Study on Dielectric Properties of Poplar Wood over an Ultra-wide Frequency Range

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The dielectric properties of poplar wood (*Populus deltoids* cv. *I-69/55*) were measured using an Agilent network analyzer over the frequency range from 0.2 GHz to 20 GHz. The effects of moisture content, grain direction, temperature, and frequency on the dielectric constant and dielectric loss factor of wood were investigated. Regression equations were also established to predict the dielectric properties of wood having different grain directions and moisture contents. Results showed that the dielectric properties were strongly affected by the moisture content. As the moisture content increased from 0% to 100%, the dielectric constants of wood at longitudinal, radial, and tangential directions increased by 820.2%, 403.0%, and 434.0%, loss factors of wood at three directions increased by 8631%, 4949%, and 3404%, respectively. As frequency was increased, dielectric constant of wood decreased slowly; however, the loss factor decreased at the beginning and then increased. Dielectric properties of the wood also increased with increasing temperature. The dielectric constant in longitudinal directions was 1.2 times higher than the constant at tangential and radial directions, but the loss factor was 1.4 to 2.5 times higher. Regression equations were determined to fully describe the dielectric properties of wood at different grain dimensions and moisture contents.

Keywords: Poplar wood; Dielectric property; Moisture content; Grain direction; Temperature

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INTRODUCTION

The application of microwave technology dates back seventy years ago. Recently, microwave generators, such as the wave magnetron, have allowed the spread of the microwave heating technique to diverse applications (Mou and Li 2004). Compared to conventional heating methods, the microwave heating technique is more effective, faster, and more energetically economical; it can thus be used in rapid drying of wood in industrial processes. In recent years, researchers have paid much attention to microwave-induced modifications of wood, other than wood drying using microwave, which can be used to prepare expanded wood (Torgovnikov and Vinden 2000; Przewloka *et al.* 2007; Torgovnikov and Vinden 2009). When subjected to a microwave field, the abilities of wood materials to store energy and transform energy into heat are closely connected with dielectric properties of wood. Previous studies have indicated that dielectric properties are correlated with (i) the microstructure of wood, (ii) the interaction mechanisms between the wood and water, and (iii) the behavior of wood under a high-frequency electromagnetic field (Cao *et al.* 1986). Many researchers have spent a considerable amount of time and effort studying the dielectric properties of wood, leading to excellent progress in this field.

Research has mainly focused on two aspects: on one side, theoretical studies have been devoted to the relationship between the dielectric properties and the wood species (Dai *et al.* 1989; Sahin and Ay 2004), grain parameters (Daian *et al.* 2005), wood density (Holmes *et al*. 2013), moisture content (MC) (Kol 2009; Phadke *et al.* 2012), frequency, and temperature (Zhou and Avramidis 1999). Cao and Zhao (Zhao *et al.* 1993; Cao and Zhao 2001a; Cao and Zhao 2001b; Cao and Zhao 2002) investigated the behavior of wood and water during adsorption/desorption and modeled the dielectric relaxation following water absorption in the amorphous cell wall regions. On the other side, practical applications have been investigated (Steele *et al.* 2000; Han *et al.* 2011; Hollertz *et al.* 2013). However, the dielectric properties of wood have mostly been studied at the low-frequency range (below 100 MHz), which is far below the microwave range that is used in the wood drying industry. Therefore, it is necessary to extend the study of the effects of moisture, temperature, and grain direction on the dielectric properties in the frequency range from 915 MHz to 2450 MHz.

This article summarizes the results of the dielectric measurements on poplar wood (*Populus deltoids* cv. *I-69/55*) samples at the frequency ranging from 0.2 GHz to 20 GHz. Furthermore, the effects of moisture, grain direction, temperature, and frequency on the dielectric constant and the loss factor were investigated in the broad frequency range to provide reliable data for industries working on the high-frequency modifications of wood.

EXPERIMENTAL

Materials

The species of wood selected for this study was green poplar wood (*Populus deltoids* cv. *I-69/55*), which was from Hunan province, China. The dielectric properties of the tested specimens were determined using an Agilent Network Analyzer (N5244A, Agilent technologies, Santa Clara, USA). The apparatus is represented in Fig. 1. The frequency range accessible with this probe is 0.2 GHz to 20 GHz. Temperature varied between -40 °C and 200 °C. When measuring the dielectric properties, the probe should be kept close to the wood surface. When the probe is in contact with the transverse section of the wood, the electric field produced is parallel to the fiber direction, which allows it to measure the longitudinal dielectric properties of wood. When the probe is brought close to the radial section (or tangential section) of wood, the dielectric properties along the tangential (or radial) direction can be determined.

