Measuring the Dielectric Constant of Paper Using a Parallel Plate Capacitor

Preliminary Communication

Vanja Mandrić Radivojević
Josip Juraj Strossmayer University of Osijek,
Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Croatia
vanja.mandric@ferit.hr

Slavko Rupčić
Josip Juraj Strossmayer University of Osijek,
Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Croatia
slavko.rupcic@ferit.hr

Mario Srnović
Josip Juraj Strossmayer University of Osijek,
Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Croatia
mario.srnovic@ferit.hr

Goran Benšić
Mechanical Engineering School of Osijek, Croatia
ured@ss-strojarska-tehnicka-os.skole.hr

Abstract *– This article is a result of measuring the dielectric constant of a dielectric used in studying the influence of dielectrics on the antennae reflection coefficients. A paper having a density of 0.797 g/cm3, moisture content of 0% and temperature of 210C, is used as a dielectric. Although the literature provides a lot of data on the dielectric properties of wood and paper, without direct measurement of the dielectric constant it is impossible to know its amount for the dielectric used in the defined frequency range. Dielectric constant measurements are performed in the frequency range from 100 Hz to 100 kHz, while the frequency range of its impact on the aperture antenna reflection coefficients is up to 2 GHz. The frequency range from 100 KHz to 10 GHz is interpolated and fitted by using measurements and available literature data and by respecting physical influences and phenomena and functional changes of the dielectric constant of paper within the given range.*

Keywords *– dielectric constant, loss factor, parallel plate method, dielectric constant measurement*

1. INTRODUCTION

Paper is made from mechanically treated wood so that water can penetrate, soften the fibers and make them more flexible. This wood processing splits and frays the fibers, producing microscopic fibers that contribute to the density and tensile strength of the manufactured paper [2]. The electrical parameters of paper depend on a large number of paper parameters: wood types and paper production methods, density, humidity, temperature and frequency. Each of these parameters can take a large range of values resulting in a large range and dispersion of electrical parameters of paper.

The earliest study dealing with the dielectric properties of the material was conducted by Debye in 1929, in which he introduces the term polar dielectrics [1]. One of the earlier measurements and studies of the dielectric properties of wood was carried out by Skaar in 1949 [2]. In this paper, we present that the dielectric constant of wood increases as the moisture content increases, and it decreases with increasing frequency of the applied field. In 1953, Kroner and Pungs [3] determined that the loss tangent depends on the moisture content and had a complex form.

Further studies (by James in 1975 [4], Gaikwad in 1981 [5], Torgovnikov in 1993 [6] and Kempf in 1997 [7]) dealt with various influences on the dielectric characteristics of the material (moisture, additions, material density, structural directions, frequency, temperature, etc.) and showed that these variables also have an important influence on the dielectric behavior of wood.

Dielectric constant measurement methods cover a number of studies and research. We would like to emphasize the following: Grove in 2004 [8] (Determining dielectric constants using a parallel plate capacitor); Venkatesh in 2005 [9]; Ganchev in 2006 [10] and Tereshchemko et al. in 2011. The main objective of this paper is to use parallel plate methods of measurement and different models and methods of calculating dielectric parameters and dielectric losses and their applicability to different materials.

A large number of studies have been carried to determine the dielectric constant of wood and paper, e.g. physical testing of paper [11] by Mark et al. in 2001 dealing with the dielectric constant of papers and different cellulosic materials. Studies by Sirvio [12] and Omari [13] in 2016 provide research and measurement of different types of paper for a number of new applications.

In this paper, we used the parallel plate method for measuring the dielectric constant of paper which involves placing a paper sample between two capacitor plates and measuring the resulting capacitance and other parameters used an equivalent capacitor model such as equivalent serial inductance, equivalent serial and parallel resistance, dissipation factor D=tanδ, the angle between the current and the voltage θ and capacitor Q factor.

In addition, linear interpolation of results available from literature is derived for the frequency range from 100 Hz to 10 GHz.

2. THE DIELECTRIC CONSTANT (PERMITTIVITY)

The dielectric constant is equivalent to relative permittivity εr or absolute permittivity ε relative to permittivity of free space ε0. The dielectric constant is generally a complex number which describes the interaction of a material with an electric field:

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon'(1 - j\tan\delta) = |\varepsilon| e^{-j\delta}, \quad (1)$$

$$\varepsilon' = \varepsilon_r \varepsilon_0, \quad (2)$$

$$\varepsilon'' = \varepsilon' \tan\delta, \quad (3)$$

where ε' is a real part of the dielectric constant or relative dielectric constant;

ε'' is an imaginary part of the dielectric constant or dielectric loss factor;

δ is a dielectric loss angle (Fig. 2a); and

$\tan\delta$ is loss tangent or the dissipation factor DF.

The dissipation factor is often used interchangeably with the term power factor which is approximately equal (Fig.2).

