PhD-Thesis

Microwave testing of sawn timber

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Abstract

Non-destructive evaluation of the physical properties of wood is a key task in modern wood manufacturing processes. Due to a rapidly increasing production speed, fast, non-contacting, reliable and robust measurement systems are demanded by the wood industry. The scope of the presented work is to discuss the challenges and demonstrate the potential of microwave testing applications. Microwave technology benefits from the anisotropic dielectric properties of wood to simultaneously identify grain angle, density, and moisture content of wood. A modern measurement setup was built and prior results in literature could be exceeded in accuracy with factor two (moisture and dry density) to factor five (grain angle). Several shortcomings of the theoretical description and modelling in previous work were revealed and addressed. Consequently, in this work the theory of free space transmission measurement is thoroughly discussed with emphasis on the characteristics of (and how to deal with) reflections occurring in real measurements. A more sophisticated calculation method for the derivation of the desired physical wood properties is presented.

Moist (moisture content 7.6…14%) and oven-dry spruce samples are tested. The detection of grain angle for moist and oven-dry wood yields an RMSE (root-mean-squared-error) of 0.14° and 0.4°, respectively. RMSE in the determination of moisture density were less or equal 1.8 kg/m³ (measured range 27 … 56 kg/m³). RMSE in the determination for dry density were maximum 11.3 kg/m³ (measured range 284 … 492 kg/m³). Moisture content is evaluated with density- and thickness-independent methods. Adapted regression models are proposed yielding an RMSE for moisture content of 0.45% for a single frequency measurement. The promising advantages of wood moisture estimation with frequency sweeps instead of fixed frequency signals are discussed and demonstrated for all samples (RMSE=0.28%). The dielectric constant of moist and oven dry spruce in the range from 8 GHz to 12 GHz is evaluated in respect to density, moisture content and temperature. The respective constants ε', ε'', and $\tan(\delta)$ are formulated in a general form via a non-linear regression and compared to existing data in literature. The advantages of a modern laboratory style setup are shown and its possible transition in an industrial-style application is discussed.

Abstract

Die zerstörungsfreie Ermittlung der Holzeigenschaften stellt eine wesentliche Herausforderung in heutigen Holzverarbeitungsprozessen dar. Aufgrund der rasant gestiegenen Produktionsgeschwindigkeiten bedarf es schneller, berührungsloser, verlässlicher und stabiler Messsysteme. Das Ziel der vorliegenden Arbeit ist es, die Herausforderungen an Mikrowellenmesssysteme und deren Potential zu diskutieren. Mikrowellentechnologie nutzt die Anisotropie der dieelektrischen Eigenschaften von Holz zur Messung von Dichte, Feuchte und Faserrichtung. Ein moderner Messaufbau wurde verwirklicht. Damit konnten die bisher in der Literatur beschriebenen Messgenauigkeiten um den Faktor zwei (Dichte, Feuchte) bis Faktor fünf (Faserrichtung) übertroffen werden. Mehrere Einschränkungen in der bisherigen theoretischen Beschreibung und Modellierung wurden aufgezeigt und behandelt. Folgerichtig wird in dieser Arbeit die Theorie der Mikrowellen-Durchstrahlungsmessung umfassend diskutiert. Dabei liegt die Betonung auf dem Auftreten von und dem Umgang mit Reflexionen. Eine leistungsfähigere Berechnungsmethode zur Ermittlung der gesuchten physikalischen Holzeigenschaften wird präsentiert.

Feuchte (7,6… 14% Holzfeuchte) und darrgetrocknete Fichtenproben wurden untersucht. Die Messung der Holzrichtung von feuchten und gedarrten Proben liefert einen RMSE (root-mean-squared-error) von 0,14° bzw. 0,4°. Der RMSE bei der Ermittlung von Feuchtedichte lag bei maximal 1,8 kg/m³ (Messbereich: 27 … 56 kg/m³). Der RMSE bei der Ermittlung der Trockendichte lag bei maximal 11.3 kg/m³ (Messbereich: 284 … 492 kg/m³). Die Holzfeuchte wurde mit dichte- und dickenunabhängigen Methoden bestimmt. Die verwendeten, adaptierten Regressionsmodelle für Holzfeuchte liefern einen RMSE von 0,45% für Messungen bei Einzelfrequenzen. Die vielversprechenden Vorteile der Holzfeuchtebestimmung auf Basis einer Mehr-Frequenz-Messung werden dargestellt und diskutiert (RMSE=0.28%). Die dielektrische Konstante von feuchter und darrgetrockneter Fichte im Frequenzbereich von 8 GHz bis 12 GHz in Abhängigkeit von Dichte, Holzfeuchte und Temperatur wurde ermittelt. Die jeweiligen Konstanten ε’, ε”, und tan(δ) wurden mittels nicht-linearer Regression in allgemeiner Form dargestellt und mit vorhandenen Literaturdaten verglichen. Die Vorteile eines modernen Laboraufbaus werden aufgezeigt und eine mögliche industrielle Umsetzung diskutiert.

Contents

On this thesis

The PhD-thesis at hand is composed in a cumulative form. Hence, the heart of this work constitute two papers of the author of this thesis. To illustrate their scientific embedding as well as their relevance both for the scientific community and the future development of industrial applications a chapter “Motivation” is given. This is followed by a chapter “Courses of Action” with a short overview of the method and the work carried out in this thesis. Moreover, it is pointed out how the two papers fit in the entire thesis. Finally, a “Conclusion and Outlook” is given.

The focus of this interdisciplinary PhD-thesis was to apply a modern microwave measurement method on wood. Besides a thorough understanding of high-frequency engineering a profound knowledge of wood science and physics was demanded. With the deputy of the Institute of Physics and Materials Science (IPM) at the University of Natural Resources and Life Sciences, Vienna, an ideal supervisor for this PhD-thesis was found. The team at the Institute of Electrodynamics, Microwave and Circuit Engineering (EMCE) at the Vienna University of Technology, Vienna, functioned as co-supervisor, built the microwave measurement setup and provided crucial input and assistance on the actual measurements, data processing and mathematical description. At the beginning of this PhD-thesis the author worked at the Kompetenzzentrum Holztechnologie which provided the essential expertise of wood anatomy and insights in the wood processing industry.

Throughout this PhD the sample preparation, the design and performance of experiment, the analysis of the measured data, the interpretation of the results, the evaluation and the partly unprecedented modelling of the desired physical properties of wood, the coordination of all project partners including the industrial partner, and the leading role in publicizing in the scientific community was carried out by and the solely responsibility of the author of this PhD-thesis.

Motivation

Over the past decades the traditional use of wood as construction material evolved to a modern, widely differentiated application spectrum. For load bearing purposes glued laminated timber (glulam) represents an industrial key product. Glulam consists of at least three dried softwood boards, which are flatwise glued together. As it is strength-graded and refined by lamination its permissible bending stress is up to 50% higher than the permissible bending stress of the usually used solid wood. Strengh-grading of glulam and its lamellas, respectively, is regulated in the EN 1912(2012). As a result of the production-procedure glulam members have smaller shrinkage-deformations and a higher resistance to cracking. Beside simple straight beams with rectangular cross-sections, members with varying cross-sections or curved shape are usual. Spatially curved or twisted members can also be manufactured. Figure 1 shows application examples in contemporary architecture.

Figure 1: (from top left to bottom right) Glulam, straight and curved shape (www.brettschichtholz.de). Brigde (www.phb.de). alveolar, roof-bearing structure (www.baunetzwissen.de). Foyer of the Austria Center, Vienna (www.archiexpo.com)

Principally, wood fiber exhibits exceeding strength related on the dead load than steel or concrete. Due to its heterogenic nature, however, wood imposes serious challenges on an optimized and efficient use. As shown in Figure 2, wood features three different anatomic directions: Longitudinal (parallel to the grain, e.g. the wood fiber), radial and tangential (both perpendicular to the grain, related to the annual ring orientations (Bodig and Jayne, 1982)). For the description of the dielectric properties of wood, an idealized orthotropic wood model proved to be a sufficient approximation (Torgovnikov, 1993). Here, the axial direction is parallel (‖) to the grain. Radial and tangential directions show similar dielectric behavior and are both considered as a single "perpendicular" (⊥) direction. Moreover, this simplification uniformly describes all possible growth-ring arrangements from quarter sawn to flat sawn.

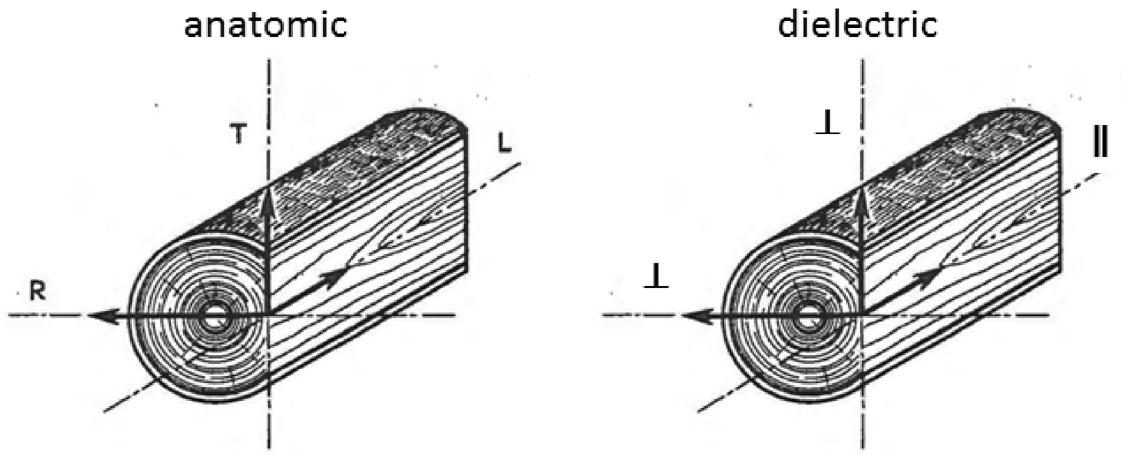

Figure 2: Left: The three anatomic directions of wood: Longitudinal (parallel to the grain), radial and tangential (both related to the annual rings). Right: For the dielectric properties of wood, radial and tangential direction are both considered as a single "perpendicular" direction. (Torgovnikov, 1993)

The growth characteristics of wood result in grain angle deviations, both on a local (knot, top rupture) and global (sweep, taper, spiral growth) scale (Figure 3). This significantly influences the strength of sawn timber (Pope et al., 2005). As a rule of thumb, bending strength is similar in radial and tangential direction but ten times higher parallel to grain, e.g. longitudinal, direction. This holds true for spruce, but doesn't vary greatly for other wood species (Kollmann and Côté, 1984). Consequently, cracks always open across the grain and therefore represent a grain direction indicator for conventional visual grading. For the application of sawn timber in products as glulam, strength grading standards define boundary values for grain deviation (see EN 1912, 2012).

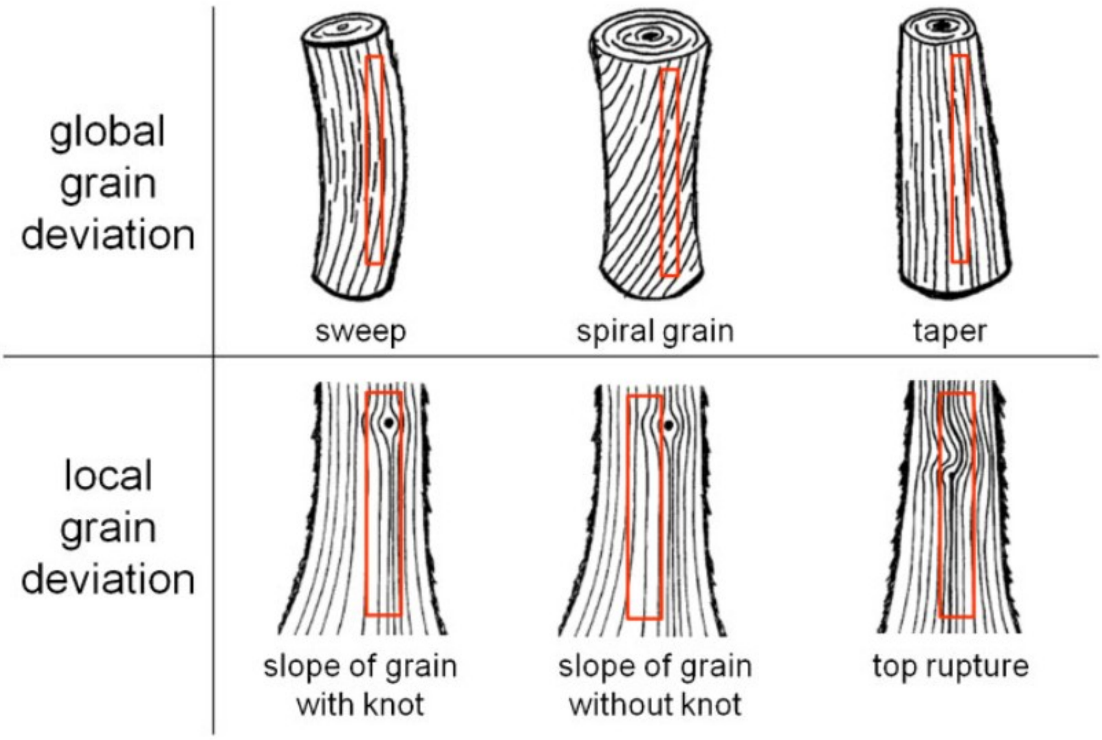

Figure 3: Grain deviations due to the natural growth characteristics of wood (Denzler et al., 2013).

With modern drying and planing technologies the occurrence of cracks has virtually been eliminated. Thus, global grain deviations remain undetected by visual grading (see Figure 4). Thus, a reliable detection of grain angle exceeding conventional visual grading is demand by the wood manufacturing industry. The use of the tracheid-effect, i.e. the extension of a circular laser light spot into an elliptical form with the major axis oriented in grain direction, (Nyström, 2003) was discussed and applied in industrial applications. However, this method stays prone to unclean and unplaned surfaces, is only testing the surface and features deficient accuracy. A fast, robust, and accurate measurement device for grain angle detection in industrial conditions still is a considerable challenge for research.

Figure 4: The pattern on sawed wood is not influenced by spiral grain. Thus, the board (top) could well originate from a log with spiral grain (bottom).

Moisture content and density represent further crucial parameter for the wood processing industry. Wood features an equilibrium moisture content, which is a dynamic quantity changing with relative humidity and temperature of the surrounding air. For glulam lamellas, production standards (EN 14080, 2013) specify minimum and maximum values of 8% and 15% of moisture content. Moisture is commonly determined with capacitance type moisture meters using high frequency signals or with resistance type pin moisture meters (Wilson, 1999). These moisture meters are able to reasonably cope with industrial needs. However, due to their measuring principles, measurements are prone to deviations in the wood grain angle. Moreover, they require density information for a reliable moisture determination. For density measurements the application of X-rays is successfully established enhancing both production speed and quality (Schajer, 2001). With their high spatial resolution, X-ray scanners even offer localized density information that yields the position of knots and allows the derivation of the quality parameter knottiness (knot area ratio). Still, X-ray systems remain rather costly and require efforts for the protection against hazardous ionizing radiation.

Microwaves have been throughout the years, yet decades, consistently been demonstrated as a promising tool to reveal the key parameters density, moisture content, and grain deviation in a fast, non-destructive and contactless manner (King and Yen, 1981). Several attempts are reported in literature to measure moisture and density of wood with microwaves (Al-Mattarneh et al., 2001; Johansson et al., 2003; Lundgren et al., 2006; Martin et al., 1987; Tiuri and Heikkila, 1979). However, the lack of grain angle information makes these measurements prone to deviations in the grain direction. An early attempt to detect wood fiber orientation with a microwave resonator was done in 1974 (Tiuri and Liimatainen, 1974). A grain angle detection using transmission measurements was presented by several authors ((Leicester and Seath, 1996; Malik et al., 2005; Shen et al., 1994). An integral approach using the microwave technology is able to determine density, moisture content, and grain angle simultaneously (Heikkila et al., 1982; James et al., 1985; Schajer and Orhan, 2006). Here, the method intrinsically accounts for the influence of all three parameters and determines every parameter separately. Phase-shift and attenuation measurements yield density and moisture content via a multivariate statistical approach, and according to depolarization the grain angle is obtained. While Schajer and Orhan (2006) used a measurement setup featuring a modulated scattering dipole to localize measurements and to avoid egde diffraction, other groups apply a focused beam (Bogosanovic et al., 2011), a local antenna array (Denzler et al., 2013), appropriate antenna and geometrical setup (Aichholzer et al., 2013) or the use of electromagnetic absorbent material (Vallejos and Grote, 2009). The theoretical formulation of all these works directly follows Schajer and Orhan (2005). Strong influence of antenna design on the quality and applicability of microwave testing was encountered (Bogosanovic et al., 2013; Denzler et al., 2014; Vikberg et al., 2012a) and evaluated (Vikberg et al., 2012b). A recent and complete summary of existing literature on detection of grain angle, moisture, density and defects of wood using microwaves is given in Bogosanovic (2012). Beside their importance as distinct quantity for the manufacturing process, grain angle, moisture content and density qualify as predictors for strength estimations. Combined with other existing technologies microwave testing may improve the quality of strength grading (Denzler and Weidenhiller, 2015; Heikkila et al., 1982; Leicester, Robert H., 1997; Lundgren et al., 2007; Nguyen et al., 2004).

