Microwave Non-Destructive Testing (MNDT) of Malaysian Woods at X-band and K-band

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***Abstract*-This work highlights the use Free Space Microwave Measurement (FSMM) system using Microwave Non-Destructive Testing (MNDT) measurement system to determine the electrical properties of Malaysian woods at X-band and K-band. The electrical properties of interest are dielectric constant, loss factor and loss tangent. Malaysian woods used as samples are Medang, Punah, Kempas, Petai and Yellow Meranti. The FSMM system consists of WILTRON 37269 Vector Network Analyzer (VNA), a pair of spot focusing antennae (transmitting and receiving) that operate in X-band and K-band, mode transitions, coaxial cables, sample holder, computer and a high performance workstation. The Thru, Reflect, Line (TRL) calibration technique were used to eliminate the effect of undesirable multiple reflection. The sample under test was placed in the middle of the two spot focusing antennae. The values of scattering parameters, S_{11} and S_{21} were measured. The electrical properties of the wood were then extracted from these measured parameters. The wood was placed according to its grain alignment and conducted from 0° to 180° rotation of the wood. It was observed that the dielectric constant (ε') is high when the wood grain is in parallel condition. In perpendicular condition of wood grain, the dielectric constant (ε') is low. The density of wood also has effect to electrical properties of wood. Kempas wood which has the highest value of density also has the highest value of dielectric constant. Petai wood which has the lowest value of density also has the lowest value of dielectric constant. Each wood sample has unique electrical properties.**

Keywords-Vector Network Analyzer (VNA), Microwave Nondestructive Testing (MNDT), Free Space Microwave Measurement (FSMM), Thru, Reflect, Line (TRL).

I. INTRODUCTION

Wood is a natural product which has unique electrical properties. Each wood has different alignment of grain and makes it difficult to configure the properties. Wood also is an anisotropy material which makes it a complex material compared to homogenous material. The electrical properties of wood which describe its characteristic when electromagnetic waves are transmitted through it strongly dependent on its grain angle, moisture content and density [1].

Wood grain plays a major part in determining the electrical properties of wood. Wood grain can be divided into two parallel to the grain and perpendicular to the grain. The value of the dielectric constant is higher for polarization parallel to the grain than across the grain [2]. The strength of the wood also has connection with the wood grain alignment. As reported, strength usually referred to as parallel to the wood grain properties [3].

The conventional method of determining the measurement (visual or scriber) of wood grain angle is inaccurate, slow, laborious and destructive [1]. FSMM using MNDT was explored on sample of wood to determine its electrical properties. This measurement system provides an alternative way to characterize sample of wood. The advantage of FSMM system is that with suitable modifications, it is possible to make precise, accurate and reproducible MNDT measurements on materials due to contactless feature of free space measurements. Another advantage of FSMM method is that the measurements can be made when incident, reflected and transmitted signals are circularly / elliptically polarized electromagnetic waves [4]. This measurement system which is contact-less and non-destructive, consists of a pair of spot focusing antenna that operate at X-band and K-band utilize the use of microwave to characterize wood.

II. THEORY

Every material has a unique set of electrical characteristics that are dependent on its dielectric properties. Permittivity is a quantity used to describe dielectric properties of material under the influence of electromagnetic waves with reflection at interfaces and the attenuation of wave energy within those materials [5]. In frequency domain, the complex relative permittivity (ε*) of a material to that of free space can be expressed as Equation (1):-

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \frac{D}{E} \quad \text{and } \varepsilon'' = \frac{\sigma}{\varepsilon_o \omega} \qquad (1)$$

where
ε^* = relative permittivity of the material
ε' = dielectric constant
ε'' = loss factor
ε_o = permittivity of free space
σ = conductivity of the material
ω = angular frequency of the field
D = electric flux density or displacement
E = electric field intensity

