Numerical and experimental investigation of metamaterial structures used in non-destructive dielectric material testing

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Abstract. In the paper the investigation of the dielectric properties of dielectric material will be described, using an artificial metamaterial structure over the aperture of waveguide sensor with aim of increasing the sensitivity of classical waveguide sensor. The possibility to use a metamaterial structure for upgrading properties of classical waveguide sensor will be emphasized by numerical simulation of 2D metamaterial structure properties and experimental measurements to determine dielectric properties of dielectric materials. The mechanical properties of the dielectric samples, alder wood in our case, are determined also by Dynamic Mechanical Analysis, in order to validate the microwave approach.

1. Introduction

Dielectric materials are the poor electric conductors (non-ideal insulator). Starting from paper and ending to special dielectrics used in solar cells, dielectrics are used in various domains with interesting practical applications. The dielectric properties determine the electrical features of materials, and these give information useful for their further utilization and characterization [1]. The dielectric properties are usually determined in resonant circuits [2], electronic bridges [3], transient methods in DC [4], etc. Measurements on low-loss materials using closed and open cavity resonators, and dielectric resonator methods have been used since 1990 [5] but microwaves (MW) measurements can be carried out now by velocity-modulated tubes, cavities, waveguide technologies and free space configurations [6]. Using the interactions between microwave and the materials, microwave waveguide sensors [7] can measure dielectric properties of materials.

Microwave waveguide sensors measures properties of materials based on microwaves interaction with materials, providing information about dielectric properties of investigated dielectric material, characterized with complex permittivity, learning information about moisture content, density, structure, and even chemical reaction [8]. Microwave sensors provide high speed and noninvasive measurement compared with conventional sensors [9]. The sensitivity of conventional sensors using microwave waveguides can be improved using metamaterials structures. In a large range of applications, the information about dielectric properties are required, but not only these, sometimes, for natural dielectric as wood, the direction of the wood grain that is changing from point to point,
making the permittivity tensor to become a random values [10]. Wood is a natural, ecological material, being used in a large range of goods, from furniture to loading bearing [11]. Wood being a heterogeneous material, it has variable properties that can be a bottleneck in some industrial applications where the material properties should be strictly defined to assure prime quality. Over the past decades the traditional use of wood as construction material evolved to a modern, widely differentiated application domains, as sonic barriers or components in small wind turbine blades, etc.

The purpose of the paper was to apply a modern microwave measurement method to determine the dielectric properties of wood samples and compare the results with Dynamic Mechanical Analysis.

2. Samples and methods

2.1. Samples

Wood is an anisotropic dielectric and can be considered as a crystal, with 3 axes of coordinates reported to the wood grain direction [12]. The high quality assurance requires rigorous testing methods. These requirements are also implemented in wood industry, sometimes even starting from the primary wood processing.

Alnus Glutinosa is the type of alder growing naturally in entire Europe, north-west of Asia and north of Africa, named also black alder or European alder. The fibers are thin and uniform, straight or twisted, depending on the weather conditions along the time, the annual rings are less visible and the pores are small and spread throughout each ring. Despite it is not recommended for resistance structure because it is a soft wood, it can be used in sonic barrier due to it resistance in water and at high temperature. Samples taken into consideration were cropped from plates of alder, to fit the inside of the rectangular microwave waveguide and others having the characteristics described in table 1.

### Table 1. Samples characteristics for DMA testing

| Cases - Load direction reported to wood structure | Samples | Moisture Contents % | Density $\rho$[g/cm$^3$] | Sizes [mm] |
|-------------------------------------------------|---------|---------------------|--------------------------|------------|
| Case 1, Tangential Bending Moment ($M_{bTg}$)   | Alder 1. | 14.8                | 0.542                    | 50 9.73 4.92 |
|                                                 | Alder 2. | 14.1                | 0.520                    | 50 9.80 4.94 |
| Case 2, Radial Bending $M_{bR}$                | Alder 3. | 14.8                | 0.517                    | 50 9.74 4.75 |
|                                                 | Alder 4. | 14.7                | 0.525                    | 50 9.84 4.97 |

2.2. Microwave testing

Measurements were done on the Vector Network Analyzer VNA MS2028C with connected close waveguide section with metamaterial structure in front of waveguide opening (Figure 1) [13]. The samples – alder wood – were placed in waveguide hard by the walls of waveguide, therefore the corrections were not necessary in relative permittivity calculation. The transmission – reflection method was used for measurement and Nicolson-Ross-Weir (NRW) conversion process [14,15] was used for relative permittivity calculation. The values of $S_{11}$ and $S_{22}$ parameters, which were measured and parameters of critical wavelength in waveguide, the sample length and the wavelength in free space were used in calculation. Thus, transmission (T) and reflection (R) coefficients are extracted from S-parameters measured by VNA using the scheme presented in Figure 2.

