PAPER • **OPEN ACCESS**

Permittivity of wood as a function of moisture for cultural heritage applications: a preliminary study

To cite this article: L D'Alvia *et al* 2022 *J. Phys.: Conf. Ser.* **2204** 012052

Permittivity of wood as a function of moisture for cultural heritage applications: a preliminary study

L D'Alvia[1], E Piuzzi[2], A Cataldo[3] and Z Del Prete[1]

[1]Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, 00184 Rome, Italy
[2]Department of Information Engineering Electronics and Telecommunications, Sapienza University of Rome, 00184 Rome, Italy
[3]Department of Engineering for Innovation, University of Salento, 73100 Lecce, Italy

E-mail: livio.dalvia@uniroma1.it

Abstract. In this work, the evaluation of moisture content in historic wooden objects starting from permittivity measurements is investigated. For this purpose, a WR430 waveguide with a 1.7-2.6 GHz range was used to estimate the complex permittivity correlated to different moisture levels. Experimental tests were carried out on poplar (Populus nigra L.), a wood typically used in central Italy in the thirteenth-sixteenth centuries as a painting support. For the considered measurement system, experimental results and calibration curves are reported.

1. Introduction

In the last ten years, the interest in safeguarding historical artifacts and buildings has considerably increased [1], thanks to the development of non-invasive and dedicated methodologies and technologies [2,3]. In particular, the measurement of water content in historical materials is an aspect of primary importance as water content changes are responsible for physical and mechanical alteration, insect attack, or fungi proliferation [4,5].

Many historical structures (buildings, furniture, timber) and objects (sculpture, carving, musical instruments, painted panels) are wooden-made, in spite of the hygroscopic nature of the material [6].

Different studies show how the water adsorption phenomenon occurs in two phases: in the range 0% to 25% or Fiber Saturation Point (FSP), the moisture is transferred into the wood cell wall; above this point, the cell walls are fully saturated, and the moisture passed into cavity cell [7,8]. A moisture content ~140% represents the Water Saturation Point (WSP). Below FSP, changes in the water content affect the physical-mechanical and rheological properties of wood (swelling, shrinking, modulus of rigidity or elasticity, or strength values), while above 5% of moisture content risks for insect infestation increase.

Currently, several non-invasive or minimal destructive methods for moisture measurements exist as Capacitive, Resistive methods, or Near-Infrared Spectroscopy [9]. An alternative approach is the use of microwave devices [10,11], recently investigated for masonry units [12].

This paper proposes a preliminary study to determine the permittivity of moisturized poplar through a WR430 waveguide with a frequency range of 1.7-2.6 GHz. In addition, measurements were performed increasing the level of the water content of the wood samples, and the empirical relationship between each considered level of water content and the corresponding measured quantity was derived.

2. Experimental Setup

2.1. Materials

As mentioned above, a sample of Poplar (*Populus nigra L.*) was proposed because it was the most common species to realize painting supports in central Italy between the 13th and 16th centuries [13]. The sample has a length L = 108.7 mm, a height H = 53.9 mm, and a width W = 19.9 mm for a dry weight of 66.29 g; the sizes were chosen to be fitted inside the WR430 waveguide. Figure 1 shows the sample with the seizes highlighted.

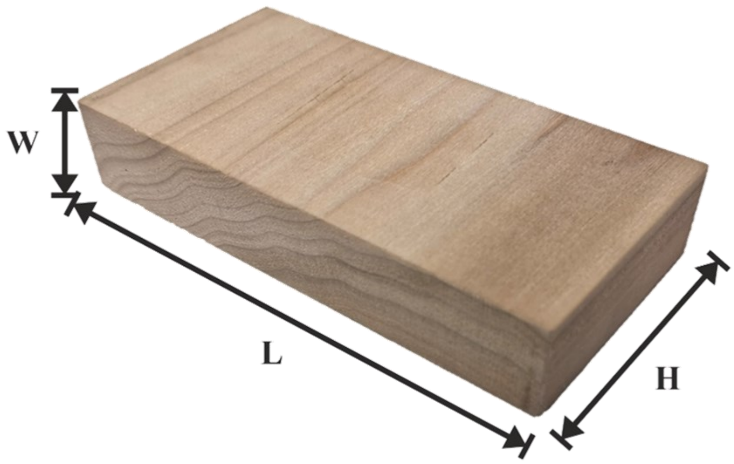


Figure 1. Poplar sample with dimensions: L = 108.7 mm, H = 53.9 mm, and W = 19.9 mm

2.2. Moisturing process

The realized sample was preliminarily dried in a ventilated oven at (105±5) °C until the sample weight had become stable for three consecutive measurements. After this process, the sample was bathed in deionized water five times, each time for a duration of 1.5 minutes, to obtain different moisture content levels in the 0% - 6 % range.