Methods

Cubic test specimens (50 mm × 50 mm × 50 mm) were selected from the sapwood region of green poplar wood. The configuration of test specimen is given in Fig. 2. Specimens were divided into two groups. One group was dried at 60 °C ± 2 °C until the desired MC was reached (ranging from 10% to 100%). At each MC step, dielectric measurements were performed in the considered frequency range at room temperature (20 °C) along longitudinal, radial, and tangential directions. The other group was first dried at 60 °C ± 2 °C until the fiber saturation point was reached, then the temperature was further increased in an oven to 103 °C ± 2 °C in an oven to reach an absolutely dry state. The oven-dried specimens were used to investigate the effect of temperature on the dielectric properties of wood in different orientations. Four temperature levels were monitored (20

°C, 60 °C, 100 °C, and 140 °C). Specimens were heated to desired temperature and stored at each temperature for 4 h, so that the core and surface temperatures could reach a stable equilibrium, and then the dielectric measurements were conducted. Each test was repeated 3 times.

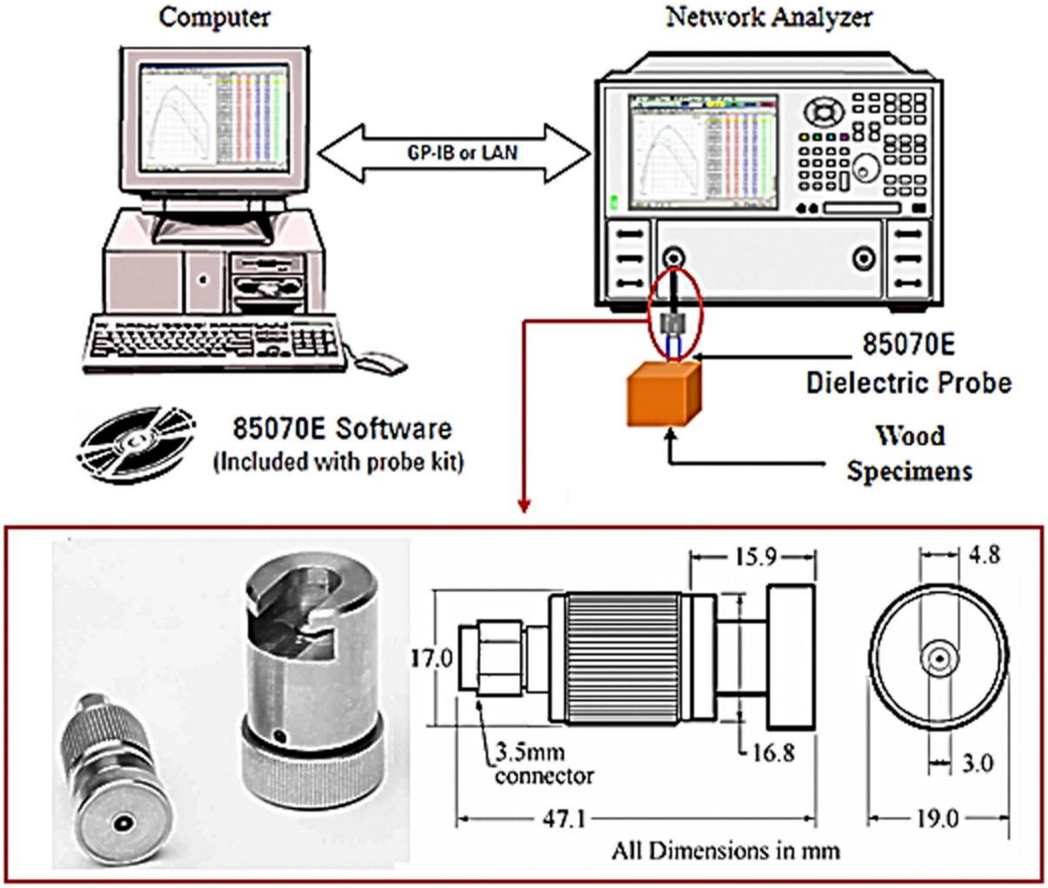

Fig. 1. Equipment used for the determination of dielectric properties of wood

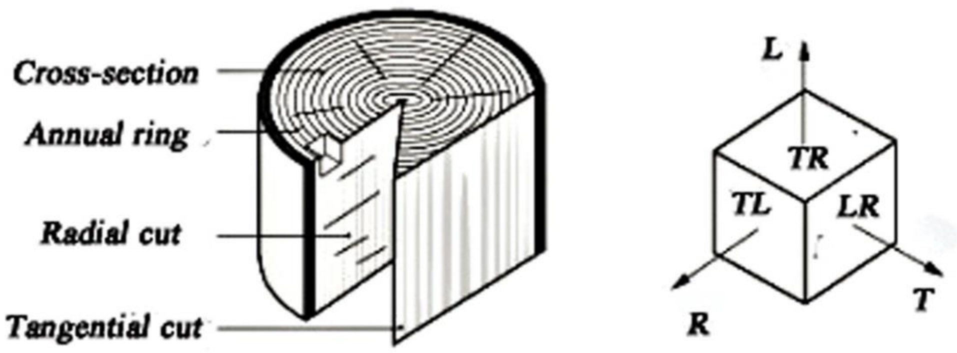

Fig. 2. Sawing method for specimens

