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Development of scanning single port free space measurement setup for imaging reflection loss of microwave absorbing materials

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ABSTRACT

This paper proposes a scanning free-space measurement (SFSM) setup for the evaluation of microwave absorption properties of microwave absorbing materials. The system comprises of a vector network analyzer (VNA), focused horn antennas attached to the VNA for transmitting/receiving microwave signals, a dual-axis automated translation stage for raster scanning of the specimen and a standard personal computer. A graphical user interface (GUI) running on the computer manages the configuration and synchronization of the VNA and the stage system, measurement reception from VNA and compilation of results for display to the user. The GUI is created in C++ using Qt framework and Qt Widgets for Technical applications. It is designed with a minimalistic approach to promote usability and adaptability.

1. Introduction

Microwave absorbing materials (MAM) have been used by defense industry for decades in applications such as electromagnetic interference (EMI) and radar cross section reduction [1]. In recent years, with the advent of wireless electronics, such materials have found use in EMI reduction inside the hi-speed electronic circuits. Researchers have devoted a great effort for solving the cross-discipline challenges in design and production of such materials. In order to achieve the desired absorption in a MAM, different methods have been proposed in literature such as the use of special composites, frequency selective surfaces and multi layering [2–5]. This increased interest in the design of efficient MAM mandates an increased focus on the performance validation and characterization methods and researchers have proposed several measurement techniques in this regard. These measurement methods can be generally classified as, closed measurement cell, open-ended probes or free-space based methods [6]. In all these methods, an electromagnetic wave of known characteristics illuminates the MAM under test (MUT). The transmitted and reflected electromagnetic power is then recorded in the form of complex scattering parameters (S-parameters) S_{21} and S_{11}, respectively. Subsequently, for a detailed assessment of the MUT, the intrinsic properties such as complex permittivity (ε), permeability (μ), reflection coefficient (Γ) and reflection loss can also be calculated from the measured s-parameters [7,8,10–13].

The closed measurement cell methods require the sample to be fitted in a measurement cell. Waveguide based measurement setup is one type of closed cell measurement method in which the sample is placed in a suitable waveguide section for measuring the transmission and reflection coefficients [14–18]. An improvement on this method has been reported for measuring the permittivity of thin dielectric materials that do not completely fill the sample holder [19]. This method requires only a single-port measurement and produces error free results. A two dimensional Fourier transformation has been employed by [20] to measure the properties of the rectangular dielectric waveguide discontinuities. Further variations on this measurement method includes a partially loaded waveguide [21,22] and a two flanged approach [16] which are useful in electromagnetic characterization of magneto-dielectric materials. Another type of closed cell method is a co-axial line measurement method, in which an annular disk of material is installed in a coaxial line with inner and outer conductor. The line is air filled with a characteristic impedance [23–25]. It is evident that the close cell methods are destructive since they require the sample to be in a specific shape. Moreover, the allowable tolerance for the waveguide or cavity becomes very stringent as the frequency increases. In order to avoid sample preparation, open-ended probes have also been employed for characterization of non-magnetic dielectric materials [26–30]. This method does not put constraints on sample shape and is thus non-destructive. Both open-ended coaxial and open-ended waveguide probes have been used but former are favored over the later for their broader frequency range and smaller size at lower frequency. However, for a given frequency, waveguide probes are better matched for measuring lower permittivity than coaxial probes of similar size. Waveguide probes can be used for the measurements of anisotropic materials since the electric field for the

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dominant mode of the rectangular waveguide is linearly polarized [6]. The open probe method is not suitable for measurements at millimeter wave frequencies due to size limitation of the probe. Additionally this method also requires the probe to be pressed against the flat material surface in order to mitigate the air gap problem.

Out of the different assessment techniques, free-space measurement sets least amount of constraints on sample size/shape and can evaluate a sample in a non-contact fashion in millimeter wave frequencies. Thus, it is well suited for performance evaluation of an MAM during its design and conception phase in lab as well as over the course of its actual use in field. An efficient method of free-space measurements and calculation of complex permittivity and permeability was proposed in [7,8]. The compressive strength of concrete was estimated using free-space measurement in [31]. A setup was proposed for bulk and thin film di-electrics by [32] in which sample was sandwiched in quarter-wavelength Teflon plates to improve the mismatch at the frequencies of measurement. A compact but unfocused antenna setup was utilized for di-electric measurements in the X - band range in [33]. This setup used a cylindrical dielectric insert for enhanced directivity and narrower main beam width. A quasi-optical free space measurement was proposed for characterization in the W-band by [34]. The free space measurements have also been utilized for characterization of liquids and powders in high- and low-temperature environments [35]. A free space setup for characterizing metamaterials at high temperature was proposed in [36]. This setup used a furnace to heat the samples in the range of 25–400 °C. All of these free space measurement setups and many others reported in the literature comprise of a vector network analyzer (VNA) along with antennas for transmitting and receiving microwaves. Focused energy antennas are generally preferred to reduce the effects of diffractions at the edges of the sample. Although horn antennas may also be used and errors stemming from diffraction maybe suppressed by using a large sample placed in front of the antenna. A free-space setup was used to confirm the characteristics of a microwave absorber for X-band application and horn antenna was placed facing the center of the MUT for making a single measurement [37].