For a good dielectric $\varepsilon'' < \varepsilon'$ (Fig. 2b):

$$\cos\theta \approx \tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{energy\ loss\ per\ cycle}{energy\ \ stored\ per\ cycle}. \quad (4)$$

The real part of the complex dielectric constant ε' is a measure of how much energy from an external field is stored in a material.

The imaginary part of the complex dielectric constant ε'' is a measure of how dissipative or lossy a material is to an external field. The dielectric loss angle δ is the angle between the real part of the dielectric constant and the absolute value of the dielectric constant, and the loss tangent $\tan\delta$ is defined as the ratio of the imaginary part to the real part of the complex dielectric constant (Fig. 1) [14].

The dielectric constant ε is not constant by changing either the frequency or the temperature. Frequency dependence is important for the considerations and analyses performed for the purpose of this paper.

One of the most important intrinsic properties of paper as a dielectric material associated with the frequency is its polarization ability. Polarization is a quantity which characterizes the material polarization effect under the influence of the external electric field. The polarization effect is caused by the change in the spatial arrangement of electrically charged particles of the wood substance under the influence of an external electric field that changes with time and excites an alternating electric current in the wood (paper) (Fig. 2).

Under this condition, wood (paper) acquires an electric moment [6].

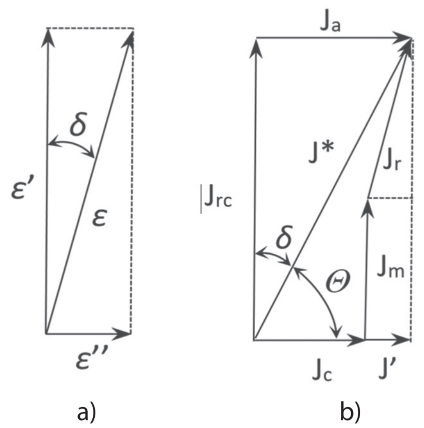


Fig. 1. a) Vector diagram of the complex dielectric constant ε; b) Vector schematic diagram of currents in wood under the action of an external alternating current field E: J* - total current; J_a active component of the current; J_{rc} - reactive component of the current; J_e - conduction current; J_m - instant displacement current; Jr - relaxation displacement current; J' - active component of the displacement current; δ - dielectric loss angle; θ - phase displacement angle [6].

The geometric sum of the electric field strength vector at a given point of the dielectric multiplied by the electric constant and of the polarization vector gives the electric displacement (electric induction) vector D at this point [11]:

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P}, \quad (5)$$

where $\vec{E}$ is electric field strength;

$\vec{P}$ is polarization of the material; and

ε_0 is the dielectric constant of vacuum.

The connection between the relative dielectric constant and the polarization of the material is as follows:

$$\vec{P} = (\varepsilon' - 1)\varepsilon_0 \vec{E}, \quad (6)$$

where ε' is the relative dielectric constant of the material.

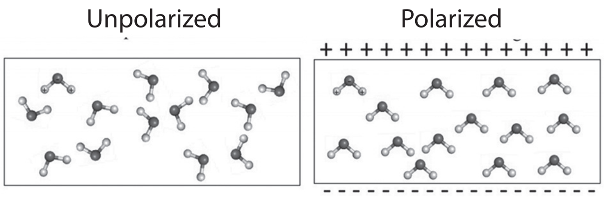


Fig. 2. Representation of material polarization in the presence of an EM field [15].

Summary polarization of wood (and paper as well) P, includes five kinds of polarization, which take place in moist heterogeneous dielectrics (Fig. 3):

$$P = P_e + P_a + P_d + P_v + P_z. \quad (7)$$

Electronic polarization P_e arises as a result of the shift of electron orbits relative to the positively charged nucleus under the influence of an external electric field.

Ionic (atomic) polarization P_a arises as a result of an elastic displacement of atoms in the molecules as well as due to a mutual displacement of charged ions of opposite signs in substances with ionic bonds.

Dipole (orientational) polarization P_d consists of the rotation of dipole molecules in the direction of an external electric field.

Upon application of an electric field to heterogeneous dielectrics, free electrons and ions start moving within each element's volume, and as a result, the element receives a dipole moment -> interfacial polarization P_v.

The material always has residual electrochemical or electrolytic polarization. At the instant of imposition of an electric field, an increase in electrolytic polarization P_z is observed. The increase of this kind of polarization is much slower than that of other types of polarization considered above. Electrolytic polarization of wood can be characterized by its time constant, which is approximately equal to 10^{-4}–10^{2} sec. [6].

The contribution of different kinds of polarization to the ε′ value is as follows: ε'_e - electronic polarization deposit; ε'_a - ionic (atomic) polarization deposit; ε'_d - dipole polarization deposit; ε'_v - interfacial polarization deposit; ε'_z - electrolytic polarization deposit; lgf - logarithm of frequency value [6].

