Feasibility Study of Density-Independent Moisture Measurement with Microwaves

WOLFGANG MEYER AND WOLFRAM M. SCHILZ

Abstract—**A new method of density-independent moisture determination with microwaves operating at one single frequency is developed. It is based on the two-parameter measurement of the complex dielectric constant being composed to a density-independent calibration factor $A(\psi)$ which is a function of the moisture content ψ. The principle is demonstrated for practical applications of the wool–water system, and a complete error analysis is given. The results confirm the promising prospects of the method which opens up a new class of density-independent moisture meters particularly suited for on-line process control.**

I. Introduction

AMONG the various physical effects which are related to the moisture content in materials and thus can be employed in determining the quantity of water adsorbed [1], [2], γ-rays, infrared (IR), and electromagnetic interaction effects are best suited for industrial applications because they are nondestructive. The actual competitors in this field are the IR and microwave radiation techniques both being contactless methods in principle but nevertheless exhibiting some basic differences: IR radiation is absorbed both by bound and free water molecules (e.g., at 1.94-μm wavelength), whereas microwaves are mainly sensitive to free water, thus meeting most practical demands.

Another practical limitation of the IR method is the comparatively short path length over which the radiation can pass through the material, typical paths would be of the order of a millimeter, whereas for microwave absorption in the X-band, typical paths would be $\sim$5 cm.

The principal disadvantage of low-frequency electrical methods—sensitive to ionic conductivity—does not apply to microwave absorption above 10 GHz in many organic materials, as broad-band measurements similar to [3] have proven. This experimental result is illustrated by Table I, which compares the imaginary part or dielectric loss ϵ'' of the dielectric constant

$$\epsilon = \epsilon' - j\epsilon'' \tag{1}$$

at 1 MHz and 12.5 GHz for a wide variety of different substances. The data are normalized to the same density ρ_d of the material, ρ_d being the dry density

$$\rho_d = \frac{m_d}{V} \qquad \text{(dry mass per volume)}. \tag{2}$$

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The authors are with Philips GmbH Forschungslaboratorium Hamburg, D-200 Hamburg 54, Federal Republic of Germany.

TABLE I
COMPARISON OF ϵ'' AT 1 MHz AND 12.5 GHz FOR DIFFERENT MATERIALS AT THE SAME MOISTURE ($\psi = 14$ PERCENT)
(ϵ'' normalized to the same density, i.e., the same amount of water per volume)

material	packaging density ρ_d $[\frac{g}{cm^3}]$	normalized density 0.26 $\frac{g}{cm^2}$ ϵ'' (1 MHz)	ϵ'' (12.5 GHz)
barley	0.55	0.13	0.14
millet	0.67	0.34	0.24
cereals	051	0.76	0.18
rice	0.81	0.80	0.24
clay	0.44	1.2	0.10
cellulose	0.26	1.5	0.14
tea	0.26	1.6	0.14
horn meal	0.63	2.3	0.20
fisch meal	0.55	4.9	0.14
tobacco	0.26	5.5	0.14
cotton	0.26	5.8	0.14
bone meal	0.71	8.0	0.25

That means, at the same moisture content ψ

$$\psi = \frac{m_w}{m_w + m_d} \qquad (m_w \text{ mass of water}) \tag{3}$$

the applicator (or moisture-sensing head) contains the same amount of water. As can easily be seen from Table I, the variation in ϵ'' is much more pronounced (by a factor of 60) at 1 MHz than at 12.5 GHz (factor 2.5). In other words, in the megahertz range, the loss is mainly governed by ionic conductivity, which depends strongly upon the chemical composition of the host material, whereas above 10 GHz the microwave absorption is due to free water relaxation only (plus a minor contribution from the bound water molecules), thereby rather independent of the dry material's composition within certain limitations.

Because of these advantages, microwave absorption has become an extremely competitive diagnostic technique for moisture determination [4]–[11] though, similarly to all existing methods, only the absolute water mass m_w in the test region was measured. But in practice, the relative moisture ψ (3) is the most interesting parameter, i.e., the mass of the dry material or its density has to be determined in addition. This can be done by using an additional

