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TWO-LAYER NONREFLECTIVE ABSORBER OF ELECTROMAGNETIC RADIATION

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Conditions for reflectionless quenching of electromagnetic radiation in the layer of absorbing dielectric applied to a nonabsorptive quarter-wave substrate have been found. These conditions as functions of the layer thickness and the dielectric properties of the coating and the substrate are investigated.

Keywords: *nonreflective two-layer absorber, quenching of electromagnetic waves.*

Introduction. Microwave absorbers of electromagnetic radiation are formed, as a rule, on the basis of a plane layer of dielectric coating [1] or dielectric coatings that contain fine-grained absorbing metallic or magnetic fillers and are applied to a metal substrate [2]. The condition of total reflectionless absorption of the normally incident radiation is ensured by the corresponding selection of the material and of the thickness of the layers and the content of the filler in them [2, 3]. At the same time, the use of the metal substrate as a bearing structure limits the applicability of such absorbers, since the possibility of their light detection in sounding is offered. In this connection, periodic layer (sandwich) structures that contain alternating absorbing and nonabsorbing layers and ensure the completeness of quenching of the electromagnetic radiation transmitted by them are preferred.

Formulation of the Problem. We consider, as the first step in solving this problem, the possibility of obtaining two-layer nonreflective absorbers with the use of a nonabsorptive-dielectric layer quarter-wave of thickness l_1 as the carrying substrate and a dielectric layer of thickness l absorbing the radiation transmitted by it as the substrate's coating. Such a two-layer system could subsequently be used as the element of multilayer absorbing periodic structures.

Depending on the position of the substrate and the coating relative to the direction of propagation of the wave we consider its reflection for the case where the coating is to be found on the front (problem A) or back (problem B) substrate surface. Since the substrate-layer thickness is prescribed and equal to a quarter of the wavelength λ_{d1} in the substrate substance, the complex value of the reflection coefficient of the wave $\hat{\rho}$ of such a two-layer system which is an air medium will be equal to

$$\hat{\rho} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}\,, \tag{1}$$

where $Z_{in} = Z\dfrac{Z_1^2/Z_0 + Z\tanh\gamma l}{Z + Z_1^2/Z_0\tanh\gamma l}$ (for problem A) and $Z_{in} = \dfrac{Z_1^2}{Z}\dfrac{Z + Z_0\tanh\gamma l}{Z_0 + Z\tanh\gamma l}$ (for problem B), $\gamma = i2\pi\sqrt{\hat{\varepsilon}}/\lambda$, $Z = Z_0/\sqrt{\hat{\varepsilon}}$, and $Z_1 = Z_0/\sqrt{\varepsilon_1}$, $\hat{\varepsilon} = \varepsilon' - i\varepsilon''$, $\varepsilon' = n^2(1 - y^2)$, $\varepsilon'' = 2n^2 y$, and $\varepsilon_1 = n_1^2$.

Condition of Reflectionless Transmission of the Wave. We introduce the notation $x = l/\lambda_d$. Then, with account for the expression for γ, we have that $\gamma l = 2\pi xy + i2\pi x$. The condition of reflectionless transmission of radiation by the two-layer system in question ($\hat{\rho} = 0$) corresponds to the equality $Z_{in} = Z_0$, which leads us to the following equations for problems A and B:

$$n\,(1 - iy) = \frac{n\,(1 - iy) + n_1^2\tanh\,(2\pi xy + i2\pi x)}{n_1^2 + n\,(1 - iy)\tanh\,(2\pi xy + i2\pi x)}\,, \tag{2}$$

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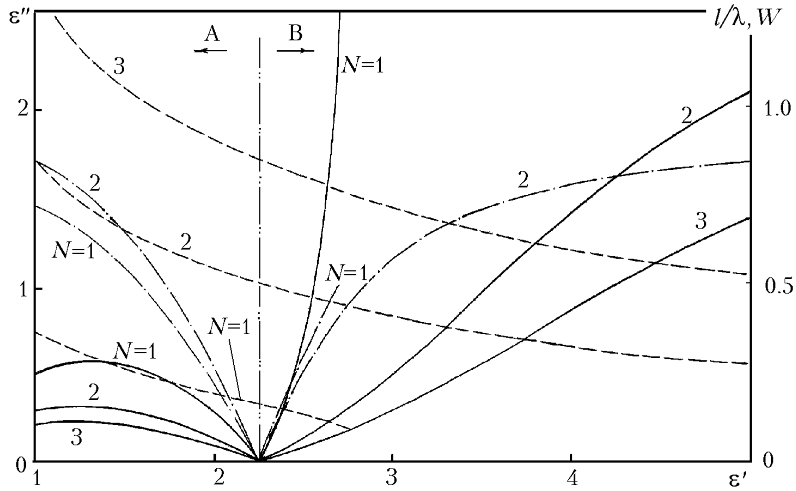

