ACTA UNIVERSITATIS AGRICULTURAE ET SILVICULTURAE MENDELIANAE BRUNENSIS
SBORNÍK MENDELOVY ZEMĚDĚLSKÉ A LESNICKÉ UNIVERZITY V BRNĚ

Volume LVI 17 Number 5, 2008

DIELECTRIC PROPERTIES OF MATERIALS AT MICROWAVE FREQUENCIES

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Received: August 19, 2008

Abstract

KŘIVÁNEK, I.: *Dielectric properties of materials at microwave frequencies.* Acta univ. agric. et silvic. Mendel. Brun., 2008, LVI, No. 5, pp. 125–132

The paper introduces the review of the present state of art in the measurement of the interaction of electromagnetic waves with different kinds of materials. It is analysis of the possibilities of the measurement of the interaction of high frequencies waves (microwaves) with materials and proposal of the experimental method for the studies mentioned above.
The electromagnetic field consists of two components: electric and magnetic field. The influence of these components on materials is different. The influence of the magnetic field is negligible and it has no impact on practical use. The influence of the electric field is strong as the interaction between them results in the creation of electric currents in the material (Křivánek and Buchar, 1993).
Experiments focused on the evaluation of the complex dielectric permitivity of different materials have been performed. The permitivity of solid material is also measurable by phasemethod, when the specimen is a part of transmission sub-circuit. Microwave instrument for complex permittivity measurement works in X frequency band (8.2–12.5) GHz, the frequency 10.1 GHz was used for all the measurement in the laboratory of physics, Mendel University in Brno. The extensive number of experimental data have been obtained for different materials. The length of the square side of the aerial open end was 50 mm and internal dimensions of waveguides were 23 mm × 10 mm. The samples have form of the plate shape with dimensions 150 mm × 150 mm × 4 mm.

dielectric permitivity, microwaves, phasemethod, waveguides

The theory is mainly focused on the microwave transmission and reflection. High-frequency electromagnetic field analysis simulates the electromagnetic phenomena in a structure using the wavelength of the signal of the same order of magnitude or smaller than the dimensions of the model (Ohlson et al., 1997). It typically examines power flow by means of electromagnetic waves, power loss due to electric loss tangent, wave scattering properties (transmission, reflection and diffraction), and frequency dependent parameters (S-parameters) that are typically measured (Risman, 1991). The underlying problems are defined as the high-frequency/full-wave electromagnetic field problem. The high-frequency band ranges from hundreds of MHz to hundreds of GHz. Typical applications include microwave passive components, antenna radiating structures, radar cross section (RCS) of an aircraft, and electromagnetic compatibility assessment of electronic components and products. Analytical expressions describing the fields exist only within simple geometries. As soon as complicated structures containing lossy material properties are encountered, equations become difficult or impossible to be solved analytically (Ackmann and Seitz, 1984). In these cases numerical modeling provides valuable information on such parameters as the electric and magnetic fields, and the power absorbed by the structure (Tinga et al., 1973).

Description of the dielectric properties

The interaction of the electromagnetic waves with material involves phenomena such as induced electronic, atomic, and space charge polarizations. The extent of this interaction depends on the extent of the wave reflection or transmission, respectively. The transmission and reflections are governed by Maxwell equations:

$$\nabla x\vec{E} = i\omega\mu^*\vec{H}$$

$$\nabla(\varepsilon^*\vec{E}) = 0$$
$$\nabla x\vec{H} = i\omega\varepsilon^*\vec{E}$$
$$\nabla.\vec{H} = 0,$$

where **E** and **H** are time – varying electric and magnetic field vectors, and μ* and ε* are the permeability and permitivity of the medium, respectively. With the exception of the ferromagnetic materials the microwave interaction is governed by the frequency (ω) dependent complex permitivity

