J Wood Sci (2004) 50:375–380
DOI 10.1007/s10086-003-0575-1

NOTE

Hamiyet Sahin · Nurgül Ay

Dielectric properties of hardwood species at microwave frequencies

Received: November 21, 2002 / Accepted: June 25, 2003

Abstract Dielectric measurements at 9.8 GHz and 2.45 GHz were made for the three hardwoods Euramerican hybrid poplar, alder, and oriental beech. The method used was based on Von Hippel's transmission line method. The measurements were carried out at room temperature of 20°–24°C. The dielectric properties of the wood species were determined for the three principal structural directions at six different moisture conditions, covering the range of 0% to 28% moisture content. Results indicated that the behavior of all wood species studied is quantitatively similar. In general, the dielectric properties increase within the range studied with rising moisture content. The grain direction of the wood also plays a significant role.

Key words Dielectric constant · Dielectric loss factor · Hardwood species · Microwave frequencies

Introduction

The application of microwave techniques in the wood industry has been developed in the past few decades, both for treatment of wood and for diagnostic purposes.[1] For treatment purposes, microwave energy has been used for heating, drying, and glueing of wood. The use of this technology for wood drying has the potential to offer several advantages. With proper understanding and control, wood can be heated rapidly, uniformly, selectively, less expensively, and with greater control than is possible with conventional methods. In conventional thermal processing, energy is transferred to the material through convection, conduction, and radiation of heat from the surfaces of the material. In contrast, microwave energy is delivered directly to materials through molecular interaction with the electromagnetic field. In heat transfer, energy is transferred due to thermal gradients, but microwave heating is the conversion of electromagnetic energy to thermal energy, rather than heat transfer. This results in rapid heating throughout the material thickness with reduced thermal gradients. Volumetric heating can also reduce processing times and save energy. In addition, microwaves can be utilized for selective heating of materials. Molecular structure affects the ability of the microwaves to interact with materials and therefore affects the efficiency of transfer energy. When materials that are in contact have different dielectric properties, microwaves will selectively couple with the higher loss material.[2]

For diagnostic purposes, a number of measuring instruments operating in microwave ranges are used for measuring the moisture content and thickness of lumber and wood-based materials, detecting defects, checking strength characteristics, estimating surface roughness, as well as inspecting other wood properties. The operation of these instruments is based on the determination of an attenuation factor in the wood during the passage of electromagnetic waves through the material or measurements of a microwave reflection factor.

All these applications (e.g., for heating purposes, designing production facilities as well as for the development of measuring instruments and for determination of moisture content), require a reliable knowledge of the dielectric properties of the wood species of interest. The dielectric constant is the physical parameter of crucial importance in the absorption of electromagnetic energy. Thus, a fundamental understanding of how microwave energy interacts with materials is the key to unlocking the technology for future and widespread use.

Therefore, the dielectric properties of wood have both theoretical and practical significance. The theoretical significance lies in the rationale that better understanding of the molecular structure of wood and wood–water interactions may result from a knowledge of dielectric behavior. The behavior of water with the constituents of wood such as cellulose and lignin can be understood more clearly by studying dielectric properties. The dielectric properties are also of practical importance because (1) their relationship

H. Sahin (✉) · N. Ay
Forest Industry Engineering Department, Karadeniz Technical University, Trabzon 61080, Turkey
Tel. +90-462-377-3248; Fax +90-462-325-7499
e-mail: hamiyet_s@hotmail.com

to the density and moisture content of wood offers a potential method for determining moisture content and density by a nondestructive electrical measurement, and (2) the dielectric properties of wood may be an important design factor where wood is to be used in a structure subjected to electromagnetic fields.[3,4] With regard to the warming up of wood and wood joints, emphasis must be put on the dielectric properties of the material to be treated. Knowledge of these features is essential for understanding a number of phenomena, such as the selectivity of microwave drying or the faster heating of one wood species when compared with another.[5]

