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INTERACTION OF VERY THIN DOUBLE-LAYER FIBRES WITH ELECTROMAGNETIC RADIATION. 1. NUMERICAL SIMULATION

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Very thin conductive fibers, whose diameter is much smaller than the wavelength, strongly absorb and scatter electromagnetic radiation. The efficiency factors of absorption, scattering and radiation pressure of metal fibers with a diameter of several micrometers in the centimeter wavelength range reach several thousand. The absorption of electromagnetic radiation in two-layer fibers has been studied. In fibers with a metal core and a lossless dielectric cladding, the absorption is the same as in solid metal fibers. In lossy cladding fibers, strong absorption occurs when the fiber diameter is several nanometers. Fibers with a dielectric core and a metal cladding strongly absorb radiation when the thickness of the cladding is comparable to the thickness of the skin layer.
Keywords: *Double layer fiber; Absorption; Scattering; Attenuation; Electromagnetic radiation*
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1. INTRODUCTION

The problem of diffraction of electromagnetic radiation on a cylinder is one of the most famous in electrodynamics. The results of its solution are presented in classic monographs [1-3] and numerous articles. Technical applications make it possible to obtain information about the cross-sectional size of the cylinder, its shape, and optical parameters [4-6].

The effect of the wave on the cylinder depends on the relationship between the wavelength and the diameter of the cylinder. It is usually strongest when the diameter of the cylinder is comparable to the wavelength. Then resonances arise, at which the interaction of the wave with the cylinder intensifies [7, 8]. Objects that are small compared to the wavelength are usually “not noticed” by it. But in works [9-12] it was shown that very thin metal wires, semiconductor and graphite fibers, the diameter of which is hundreds of times smaller than the wavelength, strongly absorb and scatter electromagnetic radiation [13].

This effect can be used to solve problems in physics and technology when it is necessary to transfer the energy of laser or microwave radiation to small objects: a spherical target in laser thermonuclear fusion installations, an active element in the form of a thin thread in fiber lasers, etc. In this case, focusing the radiation beam is not necessary. The transverse dimensions of the beam can be thousands of times larger than the size of the target.

Figure 1 shows graphs of the dependence of the absorption efficiency factor of a platinum wire on its diameter for several wavelengths with *E*- polarization of the wave (the electric vector is parallel to the axis of the wire). At certain ratios of the D/λ value, an absorption maximum is observed. For λ = 8 mm $Q_{abs\ max}$ = 962, for λ = 10 cm - $Q_{abs\ max}$ = 2615, for λ = 1 m - $Q_{abs\ max}$ = 7928. The maximum is obtained with very small wire diameters; 4.1 μm at a wavelength of 1 m, 1.5 μm at a wavelength of 10 cm, 0.3 μm at a wavelength of 8 mm.

In the case of the *H*-wave there is no effect.

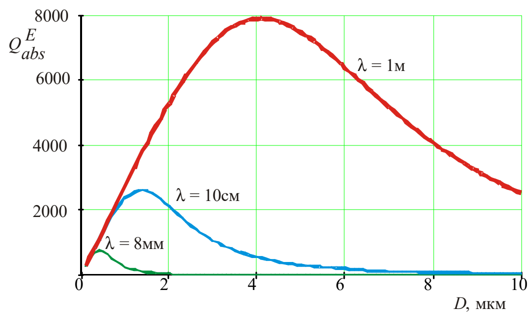

Figure 1. Dependence of the platinum wire absorption efficiency factor on its diameter

The technology also uses two-layer fibers - metal microwires in a glass shell and glass fibers with a metal coating. Therefore, there are works in which the diffraction interaction of an electromagnetic wave with such objects was studied [14-16]. It has been shown that resonances arise in the dielectric coating of a metal fiber, enhancing or weakening the interaction of the wave with it [15]. The work [16] shows the results of calculations on the interaction of microwave radiation with thin double-layer fibers.

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Further in this work, the results of studies of the interaction of an electromagnetic wave with two types of two-layer fibers will be presented - a conductor in a dielectric shell and a dielectric fiber with a metal coating.

A cross section of the fiber is shown in Fig. 2. It consists of two layers - an outer shell with a diameter D_1 with refractive index m_1 and core diameter D_2 and refractive index m_2. Both refractive indices can be complex, meaning both the core and the cladding can absorb radiation.

The wave vector of the incident radiation is perpendicular to the fiber axis. The electric vector of the wave is parallel to the fiber axis.

