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THEORETICAL RESEARCH ABOUT MEASURING OF THE ELECTRICAL PARAMETERS OF THE MICROWAVE-SPECIFIC MATERIALS

Mircea-Petru URSU
University of Oradea, Electrical Engineering and Information Technology Faculty,
e-mail: mpursu@uoradea.ro , mpursu1965@yahoo.com

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Abstract: This paper presents theoretical research concerning the measuring of the microwave-specific materials parameters, including studies about rotation and inversion microwave absorption in liquid and gaseous state. Also, material parameters measuring methods are shown here, for various frequency ranges.

1. INTRODUCTION

The material electric parameters – permittivity, loss factor, conductivity etc. (tab.1) – are quantities that determine the interaction of the substance with the electromagnetic field. These quantities are usually tensors and are direction-dependent, so they can be considered as scalars only for the isotropic substances. Knowing the material parameters is very useful in substance structure research and in electronics design, and is helpful in choosing of the adequate material according to the final purpose.

When passing through matter, the microwave electromagnetic field interacts on different structure levels – electrons, atoms or molecules – and the microwave energy absorption is frequency-dependent. If the maximum absorption level is observed at frequency *f*, then the energy variation of the interacted particle is $\Delta w = h \cdot f$, where *h* is Planck's constant. This principle is used in radio-spectroscopy, where $\Delta w = 10^{-3} \div 10^{-1}\ \mathrm{eV}$, and in visible light and infrared radiation ranges, where $\Delta w = 0.1 \div 10\ \mathrm{eV}$. Thus, radio-spectroscopy is an adequate method for investigation of the hyperfine structure of the energetic levels. The following phenomena are observed:

- microwave rotation absorption;
- electronic spin resonance;
- paramagnetic resonance;
- nucleus-quadrupolar resonance;
- dielectric interaction.

2. ROTATION AND INVERSION ABSORPTION

In gaseous or liquid states, at moderate temperature (3 ÷ 400 K) and at low pressure, most substance molecules show selective absorption phenomena in 0.1 ÷ 10 cm wavelength range. It was observed that the energy interval Δw correspond to the difference between energy levels due to the rotation of the molecules.

The molecule kinetic energy is

$$w = \frac{1}{2} \cdot k \cdot \dot{\varphi}^2 \qquad (1)$$

where *k* is the angular momentum and φ is the angular speed of the molecule.

The molecule angular momentum is quantified:

$$k \cdot \dot{\varphi} = J \cdot \frac{h}{2\pi} \qquad (2)$$

where $J = 0,1,2,...$ is the angular momentum quantum number. So the rotation energy is:

$$w_r = \frac{h^2}{8\pi^2 \cdot k} \cdot J^2 \tag{3}$$

Taking into account the approximation $J^2 \approx J \cdot (J+1)$ from quantum mechanics, we have:

$$w_r = \frac{h^2}{8\pi^2 \cdot k} \cdot J \cdot (J+1) \tag{4}$$

There is a spectral line that corresponds to each value of *J* (fig.1).

The rotation term can be calculated after dividing by $h \cdot c$:

$$T_r = J \cdot (J+1) \cdot \frac{h}{8\pi^2 \cdot k \cdot c} \tag{5}$$

The frequencies that correspond to the transitions between the quantum rotation states J_1 and $J_2 > J_1$, that is the pure rotation spectral lines frequencies, are:

$$\nu_r = (T_{r2} - T_{r1}) \cdot c = \frac{W_2 - W_1}{h} = \frac{h}{8\pi^2 \cdot k} \cdot [J_2 \cdot (J_2+1) - J_1 \cdot (J_1+1)] \tag{6}$$

However, as resulted from observed spectra, the corresponding quantum numbers cannot vary arbitrarily as they are bound to "selection rules". In rotation spectra, the quantum number *J* may vary only by ±1, that is $\Delta J = \pm 1$. Thus, the relation (6) becomes:

$$\nu_r = \frac{h}{8\pi^2 \cdot k} \cdot [(J+1) \cdot (J+2) - J \cdot (J+1)] = \frac{h}{8\pi^2 \cdot k} \cdot (J+1) \tag{7}$$

