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# REFLECTIONLESS ABSORPTION OF ELECTROMAGNETIC RADIATION IN A MAGNETIC LAYER

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*The conditions for occurrence of total reflectionless absorption of electromagnetic waves in a layer of magnetic material applied to a metal substrate have been found. Their dependence on the layer thickness and the magnetic properties of the coating has been investigated. The frequency band within which this phenomenon can exist has been determined.*

**Introduction.** Nonreflecting absorbers of electromagnetic radiation find wide use, in particular, in microwave equipment [1, 2]. They are generally formed based on a matrix nonabsorbing material (polymer, ceramic) by introducing highly dispersed metal or ferromagnetic substances as fillers into it [2]. At the same time, nonreflecting microwave absorbers can be manufactured with the use of laminated dielectrics. As has been shown in [3], with a certain selection of the thickness and properties of an absorbing substance applied to a metal substrate, one can attain the total absorption of the incident electromagnetic radiation in the substance. This result can also be obtained when magnetic materials are used as coatings of metal substrates.

**Formulation of the Problem.** To find the conditions for occurrence of total absorption of electromagnetic radiation in absorbing magnetics we consider the reflection of a plane-polarized wave incident normally on a plane magnetic layer adjustable for a thickness $l$ and located on an ideally conducting metal substrate. For such a two-layer system, the complex value of the reflection coefficient of an electromagnetic wave $\hat{\rho}$ is equal to

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

where $Z_{\text{in}} = Z \tanh \gamma l$; $\gamma = i2\pi\sqrt{\hat{\mu}}/\lambda$; $Z = Z_0\sqrt{\hat{\mu}}$; $\hat{\mu} = \mu' - i\mu''$. The quantity $Z_{\text{in}}$ can be represented in the same manner as

$$Z_{\text{in}} = Z_0\,(E + iF)\,, \tag{2}$$

where

$$E = n\,\frac{\sinh 4\pi xy + y \sin 4\pi x}{\cosh 4\pi xy + \cos 4\pi x}\,;\quad F = n\,\frac{\sin 4\pi x - y \sinh 4\pi xy}{\cosh 4\pi xy + \cos 4\pi x}\,;\quad x = \frac{l}{\lambda_{\text{mgn}}}\,;\quad n = \frac{\lambda}{\lambda_{\text{mgn}}}\,;\quad y = \tan\frac{\delta}{2}\,;\quad \delta = \arctan\frac{\mu''}{\mu'}\,;$$

$$\mu' = n^2\,(1 - y^2)\,;\quad \mu'' = 2n^2 y\,.$$

Simultaneous consideration of Eqs. (1) and (2) shows that the modulus $\rho$ can have the form

$$\rho = \sqrt{\frac{(E-1)^2 + F^2}{(E+1)^2 + F^2}}\,. \tag{3}$$

The dependence of $\rho$ on $x$, determined by Eq. (3), represents an oscillating and damping curve which tends to its limit $\rho_\infty$ for high $x$ values. Figure 1 shows typical dependences of $\rho$ on $x$ of the magnetic material; these de-

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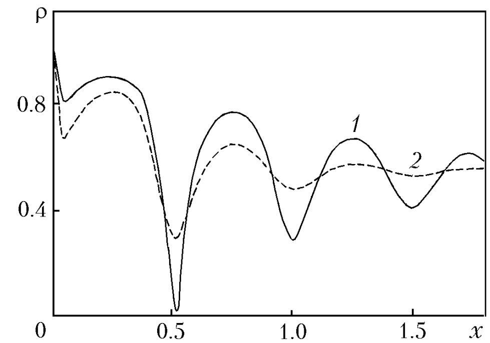


Fig. 1. Moduli of the reflection coefficient of the wave ρ vs. thickness $l$ of the liquid-magnetic layer for $\mu' = 10$, $\mu'' = 1$ (1), and $\mu'' = 2$ (2). $x = l/\lambda_{mgn}$.

pendences possess the following two features. First of all, the extrema of the function $\rho(x)$ are realized for a substance-layer thickness larger than the value multiple of $\lambda_{mgn}/4$; unlike the analogous dependences of coatings from dielectric materials, the function's minima are located near the values multiple of $\lambda_{mgn}/2$. The second feature of the behavior of the function $\rho(x)$ is the existence, in it, of two regions differing by the character of change in its extremum ρ values. In its normal region located at high $x$ values, the function $\rho(x)$ has a traditional form for which a decrease in the maximum values of ρ with growth in the extremum number is accompanied by a corresponding increase in the minimum values of ρ up to their total coincidence with the limiting value $\rho_\infty$ for large $x$. Unlike this case, in the remaining region of variation in ρ (it is called anomalous), we observe a synchronous drop in both the maximum and minimum values of ρ at low $x$ values (see Fig. 1). Except for the initial minimum of the functions $\rho(x)$, which is realized near $x = 0$, one remaining minimum of the function $\rho(x)$ that reaches zero in value can turn out to be the boundary of these regions with a certain selection of the magnetic properties of the substance. It follows that the conditions of existence of the so-called zero minimum must be determined by the conditions of occurrence of the reflectionless absorption of electromagnetic radiation incident on it in the substance.