In the last decades several patents on microwave testing of wood are registered (Arthaber et al., 2015; Biernacki, 2005; Heikkila, 1985b, 1985a, Schajer, 1990, 2005; Stanish et al., 2001; Stevens and Leicester, 1997). Moreover, reports of industrial strength grading applications using microwaves can be found (csiropedia, 2015; Heikkila et al., 1982). However, up to now, no such application could sustainably be established in the wood manufacturing industry.

Course of Action

From an R&D-point-of-view the overall goal of this work was a feasibility study to evaluate the potential of microwave testing for applications in the wood processing industry. This meant to identifiy and to cope with the difficulties that persistenly impeded such applications in the past and to point out approaches to a technically feasible and cost-effective solution for an industrial implementation.

Measurement setup

Following a study of scientific literature and patent research in a first step a microwave prototype was built in collaboration with the EMCE of the Vienna University of Technology. The chosen setup allows testing of wooden samples in free space transmission technique. The advantage over setups based on reflection measurements constitutes in a simple and robust calibration and in an equal contribution of the whole tested cross-section of a specimen. A detailled description of the measurement setup is given in the respective Materials and Methods chapter of both papers. A thorough mathematical formulation and modellation of the chosen setup is presented in the Theory chapter of Paper 2.

Several introducing measurements served to adjust the measurement setup to typical wood properties and to test the setup including the hardware control routines written exclusively for the experiments in this thesis. Generally, all findings of the experimental work essentially influenced the design of an industrial near-field testing prototyp, which was part of an industrial follow-up project to this thesis.

Paper 1

At this stage already a reliable grain angle detection of a single specimen was established. As explained in detail in the attached papers, density and moisture content can only be derived by a statistical relationship based on measurements of several specimens. Thus, a first measurement series with a plurality of samples was carried out. The motivation of this series was to reproduce and verify published results, demonstrate a reliable moisture and density estimation and to evaluate the microwave prototype. The materials and methods, the results and the conclusion of this measurement series are given in the attached Paper 1. Not only we could prove the functionality of the microwave prototype and verify published assumptions and results but the accuracy of the presented results exceeded previous work from other groups in factor two (moisture and dry density) to factor five (grain angle).

Paper 2

Subsequent experiments examined the detection of moist samples with moisture content beyond the fiber-saturation-point (>27% for spruce), with and without time gating. Deficient Signal-to-Noise-Ratio (SNR) and severe influence of multiple reflections were encountered. The former could be handled with an amplified testing signal, the latter was successfully extenuated with the use of absorbing material between the antennas and the specimen. These experiments revealed remarkable shortcomings of the actual used theory. While Schajer and Orhan (2005) at least address occuring reflections and only claim to detect an "effective" transmission coefficient, other groups didn't even mention reflections. Moreover, it turned obvious that even recent publications featured deficiant or wrong understanding of microwave propagation in wood. Thus, together with Holger Arthaber from the EMCE a more precise mathematical formulation for the derivation of the transmission coefficients was developed. This included the derivation of the dielectric constant and taking account for reflections in time-gated measurements. In the Theory chapter of Paper 2, this sophisticated mathematical derivation for wood as orthotropic material is presented and justified.

The inclusion of oven-dry wood in the estimation of grain angle, moisture, and density was the focus of a second measurement series. Density- and thickness-independent moisture measurement eventually turned out to feature superior quality and was emphasized therefore. Beside evaluations at a single frequency swept measurements were successfully introduced and discussed. All applied regessions and models are presented in the Theory chapter of Paper 2. Materials and Methods, results and conclusion of this measurement series are given in the respective chapters in the attached Paper 2.

Further work

In excess of the results presented cumulatively in Paper 1 and 2, several findings were obtained in the course of this thesis. While all these findings flowed in the design of an industrial prototype from our project partner MiCROTEC, e.g. the above mentioned free-space transmission measurement of very moist samples stays to be discussed in a peer-reviewed journal. Same holds for performed measurements of grain angle in three dimensions based on two 2d-measurements and measurements with versus without time gating, respectively.

Conclusion and Outlook

Up to now no microwave testing application could sustainably be established in the wood manufacturing industry. In this thesis, two main reasons could be identified: On one hand the challenging physical nature of microwaves, on the other hand the lack of appropriate, low-cost, and robust electronic equipment. Consequently, this work entirely discusses and accounts for reflections occurring in an actual wood measurement. Furthermore, a consistent description for microwave propagation in wood is presented. This detailed discussion on free space measurement demonstrates the requirement of a dual-linear-polarized measurement setup and emphasizes the need of coping with reflections in wood measurements. A prototype system meeting this demand was built and used to determine key physical data of moist and oven-dry spruce (*Picea abies* (L.) Karst.). Grain angle is detected with a RMSE of 0.14° (moist) and 0.4° (oven-dry) in the entire possible range from –90° to +90°. The RMSE of dry density is maximum 11.5 kg/m^3 (moist) and 12.6 kg/m^3 (oven-dry) with investigated density range from 284 kg/m^3 to 527 kg/m^3. Moisture density estimation features a maximum RMSE of 1.8 kg/m^3 (range 27…56 kg/m^3). Adapted regression models for density- and thickness-independent moisture content evaluation at a single frequency are proposed. They yield superior results to prior work for moist samples with a RMSE of 0.44% (measured range 7.6…14%) and allow the inclusion of oven-dry wood in the moisture estimation (RMSE=0.57%, range 0…14%). With frequency swept moisture measurements, all samples are described with one regression featuring a RMSE of 0.28% (range 0…14%). A moisture evaluation basing on phase shifts at two frequencies only yielded inferior results with RMSE of 0.7% and above. All moisture evaluations yield a very similar, frequency independent, and modest dependency on temperature. The idealized, orthotropic wood model proves applicable for microwave testing of wood. The common but not previously proven approximation of using "effective" transmission coefficients (Schajer and Orhan, 2005) could be justified, at least for the chosen setup in this thesis.

The presented calculation procedure for transmission coefficient and grain angle exceeds previous approaches by considering the occurring reflections and taking full benefit of the matrix algebra. Furthermore, it paved way for a mathematical formulation and modelling of multiple reflections leading to implicit forms of transmission coefficients which allow a deeper evaluation and understanding and a more general discussion of Free-Space transmission measurement of wood, e.g. non-perpendicular incidence of testing signal (Trifunovic, 2014).

The advantage of frequency swept measurements was discussed and demonstrated. Based on the results of Menke and Knöchel (1996), this procedure should also be applicable on moisture contents beyond the fiber-saturation point. Even without an applied time-gating this method is capable to cope with the effects due to multiple reflections in the wood specimen. Thus, a measurement setup with several testing frequencies can provide superior moisture measurement and simultaneously improve quality of grain angle detection. Such a measurement setup is feasible with today's progress of circuit design and measurement technology. With the fast and continuous improvement and availability of the electronic hardware and antenna design, even industrial low-cost applications with time-gating are reasonable in the near future.

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Paper 1

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ORIGINALS ORIGINALARBEITEN

Non-destructive evaluation of grain angle, moisture content and density of spruce with microwaves

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Abstract Non-destructive evaluation of the physical properties of wood is a key task in modern wood manufacturing processes. Due to a rapidly increasing production speed, fast, non-contacting, reliable and robust measurement systems are demanded by the wood industry. Common moisture meters are able to reasonably cope with industrial needs. However, modern detection of wood grain angle deviation remains an unresolved issue. Microwave technology features the ability to simultaneously identify grain angle, density and moisture content of wood by measuring attenuation, phase shift, and depolarization of transmitted signals. This paper reports on series of microwave measurements revealing the desired physical properties for spruce. Samples were tested at different frequencies in the range from 8 to 12 GHz. For each frequency the grain angles were identified with standard errors of maximum 0.15° (measuring range from −90° to +90°). Standard errors in the determination of moisture density were less or equal 1.8 kg/m^3 (measuring range from 27 to 56 kg/m^3). Standard errors determining moisture content were maximum 0.47 % (measuring range from 7.6 to 14 %), and standard errors for dry density were maximum 11.3 kg/m^3 (measuring range from 284 to 492 kg/m^3).

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Zerstörungsfreie Ermittlung von Faserwinkel, Dichte und Holzfeuchte von Fichte mittels Mikrowellen

Zusammenfassung Die zerstörungsfreie Ermittlung der physikalischen Holzeigenschaften ist eine Schlüsselaufgabe in modernen Holzverarbeitungsprozessen. Durch die stark ansteigenden Produktionsgeschwindigkeiten sind in der Holzindustrie zunehmend schnelle, berührungsfreie, verlässliche und stabile Messsysteme gefordert. Dabei erfüllen handelsübliche Feuchtemessgeräte bereits die industriellen Erfordernisse. Eine zeitgemäße Methode zur Detektion von Faserwinkelabweichungen existiert derzeit noch nicht. Mikrowellentechnologie besitzt die Fähigkeit, Faserwinkel, Dichte und Holzfeuchte gleichzeitig zu bestimmen: durch die Messung der Dämpfung, Phasenverschiebung und Depolarisation eines transmittierten Signals. Die vorliegende Arbeit beschreibt eine Serie von Messungen zur Ermittlung der besagten Holzeigenschaften von Fichte. Dabei wurden Proben bei mehreren Frequenzen im Bereich von 8 bis 12 GHz gemessen. Bei jeder Frequenz wurde die Faserabweichung mit einer Standardabweichung von 0.15° ermittelt (Messbereich −90° bis +90°). Die Standardabweichung bei der Ermittlung der Feuchtedichte war kleiner bzw. gleich 1.8 kg/m^3 (Messbereich von 27 bis 56 kg/m^3). Die Standardabweichung bei der Ermittlung der Holzfeuchte betrug maximal 0.47 % (Messbereich von 7.6 bis 14 %), die Standardabweichung für Trockendichte maximal 11.3 kg/m^3 (Messbereich 284 bis 492 kg/m^3).

1 Introduction

Wood is a natural, renewable material, which is used in a wide variety of products such as load bearing structures and furniture. However, the heterogeneous nature of wood leads to a large variability of its physical properties, which creates serious difficulties in industrial processes where well-defined material parameters are essential for manufacturing with consistent quality. Modern production lines demand sophisticated methods for quality control, and the implementation of new technologies in the wood industry is promising therefore.

When wood is used as a construction material, grain angle deviation, moisture content, and density are crucial parameters. The application of X-rays is successfully established for density measurements enhancing both production speed and quality (Schajer 2001). Still, these systems remain rather costly and require efforts for the protection against hazardous ionizing radiation. Moisture is commonly determined with capacitance type moisture meters using high frequency signals or with resistance type pin moisture meters (Wilson 1999). Due to their measuring principles, however, measurements are prone to deviations in the wood grain angle. A fast, robust, and accurate measurement device for grain angle detection in industrial conditions is a considerable challenge for research.

Many successful technologies combine a non-contacting measurement design and fast signal processing techniques, both of which are met by microwave technology. Microwaves propagating through an anisotropic dielectric material are depolarized, attenuated, and phase-shifted. The dielectric properties of wood differ along the three anatomical directions and are influenced by density, moisture, and grain direction (Torgovnikov 1993). Hence, a microwave measuring system may exhibit the ability to determine density, moisture content and grain angle of wood (King and Yen 1981).

Several attempts are reported in literature to measure moisture and density of wood with microwaves (Tiuri and Heikkila 1979; Martin et al. 1987; Danko 1994; Al-Mattarneh et al. 2001; Johansson et al. 2003; Lundgren et al. 2006). However, the lack of grain angle information makes these measurements prone to deviations in the grain direction. An early attempt to detect wood fiber orientation with a microwave resonator was done in 1974 (Tiuri and Liimatainen 1974). Grain angle detection using transmission measurements was presented by several authors (Shen et al. 1994; Leicester and Seath 1996; Malik et al. 2005).

An integral approach using the microwave technology is able to determine density, moisture content, and grain angle simultaneously (Heikkila et al. 1982; James et al. 1985; Schajer and Orhan 2005, 2006). Here, the method intrinsically accounts for the influence of all three parameters and determines every parameter separately. Phase-shift and attenuation measurements yield density and moisture content via a multi-variant statistical approach, and according to depolarization, the grain angle is obtained.

In this work, a modern microwave system, based on the design of Schajer and Orhan (2005, 2006), is used to simultaneously identify grain angle, moisture content, and density of wood. The capability of the microwave measurement technique is demonstrated by a measurement series with spruce samples. Estimations of the three parameters of interest are presented and compared with the actual values of density and moisture content.

2 Theory

The propagation of microwaves through a lossy medium such as wood is described by the following relationship (Torgovnikov 1993):

$$E(x) = E_0 \cdot \exp(-\gamma x) \qquad (1)$$

E_0 is the incident electric field strength (at $x = 0$) and $E(x)$ is the electric field strength after propagating the distance x in the lossy medium. The propagation constant γ is a complex quantity:

$$\gamma = \alpha + i\beta \qquad (2)$$

α is the attenuation factor which considers the exponential decrease of electric field strength with increasing propagation length in the material, and β is the phase factor which considers the phase shift of the electromagnetic wave propagating through the material.

For wood both constants are different in the three anatomic directions. The axial direction is parallel to the wood grain. Radial and tangential directions show similar propagation constants and are both considered as a single "perpendicular" constant. This simplification paves the way to a method for obtaining grain angle, moisture content and density as shown in Schajer and Orhan (2006).

The propagation constants γ_u and γ_v are used to describe the transmission coefficients u parallel to the grain and v perpendicular to the grain, respectively:

$$u = \exp(-\gamma_u h) \qquad (3)$$

$$v = \exp(-\gamma_v h) \qquad (4)$$

h is the thickness of the material and replaces the general length x in the exponential term in Eq. (1). u and v are complex numbers describing attenuation (magnitude) and phase shift (angle) of the transmitted microwaves.

The measurement of a linearly polarized wave parallel and perpendicular to the grain is used to determine u and v, respectively. In the general and usual case the grain direction is not initially known. Thus, four measurements with an orthogonal antenna setup are needed:

1. Initial source polarization and initial receiver polarization (same polarization as source)

2. Initial source polarization and perpendicular receiver polarization
3. Perpendicular source polarization and initial receiver polarization
4. Perpendicular source polarization and perpendicular receiver polarization

where initial refers to an arbitrarily chosen initial antenna position and perpendicular to the orthogonal position. These four measurements allow the determination of u, v, and grain angle θ in the range of −90° to 90° (Schajer and Orhan 2005). θ is defined as the counter-clockwise angle of the wood grain relative to the longitudinal position of the antenna and its polarization plane.

The grain angle θ can be directly determined by the measurements described above for a single specimen. However, density and moisture content can only be derived by a statistical relationship based on measurements of several specimens. A common assumption is that attenuation (in dB) and phase shift (in radians) are linearly dependent on moisture and dry wood density. This leads to regressions of the following forms (Schajer and Orhan 2005):

$$D_m = a_{m1} \cdot \frac{1}{h} \cdot att_{dB} + a_{m2} \cdot \frac{1}{h} \cdot \phi \qquad (5)$$

$$D_d = a_{d1} \cdot \frac{1}{h} \cdot att_{dB} + a_{d2} \cdot \frac{1}{h} \cdot \phi \qquad (6)$$

D_m is the moisture density (moisture mass per unit volume of the specimen). D_d is the dry density (dry wood mass per unit volume of the specimen) and a_{m1}, a_{m2}, a_{d1}, and a_{d2} are the respective regression coefficients. The mean attenuation, att_{dB} and the mean phase shift, ϕ are derived from,

$$att_{dB} = 20 \cdot \log_{10}\left(\frac{|u| + |v|}{2}\right) \qquad (7)$$

$$\phi = (\angle u + \angle v)/2. \qquad (8)$$

Both, u and v for each measured specimen, contribute to mean attenuation and mean phase shift. This has an averaging effect and uses only a minimum of variables, which improves the numerical stability.