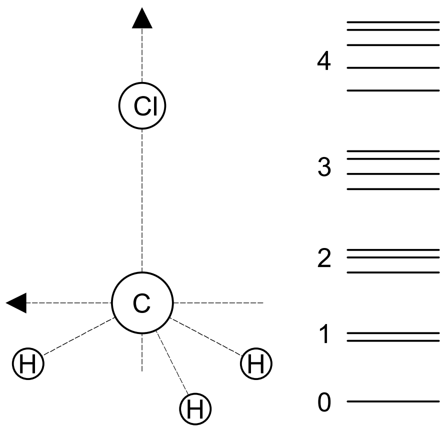

Fig.1. *The rotation energy levels for the molecule CH_3Cl.*

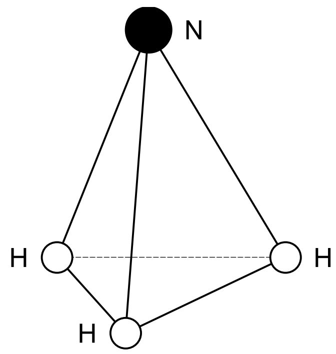

Fig.2. *The inversion of the ammonia molecule (NH_3).*

3. ASPECTS OF THE DIELECTRIC SPECTROSCOPY

The dielectric spectroscopy studies the interaction between the electromagnetic wave and the dielectric medium in a certain frequency range. The electromagnetic wave that passes through the medium is partially absorbed and dephased in the mean time. This phenomenon can be described by means of complex permittivity expression:

$$\varepsilon_r = \varepsilon_r' - j \cdot \varepsilon_r'' \; ; \; \mathrm{tg}\,\delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{8}$$

It is required that the determination of the permittivity real and imaginary components should be carried out over a frequency range as wide as possible. The dielectric losses, characterized by ε_r'', feature some maximum values according to frequency, thus an *absorption spectrum* can be identified for each material.

Tab.1. *Electrical parameters of dielectrical materials.*

Parameter	Notation / expression	Connecting relations
Complex permittivity	$\varepsilon = \varepsilon' - j \cdot \varepsilon'', \quad \left[\frac{\text{F}}{\text{m}}\right]$	
Relative complex permittivity	$\varepsilon_r = \varepsilon'_r - j \cdot \varepsilon''_r$	$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \frac{\varepsilon'}{\varepsilon_0} - j \cdot \frac{\varepsilon''}{\varepsilon_0}$
Dielectric loss factor	$\mathrm{tg}(\delta)$	$\mathrm{tg}(\delta) = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon''_r}{\varepsilon'_r}$
Conductivity	σ	$\sigma = \omega \cdot \varepsilon''$ $\sigma = \omega \cdot \varepsilon' \cdot \mathrm{tg}(\delta)$
Speed of TEM wave if $\varepsilon'' = 0$	v_f	$v_f = \frac{1}{\sqrt{\varepsilon_r \cdot \mu_r}} \cdot \frac{1}{\sqrt{\varepsilon_0 \cdot \mu_0}} = \frac{c}{\sqrt{\varepsilon_r \cdot \mu_r}}$
Relative refractive index	n'	$n' = \frac{c}{v_f} = \sqrt{\varepsilon_r \cdot \mu_r}$
Dielectric loss volumetric specific power	$P_1 = \sigma \cdot \frac{E_0^2}{2}, \quad \left[\frac{\text{W}}{\text{m}^3}\right]$	$P_1 = \omega \cdot \varepsilon' \cdot \frac{E_0^2}{2} \cdot \mathrm{tg}(\delta)$
Specific impedance of the dielectric medium	$Z_{01} = \lvert Z \rvert \cdot e^{j \cdot \xi}, \quad [\Omega]$	$Z = \left[\frac{(\varepsilon'_r \cdot \mu'_r + \varepsilon''_r \cdot \mu''_r)^2 + (\varepsilon''_r \cdot \mu'_r - \varepsilon'_r \cdot \mu''_r)^2}{(\varepsilon'^2_r + \varepsilon''^2_r)}\right]^{\frac{1}{4}}$ $\mathrm{tg}(2\xi) = \frac{\varepsilon''_r \cdot \mu'_r - \varepsilon'_r \cdot \mu''_r}{\varepsilon'_r \cdot \mu'_r + \varepsilon''_r \cdot \mu''_r}$
Propagation constant	$\gamma = \alpha + j \cdot \beta, \quad [\text{m}]$	$\alpha = \frac{\lambda \cdot \omega^2}{4\pi} \cdot (\varepsilon' \cdot \mu'' + \varepsilon'' \cdot \mu')$ $\beta = \omega \cdot \left\{\frac{\varepsilon' \cdot \mu' + \varepsilon'' \cdot \mu''}{2} \cdot \left[1 + \sqrt{1 + \left(\frac{\varepsilon' \cdot \mu'' + \varepsilon'' \cdot \mu'}{\varepsilon' \cdot \mu' + \varepsilon'' \cdot \mu''}\right)^2}\right]\right\}$
Relative refractive index of the non-ferromagnetic dielectric	n	$n = \sqrt{\frac{\varepsilon_r}{2} \cdot \left(1 + \sqrt{1 + \mathrm{tg}^2(\delta)}\right)}$
Propagation constant of the non-ferromagnetic dielectric	α	$\alpha = \frac{2\pi}{\lambda} \cdot \sqrt{\frac{\varepsilon_r}{2} \cdot \left(\sqrt{1 + tg^2(\delta)} - 1\right)}$