If the relaxation time τ of dipoles of the dielectric is the same, then the connection between the complex dielectric constant and the frequency is to be found from the Debye equation:

$$\varepsilon = \varepsilon'_\infty + (\varepsilon'_s - \varepsilon'_\infty)/(1 + j\omega\tau), \quad (8)$$

where ε'_∞ is the limiting high-frequency relative dielectric constant;

ε'_s the limiting low-frequency relative dielectric constant (static);

ω the angular frequency; and

τ the macroscopic time of relaxation [6].

The polarization process depends on the time *t* as follows:

$$P = P_0 e^{-t/\tau} \quad (9)$$

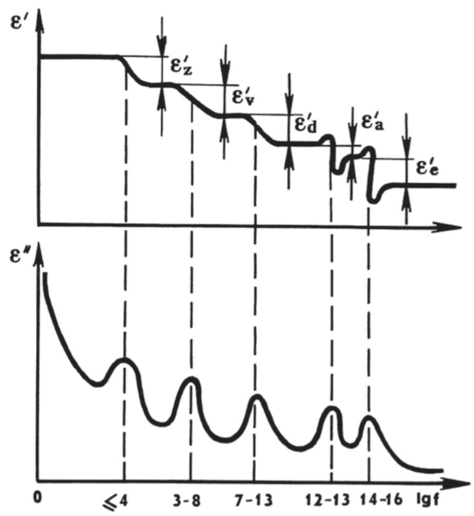


Fig. 3. Vector schematic diagram of dielectric constant ε′ and loss factor ε″ of wood versus frequency response characteristics with different kinds of polarization [6].

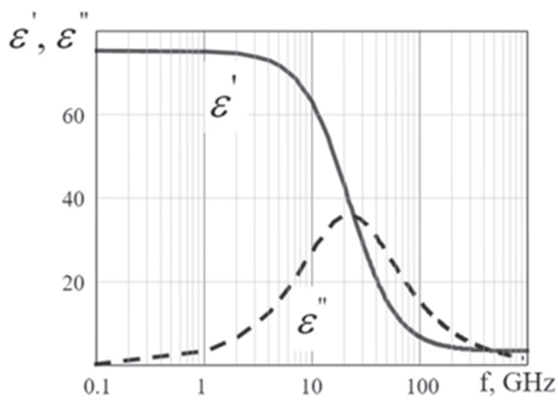


Fig. 4. Debye relaxation equation (8) for water at 30⁰C [10].

The resonant frequency f_c is identified by a resonant response in ε' and a peak of maximum absorption in ε'' (f_c = 22 GHz for water at 30^0C in Fig. 4).

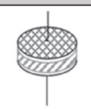
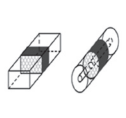
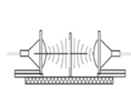
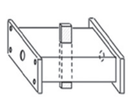
Figure 4 presents a dashed part of the diagram in Figure 3. It is focused on this dielectric constant measurement and interpolation.

3. PARALLEL PLATE METHOD - CAPACITOR METHOD

The measurement methods of dielectric material properties depend on physical and electrical parameters of the dielectric material to be measured, the frequency of interest, and the degree of accuracy required. The summary of techniques for measuring the dielectric properties of materials are presented in Table 1.

The parallel plate method uses a parallel plate capacitor as a sample holder and auxiliary parameter being measured, with the material under the measurement between plates. This method requires instruments for measuring capacitor impedance (LCR meter) or an impedance analyzer. The measured capacitance and dissipation factor is then used to calculate the real and imaginary parts of the dielectric constant. By using this method, all parameters of the equivalent model shown in Figure 5 were measured (L_s, R_s, C_p and R_p). In addition, measurements included measurement of the dissipation factor D=tanδ, the angle between the current and the voltage θ and the capacitor Q factor (Figures 4 to 6).

Table 1. Summary of techniques for measuring the dielectric properties of materials [16].

Method	Frequency range	Measuring parameter	Figure	Characteristics and applications
Parallel plate	up to 1.8 MHz *	ε_r		Accurate, best for low frequencies flat, thin sheet
Coaxial probe	100 MHz to 50 GHz	ε_r		Broadband best for lossy mat., liquids or semi-solids
Transmission line	100 MHz to 60 GHz	ε_r, μ_r		Broadband best for lossy to low lossy mat., machine able solids
Free space	1GHz to 100GHz	ε_r, μ_r		Broadband Non-contacting best for high temp., large, flat samples
Resonant cavity	3 GHz to 30 GHz	ε_r, μ_r		Accurate, best for low loss mat., small samples, substrates, thin films

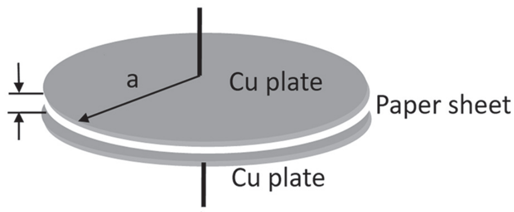
* [10]

The method uses a frequency range up to 1.8 GHz, has high measurement accuracy and involves a very simple sample preparation and setup. This method is also best for thin flat sheets of samples. The dielectric constant is derived by knowing the dimensions of the material and plates (width, length, thickness) and by measuring its capacitance and dissipation factor.