The temperature of the sample influences the mean attenuation and mean phase shift. A linear compensation of temperature sensitivity for moisture density and dry density may be included in Eqs. (5) and (6) which leads to the following more general equations:

$$D_m = \left(b_1 \cdot \frac{1}{h} \cdot att_{dB} + b_2 \cdot \frac{1}{h} \cdot \phi\right) \cdot (1 + b_3 \cdot T) \qquad (9)$$

$$D_d = \left(c_1 \cdot \frac{1}{h} \cdot att_{dB} + c_2 \cdot \frac{1}{h} \cdot \phi\right) \cdot (1 + c_3 \cdot T). \qquad (10)$$

The coefficients b_1, b_2 and b_3, and c_1, c_2 and c_3 are used to fit moisture density and dry density, respectively.

The moisture content, MC, of wood is defined as the ratio of moisture and dry density.

$$MC = \frac{D_m}{D_d} \qquad (11)$$

It was proposed (Schajer and Orhan 2005) to directly fit the moisture content using the fitting parameter d_1 and d_2 according to.

$$MC = d_1 \cdot \frac{att_{dB}}{\phi} \cdot (1 + d_2 \cdot T) \qquad (12)$$

3 Materials and methods

Spruce [*Picea abies* (L.) Karst.] was chosen as species of interest due to its prominent role in wood processing. This is particularly true for the glue-laminated timber production in Europe. To overcome influences of local anatomical peculiarities the wood originated from different sources. The moisture content of the artificially dried wood was preliminary evaluated using a handheld moisture meter with stick-in electrodes. Then, 87 samples were cut to 17 cm × 17 cm width and 4 cm thickness. Care was taken to avoid any failures in the samples like knots, resin pockets, mould, or compression wood. The dimensions and mass of each sample were measured and the density was calculated.

To obtain significant results the sample set had to vary over the entire possible range of density and moisture content. First, the large number of samples ensures variety and the applicability of statistical methods. Furthermore, density distribution was guaranteed by randomly chosen samples. Moisture content range was defined by the production standard for glue-laminated timber in Europe (EN 386 2001). It specifies minimum and maximum values of 8 and 15 %, respectively. This moisture content range should be covered in the sample set. Thus, several samples were conditioned again. Change in preliminary determined moisture content was derived gravimetrically. Dimensions were re-measured and the final density was calculated. The resulting distribution in final density and final preliminary moisture content is shown in Fig. 1a. All samples were stored individually in hermetically-sealed plastic bags. This method assured constant moisture in the sample. A delay of several days before measurement served to establish homogeneous moisture distribution in the samples.

Three series of experiments were conducted at 10, 20, and 30 °C, respectively. This corresponds to the relevant temperature range of lamellas in glue-laminated timber fabrication. In each case the entire 87 samples were tempered at least 24 h in a temperature chamber prior to the tests. Dummy samples were used in addition to validate the temperatures. They were equipped with thermocouples,

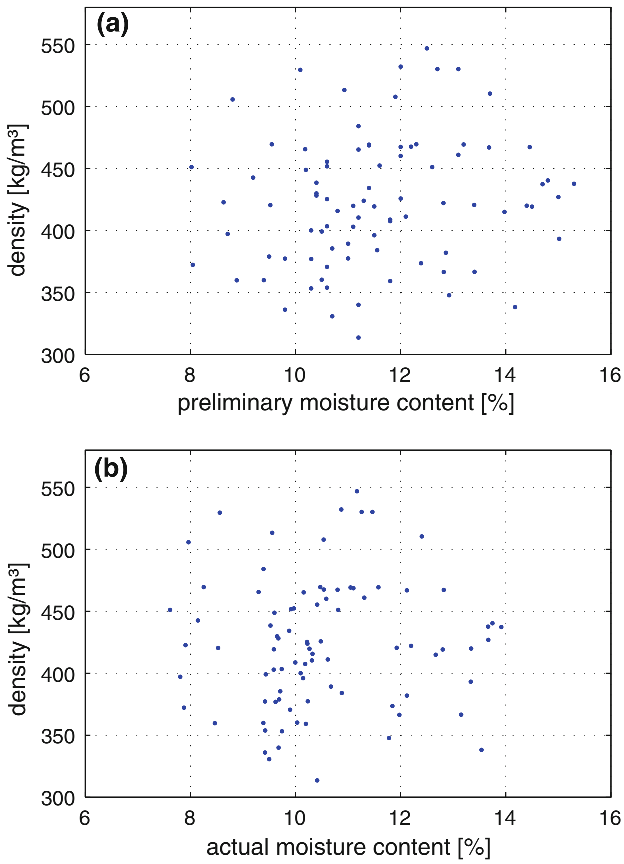

Fig. 1 Moisture content and final density (calculated from actual sample dimensions) of the test samples, **a** final preliminary distribution determined with a handheld moisture meter, **b** actual distribution determined with the drying method

Abb. 1 Holzfeuchte und Dichte (bezogen auf die tatsächlichen Probenabmessungen) der gemessenen Proben, **a** letztlich vermutete Verteilung (gemessen mit Hand-Feuchtemessgerät), **b** tatsächliche Verteilung (über Darrmethode bestimmt)

which were fixed in small drilling-holes. This allows chronologically monitoring the spatial temperature distribution of the samples in the chamber. Thus, no damaging of the samples or its sealing bag was necessary.

After the measurements the actual moisture content was determined with the drying method, e.g. gravimetrically. Moreover, this yielded the moisture density and dry density [defined in Eqs (5) and (6)]. Both added up yield the (actual) density. The distribution of actual density and actual moisture content of the investigated set of samples is shown in Fig. 1b.

The design of the measurement system is comparable to the equipment described by Schajer and Orhan (2005) and is schematically shown in Fig. 2. It consists of two opposed linearly polarized horn antennas, coaxial cables, and a vector network analyzer (VNA). The lens-corrected horn antennas ("Dorado LA-10-1") have a circular aperture with a diameter of 130 mm and a frequency range from 8 to 12.5 GHz. The dielectric lenses exhibit no advantage for this work, but were intended for potential future applications with the same equipment. Antenna fixtures with stepping motors allow separate rotation of both antennas in the range from 0° to 180°. Measurement control and further signal processing is done with a computer. For exact matching of the two polarization planes a null-finding routine in orthogonal position of the antennas is used. Time gating (Agilent Technologies 2007) was applied to mask undesired reflections of the antenna setup and for measuring the direct path only. The measurement position of the specimen is on a sample table between the two antennas with a distance of 30 mm to each antenna's aperture (see Fig. 3). In each measurement a frequency sweep is performed in 51 steps from 8 to 12 GHz. On the one hand, this should prove the entire frequency range being equally suitable for wood testing as well as revealing details about the accuracy of antennas and measurement setup in the specified frequency range. On the other hand, multiple testing spread across a wide frequency range is a prerequisite for time gating.

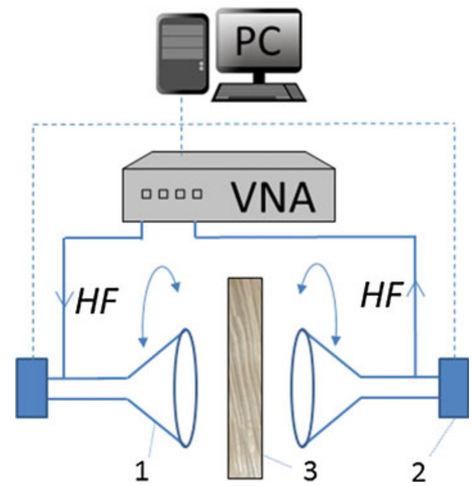

Fig. 2 Schematic diagram of the microwave system: two opposed linearly polarized horn antennas (**1**), coaxial cables, and a vector network analyzer (VNA). Antenna fixtures with stepping motors (**2**). Sample (**3**). Measurement control and further signal processing with a computer (PC)

Abb. 2 Schematische Darstellung des Mikrowellen-Messsystems: Zwei gegenüberliegende, linear polarisierte Hornantennen (**1**), Koaxialkabel und ein Vektor-Netzwerkanalysator (VNA). Antennenhalterung mit Schrittmotorsteuerung (**2**). Probe (**3**). Messsteuerung und weitere Signalverarbeitung mit einem Computer (PC)

First, reference measurements are carried out with the inserted sample table but without a specimen to compensate for the antennas' frequency response. Subsequently, the specimens are inserted and four measurements are performed with each specimen having different orthogonal antenna setups to calculate grain angle, u and v. The whole procedure is repeated in a sequence of four angular position

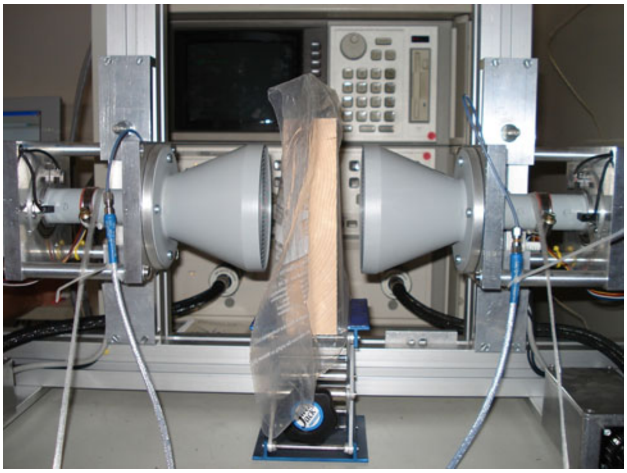

Fig. 3 Picture of the measurement setup with inserted sample
Abb. 3 Foto des Messaufbaus mit eingesetzter Probe

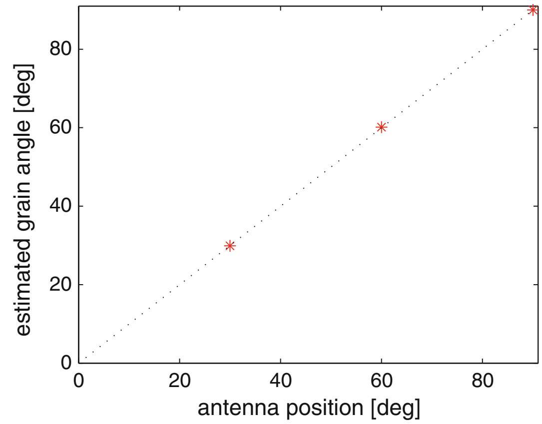

Fig. 4 Calculated grain angle at respective antenna position at 10 GHz for a single specimen. The *dashed trend line* shows the ideal behaviour
Abb. 4 Berechnete Faserwinkel bei entsprechenden Antennenpositionen bei 10 GHz einer einzelnen Probe. Die punktierte Trendlinie stellt den Idealverlauf dar

combinations of the antennas. This results in a total measuring time of 2 min for one specimen from extraction from the temperature chamber to the end of measurement, mainly due to the required time for antenna rotation and positioning and the precise measurement with the VNA.

4 Results

The results of a typical grain angle measurement at a test frequency of 10 GHz are shown in Fig. 4. Calculated grain angles are plotted versus the rotation angles of the antenna during measurement. The measurements are seemingly congruent to the ideal trend line showing a standard error of only 0.11°. This value barely varies with specimen and frequency. The influence of the test frequency on the determination of the grain angle is shown in Fig. 5. The standard error over the entire frequency range from 8 to 12 GHz is maximum 0.15°. This proves that the entire frequency range is applicable for grain angle measurements. Standard errors are of nearly the same magnitude. The undulating trend in Fig. 5 is a characteristic of the applied time gating (Agilent Technologies 2007).

The influence of moisture density and temperature on attenuation and phase shift of the transmitted microwave signal may be considered using Eq. (9). In Fig. 6a, the actual moisture density is compared to the estimated density using measurements performed at frequency 10 GHz.

Dry density is estimated using Eq. (10). This equation contains the parameter c_3, which is used to consider the influence of temperature. The evaluation shows, however, that this parameter is close to zero, within the numerical uncertainty. Obviously, a temperature independent regression performs well for dry density, and c_3 may be set to zero.

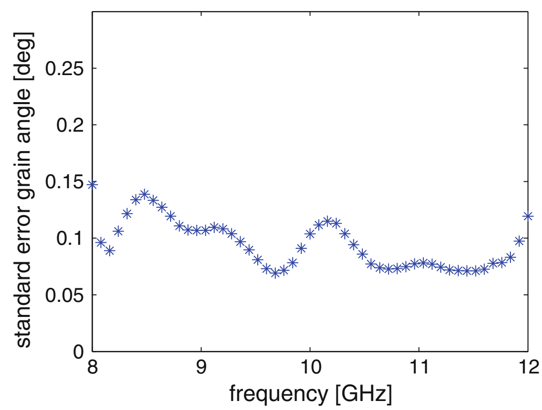

Fig. 5 Typical standard errors for grain angle measurements from 8 to 12 GHz
Abb. 5 Typische Standardabweichungen des Faserwinkels bei Messungen von 8 bis 12 GHz

$$c_3 = 0 \tag{13}$$

This supports previous assumption (Schajer and Orhan 2005), that the temperature hardly influences the propagation properties of microwaves in dry wood.

The estimated dry density using Eq. (10) and $c_3 = 0$ is compared to the actual density in Fig. 6b. The results for the three investigated temperatures are equally scattered along the trend line. The standard errors for the estimations are 1.8 kg/m^3 for moisture density and 9.5 kg/m^3 for dry density.

Regression parameters determined for each of the 51 investigated test frequencies in the range from 8 to 12 GHz are shown in Figs. 7 and 8, respectively. All regression coefficients show smooth variations with the test frequency, which proofs the robustness and applicability of the used regression methods. The coefficient b_3, which

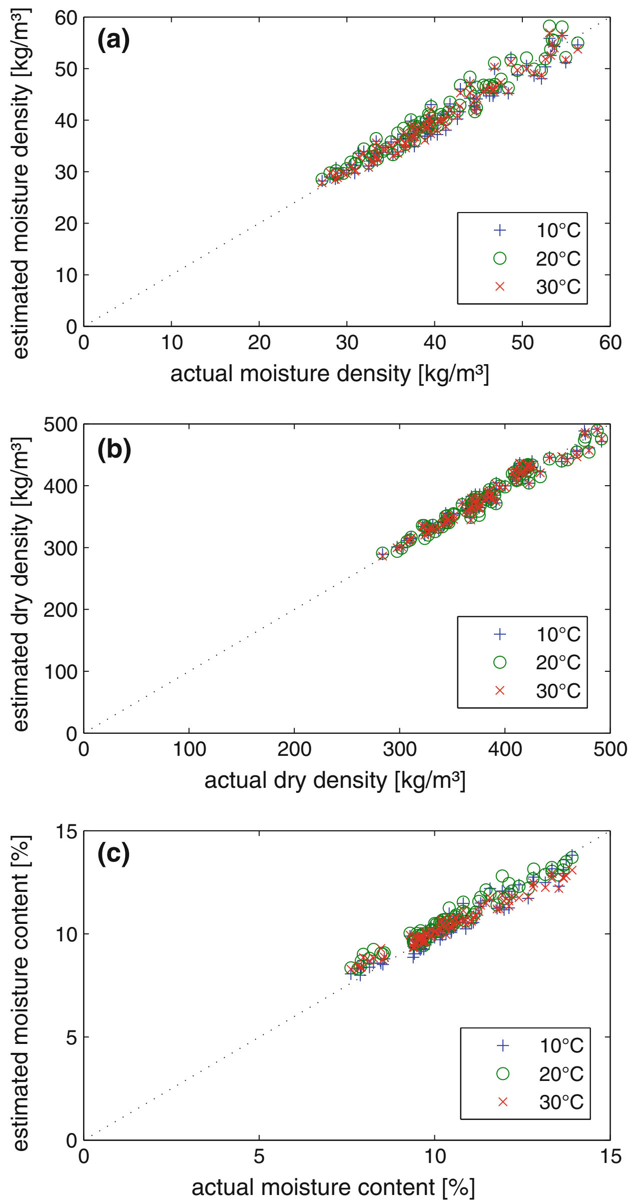

Fig. 6 Estimated vs. actual properties at 10 GHz: **a** moisture density, **b** dry density, **c** moisture content

