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# Glass-Coated Microwires and Its Application

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***Abstract***
*In this paper, solutions for two problems are proposed. One of the problems is associated with increasing the strength of objects, for instance, the strength of windows in medical buildings. The other problem is related to electromagnetic shielding for medical apparatus. Both of these problems are related to the protection form terrorist acts, since terrorists make use of concentrated electromagnetic pulses to destroy computers or other electronic equipment. The proposed solutions are based upon the manufacturing of glass windows reinforced with cast glass-coated amorphous micro- and nanowires (CGCAMNWs) having a special composition and structure, which increases their tensile strength against mechanical destruction, on the one hand, and imparts them with shielding properties against electromagnetic radiation, on the other hand. The CGCAMNW materials are of interest from both theoretical and practical points of view.*

**Keywords:** Glass-coated amorphous micro- and nanowires, modified Taylor–Ulitovsky method, natural ferromagnetic resonance, shielding for radio absorption protection.

## Introduction

One of the dangerous consequences of acts of terrorism is a traumatism of people owing to shattering of window glass of medical buildings, administration, industrial, and apartment houses. Therefore, an urgent problem is to improve the glass strength by decreasing the probability of forming and spreading the splinters during shattering.

In addition, modern acts of terrorism can occur with use of concentrated beams of radio-frequency pulses in order to disable computers and other electronic devices, running of life-support systems of cities, etc.

Furthermore, the radio-electronic intelligence service using directional electromagnetic radiation for reading information typed on the computer keyboard or displayed in the monitor, for example, via window opening, is concerned with modern acts of terrorism and espionage activity.

It is known that conventional glass almost completely passes electromagnetic radiation in the entire frequency range. Therefore, the problem of producing radio-screening glasses is also urgent.

The above problems can be solved in complex with the use of glass reinforced with glass-coated microwires prepared by the solution casting technique of the Taylor–Ulitovsky method [1-4].

The reinforcement of glass with glass-coated microwires using an adhesive film increases the durability of the glass under shock and static loadings and prevents splinter scattering in the case of glass shattering.

In addition, this glass considerably reduces the transitivity of electromagnetic radiation in a wide frequency range—from a few hundreds of megahertz to a few tens of gigahertz.

The reinforcement of glass with microwires does not reduce the light transmission ability in the entire gamut of colors, as in conventional glass, and does not worsen the transparency of the glass. Glass-coated microwires are almost imperceptible.

Another possible application of microwires in the antiterrorist purposes, also for providing a hardening and screening effect, is the reinforcement of vests and helmets made of plastic, such as

Kevlar, with microwire elements.

The microwire represents a construction composed of a continuous metal core coated with a continuous glass coating. For a more precise comparison of the theory with the experiment, a set of experimental measurements is required; they are also discussed in the paper.

The resulting microwires with an optimum chemical composition were tested for reinforcing window glass. A grid of high-strength microwires was reconstructed using linear and orthogonal winding. After that, a melt was poured into special molds to reinforce window glass to obtain a sheet blank with a thickness of about 1–3 mm.

## History

A simple production technology of cast glass-coated amorphous micro- and nanowires (CGCAMWs) was first introduced in 1924 by Taylor [1]. The principle of this method lays in the heating of a metal sample inside a horizontally positioned glass tube with a gas burner till the softening of the tube and the melting of the metal followed by rapid stretching of the tube. This method did not receive wide acceptance, as it produced microwires of limited lengths and their parameters were uncontrollable.

Later, in the period 1948 – 1957, this method was significantly modified by Ulitovsky. The essence of this method is that a continuous liquid metal filling the capillary is drawn out from a vertically positioned glass tube (see below, Figure 1). Modified Taylor–Ulitovsky method allows producing large amounts of such microwires. Interest in the cast glass-coated microwires has greatly increased over the last few years, mainly due to their technological applications, in particular, as sensor elements in various devices. Consequently, preparation of CGCFMWs by the Taylor-Ulitovsky method and the study of their magnetic properties were reported in many my publications and publications by various research groups [2-14]. It is essential that the microwires are manufactured using a rapid solidification technique. However, the main peculiarity of the aforementioned microwires is the simultaneous rapid solidification of metallic alloy covered by glass.