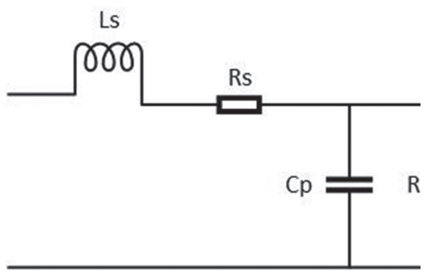
The dielectric constant is calculated as follows:

$$\varepsilon' = \frac{t_d \cdot C_p}{S \cdot \varepsilon_0}, \tag{10}$$

where t_d is the average thickness of sample (m), S is guarded electrode's surface area (m^2), ε_0 stands for permittivity of free space (8.854 × 10^{-12} F/m), and Cp corresponds to the equivalent parallel capacitance of sample (F) [13].



a)



b)

Fig. 5. a) Parallel plate capacitor with paper as a dielectric (the diameter of the plates 2a is 20 cm); b) an equivalent circuit for a capacitor.

In Fig. 5, L_s is equivalent series inductance, R_s is equivalent series resistance, R_p is equivalent parallel resistance and C_p is equivalent parallel capacitance.

4. EASUREMENT AND MEASUREMENT RESULTS

4.1. Measurement

The dielectric constant and the loss factor were measured by using the parallel plate method. Dielectric constant and loss factor measurements were performed as part of antenna aperture reflection coefficient measurements using different materials as radomes for this antenna [15], [17]. Thus, there was a need for information on the dielectric constant of wood and wood-based materials (paper) that are analyzed in this paper.

The weight of a sheet of paper used as a sample was 4.9719 g and the density of 0.797 g/cm^3.

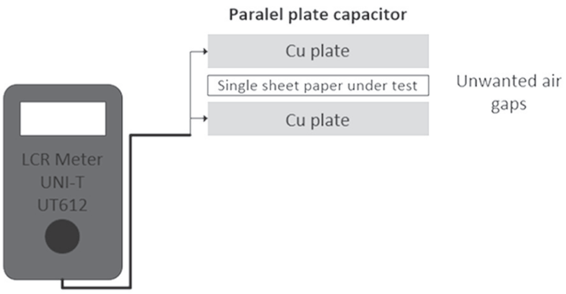
The measured value of capacitance may be thought of as two capacitors C_p and C_d in series; one is a perfect parallel capacitor filled with the dielectric material C_d and the other capacitor is a perfect parallel capacitor filled with air C_{air}:

$$\frac{1}{C_{meas}}=\frac{1}{C_p}=\frac{1}{C_d}+\frac{1}{C_{air}}=\frac{t_d}{S\cdot\varepsilon'\varepsilon_0}+\frac{t_{air}}{S\cdot\varepsilon_0} \quad (11)$$

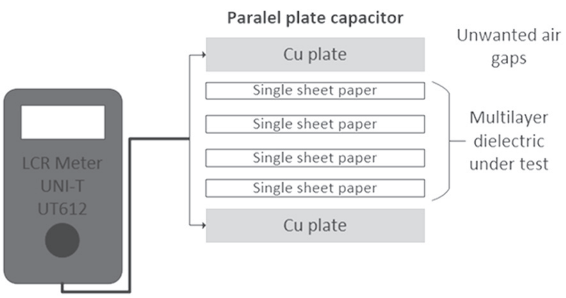
where t_d is the thickness of the dielectric material (m), t_{air} is the thickness of unwanted air gaps (m) (Fig. 6), S is the capacitor surface area (m^2), ε_0 is the permittivity of free space (8.854 × 10^{-12} F/m), and ε' is the permittivity of the dielectric material:

$$\varepsilon'=\left(\frac{1}{\frac{1}{C_p}-\frac{t_{air}}{S\cdot\varepsilon_0}}\right)\cdot\frac{t_d}{S\cdot\varepsilon_0} \quad (12)$$

The capacitor filled with air (C_{air}) is an equivalent capacitor of all air gaps between capacitor plates (Fig. 6). The influence of unwanted air gaps on the total capacity as well as on the dielectric constant and the loss factor is increased with an increase in paper layers and the thickness of the dielectric (Figures 7 and 8).



a)



b)

Fig. 6. Capacitance measurement (a) thin dielectric – single sheet paper dielectric, (b) thick multilayer dielectric.

Measurement equipment in these measurements consists of a circular shape capacitor of 8 cm in diameter and LRC meter UNI-T, type UT612.

Determining the dielectric constant value of paper at specific temperature and frequency range sometimes poses a problem. This problem appears when the dielectric constant and the loss factor in a given frequency range or at specific temperature are not available. In this paper, equation (8) available from literature does not help much because of frequency discrepancy between the experimental and theoretical determination and the lack of measured (precise) values of the interconstants of the particular observed sample (ε'_∞ is the limiting high frequency relative dielectric constant, ε'_s is the limiting low frequency relative dielectric constant (static); τ is the macroscopic time of relaxation time constants, appearing in this equation [5]).

