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REVIEW ARTICLE

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Overview and comparison of microwave noncontact wood measurement techniques

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Abstract This article presents a comprehensive review of the literature on microwave wood testing, offering a critical comparison of reported methods and techniques. The purpose of this review is to establish current achievements and evaluate the potential for the application of microwave methods in industry. All reviewed articles are classified based on the way they deal with four key issues: propagation modeling, measurement technique, hardware implementation, and determination of wood properties. Currently used methods for propagation modeling are considered first, with particular attention given to the calculation of propagation factors along the principal directions, because these methods take into consideration wood anisotropy and allow grain angle detection. Measurement techniques are also considered in more detail, with a qualitative comparison of the two most advanced techniques: the focused beam technique and the modulated scattering technique. Reported hardware implementation and methods for determining the wood properties of interest from measured data are reviewed in the final sections. The technology is mature, but more effort is needed to reach a solution suitable for an industrial environment. This article aims to help researchers in this field to identify the remaining issues.

Key words Microwave nondestructive wood testing · Propagation modeling · Focused beam technique · Modulated scattering technique

Introduction

Industrial microwave wood sensing is a vibrant research area because microwave nondestructive testing (MNDT) shows a lot of potential.[1–6] Microwave technology is the only approach that allows noncontact, bulk property measurement in a safe and noninvasive way. There are many other advantages of microwaves compared to other technologies, and these are described in several textbooks and articles available on the topic.[1–6]

This article considers only those MNDT techniques that have so far been applied to wood sensing. It has been noted that, although well established, MNDT cannot be rapidly transferred to the wood industry. Great variation in sample properties and the complex structures involved impose many problems that require advanced theoretical, empirical, and hardware solutions. An example of the great variability in wood composition and the corresponding microwave signal response is given by Fuentealba et al.[7] They recommend the use of microwave signals as a "signature" that can be used later to uniquely identify each sample. The problem of microwave propagation through such heterogeneous, anisotropic samples is very complex, and the measurement process is often very time-consuming. It is thus imperative that a prospective researcher learns from the significant achievements and many elegant solutions reported in the literature so far.

This review investigates recent advances in technology that would allow the transfer of MNDT techniques from the laboratory to an industrial environment. The techniques developed are accurate, robust, and affordable, allowing for industrial implementation. The scope of this review is limited to free space measurement techniques, as these offer fast bulk material testing suitable for rapid scanning of wood on the conveyer belts and chains that are commonly used in lumber mills.

Intensive research efforts have been made since the 1980s. A number of postgraduate research theses have been reported from universities around the world,[8–18] and potential industrial applications have been patented.[19–34] Early articles regarding microwave wood testing provided evidence that microwaves could be used for moisture content (MC) and/or density measurements. Recently reported systems offer many refined solutions, adjusted to deal with specific problems that wood as a sample imposes. To the

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authors' best knowledge, there are no articles that give as comprehensive an overview as is given here. Microwave imaging techniques are presented by Bucur,[35] but have little practical value for rapid and affordable industrial scanning. The dielectric properties of wood are well described by Torgovnikov,[36] but the sensing techniques given there are not suitable for industrial application.

On analyzing and sorting the literature findings, four key issues that need to be addressed when designing a microwave wood measurement system were identified as:

– propagation modeling,
– measurement techniques (sensor configuration),
– implementation of sensors, transmitters, and receivers,
– wood property determination techniques.

Each of the reviewed articles is analyzed based on the way they dealt with these four issues, and the most successful solutions are classified and presented in this article.

Propagation modeling

Understanding the dielectric and structural properties of wood is essential for successful development of a sensing technique. There are many reports on wood's dielectric properties, most notably by Norimoto et al.[37] Torgovnikov[36] has collated current knowledge on measured wood permittivity values and published it in a book that is widely used by researchers in the field today. Wood is strongly anisotropic, both in its physical strength and in its electrical properties. The origin of this anisotropy is in both the molecular structure of cellulose and the fiber structure of the wood, as a model and study reported by Daian et al.[38,39] demonstrated. Wood is commonly considered as an orthogonal isotropic material, whose dielectric properties are described using a complex permittivity tensor of rank two. When the electric field vector is aligned with the grain, the tensor is reduced to three diagonal complex permittivity values. The permittivity of wood is largest parallel to the grain and smallest across the grain.[36,37] In addition, the permittivity is larger in the tangential direction compared to the radial direction, but this difference is much smaller and these are often considered to be equal. Thus, only values perpendicular (⊥) and parallel (||) to the grain are usually considered.

