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ABSORPTION OF ELECTROMAGNETIC RADIATION IN A POLAR DIELECTRIC LAYER

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Conditions are investigated for initiation of nonreflecting absorption of electromagnetic radiation in a polar dielectric layer applied to a reflecting metal substrate.

In [1, 2] a method is suggested for determination of the dielectric constant ε' and the dielectric loss ε'' of polar liquids in the range of superhigh frequencies (SHF). The method is based on measuring two information parameters: the standing wave coefficient η and the thickness l of a controlled reflecting liquid layer in a measuring section short-circuited at the end, at which the reflection of the electromagnetic wave is minimum. Employing special nomograms and computer programs, this method accelerates and simplifies determination of ε' and ε'' from measured η and l at points of minimum η but leads to ambiguity in determination of these values and requires additional estimation of correctness of the solution obtained [3]. Moreover, in measuring liquid dielectrics in some cases observed in practice the method was ineffective because of the appearance of complete absorption of the electromagnetic wave in the dielectric layer in the measuring system. This fact, although restricting the application of this method, makes it possible to use the calculated relations obtained in [1, 2] to estimate the conditions and determine the radiation frequency and the properties and thickness of the dielectric layer for which this phenomenon occurs.

Reflection of an electromagnetic wave from a dielectric layer coating a metal surface will be considered in the general case. The thickness of the layer is controlled and its complex dielectric constant $\varepsilon = \varepsilon' - i\varepsilon''$ is a function of the frequency of the incident radiation. It is shown in [2] that irrespective of the type of guiding system (a waveguide, a coaxial line, or free space), the electromagnetic wave has minimum reflection under the condition

$$(1 + y^2)^2 (\lambda_b/\lambda_g)^2 = R_1 R_2 , \tag{1}$$

where $R_1 = \tanh(2\pi xy) - y \tan(2\pi x)$; $R_2 = \coth(2\pi xy) + y \cot(2\pi x)$; $x = l_m/\lambda_g$; $y = \tan(\Delta/2)$; $\Delta = \arctan[\varepsilon''/(\varepsilon' - p)]$; $p = (\lambda/\lambda_c)^2$; $\lambda_b = \lambda/\sqrt{1-p}$ is the wavelength of the electromagnetic wave in the empty guiding system; λ, λ_g are the wavelengths of the electromagnetic wave in free space and in the guiding system filled with dielectric, respectively; λ_c is the critical wavelength determined by the size of the guiding system; l_m is the thickness of the dielectric layer at the minimum point of η.

In this case the minimum η occurs at the following thickness of the dielectric layer:

$$l_m = \frac{2n-1}{4} \lambda_g + \Delta l , \tag{2}$$

where n is the number of the minimum in the dependence of η on l; Δl is the deviation of l_m from a value that is a multiple of $\lambda_g/4$:

$$\Delta l = \frac{\lambda_g}{2\pi} \arctan [B \,\mathrm{cth}\, (2\pi xy)] . \tag{3}$$

In Eq. (3) the parameters $B = (\sqrt{1 + 4A^2} - 1)/2A$ and $A = y[(1 + y^2)^2(\lambda_b/\lambda_g)^2 - (1 - y^2)]^{-1}$ depend only on the dielectric properties and the type of guiding system with λ chosen [2].

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Since the modulus of the reflection coefficient of electromagnetic radiation is $\rho = (\eta - 1)/(\eta + 1)$, then at the minimum point of the function $\eta(l)$ under condition (1) it can be expressed by

$$\rho = \left| \frac{\sqrt{R_1} - \sqrt{R_2}}{\sqrt{R_1} + \sqrt{R_2}} \right| . \tag{4}$$

It follows from (4) that the electromagnetic wave will not be reflected from the metal-dielectric system under the condition $R_1 = R_2$, which with the expressions for R_1 and R_2, leads to the equation

$$y_0 \operatorname{sh}(4\pi x_0 y_0) + \sin(4\pi x_0) = 0 , \tag{5}$$

where $x_0 = l_0/\lambda_{g0}$; l_0, λ_{g0}, y_0 are the thickness of the dielectric layer, the electromagnetic wavelength and the dielectric loss factor at $\rho = 0$.

Equation (5) is a single-valued relation between the frequency of the electromagnetic radiation, the thickness of the layer, and the dielectric properties in the case where the dielectric-metal system does not reflect the wave.