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega),$$

where the real and imaginary parts are described by the Kramers – Kronig relations:

$$\varepsilon'(\omega) = \varepsilon_\infty + \frac{2}{\pi}\int_0^\infty \frac{\varepsilon''(\omega')\omega'}{\omega'^2 - \omega^2} d\omega,$$

$$\varepsilon''(\omega) = \varepsilon_\infty + \frac{2}{\pi}\int_0^\infty \frac{[\varepsilon''(\omega') - \varepsilon_\infty]\omega}{\omega'^2 - \omega^2} d\omega,$$

where ε_∞ is permitivity at infinite frequency. In the complex plane, the imaginary terms correlate with polarization and energy loss, respectively. The dielectric loss factor or dissipation factor is defined as

$$\mathrm{tg}\,\delta = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)}.$$

This represents the fractional power loss as compared to power stored. The average power per unit volume consumed by loss mechanisms can be calculated as

$$P = \frac{1}{2\omega\varepsilon''}|E_0|^2,$$

where E_0 = varying electric field in vacuum.

The attenuation of a microwave beam directed along the ***x*** axis by an absorbing material is described by

$$P(x) = P_0\exp(-2\alpha x),$$

where the attenuation coefficient is a function of the angular frequency, complex permitivity, and complex permeability and P_0 = attenuation of a microwave beam before an absorbing material

$$\alpha = \omega\sqrt{\sqrt{\varepsilon'^2 + \varepsilon''^2}\sqrt{\mu'^2 + \mu''^2}}\, x\sin\left[\frac{arctg\left(\frac{\varepsilon''}{\varepsilon'}\right) + arctg\left(\frac{\mu''}{\mu'}\right)}{2}\right].$$

In order to find the frequency dependence of the permitivity some mechanisms of the polarization must be specified. In the given paper we limit our consideration to the microwave propagation. Polarization – relaxation phenomena have been described (Debay, 1929) as

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (\tau\omega)^2} - i\,\frac{\varepsilon_s - \varepsilon_\infty}{1 + (\tau\omega)^2}\,\tau\omega,$$

where ε_s is the static (zero frequency) permitivity, ε_∞ is the permitivity at the very high frequency limit, and τ represents the polarization relaxation time, which is the inverse of the frequency of maximum dielectric loss (Debay, 1929; Davidson and Cole, 1951; Jonscher, 1999; Ohgushi, 2001). The real and imaginary components of the complex permitivity are then described as:

$$\varepsilon'(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (\tau\omega)^2}$$

$$\varepsilon''(\omega) = \frac{\varepsilon_s - \varepsilon_\infty}{1 + (\tau\omega)^2}\,\tau\omega.$$

In the slightly more complex Cole – Cole model (Debay, 1929; Cole and Cole, 1941) the ***i*ωτ** is raised to the power of β, where β ≤ **1**. Here the polarization and dielectric loss terms can be described as

$$\varepsilon'(\omega) = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{2}\left[1 - \frac{\sinh(\beta\ln\omega\tau)}{\cosh(\beta\ln\omega\tau) + \cos\left(\frac{\beta\pi}{2}\right)}\right]$$

$$\varepsilon''(\omega) = \frac{(\varepsilon_s - \varepsilon_\infty)}{2}\left[1 - \frac{\sin\left(\frac{\beta\pi}{2}\right)}{\cosh(\beta\ln\omega\tau) + \cos\left(\frac{\beta\pi}{2}\right)}\right]$$

From these relations, it follows that a plot of ε′ versus ε″ in the complex plane, termed as a Cole – Cole plot, will form a semi – circle centered at

$$\varepsilon'(\omega) = \frac{\varepsilon\alpha + \varepsilon_\infty}{2},$$

in which β is the central angle of circular arc for the dielectric loss. There may be a difference between the experimental and theoretical data at lower frequencies. This discrepancy can be reduced by the consideration of the electrical conductivity σ

$$\varepsilon''(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau} - \frac{i\sigma}{\omega}.$$

The next meaning parameter is the penetration depth, $\boldsymbol{D_p}$, of the microwaves, the distance, where the microwave power decreased to ***1/e*** of its surface value, is very important parameter in characterizing microwave heating. Penetration depth for the material can be calculated as follows (Metaxas and Meretith,1983):

$$Dp = \frac{\lambda}{2\pi\sqrt{\varepsilon'}}\left[\sqrt{\left\{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right\}} - 1\right]^{-\frac{1}{2}}.$$

In this paper, a measuring procedure of the dielectric constant of materials at microwave frequencies suitable for high temperatures and high pressure is described (Ohlson at al., 1974). The method is based on measuring the impedance change caused by the presence of the tested material within a rectangular waveguide. To extract the value of the dielectric permittivity from this measurement, a transcendental equation in the complex plane has to be solved. As in many other cases there is no analytical solution (Risman et al., 1987).

