

Photostability of Fiber-Optic Photoacoustic Transducer Based on Silver Nanoparticle Layer

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Abstract—The work is devoted to the experimental study of the microstructural properties of nanostructures before and after of the pulsed laser irradiation of the silver nanoparticle layer within the fiber-optic photoacoustic transducer prototype. The reaction of such transducer prototype on equivalent exposition of ~ 800 J/cm² is studied with atomic force microscopy and X-ray structural analysis. High photostability of nanostructure is demonstrated, degradation of nanostructures within the fiber-optic photoacoustic transducer prototype has not been observed. This allows such type of photoacoustic transducer to be used as part of a new generation of technical diagnostics systems.

Keywords: photoacoustic transducer, optical fiber, nanoparticles

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1. INTRODUCTION

There are a number of methods of non-destructive testing, which are suitable for breakdown diagnostics of technical equipment [1, 2], industrial machines and mechanisms [3, 4]. One of the main approaches is the use of ultrasound signals as a diagnostic tool [4, 5]. Methods of ultrasound diagnostics are often used, when it is necessary to obtain high-resolution images in technical quality control [2], medical and biological testing [4]. But such diagnostics is very complicated due to conventional bulky non-destructive testing ultrasound setups. Conventional piezoelectric electroacoustic transducers are characterized by high supply voltages, large size and high weight, high electromagnetic interference susceptibility, relatively narrow operation bandwidth [5].

Photoacoustic transducer is very attractive alternative to electro-acoustic one. In photoacoustic transducers, absorber is heated and cooled, leading to mechanical deformations, which cause cycles of pressure or, in the other words, acoustic waves in ambient surrounding [6, 7]. However, the performance of such photoacoustic transducers is significantly limited by the bandwidth and large size. In order to minimize the thickness of the absorbing layer in ultrasound transducers, surface nanostructures based on layers of noble metal nanoparticles (formed by atmospheric laser ablation [8–11]) can be used. Additionally, it is necessary to use highly absorbing nanoparticles (NPs) layer at the optical fiber edge, which absorbance is associated with the surface plasmon resonance phenomenon [6, 7].

The prototype of photoacoustic transducer has been created in order to confirm the theoretical investigations previously obtained by the authors [12]. To solve the main problem that arises when creating photoacoustic transducers, namely, reducing the thickness of the absorbing layer, we used a nanostructure based on a layer of silver nanoparticles, which allows the reliable generation of ultrasound at frequencies of 10–18 MHz within a prototype of photoacoustic transducer.

The work is devoted to the experimental study of the microstructural properties of nanostructures before and after of optical irradiation within the photoacoustic transducer prototype. The reaction of the fiber-optic photoacoustic transducer prototype on equivalent exposition of ~ 800 J/cm² is studied with atomic force microscopy and X-ray structural analysis.

2. MICROSTRUCTURAL PROPERTIES AND PHOTOSTABILITY OF NANOSTRUCTURES

The transducer prototype has been created to confirm the theoretical investigations previously obtained by the authors during the study the conditions of the most effective photoacoustic generation. In accordance with the previously developed theory, layer of silver nanoparticles with average diameter of 35 nm with RMS-size of 12 nm has been deposited on the surface of the optical fiber edge in order to provide the photoacoustic transducer frequency range exceeding