RESULTS AND DISCUSSION

Figure 3 shows the effects of the MC and frequency on the dielectric constant of wood at different frequencies. The dielectric constant increased with the MC increasing and decreased with the frequency increasing. Interestingly, the trend was similar to the dielectric constant at different grain directions. When the MC was below the fiber saturation point (FSP), the decrease of dielectric constant with increasing frequency was much lower. As MC values became higher than FSP, a higher MC value was always associated with a more rapid decrease in the dielectric constant with the frequency. At the MC of 98.9%, when the microwave frequency increased from 200 MHz to 10.1 GHz, the dielectric constant at the longitudinal, radial, and tangential directions decreased by 46%, 40%, and 37%, respectively. The dielectric constant stabilized for frequencies larger than 10.1 GHz. In the explored range of frequencies, when the moisture content increased from 0% to 100%, the dielectric constant of wood at the longitudinal, radial, and tangential directions increased by 820%, 403%, and 434%, respectively.

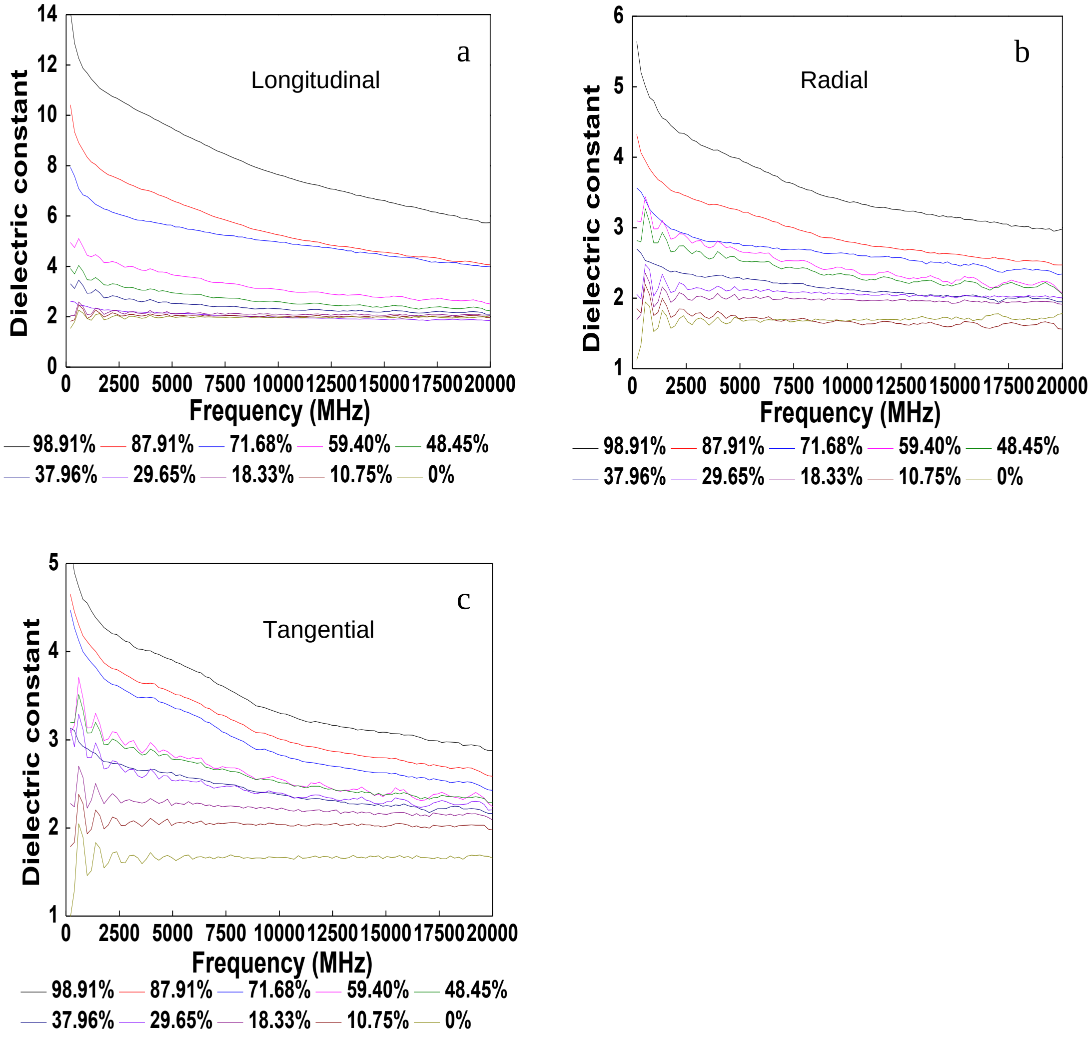

Fig. 3. The effects of moisture content and frequency on dielectric constant of wood in longitudinal (a), radial (b), and tangential (c) directions