## Casting of Glass-Coated Amorphous Magnetic Microwires

Cast glass-coated amorphous micro- and nanowires (CGCAMNWs) are prepared using a rapid solidification technique, the so-called quenching and drawing procedure, or a modified Taylor–Ulitovsky method [1–14], as shown in Fig. 1.

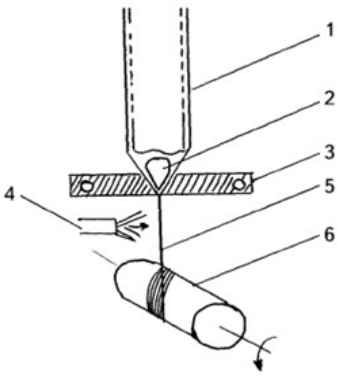



**Figure 1:** Process of casting glass-coated amorphous magnetic microwires (see Refs. [1-4] and the text below). 1. Glass tube. 2. Drop of metal. 3. Inductor. 4. Water. 5. Glass-coated microwire. 6. Rotating receiving bobbin

In this process, an alloy in an amount of a few grams is placed inside a glass tube held directly over suitable heating means, for example, a high-frequency inductor heater. The alloy is heated up to the melting point to form a droplet. The portion of the glass tube adjacent to the melting metal softens to envelope the metal droplet. A glass filament is drawn from the softened glass portion and collected onto a receiving bobbin. Under certain drawing conditions, the molten metal can fill the glass capillary; thus, a microwire in which a metal core is covered continuously with glass is formed. The glass consumption in the process is compensated by continuous delivery of the glass tube in the inductor zone, whereas the formation of the metallic core is restricted to the initial amount of the droplet. The microstructure and, accordingly, properties of a microwire considerably depend on the cooling rate, which can be controlled by a cooling mechanism when the metal-filled capillary passes through a stream of a cooling liquid (water or oil) on its way to the receiving coil.
The main advantages of this method for the production of cast glass-coated microwires are as follows [1–14]:

i. The formation of continuous long pieces of a microwire up to 104 m (in the case of a drip process). For a continuous process (see Fig. 1), the microwire length is not limited.
ii. A wide range of variations in the geometric parameters (typically the metallic core diameter Dm is in a range of 0.5–70 μm, and the glass-coating thickness is in a range of 1–50 μm).
iii. The control and adjustment of the geometric parameters (inner metallic core diameter Dm and glass thickness) during production.
iv. The reproducibility of the physical properties and geometric parameters of the microwires in large-scale production.

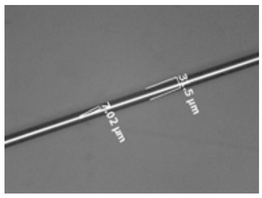
(a)  (b) 


**Figure 2:** a) Image of the microwire preparation process using the Taylor–Ulitovsky method; b) Cast glass-coated ferromagnetic amorphous microwire.

(a)  (b) 

**Figure 3:** a) Machine for preparation of CGCFMWs by the Taylor–Ulitovsky method (produced at AMOTEC Ltd, Moldova); b) Novel machine for preparation of CGCFMWs by the Taylor–

Ulitovsky method (produced at MFTI Ltd, Moldova).

Fig.3 represents the machines for the preparation of CGCFMWs by the Taylor–Ulitovsky method, which were manufactured in Moldova. Novel machine for the preparation of CGCFMWs, represented in Fig.3b, has lower energy consumption and is more compact than the machine in Fig.3a. These machines can to fabricate the cast glass-coated microwires of the different types (see Fig.1a) with the diameters in a wide range as it was indicated above.

