Density-Independent Moisture Metering in Fibrous Materials Using a Double-Cutoff Gunn Oscillator

WOLFGANG HOPPE, 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. As a first application, a double-cutoff Gunn oscillator was built, stabilized by adjacent modes of a single measuring cavity containing the moist fibrous specimen. The technique removes the need for density and sample-size corrections.

I. Introduction

The EXACT AND RAPID determination of the moisture content in solid materials, grains, sands, coal, powders, tobacco, etc., is an important task in the industrial processing of these products. This moisture content is usually defined as

$$\psi = \frac{m_{H_2O}}{m_d + m_{H_2O}} \tag{1}$$

i.e., the ratio of the mass of the water to the total mass of the product. The mass of the dry material is m_d (or density $\rho_d = m_d$ per volume) and can be measured after a well-defined drying process, which in general is different for different materials. Depending on the material, the interesting moisture content ranges from 0.1 to 50 percent.

For industrial purposes, the absorption of infrared radiation, the scattering of γ-rays, and the measurement of the dc or ac conductivity can be used for on-line measurements. In many applications, the accuracy of these methods is not sufficient and in all cases, an additional weighing is necessary to determine ψ. Furthermore, infrared systems measure only the surface layer of the material and the conductivity strongly depends on the salts dissolved in the water. In the microwave region, however, the ionic conductivity which strongly depends upon the chemical composition of the host material is decreased and, 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 [1]. This advantage, together with the well-known capabilities of microwave diagnostic techniques: being nondestructive in nature, invasive over the entire quantities or volume of the (dielectric) test material, and contactless and continuous in principle, have made microwave transmission measurements an extremely competitive tool in industrial moisture determination. But to date, the most important disadvantage of existing microwave moisture meters is the need for an additional weighing or density measurement in order to calculate the relative moisture content ψ. In this paper, we will demonstrate experimentally a method to measure the relative moisture content by pure microwave methods independent of material density. This method can be applied for many materials over a limited range of density and moisture content. It opens the way to a new class of measuring systems for rapid and continuous moisture control, removing the need for density and sample-size correction.

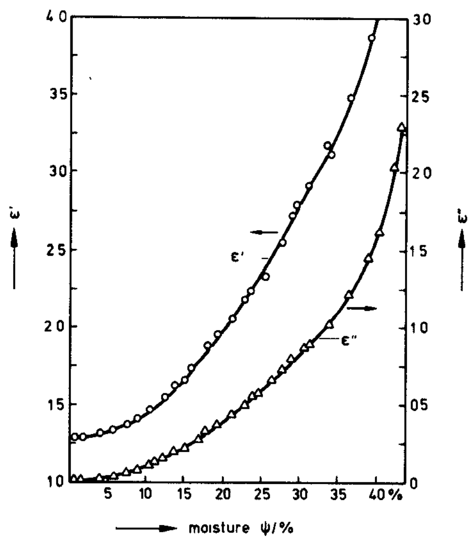

Fig. 1. Complex dielectric constant $\epsilon = \epsilon' - j\epsilon''$ of wet cotton (dry density $\rho_d = 0.24$ g/cm^3) at 12.5 GHz, measured in *Ku*-band waveguide bridge.

II. Principle of Measurement

The working principle of the microwave moisture meter is based upon the fact that, at microwave frequencies, the complex dielectric constant of water ($\epsilon = 63 - j31$ at 9 GHz) markedly differs from that of many dry substances. Consequently, the dielectric behavior of the wet material depends in a very sensitive way on the moisture content, reflected in both the real and imaginary parts of the dielectric constant $\epsilon = \epsilon' - j\epsilon''$, which is shown for cotton as an example in Fig. 1.