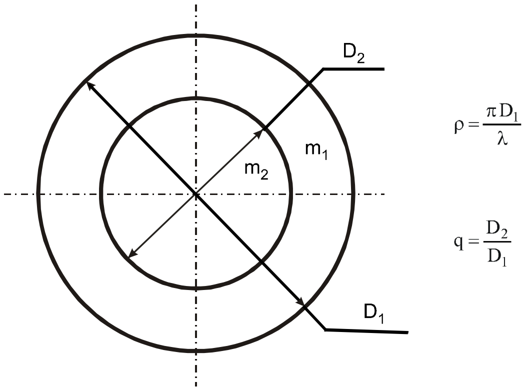

Figure 2. Problem geometry

Attenuation effectiveness factors Q, scattering Q_{sca} and absorption factor Q_{abs} can be calculated using formulas that are superficially similar to the formulas for a solid cylinder [2, 10]:

$$Q = \frac{2}{q\rho} \sum_{l=-\infty}^{\infty} \mathrm{Re}\left(b_l\right), \tag{1}$$

$$Q_{sca} = \frac{2}{q\rho} \sum_{l=-\infty}^{\infty} \left|b_l\right|^2, \tag{2}$$

$$Q_{abs} = Q - Q_{sca} \,. \tag{3}$$

Here $\rho = \pi D_1 / \lambda$, λ - radiation wavelength, $q = D_2/D_1$ or a metal conductor in a dielectric shell, $q = 1$ for a dielectric fiber in a conductive shell.

The coefficients b_l are described by the following equations:

$$b_l = \frac{\Delta_1}{\Delta}, \tag{4}$$

where

$$\Delta = \begin{vmatrix} H_l^{(2)}(\rho) & H_l^{(2)}(m_1\rho) & J_l(m_1\rho) & 0 \\ H_l^{(2)\prime}(\rho) & m_1 H_l^{(2)\prime}(m_1\rho) & m_1 J_l'(m_1\rho) & 0 \\ 0 & H_l^{(2)}(m_1 q\rho) & J_l(m_1 q\rho) & J_l(m_2 q\rho) \\ 0 & m_1 H_l^{(2)\prime}(m_1 q\rho) & m_1 J_l'(m_1 q\rho) & m_2 J_l'(m_2 q\rho) \end{vmatrix}, \tag{5}$$

$J_l(z)$ – Bessel function, $H_l^{(2)}(z)$ – Hankel function of the 2nd kind, the “prime” sign at the top of the function designation means differentiation over the entire argument.

The determinant of Δ_1 is obtained by replacing in the first column of the determinant of Δ the functions $H_l^{(2)}(\rho)$ and $H_l^{(2)\prime}(\rho)$ the functions $J_l(\rho)$ и $J_l'(\rho)$ respectively.

We will limit ourselves to the case of the *E*-wave, when the effect of strong absorption of electromagnetic radiation is observed in very thin fibers.

2. CONDUCTOR IN DIELECTRIC SHELL

Micron-diameter conductors in a glass shell are used in technology. They are used as thermistors, bolometric receivers of electromagnetic radiation, etc.

Figure 3 shows the dependence of absorption in a copper conductor in a glass shell with a refractive index $n = 1.5$. The diameter of the conductor in the sheath is 30 microns. Radiation wavelength 8 mm. Conductor diameter D_2 varies from zero to 1000 nm. The maximum absorption efficiency factor reaches 2000. The position of the maximum is determined by the formula [12]:

$$D \approx 0.1\lambda_i, \tag{6}$$

where $\lambda_i = \lambda/n$ – wavelength of radiation in metal, n – real part of the complex refractive index of a metal $m = \sqrt{\frac{\sigma\lambda}{4\pi c\varepsilon_0}}(1-i)$, σ – conductivity, c – speed of light, ε_0 – dielectric constant of free space. For copper $n = 3757$ at a wavelength in free space of 8 mm, so λ_i = 2.12 μm, and the maximum is located at $D_2 \approx 200\,nm$. In the graph, the maximum is located at D_2 = 154 nm, which is in satisfactory agreement with the theory [9].