The main technological parameters for the production of the glass-coated microwires are presented below. According to the previous analysis4-11, the most significant effect on the geometry of such microwire comes from the glass properties. The microwire radius Rg (the outer radius of the glass shell) is estimated as follows:

$$R_g \sim A\frac{\eta^{2-k}}{V_d^k \sigma_s^{1-k}},\ A \sim \frac{1}{\rho}, \quad (1)$$

where k is the parameter, which dependent on a casting rate ($0 < k < 1$); ρ is the average microwire density; $V_d$ is the casting rate; σs is the surface tension (glass); and η is the dynamical viscosity (glass):

$$\eta \sim \eta_0 \exp\left\{\frac{\Delta H}{RT} + c\left[\exp\left(\frac{\varepsilon}{RT}\right) - 1\right]\right\}, \quad (2)$$

where $\varepsilon \sim 2\cdot10^2$ kJ/mol., ΔH ~ 102 kJ/mol., R is the universal gas constant, η0 and c are the material constants.

Specific attention is paid to the parameters determining the casting and cooling rates that are responsible for the microstructure of the cast glass-coated microwires (amorphous or microcrystalline). So, the dynamical viscosity is very important parameter whose value has characteristic temperature dependence. Such typical temperature dependence of the dynamical viscosity represented below in Fig.4. The temperature region where the casting process can be implemented is indicated by the dashed lines.

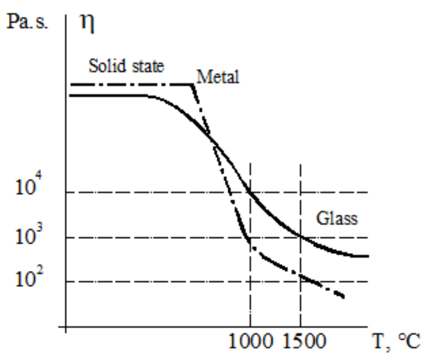



**Figure 4:** Viscosity   as a function of temperature.

$$R_g \sim \frac{\eta^{5/3}}{V_d^{1/3}\sigma_s^{2/3}\rho} \quad (3)$$

Formula (1) suggests the following – if the value of the casting rate is extremely low, then the value of $R_g$ is high and we obtain the formula similar to that given in the works[10,11]:

where $k = 1/3$.

If the casting rate is sufficiently high, we obtain for $R_g$ (see, also the articles[10,11]):

$$R_g \sim \frac{\eta^{4/3}}{V_d^{2/3}\sigma_s^{1/3}\rho} \quad (4)$$

where $k = 2/3$.

In the theoretical limit of the extremely high casting rate, i.e. when $k \to 1$, we obtain:

$$R_g \sim \frac{\eta}{\rho V_d} \quad (5)$$

At last, we present the results of theoretical simulation for the residual stresses in the microwire metallic core. The residual stresses are the result of a difference in the thermal expansion coefficients of a metal and of glass. A simple theory for the distribution of the residual thermoelastic stresses in the microwire metallic core was proposed in the works3-6,9-11. In the cylindrical coordinates, the residual thermoelastic tension is characterized by the axial, radial and tangential components which do not depend on the radial coordinate in a first approximation:

$$\sigma_r = \sigma_\varphi = P = \sigma_0 \frac{k_1 x}{\left(\frac{k_1}{3}+1\right)x + \frac{4}{3}}$$

$$\sigma_z = P\frac{(k_1+1)x+2}{k_1 x+1} \quad x = \left(\frac{R_g}{R_m}\right)^2 - 1 \quad (6)$$

where $R_m$ is the metallic core radius of a microwire; $\sigma_0 = eY_m$ , here $Y_m$ is the Young's modulus of a metal and $e = (\alpha_m - \alpha_g)(T - T^*)$, here $\alpha_m$ and $\alpha_g$ are the thermal expansion coefficients of a metal and of glass, respectively; T* is the effective solidification temperature of the composite microwire (when both a metallic core and a glass-coating solidify) and T is the experimental temperature; in addition, $k_1 = Y_g/Y_m$ , here $Y_g$ is the Young's modulus of the glass.

