Detection of Dielectric Constant of *Pinus sylvestris* Var. *mongolica* and its Influencing Factors

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The accurate measurement of wood dielectric properties and their relationship with many influencing factors are not only necessary for the study of other relevant wood properties, but also improve the wood dielectric moisture content detection method. In this study, the relationships between dielectric properties and frequency, as well as between moisture content and texture direction were analyzed. The results showed that the effect of the moisture content on the dielectric constant is significant. With increasing moisture content, the dielectric constant increased exponentially below the fiber saturation point. The effect of texture direction slightly exceeded that of the radial direction, and the change rate of the tangential direction above the fiber saturation point was higher than that of the radial direction. The relationship between the dielectric constant and frequency was related to the wood moisture content. The dielectric loss was approximately linear with the frequency below the fiber saturation point.

Keywords: Pinus sylvestris var. mongolica; Dielectric constant; Dielectric loss; Moisture content; Frequency

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INTRODUCTION

High frequency heating and drying technology was developed in the early 1970s. Due to its faster heating rate and better drying quality compared to conventional drying (Harris and Taras 1983; Trofatter *et al*. 1986; Ruddick *et al*. 2001), high frequency heating was used for drying thick wood, which is difficult to dry. In recent years, with the development of China's economy and the improvement of the level of industrialization, drying technologies have constantly improved, thus laying the foundation for the promotion of high-frequency heating technology in China's wood processing industry (Lee and Luo 2002; Zhang 2006; Fu *et al*. 2018; Liu *et al*. 2018). Among these technologies, the combined drying technology of high frequency and convection offers the characteristics of fast heating speed, low energy consumption, and easy control of drying quality, which has research value and enables the popularization of this technology (Xia and Cai 2010).

Under the process of high frequency convection, which combines heating and drying, the dielectric properties of wood determine the heating efficiency and the required energy consumption, which is also the basis for the development of on-line moisture content detection technology. Studying the dielectric properties of wood is also helpful to understand the cellular and molecular structure of wood, the binding mechanism between wood and water molecules, as well as the behavior of wood under the action of a high frequency electromagnetic field (Feng *et al*. 2002). Therefore, it is necessary to accurately measure the dielectric properties of wood and to clarify the relationship between dielectric properties and many relevant factors. The related research has attracted much attention in the related fields. Romanov (2006) measured the dielectric constant of more than 50 types of trees and preliminarily drew the conclusion that the dielectric coefficient of wood was proportional to both moisture content and temperature. Based on Von Hippel's transmission line method, Sahin and Nurgul (2004) studied the relationship between moisture content and dielectric coefficient below the fiber saturation point of three types of wood, *e.g.*, the European poplar, and reported that the relationship between moisture content and dielectric property was a positive correlation, and the texture direction played a significant role. Pentoś *et al*. (2017) analyzed the relationship between the dielectric properties of seven Polish wood core sapwoods and frequency, as well as between crystal arrangement and orientation, and reported that dielectric constant and loss coefficient were affected by both wood frequency and anisotropy. However, the frequency range was only from 1 kHz to 1 MHz, which could not meet the needs of high frequency drying. Bossou *et al.* (2010) measured the dielectric properties of tropical trees at microwave frequencies. By using the resonant cavity method, dielectric loss increases with wood density, but there is room for experimental error to improve accuracy.

Sudo *et al.* (2018) measured the dielectric constants of beech trees at frequencies ranging from 40 Hz to 10 GHz and studied the effect of the local adsorption structure of water molecules with regard to wood fiber direction on dielectric relaxation. The influencing mechanism of the dielectric constant was explained by a molecular mechanism.

The above research remains limited by the accuracy of instruments and the detection speed (the measurement process is difficult to control and it is also difficult to obtain the change in the moisture content of the samples). As a result, it has not obtained accurate values and reliable fitting equations to characterize the relationship between dielectric properties and moisture content. Therefore, rapid and accurate detection of dielectric properties and accurate determination of the influencing factors are still of great significance.