The moisture content ($MC_{\%}$) was calculated according to EN 16682-2017 [14] and shown in eq. (1)

$$MC_{\%} = \frac{m_W}{m_0} \times 100 = \frac{m_M - m_0}{m_0} \times 100 \quad (1)$$

m_W is the mass of moisture absorbed, m_0 is the mass of the dried sample, and m_M is the mass of the moist specimen; all parameters are expressed in grams. The weight has been acquired through a 10 mg resolution electronic balance before and after measurements to evaluate the evaporation effect.

2.3. Methods

For the Poplar sample, permittivity measurements were performed by inserting the sample into a customized rectangular waveguide WR430 system [15], operating in the 1.7–2.6 GHz band connected to the Agilent E8363C vector network analyzer (VNA). In addition, the instrument was equipped with Agilent 85071E permittivity measurement software, and the NIST model was used for permittivity retrieval because it is proven to be the most accurate for nonmagnetic materials [16]. The proposed system presents a sample holder flange of 109 mm × 55 mm × 100 mm. Figure 2 shows the proposed system.

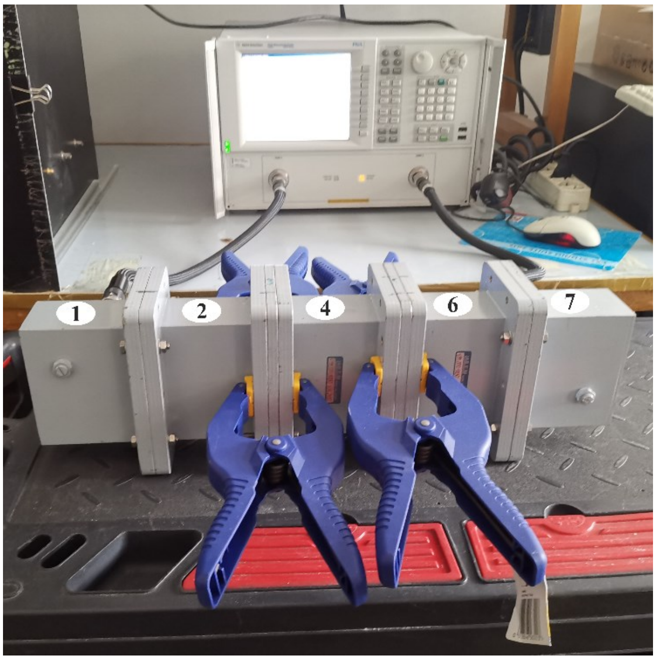


Figure 2. Measurement setup based on a WR430 connected to an Agilent E8363C vector network analyzer. The WR430 was composed of two transition sections (1 and 7), two WR sections (2 and 6), and one sample holder (4).

3. Experimental results and Discussion

Table 1 reports the gravimetric results obtained for six different moisture content ranges 0 – 6 $MC_{\%}$.

We had also evaluated the average value and the variation of $MC_{\%}$ that occurred weighing the sample before and after the measurements. The variations were assessed through semi-dispersion and showed a variation lower than 0.2% for the first five acquisitions and 0.6% for the last point.

Table 1. Gravimetric results for six different $MC_{\%}$ levels highlighted the average and semi-dispersion values due to variations in weight between the beginning and the end of measurements.

Weight before (g)	Weight after (g)	MC% before	MC% after	MC% mean	MC% semi-dispersion
66.29	66.29	0.00%	0.00%	0.00%	-
67.37	67.29	1.63%	1.51%	1.57%	±0.06%
68.15	68.03	2.81%	2.62%	2.72%	±0.09%
68.83	68.72	3.83%	3.67%	3.75%	±0.08%
69.47	69.35	4.80%	4.62%	4.71%	±0.09%
69.95	69.60	5.52%	4.99%	5.26%	±0.26%

Figures 3 (a) and (b) show the complex permittivity of the dried and moisturized sample over the 1.7-2.6 GHz range.

