Utilizing wave polarization in microwave characterization of heterogeneous anisotropic materials with application to the wood industry

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Abstract—**This paper presents a novel approach to microwave non-contact, non-destructive testing of wood, investigating additional indicators of wood structure, in particular the significance of wave polarization in transmission measurements. Contribution of wave polarization to wood characterization is studied, considering detection of rapid and gradual variations in wood structure, determination of moisture content and density distribution along the sample, as well as bulk properties detection. A set of microwave sensors in a collinear arrangement was used in two orthogonal linear polarizations. Significant findings are reported, in particular polarization dependence of moisture related attenuation, as well as improved defect detection accuracy when measurements in two orthogonal linear polarizations are considered. In addition, sorting wood samples into categories is considered and the advantages of this approach are presented.**

Keywords-Non-destructive testing, free-space microwave transmission measurement, polarization, heterogeneous media, wood, moisture content, density.

I. INTRODUCTION

Wood is a heterogeneous, anisotropic media and microwave transmission through a wood sample depends on several of its properties. Moisture content (MC), density, grain orientation and variations in wood structure are properties closely related to the quality of wood and hence need to be measured in the wood processing industry. Non-destructive, non-contact microwave inspection of wood shows great potential for application in industry. However, a detailed literature study, reported by the authors et al. [1], shows that microwave techniques are still not commonly used. Variability in wood structure presents a major problem and additional indicators of wood properties in the measured microwave transmitted wave would be very beneficial. Current microwave sensing techniques use the attenuation and phase change in the transmitted wave to obtain information about several wood properties of interest. Variation of the transmitted signal along the sample is used to detect defects and variations in wood structure (i.e. heterogeneity) [2]. The integrated average of signal attenuation and phase shift over the sample length relative to propagation through the air provides information about the moisture content and density of the sample [3, 4]. The grain angle is determined measuring depolarization of a linearly polarized wave transmitted through the sample [5].

Measurements in two orthogonal polarizations are often reported in the literature [3-7]. However, no effort was made to quantify the advantages of that approach. In most cases, the benefit of introducing additional polarization is stated as an improved R^2 for total regression with a wood property of interest. None of these studies have given us a clear indication of the actual benefit of such a measurement arrangement. This paper reports why including transmission coefficients for two orthogonal linear polarizations is beneficial for wood testing and what additional information these measurements bring. The results of a Principal Components Analysis (PCA) are also reported, further demonstrating the relationship between measurements in two orthogonal polarizations and wood properties of interest, namely moisture content and density.

A Focused Beam Antenna Technique [8] was used, as its affordability and simplicity recommend it for industrial application [1]. A detailed description of the measurement system is presented in Section II of this paper. In Section III, an empirical study of wood heterogeneity is presented, looking for defects and other, less prominent, variations in wood structure, whilst considering the advantage of transmission coefficient measurement in two polarizations. Sample categorization is considered and justified. Section IV considers measurement of wood density and moisture content. Novel findings about the behavior of the wave in two orthogonal polarizations are reported, offering a way to distinguish between two contributors to the wave attenuation, namely, moisture content and density.

II. MEASUREMENT SETUP

The transmission measurement was performed using the Agilent Network Analyzer PNA-L N5230A, at 201 frequency points over an 8 to 12.4 GHz range, at temperature T=20ºC. The measurement system, utilizing a pair of linearly polarized horn antennas, is presented in Fig 1. To create a Focused-beam Antenna, a pair of paraffin lenses ($\varepsilon r=2.23$) was used to spot-focus the diverging beam from the transmitting horn antenna. The resulting converging beam, with a 6cm beam waist at the focal distance of 17cm, allowed wave interaction with relatively small volume of the sample, offering high resolution, while minimizing scattering from surrounding objects and diffraction from sample edges. Diffraction effects are avoided only for the case when the minimum transverse dimension of the sample is greater than three times the beam-width of the antenna at the focus [8]. Thus, at least 18 cm wide sample was needed to avoid the diffraction effects. As this was not fulfilled for the first set of 22 samples, the diffraction from the sample edges was mitigated by positioning the sample between two microwave absorbers.