The dielectric properties reported here are the dielectric constant and loss factor. When wood is placed in an alternating electric field, the interaction of wood with the electric field may be described in two ways. One is the storage of electric potential energy in the form of polarization within the dielectric material, and the other is dissipation or loss of part of this energy when the electric field is removed. The ability of the material to store energy is described quantitatively by the dielectric constant (ε'), and the rate of energy loss in the dielectric is commonly expressed by the dielectric loss factor (ε'') or dissipation.[6] The ratio $\varepsilon''/\varepsilon'$ or $\tan\delta$ is called the loss tangent.[5,7] In addition, the power that is dissipated in the wood in the form of heat, relates to the absorbed power as given by[5,8]

$$P = 2\pi f E^2 \varepsilon' \tan\delta$$

where P is the absorbed power, f is the frequency, and E is the electric field strength.

This article summarizes the results of dielectric measurements conducted at frequencies of 2.45 GHz and 9.8 GHz on three hardwoods that are the most widely used tree species for industrial applications in Turkey. The effects of some parameters, e.g., moisture content, grain direction, and wood species, on the dielectric properties are discussed. The results are summarized from a thesis that investigated the dielectric properties of natural and impregnated wood species at microwave frequencies.[9]

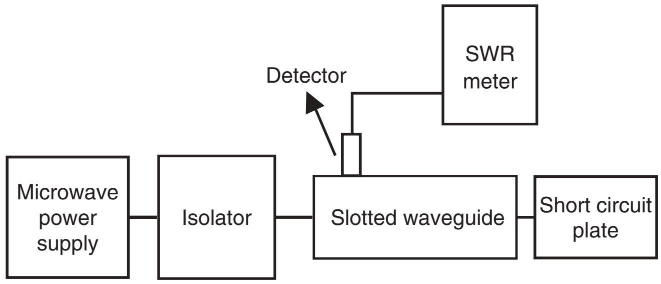

Fig. 1. Equipment used for the determination of the dielectric properties of the material

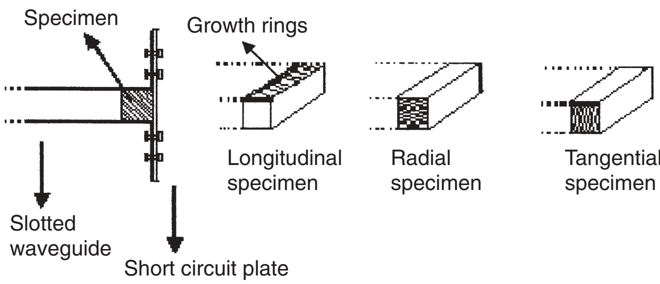

Fig. 2. Placement of the test specimens in the waveguide

Material and methods

The dielectric properties of the test materials were determined by means of a slotted waveguide and standing wave ratio meter (SWR meter). The apparatus is represented schematically in Fig. 1. Frequencies used in this study were 2.45 GHz and 9.8 GHz. These frequencies were chosen because of their importance in potential applications. With two different microwave power supplies, the desired microwave frequencies were adjusted. The microwave frequencies were kept constant at 9.8 GHz in the X-band region and at 2.45 GHz in 10 kHz–2.7 GHz band region. The method was based upon Von Hippel's transmission line method for low loss dielectric materials.[10]

The three hardwoods that were selected for dielectric measurements were Euromerican hybrid poplar (*Populus* x *Euromericana* cv. I-214), alder (*Alnus glutinosa* subsp. Barbata (C.A. Mey) Yalt), and oriental beech (*Fagus orientalis* Lipsky.). The main criteria for this selection were the commercial importance of the timbers in the Turkish market, and other factors that related to the wood itself such as density and anatomical features.

The test specimens were obtained from the sapwood region. The dimensions of the specimens were dependent on the inside dimensions of the waveguide section. The test specimens were placed in the extremity of the waveguide according to Fig. 2. The test specimens were bar-shaped and fitted exactly in the opening at the end of the waveguide, where contact between the specimen and the short circuit plate occurred. The dimensions of the specimens were as close as possible to $8.55 \times 4.25 \times 4.385$ cm for the 2.45-GHz tests and $2.28 \times 1.02 \times 1.03$ cm for the 9.8-GHz tests.