![Figure 1. Microwave testing experimental set-up.](image-url)
Figure 2. Schematic procedure of NRW method.

The reflection coefficient $\Gamma$ is calculated \[16\]

$$\Gamma = X \frac{X^2 - 1}{X}$$

where $|\Gamma| < 1$, in order to calculate the root, $X$ being replaced consequently by S parameters. $X = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}}$. The transmission coefficient is calculated

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - \Gamma(S_{11} + S_{21})},$$

noting $\Lambda$ as

$$\Lambda = \left(\frac{j}{2\pi d} \ln(\Gamma)\right)^2.$$ Using cut-off wavelength $\lambda_c$ and free space wavelength $\lambda_0$, $\lambda_{0g}$ can be determined

$$\lambda_{0g} = \frac{1}{\sqrt{\frac{\lambda_0^2}{\lambda_c^2} - 1}}.$$ Thus, complex permeability and respective permittivity are given by

$$\mu^* = \frac{\lambda_{0g}}{\Lambda} \left(\frac{1 + \Gamma}{1 - \Gamma}\right)$$

and

$$\varepsilon^* = \frac{\lambda_0^2}{\mu^*} \left(\frac{1}{\lambda_c^2} + \frac{1}{\Lambda^2}\right).$$

Thus, only transmission $S_{11}$ and reflection $S_{21}$ are used to extract the complex permittivity.

2.3. DMA testing

The tests performed at DMA consist in three points flexural bending. Figure 3 a presents the bending moment ($M_b$), orthogonal to the force. We have taken into consideration two load cases, according to direction of bending moments towards wood fibers. The mechanical properties $E'$, $E''$ and $\tan\delta$ were measured with DMA 242C Netzsch \[17\].

Figure 3. Load direction vs. wood structure: a – sample for dynamic bending test after ASTM D5023 – 07; b –tangential bending moment $M_{bTg}$; c –radial bending moment $M_{bR}$

The measurement have been carried out at $30\pm0.1^\circ$C, frequency 1Hz, during 10 minutes, 6N force amplitude and deflection 30$\mu$m.

3. Numerical simulation

Finite difference time domain (FDTD) method is used to obtain electromagnetic field distribution, after the scheme suggested by \[18\] to the Maxwell equations. The electric field vector components are orthogonal to the magnetic field vector components upon half-cell. The electric and magnetic field are evaluated under alternative half time steps. The electric and magnetic field components of TE mode are expressed by the total field FDTD equations. The simulation has been carried out in XFDTD software by REMCOM \[19\].The simulations of the electric field (TE$_{10}$ mode) on symmetry center axis of rectangular wave guide having size=22.86mm $\times$ 10.16mm are carried out: a) free space wave guide,
\[ \varepsilon_r = 1 \] and b) wood sample inside the waveguide, operating at 7.5GHz frequency (30 s). The time is set-up short because it is known that microwaving wood leads to drying and dielectric properties vary with temperature. The electric and magnetic field distribution inside the waveguide having the wood sample placed closely to the opening, are presented in Figure 4, working frequency being 7.5GHz. Since the penetration depth of wood is close to the penetration depth of microwave [18], the microwaves interacts in all volume of sample. The wave will be reflected on each interface, from air (cavity) to top surface and from lower surface of sample to air (cavity).

**Figure 4. Distribution of electromagnetic field with sample inside: a) \( E_x \); b) \( H_x \).**

The reflected and transmitted components at each interface contribute to the resonance of stationary wave inside the sample and leads to a microwave absorption peak forward from the surface subjected to incident microwaves. It can be seen that a stronger stationary wave with high amplitude is resulted from the interaction of the incident and reflected wave, due to difference between dielectric properties of air and sample.

4. Experimental results

The S parameters of metamaterials structure have been measured with Network Analyzer Agilent E5071B USA[20]. The results are presented in Figure 5.

**Figure 5. S parameters of metamaterial structure.**

The experimental measurements have been carried out using the metamaterial structure in the front of a BJ-100 rectangular waveguide having \( a = 22.86 \text{mm}, b = 10.16 \text{mm} \) dimensions. The length of the waveguide is 60mm. The waveguide walls are PEC. The flange has size of 40mm x 50mm. The metamaterial structure is formed by \( 5 \times 5 \) split ring resonators (SRR) having the resonant frequency in the range of the system operating frequency [13]. The metamaterial structure was realized with ROGERS RT/DUROID 5870 films. The wood sample was placed in the near electromagnetic field of waveguide sensor having the 2D metamaterial structure in front of it, Figure 1. Two type of samples having same high and width to fit inside the waveguide were taken into consideration: sample 1
having 50mm length and sample 2 having 30mm length. The purpose of this test is to determine the resonant frequency peaks displacement due to modification of sample dielectric properties with frequency. The results of measurements are given in Figure 6.

