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EVALUATION OF THE SELECTIVE ABSORPTION BAND OF WAVES IN A TWO-LAYER DIELECTRIC-METAL SYSTEM

É. R. Kasimov, M. A. Sadykhov, R. M. Kasimov, and Ch. O. Kadzhar

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The authors investigate the dependence of the selective absorption band of electromagnetic radiation in a two-layer dielectric-metal system on the dielectric properties and thickness of a coating near wavelengths at which in the system total absorption of incident radiation develops. The narrowing of the absorption band of this system due to an increase in the thickness of a coating material and in its refraction index is established.

In [1] it was shown that the effect of selective reflectionless (total) absorption of electromagnetic radiation incident on a system can appear in a two-layer dielectric-metal system within the region of wave dispersion of a coating material at definite wavelengths λ_0 and thicknesses l_0 of the coating. Taking into account the prospects for employing such two-layer systems in creating narrow-band absorbing devices, we decided to investigate the reflection characteristics of such a system within the limits of a small-magnitude band of wavelengths in the vicinity of λ_0. To analyze these changes, we present, with allowance for the notation used in work [1], the well-known expression for the modulus of the reflection index of the wave ρ in a two-layer system considered in the following form:

$$\rho = \sqrt{\left(\frac{P - Q}{P + Q}\right)}\,, \tag{1}$$

where

$$P = M^2 + N^2 + 1\,; \quad Q = 2M\,;$$

$$M = \frac{1}{n\,(1 + y^2)}\,\frac{\sinh(4\pi xy) - y\sin(4\pi x)}{\cosh(4\pi xy) + \cos(4\pi x)}\,;$$

$$N = \frac{1}{n\,(1 + y^2)}\,\frac{y\sinh(4\pi xy) + \sin(4\pi x)}{\cosh(4\pi xy) + \cos(4\pi x)}\,;$$

$$x = ln/\lambda\,; \quad y = \tan\delta\,; \quad \delta = \arctan\varepsilon''/\varepsilon'\,; \quad n = \frac{\lambda}{\lambda_{\text{diel}}}\,.$$

At the prescribed quantity λ and the presence of dielectric losses in the coating substance the dependence of ρ on x in conformity with expression (1) represents an oscillating and damping function. According to [1], the condition for reflectionless absorption of the wave in the system under consideration is implemented with allowance for the dielectric properties of the coating material at such thicknesses l_0 of the coating when one of the minima of the function $\rho(x)$ attains the zero value. Thus, at values of $x = x_0$ the values of the function $\rho(x)$ and of its derivative should have vanished, i.e.,

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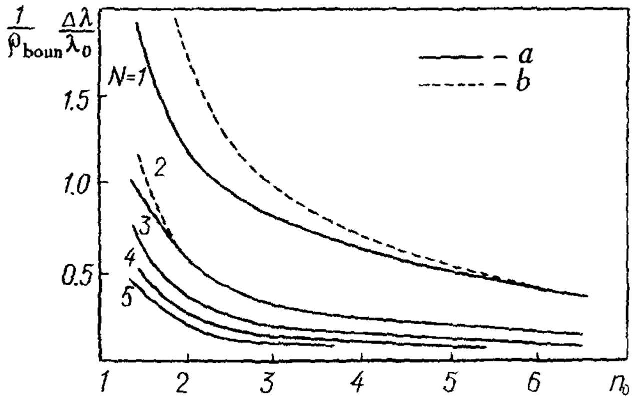

Fig. 1. Dependences of reduced values of the relative absorption band $\frac{1}{\rho_{boun}}\frac{\Delta\lambda}{\lambda_0}$ on resonance quantities n_0 of the coating material for first five zero minima of the function $\rho(x)$: a) data of calculation from Eq. (9); b) from Eq. (10).

$$[\rho]_{x_0} = 0\,, \quad [P]_{x_0} = [Q]_{x_0}\,; \tag{2}$$

$$[\rho']_{x_0} = 0\,, \quad [P']_{x_0} \cdot [Q]_{x_0} = [P]_{x_0} \cdot [Q']_{x_0}\,. \tag{3}$$