To determine the dielectric constant values at different moisture content, ranging from about 0% to fiber saturation point, specimens were prepared in tangential, radial, and longitudinal directions and were divided into six groups containing five specimens for each wood species. The configuration of test specimens is given in Fig. 2. One group of specimens was dried at $103° \pm 2°C$ for 24 h and the other five groups were conditioned at five different relative humudity levels of 32%, 65%, 77%, 93%, and 100% at 20°C until they reached an equilibrium moisture content. By regular control of the weight, the specimens that had already reached their equilibrium moisture content were selected and weighed and then the measurements were carried out. The measurements were made at room temperature (20°–24°C). After conducting the measurements, the samples were oven-dried at $103° \pm 2°C$ for 24 h to determine the moisture content of the test samples at the time of measurement. The oven-dry specific gravity was determined after calculation of the oven-dry volume. The microwave data were worked up with an ordinator after the dielectric characteristics of each sample were printed out.

Results and discussion

The average values of the dielectric constants and loss factors of three wood species at frequencies of 2.45 GHz and 9.8 GHz and at different moisture contents in tangential, radial, and longitudinal directions are given in Tables 1 and 2. Because similar trends were observed for moisture content and structural directions at both frequencies (9.8 GHz and 2.45 GHz), only the results at 9.8 GHz are given graphically in Fig. 3. The curves shown in Fig. 3 were obtained by testing different equations and taking the best fit of the experimental values.

The results indicate that the dielectric properties increase with rising moisture content within the range studied. This trend was similar for the three wood species. For both frequencies, second-order equations provided the best fitted curves for the experimental data for dielectric constants and dielectric loss factors. The relationship between moisture content, dielectric constant, and loss factor so far reported is either linear or curvilinear at low moisture content levels at microwave frequencies.[3,5,11] The increase of dielectric constant with the increase in moisture content up to 28% was also observed by James and Hamill,[3] Peyskens et al.,[5] Kabir et al.,[6,12] Jain and Dubey,[11] James,[13,14] and Tinga.[15]

This result can be explained by considering the combination of two facts. First, with increasing moisture content, the amount of water within the wood matrix increases. Because