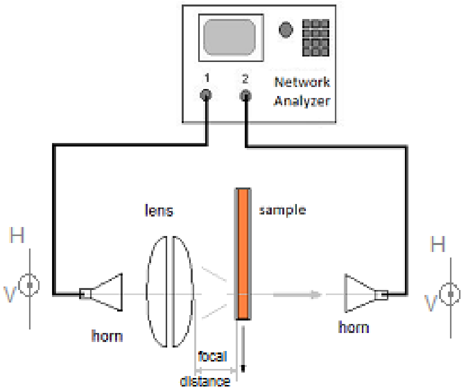

Figure 1. The measurement setup for heterogeneity study

Two calibration procedures are commonly used in free space transmission measurements [8]. In this work, SOLT procedure using Agilent Calibration Kit 85052D was performed to calibrate the Network Analyzer and a pair of coaxial cables connected to each of its ports. The second calibration was performed to eliminate free-space setup systematic error, thus dealing with uncertainty sources such as attenuation and mismatch in the components connected after the reference plane of Network Analyzer calibration (i.e. coaxial to waveguide transition of horn antenna), as well as multiple reflections between the two antennas and the surface of the sample. In this work, the TRL (Thru-Reflect-Line) [9] calibration procedure was chosen as an affordable solution and it was performed using a custom-made Matlab code.

In the wood testing experiments, samples under test were positioned horizontally at the focal distance in front of the lens antenna, so that horizontal polarization of the antennas was aligned with the axial direction of wood. Transmission measurement was performed first using both receiving and transmitting antennas in vertical polarization (VV) and then repeated with both antennas in horizontal polarization (HH). Both cross-polar polarizations (HV and VH) were also measured. Complex transmission coefficient (S_{21}) was measured at sixteen points along the sample, with two successive measurements being one centimeter apart. The beginning and end of the sample was not scanned to avoid the effect of diffraction from the sample edge.

Data files were processed in Matlab, calculating transmission magnitude and phase variation along each sample. Frequency averaged graphs (over 201 frequency points) were produced for magnitude and phase. For each graph, statistics such as range, mean and standard deviation were also calculated. In the final step of data processing, each coefficient was averaged over the whole length of a sample, in order to get a bulk value of attenuation and phase shift for each sample.

In addition to microwave measurements, forty CT scans were made for each sample, starting 5cm from the sample's edge and scanning a 20 cm length, with a 5mm step. CT scans were processed using Dicom Viewer MxLiteView, which offered images and read-out values directly proportional to density. The weight, length, width and height of each sample were measured before every microwave measurement, allowing determination of moisture density of each sample. Moisture content (MC) on dry basis was calculated as a ratio of the mass of water and the mass of dry matter in wood, expressed as a percentage [1]. The mass of dry matter in wood and bulk density were determined after oven drying each of the measured samples at 104ºC. Microwave results were compared with the data obtained using CT scans as well as a visual inspection.

III. MICROWAVE HETEROGENEITY MEASUREMENT

In this section, we report an improvement in microwave defect detection and categorization accuracy utilizing transmission measurements in two orthogonal linear polarizations. Twenty two oven-dried Pinus Radiata samples (0% MC), offering commonly met variations in wood structure, were measured at room temperature (20ºC) using the microwave system presented in Section II. All samples were 40 cm long, with cross section of 5 x 10 cm.

Using a visual and CT inspection, structural features of samples under test were identified: knots, remains of branches, needle flecks, resin pockets and change in grain direction. Distinguishing between the features was not the aim, but rather a means of grouping samples into categories. This allows for wood classification and appropriate utilization of lumber, as well as more accurate propagation modeling within each category. This was first indicated in a microwave knot detection study reported by Leicester [6], where the biggest challenge was producing an algorithm to recognize the features of microwave signals. In that work, pre-sorting the timber into special groups and applying a separate algorithm for each group was recommended. Correspondingly, in this study samples were grouped and five categories were defined (Fig. 2).