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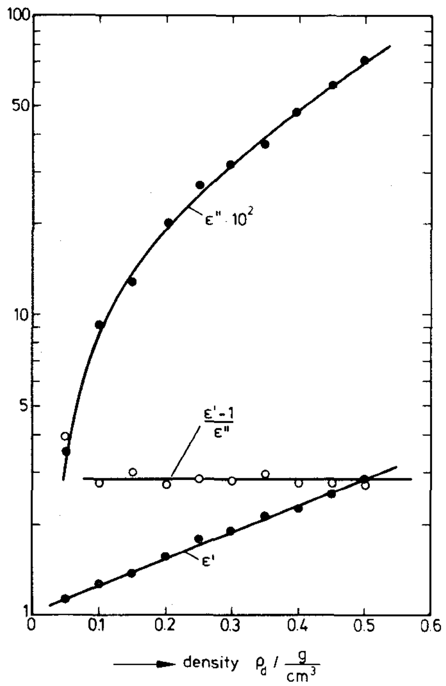

Fig. 2. Dielectric constant $\epsilon=\epsilon'-j\epsilon''$ and calibration parameter $A=(\epsilon'-1)/\epsilon''$ as a function of the dry density $\rho_d(\mathrm{g/cm^3})$ for cotton. $\psi=15$ percent, $f=12.5$ GHz.

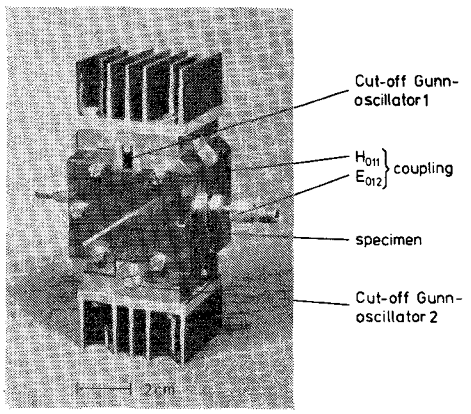

Fig. 3. Photograph of microwave moisture meter for fibrous materials (microwave part).

ϵ as a function of moisture content ψ and the material's density ρ_d cannot be derived from first principles except for very simple model substances and small moisture percentages [2] though numerous mixture formulas exist for heterogenous materials, e.g., [3]: the theoretical treatment of the interaction between the microwave and the material is complicated and possibly no closed-form solution can be found. Therefore, numerous measurements on less dense and compressible organic substances like feathers, tobacco, wool have been performed at different moisture levels which lead 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 [4]. At higher densities and moisture contents, slight aberrations occur towards a polynominal description of the density dependence, e.g., in fish meal [5] which could not be explained theoretically until now, because the absorption depends upon the shape of the water particles and its surrounding, the compressed host substance. But, in practice, the function $A(\psi)$

$$A(\psi)=\frac{\epsilon'(\psi,\rho_d)-1}{\epsilon''(\psi,\rho_d)} \tag{2}$$

is sufficiently independent of density and thereby only a function of moisture content ψ for many industrially important materials and density ranges. The experimentally determined density dependence of the dielectric constant as well as $A(\psi)$ for cotton is displayed in Fig. 2 which proves $A(\psi)$ being constant over a density range from 0.1 to 0.5 $\mathrm{g/cm^3}$; the larger 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 an 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''. Once $\epsilon'(\psi)$, $\epsilon''(\psi)$ are known at a certain density, the (mainly) density-independent parameter $A(\psi)$ is gained according to (2). Therefore, by measuring ϵ' and ϵ'' or adequate quantities of the wet sample and calibrating the instrument in terms of $A(\psi)$, the *relative* moisture ψ can be determined below certain moisture levels.

III. Practical Arrangement

The measurement of $A(\psi)$ is particularly simple for the case of small specimens (e.g., fibers). According to perturbation theory [6] the complex dielectric constant of the specimen is related to the change of quality factor (Q) and frequency (f) by

$$A(\psi)\equiv\frac{\epsilon'-1}{\epsilon''}=2\frac{(f_2-f_1)/f_2}{(1/Q_1-1/Q_2)} \tag{3}$$

where the indices 1 and 2 refer to the empty and the partially filled cavity.