**Conditions of Total Absorption of the Wave.** As follows from Eq. (3), fulfillment of the condition $\rho = 0$ requires that $E = 1$ and $F = 0$. Then, using expressions for $E$ and $F$, we write the following system of equations:

$$\sin 4\pi x_m - y \sinh 4\pi x_m y = 0 , \tag{4}$$

$$(1 + y^2) \frac{\lambda}{\lambda_{mgn}} = \tanh 2\pi x_m y + y \operatorname{ctan} 2\pi x_m , \tag{5}$$

where $x_m = l_m/\lambda_{mgn}$.

Equations (4) and (5) establish functional relationships between the wavelength λ of the incident radiation, the thickness $l$ of the layer of the coating's substance, and its magnetic properties for which we have a zero minimum of ρ. However it is quite difficult to obtain this relationship in a convenient analytical form because of the presence of transcendental functions in the equations. For simplicity of solution of the problem we take into account that the zero minimum, just as any minimum of the function $\rho(x)$ observed, is realized in accordance with Eqs. (3) for substance thicknesses close to the values multiple of $\lambda_{mgn}/2$ but not equal to them. We take that

$$x_m = \frac{N}{2} + \Delta_m , \tag{6}$$

where $N = 0, 1, 2, 3, \ldots$ and $\Delta_m$ is a certain small but nonzero quantity determined just by the magnetic properties of the coating's substance.

Substituting relation (6) for $x_m$ into Eqs. (4) and (5) and eliminating the common parameter $\Delta_m$ from the resulting expressions, we obtain

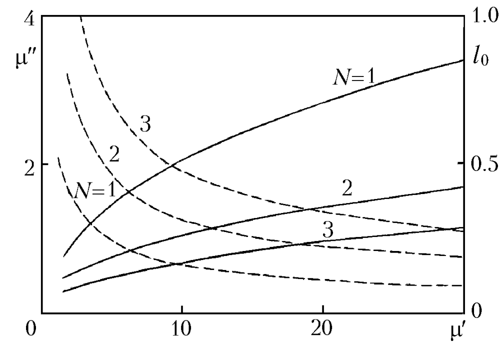


Fig. 2. Magnetic loss $\mu''$ (solid curves) and layer thickness $l_0$ (dashed curves) vs. magnetic permeability $\mu'$ of the coating substance; the dependence corresponds to the conditions of reflectionless absorption of electromagnetic radiation.

$$\pi N - \varphi = \frac{1}{y}\ln\left(\frac{1}{r}\right), \tag{7}$$

where $r = \dfrac{\sqrt{(1-n)^2 + (ny)^2}}{(1+n)^2 + (ny)^2}$ and $\varphi = -4\pi\Delta_m = \arctan\dfrac{2ny}{1 - n^2(1 + y^2)}$ are respectively the modulus and phase of the coefficient of reflection of the wave from the vacuum–magnetic boundary [1].

The thickness $l_0$ of the coating-substance layer for which the condition $\rho = 0$ is fulfilled will be determined with account for expressions for $x_m$, $\varphi$, and $\Delta_m$ by the relation

$$\frac{l_0}{\lambda_0} = \frac{1}{2\pi n}\left[\pi N - \frac{1}{2}\arctan\frac{2ny}{1 - n^2(1 + y^2)}\right]. \tag{8}$$

Since $n$ and $y$ of the magnetic material are related to its $\mu'$ and $\mu''$, Eqs. (7) and (8) establish the interrelation between the selective values of the wavelength $\lambda_0$ of incident radiation, the magnetic permeability $\mu'$, the magnetic loss $\mu''$, the thickness $l_0$ of the coating layer, and the number $N$ of the zero minimum of the function $\rho(x)$.

Figure 2 gives families (calculated from Eqs. (7) and (8)) of dependences of $\mu''$ and $l_0/\lambda_0$ on $\mu'$ respectively in the coordinate planes $[\mu', \mu'']$ and $[\mu', l_0/\lambda_0]$. Since the condition $\rho = 0$ for the initial minimum ($N = 0$) of the function $\rho(x)$ is unrealizable in the range of values $\mu' > 1$, these dependences have been given for $N = 1$, 2, and 3 of the function's zero minima. In the calculation, we used the iteration procedure of determination of the magnetic-loss factor $y$ from Eq. (7).

Characteristically, as the number $N$ of the zero minimum of $\rho$ increases, $\mu''$ plotted as functions of $\mu'$ approach the abscissa axis. This points to the possibility of the reflectionless absorption of electromagnetic radiation existing even in substances possessing an insignificant magnetic loss; in these cases the effect of reflectionless absorption of the wave is realized for higher-than-average values of the thickness of the reflecting layer of the coating's substance. Prescribing the magnetic parameters of the coating, we can, consequently, find the radiation frequency and the thickness of the coating layer for which reflectionless absorption will occur, or solve the inverse problem: to evaluate the parameters and thickness of the coating-substance layer, for which this phenomenon will be observed, by the prescribed radiation frequency. Clearly, irrespective of the formulation of the problem, a search for the unknown parameters becomes unambiguous, if the frequency dependences of $\mu'$ and $\mu''$ of the magnetic material of the metal-substrate coating are known.