In the framework of the more accurate model used for the stress distribution in the microwire metallic core, the metallic strand from its axis up to the certain internal radius b preserves the liquid state (parameter b has a certain value depending on the defined metallic alloy composition and cooling rate), while from *b* up to $R_m$ it freezes earlier and only the elastic residual stresses persist. So, at $b < r < R_m$, this model gives:

$$\sigma_{r(r)} = P\left[1-\left(\frac{b}{r}\right)^2\right],\ \sigma_{\varphi(r)} = P\left[1+\left(\frac{b}{r}\right)^2\right],\ \sigma_z \approx \nu(\sigma_{r(r)}+\sigma_{\varphi(r)}), \quad (7)$$

where ν is the Poisson's coefficient.

In addition, at $r<b$, this model gives:

$$\sigma_{r(r)} = 2K\ln\left(\frac{r}{b}\right),\ \sigma_{\varphi(r)} = 2K\left[1+\ln\left(\frac{r}{b}\right)\right],\ \sigma_z = \nu(\sigma_{r(r)}+\sigma_{\varphi(r)}), \quad (8)$$

where K is the metal thermoelastic constant. Note that a rigorous solution should be obtained by the lacing of equations (7) and (8).

## Production of Glass Reinforced with Microwires

Glass reinforced with a microwire represents a three-layered

construction consisting of two pieces of glass glued using a special adhesive film.
The adhesive film consists of an adhesive base on two sides of which pieces of a microwire are put in mutual perpendicular directions.

In the case of an electromagnetic wave incident on the interface between two media, a portion of the field is reflected from the surface; another portion permeates and spreads inside the other medium; the third portion interacts with the medium and is absorbed (transformed into heat). The coefficient of screening of the medium $|G_{eff}|$ can be written as follows:

$$|G_{eff}| = P_r / P_s, \qquad (1)$$

where $P_r$ is the power of the incident wave and $P_s$ is the power of the past wave.

Since an electromagnetic wave contains electrical and magnetic components, the interaction of an electromagnetic wave and a medium can be electrical in the case of a conducting medium and magnetic in the case of a screen with a high magnetic permeability.

(i) For screening household and working buildings, inside which electromagnetic radiation is not located, for constructions and devices requiring protection against external electromagnetic radiation, it is reasonable to apply reflecting screens containing a microwire made of conducted materials (copper, silver, and alloys based on them). Depending on the screened object, the screens can be pliable and elastic, such as fabrics containing a microwire, and rigid, such as plastics, polymers, and glass or paper products.

(ii) For screening household and working buildings, in which, in addition to protection from external radiation, it is required to inhibit (weaken) electromagnetic radiation and reradiation from an internal source of radiation, it is reasonable to apply microwire-reinforced reflecting–absorbing screens having a high impedance at the working frequencies of the source. For example, in buildings with a powerful source operating at an extremely high radiation frequency, it is reasonable to apply microwire-reinforced materials having a resonant absorption frequency of the working source.

(iii) It is reasonable to use reflecting–absorbing multilayered electromagnetic shields for screening people (service personnel) working under conditions of high-level electromagnetic radiation.

(iv) Description of the design and technology of production of shielding. To provide functionality in electromagnetic screens, a microwire should be located as a grid construction. In this case, the microwire is located in a plane of the screen in two mutually perpendicular directions. The grid construction steps and the types and number of microwires in a construction are determined from requirements for the level of loosening the radiation power, the frequency range of screening, and expediency of applying the shielding.

In implementing the stage of working out the technology for the preparation of triplex glass reinforced with microwires, technological equipment and process modes for gluing the glasses will be developed.

## Absorption Properties

The design of GCAMNW composites was described in [8-11]. We have following typical configurations:

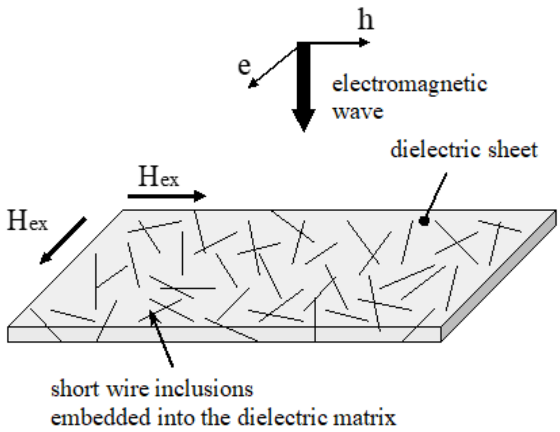



**Figure 2:** Composite shielding for radio absorption protection with GCAMNWs made with a stochastic mixture of microwires in the polymeric matrix.