Based on the reasons mentioned above, *Pinus sylvestris* var. *mongolica* was selected as the research object. As a fast-growing material, it has good cold resistance, barrenness resistance, good material quality, and straight texture. It can be used in buildings and furniture. There is a widespread trend in China of drying *Pinus sylvestris* var. *mongolica* by high-frequency heating technology. The medium characteristics of *Pinus sylvestris* var. *sylvestris* var. *mongolica* were accurately measured by the broadband dielectric impedance spectrometer. The effects of water content, frequency, and texture direction on dielectric properties were considered. An equation was fitted to the data to provide the basis for high frequency heating drying of *Pinus sylvestris* var. *mongolica* and on-line moisture content detection of wood.

EXPERIMENTAL

Materials and Instruments

Experimental materials

P. sylvestris var. *mongolica* samples were obtained from Daxing'an Mountains of Heilongjiang Province (Mohe, China). The sawn timber specifications were 2000 mm × 150 mm × 25 mm (longitudinal × tangential × radial). The samples were chosen based on the avoidance of defects, such as knots, decay, wormholes, or cracking. After truncating the end 200 mm from the end face, a thin plate was processed into 3 mm thick radial and tangential plates. Then, each thin plate was processed into 40 mm circular plates with a curve saw. A total of 150 samples were processed. Ten samples were randomly selected as initial moisture content samples and the remaining 140 samples as dielectric constant measurement samples, the tangential and radial samples account for half of the total.

Instruments and equipment

The main instruments and equipment were a Broadband Dielectric Spectrum Impedance Spectrometer (BDS) produced by Novocontrol, Montabaur, Germany and associated equipment, as shown in Fig. 1.

Fig. 1. Broadband dielectric spectrum impedance instrument

The experimental frequency was set between 5 MHz and 30 MHz. The principle of the experiment is the lumped constant loop method, and Fourier correlation analysis technology combined with current-voltage (I-U) conversion technology was adopted. The Fourier correlation technique was accomplished by an additional frequency response analyzer which can measure the complex impedance z^* (ε) of the sample (Qian 2013). When the dielectric sample is placed between the two electrodes, a capacitor forms which filled with the research material. The complex permittivity of the capacitor is expressed as the ratio of capacitance to vacuum capacitance. They were calculated using Eq. 1,

$$\varepsilon^*(\omega) = \frac{C^*(\omega)}{C_0} \tag{1}$$

where $\varepsilon^*(\omega)$ is the complex permittivity of materials ($\frac{\mathrm{C}^2}{\mathrm{N*M}^2}$), $C^*(\omega)$ is capacitor capacitance (F), and C_0 is the vacuum capacitance (F).

Other auxiliary equipment was as follows: a 450 mm vacuum dryer, a DHG-9070A electrothermal constant temperature blast dryer (Jinjian Instrument Testing Company, Chengde, China), and an electronic balance LT210 / 0.01g (Dazhan Instrument testing, Nanjing, China).

Methods

Control of moisture content

The samples used in this study were divided into seven groups according to the target moisture contents listed in Table 1, with the moisture contents ranging from 7% to 49%. The moisture content values chosen were based in the saturation point of the fibers (about 28%), and an increments/reductions range of 25% to 75%. The set of specimens was specified such that every 7% of moisture content was represented. Below the fiber saturation point, the samples were sealed in a dryer equipped with different saturated salt solutions, as listed in Table 1 (25 °C) for balance treatment. The samples were weighed every 2 h, and the moisture content reached the moisture absorption or analytical stability value when the weight differences between two weightings was below 0.02 g. The actual moisture content was calculated using both the initial weight and the absolute dry weight at this time. The target moisture content in Table 1 represents the equilibrium moisture content of saturated salt corresponding to both relative humidity and temperature. The selection of salts in Table 1 and the determination of related parameters are based on the relationships between the wood equilibrium moisture content, ambient temperature, relative humidity, and the relative humidity corresponding to saturated salts (Cai and Hayashi 2007; Wang 2007; Wang *et al*. 2018). At the saturation point of the fibers, the samples were soaked in distilled water to achieve a moisture content above 100%, then they were dried naturally at the atmosphere and weighed once every 5 min until the target weight corresponded to the target moisture content. To determine the absolute dry weight of each test specimen, the initial moisture content and the initial weight were measured and used to calculate the presumed absolute dry weight of the representative sample extracted from the test specimen before the end of the dielectric constant test. After the dielectric constant test, the samples were dried out and replaced by the actual absolute dry weight obtained from the relevant calculation formula. The environmental humidity corresponding to each specimen is shown in Table 1. The general scheme of experimentation is diagramed in Fig. 1.