The operating frequency is another factor that significantly influences the propagation model. High-loss samples, such as green wood, significantly attenuate the transmitted microwave signal, but this attenuation is less critical at the lower frequency range. However, knots and internal degradations can be detected by microwaves only if the size of the defect is comparable to the wavelength.[17] To achieve better resolution, Eskalinen[40] recommends an operating frequency as high as 15 GHz. It may also be beneficial to observe the response over a wider frequency range. This is particularly recommended for the phase measurement, where operating at more than one frequency helps to resolve the phase ambiguity that is reported by many as a source of error.[9]

The complex composition of wood encourages an empirical approach to propagation modeling.[14,41–43] The measured microwave attenuation and phase delay are often directly correlated to a wood parameter of interest, such as MC, density, or grain angle. One of the challenges is to distinguish which of the wood's parameters causes detected changes in a measured microwave signal.[14] Most articles consider the measurement of dry wood (below the fiber saturation point), with only a few investigations of green lumber.[44,45]

Only approximate theoretical models of electromagnetic field propagation through a wood sample are possible, due to the complex material composition. The sample is most often considered to be effectively homogeneous and described using a single complex propagation factor. Two models commonly used to estimate the field propagation constant are modeling wood as a homogeneous material with no boundaries[9,10] and modeling wood as a slab of dielectric material.[46–50] In addition, a model considering two orthogonal propagation factors[51–53] is slightly modified and presented here.

Wood as a material with no boundaries

While propagating through matter, an electromagnetic wave suffers loss of intensity, and its speed of propagation is reduced. A time-harmonic plane wave moving through a sample in the z-direction at time t has an electric field intensity vector given by:[1]

$$E = E_0 \exp[\mathrm{j}\omega t - \gamma z]. \tag{1}$$

Here, E_0 is the complex vector amplitude of the electric field, assumed to be constant in time (i.e., a linearly polarized wave), ω is the angular frequency, and γ is the propagation factor, related to the properties of the medium through which the wave propagates by:[1]

$$\gamma = \alpha + \mathrm{j}\beta = \mathrm{j}\omega\sqrt{\varepsilon^* \varepsilon_0 \mu' \mu_0} \tag{2}$$

Here α is the attenuation, β is the phase factor, $\varepsilon^* = \varepsilon' - \mathrm{j}\varepsilon''$ is the relative permittivity, $\mu' = 1$ is the relative permeability of wood, and ε_0 and μ_0 are the permittivity and permeability of free space, respectively. Lundgren[9] reports a study of the attenuation and phase factor distribution for several lumber samples, comparing this model with measured values. The theoretical MC values were obtained gravimetrically, while density distribution was measured using a computed tomography (CT) scanner. A relatively poor agreement was obtained, as expected from such a simplified model.

The model with two propagation factors

It is common in microwave engineering to describe wave propagation by means of a transmission coefficient T,[1] defined as the ratio of the transmitted field (magnitude of E at the point $z = d$, denoted by index T) and the incident field (magnitude of E at the point $z = 0$, denoted by index I):

$$T = \frac{E_T}{E_I} = \exp[-\gamma d] \tag{3}$$

Wood is an orthotropic material and the complex propagation factor γ varies with direction relative to the wood grain. Two extreme values of γ are obtained when the electric field vector is parallel and perpendicular to the grain, and these are often referred to as the principal directions. For dimensioned lumber of thickness d, these can be defined using two transmission coefficients, $T_{\parallel}$ parallel to the grain and $T_{\perp}$ perpendicular to the grain:

$$T_{\parallel} = e^{-\gamma_{\parallel} d} \quad \text{and} \quad T_{\perp} = e^{-\gamma_{\perp} d} \tag{4}$$