Abb. 6 Durch Regression abgeschätzte versus tatsächliche Holzeigenschaften bei 10 GHz: **a** Feuchtedichte, **b** Trockendichte, **c** Holzfeuchte

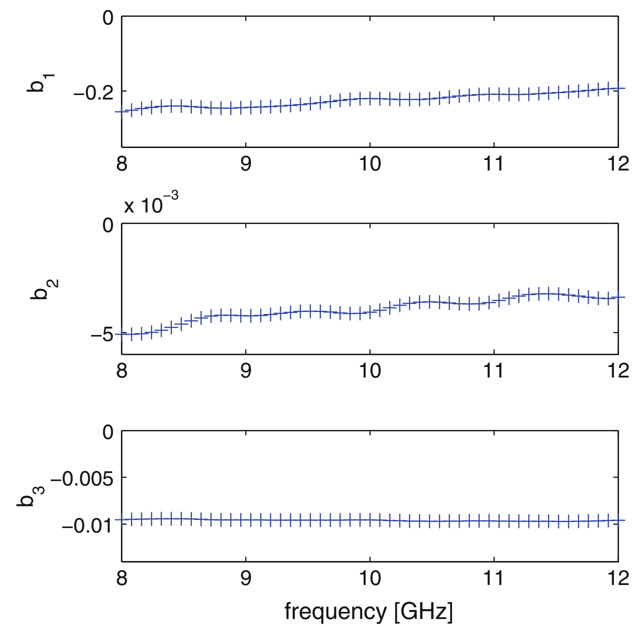

Fig. 7 Regression coefficients for moisture density estimation from 8 to 12 GHz

Abb. 7 Regressionskoeffizienten der Feuchtedichte von 8 bis 12 GHz

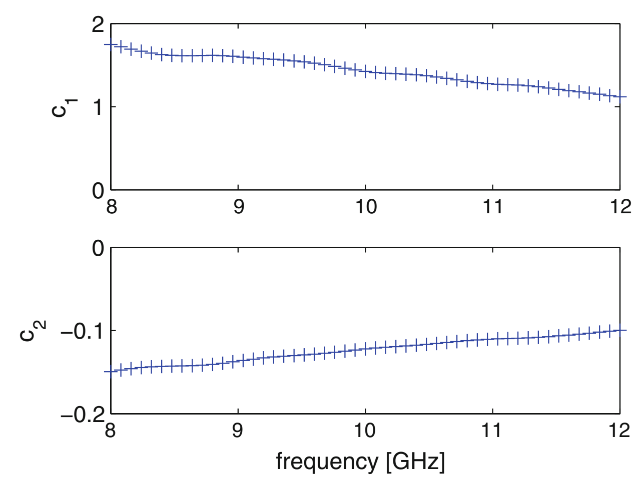

Fig. 8 Regression coefficients for dry density estimation from 8 to 12 GHz

Abb. 8 Regressionskoeffizienten der Trockendichte von 8 bis 12 GHz

considers the influence of temperature on dry density, is almost constant. This means that one and the same temperature compensation can be used for the entire frequency range. Figure 9 presents the variation of the standard errors of moisture and dry density. No significant influence of test frequency on standard errors is visible.

Moisture content was estimated using the regression Eq. (12). Figure 6c compares the estimated moisture content for frequency 10 GHz with the actually measured moisture content. The plot shows a good coincidence of the estimated moisture and the moisture measured with the drying method. Consequently, the standard error is small (0.41 %). It is remarkable that the regression coefficients d_1 and d_2 are hardly affected by the test frequency (see Fig. 10). d_1 considers the quotient of attenuation and phase shift on moisture content. d_2 considers the influence of temperature. Similar to the result discussed above, the influence of temperature is about constant within the investigated frequency range. Accuracy of the estimation of moisture content is hardly affected by the test frequency,

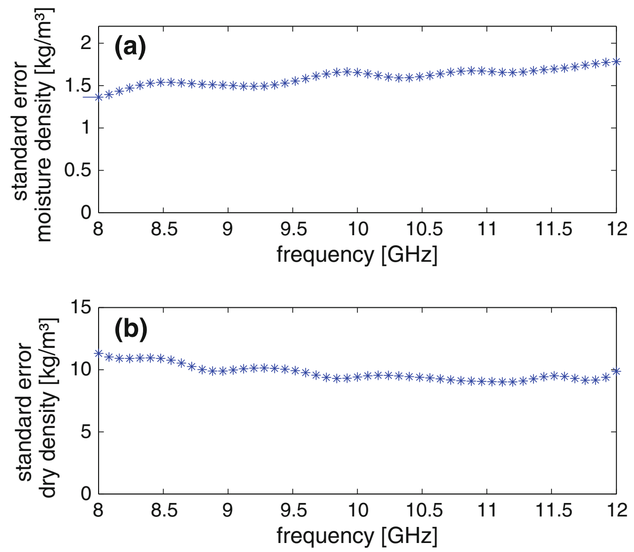

Fig. 9 Standard errors for **a** moisture density and **b** dry density estimation from 8 to 12 GHz
Abb. 9 Standardabweichungen für die Abschätzung der **a** Feuchtedichte und **b** Trockendichte bei 8 bis 12 GHz

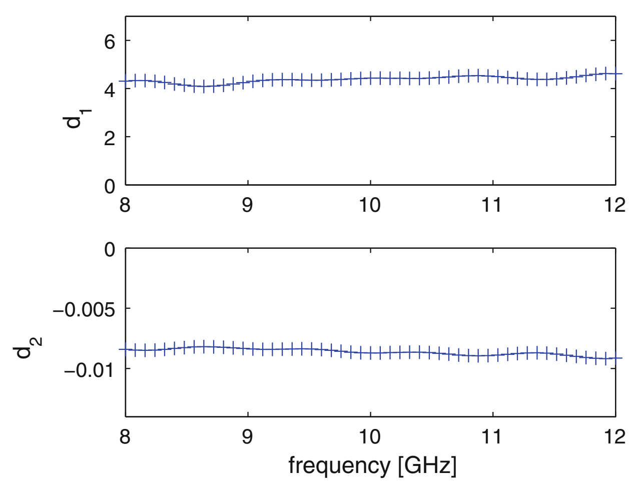

Fig. 10 Regression coefficients for moisture content estimation from 8 to 12 GHz
Abb. 10 Regressionskoeffizienten der Holzfeuchte von 8 bis 12 GHz

and standard errors shown in Fig. 11 are comparable within the investigated frequency range.

5 Conclusion

A prototype system measuring the transmission parameters of polarized microwaves (8–12 GHz) through specimens is used to determine key physical data of spruce [*Picea abies* (L.) Karst.]. Grain angle is detected with a standard error of about 0.15° (measuring range from −90° to +90°). The standard error for moisture density is maximum 1.8 kg/m^3

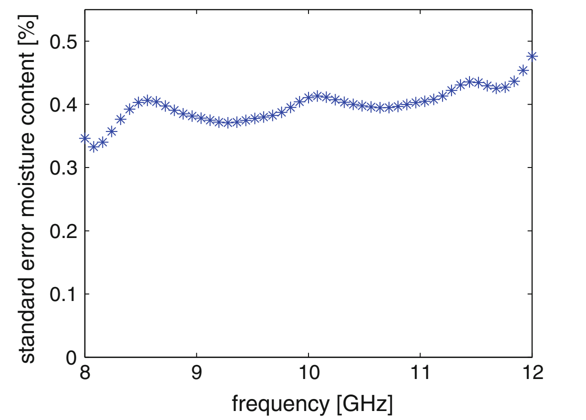

Fig. 11 Standard error for moisture content estimation from 8 to 12 GHz
Abb. 11 Standardabweichungen für die Abschätzung der Holzfeuchte bei 8 bis 12 GHz

(measuring range from 27 to 56 kg/m^3), for moisture content it is maximum 0.47 % (measuring range from 7.6 to 14 %), and for dry density the standard error is maximum 11.3 kg/m^3 (measuring range from 284 to 492 kg/m^3). Thus, the accuracy of the presented results exceeds that of previous works from other groups by factor two (moisture and dry density) to factor five (grain angle).

Tests are performed at different frequencies in the range from 8 to 12 GHz, and within the investigated ranges of density and moisture content no preferred test frequency could be noticed. Temperature compensation was proven to be negligible for dry density estimation, whereas a moderate temperature influence of about 0.9 % per degree Celsius was found for the estimation of moisture content and moisture density.

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Paper 2

Microwave Testing of Moist and Oven-Dry Wood to evaluate Grain Angle, Density, Moisture Content and the Dielectric Constant of Spruce from 8 GHz to 12 GHz

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Abstract

The scope of the presented work is to discuss the challenges and demonstrate the potential of microwave testing for applications in the wood processing industry. Microwave technology benefits from the anisotropic dielectric properties of wood to simultaneously identify grain angle, density, and moisture content of wood. Therefore, the theory of free space transmission measurement is thoroughly discussed with emphasis on the characteristics of (and how to deal with) reflections occurring in real measurements. A more sophisticated calculation method for the derivation of the desired physical wood properties is presented. The advantages of a modern laboratory style setup are shown and its possible transition in an industrial-style application is discussed. Moist (moisture content 7.6…14%) and oven-dry spruce samples are tested. The detection of grain angle for moist and oven-dry wood yields an RMSE (root-mean-squared-error) of 0.14° and 0.4°, respectively. Moisture content is evaluated with density- and thickness-independent methods. Adapted regression models are proposed yielding an RMSE for moisture content of 0.45% for a single frequency measurement. The promising advantages of wood moisture estimation with frequency sweeps instead of fixed frequency signals are discussed and demonstrated for all samples (RMSE=0.39%). The dielectric constant of moist and oven dry spruce in the range from 8 GHz to 12 GHz is evaluated in respect to density, moisture content and temperature. The respective constants ε', ε'', and tan(δ) are formulated in a general form via a non-linear regression and compared to existing data in literature.

microwave, density, moisture, grain angle, NDT, wood, permittivity, dielectric constant, spruce, moisture content, free space, transmission measurement

Introduction

Non-destructive evaluation of the physical properties of wood is a key task in modern wood manufacturing processes. Due to a rapidly increasing production speed, fast, non-contacting, reliable and robust measurement systems are demanded by the wood industry. When wood is used as a construction material, grain angle deviation, moisture content, and density are crucial parameters. Moisture is commonly determined with capacitance type moisture meters using high frequency signals or with resistance type pin moisture meters (Wilson, 1999). These moisture meters are able to reasonably cope with industrial needs. However, due to their measuring principles, measurements are prone to deviations in the wood grain angle. Moreover, they require density information for a reliable moisture determination. The application of X-rays is successfully established for density measurements enhancing both production speed and quality (Schajer, 2001). Still, these systems remain rather costly and require efforts for the protection against hazardous ionizing radiation. Grain angle deviations, both on a local (knot, top rupture) and global (sweep, taper, spiral growth) scale, significantly influence the strength of wood (Kollmann and Côté, 1984). Consequently, production standards define boundary values for grain deviation for the application of solid wood in products as glued laminated timber (EN 1912, 2012). With modern drying technologies and planing the occurrence of drying cracks has virtually been eliminated. Thus, global grain deviations remain undetected by conventional visual grading. The use of the tracheid-effect, i.e. the extension of a circular light spot into an elliptical form with the major axis oriented in grain direction, (Nyström, 2003) was discussed and applied in industrial applications. However, this method is susceptible to unclean and unplaned surfaces, is only testing the surface and features deficient accuracy. A fast, robust, and accurate measurement device for grain angle detection in industrial conditions still is a considerable challenge for research.

Microwaves have been throughout the years consistently been demonstrated as a promising tool to reveal the key parameters density, moisture content, and grain deviation in a fast, non-destructive and contactless manner (King and Yen, 1981). Several attempts are reported in literature to measure moisture and density of wood with microwaves (Al-Mattarneh et al., 2001; Johansson et al., 2003; Lundgren et al., 2006; Martin et al., 1987; Tiuri and Heikkila, 1979). However, the lack of grain angle information makes these measurements prone to deviations in the grain direction. An early attempt to detect wood fiber orientation with a microwave resonator was done in 1974(Tiuri and Liimatainen, 1974). A grain angle detection using transmission measurements was presented by several authors (Leicester and Seath, 1996; Malik et al., 2005; Shen et al., 1994). An integral approach using the microwave technology is able to determine density, moisture content, and grain angle simultaneously (Heikkila et al., 1982; James et al., 1985; Schajer and Orhan, 2006). Here, the method intrinsically accounts for the influence of all three parameters and determines every parameter separately. Phase-shift and attenuation measurements yield density and moisture content via a multi-variant statistical approach, and according to depolarization the grain angle is obtained. While Schajer and Orhan (2006) used a measurement setup featuring a scattering dipole between the antennas, recent reported setups (Aichholzer et al., 2013; Bogosanovic et al., 2011; Denzler et al., 2013; Vallejos and Grote, 2009) benefit from superior dual-linear-polarized designs. The theoretical formulation of all these work directly follows Schajer and Orhan (2005). Schajer and Orhan, however, point out that they are measuring only a so-called “effective” transmission coefficient by ignoring any kind of occurring reflections of the testing signal. Moreover, no author accounted for the complex attenuations occurring in the sample-air-interfaces.

Strong influence of antenna design on the quality and applicability of microwave testing was encountered (Bogosanovic et al., 2013; Denzler et al., 2014; Vikberg et al., 2012a) and evaluated (Vikberg et al., 2012b). All these authors report remarkable influence of diffraction at the sample edges that severely compromises testing quality. Bogosanovic et. al (2013) quantify for their focused beam setup that diffraction effects at the edges of the sample are negligible only if the minimum transverse dimension of the sample is greater than three times the beam-waist width illuminating. Consequently, for lumber dimension 10 x 5 cm, they applied additional absorbers to prevent diffraction effects.

Up to now, no industrial application of microwave testing could be sustainably established in the wood manufacturing industry. This is explained on one hand due to the, above addressed, challenging physical nature of microwaves and on the other hand due to a lack of appropriate, low-cost, and robust electronic equipment. All previous work is based on several assumptions and simplifications without submitting exact theoretical evidence that these measures are justified. In this paper we discuss the most promising method free-space transmission measurements and introduce new developments. For the first time in wood testing literature we present a complete and theoretical derivation for the transmission coefficients that addresses all the until now unjustified assumptions and applies superior complex matrix calculation. With versatile laboratory equipment we demonstrate the methods high potential and give an outlook on obvious and near future applications.

Theory

Microwave propagation in wood

Microwaves propagating through a device under test (DUT) are attenuated and phase-shifted. For wood as DUT, both attenuation and phase shift are different in the three anatomic directions. The axial direction is parallel (∥) to the wood grain.

Radial and tangential directions show similar dielectric behavior and are both considered as a single “perpendicular” (⊥) direction (Torgovnikov, 1993). This idealized orthotropic wood model proved to be a sufficient approximation, especially in view of the heterogenic nature of wood which to some degree varies radial and tangential dielectric properties within the same log or board. Moreover, this simplification uniformly describes all possible growth-ring arrangements from quarter sawn to flat sawn.

Consequently, the dielectric properties of wood as an orthotropic material exhibit an elliptical character with the major (!) axis in grain direction (Fig. 1-a). An incident linearly polarized test signal, with arbitrary polarization angle, can be decomposed into a component parallel and perpendicular to grain direction, respectively. These two components are independent waves propagating through wood with different attenuation and speed, i.e. phase shift. The resulting signal after the transmission through wood is the superposition of both components. In the general case, this resulting signal is elliptically polarized with the main axis rotated relative to the grain direction. Fig. 1-(b1)–(b3) shows possible measured signals for typical wood attenuation ratio ($att_{\parallel}$ /$att_{\perp}$=2.2) and several phase shift differences of parallel and perpendicular signal. The general case in Fig. 1-(b1) is demonstrated exemplarily with a phase shift difference of 320°. Only in special constellations, i.e. phase shift difference 0°/180° or 90°/270°, linear polarization (Fig. 1-(b2) for the case of 180°) or elliptical polarization (with minor (!) axis in grain direction, Fig. 1-(b3)) of the resulting signal is possible.

Even in recent publications (e.g. Denzler and Weidenhiller, 2015) this interrelation is misunderstood and illustrated incorrectly. However, exactly this above demonstrated behavior of wood due to its physical properties justifies and mandatorily requires a dual-linear-polarized measurement setup. Consider a detected signal that is measured in the polarization plane of the incident signal: Fig. 1-(b1)–(b3) demonstrates that signal detection in a single polarization plane is heavily prone to grain angle deviation. As a consequence, setups measuring in one polarization plane only (Johansson et al., 2003; Leicester and Seath, 1996) are always prone to systematic errors. The same holds for setups with a single, elliptically or circularly polarized testing signal. Here, the measurement of a single polarization state comprises an unresolvable superposition of two otherwise subsequently performed linear polarized measurements.