Table 1. Selection of Environmental Temperature, Humidity, and Salts Corresponding to the Equilibrium Moisture Content of Specimens

Group	Target Moisture Content of Specimens (%)	Dry-bulb Temperature/Dry-Wet-bulb Temperature Difference of Medium (°C)	Relative Humidity of Medium (%)	Selected Salts	Salts Correspond to Relative Humidity (%)
A	7	25/8.50	42	K_2CO_3	43.16
B	14	25/2.62	79	KBr	81.67
C	21	25/0.63	94	KNO_3	94.62
D	28	25/0	100	$Mg(NO_3)_2$	97.88
E	35	—	—	—	—
F	42	—	—	—	—
G	49	—	—	—	—

Dielectric property testing

Each sample was placed into the middle of the plate electrode to form a sandwich capacitor. Then, the sandwich capacitor was fixed between the upper and lower electrodes of the sample chamber. The sample chamber electrode, the additional electrode, and the sample were tightly contacted and fixed so that the sample was located in the middle of the upper and lower electrodes. After the specimen had been installed, the program to obtain the dielectric constant and dielectric loss factor of the specimen at various frequencies was started. The main frequencies used in high frequency heating of wood based on current research are 6.78, 13.56, and 27.12 MHz. In order to study the effect of frequency on the dielectric properties of wood during the high frequency heating, the dielectric constant and dielectric loss factor at 23 frequencies (which contained 6.78 MHz, 13.56 MHz, and 27.12 MHz) were measured in a range of 0 to 30 MHz. The measuring time was only 5 s. The sample was weighed immediately after testing, and the accurate dielectric constant at this moisture content was obtained.

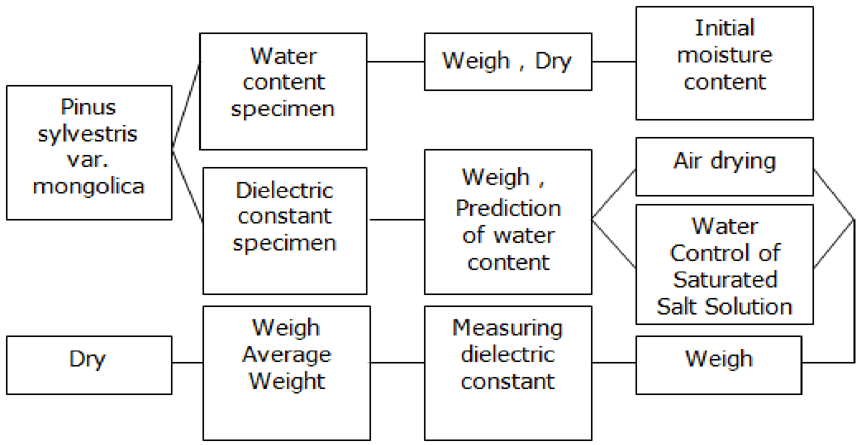

Fig. 2. Experimental Procedures

RESULTS AND DISCUSSION

Relationship between Dielectric Constant and Moisture content

The moisture content is the main factor affecting the dielectric constant. This is because the dielectric constant of water is 80.10 F/m (20 °C), which is much larger than that of wood (about 2 to 10 F/m in this experiment). The proportion of water in wood increases with increasing moisture content and thus, the dielectric constant increases. The relationship between moisture content and dielectric constant is shown in Fig. 4. The dielectric constant is positively correlated to moisture content. Wood shows different characteristics before and after the fiber saturation point due to the existence of free water in the cell cavity. The image was further analyzed, and a curve was obtained that approximates the exponential function by using non-linear fitting below the fiber saturation point. An approximate linear line was obtained above the dimensional saturation point.