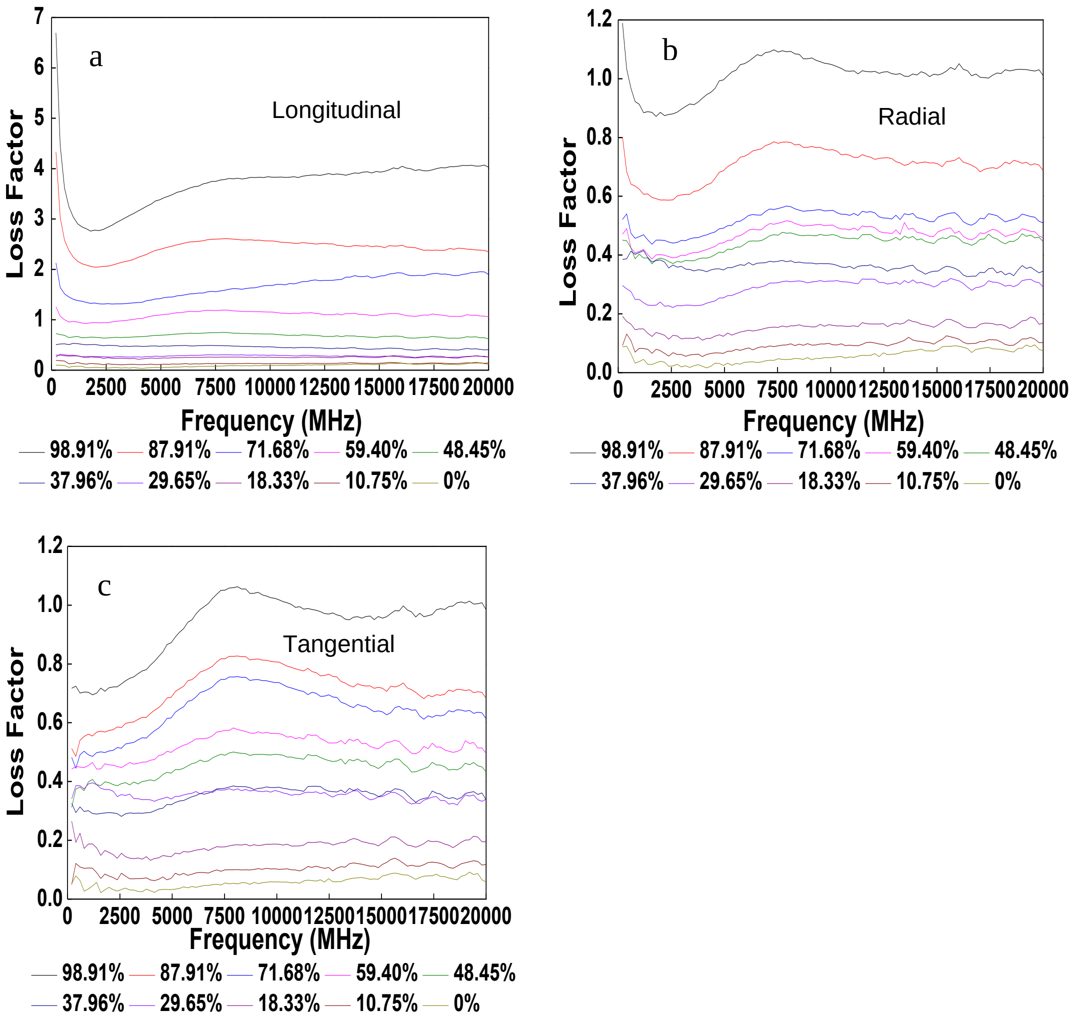

Fig. 4. The effects of moisture content and frequency on dielectric loss factor of wood in longitudinal (a), radial (b), and tangential (c) directions

Figure 4 shows the effects of the MC and frequency on the dielectric loss factor of wood in the considered frequency range. The loss factor increased remarkably with the MC increasing. As the frequency was increased, the loss factor first decreased and then increased. The higher the MC was, the greater the influence of the frequency on the loss factor. However, when the frequency exceeded 7500 MHz, the effect of frequency on the loss factor was negligible. When the MC increased from 0% to 98.9%, loss factor at the longitudinal, radial, and tangential directions increased up to 8630%, 4950%, and 3400%, respectively. In summary, from Figs. 3 and 4, the MC had the biggest influence on the dielectric constant and loss factor of wood.

