Permittivity Measurement on Construction Materials Through Free Space Method

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Abstract—This paper presents the validation and test of an experimental set-up for complex permittivity measurements of construction materials. Measurements on reference materials like Plexiglas® and PVC in an anechoic chamber and in a laboratory set up give results in agreement with literature data. The proposed set up is able to accommodate walls made with different construction materials and to measure their complex permittivity as a function of the frequency in the 2 - 6 GHz range.

Keywords—permittivity measurements, construction materials, GRL calibration

I. INTRODUCTION

The knowledge of the complex permittivity value of construction materials like bricks, concrete, glass and wood is necessary to evaluate the influence of walls present in the propagation path of electromagnetic waves. As an example, in the context of through the wall radar imaging, the electrical characterization of the wall material is fundamental in developing algorithms for the detection of targets inside buildings [1]. Moreover, permittivity measurements on building walls can be performed non-invasively and are a possible candidate for remote sensing of building health status, allowing a timely detection of possible deterioration phenomena.

Many papers have already addressed the topic of the permittivity characterization of construction materials. In [2], a dispersive material model for concrete was developed; while in [3] measurements of the real and imaginary part of permittivity were interpolated for different moisture contents. In the 30 MHz - 1 GHz frequency range, Sandrolini et al. [2] have found for the real and imaginary part of permittivity values in the 4.5-13 and 0.1-6 ranges, respectively, depending on the moisture content. At frequencies between 3 GHz and 24 GHz the real part of the permittivity was found to vary between 5 and 7 while the imaginary part between 0.1 and 0.7 [4], [5]. Brick measurements carried out in the 1.7 GHz – 18 GHz frequency range evidenced permittivity values oscillating between 3.7 and 4.6 for the real part and between 0.12 and 0.6 for the imaginary one [4]-[6]. Stones, often used in old buildings, show permittivity values between 6 and 10 depending on their moisture content [7]. The permittivity of glass was found to vary considerably with its composition and less with the frequency. In [8] values of 4 and 5.0⋅10^-4 have been found for the real and imaginary part of permittivity, respectively, at 9.4 GHz. Finally, wood permittivity is strongly dependent on the wood type and water content [9]. For dry woods real permittivity values between 1.2 and 6.8 were found with imaginary parts between 0.006 and 0.43.

Many of the above-cited measurements have been performed by using waveguide, coaxial or cavity techniques [10]. These techniques suffer from the reduced sample dimensions that does not allow taking into account the non-homogeneous nature of the real structures. Moreover, the samples have to be machined to fit the testing set-up. On the other hand, free space techniques do not have these limitations and they can be applied to inhomogeneous materials and without contacting or destroying the structure.

In this paper, two experimental set-ups, based on free space techniques, are presented. The first is realized in an anechoic chamber and is used to validate the permittivity extraction procedure through measurements on materials with known characteristics. The second one operates in a laboratory hall simulating realistic conditions and is used to characterize construction materials with unknown permittivity.

II. MATERIALS AND METHODS

Fig. 1 shows a schematic of the free-space measurement set-up realized in the semi-anechoic chamber of ENEA Research center. The used system is based on a PNA-L N5230A vector network analyzer, 300 kHz to 6 GHz, by Agilent Technologies (at present Keysight Technologies).

Fig. 1. Schematic of the experimental set-up for construction materials characterization
The PNA ports are linked, by means of low phase variation cables, to two antennas (see Fig. 2). In a first set up, two simple open waveguide antennas (3.75 - 5.67 GHz band) have been used (see Fig. 3). Measurements have been performed by using the 85071E software by Agilent [11].

For the measurement system calibration a two-step procedure has been followed. In the first step, a short-open-load-thru (SOLT) calibration has been performed at the cable extremities to remove the network and cable errors. Then a Gated-Reflect-Line (GRL) calibration has been performed for removing antennas and fixture errors.