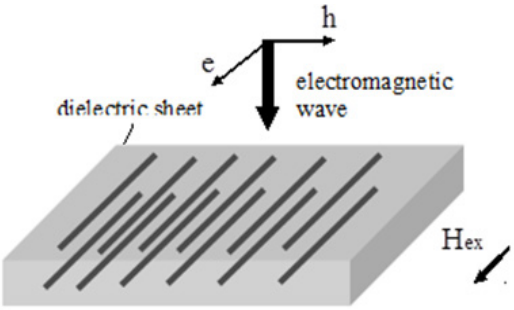



**Figure 3:** Composite shielding for radio absorption protection with GCAMNWs in the form of a grating.

Natural ferromagnetic resonance (NFMR) occurs if the sample is subjected to a microwave field without application of any biasing field other than the anisotropy field of the microwire [8-13]. Permeability dispersion is as follows:

$$\mu(\omega) = \mu'(\omega) + i\,\mu''(\omega). \qquad (2)$$

The peak in μ'' (and a zero crossing of μ'):

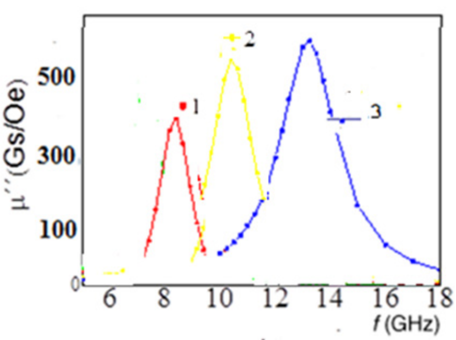



**Figure 4:** Imaginary relative permeability of components around NFMR for (1) $Co_{59}Fe_{15}B_{16}Si_{10}$, (2) $Co_{59}Fe_{15}B_{16}Si_{10}$, and (3) $Fe_{69}C_5B_{16}Si_{10}$ microwires.

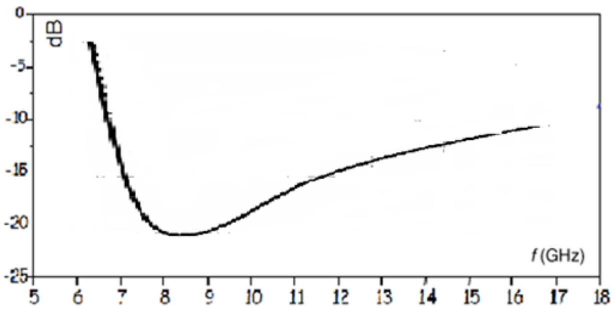



**Figure 5:** Summary absorption characteristics of shielding by composite in an HF field of components around NFMR for (1) $Co_{70}Fe_{5.5}B_{14.5}Si_{10}$, (2) $Co_{70}Mn_8B_{12}Si_{10}$, (3) $Co_{59}Fe_{15}B_{16}Si_{10}$, and (4) $Fe_{69}C_5B_{16}Si_{10}$ microwires (see [5-11]).

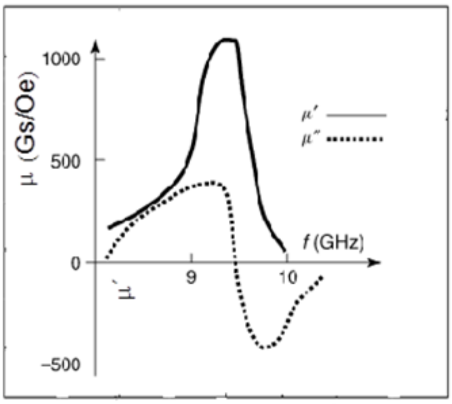



**Figure 6:** Frequency dispersion of the real and imaginary parts of relative permeability around the NFMR frequency for the Fe68C4B16Si10Mn2 microwire (see [1, 2, 5-13].