The real part (ε') is referred to as the dielectric constant and represents stored energy when the material is exposed to an electric field, while the dielectric los factor (ε") which is the imaginary part, determine the energy absorption and attenuation. When a linearly polarized, uniform plane wave is normally incident on the sample of thickness (d_s) as shown by Fig.1, the incident wave is partially reflected, transmitted and absorbed by the sample. The reflected signal and transmitted signal are comprised of an infinite number of components due to multiple reflections between the air/sample. The sample under test is assumed to be planar of infinite extent laterally so that diffraction effects at the edges can be neglected, thus the total reflected signal (S_{11}) and transmitted signal (S_{21}) are given respectively by Equation (2) and (3):-

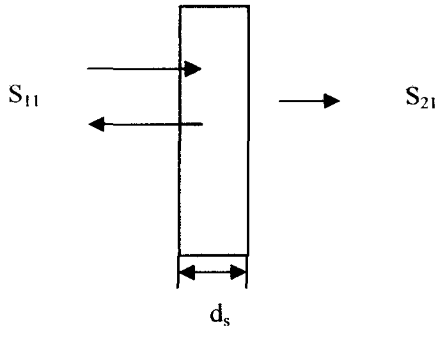

Fig.1: Schematic diagram of wood sample

$$S_{11} = \frac{\Gamma - \Gamma \exp(-2\gamma_s d_s)}{1 - \Gamma^2 \exp(-2\gamma_s d_s)} \qquad (2)$$

$$S_{21} = \frac{(1-\Gamma^2)\exp(-\gamma_s d_s)}{1 - \Gamma^2 \exp(-2\gamma_s d_s)} \qquad (3)$$

where
γ_s = propagation constant in the sample
Γ = reflection coefficient of the sample /air interface

Both are functions of the complex permittivity of the sample (ε*) and given by Equation (4):-

$$\varepsilon^* = \frac{\gamma_s}{\gamma_0}\left(\frac{1-\Gamma}{1+\Gamma}\right) \qquad (4)$$

where, $\gamma_0 = (\frac{j2\pi}{\lambda_o})$ represents the propagation constant of free space and λ_o is the free-space wavelength. Equations (1) to (4) will be the basis to the calculation of complex permittivity of wood in this work. By using equations (1) to (4), calculated S^c_{11} and S^c_{21} can be expressed in terms of ε* but ε* cannot be expressed explicitly in terms of S_{11} and S_{21}, so it is necessary to find it iteratively by assuming a guess value for the complex permittivity of the sample. This is achieved by using a zero finding technique, which finds the zeros of the error function. The error function is defined by Equation (5):-

$$E = |S^m_{21} - S^c_{21}| + |S^m_{11} - S^c_{11}| \qquad (5)$$

where S^m and S^c are the measured and calculated values of the complex transmission coefficients, respectively. The Muller method with deflation is used for calculation of zeros of the error function [6]. There was an alternative way of doing calculation for electrical properties from scattering parameters. The FORTRAN programming can be used to determine the dielectric properties and electromagnetic properties of the material such as complex permittivity.

The wood grain angle in this work is defined as an angle between the grain direction and the direction of incident electric field. Composite material such as wood causes a linearly polarized electromagnetic wave to become elliptically polarized upon transmission through it [4]. The FSSM system was used to measure polarization angle (θ) of elliptically polarized wave transmitted through the wood specimen. The θ is measured for five Malaysian woods species of Medang (Cryptocarya), Kempas (Koompassia), Punah (Tetramerista), Petai (Parkia) and Yellow Meranti (Shorea).

The influence of the electric field on wood is very strong as the interaction between them results in the creation of electric currents in the material. Under the action of an alternating electric field, the wood reveals its dielectric properties, which more often are characterized by two main indices: by the relative dielectric constant (ε') and by the dielectric loss tangent (tan δ). The electrical properties were measured when electric field was parallel, perpendicular and back to parallel to the grain direction according to the rotation of wood sample. The relative dielectric constant of a material shows how many times the force of interaction between the electric charges in the given medium is less than that in a vacuum [7].

