New Attempt to Building Materials Permittivity Measurements

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Abstract— In the work, measured results of complex permittivity of some commonly used building materials have been presented. The relative permittivity was measured in the coaxial line with TEM fundamental mode. Such a measurement condition corresponds to the free-space test, with a planar incident wave. In the literature different techniques were presented for coaxial lines permittivity determination, basing on measurements of complex values of scattering parameters. In proposed attempt the only magnitude of reflection and transmission coefficients have been used for relative permittivity determination. The relationship for calculation of the relative permittivity and analysis concerning the algorithm convergence has been discussed. Proposed calculation method allows applying this method for measuring the electric field, neglecting the phase assessing. As an example of material measurement the relative of permittivity of two kinds of bricks, concrete and cellular concrete were presented.

1. INTRODUCTION

Information about the attenuation of various building materials is important for the study of radiofrequency (RF) signal propagation in either indoor and outdoor environments [6, 7, 9, 12, 14, 20, 21]. Many researchers published investigations and numerical calculations that predict wireless local area network performance claim regarding the propagation losses through the walls at higher frequency range [2, 10, 11, 19]. In addition, ultra-wideband (UWB) wireless communication became the subject of intensive investigation due to its potential applications in high rate transmission [3–5, 15–17]. Despite that many aspects of UWB-based communication systems have not been deeply revealed the propagation of such signals and mainly the degradation of these signals in indoor environment is important issue. The signal propagation through the wall for electromagnetic waves, is governed, among other, by the properties of material in the propagation medium. Therefore, the knowledge of electromagnetic properties of building materials would provide significant insights into the capabilities and limitation of RF technology indoor and outdoor applications. Different attempts have been presented to study the propagation of RF signals through the walls. Pena et al. presented the permittivity and conductivity of brick and doubly reinforced concrete walls for the 900 MHz band [13]. Another electric parameter such as penetration loss of concrete and plasterboard walls over the frequency from 900 till 18000 MHz was analyzed by Zhang et al. [22]. On the other hand Suzuki et al. [18] presented reflection coefficients in the frequency range from 1.9 to 4 GHz for walls made of limestone blocks, glass and brick. The investigated building materials can be divided into two groups, i.e., drywall, wooden wall and glass having uniform structures and the ones such a brick and concrete with non-uniform structures. Muqaibel reported that in the frequency range from 2 to 8 GHz, the electric constants of materials with uniform structures tend to decrease with frequency whereas this parameter of non-uniform structure materials shows a more complex behavior [8]. For UWB investigation the Fourier transforms is especially recommended. In this case, using a short-duration electromagnetic pulse, the time-domain radiated measurements are used [8]. The incident pulse is partially transmitted through the slab and is partially reflected, with multiple reflections occurring between the slab boundaries.

2. MEASUREMENT SYSTEM

The permittivity measurements of solid materials are commonly performed using coaxial fixtures. At microwaves, the coaxial line technique is especially recommended for broadband frequency measurements. The method of measurements of ε based on determining the scattering parameters (S_{ik}) of the measured sample is the most popular [1]. In this work the method of permittivity determination has been developed for measurement of the slab materials in the free-space condition and in the coaxial lines. The main consideration of the developed method is to use only amplitude of the transmission (S_{21}) and reflection (S_{11}) coefficients. This means that permittivity of material has been determined uniquely from the measurement of the amplitude without measuring the phases of these coefficients. Such a method can be especially dedicated for measurements when measuring device is equipped only with amplitude measuring sensor. In the paper, proposed method is discussed for coaxial line technique with TEM mode. In such a case, the measured material completely fills the cross section of the holder.

For building material having grain-structure rather large samples are recommended for measurements to average out the fluctuation in the dielectric properties of the heterogeneous materials. This is why the coaxial lines (holder) should be enlarged to host large samples, Fig. 1. In the design of an enlarged measurement holder the outer conductor radius (b) is made larger but the inner conductor radius (a) should be adjusted for a characteristic impedance of $50\,\Omega$. However, there is a restriction for the diameters due to possible higher-order propagating modes which can be induced at higher frequencies. In the investigation the following holder diameters have been taken into consideration $a = 24,1$ mm and $b = 10.5$ mm. With such a coaxial holder measurements have been realized in the frequency range from 50 MHz to 5 GHz.