4.2. Results from available literature

The analysis performed in this section is based on the measurements of the dielectric constant and loss factors of wood and wood-based materials (paper) in [4], [6] and [13]. [4] deals with measured values of the dielectric constant and loss tangent of white oak, Douglas-fir, and four commercial hardboards at frequencies from 20 Hertz (Hz) to 50 Megahertz (MHz), moisture conditions from oven dry to complete saturation, temperatures from -20°C to +90°C, and for the natural wood, with the electric field aligned with three principal structural orientations. Oven-dry wood is obtained by using the specimens originally conditioned and tested in equilibrium with 30 percent relative humidity. These specimens were dried in a vacuum oven at 60°C. Table 2 presents the real part and loss tangent of the dielectric constant as a function of frequency for tangential oak of density 0.74 g/cm^3 and temperature ranging between 5 and 25^{0}C.

Frequency	Real part of dielectric constant 5^{0}C - 25^{0}C	Tg δ 5^{0}C - 25^{0}C
100Hz	2.50 - 2.60	0.050 - 0.0076
1kHZ	2.30 - 2.30	0.033 - 0.021
10kHZ	2.20 - 2.20	0.035 - 0.033
100kHz	2.10 - 2.20	0.038 - 0.040
1MHz	2.20 - 2.20	0.047 - 0.046
10MHz	2.10 - 2.20	0.052 - 0.054

Table 2. Real part and loss tangent of the dielectric constant of density 0.74 g/cm^3 and temperature 5-25^{0}C [4].

[6] deals with dielectric parameters of wood and wood based materials.

From this reference, for the purpose of comparing measured values and, more importantly, for interpolation purposes, measured data of the dielectric constant and the loss factor for oven-dry paper of density 0.80 g/cm^3 and temperature 20-25^{0}C with vector E oriented perpendicularly to the sheet surface, were used.

The frequency range of the dielectric constant and the loss factor is from 100 Hz to 10 GHz. The term oven-dry wood (or paper) implies wood dried to a constant mass in the air at a temperature equal to + 103 ±2 ^{0}C [6].

Using the data from the above reference, the interpolation of the dielectric constant value and the loss factor for the frequency range above the measurement range was performed.

Table 3 presents measured values of the dielectric constant and the loss factor for oven-dry paper of density 0.80 g/cm^3 and temperature 20-25^{0}C with vector E oriented perpendicularly to the sheet surface based on data from [6].

From [13], which deals with the dielectric constant of paper made of pulp of several materials based on natural products, the values of the dielectric constant and the factor of losses for agave paper were used. The agave (*agave americana*) hand sheets were prepared according to a standard papermaking method (TAPPI T205 sp-954). This paper sheet is heterogeneous (cellulose, lignin, fines, and other impurities related to extraction processes of fibers and the origin of the plant) and hydrophilic, with rough surfaces and consequently a lack of flatness, necessary for a good contact with the electrodes [13].

Table 3. The dielectric constant and the loss factor of oven-dry paper as a function of frequency with density 0.80 g/cm3 and temperature 20-250C with vector E oriented perpendicularly to the sheet surface [6].

Frequency	ε′ 20^{0}C - 25^{0}C	Tgδ 20^{0}C - 25^{0}C	ε″= ε′·tgδ 20^{0}C - 25^{0}C
100	1.80 – 3.30	0.0030 – 0.012	0.0054 – 0.0396
1kHz	1.80 – 3.30	0.0030 – 0.015	0.0054 – 0.0495
10kHz	1.80 – 3.20	0.0044 – 0.021	0.0079 – 0.0672
100kHz	1.80 – 3.10	0.0067 – 0.031	0.01206 – 0.0961
1MHz	1.80 – 3.00	0.010 – 0.043	0.0180 – 0.1290
10MHz	1.80 – 2.80	0.014 – 0.053	0.0252 – 0.1484
100MHz	1.70 – 2.60	0.013 – 0.046	0.0221 – 0.1196
1GHz	1.60 – 2.20	0.011 – 0.032	0.0176 – 0.0704
10GHz	1.60 – 2.10	0.011 – 0.030	– 0.0630

A variation of the dielectric constant and loss factors with frequency for different papers are represented in Table 4.

Table 4. Real and imaginary parts of the dielectric constant as a function of frequency for agava americana paper with a hand sheet characteristic: hand sheet weight: 1.23 g, fines content: 46.55%, average fiber length: 0.52 mm, porosity: 7637 mL/min, roughness: 10.93 μm, crystallinity rate: 44.05 % and young modulus: 715.50 MPa [13].