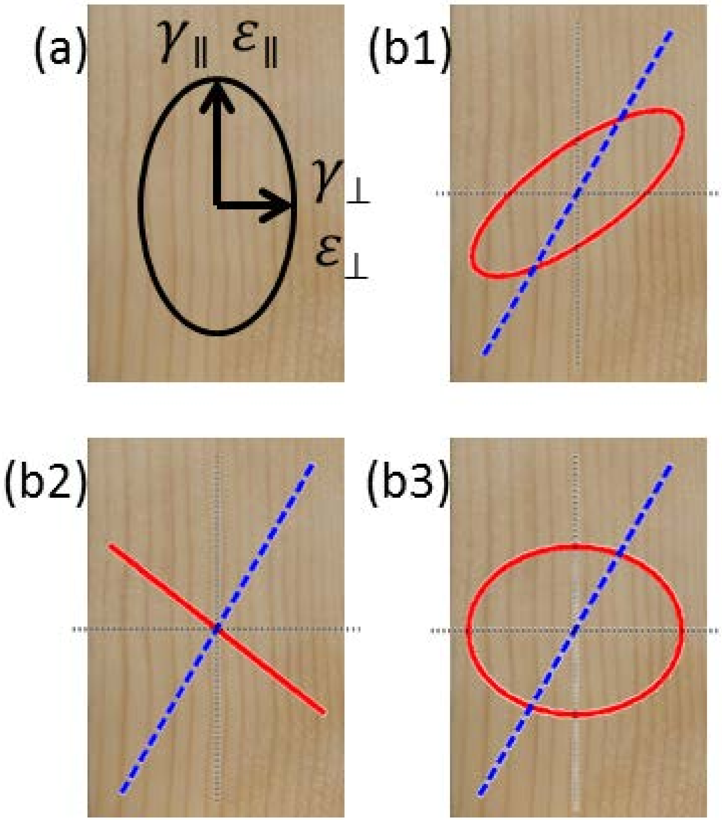

Fig. 1 (a) elliptic character of the dielectric properties of wood (the propagation constant γ and the dielectric constant ε are introduced in equation (2) and (6), respectively). (b1)–(b3): For a linearly polarized incident signal (dashed line, polarization plane 30° off grain direction) possible resulting signals (solid line) after transmission through wood are shown

However, the demonstration in Fig. 1 still is an idealized model as multiple reflections that occur within the sample are not yet considered.

Reflections

In actual measurements, reflections occur in each plane, where the characteristic wave impedance changes (Fig. 2a) (Kark, 2006). Thus, a measurement solely through air features reflections at the antennas (solid arrows in Fig. 2a) which result in multiple reflections. This undesired effect can be weakened by the use of absorbing material between the antennas (Zhang and Okamura, 1999) or compensated by the use of time-gating (Agilent Technologies, 2007). With a DUT in place, additional reflections occur every time a signal passes a DUT/air-interface (dashed arrows in Fig. 2a). On one hand, this yields subsequent reflections at the antennas and therefore a virtual additional testing signal that deteriorates the measurement quality. One the other hand, this results in multiple reflections in the sample. Multiple reflections generate a secondary signal that interferes with the direct path. For thicknesses of the DUT corresponding to half the wavelength of the testing signal in the DUT (and multiples thereof) this secondary signal even yields constructive interference and, therefore, less measured attenuation. This was shown by Robertson and Buckmaster (1992) on glass and plywood. Most work in the field neglected this effect, which is a sufficient assumption for wood at moisture contents (<30%) and thicknesses (>3cm) at interest. As a rule of thumb 10dB attenuation of the secondary signal is sufficient. The effect vanishes with increasing thickness of the DUT. However, with the use of time gating (Agilent Technologies, 2007; Kraszewski et al., 2001), that was applied in this work, only the direct path is measured. In this case, the only remaining two reflections to be accounted for in a measurement occur at both DUT/air-interfaces.

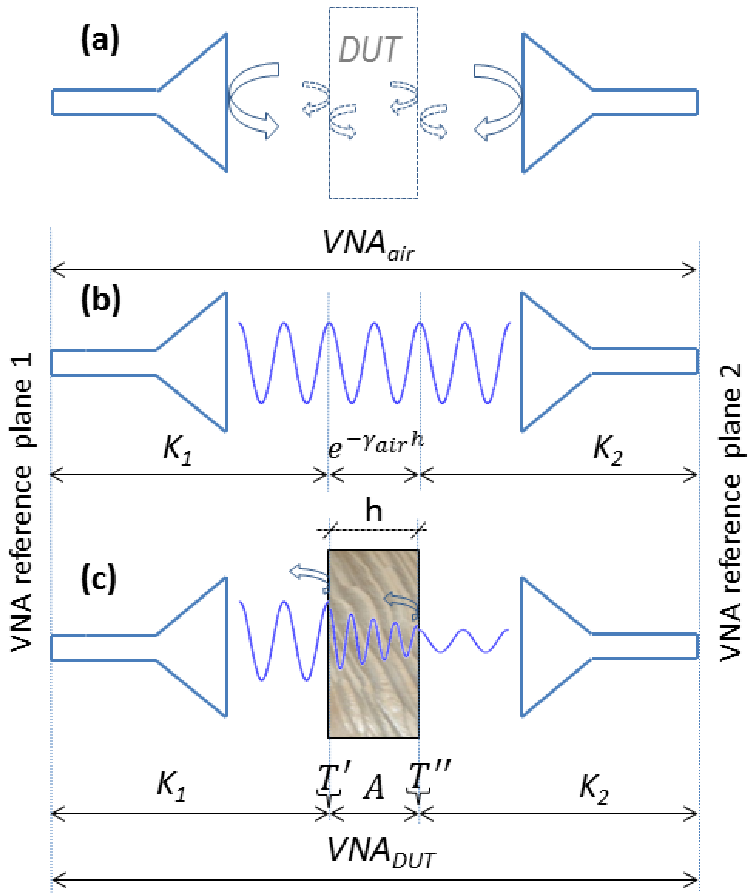

Fig. 2 Schematic of free-space transmission measurement. (a) Reflections occurring in real measurements. (b) Measurement through air. (c) Measurement of a DUT

For wood as DUT, multiple reflections occur for parallel and perpendicular path independently. Theoretically, this may even lead to positive interference in the ∥-path and negative interference in the ⊥-path at the same time and hence to a stronger, i.e. less attenuated measured signal in parallel direction. For the typical range of wood properties ($att_{\parallel}$ /$att_{\perp}$>1.5), samples (thickness >3cm, MC <30%) and testing frequency (~10 GHz), this effect has minor impact but reduces measurement accuracy. Again, with properly applied time gating, in both parallel and perpendicular directions only the direct path is measured.

Transmission measurement of an isotropic DUT

The propagation of microwaves through a DUT is generally described with the complex attenuation:

$$A = \mathrm{e}^{-\gamma_{DUT} h} \tag{1}$$

h denotes the thickness of the DUT. The propagation constant γ is a complex quantity:

$$\gamma = \alpha + i\beta \tag{2}$$

α is the attenuation factor which considers the exponential decrease of electric field strength with increasing propagation length in the material, and β denotes the phase factor which considers the phase shift of the electromagnetic wave propagating through the material. A is called transmission coefficient. It is a complex number describing attenuation (magnitude) and phase shift (angle) of the transmitted microwaves.

However, with a real test setup (e.g. a Vector Network Analyzer (VNA), as used in this work) it is impossible to directly measure the transmission coefficient of a DUT. A calibrated setup yields complex attenuation values corresponding to defined reference planes (see Fig. 2b and c). Thus, a VNA measurement of a DUT with a plane wave as testing signal may be described with

$$VNA_{DUT} = K_1\, T' A\, T'' K_2 \tag{3}$$

with K_1 and K_2 complex attenuations caused by the setup from signal generation to incidence on the sample and from the exit from the sample to signal measurement, respectively. $T'$and T'' account for the above discussed reflections by only considering the wave that passes through the DUT/air-interfaces:

$$T' = \underbrace{\frac{2}{1+\sqrt{\varepsilon_r}}}_{\mathrm{t}_{air\to DUT}} \sqrt{\mathrm{Re}\left\{\sqrt{\varepsilon_r}\right\}} \tag{4}$$

$$T'' = \underbrace{\frac{2\sqrt{\varepsilon_r}}{\sqrt{\varepsilon_r}+1}}_{\mathrm{t}_{DUT\to air}} \sqrt{\mathrm{Re}\left\{\frac{1}{\sqrt{\varepsilon_r}}\right\}} \tag{5}$$

$t_{air\rightarrow DUT}$ and $t_{DUT\rightarrow air}$ are the respective transmission factors at perpendicular incidence. The root terms constitute scaling factors between field quantities and normalized VNA-measurements. ε_r is part of the complex dielectric constant that describes the dielectric properties of the DUT as a lossy medium:

$$\varepsilon = \varepsilon_0 \varepsilon_r \tag{6}$$

with ε_0 the permittivity of vacuum and ε_r the relative dielectric constant

$$\varepsilon_r = \varepsilon' - j\varepsilon'' = \varepsilon'\left(1 - j\frac{\varepsilon''}{\varepsilon'}\right) = \varepsilon'(1 - j \cdot \tan\delta) \tag{7}$$

ε' and ε'' are the real and imaginary part of the relative dielectric constant, $\tan\delta$ the loss factor. Propagation constant and the complex dielectric constant are associated by the following identity (Kark, 2006):

$$\gamma = \alpha + i\beta = j\omega\sqrt{\mu\varepsilon} = j2\pi f\sqrt{\mu_0\mu_r\varepsilon_0\varepsilon_r} \tag{8}$$

f is the frequency, μ_0 the permeability of vacuum and the relative permeability μ_r=1 for wood.

Similar to a DUT, a measurement solely through air (Fig. 2b) is described by

$$VNA_{air} = K_1\,\mathrm{e}^{-\gamma_{air}h}\,K_2 \tag{9}$$

The dielectric properties of air at microwave frequencies are sufficiently approximated with those of vacuum. Thus, a plane wave travelling through air features no attenuation but a phase shift depending on its frequency:

$$\gamma_{air} = j\beta_{air} \tag{10}$$

$$\beta_{air} = 2\pi\frac{f}{c_0} \tag{11}$$

where f denotes the frequency and c_0 the speed of light in vacuum.

Thus, with a reference measurement through air, the complex attenuations K_1 and K_2 caused by the measurement setup are compensated:

$$C = \frac{VNA_{DUT}}{VNA_{air}} = \frac{K_1\,T'A\,T''K_2}{K_1\,\mathrm{e}^{-\gamma_{air}h}\,K_2} = T'A\,\mathrm{e}^{\gamma_{air}h}\,T'' = T'\,\mathrm{e}^{-(\gamma_{DUT}-\gamma_{air})h}\,T'' \tag{12}$$

Left and right part of (12) constitute an implicit form of a conditional equation for ε_r. With C the ratio of two complex attenuation measurements and (4), (5), (8), (10) and (11) the relative dielectric constant ε_r is solved numerically with an appropriate tool, e.g. MATLAB. We emphasize that the complex forms of T' and T'' imply that a wave transmitted through a lossy DUT encounters additional phase shifts at both air/DUT-interfaces that are not compensating each other.

$$C = \underbrace{T'\,T''}_{\arg(\,)=0.08°\dots\,1.5°}\;\underbrace{\mathrm{e}^{-(\gamma_{DUT}-\gamma_{air})h}}_{\arg(\,)=66°\dots\,368°} \tag{13}$$

For the tested samples in this work equation (13) shows that the contribution of $T'$and T'' to the measured phase shift could easily be neglected. In each case a direct numerical solution of the complex ε_r in (12) yields unstable results. Therefore, an iterative method was used. In a first step, an initial β from the phase shift of the measured *C* is derived. With the identity in equation (8), the problem of the complex ε_r is thus reduced to a real variable for numerical solving. To account for the additional phase shift at both interfaces, the argument of the $T'T''$-term is calculated with the obtained amplitude-corrected ε_r. The initial β is corrected with these interface phase shifts. In a second iteration the amplitude- and phase-corrected ε_r is obtained.

With the derived ε_r the VNA-ratio in (12) is corrected and the "relative" transmission coefficient obtained:

$$B = A\,\mathrm{e}^{\gamma_{air}h} = \mathrm{e}^{-(\gamma_{DUT}-\gamma_{air})h} = \frac{VNA_{DUT}}{VNA_{air}}\frac{1}{T'\,T''} = C\,\frac{1}{T'\,T''} \tag{14}$$

With (10) this "relative" transmission coefficient describes the absolute attenuation of the DUT and the phase shift due to the DUT relative to air. Principally, the transmission coefficient of the DUT, *A* in equation (1), is the physically relevant quantity. In (14) this would mean considering the exponential γ_{air}-term on the right side of equation. However, regressions to derive physical properties of a DUT that use *A* as predictor show the demand of an additional constant term that compensates for the phase shift that is caused by an ideal, lossless medium – vacuum or air, respectively. In contrast, regressions simplify for predictors featuring attenuation and phase shift exceedingly caused by the DUT than by an ideal, lossless medium – which is exactly this relative transmission coefficient *B* in equation (14).

The presented work in this paper revealed that a correction of the measured VNA-ratio in (14) doesn't yield any noticeable improvement in precision of the derivation of physical properties. Obviously, for the chosen setup the influence of $T'$and T'' is directly proportional to the complex attenuation *A* of the DUT. This might justify the simplification of neglecting $T'$and T'', that was applied in every former work in the field (initially Schajer and Orhan (2005)), which interprets *C* from equation (12) as "effective" transmission coefficient. As in this case no explicit calculation of the dielectric constant is necessary, this "effective" transmission coefficient directly serves as predictor for the derivation of desired wood physical properties.

With the use of time gating, that was applied in this work, and a plane wave with perpendicular incidence as testing signal, equation (12) is not only an idealized estimation but fully valid. Without time gating, reflections of the antennas will deteriorate measurement quality, as discussed above. However, a derivation for the transmission coefficient, e.g. the $T' A\, T''$-Term in equation (3) and (12), due to multiple reflections in the DUT is given e.g. in Kark (2006).

Transmission measurement of wood

For wood as DUT equation (12) is not sufficient and a more general mathematical formulation is needed. The orthotropic nature of wood is described with two propagation constants $\gamma_{\parallel}$ and $\gamma_{\perp}$ parallel to the grain and perpendicular to the grain, respectively.

$$\begin{pmatrix} C_{\parallel\to\parallel} & 0 \\ 0 & C_{\perp\to\perp} \end{pmatrix} = \begin{pmatrix} T'_{\parallel} B_{\parallel} T''_{\parallel} & 0 \\ 0 & T'_{\perp} B_{\perp} T''_{\perp} \end{pmatrix} \tag{15}$$

As in (4) and (5) $T'_{\parallel}$ and $T''_{\parallel}$ feature an $\varepsilon_{r,\parallel}$ and $T'_{\perp}$ and $T''_{\perp}$ feature an $\varepsilon_{r,\perp}$.

In the general case, the grain is not aligned with the polarization of the antennas but rotated at an angle θ (Fig. 3). This is mathematically described by

$$\begin{pmatrix} C_{H\to H} & C_{H\to V} \\ C_{V\to H} & C_{V\to V} \end{pmatrix} = \mathbf{R}^{\mathrm{T}} \begin{pmatrix} T'_{\parallel} B_{\parallel} T''_{\parallel} & 0 \\ 0 & T'_{\perp} B_{\perp} T''_{\perp} \end{pmatrix} \mathbf{R} \tag{16}$$

with **R** the rotation matrix of the form

$$\mathbf{R} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{17}$$

Now, subscripts “H” and “V” refer to the orthogonal polarization of the measurement system (Fig. 3). The used antennas feature a cross-polarization of < –31.3 dB and can therefore be neglected. Thus, only a correction of attenuation and phase shift, as discussed for equation (12), is needed. The chosen setup (see section Materials and Methods) comprises two axially aligned, mechanically rotated, linear polarized antennas. Consequently, each *C*-term on the left side of (16) constitutes a ratio of VNA_{DUT} for each polarization combination to VNA_{air}, obtained from an air measurement with aligned polarization planes of the antennas.