The obtained absorption spectrum can be attributed to the following processes:

a) absorption caused by free charge carriers that make electrical conduction; this kind of absorption does not feature maximum points and decreases as frequency increases;
b) dipolar absorption, caused by the absorbed energy that is necessary to rotate the dipolar momentum, which features maximum points when the electromagnetic field frequency equals the dipoles relaxation frequency;
c) absorption caused by the defects of the crystalline network; because the defect-free ionic crystals do not have any dipolar momentum, only the impurity centers or the crystalline defects may lead to the occurrence of spontaneous dipoles;
d) dielectric losses caused by the molecules that are adsorbed on the dielectric surface (such as water molecules); the adsorbed polar molecules feature a strong dipolar

absorption; in a system made of solid dielectric, dissolved water, crystalline water or chemically bound water feature three different chemical bonds, and each type can be determined from the temperature dependence of the complex permittivity;

e) phase transformations, which strongly influence the dielectric properties;

f) the induced dipolar absorption, which manifests for non-polar dielectric materials (atoms, molecules), where the dipole occurrence is caused by the high-frequency electromagnetic field itself; this kind of absorption is seen at the higher side of the frequency range because the formation of the induced dipoles require higher energy than their rotation.

The electric parameters of the dielectric materials are shown in tab.1.

4. MEASUREMENT OF THE PARAMETERS OF THE DIELECTRIC MATERIALS

The accurate determination of the electric properties of the dielectric materials in the frequency working range is an essential condition in the microwave devices construction, with direct influences upon reliability, taking in to account that these parameters are frequency-dependant and are known only in the ranges of low frequency and radio frequency.

The material parameters of the dielectrics – relative permittivity, relative permeability, conductivity etc – can be determined by measurements carried out in waveguides, resonant cavities or open space. The use of the millimeter-wave technique specific resonators (Fabry-Perot) is some kind of connection of the last two methods.

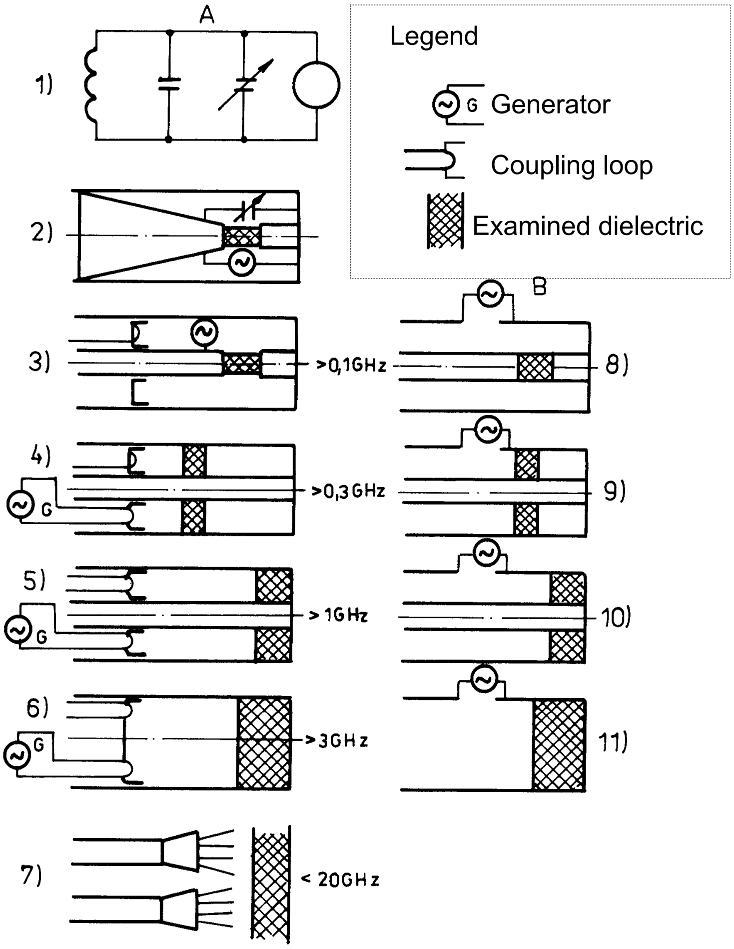

Fig.3. *Measuring methods for material parameters, used according to the frequency range.*