Fig. 1. Dielectric loss ε'' (solid curves), layer thickness l_0/λ (dashed curves), and relative value of the wave-absorption energy W (dot-dash curves) vs. permittivity ε' of the coating substance; the plots correspond to the conditions of reflectionless quenching of electromagnetic radiation in solving A or B problems. The permittivity of the substrate substance is $\varepsilon_1 = 2.25$.

$$\frac{n(1-iy)}{n_1^2} = \frac{n(1-iy) + \tanh(2\pi xy + i2\pi x)}{1 + n(1-iy)\tanh(2\pi xy + i2\pi x)} . \tag{3}$$

We introduce the notation

$$\tanh(\alpha_1 + i\beta_1) = n(1-iy), \quad \tanh(\alpha_2 + i\beta_2) = \frac{n(1-iy)}{n_1^2}, \tag{4}$$

where $\alpha_1 = -\frac{1}{2}\ln r_1$, $\alpha_2 = -\frac{1}{2}\ln r_2$, $\beta_1 = -\frac{1}{2}\varphi_1$, and $\beta_2 = -\frac{1}{2}\varphi_2$, $r_1 = \sqrt{\frac{(1-n)^2 + (ny)^2}{(1+n)^2 + (ny)^2}}$, $r_2 = \sqrt{\frac{(n_1^2 - n)^2 + (ny)^2}{(n_1^2 + n)^2 + (ny)^2}}$, $\varphi_1 = \arctan\frac{2ny}{1 - n^2(1+y^2)}$, and $\varphi_2 = \arctan\frac{2nn_1^2 y}{n_1^4 - n^2(1+y^2)}$; r_1, r_2, φ_1, and φ_2 are the moduli and phases of the coefficients of reflection of the wave from the first and second boundaries of the system's media respectively.

Let us substitute expressions (4) into Eqs. (2) and (3). We obtain for problems A and B respectively

$$4\pi xy = \alpha_1 - \alpha_2, \quad 4\pi x = \beta_1 - \beta_2; \tag{5}$$

$$4\pi xy = \alpha_2 - \alpha_1, \quad 4\pi x = \beta_2 - \beta_1 . \tag{6}$$

If the coating is nonabsorptive ($y = 0$), reflectionless transmission by such a system is possible, as follows from Eqs. (2) and (3), for equal values of the refractive indices of the coating and the substrate and for a coating-layer thickness multiple of $\lambda_d/4$. In this connection, we may assume that when an absorbent is used as the coating and the condition $\hat{\rho} = 0$ is fulfilled, the thickness l_0 of the coating layer is close to a value multiple of $\lambda_d/4$ and is determined from the expression

$$x = \frac{l_0}{\lambda_d} = \frac{2N-1}{4} + \Delta, \tag{7}$$

where N is the number of the minimum dependence of the modulus ρ on l, at which ρ attains its zero value, and Δ is the small quantity dependent on the dielectric properties of the coating substance and the number N [4]. We substitute expression (7) into Eqs. (5) and (6) and take account of the relations found for α_1, α_2, β_1, and β_2. We obtain for problems A and B respectively

$$\Delta = \frac{\varphi_2 - \varphi_1}{4\pi}, \quad \frac{1}{y} \ln \frac{r_2}{r_1} + (\varphi_2 - \varphi_1) = \begin{cases} \pi (2N - 1) & \text{for problem A}, \quad (8) \\ -\pi (2N - 1) & \text{for problem B}. \quad (9) \end{cases}$$

Since the optical parameters n, y, and n_1 of the coating and substrate substances are related to their dielectric coefficients ε', ε'', and ε_1, Eqs. (7)–(9) establish functional dependences between the selective values of the dielectric properties of the coating and the substrate, the thickness l_0 of the coating layer, the incident-radiation wavelength λ, and the number N of the zero minimum of ρ as a function of l. Figure 1 gives the families (calculated from Eqs. (7)–(9)) of ε''–ε' and $l_0/\lambda - \varepsilon'$ curves respectively in the coordinates [ε', ε''], [ε', l_0/λ]. They have been obtained for both variants of relative position of the substrate and coating layers at N = 1, 2, and 3 and when the substance with ε_1 = 2.25 was used as the material of the quarter-wave substrate. In the calculations, we have used the iteration procedure of determination of the dielectric-loss factor y of the coating from Eqs. (8) and (9).

