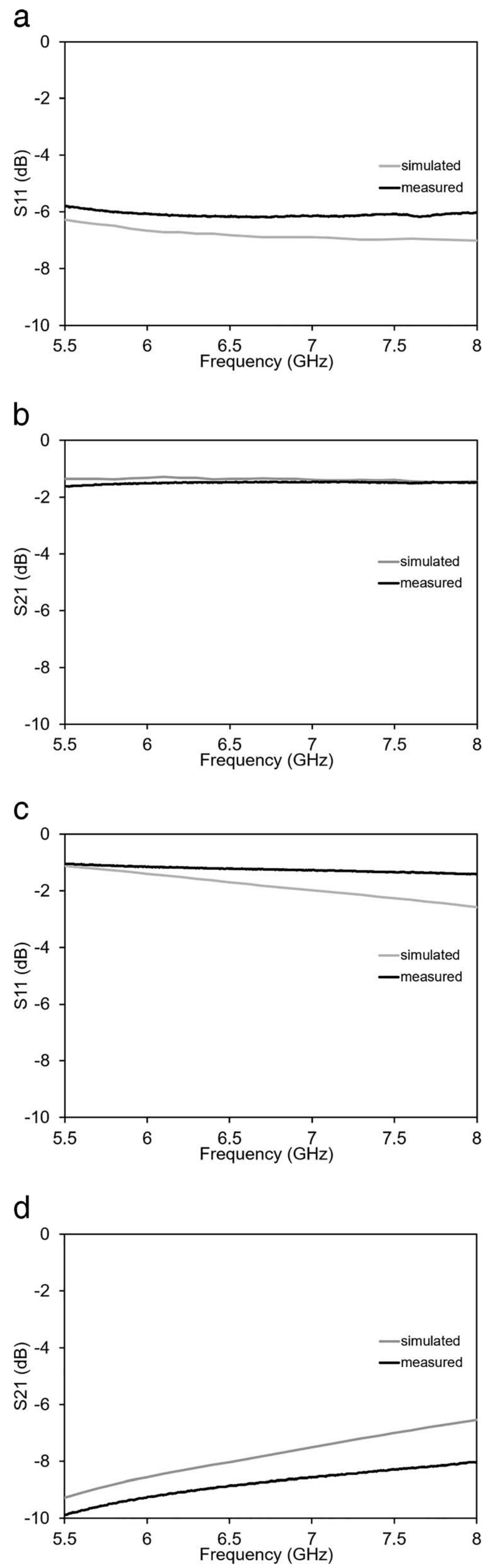

Figure 5. Simulated and measured scattering parameters in a waveguide. (a) Reflection of standard epoxy, (b) transmission of standard epoxy, (c) reflection of 20wt% biochar composite, and (d) transmission of 20wt% biochar composite.

The complex permittivity values are loaded in a full-wave simulator analyzing a rectangular waveguide with a block of the material, and the scattering parameters are retrieved. This process is tested for a standard and novel composite material, and values of scattering parameters are retrieved. This method can be applied to different waveguides operating in the whole range of the frequency band for which the complex permittivity values are available.

5. References

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