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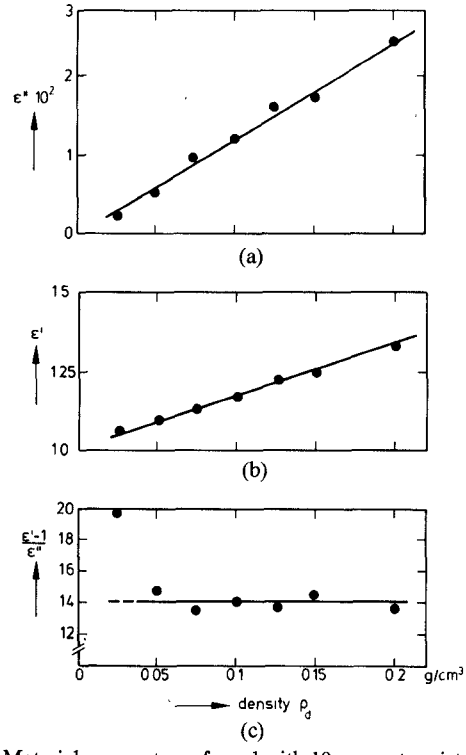

Fig. 1. Material parameters of wool with 10-percent moisture content at 18 GHz as a function of its dry density ρ_d. (a) Imaginary part of dielectric constant $\epsilon''(\rho_d)$. (b) Real part of dielectric constant $\epsilon'(\rho_d)$. (c) Function $A(\rho_d)=(\epsilon'-1)/\epsilon''$.

density meter, based on γ-rays or IR radiation, by multifrequency techniques, as suggested in [12], or by measuring two different materials' parameters at the same frequency, as intended by Kraszewski *et al.* [13], [14]. We proceed on this latter way, presenting a new method of density-independent moisture determination with microwaves, based upon the simultaneous measurement of the real and imaginary part of the dielectric constant (ϵ). This paper presents a practical application and error analysis of the proposed method for wool as the test material.

II. Principles of Measurement

The principle of density-independent moisture metering is based on the fact that both real and imaginary part of ϵ are related to the properties of the dry material and the water incorporated. As long as ϵ' and ϵ'' are linearly independent functions of ρ_d and ψ, the density variation of ϵ can be separated and ψ can be determined regardless of the material's density in a certain range. (A more detailed analysis of the basic principles and practical limitations can be found in [15].) The problem then reduces to a means to combine $\epsilon'(\rho_d, \psi)$ and $\epsilon''(\rho_d, \psi)$ in such a way that the density is canceled out.

Numerous measurements on compressible and less dense organic substances like feathers, tobacco, wool have led to the conclusion that, in the microwave region, $\epsilon'(\rho_d, \psi)-1$ and $\epsilon''(\rho_d, \psi)$ are nearly linear functions of the density over certain, sometimes great, ranges of density variation (Fig. 1). At higher densities and moisture contents, slight aberrations occur towards a polynominal description of the density dependence, e.g., in fish meal [8], which cannot be explained from first principles, because the absorption depends upon the shape of the water particles and its surrounding, the compressed host substance. Though numerous physical models of water droplet distribution have been used, a complete calculation of the density and moisture dependence of the dielectric properties of even the simplest natural products is not possible yet [4]. But in practice, the function $A(\psi)$

$$A(\psi)=\frac{\epsilon'(\psi, \rho_d)-1}{\epsilon''(\psi, \rho_d)} \tag{4}$$

is sufficiently independent of density and thereby only a function of moisture content ψ for many industrially important materials and density ranges [15]. The experimentally determined expression (4) for wool is displayed in Fig. 1(c), which proves $A(\rho_d)$ being rather constant over the density range from $\rho_d=0.05$ to 0.2 g/cm³; the large deviation at the lowest density is caused by the limited accuracy of the microwave bridge used at this low density and difficult sample preparations. The samples were oven dried at 110°C for 1 h prior to the measurements, weighed, and moistened with distilled water. The added water, and thereby the respective moisture content, was determined by additional weighing according to (1). Different lengths of *Ku*-band waveguides in the measuring arm of a microwave bridge served as sample holders. ϵ', ϵ'' were derived from the changes in the complex transmission and reflection coefficients with a relative accuracy of about 2 percent for ϵ' and 5 percent for ϵ''. By this procedure, curves like Figs.

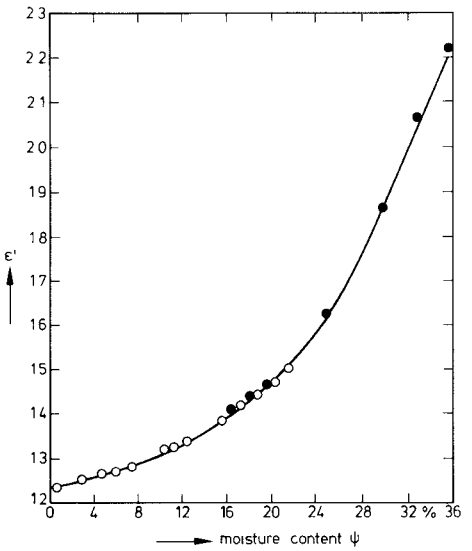

Fig. 2 Dielectric constant ϵ' of moist wool at 18 GHz; dry density $\rho_d = 0.187$ g/cm^3.