Since

$$\varepsilon' = p + (1 - y^2)(\lambda/\lambda_g)^2 , \quad \varepsilon'' = 2y(\lambda/\lambda_g)^2 , \tag{6}$$

under the condition $R_1 = R_2$ for the case of complete absorption of the electromagnetic wave Eqs. (1) and (6) can be expressed in the form

$$l_0/\lambda_{b0} = (1 + y_0^2)\, x_0 R_0^{-1} , \tag{7}$$

$$\varepsilon' = p + (1 - p)\frac{(1 - y_0^2) R_0^2}{(1 + y_0^2)^2} ; \quad \varepsilon'' = (1 - p)\frac{2 y_0 R_0^2}{(1 + y_0^2)^2} , \tag{8}$$

where $R_0 = \tanh(2\pi x_0 y_0) - y_0 \tan(2\pi x_0)$; λ_{b0} is the wavelength in the empty guiding system at $\rho = 0$.

In Eqs. (7) and (8) l_0, ε', and ε'' are functions of the same parameters x_0 and y_0 in Eq. (5). Therefore, simultaneous solution of Eqs. (5) and (8) with the eliminated parameters x_0 and y_0 establishes a relation between ε' and ε'' of the material of the reflecting layer at $\rho = 0$. In this case the corresponding values of l_0 obtained from Eq. (7) allow the desired thickness of the dielectric layer to be chosen at $\rho = 0$. For the case of wave propagation in free space, the results of simultaneous solution of Eqs. (5), (7), and (8) are presented in Fig. 1 as the relations $\varepsilon'' - \varepsilon'$ for the first four minima of η, provided that at the chosen points of the curve of η versus l the value of ρ is assumed to be 0. A specific value of the reduced thickness of the coating layer l_0/λ_{b0} corresponds to each point of these curves; for convenience of presentation of the results of solution of Eqs. (5), (7), and (8), scale divisions with values of l_0/λ_{b0} are presented for the curves of $\varepsilon'' - \varepsilon'$.

The search for the unknown values of λ_0 and l_0 at which the electromagnetic wave is absorbed completely becomes unambiguous if the dependences of ε', ε'' of the dielectric coating of the metal surface on the frequency are known.

As a rule, the properties of many polar dielectrics are described fairly well by the Debye equations [4]

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (2\pi c\tau/\lambda)^2} , \quad \varepsilon'' = 2\pi \frac{c}{\lambda} \tau \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (2\pi c\tau/\lambda)^2} . \tag{9}$$

If λ is eliminated from Eqs. (9), in the coordinates $[\varepsilon', \varepsilon'']$ the relation $\varepsilon'' - \varepsilon'$ will be a semicircle with radius $(\varepsilon_0 - \varepsilon_\infty)/2$ and center at the point $(\varepsilon_0 + \varepsilon_\infty)/2$ located on the abscissa (see Fig. 1). It is evident that in the graphic representation of Eqs. (5) and (7)-(9) in the coordinates $[\varepsilon', \varepsilon'']$, the search for the unknown values of λ_0 and l_0

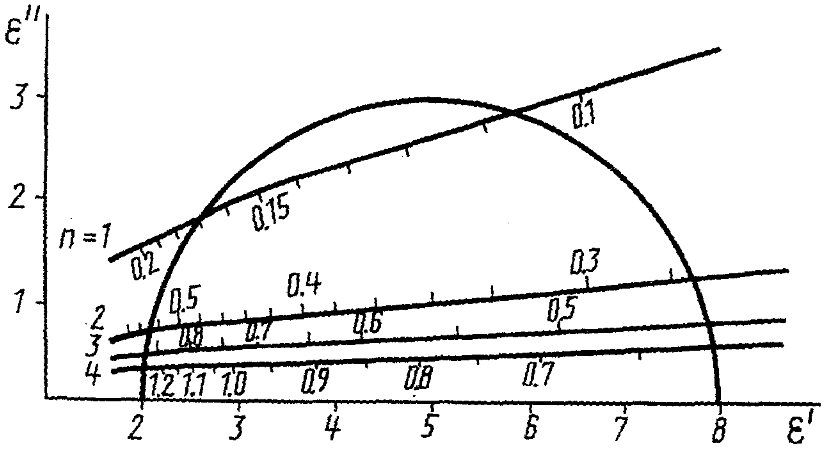

Fig. 1. Plots of dielectric permeability ε' versus dielectric losses ε'' for a polar dielectric, corresponding to the condition of complete absorption of electromagnetic radiation in the dielectric layer; n is the number of the minimum in the dependence of the standing wave coefficient on the thickness of the dielectric layer.

