Holz als Roh- und Werkstoff 57 (1999) 295–299 © Springer-Verlag 1999

Measurement of the refracting index of wood for microwave radiation

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The refracting index of wood depends strongly on its moisture content. In this work we present the results of measurements of the index using electromagnetic radiation with a frequency of 9.35 GHz that corresponds to microwaves. The relationship between the wood moisture content (MC) and the index in some softwood and hardwood species could be the basis for a determination method of moisture content, covering a wide range of values.

Refraktionsindex von Holz für Mikrowellenstrahlung

Der Refraktionsindex von Holz hängt stark von der Holzfeuchte ab. In dieser Arbeit werden Meßergebnisse mit elektromagnetischen Mikrowellen bei 9,35 GHz vorgestellt. Die Beziehung zwischen der Holzfeuchte und dem Refraktionsindex kann die Grundlage für eine Feuchtebestimmung innerhalb eines großen Feuchtebereichs bilden.

1 Introduction

In this work the variation of the wood refracting index was studied in dependence on its moisture content. The refracting index of a material is closely related to the dielectric constant. In the case of wood, the index as well as the dielectric constant depend on several parameters, such as the moisture content and the frequency of the electric field of the incident wave.

Measurements of the refracting index were carried out for several wood species in relation to their moisture content, the frequency of the radiation being 9.35×10^9 Hz, which is within the range of microwaves. It is well-known that at this frequency, most of the wood and wood-based materials in oven-dry conditions are basically transparent for electromagnetic radiation, while the molecules of liquid water are easily polarized. Therefore, microwaves offer excellent possibilities for detecting the water inside wood and to determine the amount of moisture content. On the other hand, as will be shown later, the measurement of the index is not based on the determination of intensities; thus, it can be expected that the values will be sensitive to a wide range of varying water content.

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2 Materials and methods

The refracting index has been measured for diverse softwood and hardwood species, such as *Fagus sylvatica*, *Ulmus minor*, *Pinus sylvestris*, *Pseudotsuga taxifolia*, *Pinus pinaster* and *Shorea negrosensis*.

All the planks used have very similar dimensions, approximately $9 \times 7 \times 1$ cm^3. Radial surfaces were used in the experiments, except in the case of *Pinus sylvestris* (transverse surface). At least nine planks of each species were measured.

The samples were dried in an oven according to the TAPPI standard number 264. From the oven-dry weight (P_0) of the plank, the corresponding moisture content was determined within an error of about 1%.

Assuming that wood behaves like a dielectric material (Torgovnikov 1993) one could measure the refracting index by means of the generation of a standing wave, simplifying the waveguide methods. For this purpose we used the device shown in Fig. 1. The generation of microwaves took place in a Gunn diode fed by stabilized tension. A resonant cavity was synchronized to one of the frequencies generated by the Gunn, allowing to select one of them. The wave is polarized without modulation, having a frequency of 9.35 GHz and a wavelength of 3.2085 cm; the total energy emitted is 10 mJ per second.

The receiver is a high frequency Schottky diode (BAV 46) of 20 mm in length connected to two copper threads that stay parallel to an insulator. The diode produces a potential difference proportional to the intensity of the received wave. A cable connected to the diode allows sending the potential difference to a measuring device, in this case an oscilloscope.

In absence of wood, the wave emitted by the microwave generator is reflected into a metallic badge, adding the reflected wave to the incident wave. The superposition of both waves generates a standing one, whose nodal points are separated $\lambda/2$, approximately 1.5 cm. With the aid of the detector, the position of two nodes, n_1 and n_2, is determined (Fig. 1). In node n_1 we locate the sample holder and in node n_2 the receiver. Node n_2 has to be situated between the generator and the sample.