Frequency	Real part of dielectric constant	Imaginary part of dielectric constant
100Hz	2.77	0.99
1kHZ	2.50	0.33
10kHZ	2.20	0.15
100kHz	2.00	0.09
1MHz	1.80	0.06
10MHz	0.80	0.01

The dielectric measurements were carried out at room temperature with an impedance meter (Agilent4294A) using a cell (Agilent 16451B) allowing direct measurement. The frequency range was between 100Hz and 10MHz. The samples were dried in an oven at 105^{0}C to remove residual water [13]. The dielectric constant is calculated by using equation (10).

4.3. Measurement results and interpolatione

The standard SMART LINE OFFICE A4, 80 g/m^2, MONDI paper was used as a sample paper for measurement. There are no information on dielectric properties for this paper. Since there is an extremely large number of different types of paper with different parameters, it was not possible to find information about the paper used. Measurements were made with the available equipment and they provided the measured data. Measurements were performed as part of measurements done for the antenna aperture reflection coefficient using paper as a radome for this antenna. The frequency range of the used aperture antenna is significantly greater than the scope of measurement and for that range of the frequency band the interpolation of the data from literature complies with the measured data.

Wood is a raw material for paper building. An oak sample was used in [4] to determine the dielectric constant and loss factors. The dielectric constant and the loss factor of paper used in these measurements and oak were compared [4] (with similar parameters, i.e. humidity, density and temperature), as illustrated in Fig. 9. It is evident that the dielectric properties of these two materials are very similar.

In the second part, the results obtained by using measurements of the dielectric constant and the loss factor of paper are compared with experimental values from [6] and [13] and presented in Fig. 10 and Fig. 11.

Figure 10 shows measured values of the dielectric constant and loss factors together with literature data [6] for paper of the same density, i.e. 0.8 g/m^3. Measurement of dielectric parameters is performed in the frequency range from 10^2 to 10^5 Hz, while the data from literature cover the full range of frequencies (10^2 - 10^{10} Hz). The data from 6 were interpolated for the approximate temperature at which measurements were performed (21.3^{o}C) and compared with the measurements. For the purpose of comparing data to the extent not covered by the measurements, measured data are fitted using the exponential function (equation (13)).

In this diagram, it can be seen that measured (and fitted) data of the real part of the dielectric constant, using the parallel plate method, are very close to the values mentioned in the references. It is therefore assumed that for the non-available frequency band the extrapolation of known values can be interpolated while maintaining the same conditions and parameters of the materials used.

The same procedure is performed for the data shown in Fig. 11, only by using the interpolated data of the previous analysis. The reason is that there is no data interpolated frequency band in [13].

What is still remarkable is that measured data on the dielectric constant and the loss factor of the measured paper and paper derived from the agave match very well, but there is a visible discrepancy in the curve passing through measured data and showing an exponential tendency to "saturation" and maintaining a constant value in the frequency range from 10^5 to 10^{10} Hz.

Table 5. Measured values of equivalent capacitor circuit parameters as a function of frequency for a paper dielectric sheet of density 0.797 g/ cm^3 (for a 5 g paper sheet) and temperature 21^{0}C.

Paper thickness [mm]	0.1		1		10	
f [kHz]	Cp [pF]	D	Cp [pF]	D	Cp [pF]	D
0.1	7932.0	0.214	911.0	0.219	166.0	0.392
1	6631.0	0.095	764.6	0.094	114.5	0.205
10	6125.0	0.041	707.2	0.042	96.4	0.087
100	5878.0	0.023	678.8	0.023	88.2	0.049

Table 6 presents linear *interpolated* values of the dielectric constant and the loss factor of oven-dry paper of density 0.80 g/cm^3 and temperature 21.3^{0}C with vector E oriented perpendicularly to the sheet surface based on data from [6]. The interpolation is derived for the data from Table 3 for temperature 21.3°C.

Table 6. Interpolated values of the dielectric constant and the loss factor as a function of frequency for oven-dry paper of density 0.80 g/cm^3 and temperature 21.3^{0}C with vector E oriented perpendicularly to the sheet surface [6].

Frequency	ε′	tgδ	ε″= ε′·tgδ
100Hz	2.19	0.00534	0.01169
1kHz	2.10	0.01860	0.03906
10kHz	2,06	0.00872	0.01799
100kHz	2.14	0.006084	0.01302
1MHz	2.11	0.008806	0.01858
10MHz	2.06	0.011718	0.02414
100MHz	1.93	0.011181	0.02158
1GHz	1.76	0.009352	0.01646
10GHz	1.73	0.009139	0.01594

Table 7. Interpolated values of the dielectric constant and the loss factor as a function of frequency of tangential oak, the dielectric constant and loss tangent of density 0.74 g/cm^3 and temperature 21^{0}C [4].

