Radio-absorption shielding.

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Abstract —**A correlation between the frequency of natural ferromagnetic resonance (NFMR) (1 to 12 GHz), determined from the dispersion of permeability, and alloy composition (or magnetostriction between 1 and 40 ppm) of glass-coated microwires has been systematically stadied. Absorption properties of composite (microwire pieces embedded in a polymer matrix) screens has been experimentally investigated.**

Index Terms — **glass-coated microwires, ferromagnetic resonance, micro – and nanocomposite, absorption shielding.**

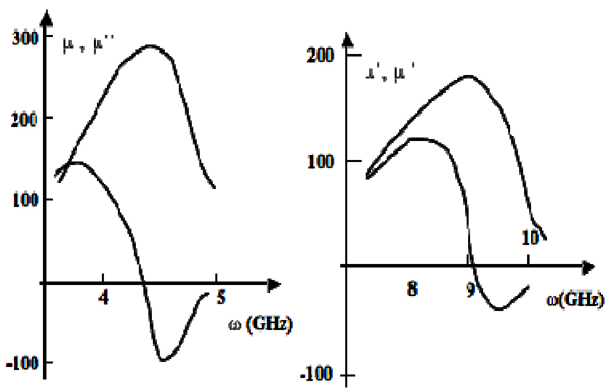
I. INTRODUCTION

Natural ferromagnetic resonance (*NFMR*) occurs when a sample is submitted to a microwave field without application of any biasing field other than the intrinsic anisotropy field of the microwire (see [1-11]).

Near the natural ferromagnetic resonance frequency, Ω, the dispersion of permeability μ. given by

$$\mu(\omega) = \mu'(\omega) + i\,\mu''(\omega), \qquad (1)$$

exhibits a peak in μ'' and a zero crossing of μ' .



a b

Fig.1 a, b. Frequency dispersion of real and imaginary relative permeability components around NFMR for $Co_{59}Fe_{15}B_{16}Si_{10}$ (a) and $Fe_{69}C_5B_{16}Si_{10}$ (b) microwires (r ~5μm, x>8 (see [1-11]).

Figures 1a and 1b show resonance frequencies of 4.4 and 9.0 GHz, and resonance widths of 1 and 0.5 GHz, for two compositions. When near resonance, μ'' is expected to be described by

$$\mu''/\mu_{dc} \sim \Gamma\,\Omega / [(\Omega - \omega)^2 + \Gamma^2], \qquad (2)$$

where μ_{dc} is static magnetic permeability and Γ is the width of the resonant curve. When very close to resonance Γ> (Ω– ω), Eq. (2) reduces to

$$\mu''/\mu_{dc} \sim \Omega / \Gamma \sim (10 \div 10^2).$$

Note that in Fig. 1a the imaginary component is rather symmetrically distributed around the resonance frequency. This is due to the symmetric distribution of the circular permeability in the near surface layer, which is within the penetration depth. In contrast, in Fig. 1b, the imaginary component shows a non-symmetric feature around the resonance frequency. This can be attributed to the inhomogeneous character of the permeability in the region close to the surface of the microwire where metastable phases form, as demonstrated by X-ray studies.

Modulating the geometry of the microwire (e.g., its diameter) and the magnetostriction through its composition enables one to fabricate microwires with tailor able permeability dispersion and for radioabsorption application:

i) Determining the resonant frequency in a range from 1 up to 12 GHz;

ii)Controlling the maximum of the imaginary part of magnetic permeability.

II. RADIO-ABSORPTION SHIEDING

High-frequency properties, pieces of microwires have been embedded in planar polymeric matrices to form composite shielding for radio absorption protection. Experiments were performed employing commercial polymeric rubber around (2 ÷ 3) mm thick. Microwires were spatially randomly distributed within the matrix prior to its solidification. Concentration is kept below (8 ÷ 10) g of microwire dipoles ((1 ÷ 3)mm long) per 100g rubber [11]. A typical result obtained in an anechoic chamber is shown in Fig. 2 for a screen with embedded $Fe_{69}C_5B_{16}Si_{10}$ microwires. As observed, an absorption level of at least 10 dB is obtained in the frequency range from 8 to 12 GHz with a maximum attenuation peak of 30 dB at around 10 GHz. In general, optimal absorption is obtained with microwires with metallic nuclei of diameter $2r$ = (1÷3) µm (2R ~ 20µm (x>10)) and length L = (1÷3) mm. Such pieces of microwires can be treated as dipoles whose length, L, is comparable to the half value of the effective wavelengths, $\Lambda_{eff}/2$, of the absorbed field in the composite material (i.e., in connection to a geometric resonance).