III. MEASUREMENT SYSTEM

The measurement system consists of WILTRON 37269B Vector Network Analyzer (VNA) which is connected to a pair of spot focusing antenna by using circular to rectangular waveguide analyzers. The spot focusing antennae connected to the two ports of Scattering-parameter test set by using the circular-to-rectangular waveguide to coaxial line adapters. These antennae consist of two spot focusing antennae which are mounted back to back in a conical horn antenna. One spot focusing antenna gives an electromagnetic plane wave and the other spot focusing antenna focuses the electromagnetic radiation at the focus. The ratio of focal distance to antenna diameter (F/D) for these antennae is equal to one and D is approximately 30.5 cm. The distance between these antennae can be changed with an accuracy of 25.4 µm by using a dial indicator. A sample holder is placed at the common focal plane for holding wood samples and is mounted on a micrometer-driven carriage.

By implementing the TRL technique, the error in the free-space measurement of Scattering-parameter due to the multiple reflections between the spot focusing antennae and the mode transitions can be eliminated. The technique is implemented along with time-domain gating to remove the effects. A thru standard is configured by keeping the distance between the two antennas equal to twice the focal distance. The reflect standards for port 1 and 2 are obtained by placing a metal plate at the focal planes of transmit and receive antenna. The line standard is achieved by separating the focal planes of transmit and receive antennas by a distance equal to a quarter of the free-space wavelength at the center of the band. When measuring the complex reflection coefficient (S_{11}), the residual post calibration errors can be reduced by using the time domain gating or smoothing function of VNA.

It is observed that the magnitude and phase of S_{11} are within the range of ± 0.1 dB and ± 0.1° from the theoretical value of 0 dB and 180° and S_{21} are within the range of ± 0.03 dB and ± 0.4° from the theoretical value of 0 dB and 0° for the metal plate. The wood sample size of 9.5 x 9.5 x 1 cm with visually measured grain angle of 0° to 180° at 30° increment steps. Wood sample was placed between the spot focusing antennae and then the measurement of S_{11} and S_{21} were carried out. The ε' and ε" of the wood sample can be extracted by S_{21} using FORTRAN software. Fig.2 to Fig.6 shows the step-by-step procedure while conducting the measurement of wood sample.