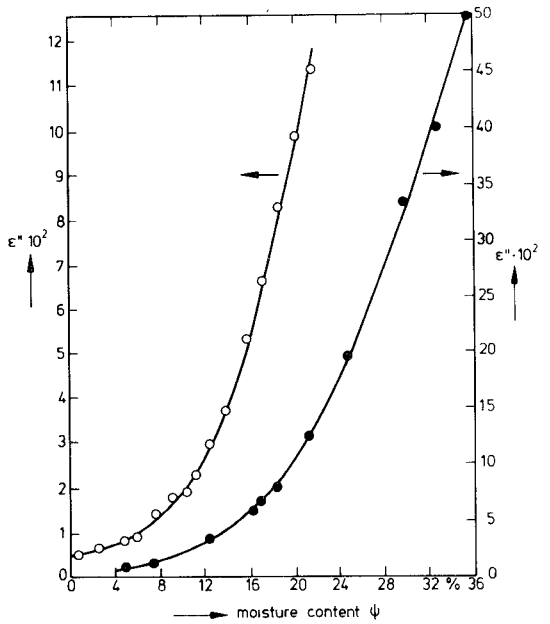

Fig. 3. Dielectric loss ϵ'' of moist wool at 18 GHz; dry density $\rho_d = 0.187$ g/cm^3.

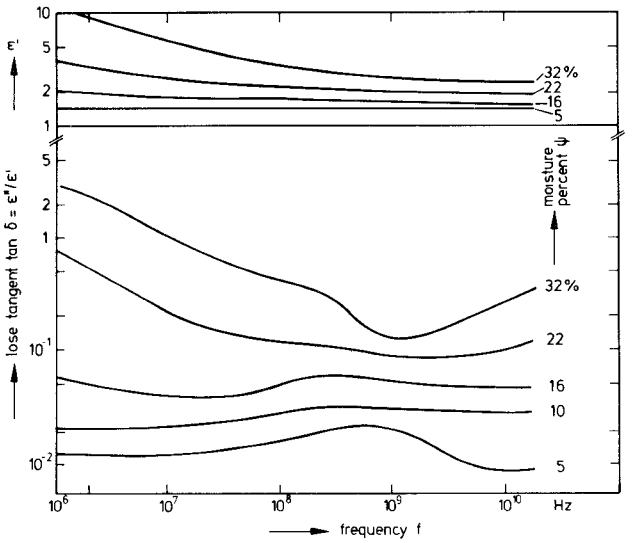

Fig. 4. Dielectric constant ϵ' and loss tangent $\tan\delta = \epsilon''/\epsilon'$ of wool ($\rho_d = 0.26$ g/cm^3) against frequency; parameter: moisture content ψ.

2 and 3 were gained at different frequencies. Once $\epsilon'(\psi)$ and $\epsilon''(\psi)$ are known at a certain density, the (mainly) density-independent parameter $A(\psi)$ is derived according to (4). $A(\psi)$ only depends upon the physical properties of the material under test; its frequency and moisture dependence is of substantial importance in designing the practical metering system.

III. Synthesis of Optimum Design

The available microwave moisture meters are not always optimized with respect to the following critical parameters: 1) operating frequency; 2) applicator type (planar, reflection, transmission); and 3) signal processing. Optimizing the system means to minimize the measuring error of the whole system or to minimize the error of each part of the system. Because the error in signal processing is not subject of this paper and, anyway, can be made as small as necessary (with sufficient manufacturing costs), we will only deal with the first two points, which are specific to the individual measuring principle, in our case the microwave method. Though applicator design and choice of operating frequency depend on each other with certain respects, we will see that all the other factors are subordinated to the operating frequency which has to be chosen according to the dielectric properties of the material under test.

A. Choice of Operating Frequency

Detailed investigations of the broad-band frequency response of the respective materials [3] deliver the fundamen-

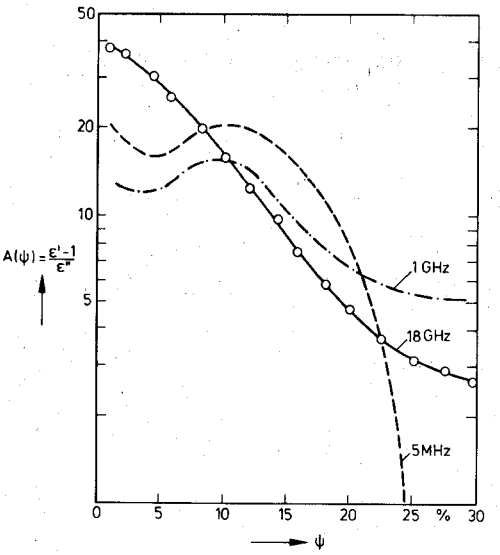

Fig. 5. The function $A(\psi)=(\epsilon'-1)/\epsilon''$ for wool at different frequencies; dry density at 5 MHz, 1 GHz: $\rho_d=0.26$ g/cm^3; at 18 GHz: $\rho_d=0.10$ g/cm^3.