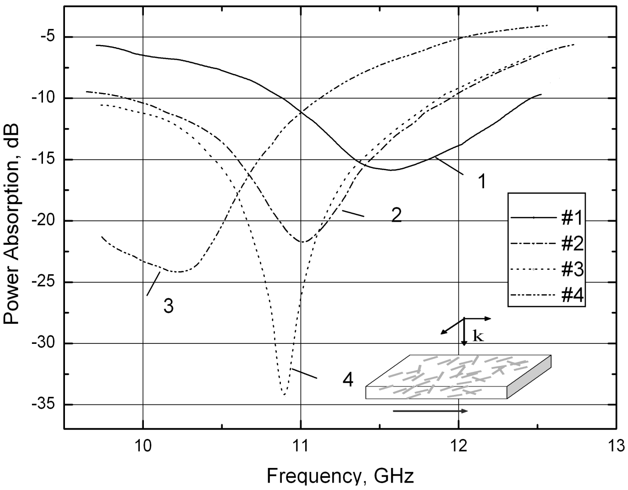


Fig. 2. Absorption characteristics of shielding by a microwire composite with *NFMR* in the *HF* - field in the range of frequencies 10-12 GHz. Curve 1 represents an initial situation of the screen; then 2, 3, 4: the screen is turned by 90 ° about a perpendicular axis each time.

Fig. 2 also shows how the frequency absorption spectrum of shielding with $Fe_{69}C_5B_{16}Si_{10}$ microwires changes when it is rotated (90º each spectrum). We attribute such attenuation change to the lack of perfect angular distribution of microwires which length not always fit within the shielding thickness. The effect doesn't even have mirror symmetry (the measurement error was less than 10% for the frequency, and while the spread of the attenuation factor was 5 dB).

Small fluctuations in concentration of dipoles at a concentration of dipoles near the percolation threshold can lead to fluctuation of the absorption curve. Similar results were presented in [12]. In addition, as observed, both frequency dependences (Fig. 1b and Fig. 2) are similar except for the half-width value of the permeability.

Although the design of absorption shielding can be based on disposing the dipolar pieces in a stochastic way, we consider, for simplicity, a theoretical analysis for a diffraction grating with spacing between wires Q < Λ (Λ is wavelength of absorbed field). (Another simple example is in Appendix).

The propagation of an electromagnetic wave through absorption shielding with microwire-based elements is characterized by transmittance, |T|, and reflectance, $|R_r|$, coefficients given by:

$$|T| = (\alpha^2 + \beta^2)/[(1+\alpha)^2 + \beta^2];$$

$$|R_r| = 1/[(1+\alpha)^2 + \beta^2], \qquad (3)$$

where $\alpha=2X_r/Z_0$, and $\beta=2\ Y/Z_0$, with $Z_0=120\pi/Q$, and the complex impedance $Z= X_r + iY$.

The absorption function, G, is correlated with the generalized high-frequency complex conductivity Σ (or high-frequency impedance Z).

Here, we use the analogy between the case of a conductor in a waveguide and that of a diffraction grating. The absorption function, given by:

$$|G| = 1 - |T|^2 - |R_r|^2 = 2\alpha / [(1+\alpha)^2 + \beta^2] \quad , \qquad (4)$$

has a maximum,

$$|G_m|=0{,}5 \geq |G|,$$

for simultaneous α=1, and β=0, for which

$$|T|^2 = |R_r|^2 = 0{,}25.$$

The minimum, |G|=0, occurs at α=0, β positive number).

Theoretical estimations taking into account only the active résistance of microwires result in attenuation within the range (5 ÷ 15) dB that is much lower than experimental results, which for spacing of microwires Q =10^{-2} m ranges between 18 and 15 dB, while for a spacing Q = 10^{-3} m it increases up to 20 to 40 dB. Thus, it becomes clear that shielding exhibit anomalously high absorption factors, which cannot be explained solely by the resistive properties of microwires.

The high-frequency conductivity, Σ_m, of a stochastic mixture of microwires in the polymeric matrix can be expressed as a function of the conductivities, Σ_i, of non-conducting (polymeric matrix) and conducting (microwire) elements, denoted by sub-indices 1 and 2, respectively, in the form of [13]:

$$\Sigma_m = B + (B^2 + A\,\Sigma_1\,\Sigma_2)^{½} \quad , \qquad (5)$$

where

$$B=1/2\{[\Sigma_1(X_1-AX_2)+\Sigma_2(X_2-AX_1)]\};$$

X_i is fractional volume:

$$(X_1+X_2)=1;$$

$A=1/(J_1-1)$, with $J_1 \sim (J+Y/X_r)$

being the fractal dimension of the system (J is the geometrical dimension of the system) and

$$Y/X_r \sim (r/\delta)^2.$$

Fig. 3 shows that in the case of a thick microwire ($r > \delta \approx 1$µm), the conductivity of the system becomes very large, even in the case of small microwire concentration, indicating the case of an antenna resonance as reported in [11].