Later on the sample is located in n_2, so that the wave strikes it perpendicularly. When placing the wood in the way of the wave, and because the refracting index of wood is different from that of air, the intensity distribution of the standing wave changes, and the position of the nodes vary. Therefore, the detector is no longer located in any node. If the metallic badge is displaced at distance D, the

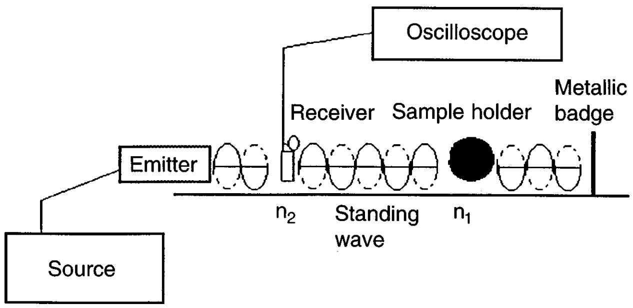

Fig. 1. Experimental setup: standing wave and nodes (n_1 and n_2)
Bild 1. Versuchsanordnung: Meßung mit stehender Welle und Knoten (n_1 und n_2)

initial situation is recovered and the receiver detects a node again.

The displacement D (mm) allows calculating the refracting index of the sample using the relationship: $n = D/d + 1$, where d is the thickness of the wooden sample. The method also allows evaluating the index value within an error of ±0.01 (0.07%) (González-Reviriego 1997; González-Reviriego et al. 1997).

The temperature of the samples during the experiments was measured giving a result of 35 ± 5 °C.

3
Results and discussion

Due to the anisotropy of wood, its behavior in the interaction with an electromagnetic wave differs according to the relative orientation between the electric field of the wave and the fibers. Therefore, for each wooden sample with a certain moisture content, two values of the refracting index, $n_{\|}$ and $n_{\perp}$, were obtained.

The results for several species present very similar characteristics. The index of refraction measured in oven-dry conditions depends on the species, but the value of $n_{\perp}$ is usually lower than $n_{\|}$, retaining this tendency when the moisture content increases.

The value of $n_{\|}$ presents, within a range of moisture content depending on the species, a behaviour that is approximately linear (Fig. 2a). For higher moisture content, the index seems to have an asymptotic trend towards a saturation value of 2 approximately. The values of $n_{\perp}$ present a similar behavior, although the range in which it can be considered linear is greater (Fig. 2b).