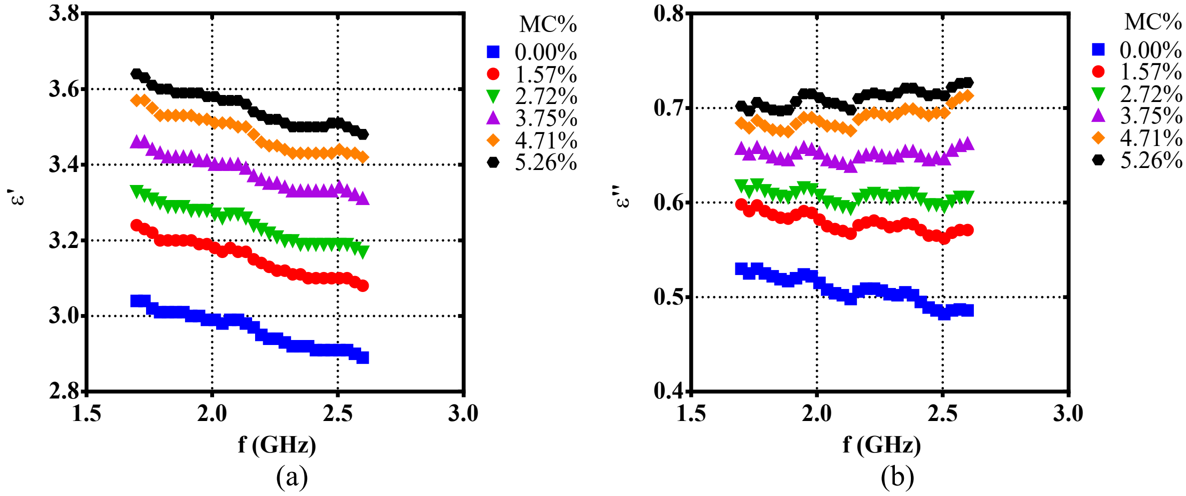


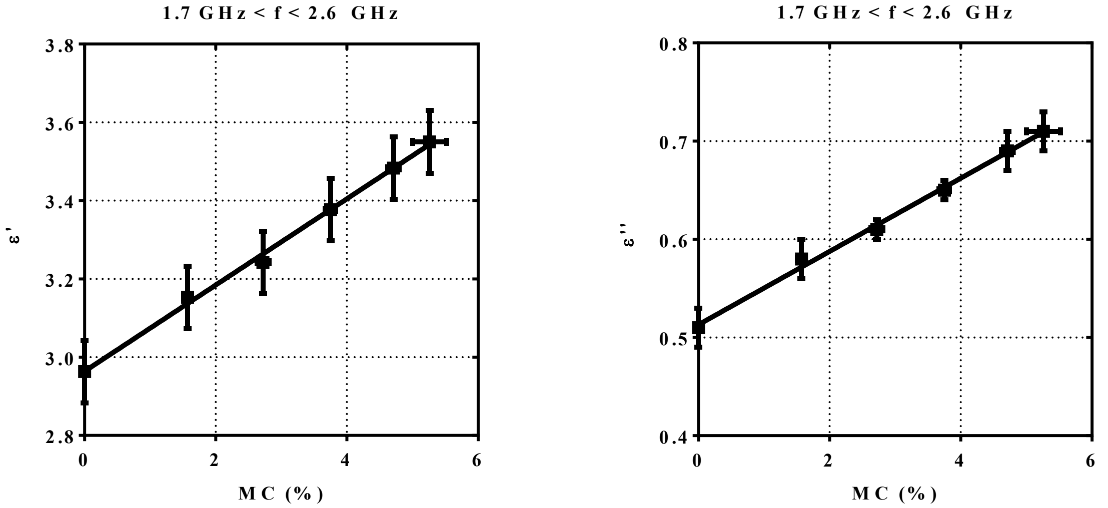
Figure 3. Moisturized Poplar Complex permittivity. (a) the real part for six $MC_{\%}$ levels, (b) the imaginary part for the six $MC_{\%}$ levels

In the figures, it is possible to observe an average increase of $\varepsilon'(f)$ and $\varepsilon''(f)$ consequent to an increase of $MC_{\%}$. Moreover, each ε' presents a coefficient of variation (CV) lower than 1.60%, while ε'' presents a CV lower than 2.70% over the frequency range. Table 2 reports the average values and their variation for each moisture content achieved.

Table 2. Average Complex Permittivity and its variation over the frequency range.