When the moisture content remains below the fiber saturation point, the change in trend of the curve is slow, and the dielectric constant increases slowly with increasing moisture content. This phenomenon can be explained by the theory of dielectric polarization (Zhang 2012): when the moisture content of wood is very low or even close to absolute dryness, water molecules exist in the form of single-layer adsorbed water. However, these water molecules can only form hydrogen bonds with polar groups in the wood, which are closely linked. Water molecules cannot rotate freely under the action of an external electric field. At this time, the polarization mainly originates from the orientation and rotation of the primary alcohol hydroxyl group in the amorphous cellulose molecular chain in the cell wall; therefore, the polarization degree is very low and the dielectric constant is small. When the moisture content gradually increases, the water molecules at the adsorption point will also increase, the adsorption thickness will increase, the adsorption force between wood molecules and water molecules will gradually weaken, and the number of water molecules that can participate in the polarization will decrease. The wood then absorbs water and expands, space gaps decrease, the volume proportion of cell wall material increases, and polarization increases, which increases the dielectric constant of the wood. Therefore, when the wood moisture content does not reach the fiber saturation point, the dielectric constant increases exponentially with increasing moisture content. The curve equations are as follows:

Tangential: $y = 0.93599x^{0.46503}$, $R^2 = 0.98028$ (2)

Radial: $y = 0.65247x^{0.58842}$, $R^2 = 0.97701$ (3)

When the fiber saturation point is exceeded, the cell wall is filled with free water. The increase or decrease of free water into the cell cavity has little effect on the water molecules in the cell wall; therefore, the influence of the free moisture content on the dielectric constant is the dominant factor. After fitting, the relationship between the free moisture content and the dielectric constant is approximately linear.

Tangential: $y = 0.14234x + 0.252$, $R^2 = 0.92572$ (4)

Radial: $y = 0.14234x + 0.252$, $R^2 = 0.92572$ (5)

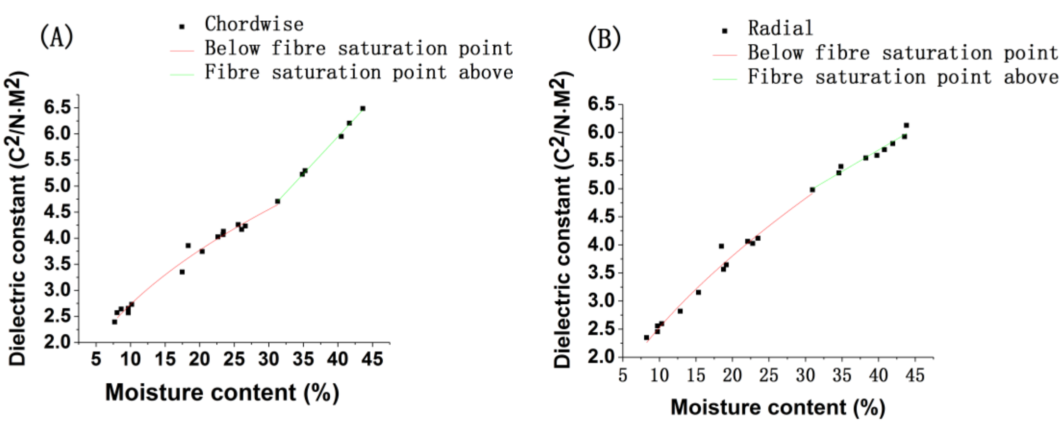

Fig. 3. A) Relationship between the dielectric constant and the moisture content (tangential); B) Relationship between the dielectric constant and the moisture content (radial)

Relationship between Texture Direction and Dielectric Constant

The texture direction exerts a specific effect on the dielectric constant. In the relationship between the moisture content and dielectric constant, the trend of the radial and tangential directions image differs slightly. Below the saturation point of the respective fiber, the radial and tangential directions image shows little difference, which is an exponential positive correlation. At the saturation point of the fiber, because the cell wall is filled with water, the dielectric constant is dominated by the free water in the cell cavity and follows a linear relationship. Among these, the trend of tangential change is more apparent than that of radial change. It can be inferred that there are more free water channels in the micro-structure of tangential wood than in radial wood. Therefore, the fractal characterization of wood texture was used to explain it (Ren *et al*. 2007). Peri-fractal analysis of the micro-structure of *P. sylvestris* var. *mongolica* shows that the fractal dimension of the diametric section is about 2.2, and the fractal dimension of the tangential section shows that the diameter section is relatively smooth, the micro-pattern texture is relatively simple, and the tangential section is relatively complex and rough (Song 2011). Consequently, it contains more resin channels. Therefore, with increasing moisture content, water is absorbed into the radial and tangential directions material, while the radial and tangential directions material shows a better water adsorption process in the resin channel; therefore, the radial and tangential directions material has more self-contained cells than the radial material. Due to the presence of water, the image shows that the dielectric coefficient of the chord material above the fiber saturation point is greatly affected by the moisture content. This indicates good dielectric properties.