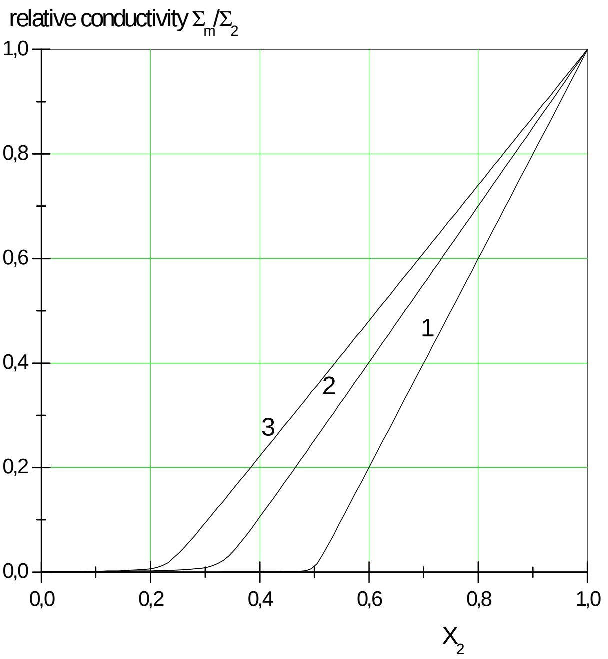


Fig. 3. Generalized conductivity calculated using formula (18) for $\Sigma_2 / \Sigma_1 \sim 10^4$.
1 thin microwire ($r<\delta\sim 1$ μm) J =2, Y =0
2 thin microwire ($r<\delta\sim 1$ μm) J =3, Y =0
3 thick microwire ($r>\delta\sim 1$ μm) J_1 =4, Y/X_r = 1

Let us consider the effective absorption function, (as in Eq. (4))**:**

$$|G_{eff}| \sim \Gamma_{eff}\, \Omega_{eff} / [(\Omega_{eff} - \Omega)^2 + \Gamma_{eff}^2], \qquad (6)$$

where $\Gamma_{eff} \geq \Gamma$ (see Eq. (12)) and $\Omega \sim \Omega_{eff} = 2\pi c/\Lambda$.
A microwave antenna will resonate when its length, L, satisfies

$$L \sim \Lambda / 2(\mu_{eff})^{1/2} \ . \qquad (7)$$

The maximum absorption (see Fig. 2) occurs for

$\Omega_{eff} \sim 10$ GHz ($\Lambda \sim 3$ cm) and $\mu_{eff} \sim 10^2$, (according to Fig. 1). This corresponds to:

$$L \sim (1{,}5 \div 2) \text{ mm}, \qquad (8)$$

when the microwire concentration ((see Fig.3) $X_2<0{,}2$) is much less than the percolation threshold.. A greater concentration of dipoles increases absorption, $|G_{eff}|$, but also increases reflectance, $|R_{r1}|$, which can be simply evaluated to be [14]:

$$|R_{r1}| \sim 1 - 2\sqrt{(\Omega/2\pi\, \Sigma_m)} \ , \qquad (9)$$

where $\Omega/2\pi \sim 10^{10}$ Hz.

The formula is applicable, and calculation of small reflectance, $|R_{r1}|$ is possible, only if

$$\Sigma_m \sim 10^{11} \text{Hz},$$

for concentration below the percolation threshold

$$(\text{as } \Sigma_2 \sim 10^{15} \text{ Hz}).$$

Thus, for very thin microwires (i.e., thinner than 1 μm diameters) embedded in a composite matrix with concentration larger than the percolation level $X_2 \sim 0{,}2$ a noticeable absorption effect should be expected.

III. CONCLUSION

The microwave electromagnetic response has been analyzed for a composite consisting of dipoles of amorphous magnetic glass-coated microwires in a dielectric. This material can be employed for radio absorbing screening. The spontaneous *NFMR* phenomena observed in glass-coated microwires has opened the possibility of developing novel materials with broadband radioabsorption.

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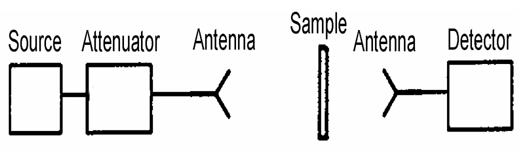
APPENDIX



It is well known, that the simple model relating the contact of vacuum with the absorbing material gives the following equations [14] (the general theory is presented in Ref. [15]; see also Ref. [16]):

$$1 + R_r = T, \qquad (A.\ 1)$$

$$(\alpha + i\ \beta)\,(1 - R_r) = T;$$

that gives

$$R_r = \frac{1-\alpha-i\beta}{1+\alpha+i\beta}, \qquad (A.\ 2)$$

and at $\beta = 0$, $\alpha = 1$,we find

$$R_r = 0. \qquad (A.\ 3)$$

From the above it is possible to obtain a simple criterion for matching the vacuum with a radio absorbing material:

$$\mu_m \sim \Sigma_m / \Omega, \qquad (A.\ 4)$$

(where μ_m is effective magnetic permeability of composite). This condition cannot be satisfied for composites containing amorphous magnetic wires. This forces us to use other physical principles for creating radio absorbing materials presented above).

We note that similar results were also obtained in Ref. [16].

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