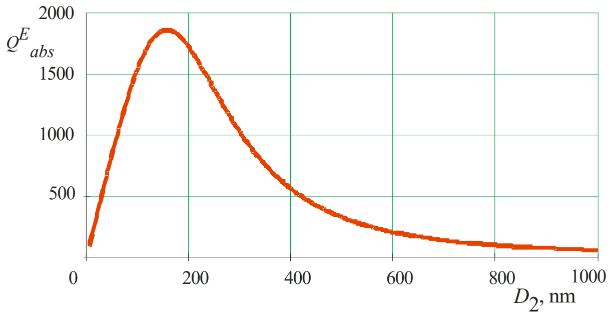

Figure 3. Absorption in glass-clad copper wire (λ = 8 mm, n = 1.5)

The refractive index of the shell does not affect the position of the maximum. It is determined only by the properties of the core metal. But the magnitude of the maximum depends on the shell material. So, for the refractive index of the shell n = 1.5 – absorption at maximum is Q_{abs} = 1865, for n = 4 – Q_{abs} = 1879, for n = 9 – Q_{abs} = 1948. Apparently, the shell focuses the radiation onto the core.

If the shell absorbs radiation, the picture changes. Figure 4a shows the dependence of the absorption efficiency factor of a copper wire in a cladding with a complex refractive index $m = 1.5 - 1i$ (colored absorbing glass) on the core diameter. The general picture is the same as in the previous case, the maximum is in the same place, it is the same in size. But at very small wire diameters, absorption increases. The region of strong absorption is very narrow. Its width, determined by the minimum on the graph, is 9 nm.

Absorption increases with increasing both the real and imaginary parts of the refractive index of the shell. The position of the minimum shifts towards increasing diameter. The minimum value increases. Figure 4b shows a graph for $m = 5 - 5i$ (semiconductor in the microwave range). The minimum is located at 41 nm and is close in value to the absorption maximum. At high refractive indices, the maximum disappears, and the $Q_{abs}(D_2)$ curve decreases monotonically as D_2 increases.

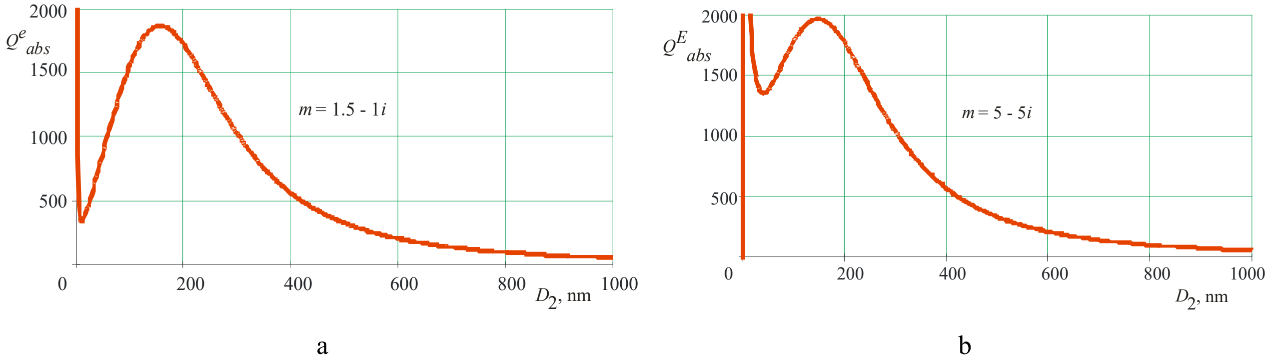

Figure 4. Absorption in copper wire with absorbent sheath a – m = 1.5 – 1i, b – m = 5 -5i

It is clear from the graphs that the effect of strong absorption is observed when the diameter of the conductive core is very small - no more than several hundred nanometers.

3. DIELECTRIC IN A METAL SHELL

Such an object can be a glass fiber coated with a thin layer of metal or other electrically conductive material (graphite, semiconductor).

Figures 5a and 5b show the results of interaction of a 10 cm long electromagnetic wave with a nickel-coated glass fiber. Fiber diameter 30 microns. It is shown how the absorption efficiency factor changes with a change in the diameter of the glass core.