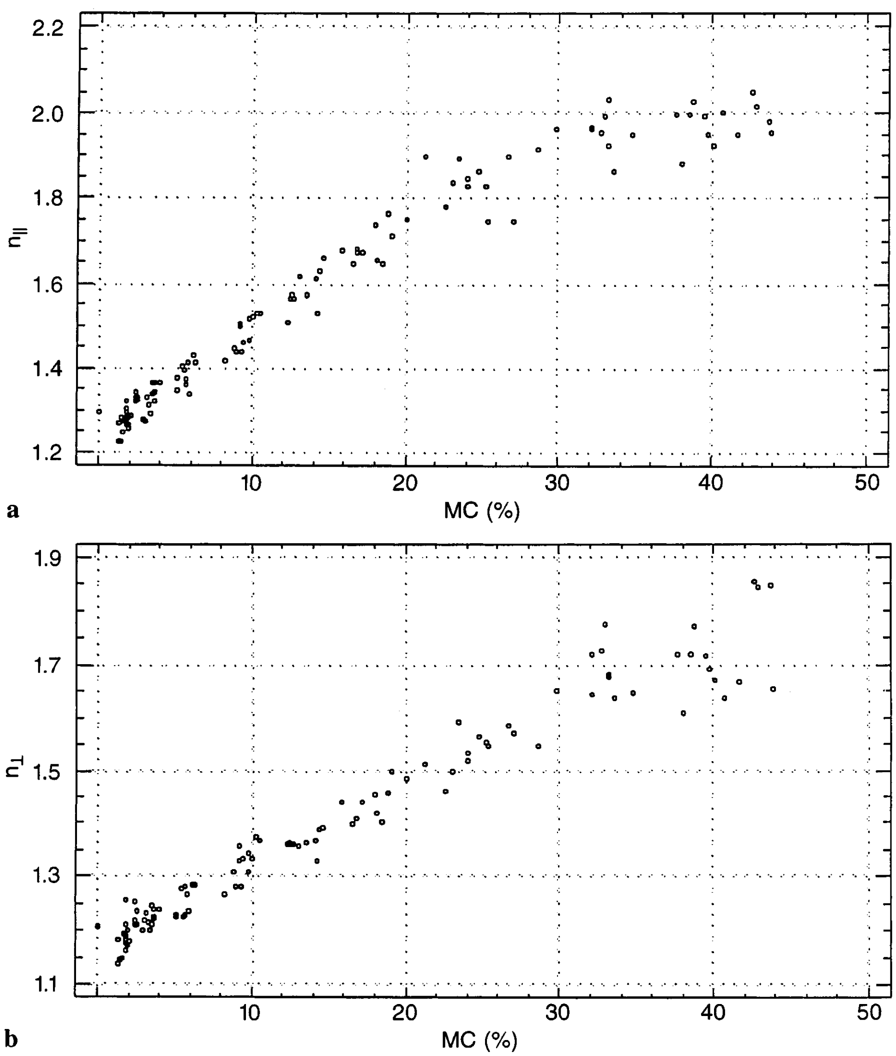

Fig. 2a, b. $n_{\|}$ (a) and $n_{\perp}$ (b) versus wood moisture content (MC) for *Shorea negrosensis*. The relationship is linear until a value of MC of about 50% for $n_{\perp}$ and 30% for $n_{\|}$
Bild 2a, b. Refraktionsindex n, parallel (a) und senkrecht (b) zur Faser in Abhängigkeit von der Holzfeuchte für *Shorea negrosensis*. Die Beziehung ist linear bis zu einem Feuchtewert von 50% (senkrecht) bzw. 30% (parallel)

Table 1. Slopes of the linear regression (p), maximum moisture content for linear behavior ($n_\perp$ and $n_\parallel$), indices of refraction and density in oven-dry conditions
Tabelle 1. Steigung der linearen Regression (p) maximale Feuchte für lineares Verhalten ($n_\perp$ and $n_\parallel$), Refraktionsindex und Dichte (ofentrocken)

Species	$n_\perp$/MC		$n_\parallel$/MC		Oven-dry conditions		
	p	Max MC (%)	p	Max MC (%)	d (×0.01 g/cm^3)	$n_\perp$	$n_\parallel$
Shorea negrosensis	0.0141	50	0.0243	30	41	1.180	1.289
Pinus pinaster	0.0139	30	0.0190	35	45	1.221	1.303
Pinus sylvestris	0.0148	30			51	1.262	–
Pseudotsuga taxifolia	0.0158	40	0.0175	30	51	1.264	1.346
Ulmus minor	0.0143	40	0.0170	25	57	1.290	1.394
Fagus sylvatica	0.0160	25	0.0200	40	64	1.342	1.447

In order to establish an analytic relationship between the values of the index and the moisture content, a least-square fit in the zone that can be considered linear was carried out. The statistical results are shown in Table 1, in which the predicted slopes p are indicated as well as the values of the indices in oven-dry conditions and the range of moisture content in which the linear approach applies.

Figures 3 and 4 present the straight regression lines obtained for softwood and hardwood species respectively, in the range of a moisture content from 0% to 30%, in which most of the species show a linear behavior. As can be observed in these figures, for the same moisture content the value of the index increases with wood-density when considering softwood or hardwood separately.

The relation between $n_\parallel$ and $n_\perp$ and the moisture content below the saturation point is in agreement with the behavior of other dielectric properties related to the index of refraction, such as the absorption coefficient or the dielectric constant.

Martin et al. (1993, 1994) and Fernández-Pareja (1996) have shown in their studies that the absorption coefficient of wood differs according to the relative orientation of the