$\overline{MC_{\%}}$	$\overline{\varepsilon'(f)}$	ε' CV	$\overline{\varepsilon''(f)}$	ε'' CV
0.00%	2.96	1.50%	0.51	2.68%
1.57%	3.15	1.47%	0.58	1.59%
2.72%	3.24	1.43%	0.61	1.03%
3.75%	3.38	1.29%	0.65	0.81%
4.71%	3.48	1.35%	0.69	1.37%
5.26%	3.55	1.25%	0.71	1.20%

Figures 4 (a) and (b) show the calibration curve of the complex permittivity for the dried and moisturized sample. To realize the calibration curve, we have taken into account both $MC_{\%}$ and permittivity variations. In both cases, we have obtained a linear relation between the moisture content and permittivity with an R^2 of 0.997 and 0.996, respectively, for the real and imaginary parts. Moreover, the resulting sensitivities $\partial\varepsilon'/\partial MC_{\%}$ and $\partial\varepsilon''/\partial MC_{\%}$ were in the order of 9 and 26. The Student's t-test analysis reported a p-value < 0.001, pointing out that the proposed system correctly recognized different $MC_{\%}$ levels for the considered frequency range despite the overlap of complex permittivity over the same frequency range.



(a) (b)

Figure 4. Calibration curve of (a) the real part and (b) the imaginary part for the six $MC_{\%}$ levels

4. Conclusion

In this work, a microwave-based preliminary setup for monitoring water content in wood materials was presented. Placing a Poplar sample in a waveguide makes it possible to associate the complex permittivity to the sample water content. As a result, the experimental relationship between ε′- ε″ and water content was obtained. Measurements were performed for six moisture content levels in the 0%-6% range, showing good linearity. The obtained results could be used to realize a specific non-destructive and non-invasive probe for direct moisture measurement (e.g., patch resonator, split ring resonator) in wood objects. As future developments, measurements with other wood samples will be performed.

References

[1] D'Alvia L, Palermo E, Rossi S and Cappa P 2016 *IMEKO Int. Conf. Metrol. Archeol. Cult. Heritage, MetroArcheo 2016* 100–5
[2] Proietti A, Leccese F, Caciotta M, Morresi F, Santamaria U and Malomo C 2014 *Sensors (Switzerland)* **14** 9813–32
[3] Proietti A, Panella M, Leccese F and Svezia E 2015 *Measurement* **66** 62–72
[4] Pavlogeorgatos G 2003 *Build. Environ.* **38** 1457–62
[5] Marconi E, Tuti S, Fidanza M R, Leccese F, Galetti A and Geminiani F 2019 *2019 IMEKO TC4 Int. Conf. Metrol. Archaeol. Cult. Heritage, MetroArchaeo 2019* 429–34
[6] Hunt D 2012 *J. Cult. Herit.* **13** S10–5
[7] Moron C, Garcia-Fuentevilla L, Garcia A and Moron A 2016 *Sensors (Switzerland)* **16** 1–9
[8] Dietsch P, Franke S, Franke B, Gamper A and Winter S 2015 *J. Civ. Struct. Heal. Monit.* **5** 115–27
[9] Rotta P, Abanto F, Ipanaque W, Ruiz G, Soto J and Manrique J 2019 *2019 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON)* (IEEE) pp 1–7
[10] Gallardo D, Reyes N, Monasterio D and Finger R 2018 *2018 IEEE MTT-S Latin America Microwave Conference (LAMC 2018)* (IEEE) pp 1–3
[11] Aichholzer A, Schuberth C, Mayer H and Arthaber H 2018 *Eur. J. Wood Wood Prod.* **76** 89–103
[12] D'Alvia L, Palermo E, Prete Z Del, Pittella E, Pisa S and Piuzzi E 2019 *2019 IMEKO TC4 Int. Conf. Metrol. Archaeol. Cult. Heritage, MetroArchaeo 2019* 149–53

[13] Mazzanti P, Togni M and Uzielli L 2012 *J. Cult. Herit.* **13** S85–9
[14] UNI EN 16682:2017 2017
[15] Piuzzi E, Cannazza G, Cataldo A, Chicarella S, De Benedetto E, Frezza F, Pisa S, Prontera S and Timpani F 2016 *IEEE Trans. Instrum. Meas.* **65** 1051–9
[16] Baker-Jarvis J, Vanzura E J and Kissick W A 1990 *IEEE Trans. Microw. Theory Tech.* **38** 1096–103