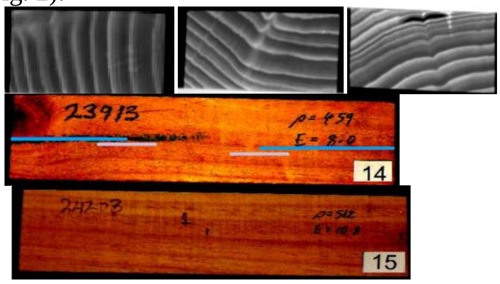

Figure 2. Representative samples for five sample categories: samples 4, 10, 5, 14 and 15

In *Category 1*, samples with large defects (knots) were considered, with knot size ranging from 2 to 5 cm, with varied position and orientation (samples 2, 4, 8, 9, 11, 12, 19). In *Category 2*, samples 3, 10, 16, 17, 18, 20, 22 were grouped, based on the presence of small defects in the sample, such as needle flecks. Samples 5 and 21 in *Category 3* had some anomalies in the structure: resin pocket (sample 5) and grain twist (sample 21). Samples 7 and 14 in *Category 4* were clear, but had a defect outside the observed volume, while samples 1, 6, 13 and 15 in *Category 5* had no defects.

The Transmission coefficient magnitude was investigated first and the frequency averaged value was calculated. The resulting transmission magnitude distribution along a sample shows larger variation in values for samples with knots than for clear samples, for both VV polarization and HH polarization, as seen in Fig. 3. Results show that transmitted microwaves react significantly to the presence of knots, regardless of their position within the beam, as demonstrated in Fig. 3 for category representatives given in Fig. 2.

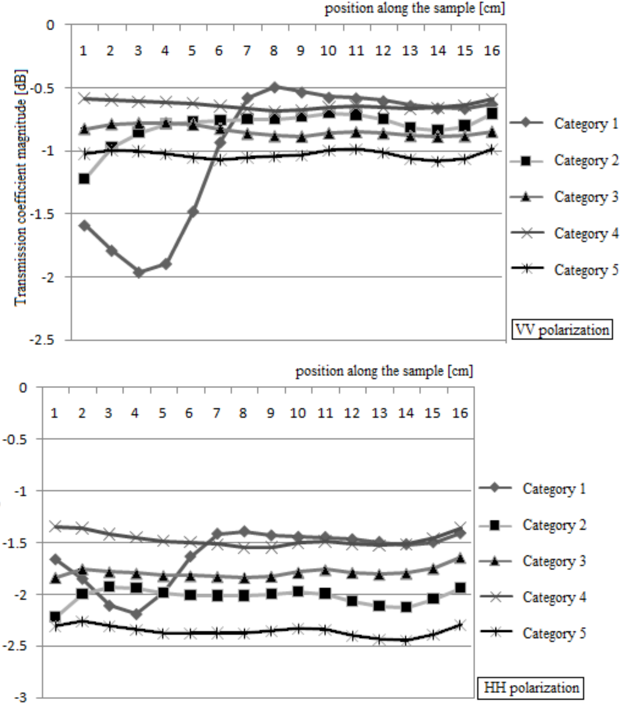

Figure 3. Distribution of transmission coefficient magnitude along the sample for VV (top) and HH (below) polarization

The variation in magnitude value was expressed using a Range of Magnitude Values (RMV) parameter, defined as a difference between maximum and minimum transmission magnitude value along the observed sample. The data for the RMV was calculated for both VV and HH linear polarizations and presented together in a scatter plot in Fig. 4. A clear grouping of the samples from each category can be noticed when utilizing both polarizations. When samples with large defects (knots) were omitted (Fig. 4, top), a clear distinction between samples with small defects (*Category 2* given in blue diamonds) and samples with no defects (*Categories 4 and 5* given as yellow triangles and green circles) exist. It is also important to notice that the existance of a defect outside of the observed area (as in category 4) does not affect the measurement with the Focused Beam Antenna, and that these samples are still correctly categorized as samples with no defects. When single polarization is observed, it can be noted that better results are achived with VV polarization than with the HH polarization.