Cavity-perturbation techniques have been used previously in determining the dielectric properties of materials [7], also of yarns and textiles [8], but merely on a laboratory scale and not with respect to moisture measurements. Our system, designed for industrial application (Fig. 3), is a double Gunn oscillator in cutoff technique. It consists of two Gunn diodes each placed in a waveguide below cutoff. The rectangular waveguides behave like a pure inductance below cutoff, thus forming a nonresonant embedding for the active device in contrast to regular Gunn oscillators which are coupled to the stabilizing cavity via coupling lines with all their resonance problems. The cutoff technique avoids these difficulties thus leading to very-broad-band devices as has been shown in the literature [9].

The actual oscillator frequencies are determined by the eigenfrequencies of two adjacent modes of one cylindrical

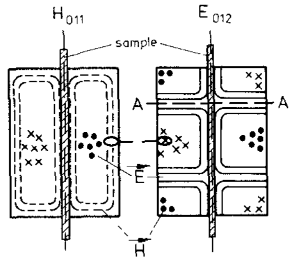

Fig. 4. Eigenmodes of cylindrical stabilizing cavity.

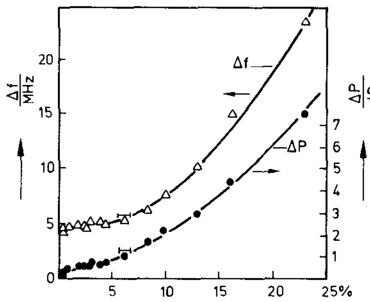

Fig. 5. Variation of differential frequency Δf and output power ΔP of double Gunn oscillator, after inserting cotton threads with differing moisture contents ψ.

cavity, the H_{011} and E_{012} mode (Fig. 4). The frequencies are centered around 11.5 GHz. The mode configurations are chosen such that at the place of the specimen, i.e., at the center axis of the resonator, the electric field of the E_{012} mode has its maximum whereas the E field of the H_{011} mode vanishes. Because the sample interacts only with the respective E field, the E_{012} oscillation is shifted in frequency whereas the H_{011} resonance remains constant when inserting the specimen. The latter acts as the LO (local oscillator) at one port of a balanced mixer; at the mixer's output the E_{012} power P and the difference frequency Δf are measured. The frequency difference of the two eigenmodes of the empty cavity is nearly temperature independent because the temperature drift of the cavity changes both frequencies simultaneously.

IV. Experimental Results

As the cutoff oscillator is a very-broad-band device [9], its output power remains constant within ± 0.1 dB over a 50-MHz bandwidth when passively detuning the cavity by inserting a lossless dielectric. This is of fundamental importance because, as a consequence, the output power P is a monotonic function of the dielectric loss ϵ'' of the specimen and its water content (Fig. 5). As the frequency shift Δf is an unambiguous function of $\epsilon' - 1$ or the water content ψ (Fig. 5), we arrive at a density-independent measure similar to (2) by simply taking $\Delta f/\Delta P$ as a function of ψ. A comparison of values for $(\epsilon' - 1)/\epsilon''$ gained from frequency and quality measurements according to (3), and $\Delta f/\Delta P$ measured in the double Gunn oscillator described above are plotted in Fig. 6 and exhibit nearly the same shape. As expected, both curves turn out to be independent of density of the carrier substance over

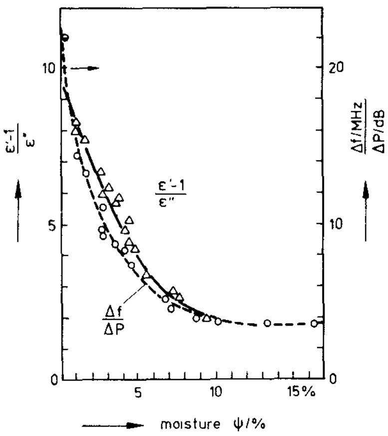

Fig. 6. Measured $A(\psi) = [\epsilon'(\psi) - 1]/\epsilon''(\psi)$ for cotton threads, as a function of moisture content, determined by a) passive resonator method according to (3) (triangles), and b) active double Gunn oscillator, $\Delta f/\Delta P$.