Relationship between Frequency and Dielectric Constant

Figure 4 shows the effect of frequency on the dielectric constant in the frequency range of 0 to 30 MHz for each group of specimens with different moisture contents. It is shown that the dielectric constant of the sample below the fiber saturation point does not change much with frequency and can be approximately regarded as a straight line. The reason is that water molecules exist in the inner part of the capillary tube due to water absorption below the fiber saturation point. Water is closely bound to wood and the change of electric field frequency has little influence on the polarization of water molecules. When the fiber saturation point is exceeded, there is a segmented phenomenon. This means that when the frequency is below 15 MHz, the dielectric constant of wood correlates negatively with frequency.

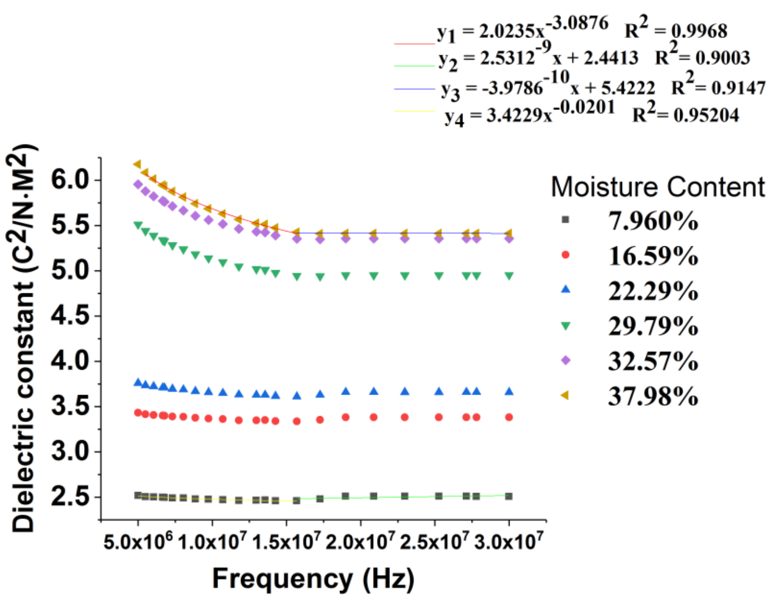

Fig. 4. Relationship between frequency and dielectric constant for different moisture contents (tangential)

The approximate exponential relationship is obtained by fitting the non-linear curve in Eq. 6.

$$y = 33.23454\text{x} \times x^{-0.10957},\ R^2 = 0.99684 \quad (6)$$

However, in the range from 15 MHz to 30 MHz, the dielectric constant varies slightly with frequency and can be approximately regarded as having no effect. This is due to the strong polarization of polar molecules in the wood with increasing electric field frequency, and the polarization change cannot catch up with the change of electric field; therefore, the polarization lags behind. The motion of the dipole is opposite to the frequency of the electric field, which decreases the dielectric constant and increases the dielectric losses caused by polarization. When the frequency exceeds a specific value, the change of polar molecules cannot keep up with the change of the electric field frequency. The polar molecule is viscous, and the orientation polarization becomes smaller, which tends to lead to a stable change of dielectric constant. When the electric field frequency is low, the dielectric constant of wood with higher moisture content (especially above the fiber saturation point) decreases more apparently with increasing frequency. This is because at low frequencies, polar molecules, especially water molecules, are more easily able to establish polarization. Therefore, the shorter the polarization time of wood with higher moisture content is, the faster the declining trend of the dielectric constant will be.

Relationship between Frequency and Dielectric Loss

Dielectric loss is the imaginary part of the complex dielectric constant. It is also a heating phenomenon caused by the loss of electric energy in an alternating electric field. Dielectric loss is directly related to the high frequency absorption power in the high frequency drying of wood and affects its heating efficiency. The relationship between dielectric loss and both the moisture content and frequency was explored by investigating three moisture content gradients with the same interval at the fiber saturation point. The results are shown in Fig. 5.