When a linearly polarized electromagnetic wave enters a wood sample so that its polarization direction coincides with a principal direction, the field is subject to the corresponding propagation constant and will experience an according attenuation and phase delay. However, if the incident linearly polarized field vector is neither parallel nor perpendicular to the grain, each of its components along these two directions is subject to the corresponding propagation factors, experiencing a different attenuation and phase delay for each direction. Consequently, two components of the field leaving the sample have different phases and amplitudes and the resulting field is elliptically polarized. Thus, the dielectric anisotropy of wood causes a linearly polarized wave to be depolarized upon transmission through the material when the wave polarization plane does not coincide with the principal directions of anisotropy.

This can be modeled by observing the sample illuminated by two orthogonal linearly polarized waves, which, without a loss of generality, are assumed to be vertically and horizontally polarized and are denoted by indices V and H, respectively. Complex amplitudes of the incident waves (at $z = 0$) are then E_{IV} and E_{IH}, while transmitted waves ($z = d$) have complex amplitudes denoted as E_{TV} and E_{TH}, for vertical and horizontal waves, respectively. If the sample is positioned so that its grain direction coincides with the vertical wave polarization, the incident and transmitted fields are related by transmission coefficients as:

$$\begin{bmatrix} E_{TV} \\ E_{TH} \end{bmatrix} = \begin{bmatrix} T_{\parallel} & 0 \\ 0 & T_{\perp} \end{bmatrix} \begin{bmatrix} E_{IV} \\ E_{IH} \end{bmatrix}. \tag{5}$$

Zero off-diagonal elements in the transmission matrix indicate the absence of depolarization. In other words, illumination in one polarization plane only gives rise to a received wave with the same polarization. This agrees with the intuitive description considered above.

However, to perform the measurement of transmission coefficients $T_{\parallel}$ and $T_{\perp}$, one needs to know the grain angle θ of the sample under test; in practice, this information is usually not available. Thus the transmission matrix given in Eq. 5 must be defined for a general case in which the field polarization does not coincide with the principal propagation factors. The transmission matrix is no longer diagonal and is given as:

$$\begin{bmatrix} E_{TV} \\ E_{TH} \end{bmatrix} = \begin{bmatrix} T_{VV} & T_{VH} \\ T_{HV} & T_{HH} \end{bmatrix} \begin{bmatrix} E_{IV} \\ E_{IH} \end{bmatrix}. \tag{6}$$

Four elements of the transmission matrix describe nominal and cross-polar transmission coefficients. For example, the vertically polarized antenna will receive:

$$E_{TV} = T_{VV} E_{IV} + T_{VH} E_{IH}. \tag{7}$$

Thus, the transmission coefficient T_{VV} can be measured with both receiving and transmitting antennas in vertical polarization, while keeping the incident horizontally polarized wave to zero. To determine the transmission coefficient T_{VH}, we transmit with the horizontally polarized antenna and receive with the vertically polarized antenna.[53] This can be written as:

$$T_{VV} = \left.\frac{E_{TV}}{E_{IV}}\right|_{E_{IH}=0} \quad \text{and} \quad T_{VH} = \left.\frac{E_{TV}}{E_{IH}}\right|_{E_{IV}=0} \tag{8}$$

The same reasoning applies for coefficients T_{HH} and T_{HV}, which are calculated from measured E_{TH}, E_{IH} and E_{IV}. $T_{\parallel}$, $T_{\perp}$, and grain angle θ may be calculated from all four measured transmission coefficients using:[51]

$$\begin{aligned} T_{\parallel}, T_{\perp} &= \frac{T_{VV} + T_{HH}}{2} \pm \sqrt{\left(\frac{T_{VV} - T_{HH}}{2}\right)^2 - \left(\frac{T_{VH} + T_{HV}}{2}\right)^2} \\ \theta &= \frac{1}{2}\arctan\frac{T_{VH} + T_{HV}}{T_{VV} - T_{HH}} \end{aligned} \tag{9}$$