TABLE 1. Calculated Wavelengths λ_0 of Electromagnetic Radiation and Thicknesses l_0 of the Coating Layer for Particular Polar Liquids, at Which Absorption of Electromagnetic Radiation Is Complete

Compound	Dielectric properties at 20°C			Number of the minimum n	Low-frequency branch of spectrum		High-frequency branch of spectrum	
	ε_0	ε_∞	$\tau \cdot 10^{12}$, sec		λ_0, mm	l_0, mm	λ_0, mm	l_0, mm
Acetone	21.6	1.90	3.2	1	19.2	1.10	0.50	0.10
				2	57.2	9.15	0.22	0.11
				3	102.3	27.4	0.13	0.12
				4	147.1	54.4	0.08	0.09
Pyridine	13.6	3.05	7.1	1	24.9	1.92	4.26	0.61
				2	78.0	16.2	1.03	0.44
				3	149.2	51.5	0.64	0.46
				4	219.1	104.1	0.38	0.39
Diethylpyridine	8.33	2.39	14.8	1	33.8	3.61	11.1	1.67
				2	134.0	35.7	3.32	1.62
				3	224.0	97.7	2.08	1.68
				4	319.9	194.5	1.51	1.68
Anisole	4.39	2.60	12.3	1	–	–	–	–
				2	27.7	11.0	16.0	6.94
				3	61.1	37.6	6.99	5.24
				4	96.8	81.9	4.44	1.18

reduces to determining the intersection points of the Debye semicircle and the corresponding relation $\varepsilon''-\varepsilon'$ described by Eqs. (5) and (8); then, these two intersection points correspond to two wavelengths λ_{01} and λ_{02} of electromagnetic radiation and the corresponding thicknesses of the material layer, at which there is no reflection of the electromagnetic wave from the dielectric-metal system for the chosen number n of the minimum in the curve of η vs l (see Fig. 1).

As n increases, the curves $\varepsilon'' - \varepsilon'$ described by Eqs. (5) and (8) decrease in height and approach the abscissa. Then it follows that for a polar dielectric even with insignificant wave dispersion, it is always possible that the Debye semicircle can intersect the theoretical curves of $\varepsilon''-\varepsilon'$, starting from some critical n_c. This fact indicates that in the dispersion region of the material coating the metal surface and having wave dispersion a spectrum of frequencies should be revealed at which in the dielectric-metal system the effect of complete absorption of incident electromagnetic radiation appears at specially chosen thicknesses of the coating layer.

Table 1 shows results of a graphical calculation of λ_0 and l_0 for several hypothetical coatings of the metal surface, provided that the electromagnetic radiation propagates in free space. Polar liquids with wave dispersion in the SHF range are chosen as coating materials [4]. The shape of the frequency spectrum considered is individual for the coating material and is determined by its static and dynamic dielectric properties. The spectrum consists of two branches, namely, low-frequency and high-frequency ones, distinguished only by the behavior of the spectral absorption frequencies with increase in the required thickness of the coating layer of material (see Table 1).

The conditions found for existence of the phenomenon of complete absorption of electromagnetic radiation in the layer of polar dielectric will be extremely useful for the purposeful search for materials for nonreflecting absorbers of electromagnetic radiation in preset frequency ranges.

NOTATION

c, velocity of light; i, imaginary unit; l, thickness of the dielectric layer; l_m, thickness of the dielectricc layer at the minimum of the reflected wave; n, the number of the minimum of the reflected wave; n_c, critical number of the minimum of the reflected wave; y, dielectric loss factor; Δ, dielectric loss angle; ε, complex dielectric constant; ε_0, ε_∞, static and high-frequency dielectric constants, respectively; ε', dielectric constant; ε'', dielectric loss; η, standing wave coefficient; λ, λ_g, λ_b, wavelength in vacuum, dielectric, and guide system, respectively; λ_c, critical wavelength; ρ, modulus of the wave reflection coefficient; τ, relaxation time. The subscript 0 denotes the case of complete absorption of electromagnetic radiation.

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