The dielectric properties increased with the MC value increasing. This was observed in previous studies (Ji and Ji 1997; Sahin and Ay 2004; Phadke *et al.* 2012), and can be explained considering the combination of two facts. First, when the MC increased, the amount of water within the wood matrix increased. Because both the dielectric constant and the dielectric loss factor of water were many times higher than those of wood, the dielectric properties of wood increased accordingly.

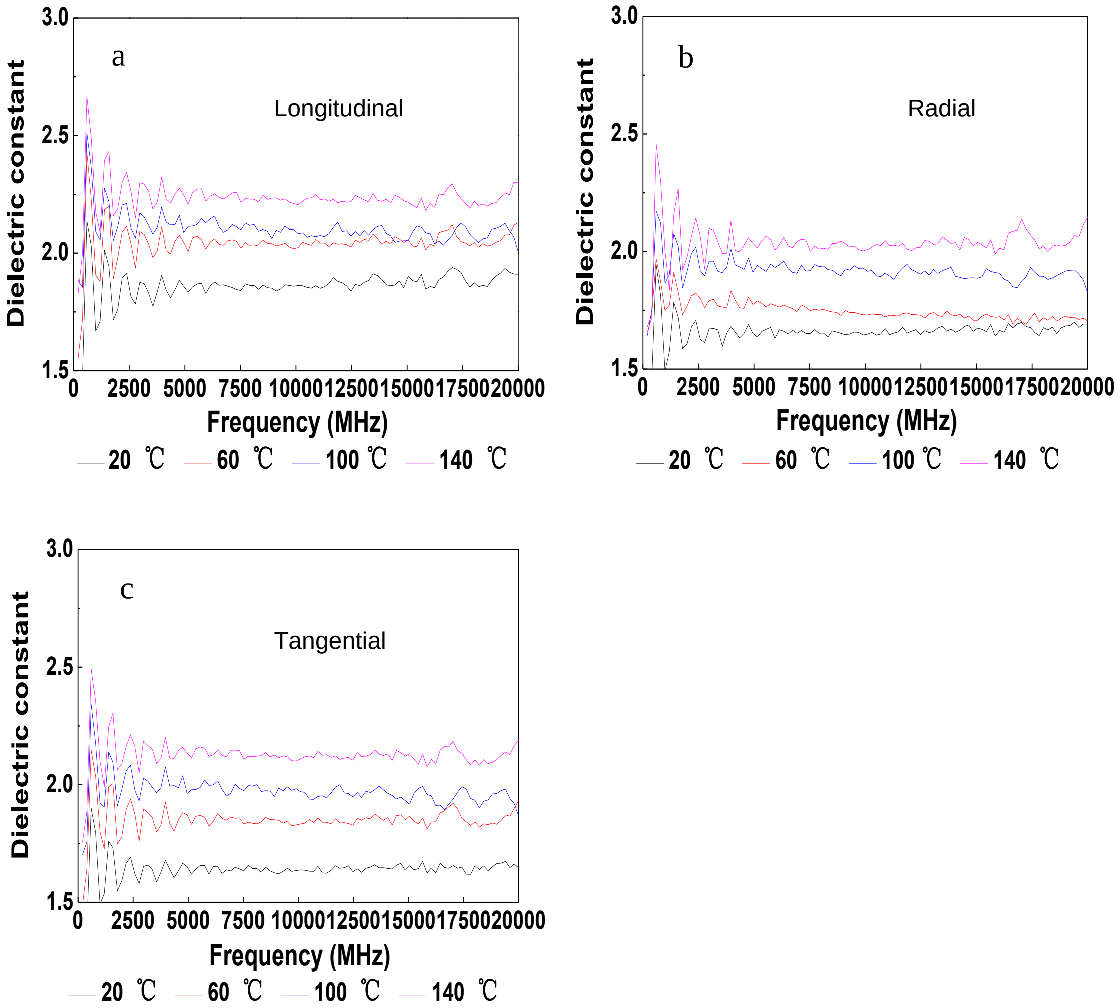

Fig. 5. The effects of temperature on the dielectric constant of wood in longitudinal (a), radial (b), and tangential (c) directions