The conditions of reflectionless absorption of electromagnetic radiation have been obtained in propagation of the wave in free space. They can be generalized to the case of employment of waveguide or other electromagnetic-radiation channeling systems used in the superhigh-frequency range.

**Band of Selective Absorption of the Wave.** In developing metal-backed absorbing coatings, it is important to evaluate the degree of absorption of the incident radiation within a certain band of radiation wavelengths near the

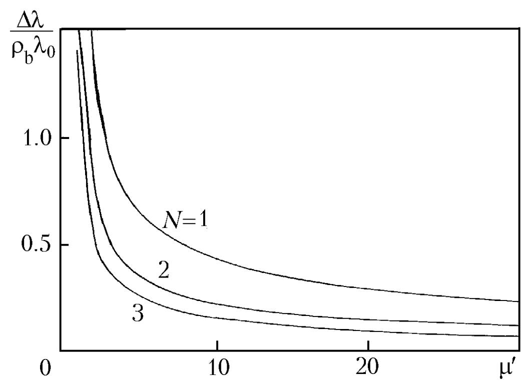


Fig. 3. Relative band of selective absorption $\Delta\lambda/\rho_b\lambda_0$ of electromagnetic radiation vs. magnetic permeability $\mu'$ of the coating material for different numbers $N$ of the zero minimum of the modulus of the reflection coefficient of the wave $\rho$ as a function of $l$.

selective values $\lambda_0$ and $l_0$ for which conditions for reflectionless wave absorption are created in the substance. In [4], it has been shown that for the selective thickness of the coating layer and the frequency dependence (determined by Eq. (3)) of the modulus of the reflection coefficient of the wave $\rho$, the range of variation in the wavelength $\Delta\lambda$ within which the value of $\rho$ is no higher than a certain prescribed value of $\rho_b$ at its boundaries can be found from the expression

$$\Delta\lambda = \frac{4\rho_b}{\sqrt{(E_0')^2 + (F_0')^2}}, \tag{9}$$

where $E_0'$ and $F_0'$ are the derivatives of respectively the material and imaginary parts of the input resistance of the two-layer system for the selective values $\lambda_0$ and $l_0$.

Using the expressions for $E$ and $F$ to determine $E_0'$ and $F_0'$ and substituting them into (9), we obtain

$$\frac{\Delta\lambda}{\rho_b\lambda_0} = \frac{\sinh 4\pi x_0 y_0}{\pi x_0}, \tag{10}$$

where $x_0$ and $y_0$ are the selective values of $x$ and $y$ for which the condition of total absorption of the incident electromagnetic radiation is fulfilled.

From expression (10) it follows that, with a selected level of $\rho_b$ of reckoning of the absorption band $\Delta\lambda$ near $\lambda_0$, the size of the band is dependent on the number $N$ of the minimum of the function $\rho(x)$ and the magnetic properties of the coating material at $\lambda = \lambda_0$. Figure 3 gives the dependences (computed from Eq. (10)) of the reduced values of the relative absorption band $\Delta\lambda/\rho_b\lambda_0$ on the selective values of $\mu'$ of the coating substance for the first three zero maxima of the function $\rho(l)$. They demonstrate that for the prescribed level of $\rho_b$ the relative absorption band near $\lambda = \lambda_0$ decreases in value with increase in $\mu'$ and $N$.

**Conclusions.** We have theoretically substantiated the possibility and have determined the conditions for the occurrence of the effect of reflectionless (total) absorption of electromagnetic radiation in a layer of magnetic material applied to a metal substrate. The frequency band of selective radiation as a function of the magnetic properties and thickness of the coating has been evaluated. The results obtained allow a target-oriented search for composites for radiation absorbers not only in the superhigh-frequency range but also in any portion of the electromagnetic radiation.

## NOTATION

$l$, coating-layer thickness; $n$ and $y$, refraction index and magnetic-loss factor of the coating substance; $N$, No. of the zero minimum of the reflected wave; $Z_0$ and $Z$, wave resistances of vacuum and the coating substance; $Z_{in}$, input resistance of the two-layer magnetic–metal system; $\gamma$, propagation constant of the wave in the coating substance; $\lambda$ and $\lambda_{mgn}$, wavelength in vacuum and in the coating substance; $\Delta\lambda$, band of selective absorption of the wave; $\mu'$ and $\mu''$, magnetic permeability and magnetic loss of the coating substance; $\hat{\rho}$ and $\rho$, complex value and modulus of the reflection coefficient of the wave; $\rho_b$, modulus of the reflection coefficient of the wave at the boundaries of the band of selective absorption in the wave. Subscripts: 0, reflectionless absorption of electromagnetic radiation in the coating layer; mgn, magnetic coating; b, boundary value; in, input; m, minimum value.

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