Figures 4–6 show resonance frequencies of 7.5, 8.5, 10.5, and 13.5 GHz and resonance widths of 1.5, 2, 3, and 4 GHz.

Near μ" resonance is expected to be described as follows:

$$\mu''/\mu dc \sim \Gamma\,\Omega / [\,(\Omega - \omega)^2 + \Gamma^2], \quad (3)$$

where $\mu_{dc}$ is the static magnetic permeability and Γ is the width of the resonant curve. Very near resonance, where $\Gamma > (\Omega - \omega)$, Eq. (3) reduces to

$$\mu''/\mu dc \sim \Omega / \Gamma \sim (10 \div 10^2\,). \quad (4)$$

Monitoring the geometry of the microwire (i.e., wire diameter) and the magnetostriction through the microwire composition makes it possible to prepare microwires with desirable permeability dispersion and for absorption materials: (i) determining the resonant frequency in a range of 1-12 GHz and (ii) controlling the maximum of the imaginary part of magnetic permeability.

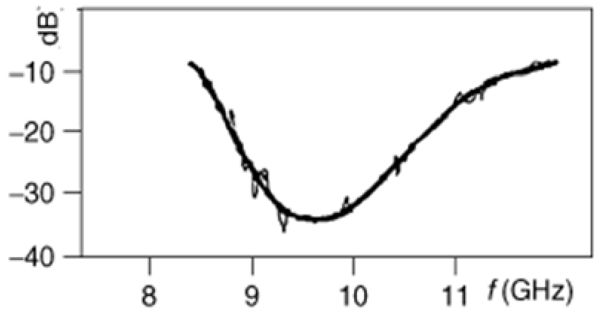



**Figure 7:** Typical absorption characteristics of shielding by a microwire composite with NFMR in an HF field in a frequency range of 10 GHz.

Figure 7 also shows the frequency absorption spectrum of shielding with $Fe_{69}C_5B_{16}Si_{10}$ microwires. The varying attenuation is attributed to the lack of an ideal angular distribution of microwires, the length of which does not always fit into the shielding thickness.

Pieces of microwires were embedded in planar polymeric matrices to form a composite shielding for radio absorption protection. Experiments were performed employing a commercial polymeric rubber with a thickness of about 2–3 mm. Microwires were spatially randomly distributed over the matrix before its solidification. The concentration was maintained below 8–10 g of microwire dipoles (1–3 mm long) per 100 g of rubber [1, 5–7]. A typical result obtained in an anechoic chamber is shown in Fig. 6 for shielding with embedded $Fe_{69}C_5B_{16}Si_{10}$ microwires.

It is evident that an absorption level of at least 10 dB is obtained in a frequency range of 8–12 GHz with a maximum attenuation peak of 30 dB at about 10 GHz. In general, optimum absorption is obtained using microwires with metallic nuclei with a diameter of 2r = 1–3 μm (2R ~ 20 μm (x >10)) and a length of L = 1–3 mm. These pieces of microwires can be treated as dipoles whose length L is comparable to the half value of effective wavelengths $\Lambda_{eff}/2$ of the absorbed field in the composite material (i.e., in connection to a geometric resonance).

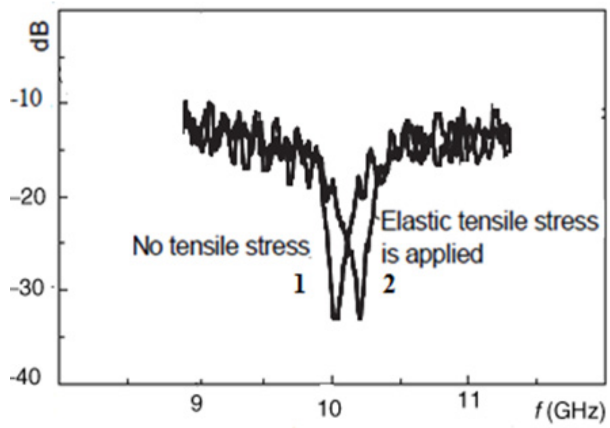



**Figure 8:** (1) Average absorption characteristics of a shielding containing a microwire composite exhibiting NFMR in a microwave frequency range of 10–10.2 GHz for $Fe_{68}C_4B_{16}Si_{10}Mn_2$ microwires ([2, 5–12]) and (2) absorption curve in the case of an external pressure (see [5–12]).

