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A Novel Free-Space Gaussian Beam Method for the Characterization of Anisotropic Materials

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***Abstract*—This paper presents a novel design of a system for free-space characterization of RF anisotropic materials. This proposed method utilizes three probes to capture full scattering matrix data as a function of incident angle and frequency to extract the intrinsic material parameters. This system was designed, implemented, and integrated with LabView to provide automated measurement capabilities. Finally, the results were validated by fabricating and testing a frequency selective surface.**

I. Introduction

Characterization of material properties is an important step in the development of modern RF devices. The permittivity and permeability of a material are an integral variable that engineers consider during the design process. For most RF components (antennas, filters) the material is assumed to be uniform and traditional material measurement methods suffice; however, for some applications, such as frequency selective surfaces and the development of metamaterials [1], uniform performance may not occur. These are known as anisotropic materials, which are any material whose constitutive parameters are a function of the direction of the impinging field. To measure these materials off broadside traditional methods, such as a waveguide or two-probe free-space characterization, cannot be used. To completely characterize an anisotropic material a system must be able to capture full scattering matrix data over all possible incident angles, which lead to the development of the system that is now being presented. This requires the addition of a third probe that rotates in tandem with the sample under test, allowing the capture of both the transmitted and reflected components of the impinging wave and thus the application of material characterization algorithms.

II. Proposed Method

1) Hardware Setup: The proposed RF scanner, pictured in Figure 1, utilizes six linear actuators constructed with aluminum rails with lead screws that can be used to move trolleys mounted on them. Each linear actuator has a stepper motor attached that is used to position the trolleys and allows the entire measurement process to be automated. Three of the rails are mounted horizontally around a single axis where the material under test is also mounted on a rotary table. Two of these three rails are fixed and opposite to each other around the material. The third rail is controlled by a rotary table and allowed to rotate freely around the sample.

Each of the three horizontal rails has a trolley mounted on it upon which is mounted another linear actuator. These three rails can position their trolleys vertically and upon each trolley a probe is mounted. This allows for each of the three probes to move both up/down and closer/farther from the sample independently.

2) Control System: All of the stepper motors that drive the linear actuators are controlled by two TinyG CNC controller boards. These are controlled by sending commands to the TinyG USB port that interfaces with the controlling computer. Additionally, limit switches are mounted on all of the linear actuators at known positions to allow the system to automatically home itself and prevent damage to the system.

The VNA used for this system is a Copper Mountain Planar 804/1 with two ports. Because the VNA has only two ports, while there are three probes required to take the transmission and reflection measurements when not at broadside, an RF switch was used to switch the second port between the probes receiving the transmitted and reflected waves. To communicate with this switch an Arduino Uno was used to control a solid state relay that delivered the 24 V required to operate the switching action.

3) Antennas: Each probe is a dielectric rod antenna designed for 7.5 GHz (WR112). These antennas were customized for this application due to their narrow beamwidth (10°) and spot size focus beam characteristics that focus the energy in short distances. Antenna probes with small dimensions contributed to a reduction in the size of the entire testing apparatus. The antennas must be at least their far-field distance away from the sample to take an accurate measurement.

4) Sample Size: An important consideration in this system is the size of the sample under test. If the area illuminated by the test beam approaches or crosses the edge of the sample then direct transmission and edge diffraction will occur, both of which will cause inaccurate measurements to be taken. Because of this the samples height and width should be at least 1.5 times larger than the antenna beamwidth [2]. The sample thickness must also be small with respect to the wavelength ($l << \lambda_r/2$). In this system the antenna beam projection on the MUT is always smaller than the sample dimensions.