![Figure 6. Microwave measurements - dielectric constant vs frequency: a) sample 1; b) sample 2](image)

In order to validate the method, the samples were destructive tested using Dynamic Mechanical Analyzer DMA 242C by Netzsch Germany.

![Figure 7. Representation of storage and loss modulus of alder in time: a) radial structure; b) tangential structure](image)

Dynamical modulus of elasticity is smaller than statically one indifferent of loading. Thus, in case of longitudinal flexural, statically elastic modulus is 1.48 times higher than elastic modulus determined by ultrasound method [21, 22] and 1.68 times higher than dynamic modulus determined with DMA.

5. Conclusions
The possibility to use of artificial metamaterial structure in microwave waveguide for improving sensitivity properties of classical waveguide sensor is taken into account. The microwave methods are nowadays used especially for the dielectric materials investigation, their advantages allowed us to measure without contact medium. The dielectric properties of wooden samples were measured in X – band frequency region and results showed the frequency dependence of wood dielectric properties. The knowledge of this dependence is important for very precise tracking the dielectric properties changes connecting with various factors which occur in processes connected with wood processing and is important also in restoration processes of old wood artefacts where the quality of old wood should be known.
The numerical analysis has allowed the determination of optimal frequency required to excite the microwave waveguide in order to test wood samples. The mathematical allowed the determination of reflection and transmission coefficients using S-parameters. The obtained values for dielectric characteristics have been validated by DMA analysis. Using the results obtained by DMA, and completing with dielectric characteristics, a complete characterization of alder samples taken into consideration, promoting them for use in different practical application as sound barrier, acoustic cavities, etc.

Future works will take in analysis other local species of wood for further development of new applications taking into consideration also the moisture content.

Acknowledgements
This work was partially supported by a grant of the Romanian Ministry of Research and Innovation, CCCDI – UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0239/60PCCDI 2018 within PNCDI III, Nucleus Program PN 19 28 01 02 and by the Slovak Research and Development Agency under the contract No. APVV-17-0218.

References
[1] Baker-Jarvis J, Geyer RG, Grosvenor JH, Janezic MD, Jones CA, Riddle B, Weil CM and Krupka J 1998 IEEE T Dielect. El. Ins. 5(4) 571
[2] Anis M, Jostingmeier A, Meyer T and Omar AS 2005 IEEE AP-S 1 421
[3] Singh S, Mohsin MM and Masood A 2016 IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES) 1
[4] Walker E, Glover PWJ and Ruel J 2014 J. Geophys. Res.Sol- EA 119 (2) 957
[5] Bahl I and Ely K 1990 Microwave J. 33 131
[6] Okress EC ed 2017 Microwave Power Engineering: Generation, Transmission, Rectification, Vol. 1 (London: Academic Press)
[7] Istenikova K and Faktorova D 2012 Electr. Rev. 88 (7b) 223
[8] Baena JD, Bonache J, Martin F, Sillero RM, Falcone F, Lopetegi T, Laso MA, Garcia-Garcia J, Gil I, Portillo MF and Sorolla M 2005 IEEE T. Microw. Theory 53 (4) 1451
[9] Lai A, Itoh T and Caloz C, 2004 IEEE Microw. Mag. 5 (3) 34
[10] Torgovnikov GI 1993 Dielectric Properties of Wood and Wood-Based Materials (Berlin: Springer Verlag)
[11] Aichholzer A, Arthaber H, Schuberth C and Mayer H 2013 Eur. J. Wood Wood Prod. 71 (6) 779
[12] Olmi R, Bini M, Ignesti A and Riminesi C. 2000 J. Microw. Power EE 35 (3)135
[13] Ittimie N, Faktorová D, Fabo P, Savin A and Steigmann R. 2018 IOP Conference Series: Mat. Sci. and Eng. 444 022007.
[14] Nicolson A and Ross G 1970 IEEE T. Instrum. Meas. 19 377
[15] Weir WB 1974 Proceedings of the IEEE 62 33
[16] Rutpralom T, Chamnongthai K, Kumhom P and Krairiksh M 2006 IEEE Int Symp Circ S 4 1351
[17] Stanciu MD, Curtu I, Grimberg R and Savin A 2013 Pro Ligno 9 (4) 587
[18] Rattanadecho P 2006 Chem. Eng. Sci. 61(14) 4798
[19] ZhangQ, Yuan CW and Liu L 2012 IEEE T on Microw. Theory 60 (4) 1018
[20] Savin, A, Steigmann R, Bruma A and Sturm R 2015 Sensors 15 (7) 15903
[21] Bucur V 2006 Acoustics of Wood (Berlin, Springer)
[22] Páneck M and Trgala K 2016 Forestry J. 62 (3) 164