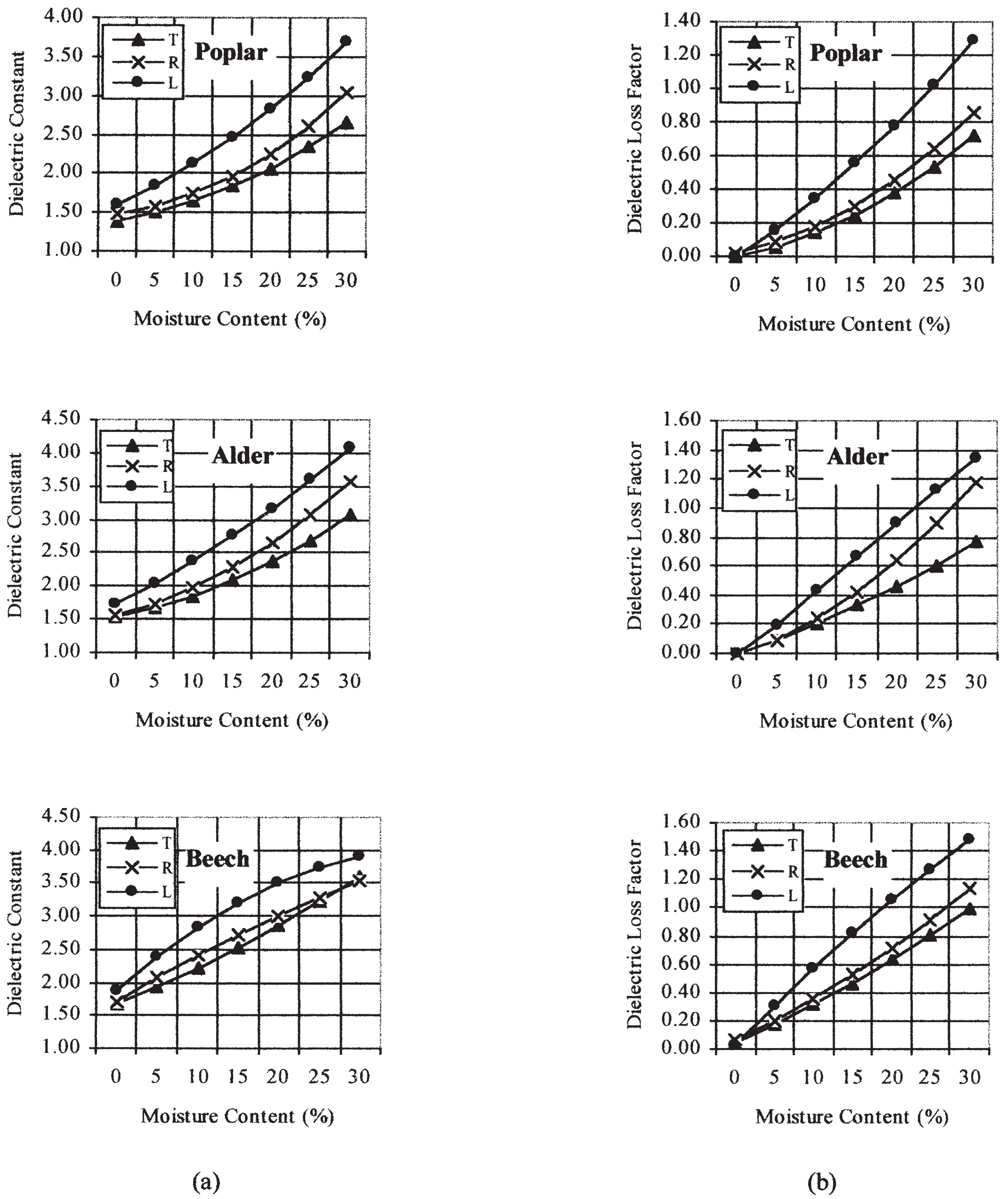

Fig. 3. a Dielectric constant and **b** dielectric loss factor of poplar, alder, and beech as a function of the moisture content for the longitudinal (*L*), radial (*R*), and tangential (*T*) directions at 9.8 GHz

Table 1. Dielectric properties of Euramerican hybrid poplar, alder, and oriental beech woods at different moisture contents and structural directions at 9.8 GHz

Wood species	Dielectric properties	Moisture content (%)					
		0	8	12	15	22	28
Poplar	ε'_T	1.41	1.61	1.72	1.95	2.16	2.48
	ε'_R	1.47	1.68	1.85	1.95	2.38	2.97
	$\varepsilon'_\perp$	1.44	1.65	1.79	1.95	2.27	2.73
	$\varepsilon'_{//}$	1.62	2.00	2.28	2.66	3.18	3.57
	ε''_T	0.030	0.112	0.180	0.290	0.548	0.654
	ε''_R	0.030	0.104	0.240	0.286	0.538	0.778
	$\varepsilon''_\perp$	0.030	0.108	0.210	0.288	0.543	0.716
	$\varepsilon''_{//}$	0.052	0.27	0.424	0.668	0.898	1.166
Alder	ε'_T	1.58	1.76	1.96	1.99	2.65	3.07
	ε'_R	1.65	1.85	2.06	2.29	2.74	3.35
	$\varepsilon'_\perp$	1.62	1.81	2.01	2.14	2.70	3.21
	$\varepsilon'_{//}$	1.87	2.11	2.49	2.86	3.46	3.71
	ε''_T	0.040	0.206	0.232	0.272	0.598	0.762
	ε''_R	0.040	0.182	0.312	0.374	0.736	0.903
	$\varepsilon''_\perp$	0.040	0.194	0.272	0.323	0.667	0.833
	$\varepsilon''_{//}$	0.066	0.312	0.508	0.730	1.008	1.260
Oriental beech	ε'_T	1.80	2.11	2.36	2.65	3.31	3.65
	ε'_R	1.91	2.17	2.53	2.64	3.25	3.48
	$\varepsilon'_\perp$	1.86	2.14	2.45	2.63	3.28	3.57
	$\varepsilon'_{//}$	2.10	2.56	3.05	3.39	3.79	3.27
	ε''_T	0.052	0.266	0.326	0.564	0.740	0.976
	ε''_R	0.068	0.272	0.388	0.604	0.766	1.122
	$\varepsilon''_\perp$	0.060	0.269	0.357	0.584	0.753	1.049
	$\varepsilon''_{//}$	0.080	0.486	0.828	0.860	1.136	1.454