In the GRL calibration, a thru (see Fig. 3) and a metal plate (see Fig. 4) are used as calibration standards. The software defines a sample holder and a sample (the material), and needs to know the sample thickness, the distance between port 1 and the sample and the thickness of the metal plate used for the calibration (see Fig. 5). Finally, through a TDR measurement in the absence of the sample the search range used to locate the sample holder and the gate span and shape used for the free space calibration are provided (see Fig. 6). At the end of this procedure, the system is able to estimate the error network parameters and to move the reference planes at the metal plate surface. Concerning the algorithms used to convert scattering parameter measurements into complex permittivity values, the 85071E software makes available the Nicolson-Ross, the NIST and the transmission methods [11].
III. MEASUREMENT SYSTEM VALIDATION

In order to validate the anechoic chamber measurement setup, materials with known complex permittivity have been measured. In particular, panels of Plexiglas®, black PVC and white PVC have been considered. Table I shows the obtained results in terms of real ($\varepsilon'$) and imaginary ($\varepsilon''$) part of the relative permittivity as averaged over the 4-6 GHz band. The table also shows a comparison with literature data. A good agreement between the two can be observed.

Table I: Measurement of the complex relative permittivity of standard materials and comparison with literature data.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varepsilon'$</th>
<th>$\varepsilon''$</th>
<th>$\varepsilon^H'$</th>
<th>$\varepsilon^H''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas. [12][3GHz]</td>
<td>Meas. [12][3GHz]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plexiglas®</td>
<td>2.61</td>
<td>2.60</td>
<td>0.011</td>
<td>0.0148</td>
</tr>
<tr>
<td>PVC black</td>
<td>2.87</td>
<td>2.94</td>
<td>0.100</td>
<td>0.0999</td>
</tr>
<tr>
<td>PVC white</td>
<td>2.70</td>
<td>2.65</td>
<td>$\approx 0$</td>
<td>0.0347</td>
</tr>
</tbody>
</table>

IV. MEASUREMENT RESULTS

The experimental set up to perform measurements on construction materials has been assembled in a hall of the ENEA Research center laboratory (see Fig. 7). In this case, the used antennas are two double-ridged horns (1 – 18 GHz band). Moreover, in order to reduce the lateral leakage of the transmitted radiation, two towers of absorbing wedges have been placed at the panel sides. A preliminary measurement has been performed on the same Plexiglas® material tested in the anechoic chamber. Fig. 8 shows a comparison between the real part of relative permittivity (a) and imaginary part of the relative permittivity (b) as function of the frequency measured in the anechoic chamber (red line) and in the laboratory (blue line). A good agreement between measurements can be observed. The flatter frequency behavior of the laboratory hall measurement ($\varepsilon' = 2.62 \pm 0.3\%$) (average $\pm$ standard deviation) as compared to the anechoic chamber one ($\varepsilon' = 2.61 \pm 3.1\%$) can be explained with the better planarity of the Plexiglas® plate when placed in vertical position in the laboratory hall setup with respect to the horizontal arrangement in the anechoic chamber, which is more prone to sample bending. Moreover, the free-space laboratory set-up is likely subject to less spurious reflections as compared to the anechoic chamber one, where reflections from the floor might be non-negligible. Finally, different walls of construction material like brick, travertine, and tuff have been measured. As an example, Fig. 9 shows the set up in the presence of a brick wall (90×25×120 cm). The measurements for the real relative permittivity of bricks are reported in Fig. 10. The obtained results are close to literature data [13]. However, further investigations will be performed to improve the calibration technique in the presence of thick walls and to reduce the crosstalk between the two antennas.

Fig. 7. Experimental set up to perform measurements on a Plexiglas® panel

Fig. 8. Comparison between the real part of relative permittivity (a) and imaginary part of relative permittivity (b) as function of the frequency obtained in the anechoic chamber (red line) and in the laboratory hall (blue line) for a plexiglass sample
Fig. 9. Experimental set up to perform measurements on a brick wall

Fig. 10 Measured real relative permittivity of a brick wall as a function of frequency

REFERENCES