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Resonans Reflectionless Absorption of Electromagnetic Waves In Solutions

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To study dielectric properties of polar liquids and solutions in the microwave (MW) range, the methods of measurement, based on characterization of reflected electromagnetic waves from a layer with regulated thickness, are often used [1]. Accordance with [2,3], there can be conditions which allows observation of resonant reflectionless absorption of wave. In order to find out such conditions, let us consider the reflection of a electromagnetic wave from a layer with defined thickness and complex dielectric constant $\hat{\varepsilon} = \varepsilon' - i\varepsilon''$, the functionally depending on the frequency of incident radiation, placed on an ideally conducting metal surface. In this case, the reflection coefficient is

$$\rho = \left| \frac{zth\hat{\gamma}\ell - z_0}{zth\gamma\ell + z_0} \right|, \tag{1}$$

where z_0, z are the impedances for an empty and dielectric-filled waveguide, respectively; $\hat{\gamma} = i2\pi\sqrt{\hat{\varepsilon} - p}/\lambda$ is the dielectric propagation constant $p = [\lambda/\lambda_k]^2; \lambda$ is wave length in empty space; λ_k is critical the wave length defined by the size of the directing system and ℓ is the thickness of the layer.

If the layer has dielectric loss ε'', dependence of $\rho(\ell)$ presents an oscillating curve which, with increasing ℓ, asymptotically approaches a limiting value.

As such, minimal reflection of waves is observed at thicknesses of the dielectric layer close to $(\mathbf{2n} - \mathbf{1})\lambda_g/\mathbf{4}$, where $\mathbf{n}$ is the number corresponding to $\rho(\ell)$ curve minimum and λ_g is wave length in the waveguide filled with dielectric Evidently, reflectionless absorption of electromagnetic waves in the material can take place under the conditions ρ=0 and ρ'=0. For ρ=0, and taking into account expressions for z_0, z, γ, results in the following equation:

$$ysh(4\pi\ell_0 y/\lambda_g) + sin(4\pi\ell_0/\lambda_g) = 0, \tag{2}$$

where ℓ_0 is the thickness of dielectric layer at ρ=0.

In the equation (2) λ_g and loss factor **y** are functionally related to the evalues of ε' and ε'':

$$\varepsilon_1 = (1 - y^2)(\lambda_b/\lambda_g)^2; \qquad \varepsilon_2 = 2y(\lambda_b/\lambda_g)^2 \tag{3}$$

where $\varepsilon_1 = (\varepsilon' - p)/(1 - p), \varepsilon_2 = \varepsilon''/(1 - p)$, and $\lambda_b = \lambda/\sqrt{1 - p}$-is the wavelength in an empty waveguide. Using the condition ρ=0 and the method of finding extremal values of ρ in the dependence $\rho(\ell)$ given in [3], results in the following equation:

$$(1 + y^2)\lambda_b/\lambda_g = th(2\pi\ell_0 y/\lambda_g) - ytg(2\pi\ell_0/\lambda_g), \tag{4}$$

which, together with the equation (2), defines the conditions of existence of resonant reflectionless absorption in a layer of polar dielectric. Results of simultaneous solution of equations (2) and (4) taking into account expressions for ε_1 and ε_2 are presented in Figure 1 as the dependences of ε_2 and ℓ_0/λ_b on ε_1, correspondingly, for the first three minima of oscillating curve $\rho(\ell)$ under the conditions $\rho = 0$ and $\rho' = 0$ in the selected points of minimum. It is specific that with increasing number n of the minimum ρ the dependences ε_2 on ε_1 decrease with height and approach to the axis. The reverse picture is observed for the dependence of ℓ_0/λ_b on ε_1. This indicates the possible existence of reflectionless absorption of electromagnetic waves, even in materials with insignificant values of dielectric loss; in these cases, reflectionless absorption is realized by larger thickness of reflecting layer.