Second, as the MC in wood increased from the oven-dry condition, the polar components of the cellulose and the cell walls possessed more freedom of rotation with the electric field, which contributed to the higher dielectric properties. In the oven-dry state, cellulose macromolecules in wood are mutually bound by secondary valence forces that prevents the displacement of molecular dipoles under the influence of an alternating electric field. During the process of humidification, water molecules penetrate into cellulose, which weakens the transverse bonds, resulting in the increase in the mobility of dipoles and the dielectric properties (Zhou 1996; Wang and Zhou 2015). Dielectric constants slowly decreased with the increase of frequency. Dipole polarization was expected to be mostly affected by the frequency value. At low frequencies, there was enough time for the polar molecules in wood to change their directions with the electromagnetic field. Thus, a large dielectric constant was expected. As the frequency increased, wood dipoles could no longer follow the electric field, which reduced the polarization degree and lowered the dielectric constant. A maximum of the loss factor appears when the frequency was about 7500 MHz. Dai *et al.* (1989) found that when the frequency of electric field varies to the corresponding frequency of dipole relaxation time, the maximum of loss factor appears. As the frequency continue to increase, the dielectric loss factor decreases. The reason is that the angle of rotation of dipole can be decreased significantly in each cycle of frequency, and the internal friction motion is relatively weak. The relaxation frequency of free water was about 18GHz, while the oven-dried wood's was 10 MHz. When the MC of wood above fiber saturation point, the dielectric properties of the wood were mainly affected by the free water. Therefore, the maximum of the loss factor appears at 7500 MHz.

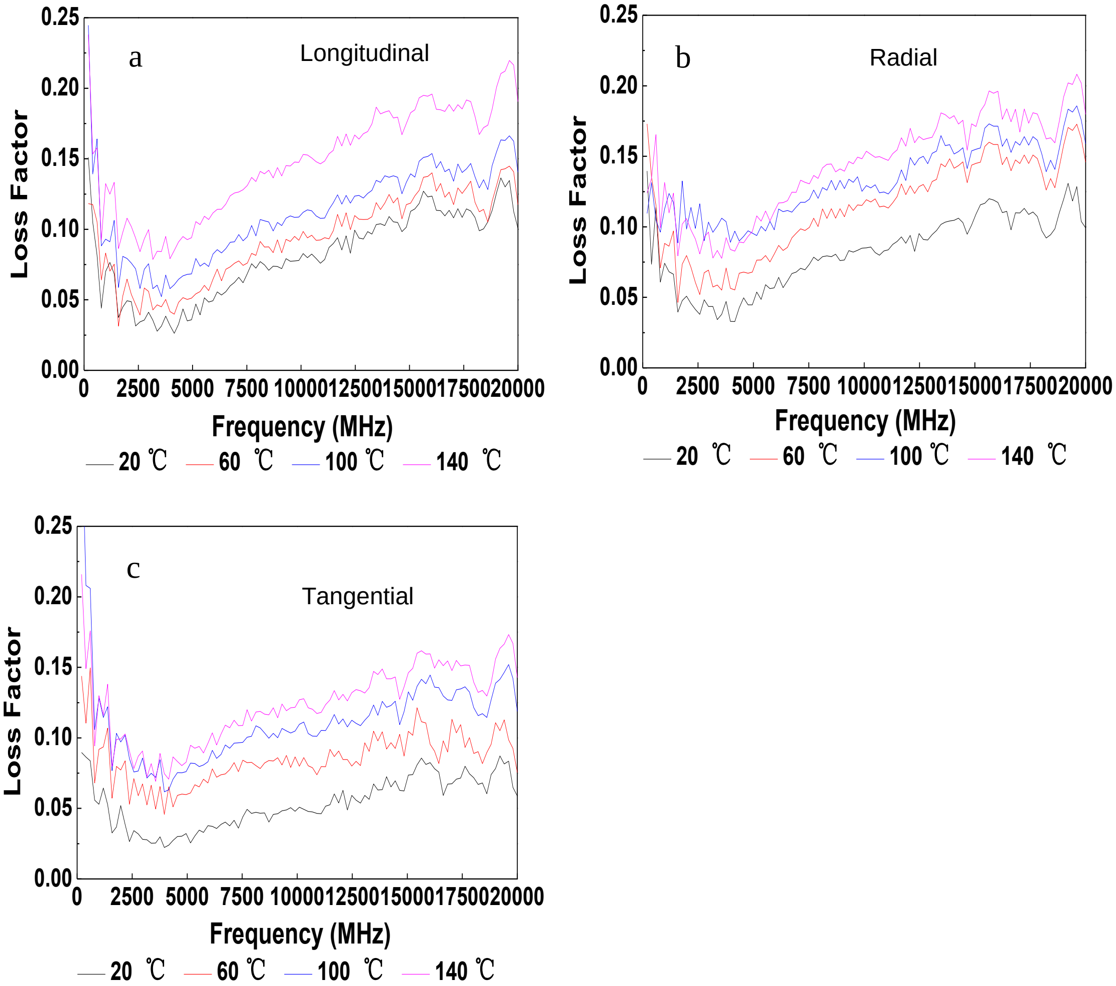

Fig. 6. The effects of temperature on the dielectric loss factor of wood in longitudinal (a), radial (b), and tangential (c) directions