Data collected at temperature 20°–24°C

ε'_T, dielectric constant in tangential direction; ε'_R, dielectric constant in radial direction; $\varepsilon'_\perp$, dielectric constant in transverse direction; $\varepsilon'_{//}$, dielectric constant in longitudinal direction; ε''_T, dielectric loss factor in tangential direction; ε''_R, dielectric loss factor in radial direction; $\varepsilon''_\perp$, dielectric loss factor in transverse direction; $\varepsilon''_{//}$, dielectric loss factor in longitudinal direction

Table 2. Dielectric properties of Euramerican hybrid poplar, alder, and oriental beech woods at different moisture contents and structural directions at 2.45 GHz frequency

Wood species	Dielectric properties	Moisture content (%)					
		0	8	12	15	22	28
Poplar	ε'_T	1.44	1.63	1.84	1.92	2.33	2.67
	ε'_R	1.52	1.81	2.03	2.19	2.45	3.02
	$\varepsilon'_\perp$	1.48	1.72	1.94	2.06	2.39	2.85
	$\varepsilon'_{//}$	1.70	1.98	2.49	2.88	3.27	3.93
	ε''_T	0.018	0.113	0.195	0.231	0.353	0.473
	ε''_R	0.027	0.149	0.248	0.317	0.361	0.655
	$\varepsilon''_\perp$	0.023	0.131	0.222	0.274	0.357	0.564
	$\varepsilon''_{//}$	0.046	0.191	0.443	0.635	0.924	0.968
Alder	ε'_T	1.59	1.85	2.17	2.27	2.95	3.32
	ε'_R	1.67	2.02	2.37	2.41	3.08	3.47
	$\varepsilon'_\perp$	1.63	1.94	2.27	2.34	3.02	3.40
	$\varepsilon'_{//}$	1.88	2.51	2.87	3.10	3.67	4.33
	ε''_T	0.029	0.128	0.302	0.327	0.541	0.742
	ε''_R	0.034	0.171	0.357	0.384	0.686	0.889
	$\varepsilon''_\perp$	0.032	0.150	0.329	0.356	0.614	0.816
	$\varepsilon''_{//}$	0.053	0.341	0.576	0.706	1.690	1.761
Oriental beech	ε'_T	1.88	2.23	2.60	2.89	3.39	4.37
	ε'_R	1.98	2.40	2.81	3.19	3.47	4.38
	$\varepsilon'_\perp$	1.93	2.32	2.71	3.04	3.43	4.38
	$\varepsilon'_{//}$	2.26	2.82	3.36	3.38	4.18	4.77
	ε''_T	0.045	0.169	0.411	0.481	0.788	1.240
	ε''_R	0.044	0.220	0.428	0.639	1.247	1.640
	$\varepsilon''_\perp$	0.045	0.195	0.420	0.560	1.018	1.440
	$\varepsilon''_{//}$	0.077	0.347	0.845	0.997	2.506	2.828