Therefore, a numerical procedure should be applied for the intrinsic complex propagation factor of the dielectric material γ_ε as it depends on the relative complex permittivity ε_r^* of the material (Von Hippel, 1954).

Using conversion of the wave length to the frequency and of the wavelength difference in the dielectric and in the free space to the propositional phase shift $\Delta\varphi$, the following formula can be used

$$\Delta\varphi = K.d.f(\sqrt{\varepsilon'_r} - 1).$$

ε'_r = real component of relative permittivity
$\Delta\varphi$ = phase difference at the output of measuring and reference channels
f = frequency of generator (GHz)
d = thickness of the dieletric sample (m)
K = device constant.

By appropriate modification of the formula the real component of the relative permittivity of the dielectric can be calculated if the phase difference of the dielectric was measured (De Loor, 1968).

The final formulae used for the material properties calculations from the measured data are:

$$\varepsilon'_r = \left(1 + \frac{\lambda.\Delta\varphi}{360.d}\right)^2.$$

$$\mathrm{tg}\delta = \sqrt{\left[\frac{1}{2\varepsilon'_r}\left(\frac{\lambda.b_d}{8.868}\right)^2 - 1\right]}.$$

b_d = damping (dB.m^{-1})
λ = wave length in vacuum.

Description of the experimental methods

The dielectric properties of different materials in microwave region are determinable by several methods. The methods use different microwave measuring sensors (Kraszewski, 1980). The methods of measuring of these properties vary, except other, in individual frequence ranges. Nyfors and Vainikainen (1989) describe four groups of the measuring methods: condensator capacity detection by use of the resonance circuit, the cavity method, the phase method and the method of wave lenght determination in the clear space.

The capacity method uses the specimen as a part of circuit dielectric. This method is usable only for frequencies not exceeding 100 MHz. All kinds of materials are measurable, except gas, but the method is not suitable for low-loss materials.

Determination of permitivity by means of cavity method employes microwave resonator which is partly or fully filled by tested material. Partly filled resonator (the perturbation method) is often calibrated by use of the specimen with defined ε′ i ε″. The range of measuring frequencies ranges between 50 MHz and more than 100 MHz. The permitivity of material is also measurable by phase method, when the specimen is a part of transmission sub-circuit. Such way enables measuring of all liquid and solid materials. The low permitivity of gases prevents their permitivity measuring by this method. There are some problems with the specimen preparation and measurement accuracy is not as satisfactory as for cavity methods. The range of measuring frequencies for the phase methods with coaxial cable is wide, specifically from VHF (30–300) MHz to almost 20 GHz (Risman et al., 1971).

Measuring over 20 GHz is performable only by one configuration – with partly filled microwave or dielectric waveguides. This way we can reach in the 100 GHz region.

When using the frequencies over 3 GHz, it is possible to measure the influence of material on the wave propagation in the clear space from one antenna to another. The measuring is similar to the phase method. The measured materials must be of loss type and the specimen must be big enough. The maximum frequency can exceed 100 GHz (Nyfors and Vainikainen, 1989).

One of the most frequent methods employes the microwave resonators. If the specimen has always the same shape and volume, the difference in the resonance frequency is directly converted to permitivity. The loss factor can be determined according to the change of ***Q*** factor of the resonator. These methods can be very accurate and they are sensitive even for low-loss dielectrics (Kent and Kress – Rogers, 1987; Hewlet-Packard, 1992).

The systems with resonance cell limit the measuring to one frequence only. But on the other hand, the ISM regulations limit the frequency choise anyway. Each resonator must be calibrated, but once the calibration curve exists, the calculation is very quick. The sample preparation is relatively easy and during a short time many experiments can be performed. This method is easily convertable for either high (up to 140 °C) temperatures or low (–20 °C) temperatures (Ohlsson and Brengtsson, 1975).