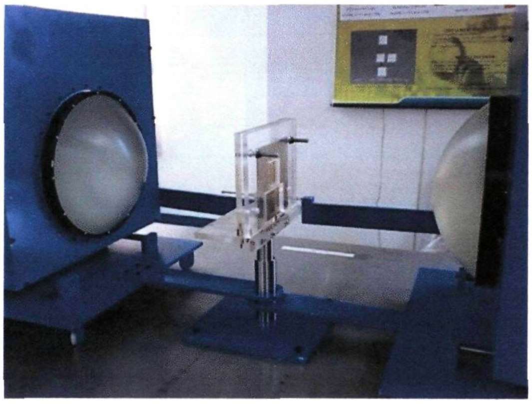

Fig.2: Calibration using TRL

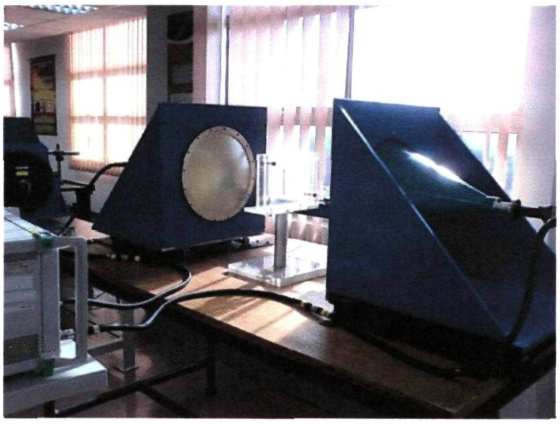

Fig.3: FSMM system

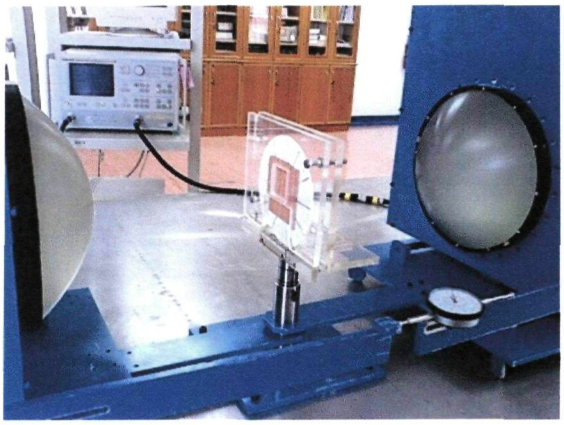

Fig.4: Measurement in progress

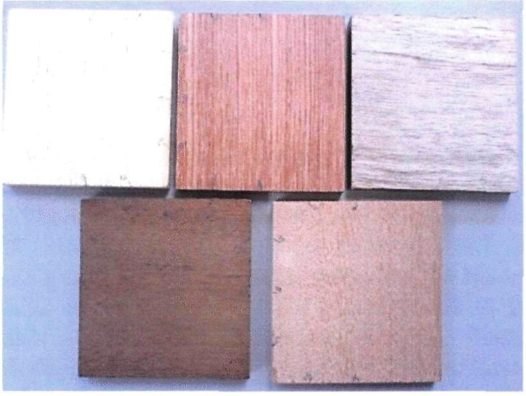

Fig.5: Various samples of wood

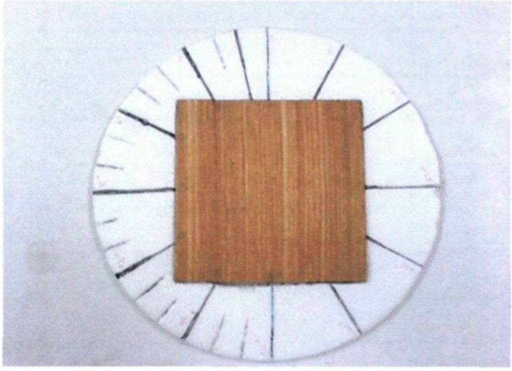

Fig.6: Rotation angle on wood sample

IV. RESULTS & DISCUSSION

The electrical properties of the wood were extracted from S_{11} and S_{21} parameters. The results at mid band of X-band, 10 GHz and mid band of K-band, 22 GHz were taken into account for every wood that has been measured.

The density of woods has effect with the electrical properties of wood. Wood with higher density value also has the highest electrical properties comparison to the lowest density value of wood. Table 1 shows the density value for various samples of wood.

Table 1: Density of wood sample

Types of Wood	Density (kg/m^3)
Kempas	897.4
Medang	789.54
Punah	674.9
Yellow Meranti	622.4
Petai	359.3

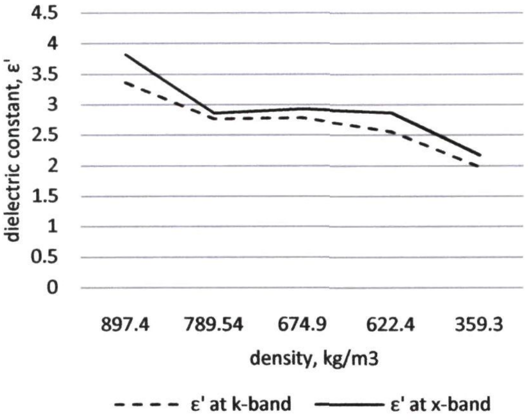

Fig.7: Dielectric Constant (at 0° rotation angle) Vs Density of Wood

Fig.7 shows the dielectric constant of wood sample at 0° rotation angle (electric field parallel to the grain) at X-band and K-band versus the density of woods sample. X-band frequency has the highest value of dielectric constant compared to K-band.