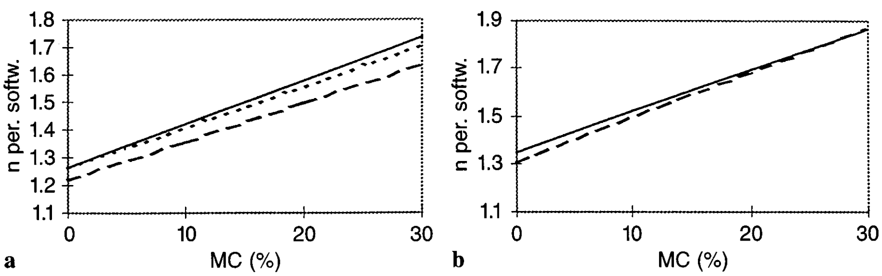

Fig. 3a, b. Straight lines obtained for $n_\perp$ (a) and $n_\parallel$ (b) in softwood species in a range of moisture content 0%–30%. *Pseudotsuga taxifolia* (——), *Pinus pinaster* (– – – –) and (only perpendicular), *Pinus sylvestris* (.....)
Bild 3a, b. Regressionsgeraden für Nadelholzarten senkrecht (a) und parallel (b) zu Faser in einem Feuchtebereich zwischen 0 und 30%: *Pseudotsuga taxifolia* (——), *Pinus pinaster* (– – – –) und (nur senkrecht), *Pinus sylvestris* (.....)

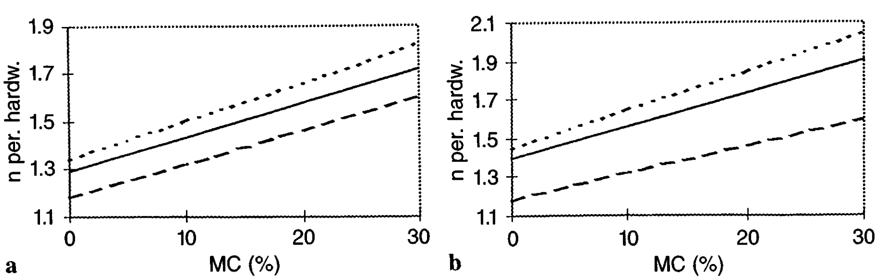

Fig. 4a, b. Straight lines obtained for $n_\perp$ (a) and $n_\parallel$ (b) in hardwood species in a range of moisture content 0%–30%. *Ulmus minor* (——), *Shorea negrosensis* (– – – –) and *Fagus sylvatica* (.....)
Bild 4a, b. Regressionsgeraden für Laubholzarten senkrecht (a) und parallel (b) zu Faser in einem Feuchtebereich zwischen 0 und 30%: *Ulmus minor* (——), *Shorea negrosensis* (– – – –) und *Fagus sylvatica* (.....)

vectorial field to the fibers. These coefficients, like the refracting index measured in this work, present a linear increase when the moisture content is below 30%, the values being greater when the field is orientated perpendicular to the fibers for a given moisture content.

On the other hand, the values of the measured indices are compatible with the values of the dielectric constant, ε', and loss factor tagδ given in the literature. The relationship between the refracting index and the dielectric constant can be described by the expression

$$n = \frac{1}{\sqrt{2}}\left[\left(\varepsilon'^2 + \varepsilon''^2\right)^{\frac{1}{2}} + \varepsilon'\right]^{\frac{1}{2}} = \frac{1}{\sqrt{2}}\left[\varepsilon'\left(1 + (1 + \text{tag}^2\delta)^{\frac{1}{2}}\right)\right]^{\frac{1}{2}}$$

where ε' is the dielectric constant, ε'' is the loss factor and tagδ is the loss tangent.

Table 2 shows the values of $n_\perp$ and $n_\perp$ calculated from this expression, for oven-dry wood as a function of density. The indices have been calculated using the values of $\varepsilon'_{\perp(\|)}$ and tag$\delta_{\perp(\|)}$ at a frequency of 10 GHz and at a temperature of 35 °C given by G.I. Torgovnikov (1993). The values of $\varepsilon'_{\perp(\|)}$ and tag$\delta_{\perp(\|)}$ have been extrapolated from many experiments by the mentioned author who reports that the dispersion between his calculations and the experimental data taken from the literature is about 12%, resulting in an error of about 6% for the indices calculated from these data.

As can be observed, comparing the results of Table 1 with those of Table 2, the values of the indices obtained in the experiments are consistent with the values calculated from dielectric parameters given in the literature.

The values of $n_\|$ and $n_\perp$ obtained for the different species in dependence on wood moisture content show, in the linear zone, a good agreement with the values of $n_\|$ and $n_\perp$ calculated from the values of $\varepsilon'_\perp$ (MC), $\varepsilon'_\|$(MC), tag$\delta_\perp$ (MC) and tag$\delta_\|$ (MC). As an example, Tables 3 and 4 show the values obtained for two of the species studied in this work: *Shorea negrosensis* and *Pseudotsuga taxifolia*.