Theoreticaly obtained results can be verified by the analysis of frequency dependence of ε' and ε'', and selection of the frequencies, at which values of ε' and ε'' coincide with resonant values of ε_0' and ε_0'' found from equations (2)-(4). However, such a method requires a whole complex of apparatus in various ranges of waves. The most simple and convenient way to experimentally verify the existence of resonant reflectionless absorption in a material is by changing the dielectric properties of a liquid polar dielectric by dissolving into it non-polar dissolvent. The advantage of this method is that it can be realized by fixed frequency and temperature of measurement.

Since non-polar dissolvent has ε''=0, with increasing concentration x of polar component in the binary solution, the dependence of reduced values ε_2 on ε_2 for such solutions will begin from a point on the axis ($x = 0$) see Fig. 1 and end in the upper right plane $[\varepsilon_1, \varepsilon_2]$ at the point with coordinates corresponding to polar material. The dependence of ε_2 on ε_1 obtained in this way will cross the curves of resonant reflectionless absorption in the material defined by Equations (2)-(4). Taking into account the character of location of the family of curves $\varepsilon_2(\varepsilon_1)$ calculated theoretically, the existence of an infinite sequence of concentrations x of polar component and thicknesses ℓ of the reflecting layer of solution, at which such absorption occurs, can be expected.

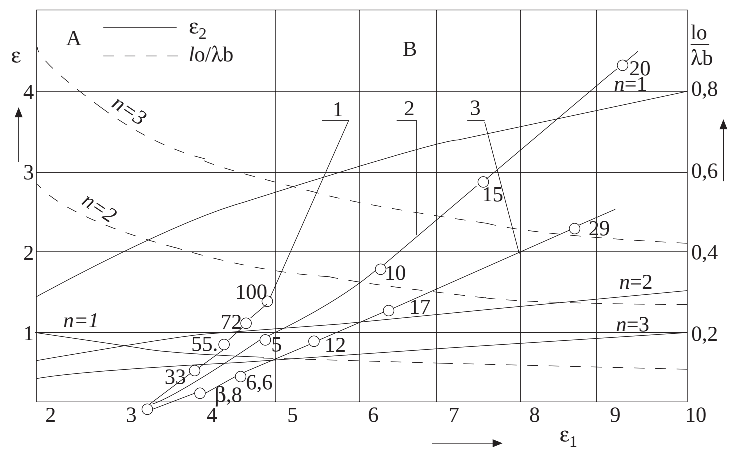

Figure 1. Relation between reduced values of dielectric constants ε_1 and ε_2 and thickness $1_0/\lambda_b$ of reflecting solution layer: A - Corresponding to the condition of reflectionless absorption of electromagnetic radiation in polar materials; B - For the solutions of acetone (3), acetonitril (2) and anizole (1) in benzole at the temperature T=20°C and wavelength λ=1,5 cm. Molar concentrations x of polar components in solutions given in %.

For experimental verification of theoretical conclusions, binary solutions of aceton, acetonitril and anizole in benzole were obtained. Dielectric properties of these solutions have been well researched in the microwave range [4]. Pure polar components of the solutions differ significantly by values of static dielectric permittivity ε_0 and relaxation time τ; however, the behaviour of ε' and ε'' of these materials is defined precisely enough by Debye equations. Measurements of reflection characteristics of the solutions were taken at the wavelength λ=1,5 cm and temperature T=20°C using a panoramic waveguide reflectometer R2-66 and IR2-67 and with a shorted waveguide cell connected with it. The latter was thermostatic and had a cell for regulating thickness of the reflecting solution layer. To determine ε' and ε'' of the solutions the method of varied thicknesses has been used, based on the measurement of standing wave coefficient η and thickness ℓ of the solution layer within the cell in the extremal points of the $\rho(\ell)$ curve [5].