## Theory for Absorption Materials

The propagation of an electromagnetic wave through absorption shielding with microwire-based elements is characterized by transmittance |T| and reflectance |Rr| (coefficients given in [2, 5–13]:

$$|T| = (\alpha^2 + \beta^2)/[(1+\alpha)^2 + \beta^2]; \quad |R_r| = 1/[(1+\alpha)^2 + \beta^2], \tag{5}$$

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

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

$$|G| = 1 - |T|^2 - |R_r|^2 = 2\alpha / [(1+\alpha)^2 + \beta^2] \tag{6}$$

has a maximum

$$|Gm| = 0.5 \geq |G|,$$

for simultaneous $\alpha = 1$ and $\beta = 0$, for which

$$|T|^2 = |R_r|^2 = 0.25.$$

The minimum |G|=0 occurs at $\alpha = 0$ and $\beta$ of any positive number.

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

Let us consider the effective absorption function [2, 5–13]:

$$|G_{eff}| \sim \Gamma_{eff}\Omega_{eff} / [(\Omega_{eff} - \Omega)^2 + \Gamma_{eff}^{\ 2}], \tag{7}$$

where $\Gamma_{eff} \geq \Gamma$ and $\Omega \sim \Omega_{eff} = 2\pi c/\Lambda$.

A microwave antenna will resonate when its length L satisfies to the condition

$$L \sim \Lambda / 2(\mu_{eff})^{1/2} \ . \tag{8}$$

Absorptions maximum (see Fig. 7) occurs for Ωeff ~ 10 GHz ($\Lambda \sim 3$ cm) and $\mu_{eff} \sim 10^2$ [2, 5–13].

This corresponds to

$$L \sim 1.5\text{–}2 \text{ mm}, \tag{9}$$

where the microwire concentration is much less than the percolation threshold. A higher concentration of dipoles leads to an increase in absorption $|G_{eff}|$ and an increase in reflectance $|R_{r1}|$, which can be simply estimated as [2, 5–13]:

$$|Rr_1| \sim 1 - 2\sqrt{(\Omega/2\,\Sigma_m)}\ , \tag{10}$$

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

The formula is applicable, and calculation of small reflectance |Rr1| is possible, only if

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

for concentration below the percolation threshold (as $\Sigma_2 \sim 10_{15}$ Hz).

## Conclusions

Microwave electromagnetic response has been analyzed for composites consisting of dipoles and a diffraction grating of amorphous magnetic glass-coated microwires in a dielectric. These materials can be employed for radio absorbing screening. The spontaneous NFMR phenomena observed in glass-coated microwires has opened the possibility of developing novel broad-band radio absorbing materials.The described studies provide the following basic conclusions [8]:

(a) Cast GCAMNWs exhibit NFMR whose frequency depends on the composition, geometrical parameters, and deformation of the microwire. The NFMR phenomenon observed in glass-coated magnetic microwires opens up the possibility of developing new radio-absorbing materials with a wide range of properties. An important feature of cast microwires with an amorphous magnetic core is the dependence of the NFMR frequency on the deformation (stress effect). The calculations have shown that the shift of the NFMR frequency caused by the stress effect achieves 20% before the degradation of the composite.

(b) The general technology of magnetic wire composites is cost-effective and suitable for large-scale applications.

Here, the electromagnetic properties of composites with magnetic wires showing NFMR phenomena have been discussed. A striking property of these materials is that the spectra of the effective electromagnetic parameters (permittivity and permeability) can be actively tuned.

The technology of glass coated amorphous microwires provides the preparation of continuous wires.

## Acknowledgments

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