Figure 5 shows that the dielectric loss increases with increasing moisture content. The reason is that water is the main part of the polar molecules in wood. The higher the moisture content is, the greater the dielectric loss. However, the difference of dielectric loss is large above and below the fiber saturation point. The reason is that below the fiber saturation point, water is absorbed in the cell wall of wood where it closely attaches to the wood. Above the saturation point of the fiber, the free water in the cell cavity occupies the main part, the degree of freedom is larger, the range of motion is wider, and the dielectric loss changes greatly.

When the fiber saturation point is exceeded, the dielectric loss decreases rapidly with increasing frequency at a frequency range of 0 to 18 MHz. The fitting degree is presented in Eq. 7.

$$y = 3.3559 - 2.98718x + 9.00091x^2 \tag{7}$$

The fitting non-linear curve's R^2 is 99.498. The dielectric loss in the range of 18 MHz to 30 MHz decreases with increasing frequency, following a linear relationship. After fitting, the fitting degree is shown in Eq. 8.

$$y = 1.89324 - 3.91023x,\ R^2 = 98.415 \tag{8}$$

According to the relationship between the frequency and dielectric constant mentioned above, the piecewise phenomenon near 18 MHz can also be explained in that when the frequency exceeds a specific value, the change of polar molecules cannot keep up with the change of the electric field frequency, the polar molecule becomes viscous, fewer polar molecules make a polarization turn, and thus, the dielectric loss decreases.

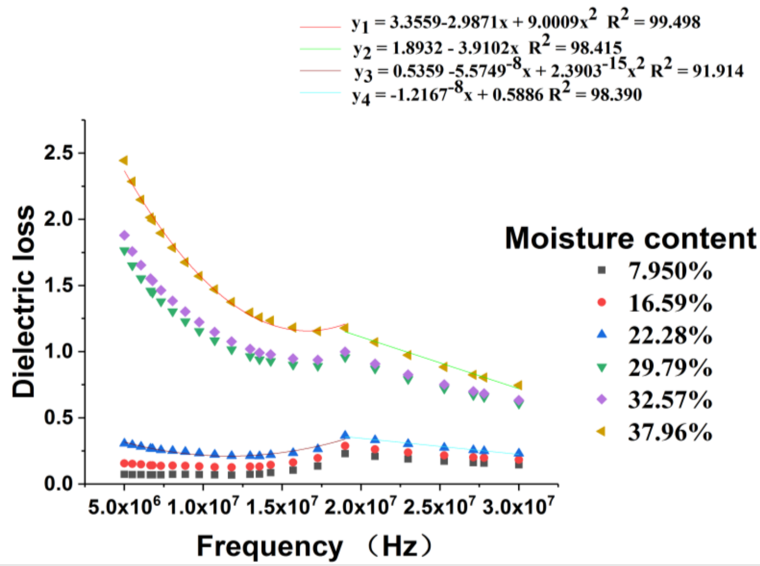

Fig. 5. Effect of frequency on dielectric loss (Radial)

CONCLUSIONS

1. The dielectric constant is affected by moisture content, texture direction, frequency, and other factors. Among these, the influence of the moisture content is the dominant factor, which increases with increasing moisture content. Below the fiber saturation point, the dielectric constant and moisture content are approximately exponential; above the fiber saturation point, the relationship is approximately linear. This phenomenon is mainly related to the proportion of water molecules in the wood under different moisture contents, and also to the water binding of macromolecules in wood.
2. The texture direction slightly influences the dielectric constant. When the tangential dielectric constant is slightly higher than the radial constant at the same moisture content and above the fiber saturation point, the changing rate of the tangential dielectric constant exceeds the radial constant. This is related to the difference of the micro-structure of the tangential direction. The existence of resin channels leads to a slightly different structure of the tangential direction, which affects the water adsorption process.
3. Above the fiber saturation point, the relationship between frequency and dielectric constant is negatively correlated in the range of 0 to 15 MHz. Within 15 to 30 MHz, the dielectric constant can be approximately regarded as a fixed value, and the frequency affects it little. Below the saturation point of the fiber, the dielectric constant is approximately a fixed value, which affects the frequency change little.
4. The dielectric loss increases with moisture content, showing a positive correlation, and the influence above the fiber saturation point is strong, which is more abrupt than that below the fiber saturation point. Dielectric loss is also related to frequency. In general, below 18 MHz it follows a quadratic function, and above 18 MHz it follows a linear negative correlation. The effect of wood texture direction on dielectric loss is not obvious. The reason is related to the state of water absorption in the wood.

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