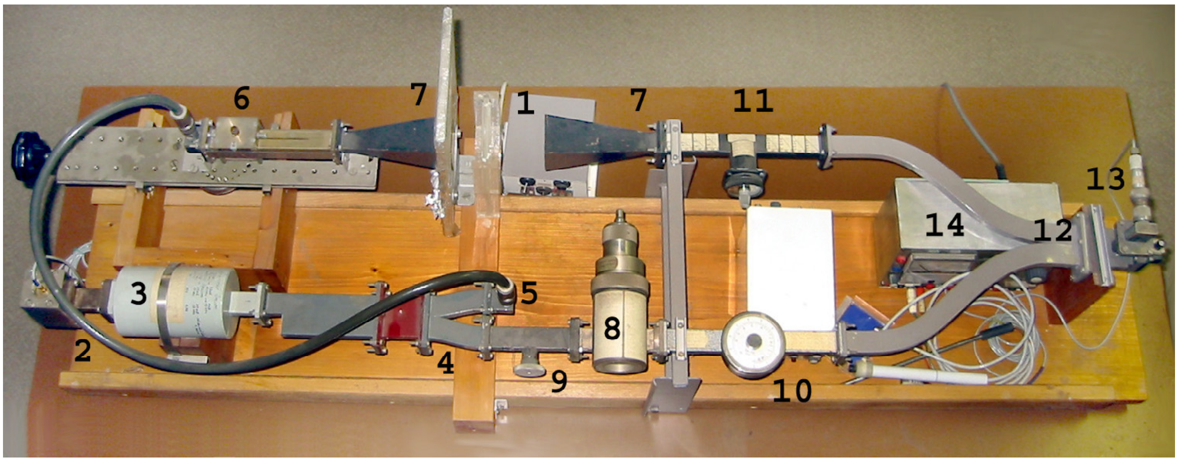
Except resonator methods, there are two more popular procedures – the method with the probe with open waveguide ending and the phase method. The probe method has coaxial sub-circuit with a special tip. The tip is placed close to the measured material by means of contact of the probe with flat front of the solid material or by its dipping into liquid. The reflected signal is related to dielectric properties of material. The whole method is very easy and the measuring range is relatively wide (500 MHz–110 GHz), but the accuracy is unfortunately limited particularly when measuring low values of ε′ and ε″ (Engelder and Buffler, 1991; Hewlet-Packard, 1992).

The phase methods use following system. The specimen is placed into one of two closed sub-circuits. The signal loss and phase difference are measured. Although this method is more accurate and more sensitive in comparison with probe method, it has smaller frequency range. The specimen preparation is rather time demanding. The reason for this demand factor is that material must fill the whole cross section of the sub-circuit (in the coaxial or rectangle way) (Engelder and Buffler, 1991; Hewlet-Packard, 1992).

The methods of time spectroscopy (or reflectometry) were extensively developed in 80th of the last century. They cover the frequency range from 10 MHz to 10 GHz. The measuring is fast and the accuracy is high with the error of several per cents. The specimen measured is very small and measured material must be homogenous. These methods are still rather expensive (Mashimo et al., 1987).

MATERIALS AND METHODS

Microwave instrument for complex permittivity measurement with using the phase method is presented in Fig.1. Method has been realized by the firm OMNI-BIO in the laboratory of physics, Mendel University in Brno. It works in X frequency (8.2–12.5) GHz.



1: *Photography of the microwave instrument*

1 – source of DC voltage
2 – microwave generator
3 – ferrite isolator
4 – wave power divider
5 – transition of waveguide-coaxial line
6 – stationary waves ratio meter
7 – horn antennas
8 – wavemeter
9 – variable damping (0–10) dB.cm^{-1}
10 – variable damping (0–30) dB.cm^{-1}
11 – phase shifter 0°–180°
12 – waveguide bridge – „magic T“
13 – detector diode
14 – millivoltmeter

RESULTS AND DISCUSSION

In dielectric materials currents are shifted relative to electric intensity **E**. This phenomenon can be characterized by the complex description of permittivity (specific dielectric conductivity):

$$\varepsilon^* = \varepsilon' - i\varepsilon''$$

ε′ = real component of the complex permittivity
ε″ = imaginary component of the complex permittivity (phase shifted by 90°).