To evaluate the changes in the quantity ρ near the zero value, we rearrange expression (1) in the form of

$$V = \frac{P}{Q} = \frac{1+\rho^2}{1-\rho^2}\,. \tag{4}$$

At the fixed quantity l_0 we restrict ourselves to analysis of behavior of the function V in the region of its small deviations from the values of λ_0 and ρ_0, which makes it possible to neglect the change in the dielectric properties of the coating material depending on the incident radiation frequency and to admit their constancy within the limits of the investigated range of variation of λ and ρ. We expand the function $V = P/Q$ into a Taylor series in terms of x and restrict our consideration only to the first three terms of expansion near x_0. Taking into account conditions (2) and (3), we obtain

$$V = 1 + 2\pi^2 (x - x_0)^2 \,[(M')^2_{x_0} + (N')^2_{x_0}]\,, \tag{5}$$

where $x_0 = l_0 n_0/\lambda_0$; n_0 is the quantity of the refraction index of the coating material at $\lambda = \lambda_0$. The small deviation of x from x_0 is accompanied by insignificant change in the quantity of the modulus of the reflection index of the wave ρ in comparison with its zero value. Therefore the right-hand side of expression (4) in the first approximation can be represented as

$$V = 1 + 2\rho^2_{boun}\,, \tag{6}$$

where ρ_{boun} is the quantity ρ on the boundary of the absorption band being evaluated in the two-layer system under consideration.

From comparison of expressions (5) and (6) it follows that

$$|x - x_0| = \frac{\rho_{boun}}{\pi} \frac{1}{\sqrt{(M')^2_{x_0} + (N')^2_{x_0}}}\,. \tag{7}$$

By definition from [1], reflectionless absorption of the wave appears at the minimum points of the function $\rho(x)$ when

$$x_0 = \frac{2N - 1}{4} + \Delta, \tag{8}$$

where N is the number for the corresponding zero minimum of the function $\rho(x)$ [1].

The parameter Δ, entering into Eq. (8), depends on the dielectric properties of the coating substance and the number N for the minimum of the function $\rho(x)$. As N rises, the quantity of the parameter Δ decreases and becomes insignificant with $N \geq 3$ [2]. We will take into account the symmetry of the discrete absorption line of the wave. Then, using the relations for M, N, and x_0 from expression (7) and taking $\Delta = 0$, we obtain an expression for the relative absorption band of the wave in the two-layer dielectric-metal system near λ_0

$$\frac{1}{\rho_{\text{boun}}} \frac{\Delta\lambda}{\lambda_0} = \frac{4 \sinh [\pi y_0 (2N - 1)]}{\pi (2N - 1)}, \tag{9}$$

where y_0 is the value of the dielectric loss factor of the coating material at which the condition for total absorption of the incident electromagnetic radiation is satisfied.

From expression (9) it follows that at the level of ρ_{boun} selected for reading the absorption band $\Delta\lambda$ near λ_0, its quantity depends on N and the dielectric properties of the material at $\lambda = \lambda_0$. Figure 1 presents the dependences of the reduced values, calculated from Eq. (9), of the relative absorption band $\frac{1}{\rho_{\text{boun}}} \frac{\Delta\lambda}{\lambda_0}$ on the resonance quantities n_0 of the coating material for the first five zero minima of the function $\rho(x)$. These dependences indicate that at the prescribed level of ρ_{boun} the relative absorption band near $\lambda = \lambda_0$ decreases in magnitude with an increase in n_0 and N.

From the investigations carried out in [3, 4] for the reflection characteristics of binary solutions of polar substances in nonpolar solvents, it was established that the implementation of the zero minima of the function $\rho(x)$ at the increased values of N is possible in diluted solutions of these substances under the condition of smallness of the dielectric loss factor y_0. In view of this, it can be assumed that in the case of small y_0 the following ratio is valid:

$$\tanh \left[\frac{\pi y_0}{2} (2N - 1)\right] = \frac{1}{n_0}$$

and expression (9) can be represented in the simplified form

$$\frac{1}{\rho_{\text{boun}}} \frac{\Delta\lambda}{\lambda_0} = \frac{8}{\pi (2N - 1)} \frac{n_0}{n_0^2 - 1}. \tag{10}$$

Thus, for the level of ρ_{boun} selected for reading the absorption band of the wave near the points λ_0 its relative quantity is inversely proportional to the number N for the zero minimum of the function $\rho(x)$. Comparison with the result of calculation by means of Eqs. (9) and (10) shows that the calculated absorption bands in both cases are close for $N \geq 3$. The deviations observed at $N = 1$ and $N = 2$ between the behavior of the dependences calculated by means of Eqs. (9) and (10), respectively, are not so significant and are associated with the neglect of the parameter Δ during their derivation.

The relationship determined can be a basis for creating narrow-band absorbing SHF devices. As a working body, it is possible in this case to use a slightly absorbing substance layer of noticeable thickness, coated on a metal substrate.

NOTATION

l, coating thickness; n and y, refraction index and dielectric loss factor; ε', dielectric permeability; ε'', dielectric losses; ρ, modulus of reflection index of wave; λ, λ_{diel}, wavelength in vacuum and in substance (in dielectric); δ, angle of dielectric losses. Subscript 0, reflectionless absorption of electromagnetic radiation.

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