Frequency	ε′	tgδ	ε″= ε′·tgδ
100Hz	2.58	0.18318	0.47260
1kHz	2.30	0.04370	0.10051
10kHz	2,20	0.07260	0.15972
100kHz	2.18	0.08720	0.19009
1MHz	2.20	0.10120	0.22264
10MHz	2.18	0.11554	0.25188

Table 7 presents linear *interpolated* values of the dielectric constant and the loss factor of tangential oak, the dielectric constant and loss tangent of density 0.74 g/cm^3 and temperature 21^{0}C.

The parallel plate method is suitable for thin dielectrics and deviations and errors due to unwanted air gaps are the smallest in the dielectric constant and loss factors for dielectric thickness of 0.1 mm.

Therefore, if the values of the real and the imaginary part of the dielectric constant of the tiny dielectric (0.1 mm) are taken as a reference, the deviations and errors of these parameters at two thicknesses (1 and 10 mm) can be determined. These errors are listed in Table 8.

It can be seen that the relative error of the dielectric constant increases with increasing of the dielectric thickness, i.e. an increase in unwanted air gaps as well as the dispersion of the electric field outside the space between the capacitor plates.

Table 8. Relative errors of the real and the imaginary part of the dielectric constant with the dielectric parameters of smallest thickness dielectric (0.1 mm) as a reference.

Freq.	1kHz		10kHz		100 kHz	
t_d mm	Real $_{Err}$ %	Ima $_{Err}$ %	Real$_{Err}$ %	Ima $_{Err}$ %	Real $_{Err}$ %	Ima $_{Err}$ %
0.1	-1.,49	-62.93	-22.81	-85.21	-25.96	-92.043
1	-16.16	-64.01	-22.56	-85.15	-25.61	-92.1871
10	-30.99	-63.91	-42.04	-87.14	-46.90	-93.3626

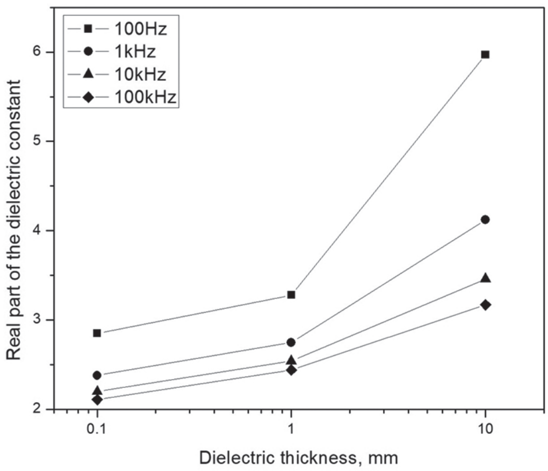


Fig. 7. A plot of the real part of the dielectric constant versus the dielectric thickness for paper sheet with density 0.797 g/cm^3 at 21^0 C calculated using equations (10) and (3) from measured values presented in Table 5.

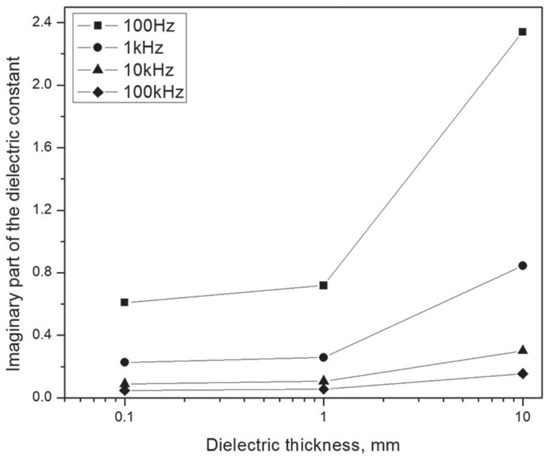


Fig. 8. A plot of the imaginary part of the dielectric constant versus the dielectric thickness for paper sheet with density 0.797 g/cm^3 at 21^0 C calculated using equations (10) and (3) from measured values presented in Table 5.

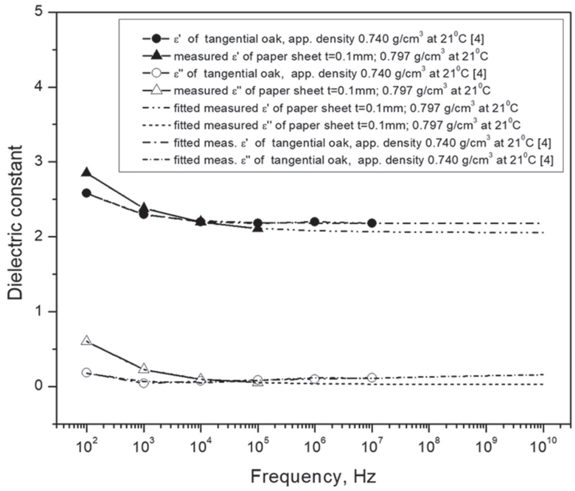


Fig. 9. Measured, linear interpolated and fitted dielectric constant (real and imaginary part) as a function of frequency for 0.1 mm paper sheet and measured dielectric constant of oak (tangential) [4].