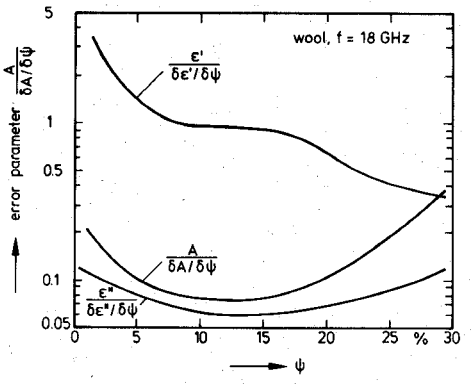

Fig. 6. Error in moisture measurement due to material's properties; physical error parameter $A/(\partial A/\partial\psi)$ for wool at 18 GHz (ϵ', ϵ'' data taken from Figs. 2, 3).

tal data for designing the instrument. New data for wool are shown in Fig. 4, which were obtained with laboratory measurement equipment described in detail elsewhere [3]: basically it consists of one sample holder suited for the whole frequency range, which is used as a coaxial condenser between 1 and 100 MHz, as a coaxial transmission line up to 10 GHz, and as a microwave resonator at the highest frequencies. The specimens were treated in the same manner as described in the preceding chapter.

By inspection of the measured curves (Fig. 4) we may arrive at the qualitative conclusion that three different effects occur in the respective frequency ranges: At low frequencies, the attenuation as well as the real part of ϵ increase strongly due to ionic conduction. Between 0.1 and 1 GHz, a more or less pronounced Debye relaxation might be visible which seems to be a common feature of cellular organic materials due to the hindered rotation of bound water molecules. Above 10 GHz, the loss mainly depends on the free water content, which is most obvious at high moisture levels ($\psi \geqslant 30$ percent) where the absorption increases with frequency, thus reflecting the free water absorption with its relaxational maximum centered around 17 GHz at room temperature [1]. But, starting with the dry material, the added water does not contribute to the three ranges in the same manner. It is thought that the first monolayers of water are attached to the host material by chemosorption whereas at higher moisture contents the water is held within the material by capillary forces [3].

But this behavior is still the topic of research [4] and goes beyond the scope of this paper. For our present purpose, it should be sufficient to note that at different frequencies the variation of $\epsilon'(\psi), \epsilon''(\psi)$ is more or less pronounced which, consequently, leads to different curves of the density-independent calibration curve $A(\psi)$. This is demonstrated in Fig. 5, which shows $A(\psi)$ for wool at three different frequencies. The underlying ϵ values were taken from Figs. 2, 3, 4. Without doubt, the 18-GHz curve is best suited for determining ψ because of the ambiguities at 1 GHz and 5 MHz for moisture contents <15 percent. This qualitative result is confirmed by a detailed error analysis.

B. Error Analysis

The absolute error $d\psi$ of the moisture measurements follows from the total differential of the measured quantity $A(\psi)$

$$dA=\frac{\partial A}{\partial \rho_d}d\rho_d+\frac{\partial A}{\partial \psi}d\psi. \tag{5}$$

Inserting $A(\psi)$ from (4) yields

$$d\psi=\left(\frac{\partial \epsilon'}{\partial \psi}\frac{1}{\epsilon'-1}-\frac{\partial \epsilon''}{\partial \psi}\frac{1}{\epsilon''}\right)^{-1}\frac{dA}{A} - \frac{\dfrac{\partial \epsilon'}{\partial \rho_d}\dfrac{1}{\epsilon'-1}-\dfrac{\partial \epsilon''}{\partial \rho_d}\dfrac{1}{\epsilon''}}{\dfrac{\partial \epsilon'}{\partial \psi}\dfrac{1}{\epsilon'-1}-\dfrac{\partial \epsilon''}{\partial \psi}\dfrac{1}{\epsilon''}}d\rho_d. \tag{6}$$