Using two orthogonal propagation factors was first proposed in the 1980s by Yen.[17] Schajer et al.[51,52] measured two propagation factors using the modulated scatterer technique, while a measurement using the focused beam technique has been reported by Bogosanovic et al.[53]

Wood as a slab of dielectric material

An alternative approach is to model wood in a way that is commonly used in microwave material testing, as a slab of homogeneous dielectric material. This model has been applied to the testing of many homogeneous materials[54–58] and demonstrates high accuracy. When a uniform plane wave approaches at normal incidence a wood sample with a planar surface and finite, uniform thickness d, part of the wave propagates through the medium, while the other part is reflected back into the air. Reflections occur at both wood/free space boundaries. In addition, there are an infinite number of transmitted and reflected waves, as multiple reflections occur between the two boundaries. This is commonly described using a matrix of S parameters[59] as:

$$S_{11} = \frac{\Gamma\left(1 - T^2\right)}{1 - \Gamma^2 T^2} \quad \text{and} \quad S_{21} = \frac{T\left(1 - \Gamma^2\right)}{1 - \Gamma^2 T^2} \tag{10}$$

where T is the transmission coefficient through the wood material over a distance d, given in Eq. 3, while Γ is the reflection coefficient at each wood/free space boundary, defined as:[59]

$$\Gamma = \frac{1 - \sqrt{\varepsilon^*}}{1 + \sqrt{\varepsilon^*}} \quad \text{and} \quad T = e^{-\gamma d} \tag{11}$$

The relative effective permittivity ε^* of the wood sample under test is thus computed from the measured values using Eqs. 10 and 11. However, the exact solution for ε^* is not straightforward due to the multiple roots for Eq. 10, and an iterative technique is often used.[54–58]

Further measurements using focused beam antennas are presented by Alabaster and Dahele.[58] The degree of the wave depolarization is directly related to the grain angle. For a lesser sample thickness, the polarization angle is less than the true grain angle by a factor defined as the depolarization index.[17] The changes in the signal due to grain angle and knots were also considered by Malik et al.,[50] Leicester and Seath,[60] and Baradit et al.,[61] as well as in a patent by Stevens et al.[30]

It must be noted here that neither of the presented models takes into account natural variations in material density and composition, which may behave as boundaries between regions with two different dielectric constants within the sample and thus may cause significant scattering, multiple reflections, and refraction of the wave. Lundgren[9] demonstrated this by modeling the propagation using the finite element method (FEM) with reference data obtained using a CT scan (density distribution), gravimetrically determined MC, and correcting the changes in the wood geometry due to drying shrinkage. The resulting model is then compared with microwave data from the modulated scattering sensor array (Satimo[62]). The model demonstrates the existence of multiple scattering from internal variations in sample density and explains the disagreement of the measured signal and the theoretical model using plane wave transmission through media with no boundaries.

More advanced models for propagation through wood samples are presented by Sjödén,[8] Yen,[17] Daian et al.,[38] and Liu et al.[63] For industrial purposes these numerical models have little practical value, but they help with better understanding of the response of the microwave measurement system to various wood properties. Some interesting propagation modeling is reported by Kharadly and Chan,[45] who measured propagation in a waveguide partially filled with a wood sample and report a correlation between the MC and the field distribution in the air-filled part of the waveguide. Heikkila et al.[41] considered a knot in wood as a circular dielectric waveguide capable of transmitting a hybrid mode of propagation. Patented knot detection solutions are presented by Kinanen et al.[28] and Jakkula.[29]