Data collected at temperature 20°–24°C

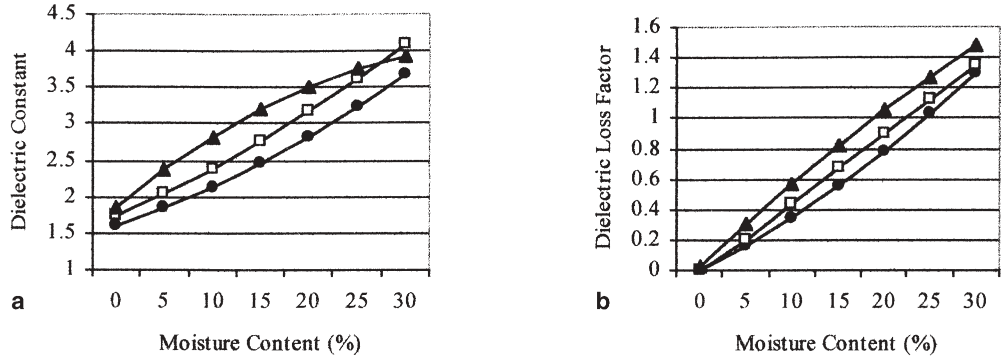

Fig. 4. **a** Dielectric constant and **b** dielectric loss factor of poplar, alder, and beech as a function of moisture content for the longitudinal direction at 9.8 GHz. *Circles*, poplar; *squares*, alder; *triangles*, beech

the dielectric constant and loss factor of water are many times higher than those of wood, a trend of increased dielectric properties of wood is expected. Furthermore, as the moisture content increases from the oven-dry condition, the polar components of the cell wall and cellulose attain more freedom of rotation at higher moisture content and in this way also contribute to a more pronounced dielectric behavior. In the oven-dry state, the macromolecules of cellulose in wood are mutually bound by secondary valence forces that prevent the dipoles of the molecules from displacing under the influence of the electromagnetic field. The process of humidification leads to the penetration of water molecules into the cellulose and to the weakening of the transverse bonds, which results in an increased mobility of dipoles.

The second important result of this research is the relationship between the structural direction and the dielectric constant and loss factor. According to this relationship the dielectric parameters of the three wood species in longitudinal direction are rather higher than those in the transverse direction. For poplar, alder, and beech, the longitudinal dielectric constant values at 2.45 GHz and 9.8 GHz were 1.3, 1.3, and 1.2, and 1.3, 1.2, and 1.2 times higher than the transverse values, respectively. Also, the longitudinal dielectric loss factor values at 2.45 GHz and 9.8 GHz were 2.0, 2.1, and 2.0, and 1.3, 1.2, and 1.2 times higher than the transverse ones, respectively. With increasing frequency, the coefficient values showed a negligible decrease. The radial values were somewhat higher than the tangential ones. However, this distinction is negligible compared with that between the longitudinal and transverse directions. The difference in dielectric properties between the longitudinal, radial, and tangential directions is attributable to the differences in the arrangement of the cell wall and lumen, the specific molecular structure of the cell wall, and the anisotropy of the cell wall substances. The greater dielectric constants in longitudinal direction has been explained by Norimoto and Yamada[16] on the basis that the transition probability of dipole jump to an adjacent site when the field is applied in the longitudinal direction is considerably greater than that when electric fields are applied in other directions. The chemical constituent of wood may also be responsible for the dielectric anisotropy. According to Norimoto and Yamada,[17] the dielectric properties of wood are strongly influenced by cellulose and mannan in the longitudinal direction, but in the transverse direction the dielectric properties are influenced by lignin. Lignin has lower dielectric properties than cellulose. In addition, in previous research it was considered that the hydroxyl groups of cellulose are likely to have more freedom of rotation in the longitudinal direction.[18] Therefore, it is expected that transverse values are lower than longitudinal values.

The effect of the wood species can be best studied under longitudinal direction because the dielectric properties differentiate themselves as a function of the moisture content most clearly in this direction. Figure 4, which gives the relationships between moisture content and dielectric constant and dielectric loss factor, shows a difference between the respective wood species that becomes more pronounced as the moisture content of the wood increases. Considering the whole range of moisture content up to 25%, poplar and beech manifest the lowest and highest dielectric constant and loss factor values, respectively. After this point, the curve for dielectric constant of alder exceeds that of beech, but this situation was not observed for dielectric loss factor.