The second term of the sum gives the error in ψ due to the residual density dependency of $A(\psi)$. If ϵ' and ϵ'' behave linear with ρ_d, as shown in Fig. 1 and described by the following relations:

$$\epsilon'(\psi,\rho_d)=1+(\epsilon'(\psi)-1)\frac{\rho_d}{\rho_0} \tag{7}$$

$$\epsilon''(\psi,\rho_d)=\epsilon''(\psi)\cdot\frac{\rho_d}{\rho_0} \tag{8}$$

(ρ_0 normalizing density), this second term approaches zero. In this case, the measurement error only depends upon the relative accuracy dA/A of the complex ϵ determination, and the error parameter

$$\frac{A}{\partial A/\partial \psi}=\left(\frac{\partial \epsilon'}{\partial \psi}\frac{1}{\epsilon'-1}-\frac{\partial \epsilon''}{\partial \psi}\frac{1}{\epsilon''}\right)^{-1}. \tag{9}$$

Whereas dA/A is due to the practical design of the test assembly, preferably the applicator configuration (see next section), the error parameter defined by (9) only depends upon the dielectric properties of the test material. This parameter varies with frequency (and moisture content, of course). It should be smallest in the interesting range of moisture percentages, thus delivering the optimum operation frequency. In case of wool, this optimum is about 18 GHz; the accompanying error parameter is displayed in Fig. 6 which additionally contains the error factors governing the usual one-parameter methods

$$d\psi=\frac{\epsilon'}{\partial \epsilon'/\partial \psi}\cdot\frac{d\epsilon'}{\epsilon'} \tag{10}$$

in case of moisture determination by phase measurements, and

$$d\psi=\frac{\epsilon''}{\partial \epsilon''/\partial \psi}\cdot\frac{d\epsilon''}{\epsilon'} \tag{11}$$

in case of attenuation measurements. The underlying ϵ', ϵ'' data were taken from Figs. 2, 3. From the material's point of view, ϵ'' is much more sensitive to variations in ψ than ϵ', suggesting that attenuation techniques should be preferred. With regard to the practical test set, the opposite might be true because phase differences can be detected with highest precision. The density-independent error parameter according to (9) is a compromise, being composed of ϵ' and ϵ'' but approaching the high-sensitivity attenuation curve quite closely. Beside this, again the fact should be stressed that in contrast to our method, one-parameter measurements never allow the determination of the *relative* moisture content but only the absolute water quantity within the sensing volume.

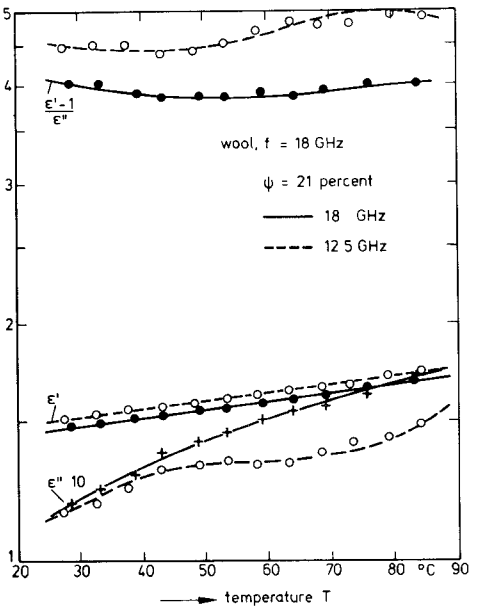

Fig. 7. $\epsilon', \epsilon'', A=(\epsilon'-1)/\epsilon''$ for wool ($\rho_d=0.187$ g/cm^3) at 12.5 and 18 GHz for varying temperatures.

C. Temperature Variations

Considering variations of the ambient temperature T which are likely to be found in industrial processes (e.g., heating and drying), an additional error shows up in the moisture-determination accuracy $d\psi$ (see (6))

$$d\psi=\frac{\partial A/\partial T}{\partial A/\partial \psi}dT$$

$$d\psi=-\frac{\dfrac{\partial \epsilon'}{\partial T}\cdot\dfrac{1}{\epsilon'-1}-\dfrac{\partial \epsilon''}{\partial T}\dfrac{1}{\epsilon''}}{\dfrac{\partial \epsilon'}{\partial \psi}\dfrac{1}{\epsilon'-1}-\dfrac{\partial \epsilon''}{\epsilon \psi}\dfrac{1}{\epsilon''}}dT. \tag{12}$$

Whereas the denominator was evaluated already ((9), Fig. 6), further experimental data in $\epsilon'(T), \epsilon''(T)$ for the specimen are necessary. Similar to the microwave properties of free water with its positive and negative temperature coefficients of ϵ depending upon frequency [1], the temperature coefficients of moist materials are different at different frequencies (Fig. 7). They also depend upon the actual moisture content in the material and the temperature considered. By these complex relations, any optimizations with respect to frequency are a compromise being valid for a certain range of temperature, moisture content, and density. For wool at room temperature, 18 GHz turned out to be an acceptable operating frequency; for these conditions