Measurement techniques

Measurement techniques and applied sensor solutions have evolved during the past 20 years. In early microwave systems developed in the 1980s, horn antennas were used mostly in transmission configurations.[23–27] The first attempt to install industrial microwave wood sensors was made by a group of researchers from Finland.[41–43] The microwave sensor was considered for MC measurement only, while a gamma-ray sensor was used for density measurement and the temperature of the timber was measured by an infrared sensor. As only the power level of the microwave signal was measured, the receiver was simple and affordable. It was not uncommon to combine microwave sensors with other technologies. Kioyobe and Hirano[19] use beta rays for additional information on the material basis weight. Another example is the StressGrader machine presented by Leicester and Seath,[60] which improved the performance of the conventional machine stress grader unit by combining it with two sets of microwave scanners, a knot detector and a slope-of-grain measurement unit. However, one may argue that such duplication of technologies is not necessary, as all these wood parameters can be measured using microwave technology alone. Martin et al.[64,65] demonstrated that microwaves are capable of detecting wood density. The system they presented measured both phase and amplitude of the microwave signal, and strong correlation between measured phase and density was obtained. In 1981, King and Yen[22,66,67] used a rotating modulated scattering dipole for simultaneous and rapid estimation of density, MC, and grain angle, by measuring the loss, phase shift, depolarization ratio, and polarization angle of a microwave signal transmitted through dimension lumber. In 1994 Shen et al.[47] proposed a grain angle measurement device using the depolarization of the wave transmitted through an anisotropic sample, noting that knowledge of MC and density of the sample improves the accuracy of the empirical model for grain angle prediction. Shen et al.[47] also indicated that there was no need for a separate sensor for MC and density detection, proposing the use of phase measurement, since "the phase measurements show that a relationship between phase change and MC and specific gravity exists." There are many other references which confirm that microwaves are capable of simultaneously detecting more than one wood property of interest.[9–17] The challenge is to distinguish between the contributing factors in such an information-rich signal.

At present, two techniques that stand out from the viewpoint of accuracy, sensitivity, and simplicity are free space transmission in a focused beam (FB) arrangement[20–21,46,48–50,54–58] and near field probing using a modulated scattering technique (MST).[22,66–75] Both techniques offer a very accurate measurement of the E field and its distribution in front of the sample. In addition, they allow coherent detection of elliptically polarized waves transmitted through the wood sample. These are the main improvements that recently published techniques have when compared to the solutions reported in the 1980s.

In the following section, these two techniques are considered in more detail. Furthermore, this article presents a qualitative comparison of these two techniques, based on the literature findings. It is hard to compare them quantitatively, because the FB technique has never been tested for simultaneous measurement of MC, density, and grain angle, although this has been done with MST.[9] With the FB technique, only a single wood property was considered in each of the published articles.[46,48–50] On the other hand, the accuracy of the MST as a permittivity measurement technique has never been tested on standard dielectric samples, although this has been done with the FB technique. More research is needed for better comparison of the two systems.

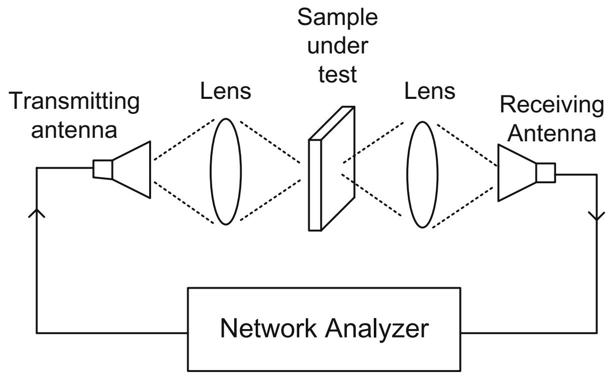

Fig. 1. Focused beam technique (FB)

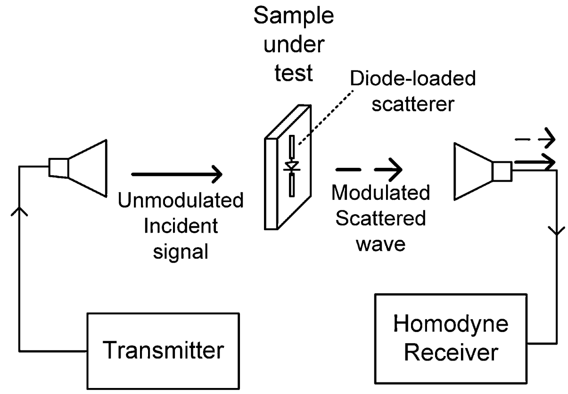

Fig. 2. Modulated scattering technique (MST)