A. *X-band Result*

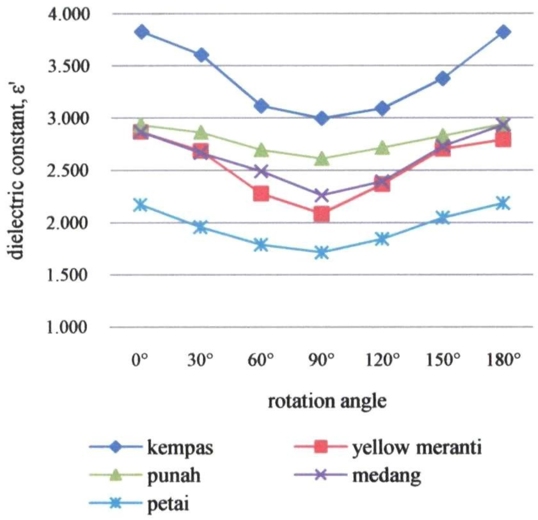

Fig.8: Dielectric Constant Vs Rotation Angle

Fig.8 shows the measured dielectric constant for samples of woods in a different angle of rotation at 10 GHz. Kempas wood has the highest value of dielectric constant as compared to the other woods such as Yellow Meranti, Punah, Medang and also Petai. Petai wood has the lowest value of dielectric constant as compared to other woods.

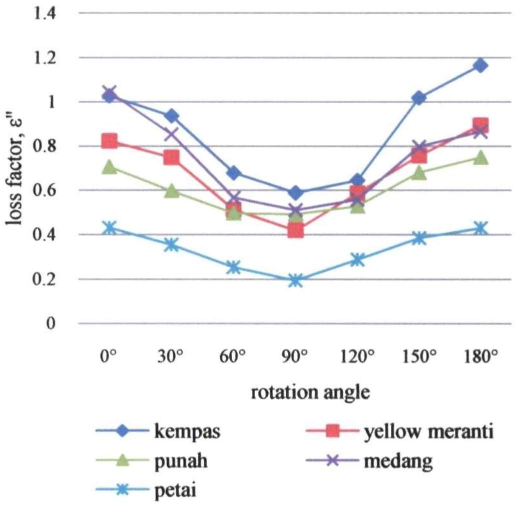

Fig.9: Loss Factor Vs Rotation Angle

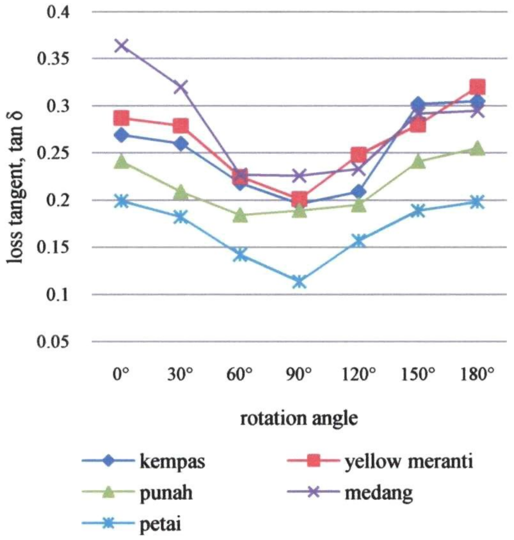

Fig.10: Loss Tangent Vs Rotation Angle

The plot of loss factor and loss tangent of the various wood samples at 10 GHz as indicated by Fig.9 and Fig.10. It was observed that at 90° rotation angle of loss factor, the arrangement of woods sample was according to the density arrange from Table 1. Each material has a unique loss factor and loss tangent respectively.