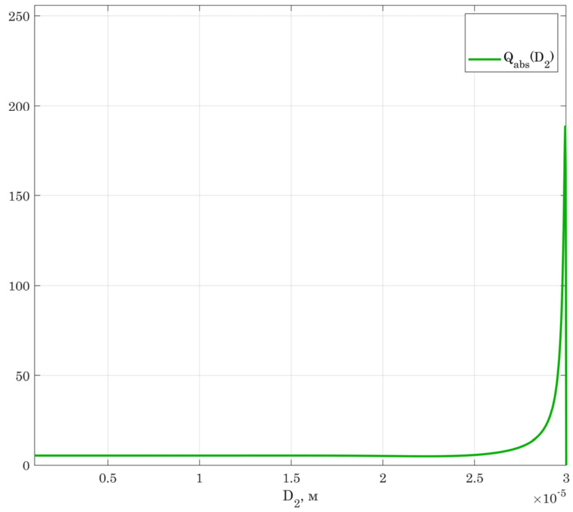

Figure 5a. Absorption in nickel-clad glass fiber

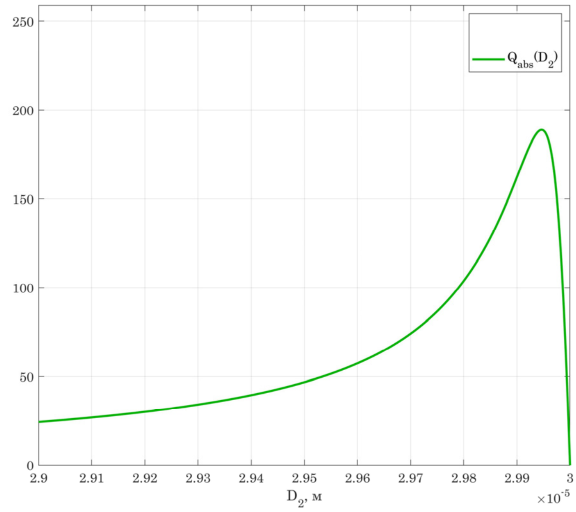

Figure 5b. Absorption in glass fiber with a nickel shell (maximum region)

Figure 5a shows that when the core is thin and the cladding thickness is much greater than the skin thickness, the absorption in the fiber is the same as in a solid metal cylinder with a diameter of 30 μm (*Qabs* = 5.38). When the thickness of the shell becomes comparable to the thickness of the skin layer (in nickel at a wavelength of 10 cm it is 3.25 μm), absorption increases and reaches a maximum at a shell thickness of 54 nm - *Qabs* = 187.8 (Fig. 5b). This is 35 times more than for solid nickel fiber with a diameter of 30 microns. For nickel fiber to have an absorption factor of 187.8, its diameter must be 1 micron, that is, it must be very thin.

Therefore, thicker two-layer dielectric fibers with a thin metal shell are much more convenient to use than solid homogeneous metal fibers.

Calculations show that the maximum absorption value does not depend on the conductivity of the shell material. The thickness of the shell at which maximum absorption is observed depends on the conductivity. It is proportional to the resistivity of the material. This is true for a very wide range of resistance values (Fig. 6). There, such a dependence is plotted on a logarithmic scale. The dots indicate resistivity values for several materials.

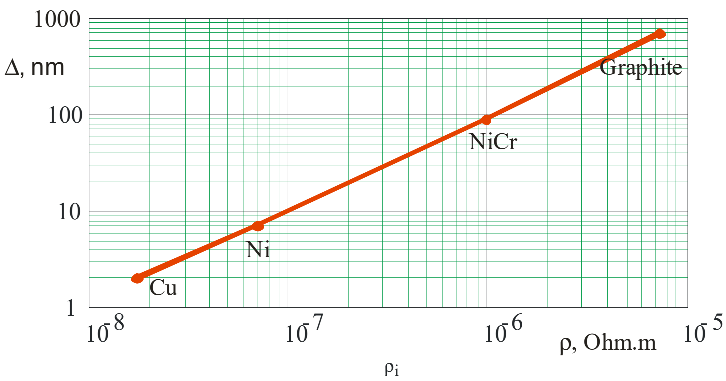

Figure 6. Dependence of the optimal thickness of the metal shell on the resistivity of the material

Figure 7 shows how the optimal cladding thickness depends on the wavelength of the radiation that is incident on the fiber (line 1). The graph is plotted for glass fiber with a diameter of 10 microns with a copper sheath. This is also a linear relationship over a very wide range (in the graph - from 8 mm to 10 m). The same figure shows the dependence of the absorption efficiency factor on the wavelength (line 2). This is also a linear relationship. It differs from the same dependence for a continuous fiber, where absorption is proportional $\sqrt{\lambda}$ [12].

It was indicated above that absorption in the shell becomes strong when its thickness is comparable to the thickness of the skin layer in it. The identical nature of the dependence of the optimal shell thickness on resistivity and wavelength also indicates that it is related to the thickness of the skin layer:

$$\delta = \sqrt{\frac{\lambda\rho}{\pi c \mu \mu_0}}, \tag{7}$$

where λ - wavelength, ρ - resistivity, c – speed of light in free space, μ - relative magnetic permeability of the shell material, μ_0 - magnetic permeability of free space.