The focused beam measurement technique

The FB technique is one of the more recently developed MNDT techniques (Fig. 1). It has become one of the standard methods for material permittivity measurement.[20,21,54–58] It evolved from a free space measurement using two horn antennas surrounding a sample under test,[1] which suffers from two significant sources of error: diffraction at the edges of the sample and multiple reflections between antennas and the sample. In 1989, Ghodgaonkar et al.[54] presented a focused beam, free space system suitable for combating these error sources. Diffraction effects at the edges of the sample are negligible due to the spot focusing of the lens antennas, providing that the minimum transverse dimension of the sample is greater than three times the beam width of the antenna at the focus. Furthermore, free space calibration eliminates the effects of multiple reflections. The calibration is feasible because the field at the focus is nearly a plane wave, providing a precise reference plane. Two measurement setups have been proposed to measure both permittivity and permeability using a reflection[54] or a transmission[55] method. Application of this technique to permittivity measurement was reported and good accuracy was achieved, in particular for lossy materials, even where other techniques fail.[56] Agilent includes this technique in the list of standard methods for material testing,[76] offering their own calibration procedure and software for the Agilent Network Analyser.

Four articles were found on microwave wood sensing using the FB technique,[46,48–50] and in each a particular aspect of wood was observed, either MC, density, or grain angle. Other properties were kept under control and only small samples (1 cm thick, 10 × 10 cm in size) were used. This approach is useful to test if the particular property influences the microwave signal, but not if the system is to be applied to a real-life situation where all the parameters are involved. The authors offer theoretical solutions, performing calibration of the system, measuring the S parameters, and then calculating the permittivity using the Nicholson-Ross[76] procedure. Theories such as mixture models or the use of Stokes parameters for grain angle measurements were also successfully applied.

The modulated scattering technique

MST is an accurate method for measurement of electromagnetic field in close proximity of an object under test, originally developed as a method for measurement of antenna characteristics in the near field zone (Fig. 2). It is very difficult to implement such diagnostics using standard antenna measuring techniques because putting a probe-antenna and connecting transmission lines in the near field zone may significantly disturb the measured field distribution. An alternative method, proposed in 1955 by Justice and Rumsey[70] and Richmond,[71] is to use a small passive resonant antenna (scatterer) which causes negligible disturbance to the measured field.

The current induced on the scatterer is proportional to the component of the incident field that is parallel to its axis. The voltage at the receiving antenna terminals is proportional to the square of the tangential electric field intensity at the same position in the absence of the scatterer. However, a small scatterer produces a weak reflected signal. The scattered signal must be combined with a feature that the receiver may recognize. This is achieved by modulating the scatterer's response with a low frequency signal. By moving a single probe and recording both phase and amplitude for each measurement point, a spatial map of the measured field components can be obtained. Alternatively, an array of resonant scatterers can be used for rapid field scanning.[74] The modulated signal is collected by the receiving antenna and demodulated to extract the measured field information. Coherent detection using homodyne receivers, introduced by King,[69] is an inexpensive and accurate way to measure complex fields. A detailed description of MST can be found in a book written by Bolomey and Gardiol.[68] Several industrial solutions are offered, most notably by Satimo.[9,14,62,74,75]

Comparison of the focused beam technique and the modulated scattering technique

In the FB technique, wood measurement is treated as a microwave material testing problem. The solution is chosen among testing techniques that are commonly used for permittivity measurement.[76] As such, the FB transmission technique is well tested on "standard" samples, using homogeneous materials of known permittivity and its accuracy as a material testing method is well documented. This permittivity measurement technique has been adopted by Agilent as one of the standard techniques, so it has support in other aspects such as calibration procedures, fixtures, and standards. The sample is modeled using microwave network theory[59] and the S parameter matrix is determined, taking into account reflections from the sample's boundaries, transmission through the sample, as well as multiple reflections between the two air/wood boundaries. The measurement setup is calibrated, which allows measurement of the propagation in the sample only and corrects the errors caused by other elements in the measurement setup. Material properties are tested over a wide frequency range, which may be beneficial in resolving phase ambiguity issues, distinguishing between MC and density contributions or, simply, minimizing random errors.