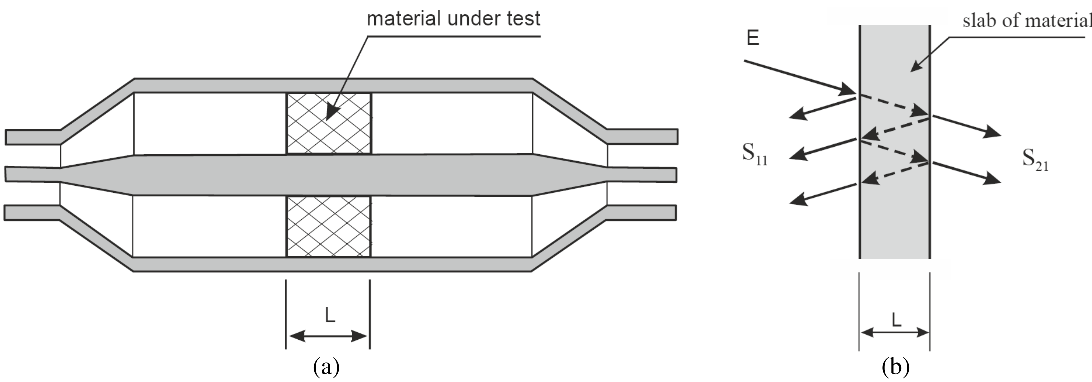

Figure 1: Schematic drawing of an enlarged coaxial line (holder), (a) longitudinal view, (b) multiple reflections in the sample of material.

The single-slab plane-wave model was developed to compute the relative permittivity of the measured material. The material is characterized by unknown complex relative electric permittivity $\varepsilon = \varepsilon' - j\varepsilon''$. The reflection and transmission S-parameters in coaxial line when the incident electromagnetic field is treated as plane wave can be interpreted as the infinite series of rays as a multiple reflections between the two surfaces of the sample — Fig. 1(b). The reflection and transmission of rays can be described according to the theory of optics [1] and the S-parameters are done in a complex forms.

In the presented method only magnitudes of S_{11} and S_{21} are available in the measurements, thus these equations cannot be solved in an analytical form. Zhihong et al. [23] discussed similar attempt but only samples with large attenuation were taking into consideration. In their case the multiple reflections in the sample were neglected, yielding to technique which was signifier simplification of the method. In this work no simplification was taken into account. Full model of multiple reflections allows to transformed equations based on multiple reflections into the following magnitude forms;

$$|S_{11}| = \left|\frac{\left(1-E^2\right)\left(1-e^{-2\gamma L}\right)}{(1+E)^2-(1-E)^2 e^{-2\gamma L}}\right| \tag{1}$$

$$|S_{21}| = \left|\frac{4Ee^{-\gamma L}}{(1+E)^2-(1-E)^2 e^{-2\gamma L}}\right| \tag{2}$$

where: $|S_{11}|$, $|S_{21}|$ — magnitudes of measured S-parameters,

$$E = E' + jE'' = \sqrt{\varepsilon' - j\varepsilon''}$$
$$\gamma = j\omega\sqrt{\varepsilon_0\mu_0}\sqrt{\varepsilon} \text{ — propagation constant,} \quad L \text{ — thickness of the sample.}$$

Two unknown values of permittivity (ε', ε'') can be solved iteratively form Equations (1) and (2). In this iterative approach the Newton's numerical method for root determination has been used. However, when solving such equations iteratively there is a problem with convergence and uniqueness of solution. The right side of Equations (1) and (2) are ambiguous functions of frequency. In fact, these relationships are also ambiguous functions of permittivity. From this point of view the unique solution can be obtained when good initial guess is available. To determine unknown and changeable values of ε' and ε'' in function of frequency the additional techniques should be introduced to omit this ambiguities. In this approach the E' and E'' as unknown parameters have been solved iteratively form Equations (1) and (2) and the final data can be determined according the relationship $\varepsilon' - j\varepsilon'' = E^2$. Such attempt yields to much stable solution.