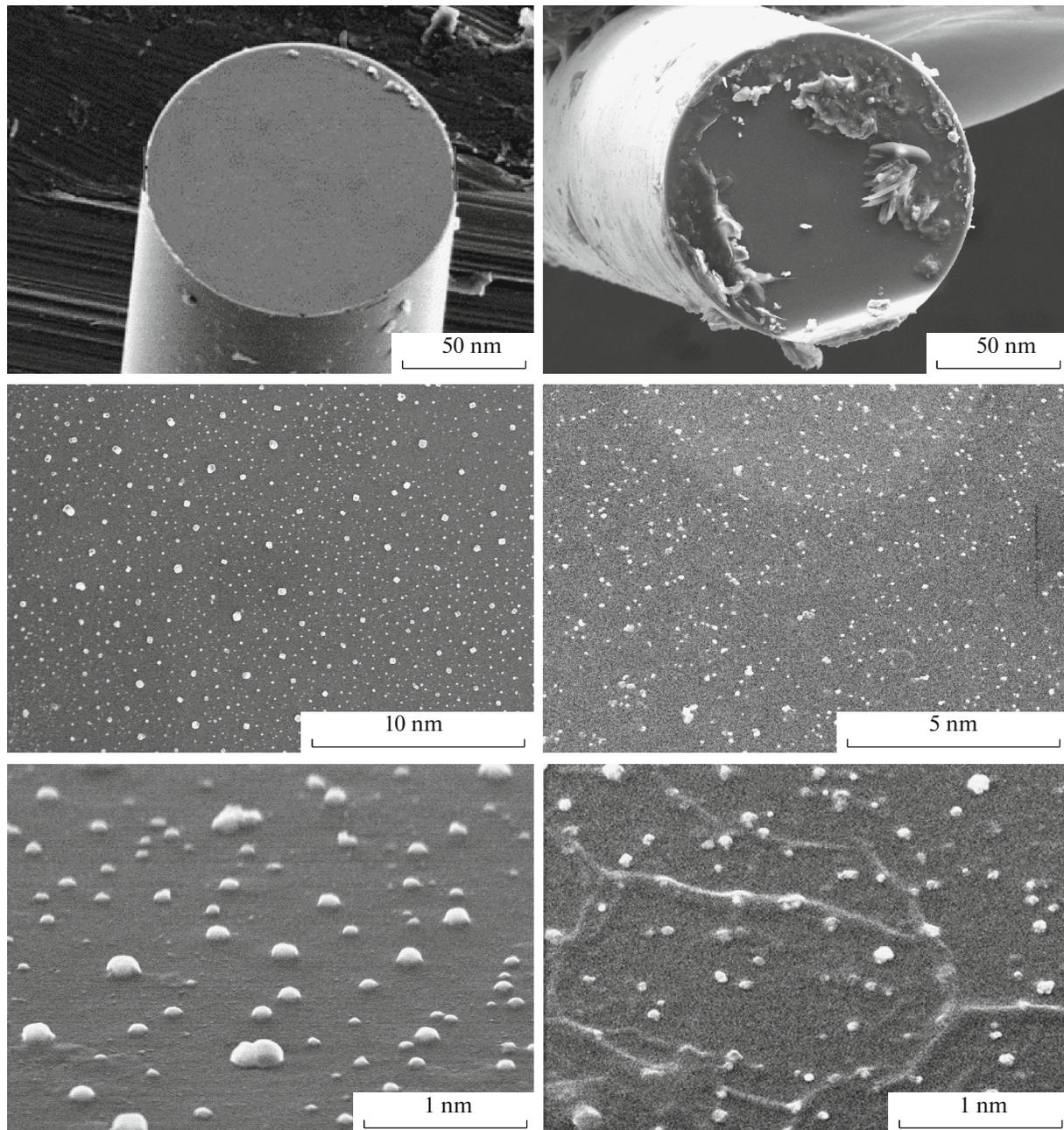


Fig. 1. Microphoto of photoacoustic transducer surface with layer of silver nanoparticles before (left column) and after (right column) measurement of acoustic signal with effective exposition of approximately 800 J/cm^2 .

10 MHz [12]. Silver NPs layer has been deposited on the optical fiber edge using pulsed laser deposition method. The pulsed YAG:Nd³ laser LOTIS-TII with a wavelength of 1064 nm and beam intensity of within the diameter of 1 mm has been used for experiments. Laser pulse has been focused on a silver 99.99% target (it was constantly moved to provide initial surface for laser deposition), which is mounted at angle of 45° with respect to the laser beam propagation. Preparation of the surface nanostructure for photoacoustic transducer prototype has been carried out at room

temperature with the typical exposure time for of 2–3 min (approximately 600–900 laser 20 ns pulses) [11].