However, S parameter measurement requires the use of a network analyzer. This instrument is too expensive for industrial applications, but can be replaced by its more affordable substitute, the six-port analyzer.[77] Still, even with an affordable option, measurement and calibration of a network analyzer requires time (interrupting industrial processes) and skill (qualified workers). As a solution, an automated electronic calibration process is envisioned, similar to Agilent's ECal calibration kit.[76] However, an efficient and accurate six-port receiver with automated calibration is yet to be reported.

The second measurement technique presented in this article is the MST, which is used in a single probe or array arrangement. This technique offers very accurate, high-resolution measurement of the field distribution in the close proximity of the sample under test. The approach taken ensures minimal disturbance of the field while retaining the sensitivity of the probe. As the scatterer is modulated, the filtering in the receiver can reduce a lot of a background noise.

The main advantage of the MST is that it offers the magnitude and the phase of the measured electric field vector in a single point in space, which makes it suitable for high-resolution testing, defect detection, moisture or density distribution measurement, and even simple imaging purposes.[14] In addition, measuring the field in the close proximity to the sample enables one to detect not only the radiating field but also the evanescent fields. This is not possible with the FB antenna, as it is positioned at a distance where the evanescent field components have diminished. The MST employs a simple homodyne receiver and the measurement is made on a single microwave frequency. This is a simple and affordable solution. However, problems with phase ambiguity are reported and, in dealing with these, operating over a wider bandwidth would be beneficial.

MST measurements are usually accompanied with the propagation model describing the sample as a homogeneous medium with no boundaries. This is an oversimplification, as Lundgren has demonstrated.[9] However, one may argue that propagation through wood varies so much between samples (not only from different species or different trees but even from the same log), that the error which this variation introduces in any model may be larger than the error due to this oversimplification. Thus the approach taken by Lundgren[9] of probing the field in as many spatial points as possible in order to calculate the average attenuation and phase delay that the sample introduces, and then applying a powerful multivariate regression analysis to correlate this directly to MC and density, may prove to be as accurate as any other approach. Still, the fact remains that errors introduced by the measurement system, which in the FB are calibrated and corrected, remain in amplitude and phase values measured using the MST. To support this claim, we refer to Paper VII in Lundgren's thesis,[9] where the modulated scatterer array developed by Satimo[62] was utilized with a simple free space calibration and a noticeable improvement in accuracy was reported. James et al.[67] indicate that a potential problem with this structure may be a spurious reflection from the specimen handling apparatus. Marath et al.[73] report that the main limiting factors in the performance of the homodyne receiver may be reflection from nearby objects and carrier leakage.

It has to be pointed out that MST was never really a material testing technique. There are no articles demonstrating the ability of this method to provide an accurate absolute value of a sample's permittivity or propagation factor. This is essentially a field probing technique and its primary purpose is radiation field measurement. It would be beneficial to see this technique tested on standard, homogeneous materials such as Teflon (PTFE) and to prove that this technique is not only suitable for finding discontinuities in the material under test, but also for providing an accurate absolute value of the material property under test (either the complex permittivity or propagation factor).

It is hard to compare the FB and MST techniques, as the results reported are not given in the same format. Namely, results using a focused beam antenna are more on a laboratory level, where each of the parameters (MC, density, and grain angle) were observed separately. On the other hand, the Satimo system[62] used for MST experiments is an industrial sensing solution, and the results presented are much closer to industrial application, with powerful multivariate software providing results for all parameters of interest at the same time. Yet, some undoubted advantages of both presented systems can be noted, such as the high resolution achieved by MST, as demonstrated by Lundgren and Johansson,[9,14] as well as the capability of these sensors to detect the evanescent fields, which may contribute to their high sensitivity. The main advantages of the FB technique are the calibration procedures and the capability to operate over a wide frequency range.

Implementation of transmitters and receivers

FB transmission measurement requires either a vector network analyzer[76] or its more affordable substitute, a six-port analyzer.[77] Microwave measurements are commonly described using S parameters[59] and often require one or more calibration procedures. On the other hand, MST employs a homodyne receiver.[69] These receivers are fairly simple and affordable, but they usually operate on a single microwave frequency.