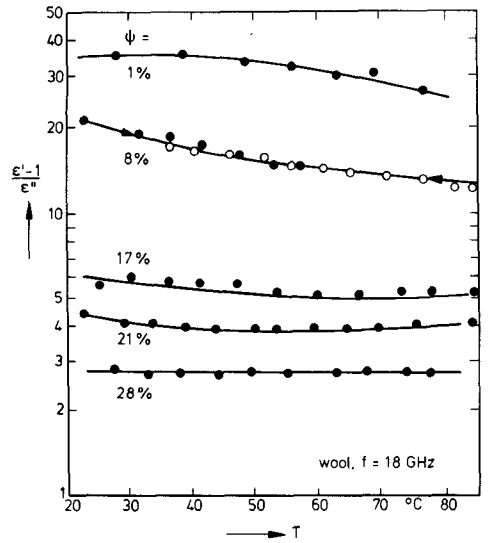

Fig. 8. Temperature dependence of $A(\psi)=[\epsilon'(\psi)-1]/\epsilon''(\psi)$ for wool at 18 GHz, different moisture contents.

TABLE II
RELATIVE ERROR DUE TO TEMPERATURE VARIATIONS IN ONE- AND TWO-PARAMETER MEASUREMENTS OF MOISTURE IN WOOL ($\rho_d=0.187$ g/cm^3)

ψ [%]	$\frac{\partial\epsilon'}{\partial T}/\epsilon'$ [grad^{-1}]	$\frac{\partial\epsilon''}{\partial T}/\epsilon''$ [grad^{-1}]	$\frac{\partial(\frac{\epsilon'-1}{\epsilon''})}{\partial T}/(\frac{\epsilon'-1}{\epsilon''})$ [grad^{-1}]	$\frac{\partial A/\partial T}{\partial A/\partial\psi}$ [%/10 grd]
1	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	< 0.1
8	$0.6\cdot10^{-3}$	$1.2\cdot10^{-2}$	$- 10^{-2}$	- 0.8
17	$1.3\cdot10^{-3}$	$2.1\cdot10^{-2}$	$- 7.6\cdot 10^{-3}$	- 0.6
21	$2.7\cdot10^{-3}$	$1.1\cdot10^{-2}$	$- 6\cdot 10^{-3}$	- 0.7
28	$3\cdot10^{-3}$	$1.2\cdot10^{-2}$	$< 10^{-3}$	< 0.1

the calibration curve $A(\psi)$ as a function of temperature is displayed in Fig. 8. From this figure, the relative temperature variation $(\partial A/\partial T)/A$ was gained and compared to the one-parameter measurement of ϵ' and ϵ'', respectively, in Table II. Additionally, the table contains the overall temperature error in $d\psi$ (12), which at room temperature is smaller than 1 percent for 10° temperature variation at any moisture content.

IV. APPLICATOR CONSIDERATIONS

The complex dielectric constant ϵ, displayed in Figs. 2 and 3, was gained from the measurements of attenuation and phase constant of the sample-filled waveguide. In this case, the waveguide section serves as the applicator which brings the electromagnetic field into contact with the test material. For industrial purposes, however, open applicators are preferable for on-line operation, e.g., plane-wave (horn) applicators. The applicator relates the dielectric constant or the function $A(\psi)$ from (4) to measurable quantities (phase shift, attenuation) via the applicator characteristic which is derived below for plane-wave applicators including the waveguide. The calculation starts with the complex propagation constant γ_ϵ of an electromagnetic wave traveling through a lossy medium with $\epsilon=\epsilon'-j\epsilon''$

$$\gamma_\epsilon \equiv \alpha_\epsilon - j\beta_\epsilon = j\sqrt{\left(\frac{\omega}{c_0}\right)^2(\epsilon'-j\epsilon'')-k_c^2}. \tag{13}$$

Therewith ϵ is derived from experimental data via the equations

$$\epsilon'' = \frac{2\alpha_\epsilon\beta_\epsilon}{\beta_0^2} \tag{14}$$

and

$$\epsilon' = \frac{\beta_\epsilon^2-\alpha_\epsilon^2+k_c^2}{\beta_0^2} \tag{15}$$

with

$$k_c = \begin{cases} \frac{\pi}{a}, & H_{10} \text{ waveguides} \\ 0, & \text{plane waves} \end{cases}$$

$$\beta_\epsilon = \sqrt{\left(\frac{\omega}{c_0}\right)^2\epsilon'+\alpha_\epsilon-k_c^2} \simeq \sqrt{\left(\frac{\omega}{c_0}\right)^2\epsilon'-k_c^2}$$