The values of ε' and ε'' for the solutions obtained experimentally at different concentrations of benzole were used for plotting dependences of reduced values ε_2 on ε_1 of corresponding solutions on the plane $[\varepsilon_1, \varepsilon_2]$. Putting them together with the curves $\varepsilon_2(\varepsilon_1)$ calculated from Equations (2)-(4), coordinates of intersection points have been found from the graph (Fig. 1), and from the corresponding resonant values of benzole concentration in the solution has been found. As it follows from Fig.1, for the solutions of aceton and acetonitril in benzole, all minima of $\rho(\ell)$ dependence, beginning from the first one, reach zero value with changing concentration of benzole. As for anizole-benzole solution, the same occurs only with the second and further minima of the $\rho(\ell)$ dependence.

Table 1. Measured x_e and calculated x_c values of resonant molar concentrations of polar component of the solutions of acetone, acetonitril and anizole in benzole at the temperature T=20° C and wavelength λ=1,5 cm. $\varepsilon_0, \tau\ 10^{12}_s$ are statical dielectric permittiity and relaxation time of the polar component of the solution. Critical wavelength λ_k=2,3 cm.

SOLUTIONS		ACETONE-BENZOLE			ACETONITRIL-BENZOLE			ANIZOLE-BENZOLE	
$\varepsilon\ T$		21.60	3.20		36.80	3.30		4.39	12.30
		x_e	x_c		x_e	x_c		x_e	x_c
NUMBERS OF	1	55.0	54.4		19.4	19.4	-	-	
MINIMUS	2	16.6	15.8		7.4	6.6		65.0	63.5
	3	8.9	8.4		4.8	4.6		37.2	34.6
	4	6.1	6.0		3.6	3.4		26.0	24.5

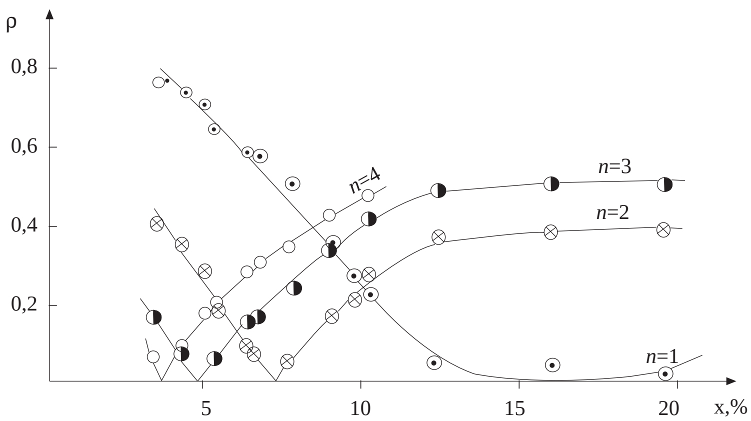

Figure 2. Dependence of the value of wave reflection coefficient ρ on molar concentration x of polar conponent for acetonitril-benzole solution at the temperature T=20° C and wavelength λ=1,5 cm.

The resonant values of benzole concentration in selected solutions obtained by this graphic method are listed in the table. For comparison, the values of x are given, obtained from the analysis of experimentally measured concentration dependences of the values of wave reflection coefficient in minimum points of $\rho(\ell)$ curves. On Fig.2, a typical family of such concentration dependences is shown for acetonitril-benzole solutions at λ=1,5 cm. Regardless of number n of the minimum of $\rho(\ell)$ curve, concentration dependences of ρ for these solutions have clearly seen zero minima of ρ at certain values of benzole concentration with increasing n, zero minimum ρ of concentration dependences shifts towards lower concentrations of polar components of the solution. At the same time the distances between neighbouring minima of ρ decrease and tend to zero at larger n. Calculated and measured values of resonant benzole concentration given in the Table are in good agreement. The same behaviour of minimal ρ values with changing benzole concentration is observed for the remaining solutions.

It is obvious that with further increase of benzole concentration in the solutions observed the conditions for the occurrence of resonant reflectionless absorption of electromagnetic waves, also for larger values of n minima of $\rho(\ell)$ dependence.

The effect of resonant reflectionless absorption of electromagnetic waves in solutions has general character and can be observed in many solutions of polar dielectrics at certain frequency, temperature and composition of the solution researched.

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