The complex permittivity ε* specifies not only the intensity of dielectric currents in a dielectric but also their phase shift relative to the intensity of the electric current which produced those currents (Ragheb, 1991). DC conductivity σ and complex permittivity components ε′ and ε″ characterize the material of a dielectric properties and its structure. They depend on the frequency, intensity of electric field, and on temperature. Dielectric materials (their dielectric properties) can be simply compared by means of the relative permittivity ε_r, which is defined as

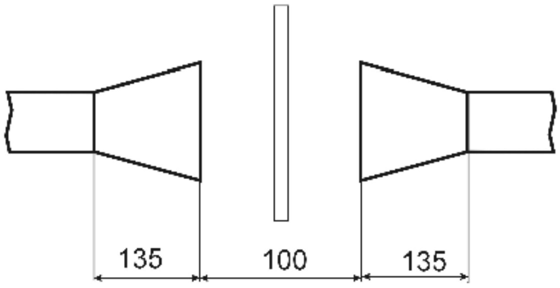
$$\varepsilon'_r = \frac{\varepsilon'}{\varepsilon_o} \quad \text{and} \quad \varepsilon''_r = \frac{\varepsilon''}{\varepsilon_o},$$

where ε_o is the permittivity of vacuum (Engler, 1991).

The real component of the relative permittivity (ε_r') specifies, how many times the permittivity of described material is higher than relative permittivity of vacuum (ε_r' = 1 of vacuum). The real component of the relative permittivity and the high frequency specific conductivity can be determined by experimental measurements of the damping and the phase shift. When a signal goes through a measuring branch with an inserted sample, the amplitude of the signal is decreasing (the signal is partially damped). Therefore, a variable damping must be set in a reference branch, which decreases the amplitude of the signal to the same level as in the measuring branch. In this way the value of signal damping can be determined in the sample.

After dividing microwave energy from the generator into two identical waveguide channels (the measuring channel and the reference one) and putting the dielectric to be measured into the measuring channel, the phase of the electromagnetic wave at the output of those two channels will be different (Máchal et al., 1997). The difference is varied when the relative permittivity ε_r' of the measured dielectric is changed. The difference depends also on the thickness l of the dielectric and on the ration l/λ.

The frequency 10.1 GHz was used for the measurement. Internal dimensions of waveguides were 23 mm × 10 mm. Samples were positioned in the center between emitting and receiving antennas whose mutual distance was 100 mm (Fig. 2). The length of the square side of the antenna open end was 50 mm. Measurements were carried out for several samples summarized in Tab.I. The samples have form of the plate shape with dimensions 150 mm × 150 mm × 4 mm.



2: *Detail of samples positioned between emitting and receiving antennas*

I: *Phase shift and damping of the microwave energy after passing through the dieletric material and calculated real component of relative permittivity* ε_r' *and loss factor* tgδ.

Material	Δφ [deg]	ε_r'	b_d [dB.m^{-1}]	**tg** δ.10^{-3}
Bakelite resin	36.2	3.05	738	43.5
Balsa	5.10	1.22	466	8.40
Natural rubber	27.9	2.48	664	4.60
Hardened rubber	36.9	3.10	743	18.2
Silicon rubber	63.2	5.30	972	81.2
Organic glass	29.4	2.58	678	6.50
Glass	58.5	4.87	931	6.90
Pertinax	63.2	5.30	976	83.2
Polystyrene	28.9	2.55	674	0.450
Polystyrene foam	0.48	1.02	426	0.140
Polyvinylchlorid	32.8	2.81	708	19.6
Plywood	14.6	1.69	549	24.7

CONCLUSIONS

In this paper a review of dielectric properties of materials at high frequencies corresponding to the microwaves is presented. The present knowledge enables to propose a proper experimental methods for the study of the interaction of the microwaves with different materials. The corresponding method has been suggested and realized. The extensive number of experimental data have been obtained for different materials (Máchal and Křivánek, 2000).