$\beta_0=\omega/c_0=$free space propagation constant, and α_ϵ, β_ϵ are the attenuation and phase constant per unit length in the sample, respectively. They are related to the attenuation L_m[dB] and phase difference Φ_m[grad] measured in a bridge arrangement, by

$$\Phi_m[\text{grad}]=(\beta_\epsilon-\beta_g)l \tag{16}$$

$$L_m[\text{dB}]=(\alpha_\epsilon-\alpha_g)l, \qquad \alpha_g\to 0 \tag{17}$$

with

$$\beta_g \cong \sqrt{\left(\frac{\omega}{c_0}\right)^2-k_c^2}$$

empty waveguide phase constant and $l=$length of sample.

With (16), (17), ϵ can be expressed by measurable quantities

$$\epsilon'-1=\frac{\Phi_m^2-L_m^2}{\beta_0^2l^2}+\frac{2\beta_g\Phi_m}{\beta_0^2l} \simeq \frac{\Phi_m^2}{\beta_0l^2}+\frac{2\beta_g\Phi_m}{\beta_0^2l}, \quad \text{for } \frac{L_m}{\Phi_m}\ll 1 \tag{18}$$

$$\epsilon''=2\frac{L_m\Phi_m}{\beta_0^2l^2}+2\cdot\frac{L_m\beta_g}{\beta_0^2l}. \tag{19}$$

By these equations, the well-known experimental observation is verified that L_m/l and Φ_m/l are independent of variations in sample length. Consequently, L_m/Φ_m is only a function of the dielectric properties (or the material's moisture content, respectively) and not of sample thickness. This is of great practical importance in continuous metering of arbitrary material layers on a conveyor belt, for instance.

Dividing (18), (19) yields the density-independent functions $A(\psi)$

$$A(\psi)=\frac{\epsilon'-1}{\epsilon''}=\frac{\Phi_m}{L_m}\frac{\beta_\epsilon+\beta_g}{2\beta_\epsilon} \tag{20}$$

which, with $k_c=0$, reduces to the simple relation for plane waves

$$\frac{\Phi_m}{L_m}=\frac{\epsilon'-1}{\epsilon''}\frac{2\sqrt{\epsilon'}}{\sqrt{\epsilon''}+1}. \tag{21}$$

Therefore, complete elimination of sample thickness *and* density dependence in moisture measurement is not possible with this type of plane-wave applicator. But, for practical applications, the remaining density dependence incorporated in $\epsilon'(\rho_d)$ and expressed by the term $2\sqrt{\epsilon'}/(\sqrt{\epsilon'}+1)$ in (21), ranging from $1(\epsilon'=1)$ to $2(\epsilon'\to\infty)$, is negligible for small $\epsilon'\simeq 1$.

For the whole range of densities displayed in Fig. 1, for instance, this term varies from 1.02 to 1.06, which means an additional relative error of 4 percent, in obtaining $A(\psi)$ by simply taking the measured phase–attenuation ratio. As Φ_m and L_m can be determined with about 3-percent accuracy in industrial test equipment, the instrumental error dA/A from (6)

$$\frac{dA}{A}=\sqrt{\left(\frac{d\Phi_m}{\Phi_m}\right)^2+\left(\frac{dL_m}{L_m}\right)^2} \tag{22}$$

amounts to less than 5 percent in general.

V. Practical Results

The formalism described above, was applied to an actual measurement of moist wool samples between two *Ku*-band (12.4–18 GHz) horn antennas, 5 cm apart. With moisture ψ and frequency f kept constant, the material's density ρ_d was varied by a factor of more than six. The measured transmission loss L_m[dB] and phase Φ_m[grad] are displayed in Fig. 9, increasing nearly linearly with density. Consequently, Φ_m/L_m is constant, within 5-percent standard deviation over the whole range of densities.

The mean value

$$\frac{\Phi_m/\text{grad}}{L_m/\text{dB}}=28.8$$

refers to a relative moisture content of $\psi=22$ percent (Fig. 10). Fig. 10 was gained by calibrating the transmission horn applicator with wool samples of known moisture content and constant density. The curve resembles the shape of the density-independent function $A(\psi)$ (see Fig. 5)

$$\frac{\Phi_m/\text{grad}}{L_m/\text{dB}}\simeq 7\cdot\frac{\epsilon'-1}{\epsilon''} \tag{23}$$

which corroborates (21) quite well.