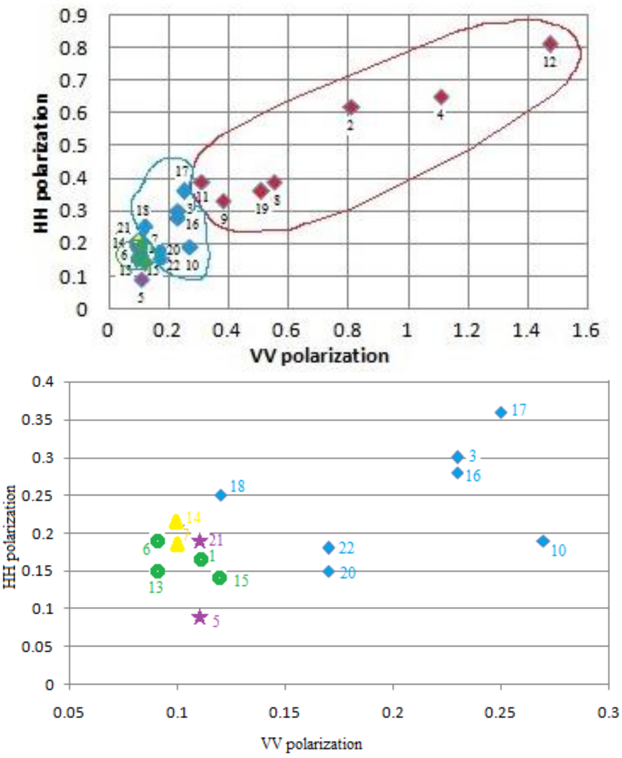

Figure 4. Scatter plot of RMV for both HH and VV polarisations for all samples (top) and without large defects (below)

The Range of Phase Values, defined as the difference between maximum and minimum transmission phase along the observed sample and measured in two nominal polarizations (VV and HH) equally well indicates the presence of large defects in the sample. However, it was not possible to detect less prominent defects. A similar conclusion was made observing the Range of Magnitude Values for cross-polarizations (VH and HV). A high range of cross-polar magnitude values is expected when the grain direction changes along the sample [5]. However, the change in the grain angle does not exclusively occur in the presence of defects and thus cannot be used as a clear defect detection indicator.

Finally, a study of bulk density was conducted to demonstrate the advantage of sample categorization. Using the mean transmission coefficient value, calculated by averaging sixteen measured data points along each sample, the correlation with gravimetrically determined bulk density was calculated. For VV polarization, R^2=0.672 was obtained, but it improved significantly when samples with knots were omitted, showing R^2 of 0.837. For HH polarization, the Insertion loss and bulk density are highly correlated with an R^2 of 0.9345, with no significant change when the samples with knots are omitted.

IV. UTILIZING POLARIZATION IN DENSITY DISTRIBUTION MEASUREMENT

The study of wave polarization significance in moisture content and density measurements, presented in this section, was performed using the measurement system described in Section II. In addition, Principal Component Analysis of measured data was performed using a PCA module in open-source statistics software R (The R Foundation for Statistical Computing, version 3.0.2). Two experiments were performed, focusing on density variation and moisture content variation, respectively.

In the first experiment, the transmission coefficient magnitude was measured on the set of 22 Pinus Radiata samples (as in the Section III) with varied dry density and heterogeneity. Samples were measured at two moisture content levels: 0% and 11%. Comparing the results in VV and HH polarizations, it was noted that similar magnitude values were obtained for oven dry samples, indicating that variation in sample density was not significantly influential. However, when MC was increased to 11%, a significantly lower magnitude was obtained for HH polarization than for VV polarization. Fig. 5 shows this for sample 12, showing bigger change in attenuation for HH (~8dB) than for VV polarization (~5dB).

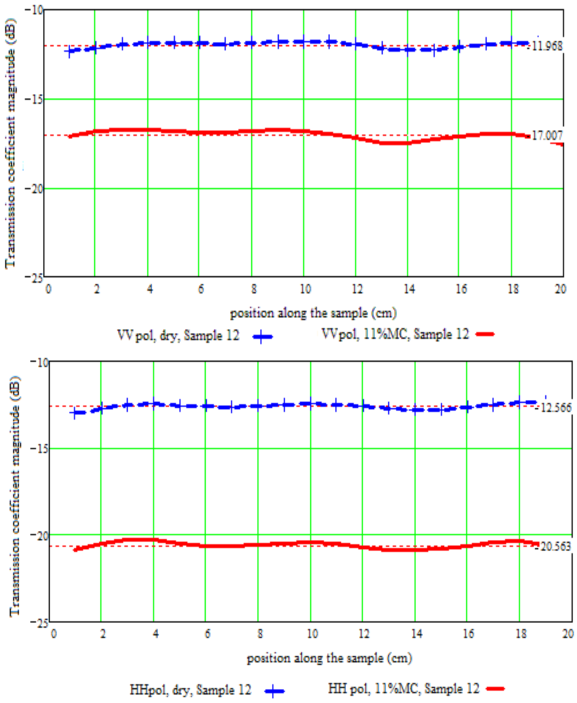

Figure 5. Transmission through Sample 12 at 0% MC and at 11% MC in VV (left) and HH (right) polarization