The relative dielectric constant of material shows how many times the force of interaction between the electric charges in the given medium is less than that in a vacuum.

The dielectric loss tangent defines the part of the power applied to materials that is absorbed by materials under the influence of the electric field.

SUMMARY

This review of the present state of art presents results of measurements of the interaction of electromagnetic waves with different kinds of materials and analyses possibilities of measuring of interac-

tions existing between high frequencies waves (microwaves) and dieletric materials. The interaction of electromagnetic waves was performed in the X frequency band of (8.2–12.5) GHz.
The complex permittivity ε* specifies not only the intensity of dielectric currents in a dielectric but also their phase shift relative to the intensity of the electric current, which produced those currents. DC eletrical conductivity σ and complex permittivity components ε′ and ε″ (real and imaginary part) characterize the material of a dielectric and its structure. They depend on the frequency and intensity of electric field (Buffler, and Stanford, 1991).
After dividing microwave energy from the generator into two identical waveguide channels (the measuring channel and the reference one) and putting the dielectric to be measured into the measuring channel, the phase of the electromagnetic wave at the output of those two channels will be different. The difference is varied when the relative permittivity ε_r' and the dielectric loss factor ***tg*** δ of the measured dielectric is changed. The difference depends also on the thickness ***d*** of the dielectric. The frequency 10.1 GHz was used for the measurement.
In the given paper some review on the dielectric properties of izolants at high frequence corresponding to the microwaves. The knowledge enables to propose a proper experimental methods for the study of the interaction of the microwaves with materials. The corresponding method has been suggested and realized during spring 2008.
The specimens have been composed with varying materials nominal dimensions
150 mm × 150 mm × 4 mm. The extensive number of experimental data have been obtained for this dieletric materials.

SOUHRN

Dielektrické vlastnosti materiálů při mikrovlnných frekvencích

V práci je popsán přehled současného stavu výzkumu měření interakcí elektromagnetických vln s různými druhy materiálů, dále analýza možností měření interakcí vysokofrekvenčních vln (mikrovln) s materiály a vlastní měření interakce elektomagnetického záření s dielektrickými vzorky ve frekvenčním rozsahu X (8.2–12.5) GHz s vyčíslením reálné části relativní permitivity a ztrátového faktoru, dále odhadnutí vysokofrekvenčního ztrátového faktoru na vzorcích.
Komplexní permitivita ε* nejen určuje velikost dielektrických proudů v dielektriku, ale i jejich fázový posuv vzhledem k intenzitě elektrického pole, které proudy vyvolalo. Stejnosměrná elektrická vodivost σ a složky komplexní permitivity ε′a ε″ (reálná a imaginární část) charakterizují materiál dielektrika, jeho strukturu, ale jsou i závislé na frekvenci, časovém průběhu a velikosti intenzity elektrického pole (Buffler and Stanford, 1991).
Rozdělí-li se mikrovlnná energie z generátoru na dva stejné vlnovodné kanály, měřící a referenční a vloží-li se do měřícího kanálu sledované dielektrikum, bude fáze elektromagnetické vlny a její amplituda na výstupu z obou kanálů rozdílná. Rozdíl se bude měnit se změnou relativní permitivity ε_r' a ztrátového faktoru ***tg*** δ měřeného dielektrika. Rozdíl se bude také zvětšovat s tloušťkou dielektrika ***d***. Při měření byla použita frekvence generátoru 10.1 GHz.
Je podán přehled dielektrických vlastností elektricky nevodivých materiálů při vysoké frekvenci odpovídající mikrovlnám. Tyto znalosti umožňují navrhnout experimentální metody pro další studování interakcí mikrovln s těmito materiály. Fázová metoda měření byla realizována na jaře roku 2008. Zkoumané vzorky byly vyrobeny o rozměrech 150 mm × 150 mm × 4 mm. Měřením bylo získáno velké množství experimentálních dat těchto dielektrických materiálů.

ACKNOWLEDGEMENTS

The research has been supported by project of MSMT – MSM 6215648905.

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