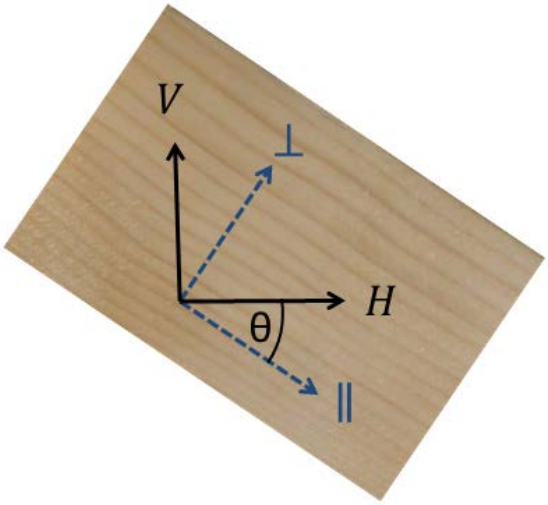

Fig. 3 Orientation of the polarization plane "V" and "H" of the testing signal and the angle θ relative to the grain direction

The Matrix-equation (16) has the typical form of an eigenvalue problem with

$$\mathbf{C} = \begin{pmatrix} C_{H\to H} & C_{H\to V} \\ C_{V\to H} & C_{V\to V} \end{pmatrix} = \mathbf{R}^{\mathrm{T}} \begin{pmatrix} C_{\parallel,\parallel} & 0 \\ 0 & C_{\perp,\perp} \end{pmatrix} \mathbf{R} \tag{18}$$

The eigenvalues of **C** correspond to $C_{\parallel,\parallel}$ and $C_{\perp,\perp}$, respectively. With (15) this yields a set of two conditional equations in the form of (12). Following the same procedure as shown for an isotropic DUT $B_{\parallel}$ and $B_{\perp}$ are derived. The corresponding eigenvectors constitute the rotation matrix, and therefore by implication the angle of grain direction (θ), relative to the orientation of polarization plane "H" (Fig. 3).

Due to the indistinguishability of the two eigenvalues, they have to be assigned to $C_{\parallel,\parallel}$ and $C_{\perp,\perp}$, respectively. This is typically carried out by sorting on attenuation, with $C_{\parallel,\parallel}$ the more attenuated transmission coefficient. As discussed above, it is theoretically physically possible that due to multiple reflections the measured attenuation perpendicular to the grain exceeds parallel attenuation. For wood and 10GHz testing frequency this would imply thin (~1cm), moist samples. In this rare case the method could yield grain angles with a 90°-error. However, this is a physical shortcoming that holds for every approach reported (refer chapter Introduction) although it was not discussed there.

An assignment of the respective eigenvalues to $C_{\parallel,\parallel}$ and $C_{\perp,\perp}$ via phase-shift is equally suitable, with the higher phase shift corresponding to $C_{\parallel,\parallel}$. This is suitable, as long as phase shift doesn't exceed 360°. To identify phase shifts beyond 360° the typical ratio of phase shift in vs. perpendicular to grain reported in Schajer and

Orhan (2006) and Aichholzer et. al (2013) can be used. For measurements at two frequencies, or in case of a multi-frequency-measurement, Trabelsi et. al. (2000) showed a solution for phase ambiguity.

Note that an explicit calculation of the right side of (16) shows that both off-diagonal elements are the same. The physical interpretation is that $C_{H\to V} = C_{V\to H}$. This can also be derived from geometrical considerations and directly follows from to the reciprocity of the measurement setup. Reciprocity means, that source and receiving antennas may be exchanged with each other in a measurement but still yielding the same measured values. Thus, principally only $C_{H\to V}$ or $C_{V\to H}$ has to be measured. However, measuring and considering both values in the calculation exhibits an averaging effect. Similarly, both eigenvectors yield a grain angle value. If both are considered, this implies an averaging effect for the determination of the grain direction.

Exceeding previous work, equation (16) now constitutes an expedient mathematical formulation for the discussed phenomena in Fig. 1, including the consideration of reflections, for the chosen setup.

Derivation and modeling of wood physical properties

The grain angle θ can be determined directly with the procedure described above for a single specimen. However, density and moisture content can only be derived by a statistical relationship based on measurements of several specimens.

Attenuation and phase shift of a specimen are both linearly dependent of dry density and moisture density (Torgovnikov, 1993). Moisture density D_m is defined as moisture mass per unit volume of the specimen. Dry density D_d is defined as dry wood mass per unit volume of the specimen. In a reversal approach (Schajer and Orhan, 2005), D_d and D_m can be estimated in a generalized form

$$D_d = a_1 \cdot \frac{1}{h} \cdot att_{dB} + a_2 \cdot \frac{1}{h} \cdot \phi \tag{19}$$

$$D_m = \left(b_1 \cdot \frac{1}{h} \cdot att_{dB} + b_2 \cdot \frac{1}{h} \cdot \phi\right)(1 + b_3 T) \tag{20}$$

a_1, a_2, b_1, b_2, and b_3 are the respective regression coefficients, T the temperature in °C. As it was shown in Schajer and Orhan (2006) and Aichholzer et. al. (2013), D_d is not susceptible to temperature in the desired range of wood manufacturing (~4°C to 30°C). Therefore, no temperature-related term is needed in (19). The mean attenuation, att_{dB} (in dB) and the mean phase shift, ϕ (in radians) are derived from

$$att_{dB} = 20 \log_{10}\left(\frac{|B_{\parallel}| + |B_{\perp}|}{2}\right) \tag{21}$$

$$\phi = \frac{\text{phase}(B_{\parallel}) + \text{phase}(B_{\perp})}{2} \tag{22}$$

phase($B_{\parallel}$) and phase($B_{\perp}$) are the respective unwrapped phases of $B_{\parallel}$ and $B_{\perp}$, e.g. the respective arguments but corrected by multiples of 360° if necessary. Both, $B_{\parallel}$ and $B_{\perp}$ for each measured specimen, contribute to mean attenuation and mean phase shift. This has an averaging effect and uses only a minimum of variables, which improves the numerical stability.

Note that geometrical considerations suggest to only apply $B_{\perp}$ in (21) and (22). It is clearly understood that the measurement represents a projection of the three-dimensional wood fiber gradient in the plane perpendicular to the incident testing signal. With the chosen setup this projection plane coincides with the planed surface of the samples. Thus, in the case of diving grain the derived $B_{\parallel}$ is actually a combination of $B_{\perp}$ and $B_{\parallel}$. The actual impact on the results will be discussed at the end of the results chapter.

Obviously, (20) only holds for moist samples, as an oven-dry specimen with D_m=0 still features both attenuation and phase shift. Moreover, assumption of linearity of (19) and (20) is only valid within a specific moisture content range with the same physical process of inclusion of water in the wood fiber. For spruce, this means moisture contents from 5% to below fiber-saturation-point, i.e. about 27% (Torgovnikov, 1993).

Density, i.e. gross density, of wood is defined as the sum of moisture density and dry density

$$D = D_m + D_d \tag{23}$$

The moisture content, *MC*, of wood is defined as the ratio of moisture and dry density

$$MC = \frac{D_m}{D_d} \tag{24}$$

The density-independent evaluation of moisture content for dielectric materials is reviewed in Nelson et. al. (2001). The applicability on wood was demonstrated by Schajer and Orhan (2006). We propose an improved equation that allows to include oven-dry samples into the regression

$$MC = \left(c_1 \frac{att_{dB}}{\phi} + c_2\right)(1 + c_3 T) \tag{25}$$

as our additional constant term c_2 compensates for the att_{dB}/ϕ-ratio of oven-dry wood. This ratio features a non-linear behavior over moisture. Thus we propose a quadratic equation to model non-linearity:

$$MC = \left(d_1 \left(\frac{att_{dB}}{\phi}\right)^2 + d_2 \frac{att_{dB}}{\phi} + d_3\right)(1 + d_4 T) \tag{26}$$

Menke and Knöchel (1996) discussed and demonstrated a superior, density- and thickness-independent method to determine moisture content of tobacco by using frequency swept signals:

$$X = \frac{\frac{\Delta att_{dB}(\omega)}{\Delta\omega}}{\frac{\Delta\phi(\omega)}{\Delta\omega}} = \frac{1}{N-1} \sum_{n=1}^{N-1} \frac{att_{dB}(\omega_{n+1}) - att_{dB}(\omega_n)}{\phi(\omega_{n+1}) - \phi(\omega_n)} \tag{27}$$

ω is the (angular) frequency, N the number of tested frequencies. Menke and Knöchel (1996) provide no explicit form of how they exactly derive X. Therefore, the right side of equation (27) represents our calculation routine. With att_{dB} from (21) and ϕ from (22) we apply this method on wood. The parameter X is a single value derived from the measurement of one specimen at all tested frequencies. This requires a linear behavior of the dielectric properties of the specimen over the tested frequency range. We derive moisture content with a regression applicable for both moist and dry samples

$$MC = (e_1 X^2 + e_2 X + e_3)(1 + e_4 T) \tag{28}$$

with the additional temperature-sensitive term in parenthesis expanding the form reported by Menke and Knöchel.

Based on Menke and Knöchel, Zhang and Okamura (1999) proposed the determination of MC using phase shift measurements at two frequencies. They apply a quadratic regression, which we expand with the parameter temperature to the form

$$MC = \left(f_1 \left(\frac{\phi_2}{\phi_1}\right)^2 + f_2 \frac{\phi_2}{\phi_1} + f_3\right)(1 + f_4 T) \tag{29}$$

with ϕ_2 and ϕ_1 the phase shift at higher and lower frequency, respectively.

The relative dielectric constant was determined already for each specimen applying (4), (5), and (12). To combine all derived values in a general formulation of ε', ε'', and $\tan\delta$ as a function of moisture density, dry density, temperature and frequency a nonlinear model was used in the form of

$$\varepsilon' = 1 + \left((g_1 D_m + g_2 D_d)(1 + g_3 f)(1 + g_4 T)\right) \quad (30)$$

$$\varepsilon'' = (h_1 D_m + h_2 D_d)(1 + h_3 f)(1 + h_4 T) \quad (31)$$

$$tg\delta = (i_1 D_m + i_2 D_d)(1 + i_3 f)(1 + i_4 T) \quad (32)$$

with g_i, h_i, and i_i the respective fit parameters, *f* the frequency in GHz, and *T* the temperature in °C. The additional constant term in (30) bases on the same considerations as the discussion on *B* versus *A* (see equation (14) and following). To evaluate this equations for specific values of moisture content and density refer to (23) and (24). A discrete evaluation of the dielectric properties for moist and oven-dry samples, respectively, promises an even better model. For moist samples (30)–(32) apply similarly. For oven-dry wood (30)–(32) simplify to equations without D_m-term. In this case $D_{d,oven\text{-}dry}$ becomes identical to density of the oven-dry samples.

Materials and Methods

Spruce (*Picea abies* (L.) Karst.) was chosen as species of interest due to its prominent role in wood processing. This is particularly true for the glue-laminated timber production in Europe. To overcome influences of local anatomical peculiarities the wood originated from different industrial sources that had already been stored for several weeks after the drying process. The moisture content of the artificially dried wood was preliminary evaluated using a handheld moisture meter with stick-in electrodes. Then, 87 samples were cut to 17 cm x 17 cm width and 4 cm thickness. Care was taken to avoid any defects in the samples like knots, resin pockets, mould, or compression wood. The dimensions and mass of each sample were measured and the density was calculated.

To obtain significant results the sample set had to vary over the entire possible range of density and moisture content. First, the large number of samples ensures variety and the applicability of statistical methods. Furthermore, density distribution was guaranteed by randomly chosen samples. Moisture content range was defined by the production standard for glue-laminated timber in Europe (EN 386, 2001). It specifies minimum and maximum values of 8% and 15%, respectively. This moisture content range should be covered in the sample set.

Thus, several samples were conditioned again. Change in preliminary determined moisture content was derived gravimetrically. Dimensions were remeasured and the final density, i.e. the actual density of the measured moist samples, was calculated. All samples were stored individually in hermetically-sealed plastic bags. This method assured constant moisture in the sample.

Three series of experiments were conducted at 10°C, 20°C, and 30°C, respectively, with the moist samples. This corresponds to the relevant temperature range of lamellas in glue-laminated timber fabrication. In each case the whole 87 samples were tempered at least 24 hours in a temperature chamber prior to the tests. Several thermocouple-equipped dummy samples were used to validate the spatial temperature distribution in the chamber.

After the measurements the actual moisture content of the measured moist samples was determined with the drying method, e.g. gravimetrically. Moreover, this yielded the moisture density and dry density (see (23) and (24)). The now oven-dried samples were subjected to the same preparation and measurement procedure again: The dimension and weight of each oven-dry specimen was determined. This yielded the density, which in this case is identical with the dry density D_d of the oven-dry samples. Again, samples were stored individually in hermetically-sealed plastic bags and another three series of experiments were conducted at 10°C, 20°C, and 30°C, respectively, with the oven-dry samples.

It is a physical fact that the theoretical resolution of measurement is limited to half of the wavelength. Consequently, Torgovnikov (1993) clearly argues that with microwave testing at around 10 GHz, which corresponds to a wavelength of 3 cm, defect-free wood may be considered as homogenous material. In this work we focus on a demonstration of achievable measurement quality. For exactly this reason we took care of preparing virtually perfect wood samples as described above. For an even more homogenous measurement we chose an antenna-setup that allows to evenly test a preferably big part of the entire specimen as equably as possible.

The design of the measurement system is schematically drawn in Fig. 4.

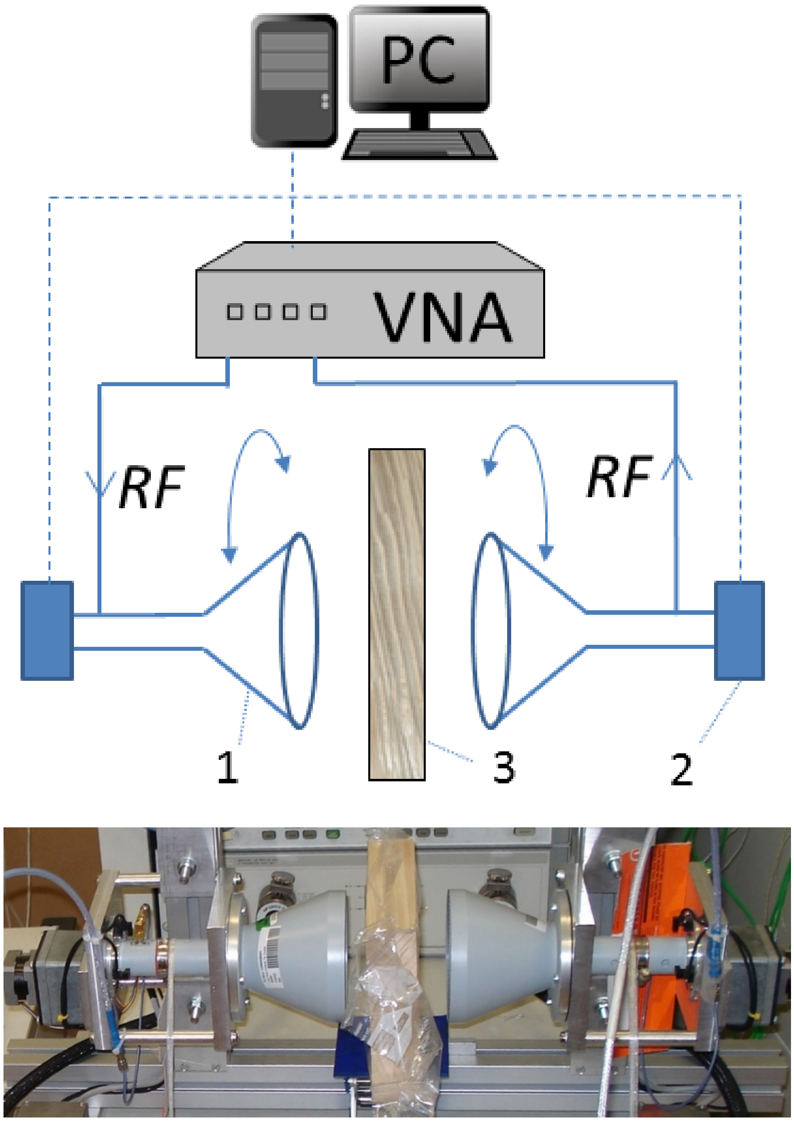

Fig. 4 Picture and schematic diagram of the microwave system: Two opposed linearly polarized horn antennas (1), coaxial cables, and a vector network analyzer (VNA) for signal processing. Antenna fixtures with stepping motors (2). Sample (3). Measurement control and further data processing with a computer (PC)

It consists of two opposed linearly polarized horn antennas, coaxial cables, and a vector network analyzer (VNA). The lens-corrected horn antennas ("Dorado LA-10-1") have a circular aperture with a diameter of 130 mm and a frequency range from 8 to 12.5 GHz. As we ascertained on an antenna test facility, they feature a smooth footprint on the sample even under near-field conditions, with only a slight amplification of the center area. Antenna fixtures with a stepping motor allow separate rotation of both antennas in the range from 0° to 180°. Measurement control and further signal processing is done with a computer. For exact matching of the two polarization planes a null-finding routine in orthogonal position of the antennas is used. The setup features a measured cross-polarization suppression of > 31.3 dB. Time gating was applied to mask undesired reflections of the antenna setup and for measuring the direct path only. The measurement position of the specimen is on a sample table between the two antennas with a distance of 30 mm to each antenna's aperture. The short distance from antenna aperture to specimen is beneficial to avoid diffraction at the edge of the specimen. However, the derivations in the theory chapter base on the assumption of plane waves, which is truly valid only in far field conditions, i.e. with the present measurement setup a sample-antenna distance of more than 50cm. Thus, measurements presented in this paper are performed in near field conditions. Nonetheless, the results chapter will prove the theoretical derivations are sufficiently approximated with the chosen setup.