The measurement setups presented in the literature focus on measuring the characteristics of a certain point on an MUT. However, this measured point may not be considered as a representative of the MUT's performance across its whole surface. Since variations in the production-process and degradation over time may only affect certain regions of the MUT, so an exhaustive scan of the full surface is mandatory to ensure the performance of the MUT. This paper proposes a scanning free-space measurement setup for the characterization of the MAM based structures. The setup comprises of focused horn antenna, linear translational stages, vector network analyzer (VNA) and general-purpose computer. The setup can scan a predefined area of an MUT and record the scattering parameter S_{11}at each point in the scanned area. The distance between each measurement point within the scan area is changeable in the range of 1–60 mm. This allows for a flexible spatial resolution setting according to user's need e.g. a coarse but faster setting maybe chosen for an initial scan of a large MUT followed by finer scan of an area of interest. Diffraction effects on the edges of the MUT are minimized by a focused horn antenna. The setup is useful for post-formation quality assurance of an MAM to uncover any regions not conforming to the designed specifications due to anomalies in the formation process. It is also useful for monitoring the performance of an MAM based structure over the period of its deployment to uncover any performance degradations due to external factors or age. The setup evaluates the performance of a specimen in X-band (8.2–12.4 GHz) range and displays the results in real time during the scan.

This paper is organized in five sections. Section 2 explains free-space measurement as well as their meaning and significance in evaluating an MUT. Section 3 describes the SFSM setup and its functioning in detail. Section 4 includes the results of different specimen characterization. Finally, concluding remarks are given in Section 5.

Fig. 1. A dual port network showing the input and output signals.

2. Measurements

A microwave measurement technique relies on illuminating an MUT with a microwave signal. Various properties of the MUT can then be obtained based on the reflection from and the transmission through the MUT, as both the reflected and transmitted waves have strong dependence on the electric and magnetic properties of the MUT and its thickness. Frequency of the incident microwave signal can also be varied in order to gauge the properties of the MUT for all the frequencies of interest. S-parameters are used for measuring the reflected and transmitted waves.

S-parameters are used to describe the response of any network to the signals present at its port(s) [9]. The network could be any device under test such as a passive antenna, an active amplifier, or – as in this writing- an MUT in free space. Given a network, with port(s) for signal interaction, the S-parameters describe the magnitude and phase relationship between the incident and reflected waves on its port(s). A Scattering parameter (S-parameter) is commonly assigned subscripts to ascertain the receiver port and the source port such as in S_{ij} i denotes the receiver and j denotes the source port. Fig. 1 shows an example of a two port network with a and b respectively denoting input and output signals. As expressed in Eq. (1), the output at each port is a linear combination of signals entering the network from either ports.

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned} \tag{1}$$

Terminating the individual ports with matching/characteristic impedance enables the measurement of individual s-parameters. i.e.

$$\begin{aligned} S_{11} &= \frac{b_1}{a_1}, \quad S_{21} = \frac{b_2}{a_1}{-}{-}{-}{\rightarrow}a_2 \textit{ terminated} \\ S_{12} &= \frac{b_1}{a_2}, \quad S_{22} = \frac{b_2}{a_2}{-}{-}{-}{\rightarrow}a_1 \textit{ terminated} \end{aligned} \tag{2}$$

In practice, a vector network analyzer (VNA) is used for measuring these s-parameters. In the context of free-space measurements, VNA generates an EM (Electromagnetic) signal through its transmit port, illuminating the MUT with microwaves. The signal experiences partial reflectance back to the transmitting port and partial transmittance through to the other (receiving) port. VNA separates these waves by means of couplers or bridges and measures the phase and magnitude of each wave to compute the individual s-parameters. Furthermore, using the measured s-parameters the real and imaginary parts of magnetic permeability, μ and dielectric permittivity, ε can also be determined using any of the several models such as Nicolson-Ross model [11,12].

The reflection coefficient (Γ) of a material dictates how much of an incident EM wave will be reflected back. It depends on the impedance of the material as well as the free space impedance [10]. Closer matching of material impedance to that of free space impedance results in less amount of reflection from the material and so smaller value of Γ as expressed by Eq. (3).

$$\Gamma = \left| \frac{Z_{mut} - Z_{fs}}{Z_{mut} + Z_{fs}} \right| \tag{3}$$

where Z_{fs} denotes the impedance of the free space also expressed as $\sqrt{\mu_0/\varepsilon_0} \approx 377\ \Omega$, and Z_{mut} is the impedance at air-MUT interface. Alternatively, reflection loss in decibels (dB) can be used to evaluate the reflectivity of the MUT as is expressed in Eq. (4).