Characteristically, ε'' plotted against ε' approaches the abscissa axis with increase in the number N in both variants of position of the layers. This points to the fact that reflectionless quenching of the radiation transmitted by the system is possible even in the presence of its weak damping in the coating substance; in these cases the effect of reflectionless quenching of the wave is realized for increased coating-layer thicknesses. If the condition $\varepsilon' < \varepsilon_1$ is feasible, Eq. (8) for problem A becomes solvable; otherwise, Eq. (9) for problem B becomes solvable. The permittivity of the absorbing substance of the coating is higher, as a rule, than the permittivity of the nonabsorbing substance of the substrate. This circumstance makes the solution of problem B in which the coating is applied to the back surface of the substrate of the two-layer system technically realizable.

Evaluation of the Degree of Quenching of the Wave in the Two-Layer System. In reflectionless transmission of the wave by the two-layer system in question, the relative value of the radiation energy W absorbed in the absorbing-coating layer for its different selective thicknesses is an important index of the system. The value of the energy is determined with the following equations [4] for problems A and B respectively:

$$W = 1 - n_1^2 \sqrt{\frac{[1 - n^2 (1 + y^2)]^2 + 4n^2 y^2}{[n^2 (1 + y^2) - n_1^2]^2 + 4n_1^4 n^2 y^2}}, \quad (10)$$

$$W = 1 - \frac{1}{n_1^2} \sqrt{\frac{[n_1^4 - n^2 (1 + y^2)]^2 + 4n_1^4 n^2 y^2}{[n^2 (1 + y^2) - 1]^2 + 4n^2 y^2}}, \quad (11)$$

where the optical parameters involved in Eqs. (10) and (11) correspond to the conditions of reflectionless transmission of the wave by the absorbing system and are functionally interrelated by Eqs. (7) and (9). Figure 1 plots W against the selective value of the permittivity of the coating substance for problems A and B respectively (dot-dash curves). These plots have been obtained for N = 1 and 2 and ε_1 = 2.25. The quantity W increases with difference of ε' and ε_1. Should the need arise, the degree of absorption of the transmitted electromagnetic radiation can be increased by formation of a periodic layer structure consisting of a set of the considered two-layer systems of the same design. Thus, when problem B for N = 1 is solved and substances with selective values of ε_1 = 2.25, ε' = 2.6, and ε'' = 1.0 are selected as the substrate and coating materials, the layer structure containing a package of four two-layer systems will ensure a 75% quenching of the electromagnetic radiation transmitted by the package.

Conclusions. We have theoretically substantiated the possibility and have determined the conditions of reflectionless transmission of electromagnetic radiation by the plane layer of absorbing dielectric applied to the nonabsorptive quarter-length dielectric substrate. It has been shown that multilayer periodic structures formed on the basis of such a two-layer system make it possible to ensure the completeness of the quenching of electromagnetic radiation transmitted by them.

NOTATION

l and l_1, thickness of the coating layer and the substrate; n and n_1, refractive indices of the wave of the coating and substrate substances; y, dielectric-loss factor of the coating substance; W, value of the energy absorbed in the coating layer; Z_0, Z, and Z_1, wave resistances of vacuum and of the coating and substrate substances; Z_{in}, input resistance of the two-layer coating–substrate system; γ, constant of propagation of the wave in the coating substrate; λ, λ_d, and λ_{d1}, wavelength in vacuum and in the coating and substrate substances; ε' and ε_1, permittivities of the coating and substrate substances; ε'', dielectric loss of the coating substance; $\hat{\rho}$ and ρ, complex value and modulus of the reflection coefficient of the wave. Subscripts: 0, reflectionless quenching of electromagnetic radiation in the coating layer; 1, substrate; d, dielectric coating; in, input.

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