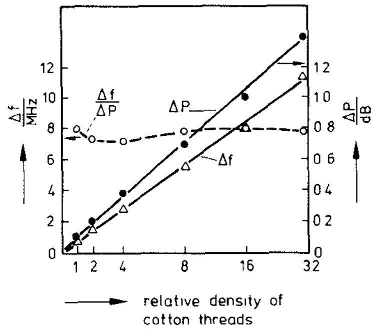

Fig. 7. Differential frequency Δf and output power ΔP after insertion of different numbers of cotton thread of equal moisture content ($\psi \simeq 4.5$ percent) into the stabilizing oscillator cavity.

a fairly wide range: Fig. 7 shows the variation of the frequency shift and the output power of the double Gunn oscillator when the density of the cotton threads in the cavity is changed by a factor of 32. The result for $\Delta f/\Delta P$ is substantially constant at 7.5 ± 0.2 MHz/dB which equals a moisture content within the cotton of $\psi = 4.5$ percent with an experimentally determined error of $\Delta = \pm 0.1$ percent over the whole density range.

V. Conclusion

A new principle of density-independent moisture determination has been worked out, based upon a two-parameter microwave measurement at fixed frequency. As a first application, a double-cutoff Gunn oscillator for measuring fibrous materials has been developed. Its feasibility for cotton threads has been proven; further applications are possible [10], [11]. The method for the first time brings about relative moisture measurement using microwaves at one frequency, without need for density and sample-size corrections.

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Electromagnetic-Energy Deposition in an Inhomogeneous Block Model of Man for Near-Field Irradiation Conditions

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Abstract—**The plane-wave spectrum approach is used to calculate the electromagnetic-energy deposition and its distribution in a 180-cell, inhomogeneous block model of man for a prescribed two-dimensional leakage electric field generated by RF sealers and other electronic equipment. The whole-body-averaged energy dose increases approximately as $(\Delta_1^2\Delta_2^2/\lambda^4)$ to the asymptotic plane-wave value, where Δ_1/λ and Δ_2/λ are the vertical and horizontal widths (in wavelengths) of the best fit half-cycle cosine functions to the prescribed leakage fields. The effect of phase variations shows that the worst case (maximum deposition) is always obtained for constant phase in the prescribed fields. The need for exact phase measurements is, therefore, obviated since the upper bound on the deposited energy is often the desired quantity.**

INTRODUCTION

A GREAT DEAL of progress has been made in the quantification of electromagnetic absorption by humans under plane-wave irradiation conditions [1], [2]. However, to date, little work has been done with near-field exposure conditions which are of greater concern to workers involved in the operation of equipment using electromagnetic energy for communication, radar, and industrial and biomedical applications. Electromagnetic fields near several pieces of high-power industrial equipment have been measured and found to be fairly intense, with electric fields as high as 500–2000 V/m for 27.12-MHz RF sealers [3], [4], the fields being measured typically within 1 m of the RF source.

In many near-field problems, the sources are loosely coupled to the human operator, so that the incident field is not altered by the presence of the operator. Such a class of problems has been considered in this paper. Important examples are the leakage fields from RF sealers as well as broadcast and television equipment.

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PROCEDURE FOR DETERMINING ENERGY-DENSITY DEPOSITION

The 180-cell inhomogeneous block model of man [5] and the coordinate system used in the calculations are illustrated in Fig. 1. Anatomical drawings [6], [7] were used to determine the contents of each cell based on twelve tissue types. The volume-weighted complex permittivity of each cell was calculated using measured values for the various tissue types [8]–[11]. The height of the model is 1.75 m.

The computations require values of the calculated or measured leakage electric fields tangent to a plane (Y–Z plane in Fig. 1) just in front of the intended location of the block model target. The prescribed incident electric-

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