Photoacoustic transducer prototypes have been studied by means of scanning electron microscope Hitachi S-4800 with the resolution of 1 nm and relative uncertainty less than 5%. Figure 1 shows the microphoto of photoacoustic transducer surface with layer of silver nanoparticles before measurement of acoustic signal (obtained with scanning electron microscope Hitachi S-4800). One can see that shape

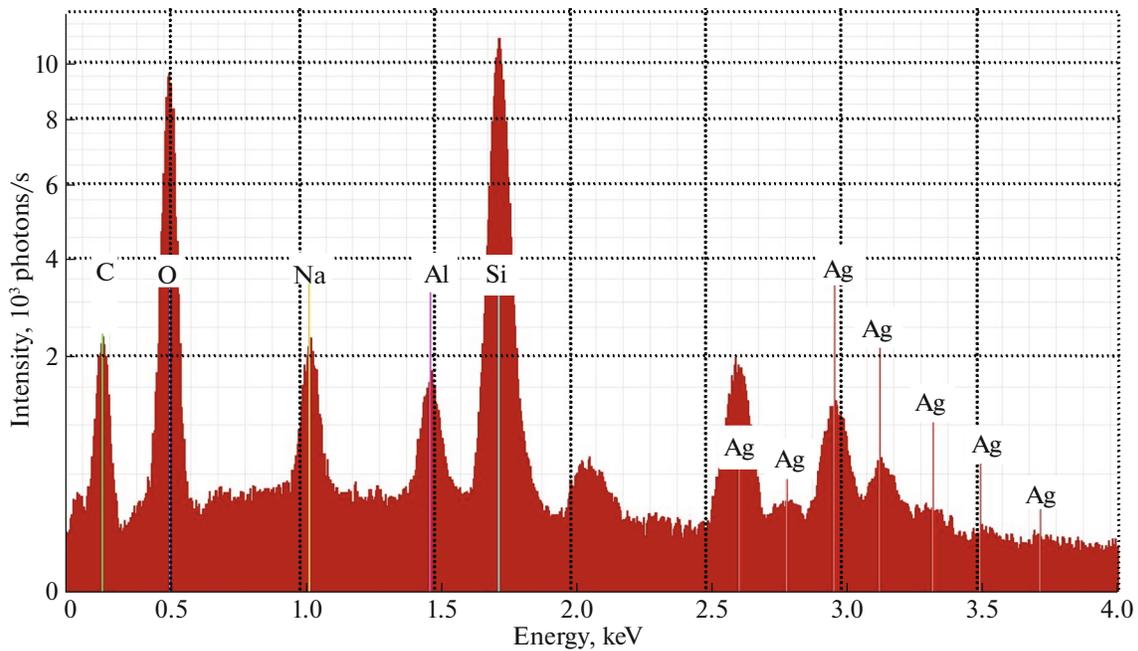


Fig. 2. X-ray structural analysis data for photoacoustic transducer surface with layer of silver nanoparticles after (right column) measurement of acoustic signal with effective exposition of approximately 800 J/cm^2 .

of NPs is spherical. The analysis of binarized photos allows to conclude that NPs are characterized by gamma-distribution with size-parameter of $k_\Gamma = 8.51$ and scale-parameter of $\theta_\Gamma = 4.11$ (parameters of gamma-distribution are found by means of the non-linear least square method). From the statistical properties of gamma-distribution, mean size and its round mean square are calculated from the size-parameter and scale-parameter correspondingly by means of the following formulas [12]:

$$\bar{d} = k_\Gamma \theta_\Gamma,$$

$$\sigma = \sqrt{k_\Gamma} \theta_\Gamma.$$

For the case under consideration, nanoparticles mean size is 35 nm and size round mean square is 12 nm. Surface occupation density is estimated to be of 3.8%. There are some nanoparticles with radius of 135 nm on microphoto. The overall surface occupation density of such nanoparticles is estimated to be less than 0.076%.