The differences in the dielectric behavior among wood species are related to one or more of their specific characteristics. Among these, the factors governing the sorptive behavior of wood and global structure of each species, determining a specific density and a specific permeability, may be decisive. The average specific gravity of poplar, alder, and beech were 0.363, 0.475, and 0.658 g/cm^3, respectively.[9] The general trend of specific gravity of the wood species is identical to the trend of their of dielectric behavior. In addition, poplar, alder, and beech have air volumes of 75.8%, 68.3%, and 56.1%, respectively.[9] When an alternating voltage is applied to a dielectric, the molecules tend to align themselves with the field, and the movement depends on the internal binding forces in the material. According to this, in less dense woods, there are fewer polar groups to accompany dielectric polarization, which means that the dielectric properties of less denser woods are lower than those of denser woods. Because of this reason, it can be claimed that the differentation of dielectric properties of wood species found in this study are strongly related to the specific gravity and sorptive capacity of the wood species. The trend of dielectric constant of beech wood differs from the other wood species, expecially at high moisture content. This specific result for beech wood may be explained by the chemical content of beech because Lin[18] also mentioned that a relationship should exist between the dielectric properties and the ash or mineral content of the wood.

References

1. Olmi R, Bini M, Ignesti A, Riminesi C (2000) Dielectric properties of wood from 2 to 3 GHz. J Microwave Power E E 35:135–143
2. Thostenson ET, Chou T-W (1999) Microwave processing: fundamentals and applications. Composites Part A 30:1055–1071
3. James WL, Hamill DW (1965) Dielectric properties of Douglas-fir measured at microwave frequencies. Forest Prod J 15:51–56
4. Kabir MF, Daud WM, Khalid KB, Sidek HA (2000) Equivalent circuit modeling of the dielectric properties of rubber wood at low frequency. Wood Fiber Sci 32:450–457
5. Peyskens E, Pourcq M, Stevens M, Schalck J (1984) Dielectric properties of softwood species at microwave frequencies. Wood Sci Technol 18:267–280
6. Kabir MF, Khalid KB, Daud WM, Aziz SHA (1997) Dielectric properties of rubber wood at microwave frequencies measured with an open-ended coaxial line. Wood Fiber Sci 29:319–324
7. Torgovnikov GI (1993) Dielectric properties of wood and wood-based materials. Springer, Berlin Heidelberg New York, pp 1–19
8. Brelid PL, Simonson R, Risman PO (1999) Acetylation of solid wood using microwave heating. Holz Roh Werkst 57:259–263
9. Şahin H (2002) Dielectric properties of natural and impregnated wood species at microwave frequencies. Ph D Thesis, Karadeniz Technical University, Trabzon
10. Chatterjee R (1988) Advanced microwave engineering special advanced topics. Ellis Horwood, Chichester, England, pp 493–495
11. Jain VK, Dubey YM (1988) Dielectric constant of some indian timbers in axial direction at microwave frequencies. J Ind Acad Wood Sci 19:25–36
12. Kabir MF, Daud WM, Khalid K, Sidek HAA (1998) Dielectric and ultrasonic properties of rubber wood. Effect of moisture content, grain direction and frequency. Holz Roh Werkst 56:223–227
13. James WL (1977) Dielectric behavior of Douglas-fir at various combinations of temperature, frequency, and moisture content. Forest Prod J 27:44–48
14. James WL (1975) Dielectric properies of wood and hardboard: variation with temperature, frequency, moisture content, and grain orientation. USDA Forest Service Research Paper, FPL 245:1–32
15. Tinga WR (1969) Dielectric properties of Douglas fir at 2.45 GHz. J Microwave Power 4:161–164
16. Norimoto M, Yamada T (1971) The dielectric properties of wood V, on the dielectric anisotropy of wood. Wood Res 51:12–32
17. Norimoto M, Yamada T (1972) The dielectric properties of wood VI, on the dielectric properties of chemical constituents of wood and the dielectric anisotropy of wood. Wood Research, 52:30–43
18. Lin RT (1967) Review of the dielectric properties of wood and cellulose. Forest Prod J 17:61–66