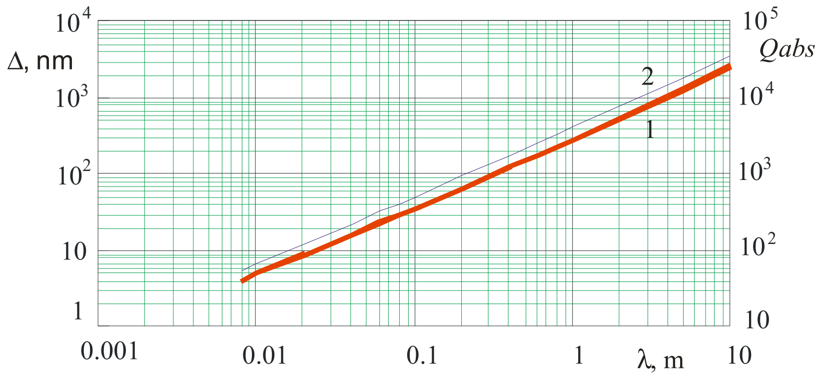

Figure 7. Dependence of the optimal thickness of the metal shell on the radiation wavelength
1 – shell thickness, nm, 2 – absorption efficiency factor

Figure 8 shows that the optimal shell thickness is proportional to the square of the skin layer thickness, which means, as can be seen from expression (4), it should be proportional to the wavelength and resistivity, which is confirmed by the graphs in Figures 6 and 7.

The proportionality coefficient in these relationships depends on the electrical properties of the core and shell and can be found from the analysis of expressions (1) – (3), (7).

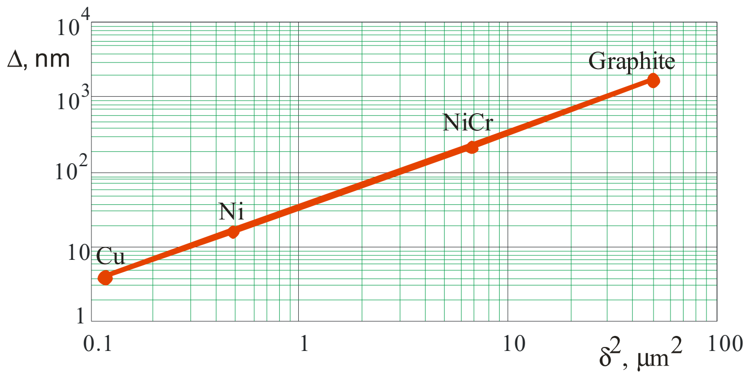

Figure 8. Dependence of the optimal thickness of the metal shell on the thickness of the skin layer

CONCLUSION

1. Absorption of electromagnetic radiation in a thin fiber ($D << \lambda$) with a metal core and a lossless dielectric shell is the same as in a homogeneous metal cylinder with a diameter the same as the core diameter. The absorption maximum in the microwave range is at $D \approx 0.1\lambda_i$, where λ_i – wavelength of radiation in a metal. In the microwave range D = 100…300 nm. In a fiber with a high refractive index of the cladding, absorption increases somewhat due to the focusing of radiation by the cladding onto the core.
2. If there is energy loss in the shell, strong absorption occurs in the metal core of nanometer diameter.
3. Dielectric fibers with a metal sheath strongly absorb electromagnetic radiation when the diameter of the sheath is comparable to the thickness of the skin layer.
4. For the same absorption, metal-coated dielectric fibers have a significantly larger diameter than solid metal fibers. This creates significant convenience in their technical applications.

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ВЗАЄМОДІЯ ДУЖЕ ТОНКИХ ДВОШАРОВИХ ВОЛОКОН З ЕЛЕКТРОМАГНІТНИМ ВИПРОМІНЮВАННЯМ. 1. ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ

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Дуже тонкі провідні волокна, діаметр яких набагато менше довжини хвилі, сильно поглинають і розсіюють електромагнітне випромінювання. Фактори ефективності поглинання, розсіювання та тиску випромінювання металевих волокон діаметром кілька мікрометрів у сантиметровому діапазоні довжин хвиль досягають кількох тисяч. Досліджено поглинання електромагнітного випромінювання у двошарових волокнах. У волокнах з металевою серцевиною та діелектричною оболонкою без втрат поглинання таке ж, як у суцільних металевих волокнах. У волокнах з оболонкою з втратами з'являється сильне поглинання, якщо діаметр волокна дорівнює декільком нанометрам. Волокна з діелектричною серцевиною і металевою оболонкою сильно поглинають випромінювання, коли товщина оболонки порівнянна з товщиною скін-шару.
Ключові слова: *двошарове волокно; поглинання; розсіювання; ослаблення; електромагнітне випромінювання*