Our results differ from the values calculated from dielectric parameters given by Torgovnikov amounting to less than 5%. This value ranges within deviations (±8%) usually accepted for such measurements.

4 Conclusions

As can be expected for an anisotropic material, the values of the index depend on the relative orientation between the electric field and the fibers, resulting in two different values according to the field being parallel ($n_\|$) or perpendicular ($n_\perp$) to the fibers. The values of $n_\|$ and $n_\perp$ increase with moisture content, the variation of $n_\|$ being greater than that of $n_\perp$.

For the species studied, a linear relation can be established between the value of the indices and the moisture content, for ranges of the last variable that varied from one species to another between 20% and 44%.

Finally, it can be concluded that the refracting index is a good indicator for the moisture content of wood. The development of a method for its determination, however, would imply an exhaustive and meticulous study of this parameter in dependence on the species, the origin of the wood, the temperature of the sample and other circumstances influencing the wood moisture content.

Table 2. Values calculated from dielectric parameters given by Torgovnikov (1993) for some wood densities (T = 35 °C, $f = 10^{10}$ Hz)
Tabelle 2. Berechnete Werte aufgrund dielektrischer Parameter (Torgovnikov 1993) für verschiedene Holzdichten

Density (g/cm^3)	$n_\perp$	$n_\|$ (softw.)	$n_\|$ (hardw.)
0.4	1.23	1.32	1.30
0.5	1.31	1.40	1.38
0.6	1.34	1.44	1.42
0.7	1.42	1.52	1.50

Table 3. (a) Values calculated from dielectric parameters given by Torgovnikov (1993) for ρ = 0.4 g/cm^3, T =35 °C, $f = 10^{10}$ Hz. (b) Values obtained from linear regressions of experimental data $n_\perp$ (W) and $n_\|$ (W) for *Shorea negrosensis*, ρ = 0.41 g/cm^3 (See Table 1)
Tabelle 3. (a) Berechnete Werte aufgrund dielektischer Parameter (Torgovnikov 1993) für ρ = 0.4 g/cm^3, T = 35 °C, $f = 10^{10}$ Hz. (b) Werte, berechnet aus der linearen Regression der experimentellen Daten $n_\perp$ and $n_\|$ (W) bei *Shorea negrosensis* bei ρ = 0.41 g/cm^3 parallel und senkrecht zur Faser (vgl. Tab. 1)

MC (%)	$n_\perp$ (a)	$n_\perp$ (b)	$n_\|$ (a)	$n_\|$ (b)
0	1.23	1.18	1.30	1.29
5	1.30	1.25	1.35	1.38
10	1.35	1.32	1.48	1.48
15	1.42	1.40	1.62	1.58
20	1.48	1.46	1.75	1.67
25	1.59	1.53	1.95	1.77
30	1.73	1.60	2.12	1.84

Table 4. (a) Values calculated from dielectric parameters given by Torgovnikov for ρ = 0.5 g/cm^3, T = 35 °C, $f = 10^{10}$ Hz. (b) Values obtained from linear regressions of experimental data n. (MC) and n. (MC) for *Pseudotsuga taxifolia*, ρ = 0.51 g/cm^3 (See Table 1)
Tabelle 4. (a) Berechnete Werte aufgrund dielektischer Parameter (Torgovnikov 1993) für ρ = 0.5 g/cm^3, T = 35 °C, $f = 10^{10}$ Hz. (b) Werte, berechnet aus der linearen Regression der experimentellen Daten für *Pseudotsuga taxifolia* bei ρ = 0.41 g/cm^3 parallel und senkrecht zur Faser (vgl. Tab. 1)

MC (%)	$n_\perp$ (a)	$n_\perp$ (b)	$n_\|$ (a)	$n_\|$ (b)
0	1.31	1.26	1.38	1.35
5	1.34	1.34	1.41	1.45
10	1.42	1.42	1.55	1.55
15	1.51	1.50	1.72	1.66
20	1.57	1.58	1.87	1.77
25	1.70	1.66	2.10	1.87
30	1.84	1.64	2.30	1.98

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