The difference in VV and HH transmission coefficient magnitudes (VV-HH) was calculated for each of 22 samples with 11%MC and is given in Fig.6. On the same graph, the difference between VV and HH polarization for the same set of samples in oven dry state (0%MC) is given as ‘dVV-dHH’. Comparing two graphs, we can see that a larger difference between transmission coefficients in two polarizations is obtained for samples with larger MC, regardless of density variation or presence of defects. A possible explanation can be found in the micro-structure of wood, hypothesizing that the way the water binds along the cellulose chains has a significant effect on wood anisotropy [1]. This difference in two orthogonal nominal polarizations can be used to alleviate the problem of simultaneous detection of density and moisture from the same data set.

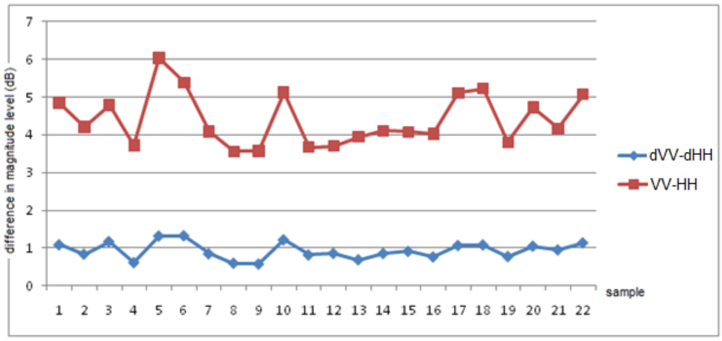

Figure 6. Difference between dry and 11%MC magnitude level for HH and VV polarisation

Further analysis of the graph of the wood in an oven dry state (dVV-dHH) in Fig. 6. shows that samples with different density exhibit different attenuation. However, this variation is more pronounced when moisture is added, as in the graph VV-HH. Good correlation between sample density and difference in transmisssion coefficient magnitude in two polarizations was obtained for both moisture content levels, with R^2 =0.706 for 11%MC (VV-HH) and R^2 = 0.803 for dry samples(dVV-dHH).

To further investigate the dependence of this difference in transmission coefficient magnitude in two polarizations on moisture content, a separate set of seven Pinus Radiata samples was measured at four moisture content levels: 15%, 8%, 6% and 0.2%. The densities of samples were: 342, 349, 409, 436, 449, 460 and 459 kg/m^3. The differences between transmission coefficient magnitudes in VV and HH polarizations for all seven samples are given in Table I. The results show that the difference between the magnitudes in VV and HH polarizations increase both with the increase in density and increase in MC level. However, the influence of MC is much more pronounced. The results obtained in the first experiment were confirmed, showing that HH polarization is affected to a greater degree by the change in the moisture content than VV polarization.

TABLE I. DIFFERENCE IN TRANSMISSION COEFFICIENT MAGNITUDES FOR VV AND HH POLARIZATION (VV-HH)

MC (%) **Density** **(kg/m^3)**	**0 %**	**6%**	**8%**	**15 %**
342	0.59	1.41	2.67	4.88
349	0.68	1.61	1.94	5.71
409	0.87	2.15	2.06	6.91
436	0.77	1.87	2.29	6.89
449	0.93	2.18	2.8	7.54
460	0.9	2.16	2.85	7.81
469	0.92	2.2	2.85	8.04

This was further investigated using Principal Component Analysis (PCA) . PCA was performed on the data set given in Table I and the dimensionality of the problem and the relationship between the measured wood parameters was studied. For each density and MC pair, measured transmission coefficient magnitudes in VV and HH polarizations were entered (given as VVmag and HHmag in Fig.7), as well as the difference between them (VV-HH). In addition, measured transmission coefficient magnitude for cross-polarization measurement (VHmag and HVmag) and transmission coefficient phase in both VV and HH polarizations were also considered (VVPhase and HHphase in Fig.7). As the data was not expressed in the same units, a data standardization was performed by mean-centering the data and dividing it by standard deviation. The eigenvalues for the calculated covariance matrix were determined in R using prcomp() function and presented in Table II. The result indicates three significant principal components. The original data were re-expressed in terms of Principal Components and presented as 'scores' (points marked by a sample number) on a biplot in Fig. 7. In addition, the biplot shows the variables (measured wood properties) presented as vectors.