In each measurement a frequency sweep is performed in 51 steps from 8 GHz to 12 GHz. This yields the necessary data for the evaluation of the dielectric constant. Multiple testing spread across a wide frequency range is a prerequisite for time gating and moisture evaluation with equation (28) and (29).

First, a reference measurement is carried out to compensate for the frequency response of the measurement setup. This yields the respective VNA_{air} -value for equation (15).

Subsequently, the specimens (still wrapped in the hermetically sealed plastic bags) are inserted and four measurements are performed with each specimen with an orthogonal antenna setup. This yields the respective VNA_{DUT} -values for equation (15) and allows the calculation of grain angle, $B_{\perp}$ and $B_{\parallel}$. The whole procedure is repeated with 30°, 60°, and 90° rotation of the coordinate system of the measurement. This makes it possible to prove the method is equally suitable over the entire possible range of grain angle deviation. Multiple measurements on one specimen at different orientations is a prerequisite for the error estimation of grain angle measurement.

For the estimation of error the root-mean-squared error (RMSE) is consistently used in this work:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \qquad (33)$$

with y_i the estimated values and $\hat{y}_i$ the actual values.

Results and Discussion

Grain angle detection is presented first. This is followed by the derivation of dry density and moisture density for each of the 51 frequencies. Subsequently, moisture content estimation using single frequency signals and frequency swept signals, respectively, is shown. Finally, the evaluation and modelling of the dielectric constant is presented. We close the chapter with general discussions.

Grain angle

The quality of grain angle detection is exemplarily shown in Fig. 5 for one specimen. As it is impossible to obtain exact grain angles from the sample for a comparison with measured values, following Schajer and Orhan (2006) another approach is chosen. Due to the highly precise antenna positioning, grain angle values derived at different antenna positions are compared. This is performed separately for each of the 51 measured frequencies. Hence, the derived error is a measure for the reproducibility of the grain angle measurement at a specific frequency. RMSE over the entire frequency range from 8 to 12 GHz is maximum 0.14° for moist samples and 0.40° for oven-dry samples, respectively. The undulating trend of the RMSE over frequency is a characteristic of the applied time gating. The magnitude of the error for oven-dry samples is mainly caused by an unexpected variation of the attenuation values in the measurements. Obviously, oven-dry samples show a stronger impact of near-field effects of the antennas. Still, even the oven-dry samples feature superior quality of grain angle detection compared to other work in the field.

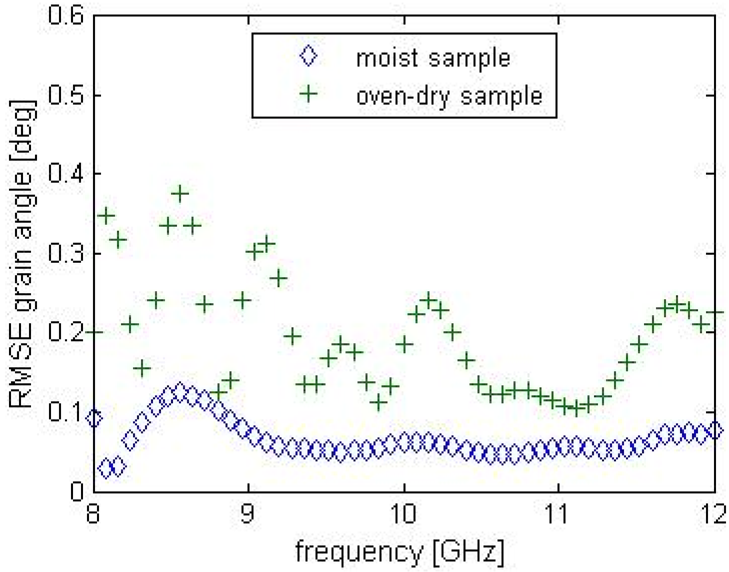

Fig. 5 Typical standard errors for grain angle measurements from 8 to 12 GHz for one single specimen

Dry density

Dry density estimation (measured range from 284 kg/m^3 to 527 kg/m^3) for both moist and oven-dry samples, respectively, was performed for each of the 51 measured frequencies. The respective estimation errors are shown in Fig. 6. We additionally tried to apply the derived regression for $D_{d,moist\ (samples)}$ to estimate $D_{d,dry\ (samples)}$. The results show very similar standard deviation like the other D_d-estimations (12.5 kg/m^3) but are heavily biased, featuring a RMSE of 48 kg/m^3. This demonstrates, that equation (19) for $D_{d,moist}$ is limited to moisture contents of 5% to 27%, where the assumption of linearity is reasonable (as discussed in the theory chapter). However, this still covers the entire moisture content range relevant for the production of glued laminated timber.

Estimations for $D_{d,dry}$ (RMSE maximum 12.4 kg/m^3) feature similar RMSE than $D_{d,moist}$ (maximum 11.5 kg/m^3). However, the devolution of $a_{i,oven\text{-}dry}$ over frequency shows that the regression is compensating for the encountered variation in oven-dry attenuation measurement. Therefore, we additionally performed an estimation of $D_{d,oven\text{-}dry}$ exclusively with the dominant quantity for oven-dry samples, phase shift. The regression yielded one single coefficient $a_{2,oven\text{-}dry,\ \phi\ \text{-}only}$ that shows a smooth behavior over frequency and a similar RMSE of maximum 12.6 kg/m^3 (Fig. 6).

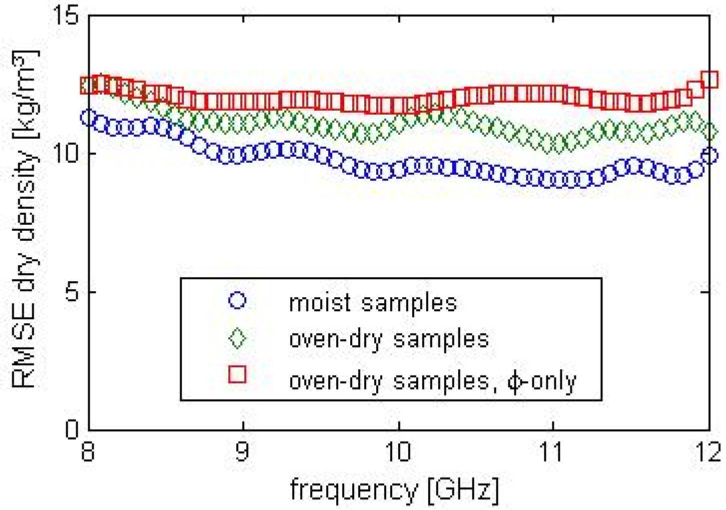

Fig. 6 RMSE for dry density estimation from 8 to 12 GHz

Moisture density

The estimation of moisture density D_m (measured range from 27 to 56 kg/m^3) was performed for each of the 51 measured frequencies. The respective RMSE are given in Fig. 7 with a maximum of 1.8 kg/m^3.

As for dry density, due to the same physical processes and consequential linearity, these results can be extrapolated for spruce samples with moisture contents from 5% to 27%.

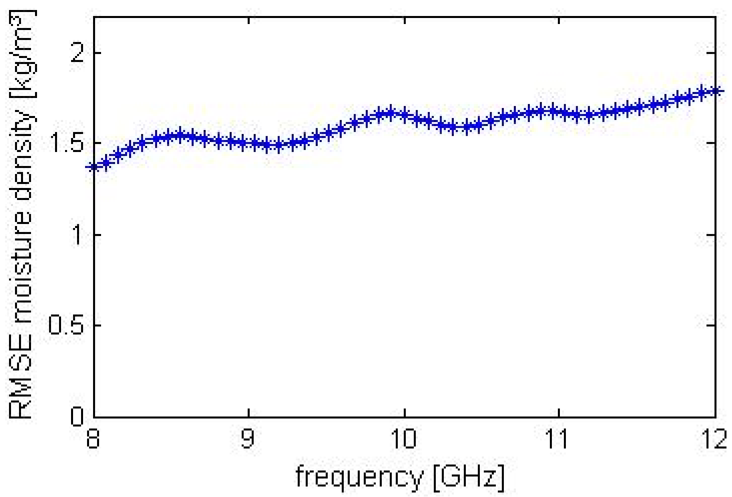

Fig. 7 RMSE for moisture density estimation from 8 to 12 GHz

Moisture content (single frequency)

An explicit calculation of moisture content with equation (24) yields an error of about 1%. The direct evaluation of moisture content with a density-independent approach in equation (25) yields superior results, presented in Fig. 8 and 9. Tested range spans from 0% (both oven-dry and moist samples) or 7.6% (moist samples only), respectively, to 14%. Fig. 8a shows estimated vs. actual moisture content at 10 GHz for regression exclusively with moist samples. Fig 9 shows the RMSE at the respective frequency with a maximum of 0.45%. The use of an additional constant parameter c_2 is justified as it compensates for the att_{db}/ϕ-ratio of oven-dry wood. The improvement manifests not only in a smaller estimation error but also an even distribution in Fig. 8a. Prior work (Aichholzer et al., 2013) showed a moisture content distribution slightly inclined to the ideal trend line and an estimation error of maximum 0.47%. As discussed, these results can be extrapolated for spruce samples with moisture contents from 5% to 27%.

Including oven-dry samples in the regression (25) an extension of detectable moisture content range is proposed. Fig. 8b shows the estimated vs. actual moisture content at 10 GHz for regression with all, i.e. both moist and oven-dry samples. The distribution of the moist samples is slightly deteriorated, the estimation error ($RMSE_{all}$ in Fig 9) slightly higher. However, with a typical RMSE of smaller than 0.6% it still proves reasonable to describe both dry and moist samples in one regression model. The estimation error of only the moist samples, basing on the regression (25) derived for all samples, $RMSE_{all,moist\text{-}only}$ is maximum 0.55% (Fig 9). All regression coefficients feature a smooth devolution over frequency. A quadratic regression term, as shown in (26), yielded no remarkable changes for the estimation of moist samples. However, for the regression with all samples, RMSE was noticeably better but the additional term scattered heavily due to the variations in oven-dry measurements and was therefore omitted.

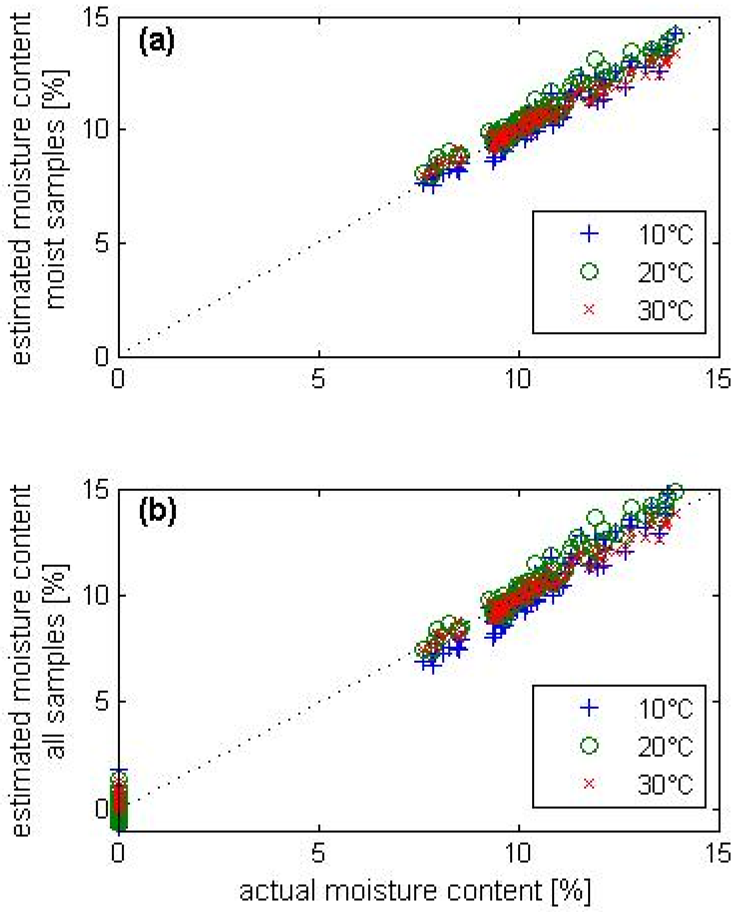

Fig. 8 Estimated vs. actual moisture content at 10 GHz: a) moist samples b) all, i.e. moist and oven-dry, samples

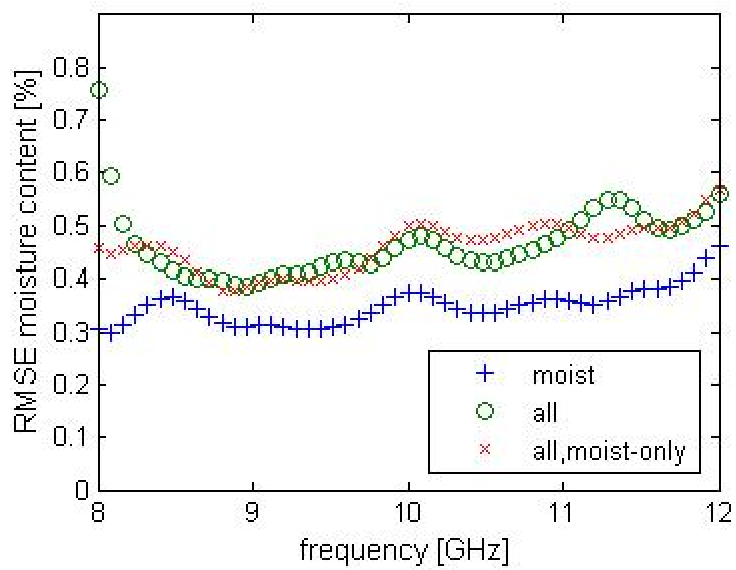

Fig. 9 RMSE for moisture content estimation at a single frequency from 8 to 12 GHz. $RMSE_{all,moist-only}$ is the estimation only for moist samples but based on the regression for all, i.e. both moist and oven-dry, samples

Moisture content (frequency sweep)

Moisture content estimation with equation (28) is based on frequency swept signals and yields superior results. Again, tested range spans from 0% (oven-dry and moist samples) or 7.6% (moist samples only), respectively, to 14%. For each frequency sweep from 8 to 12 GHz one single estimation parameter X (from equation (27)) is derived. Fig 10 shows the parameter X plotted versus the actual moisture content. For the estimation of moist samples, exclusively, a simple and robust model with only a linear term and temperature compensation is sufficient (dotted lines). With the coefficients e_2= –422.3, e_4= –0.0092, and e_1=e_3=0 this yields an RMSE of 0.32%. Fig 11a compares the estimated with actual moisture content values for moist samples. Again, this result may be extrapolated for spruce samples with moisture contents from 5% to 27%. For an entire description of all, i.e. both moist and oven-dry, samples all five coefficients of (28) are needed. The corresponding regression for all samples is plotted in Fig 10 (dashed lines). We derive regression coefficients for all samples with e_1=–3751, e_2=746.3, e_3=–5.275, e_4=–0.0105. Fig 11b shows the estimated vs. actual moisture contents. The estimation error for all samples is $RMSE_{all}$=0.39%. The estimation error only for moist samples, basing on the regression for all samples, is $RMSE_{all,moist-only}$=0.37%. Following Menke and Knöchel (1996) this method is assumed to apply not only for moisture contents up to fiber-saturation-point but even beyond. In addition, basing on frequency swept data it exhibits an intrinsic averaging effect. Phase measurement is improved by phase tracking versus frequency in contrast to estimating integral phase through a layer of wood, which is prone to phase ambiguity. Even without an applied time gating, the calculation of X in (27) compensates for notches in the frequency response (erroneous measurement at single frequencies due to multiple reflections). Moreover, such single erroneous measurements are revealed by irregularities in the devolution of the att_{dB}/ϕ-ratio over frequency and may selectively be discarded. This ability simultaneously allows for improved grain angle detection via selecting, and averaging over, only properly measured values. Thus, even without time-gating but suitable measures to weaken undesired antenna reflections (as discussed in the theory chapter), this method is expected to yield very similar results for moisture content and grain angle detection as presented in this work.