Additionally, Figure 1 shows the microphoto of photoacoustic transducer surface with layer of silver nanoparticles before and after the 1 h measurement of acoustic signal (equivalent exposition of $\sim 800 \text{ J/cm}^2$). One can see that there is no observable effect of photoacoustic transducer operation on the surface nanostructure microscopic parameters. Acoustic signal has been generated using optical 50 mW pulses with a period of 10 ms, a duration of 50 ns, fronts less than 12 ns.

Figure 2 shows X-ray structural analysis data for photoacoustic transducer surface with layer of silver nanoparticles after measurement of acoustic signal. One can see that there are three sets of inclusions:

- (1) O, Al, Si associated with optical fiber;
- (2) Ag associated with nanoparticles;
- (3) C, Na associated with surface organic contamination during preparation and operation.

Thus, atomic force microscopy and X-ray structural analysis show that even after the equivalent exposition of $\sim 800 \text{ J/cm}^2$, nanoparticles mean size remains to be of 35 nm and size round mean square to be of 12 nm. Despite of surface organic contamination during preparation and operation, the nanoparticle material is shown to be Ag.

As it demonstrated previously [12], photoacoustic transducers based on such nanostructures can be successfully used because the frequency performance of such structure based on Ag NPs weakly depends on the surface occupation density. It is seen that contamination and mechanical damage appeared on the surface outside the core of the optical fiber. However, no degradation of the power spectral density of the output ultrasonic signal is observed.

It can be seen that the layer of nanoparticles deposited on the edge of the optical fiber has good adhesion—the size of the nanoparticles and the surface occupation density of the substrate do not change. Note, some samples have “grooves” associated with surface contamination. The presence of fine grain in microphotos is associated with the features of the

study using scanning electron microscopy, when a technological layer of Pt was applied to the sample before the study.

3. CONCLUSIONS

In the paper, the photostability of the photoacoustic transducer prototype is studied. It is shown that effective exposition of approximately 800 J/cm^2 does not affect the nanostructure based on a layer of silver nanoparticles with size gamma-distribution, the average diameter of 35 nm with RMS-size of 12 nm, which is synthesized by laser deposition method.

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REFERENCES

1. R. Smith, A. Arca, X. Chen, L. Marques, M. Clark, J. Aylott, and M. Somekh, *J. Phys.: Conf. Ser.* **278**, 012035 (2011).
2. Nan Wu, Ye Tian, Xiaotian Zou, and Xingwei Wang, *Proc. SPIE* **8694**, 86940 (2013).
3. Tian Ye, Wu Nan, Zou Xiaotian, H. Felemban, Cao Chengyu, and Wang Xingwei, *J. Opt. Eng.* **52**, 065005 (2013).
4. Hou Yang, Kim Jin-Sung, Ashkenazi Shai, Huang Sheng-Wen, and Guo L. Jay, *Appl. Phys. Lett.* **91**, 073507 (2007).
5. Zou Xiaotian, Wu Nan, Tian Ye, Wang Xingwei, and M. J. Clark, *J. Acoust. Soc. Am.* **137**, 219 (2015).
6. A. P. Mikitchuk and K. V. Kozadaev, *Semiconductors* **52**, 1839 (2018).
7. A. P. Mikitchuk and K. V. Kozadaev, *Quantum Electron.* **48**, 630 (2018).
8. V. K. Goncharov, R. V. Kozadaev, V. V. Makarov, and D. V. Shchegricovich, *J. Eng. Phys. Thermophys.* **86**, 798 (2013).
9. V. K. Goncharov, R. V. Kozadaev, and D. V. Shchegricovich, *Opt. Mem. Neural Network (Inform. Opt.)* **20**, 255 (2011).
10. A. P. Mikitchuk and K. V. Kozadaev, *Przeglad Elektrotech.* **3**, 129 (2020).
11. V. K. Goncharov, K. V. Kozadaev, A. P. Mikitchuk, and M. V. Puzyrev, *Semiconductors* **53**, 1950 (2019).
12. A. P. Mikitchuk and K. V. Kozadaev, *J. Belarus. State Univ. Phys.* **1**, 4 (2020).