Referring to the error analysis mentioned above, the overall error of moisture measurement in this particular case amounts to

$$d\psi=\frac{A}{\partial A/\partial\psi}\sqrt{\left(\frac{dA}{A}\right)^2+\left(\frac{\partial A/\partial T}{A}\cdot dT\right)^2}$$

$$\lesssim 1\text{-percent relative moisture content} \tag{24}$$

over the range of densities considered (0.022 to 0.176 g/cm^3).

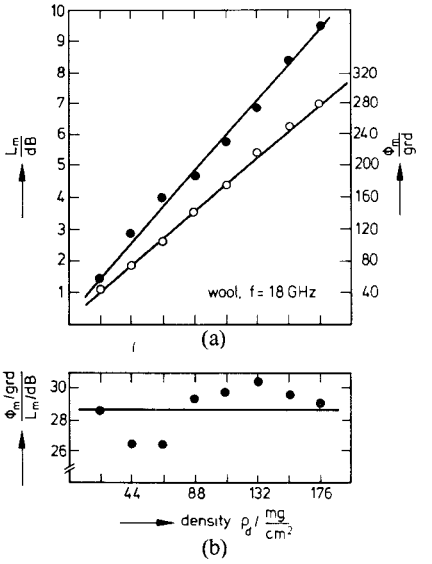

Fig. 9. (a) Measured attenuation and phase shift of horn applicator after introducing wool specimens with varying densities and moisture content $\psi\cong 22$ percent, $f=18$ GHz. (b) The function $\Phi_m/L_m\sim(\epsilon'-1)/\epsilon''$ for wool ($\psi\simeq$ 22 percent, $f=18$ GHz) with varying densities mean value: 28.75 grad/dB; standard deviation: 1.46 grad/dB.

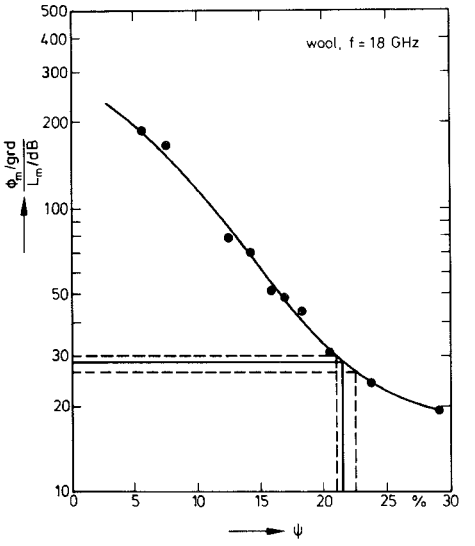

Fig. 10. Calibration of transmission horn applicator for wool at $T=25°C, f=18$ GHz.

VI. Conclusion

The feasibility of a newly developed microwave method for moisture determination in solids regardless of the material's density has been experimentally proven for the

wool–water system contained in a transmission horn applicator. Based on a detailed error analysis of frequency and temperature dependence of the relevant calibration curves, the operating frequency was optimized to 18 GHz in this particular case. For a variety of other materials being aspirants for industrial process control, similar developments are possible following the scopes outlined in this paper, thus opening the way for a new class of density-independent moisture meters [16].

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Short Papers

The Stability of Magnetrons Under Short Pulse Conditions

B. VYSE AND H. LEVINSON

Abstract—**The relationship between missing pulses, front edge jitter, and video inter-spectral noise is discussed for magnetrons operating under short pulse conditions. The measurement of missing pulse count can determine the rate of RF power growth at the start of oscillation.**

INTRODUCTION

This paper is concerned with the pulse performance of a range of small, rugged magnetrons that operate in the *X*- and *Ku*-band, and have a number of special characteristics including very small size and weight, rapid switch-on, and extreme ruggedness. They have also been designed to have very good pulse stabilities, and it is the meaning and understanding of this feature that is discussed below.

Traditionally magnetron stability has been measured by the missing pulse count; a pulse is said to be missed when the energy in that pulse is less than 70 percent of the mean pulse energy. In a practical measurement the rectified RF output pulse of the magnetron is fed into an integrator which determines the mean pulse energy over a large number of pulses. Any pulse not recording 70 percent of the mean pulse energy (whether by reduced amplitude or pulselength) is counted as a missing pulse. A number of mechanisms resulting in a missed pulse are known, e.g., electrical breakdown in the device, failure to start and moding, which is oscillation in a frequency other than the dominant one. A marine radar magnetron may have a missing pulse specification of about 1 percent, the devices here are better than 0.01 percent. Clearly a missing pulse as defined above is a fairly rare event associated with an appreciable departure from the average behavior of the magnetron.

The trend in modern systems is towards higher pulse repetition

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The authors are with the M-O Valve Company, Ltd., Brook Green Works, Hammersmith, London W6 7PE, England.

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