The number and size of unwanted air gaps are too large for a large number of paper sheets to cause significant errors when using the parallel plate method. Therefore, a single sheet of paper was taken as relevant, and the results of the comparison with the measured values in the literature confirm this claim. The measured values of the dielectric constant and the loss factor when compared with the measurements in the literature show good value matching.

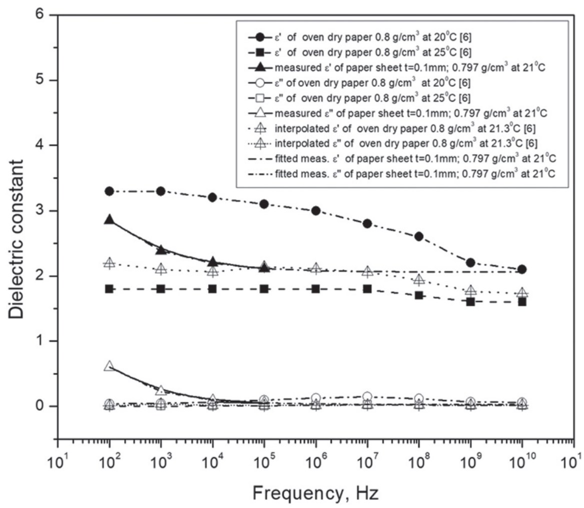


Fig. 10. Measured, linear interpolated and fitted dielectric constant (real and imaginary part) as a function of frequency for 0.1 mm paper sheet and measured dielectric constant of the oven-dry sheet paper [6].

Measured data as well as measured data from the literature are fitted and inserted in Figures 9 to 11. Exponential fitting of results was performed according to the formula:

$$y = A\exp(-x/t) + y_0 \qquad (13)$$

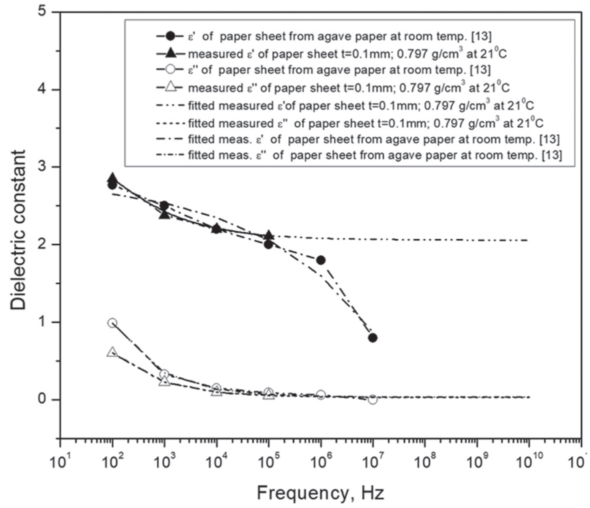


Fig. 11. easured, linear interpolated and fitted dielectric constant (real and imaginary part) as a function of frequency for 0.1 mm paper sheet and measured dielectric constant of the papers with fibers from agave [13].

Maximum deviations from the fitted result of measurement and measurement results according to the literature at the frequency of interest (2 GHz) are presented in Table 9.

Table 9. Relative errors of the real and the imaginary part of the dielectric constant of fitted measured results and measured results from literature

Dielectric constant	Real part error %	Imag. part error %
Tangential oak paper [4]	-5.86	+79.85
Dry-oven paper [6]	-17.24	-49.02
Agava paper [13]	-	+11.28

The deviations of the real part of the dielectric constant do not exceed 18%, while the deviations of the imaginary part are significantly higher. This can be explained by the very low values of the imaginary part and hence the greater probability of measurement and equipment inaccuracy. Furthermore, it is highly likely that the exponential fitting model is not appropriate for an area of about 2 GH for the imaginary component of the dielectric constant.

5. CONCLUSION

In this paper, the parallel plate method is used to measure capacitor parameters with paper as a dielectric.

Based on the measurement, in the frequency range from 100 Hz to 100 kHz, the values of the real and the imaginary part of the dielectric constant of paper are calculated. Furthermore, the fitting of measured data was made by using the exponential function for the entire range of frequencies of interest (from 100 Hz to 10 GHz). The obtained values are compared with linear interpolated and exponential fitted values of different paper of the same density, temperature and initial values of the dielectric parameters at the frequency range from 100 Hz to 10 GHz from the available literature. This comparison showed relatively small deviations of the real part of the dielectric constant of up to 17.5%. Bigger deviations of the imaginary part of the dielectric constant are the result of very low measured values as well as the imprecision of the measured equipment and the inadequacy of the exponential fitting in that frequency bandwidth. The measured values of the dielectric constant and the loss factor correspond well to the measurements in the literature. The data thus obtained are necessary for the simulation and measurement of the reflection coefficient of the antenna aperture with a radom made of materials of similar dielectric characteristics such as paper and paper-based materials. Important applications of paper could be shown as dielectric materials in the construction of radomes. This will be further elaborated in our future work related to this paper.

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