Fig.3. shows the application of the various measuring methods according to the working frequency range. For the methods included in column A, the examined dielectric is placed in the electric field of a concentrated constants circuit (1 and 2) or in resonant cavities (3 ÷ 7). The methods included in column B are based on measurements carried out on measuring lines (S-meter). When measuring the complex permittivity of non-ferromagnetic lossy materials, it is recommended to make measurements that can provide two kinds of data; for example, when carrying out measurements in resonant cavities, one must determine the variations of the resonance frequency and of the quality factor caused by placing the dielectric into the cavity. When performing measurements in waveguides, they must be completely filled with the dielectric material to be examined, so that their surfaces in contact with air should be perpendicular to the waveguide axis. In case of more intricate geometric configurations, the assessment of the measurement results becomes difficult. Fig.4 shows the waveguide measurement principle and fig.5 shows its practical application. According to fig.5, no-load or short-circuit can be achieved in plan *BB*' by adjusting the mobile short-circuiting piston.

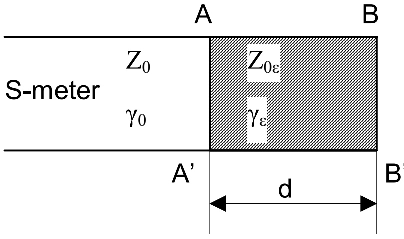

Fig.4. *The dielectric sample, placed in a waveguide with short-circuited end.*

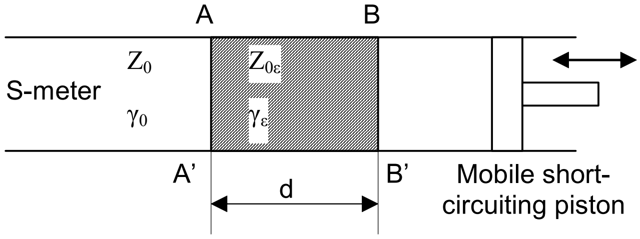

Fig.5. *Practical measurement.*

As a matter of fact, the experiment consists of merely measuring the input impedance Z_A, the standing wave factor *S* and the minimum point displacement x_{min}, by means of the measuring slotted line shown in fig.6

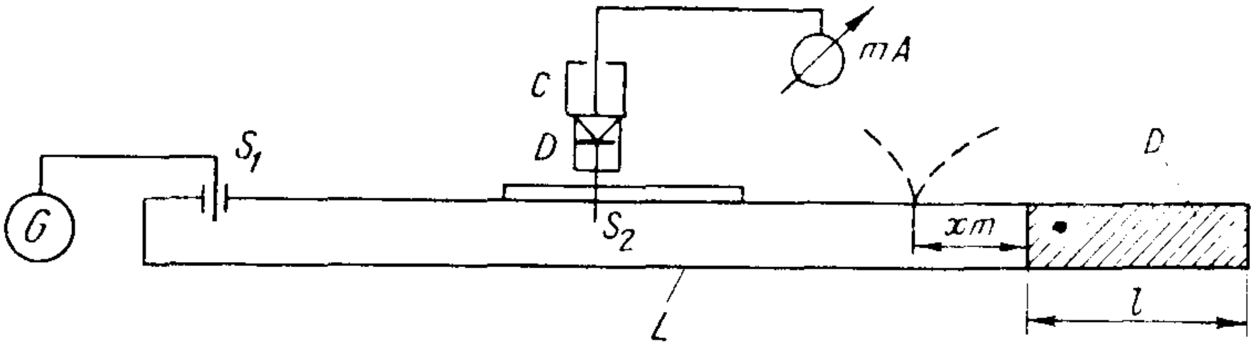

Fig.6. *Measuring slotted line, used for determining the parameters of dielectric materials.*

5. CONCLUSIONS

The measurement of the material electric parameters is very important in the design of microwaves instruments and devices, as well as in the prediction of their performances in the nominal working conditions.

According to the dimensions of the examined material, the experiments can be carried out in waveguide, resonant cavity or open space, and each measurement method is adequate for given situations and features its own advantages and disadvantages.

By means of these measurements, the sorting of the most adequate materials can be carried out according to the specific given application, performance criteria, material saving, machinability etc.

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