Effects of the temperature on the dielectric properties of poplar wood are shown in Fig. 5 and 6. When the samples were tested at room temperature (approximately 20 °C), the dielectric constant was about 1.7, independently from the frequency. The dielectric constants and loss factor values of the three directions resulted in a similar small increase with temperature. When the temperature was raised to 140 °C, the dielectric constant and loss factor increased by 41% and 272%, respectively. When microwaves was used in wood modification, the dielectric properties of the wood at high MC were mainly affected by the free water molecules, and the relaxation frequency of the wet wood (approximately 18 GHz) was far higher than the microwave frequency (915 MHz and 2450 MHz). At ambient temperatures and the microwave range, the loss factor had a negative temperature coefficient. The colder regions of wood were thus able to absorb a higher amount of energy and increase their temperatures, while the high-temperature regions increased their temperatures more slowly. Consequently, this heterogeneous heating led to a uniform heating of the wood. In addition, the loss factor was higher in the high-MC regions (Fig. 4). The wood was then able to absorb more energy and evacuate the excess water faster *via* evaporation. In the last stage of wood drying, the MC of wood was low (MC < 15%), and the dielectric properties of the wood were therefore close to those of the oven-dried wood. The relaxation frequency in low-MC wood was lower than the microwave frequency (915 MHz and 2450 MHz). Hence, the loss factor increased with the increase of temperature. At a hotter region of the wood the temperature would rise more quickly, and this would lead to further increase in the loss factor. This resonance could generate much higher temperatures in some regions of wood and possible burns. Therefore, microwave pretreatment was more suitable for wood at a high MC.

The effects of the grain direction on the dielectric constant and loss factor of wood are shown in Fig. 7 and 8, respectively. The dielectric properties of wood at longitudinal direction were higher than those at transverse direction. Similar properties were found within tangential and radial orientations. The longitudinal dielectric constant value was about 1.2 times higher than that of the transverse one. The dielectric properties in the radial direction were slightly higher than those at tangential direction.

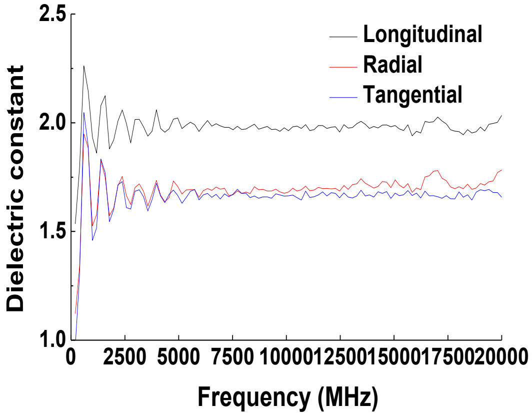

Fig. 7. The effects of grain direction on dielectric constant of wood

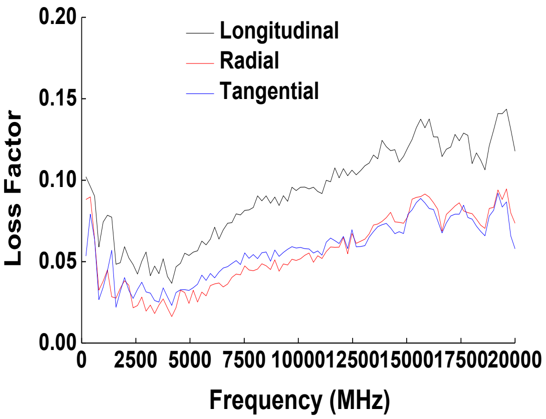

Fig. 8. The effects of grain direction on loss factor of wood

Norimoto (1976) pointed out that the difference in dielectric properties between the longitudinal, radial, and tangential directions could result from 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. Hydroxyl groups in the cellulose are likely to have a higher degree of rotational freedom in the longitudinal direction (Lin 1967). When the applied electric field direction was parallel to the fiber orientation, substances in the cell walls were in independent states. Therefore, the polarization degrees in the longitudinal direction were higher than those in the transverse direction. This explains why the longitudinal dielectric properties were higher. The reason why the dielectric properties along the radial direction were slightly larger than those along the tangential direction was due to the presence of a higher lignin content along the tangential direction of wood. Lignin typically possesses lower dielectric properties with respect to cellulose, and thus the dielectric properties of wood decreased with the increase in lignin content. From the results discussed above, it was concluded that the dielectric properties were mainly correlated with the MC. Moreover, in an actual production scenario the effect of the grain direction, together with frequency-related effects, could be ignored.