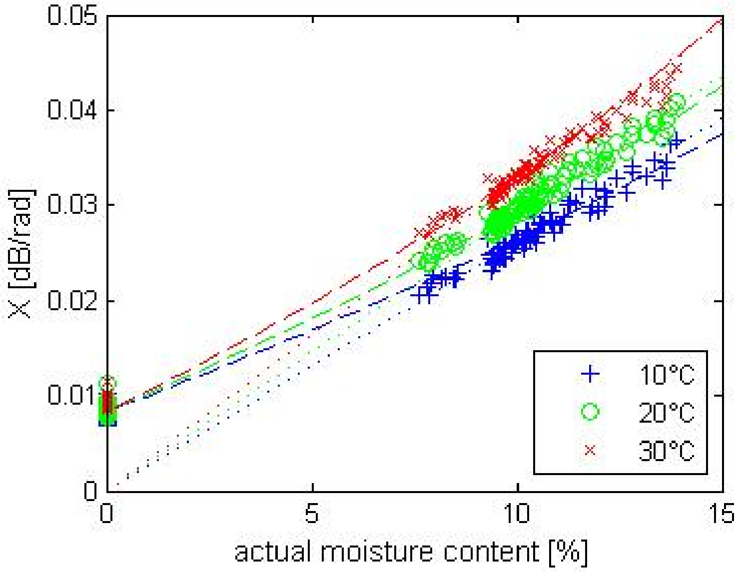

Fig. 10 Fit parameter *X* (derived from frequency swept signal) at different temperatures vs. actual moisture content. The linear regression solely for moist samples (dottet) and the more sophisticated regression for all samples (dashed) is drawn for all temperatures

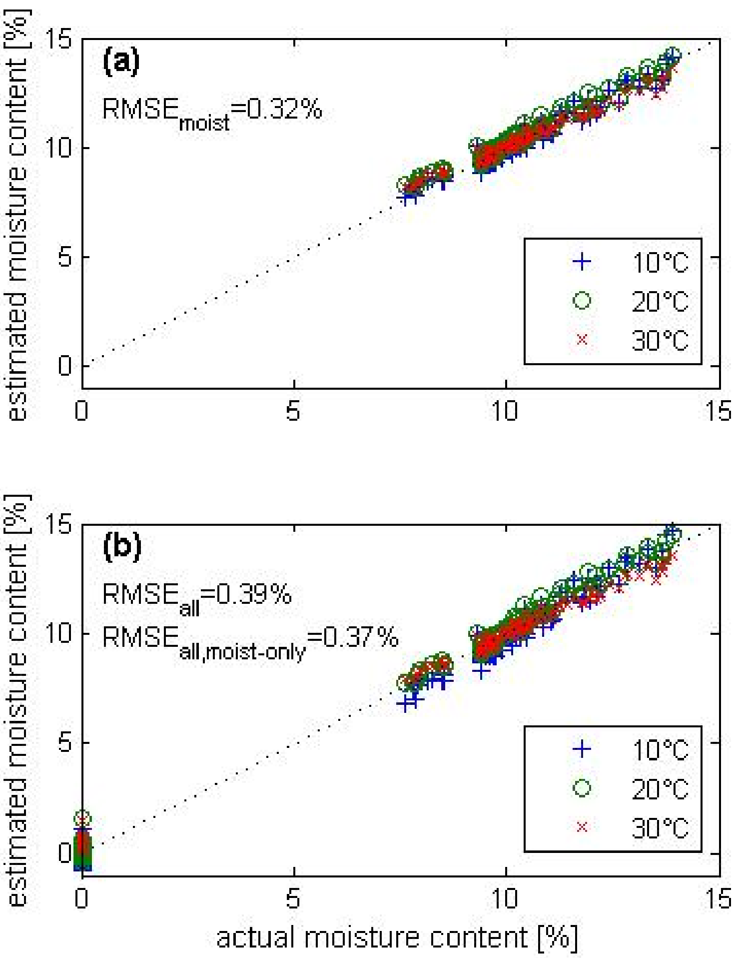

Fig. 11 Estimated vs. actual properties of moisture content of the frequency swept method. a) Linear Regression solely for moist samples. b) Non-linear Regression for all, i.e. both moist and oven-dry, samples

Moisture estimation following Zhang and Okamura (equation (29)) bases on the ratio of phase shift measurements at two different frequencies. However, this ratio features rather strong variation for similar actual moisture contents, including the oven-dry samples. Hence, a moisture content estimation basing on all samples yields an $RMSE_{all}$=1.50%. This value is derived for ϕ_1 at 8.6 GHz and ϕ_2 at 11.4 GHz, but it doesn't change significantly with other frequencies. Considering only moist samples and a linear regression, i.e. $f_1 = 0$ in (29), we derive an $RMSE_{moist}$=0.70%. In this case the use of a quadratic term in (29) for moist samples slightly improves the quality of the regression but shows strange behavior at lower moisture content. Obviously, samples with a wide spread moisture content spectrum are demanded for a robust regression. Therefore, this method is inferior to other presented procedures to evaluate moisture content. However, we report similar results compared to Zhang and Okamura, but in consideration of the additional regression parameter temperature.

Dielectric constant

Equations (30)–(32) describe the dielectric constant for spruce in respect to tested moisture density, dry density, temperature and frequency. The derived coefficients for the respective conditional equation are given in Table 1. The encountered variations in some of the attenuation measurements of oven-dry wood resulted in sporadic values very close to zero for $\varepsilon''_{\perp,oven-dry}$ and $\tan\delta_{\perp,oven-dry}$.

The fit of the dielectric constants is linear in frequency. A quadratic term didn't yield any advantage and was therefore omitted. This also justifies the application of equation (27) for the use of frequency-swept data, which implies linear dependency on frequency in the tested range. A discrete evaluation of moist and oven-dry samples, respectively, featured slightly better estimation errors but tended to model measurement uncertainties and yielded unphysical behavior (positive frequency coefficient for $\varepsilon''_{\parallel,oven-dry}$ and negative D_d coefficient for $\varepsilon''_{\parallel,moist}$ and $\varepsilon''_{\perp,moist}$). Thus, one single equation is preferably used to describe one dielectric constant for all tested samples.

Using eqns (23) and (24) dielectric constant values for moisture content of 0% and 10%, density of 300 kg/m³ and 500 kg/m³, temperature of 20 °C, and frequency of 10 GHz are derived and compared to reported values from Torgovnikov (1993) in Table 2. Small variations are expected, as wood is not homogeneous but a natural, heterogeneous material. Thus, equations (30) –(32) with the parameters from Table 1 generate a full set of dielectric constants a that is applicable for simulation and modelling of spruce in respect of moisture density (or moisture content), dry density (or density), frequency (8–12 GHz), and Temperature (10–30 °C).

spruce (MC 0 … 14%)	eq.	coeff.	coefficient index i				range of values	regression RMSE
			1	2	3	4		
$\boldsymbol{\varepsilon'_{\parallel}}$	(30)	$g_{\parallel,i}$	0.0109	0.0019	–0.0103	0.0057	1.53 … 2.75	0.0419
$\boldsymbol{\varepsilon''_{\parallel}}$	(31)	$h_{\parallel,i}$	0.0052	$9.410*10^{-5}$	–0.0152	0.0296	0.021 … 0.673	0.0262
$\boldsymbol{tg\delta_{\parallel}}$	(32)	$i_{\parallel,i}$	0.0023	$5.706*10^{-5}$	–0.0081	0.0212	0.012 … 0.263	0.0093
$\boldsymbol{\varepsilon'_{\perp}}$	(30)	$g_{\perp,i}$	0.0067	0.0013	–0.0072	0.0041	1.36 … 2.23	0.0318
$\boldsymbol{\varepsilon''_{\perp}}$	(31)	$h_{\perp,i}$	0.0023	$2.941*10^{-5}$	–0.0184	0.0288	0.000(*) … 0.282	0.0128
$\boldsymbol{tg\delta_{\perp}}$	(32)	$i_{\perp,i}$	0.0013	$2.029*10^{-5}$	–0.015	0.0236	0.000(*) … 0.133	0.0051

Table 1 The derived dielectric constants of spruce. The coefficients of the respective equations (30)–(32) for a general description. The range of values and the RMSE of the non-linear fit. (*) These values are discussed in the results chapter

T=20°C, f=10 GHz *MC* = 10%	*D* = 300 kg/m³		*D* = 500 kg/m³	
	this work	Torgov.(1993)	this work	Torgov.(1993)
$\boldsymbol{\varepsilon}'_{\parallel}$	1.80	1.86	2.34	2.32
$\boldsymbol{\varepsilon}''_{\parallel}$	0.23	0.14	0.38	0.31
$\boldsymbol{tg\delta}_{\parallel}$	0.102	0.075	0.171	0.135
$\boldsymbol{\varepsilon}'_{\perp}$	1.54	1.6	1.90	2.0
$\boldsymbol{\varepsilon}''_{\perp}$	0.090	0.08	0.15	0.18
$\boldsymbol{tg\delta}_{\perp}$	0.050	0.05	0.083	0.09
T=20°C, f=10 GHz *MC* = 0%	*D* = 300 kg/m³		*D* = 500 kg/m³	
	this work	Torgov.(1993)	this work	Torgov.(1993)
$\boldsymbol{\varepsilon}'_{\parallel}$	1.56	1.62	1.93	1.97
$\boldsymbol{\varepsilon}''_{\parallel}$	0.038	0.034	0.064	0.065
$\boldsymbol{tg\delta}_{\parallel}$	0.022	0.021	0.037	0.033
$\boldsymbol{\varepsilon}'_{\perp}$	1.39	1.4	1.65	1.7
$\boldsymbol{\varepsilon}''_{\perp}$	0.011	0.020	0.019	0.037
$\boldsymbol{tg\delta}_{\perp}$	0.008	0.014	0.013	0.022

Table 2 The dielectric constants from the regressions (30)–(32) at T=20°, f=10GHz, and moisture content 0% and 10%, respectively, compared to data reported from other authors (Torgovnikov, 1993)

Discussion

As proposed in the theory chapter, all regressions for densities and moisture content were additionally performed only with $B_{\perp}$ as predictor. All results deteriorated by about 20%. Obviously, the impact of averaging over both relative transmission coefficients $B_{\parallel}$ and $B_{\perp}$ supersedes the geometrical uncertainty of $B_{\parallel}$, at least for the tested samples in this work. Thus, for typical diving grain values (<10°) the averaging over $B_{\parallel}$ and $B_{\perp}$ turns out to be a superior predictor of the heterogeneous wood anatomy.

As already pointed out in the theory chapter, an evaluation based on *C* as predictor yielded virtually the same results. This interpretation of *C* as "effective" transmission coefficient avoids the corrections in (14) and the explicit calculation of ε_r, which simplifies the evaluation. We emphasize that this finding is only valid for the presented setup with time gating and not necessarily expandable on other setups with unconsidered or undefined reflections.

Throughout this work in all regressions with temperature an additional quadratic temperature term was tested but yielded no improvement of the regressions. Furthermore, no influence of the antenna position, i.e. orientation of the polarization plane of the incident signal, relative to the grain direction, could be detected in any of our evaluations. This emphasizes, that the method is equally suitable for all possible grain directions.

Implementation

The scope of this work was a feasibility study. Consequently, the chosen measurement setup featured laboratory style equipment. For industrial applications, this equipment is too expensive, unsuited for the targeted environment, and has a too large noise figure. While the latter isn't a problem for classical VNA measurements, it requires strong averaging if very low power levels are used, as required by EMC/emission-directives. Using a VNA therefore requires strong averaging, resulting in long measurement times.

An industrial implementation is highly specified for its very purpose and features the same accuracy as a laboratory setup. The rotating antennas of the setup in this work shall be replaced by dual-polarized antennas with electronic polarization control. Such antennas allow switching between both polarization planes within a few nanoseconds. Doing a one-time calibration of the antennas impairments and applying the calibration to measurements, the setup yields the same accuracy as mechanically rotated single polarized antennas. By further using low noise amplifiers, the noise level can be dramatically reduced, which translates into higher measurements speeds of a dedicated hardware compared to a VNA. A quantitative example for such a built-up is given in Leder (2012) where a low-cost, noise optimized setup features >100,000 single frequency measurements per second. Contemporary progress of circuitry-wise know-how and hardware even allows considerably more performance. Frequency swept measurements are reasonable with about 1,000 measurements per second. However, as the limiting factor on measurement speed, signal-to-noise-ratio (SNR), scales with transmitting power, higher magnitudes of measurements per second are achievable. While this amplified testing signal would potentially require a housing fitted with noise suppression, the amplitude would still be in the milliwatt-range. Thus, we emphasize that even an amplified testing signal constitutes no harm for men and no shielding measures, as they are mandatory for e.g. X-ray-based scanners, are needed.

More localized measurements are also possible, e.g. by application of the modulated scattering technique (Schajer and Orhan, 2005), a focused beam setup (Bogosanovic et al., 2013), or a localized antenna array (Denzler et al., 2013). However, as pointed out in Materials and Methods, the theoretical resolution of measurement is physically limited to half of the wavelength. Moreover, actual applications realistically feature resolution limits of one or one-and-a-half wavelength. Edge diffraction, especially for small timber dimensions, is a physical fact and design issue. Its deteriorating impact on measurement quality can be addressed by appropriate antenna and setup design as well as by advanced mathematical routines. This is a scope of future work.

Conclusion

A detailed discussion on free space measurement demonstrated the requirement of a dual-linear-polarized measurement setup and emphasized the need of coping with reflections in wood measurements. A prototype system meeting this demand is used to determine key physical data of moist and oven-dry spruce (*Picea abies* (L.) Karst.). Grain angle is detected with a RMSE of 0.14° (moist) and 0.4° (oven-dry) in the entire possible range from –90° to +90°. The RMSE of dry density is maximum 11.5 kg/m^3 (moist) and 12.6 kg/m^3 (oven-dry) with measured range from 284 kg/m^3 to 527 kg/m^3. Moisture density estimation features a maximum RMSE of 1.8 kg/m^3 (range 27…56 kg/m^3). Adapted regression models for density- and thickness-independent moisture content evaluation at a single frequency are proposed. They yield superior results to prior work for moist samples with a RMSE of 0.44% (measured range 7.6…14%) and allow the inclusion of oven-dry wood in the moisture estimation (RMSE=0.57%, range 0…14%). With frequency swept moisture measurements, all samples are described with one regression featuring a RMSE of 0.39% (range 0…14%). A moisture evaluation basing on phase shifts at two frequencies only yielded inferior results with RMSE of 0.7% and above. All moisture evaluations yield a very similar, frequency independent, and modest dependency on temperature. The idealized, orthotropic wood model proves applicable for microwave testing of wood.

The presented calculation procedure for transmission coefficient and grain angle exceeds previous approaches by considering the occurring reflections and taking full benefit of the matrix algebra. Furthermore, it paves way for a mathematical formulation and modelling of multiple reflections leading to implicit forms of transmission coefficients which allow a deeper evaluation and understanding and a more general discussion of Free-Space transmission measurement of wood, e.g. non-perpendicular incidence of testing signal. This will be the scope of future work.

The advantage of frequency swept measurements was discussed and demonstrated. Based on the results of Menke and Knöchel (1996), this procedure should also be applicable on moisture contents beyond the fiber-saturation point. Even without an applied time gating this method is capable to cope with the effects due to multiple reflections in the DUT. Thus, a measurement setup with several testing frequencies can provide superior moisture measurement and simultaneously improve quality of grain angle detection. Such a measurement setup is feasible with today's progress of circuit design and measurement technology. With the fast and continuous improvement and availability of the electronic hardware and antenna design, even industrial low-cost applications with time-gating are reasonable in the near future.

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