5) Algorithm: To extract the material parameters, the Nicolson-Ross-Weir (NRW) method is employed. This is the most commonly used algorithm for the characterization of materials in free space mainly due to its straightforward use

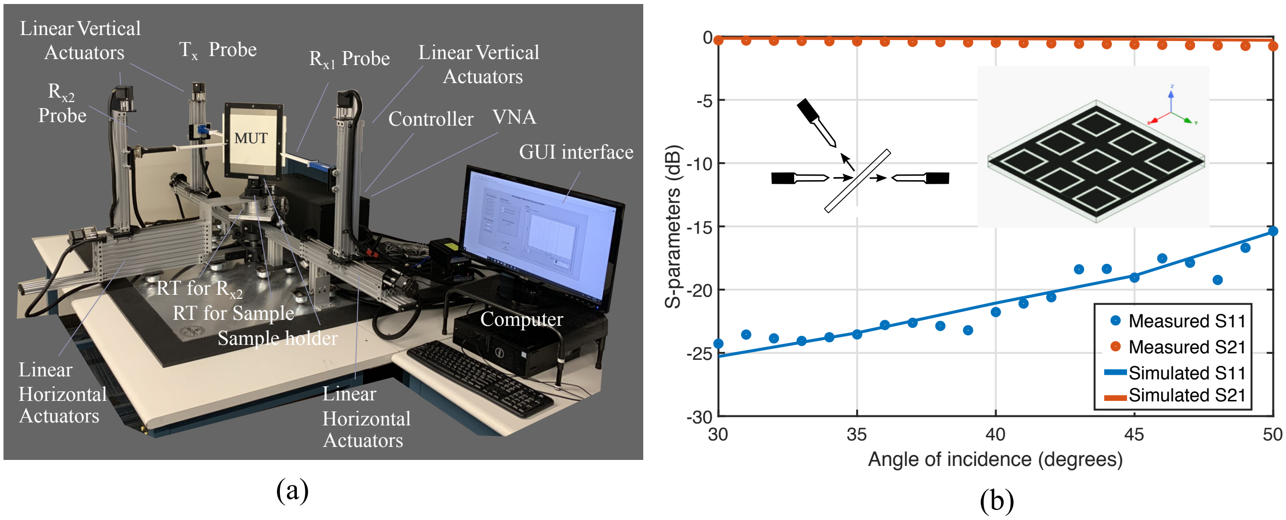

Fig. 1. (a) RF Scanner setup for anisotropic material characterization, (b) Comparison of measurement and simulation results (S-parameters) of frequency selective surface used as sample of anisotropic material as a function of incident angle.

and small computational requirements and is described in [3] and [4]. However, the NRW extraction algorithm suffers from one major flaw: the extracted parameters are ambiguous due to the periodic nature of the complex logarithmic function. This is known as a branch ambiguity, and occurs when the sample thickness becomes large with respect to the wavelength. This is documented in [1].

6) Calibration: An automated calibration procedure was developed for the system. The calibration procedure changes slightly depending on if the scanner is taking broadside or angular sweep measurements, with Transmission-Reflection-Line (TRL) being used for broadside and Transmission-Reflection for the angular sweep. For both calibration methods, the first step is homing all of the rails using the installed limit switches. The next step is taking the Transmission measurement. If the system is taking measurements in broadside, it will also take a Line measurement. To take the last standard, the system will prompt the user to input the Reflection standard before taking the measurement. Finally the system applies and saves a calibration state.

III. Results

To validate our results measurements were taken of isotropic materials with known constitutive parameters and a frequency selective surface (FSS) that was fabricated in the lab. The S-parameters of the FSS over an angular sweep are shown in Figure 1.

Rogers 4350B was also measured at normal and oblique incidences and the errors were quantified given that $\epsilon_r = 3.48$. The maximum error for normal incidence was 4.53% for the real component of the permittivity and 7.78% for the imaginary component. When the sample was tested over oblique incidences more errors were introduced, with the max real permittivity error being 17.90% and an imaginary permittivity error of 24.24%. This is most likely due to diffraction from the edge of the sample and direct transmission errors, which occur when a portion of the beam does not pass through the sample and instead propagates directly to the other R_X probe which increases the measured magnitude.

For most of the measured parameters we have strong agreement with the simulated values. The S_{21} of the FSS and the extracted constitutive parameters of the RO4350B all showed good agreement. To improve on these results a larger sample could be used as well as incorporating more directive antennas to reduce the effect of direct transmission errors. Using antennas with a closer far-field range and more planar phase front would also help alleviate these issues.

IV. Conclusions

A new RF scanner system developed for the characterization of anistropic materials is presented. The system showcases a novel three-probe design to characterize the constitutive parameters of materials at oblique incidence angles. Control software was also created in LabView to provide automated free-space calibration and accurate measurements.

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