To accurately describe the relationship between the moisture content (M) and the dielectric properties of wood, several mathematical models were established (Table 1) and verified using the dielectric measurements (Fig. 9 and 10).

Table 1. Predictive Equations for the Dielectric Properties of Poplar Wood as a Function of Moisture Content (M)

Dielectric Property	Grain Direction	Regression Equation	R^2
Dielectric Constant	Longitudinal (L)	$y = 0.0012M^2 - 0.0284M + 2.0811$	0.9864
	Radial (R)	$y = 1.68 \times 10^{-4}M^2 + 0.0133M + 1.57941$	0.9644
	Tangential (T)	$y = -6.42 \times 10^{-5}M^2 + 0.0357M + 1.5619$	0.9682
Loss Factor	Longitudinal (L)	$y = 3.46 \times 10^{-4}M^2 - 0.0061M + 0.1658$	0.9917
	Radial (R)	$y = 2.44 \times 10^{-5}M^2 + 0.0053M + 0.0550$	0.9095
	Tangential (T)	$y = -2.22 \times 10^{-5}M^2 + 0.0083M + 0.0486$	0.9277

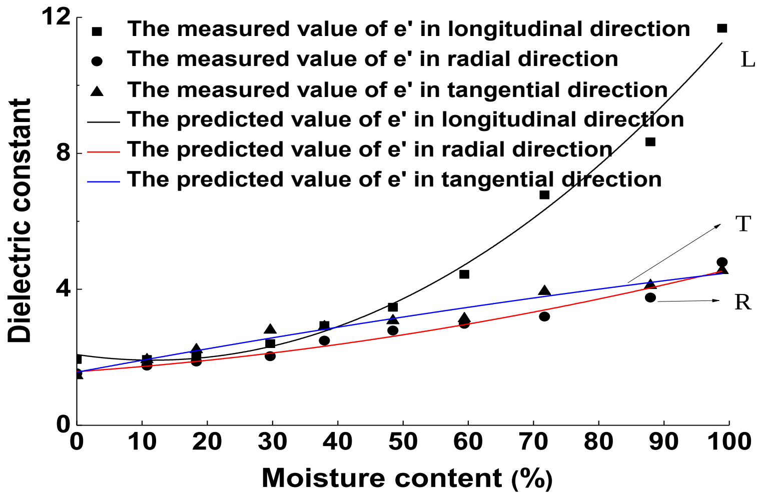

Fig. 9. Comparison of experimental and predicted values of the dielectric constant of wood

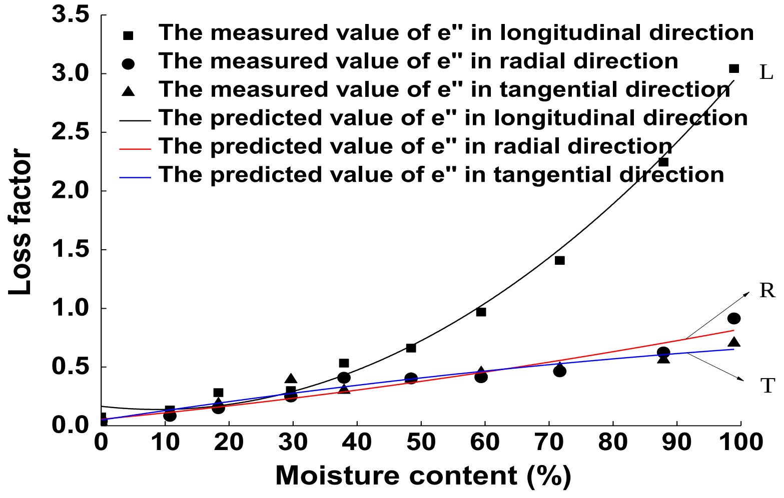

Fig. 10. Comparison of experimental and predicted values of the loss factor of wood

As shown from the table and figures, the squares of regression coefficients were always above 0.90. This indicated that equations could appropriately describe the relations between the dielectric properties and the MC.

CONCLUSIONS

1. The dielectric properties were mainly correlated with the MC. When the MC increased from 0% to 100%, the dielectric constant and loss factor increased 820% and 8630%, respectively.
2. The dielectric properties of wood increased with the temperature increasing. When the temperature rose from 20 °C to 140 °C, the dielectric constant and loss factor increased 41% and 272%, respectively.
3. The dielectric properties of wood were anisotropic: the longitudinal dielectric properties were higher than those found at the transverse or radial directions (the latter two being similar to one another).
4. The dielectric constant decreased slightly with the frequency increasing. The higher the MC was, the more rapidly the dielectric constant decreased with the frequency.
5. The regression equations represented an accurate fit to the experimental trends, and these equations could be particularly helpful to predict the relationship between the dielectric properties and MC.

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