TABLE II. EIGENVALUES FOR THE OBSERVED DATA SET

2.083872e+00	1.641599e+00	1.096168e+00
6.615434e-01	5.082639e-01	2.189400e-01
1.251228e-01	3.854693e-02	2.610549e-10

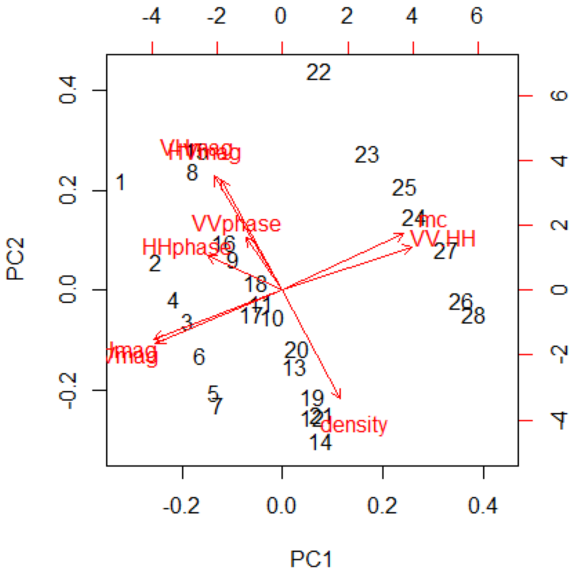

Figure 7. Biplot obtained by PCA in R

As seen on the biplot in Fig. 7, the first Principal Component (PC1) is very close to the change in MC. This component accounts for 48% of variation in the data set. The second, orthogonal, Principal Component (PC2) has correlation with density and it accounts for almost 30% of variation. There are three significant Principal Components in this data set which have 91.5% cumulative proportion of variance. Observing the vectors in the biplot (measured properties), it can be noticed that the difference between transmission coefficient magnitude in VV and HH polarization (VV-HH) is closely related to moisture content (as indicated by the small angle between the two vectors in the biplot) and has very little correlation to the density (being almost orthogonal to the density vector) . This is in agreement with conclusions made in the above experiments. The plot also shows good negative correlation between moisture content and nominal polarization magnitude, while density has strong negative correlation to the phase in VV polarization and both cross-polarization magnitudes.

V. CONCLUSION

This paper presents the findings of a wood testing study, exploring a novel way to maximize the number of parameters used to characterize wood samples. A Focused Beam Antenna was used as a sensor, utilizing frequency response, attenuation, phase delay and, in particular, polarization to provide more information on the sample under test.

The first part of the study is concerned with the detection of wood structural features by means of the microwave Focused Beam Antenna, aiming to identify distinctive variations in wood structure such as knots, needle flecks and resin pockets. Defect detection studies conducted to date were limited to knot detection, while this study was extended to include other variations in wood structure. Visual inspection and CT scan were used to categorize samples, based on the presence of defects. The results demonstrate that the range of transmission coefficient magnitude values over the sample length is a good indicator of defect presence. It has been demonstrated that more accurate information can be extracted when both polarizations were observed than from the individual measurements, in particular when polarization was not aligned with the axial axis of the wood. The importance of sample categorization was demonstrated, using examples in which the correlation between bulk density and mean magnitude improves from 0.672 to 0.837 when samples with defects were omitted.

The density and MC of wood samples were correlated with microwave transmission magnitude measured in two orthogonal polarizations. The results show that measurements conducted in two orthogonal polarizations respond differently to a change in moisture content. The wave in linear polarization, aligned with the axial direction of wood is much more affected by the change in moisture content than its orthogonal counterpart. This is a significant new finding, which can be considered as a novel indicator of wood structure and a factor which can contribute to the long debated issue of resolving between MC and density contribution in microwave attenuation measurement.

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