Wood property determination techniques

The transmitted microwave signal depends on several wood properties, such as MC, density, temperature, internal defects (knots), grain angle, and amount of free water in the sample, to name just a few. Lundgren[9] reports a high correlation between microwave measurements and results obtained using a four-point bending machine. Comparison with a commonly used X-ray machine shows that microwaves have better correlation with strength indicators (modulus of elasticity and modulus of rupture) than X-rays have.

One of the main problems of microwave wood measurement is the “richness” of information embedded in a measured microwave signal. The wave passing through a sample is affected by many of wood’s properties, and the resulting information is often an integrated average; it is thus very hard to determine the actual contributing factors. The variability in the sample structure does not permit analytical solutions and an empirical approach is inevitable.

Empirical models are usually derived separately for samples below the fiber saturation point and those above it. Two reasons for this are that a receiver intended for measuring the whole range of MC needs to have a very large dynamic range and that the different dielectric behavior of bound and free water dictates the need for separate empirical models for the two MCs ranges.

There are two general approaches when calculating MC and density. In the first, the effective permittivity of the sample is calculated from the measured microwave signal as an intermediate step. Then, in a separate step, MC and density are determined empirically from the permittivity. Nyfors and Vainikainen[1] recommend this “intermediate” step, because in this case, empirically derived expressions for MC and density are not related to the sensor design. This eliminates the influence of variations between individual sensors on the accuracy of the empirically derived model. Furthermore, small changes and upgrades in hardware will not require a new empirical model. This saves significant time and resources, as usually a large number of measurements are needed for the derivation of a reliable empirical model. The opponents of this approach argue that knowledge of the complex permittivity is not a goal in itself, but an intermediate step that introduces undesired computational complexity and as such should be avoided in industrial applications. The alternative approach is therefore to derive MC and density directly from the measured microwave signal. This approach was adopted by King and Yen[66] and Shen and Schajer,[47] among others. The accuracy of MC and density measurement was significantly improved by using some advanced data analysis techniques, such as the multivariate analysis reported by Johansson.[14]

There are many more applications of microwave technology in the wood industry, such as microwave imaging, studied by Kaestner (microwave polarimetry tomography[13]) and Salvade et al.,[78] and microwave drying and processing.[10] However, microwave imaging is not suitable for rapid industrial testing of wood, and as such is not considered here in great detail. Microwave high-power wood drying and processing usually does not provide any wood sensing and therefore is not further analyzed here.

Conclusions

Microwave techniques offer an affordable noncontact bulk property measurement that can be performed in a safe and noninvasive way. As all other techniques either detect surface features only, need contact with the sample, or may be a health hazard and not safe for handling, microwaves seem to be an ideal option for industrial sensing.

In this article, an overview of the current status of microwave wood sensing technology is given, aiming to answer two significant questions: what is the most advanced microwave technology available for the testing of wood properties, and is the technology ready for industrial application?

It has been demonstrated that the transmitted microwave signal depends on several wood parameters, including MC, density, temperature, internal defects, and grain angle. The most advanced solutions offer simultaneous detection of these parameters, providing, in addition, information on their spatial distribution. The current challenge is to better understand this information-rich signal. Current reports offer experimental data obtained using a combination of microwave scanners and CT scanners, advanced statistical data analysis, as well as theoretical analysis and computer models of the dielectric properties of wood. However, more effort is needed to generate further knowledge on this complex dielectric material, with great sample variability being identified as one of the biggest problems.

Two important problems facing microwave industrial devices are the price and the requirement for qualified technicians/operators. Advances in the communications industry are responsible for a continuous reduction in price and the widespread availability of microwave components, while modern microwave measurement equipment offers automated calibration and measurement processes, thus reducing requirements for highly qualified equipment operators.

The technology has reached a degree of maturity, with two techniques – modulated scattering and focused beam – offering the best results. Even though reported results are coming from universities, most of the hardware used is now commercially available, providing technological support for further research and development. Further research in all four identified areas will provide more accurate, robust, and affordable solutions, suitable for rapid and automated industrial microwave wood sensing.

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