3. RESULTS

The measurement equipment includes a vector network analyzer and a coaxial line with enlarged holder and calibration kit. The measured samples were located in the holder. Measurements were carried out for 4 samples as representative of building materials, i.e., a brick, a clinker brick, a concrete, and a cellular concrete. The thicknesses of samples were as follows: a brick $L = 7.1\,\mathrm{mm}$, a clinker brick $L = 8.4\,\mathrm{mm}$, a concrete $L = 9\,\mathrm{mm}$, a cellular concrete $L = 8.3\,\mathrm{mm}$. The obtained results of real and imaginary permittivity in frequency range from 50 MHz to 5 GHz have been presented in Figures 2 and 3.

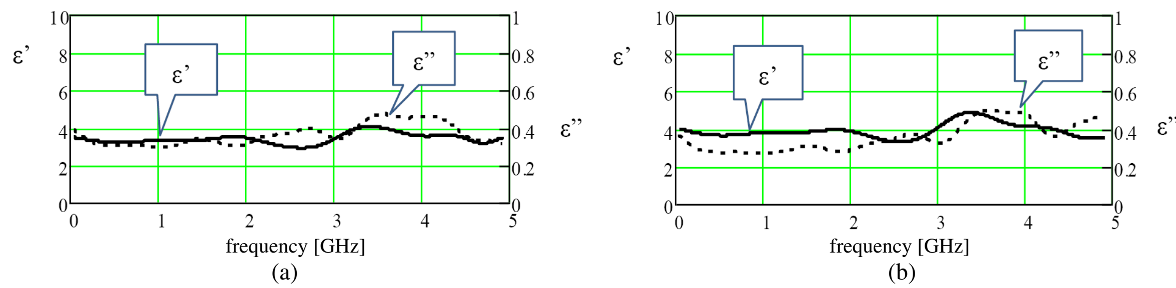

Figure 2: Real (ε') and imaginary (ε'') parts of the relative permittivity for: (a) brick, (b) clinker brick.

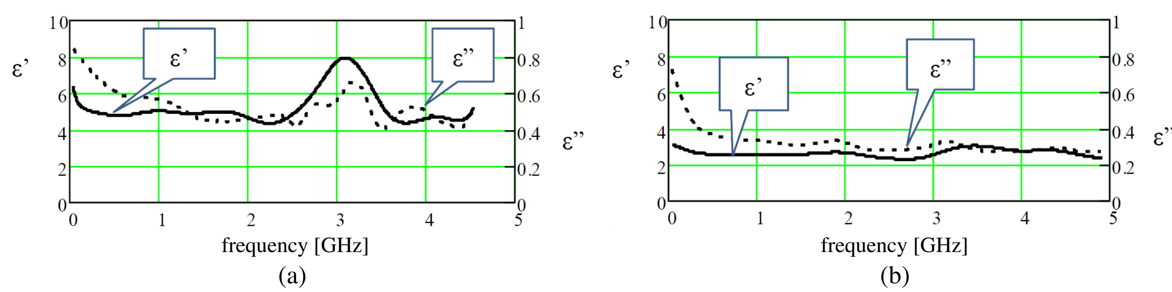

Figure 3: Real (ε') and imaginary (ε'') parts of the relative permittivity for: (a) concrete, (b) cellular concrete.

The relative permittivity of brick and clinker brick is quite similar in function of frequency and value of the real part is contained in between 3 and 5. The imaginary part value is in between 0.3 and 0.5. The highest values of permittivity were observed for concrete and for this building material real part is in between 5 to 8 and imaginary part is 0.4 to 0.65. On the other hand, the lowest value was measured for cellular concrete.

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