B. *K-band Result*

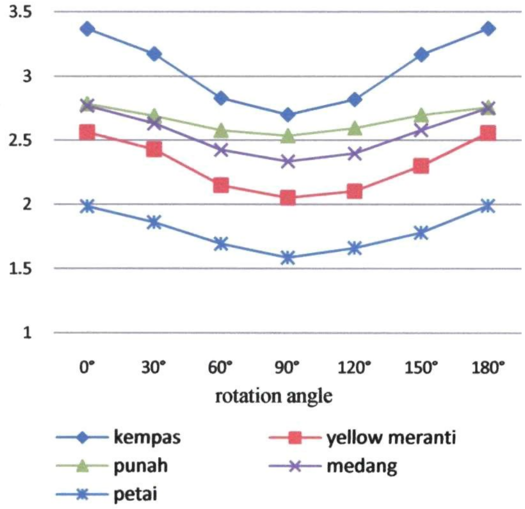

Fig.11: Dielectric Constant Vs Rotation Angle

Fig.11 observed the measured dielectric constant for samples of woods in a different angle of rotation at 22 GHz. Kempas wood has the highest dielectric constant. Petai wood has the lowest dielectric constant as compared to other woods.

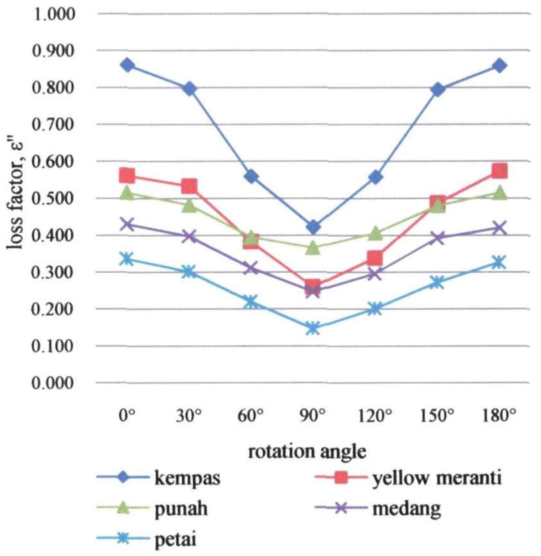

Fig.12: Loss Factor Vs Rotation Angle

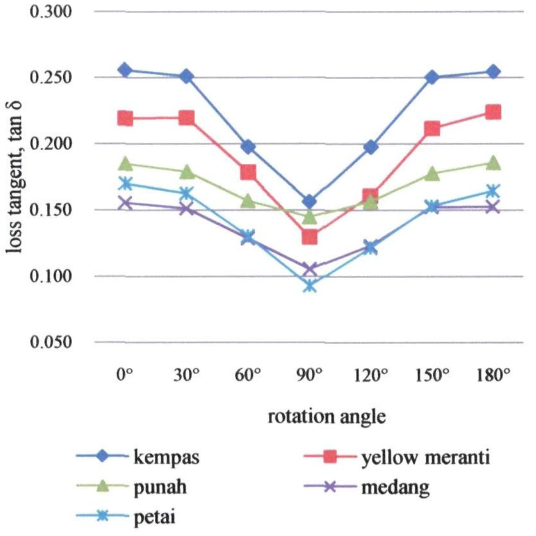

Fig.13: Loss Tangent Vs Rotation Angle

Fig.12 and Fig.13 were illustrated the plot of loss factor and loss tangent of the various wood samples at K-band. It was observed that each material has a unique loss factor and loss tangent respectively.

V. CONCLUSION

FSSM, MNDT can be used to measure the electrical properties of Malaysian wood. It was observed that the dielectric constant of wood is high when the wood grain is in parallel condition whereas in perpendicular condition of wood grain, the dielectric constant (ε') is low. Kempas has the highest value of dielectric constant and Petai has the lowest value of dielectric constant. Each wood sample has unique electrical properties.

VI. FUTURE DEVELOPMENT

More measurement should be carried out for sample of various wood and hence development a database of electrical properties of Malaysian woods.

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