Formation of optical antennas interfaces by laser processing of thin metal coatings

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Abstract The work is devoted to the problem of creating interfaces of metallic nanoantennas for optoplasmonics. The technology of micro- and nanoscale elements topology formation by the method of selective laser ablation of thin-film coatings is described. The possibility of using the femtosecond laser complex for rapid prototyping of various geometric configurations of optical antennas interfaces is shown.

1. Introduction
Nano-antennas are the optical equivalent of classical antennas used for receiving and transmitting information on radio and microwave frequencies. Like radio frequency antennas, nano-antennas are able to efficiently convert optical radiation into highly localized fields (receiving antennas), and reverse the transformation (transmitting antennas).

A characteristic feature of such antennas is the ability to amplify photophysical phenomena. This property, in particular, makes nanoantennas extremely promising elements for use in optoplasmonics for solving problems of generating surface plasmon polaritons (SPPs). Such antennas are two-component structures that include a dielectric substrate covered with a thin metal film.

Figure 1. The operating principle of optical nanoantennas.
Surface plasmons are generated as a result of the interaction of light of a suitable frequency with electrons of a conducting surface at the metal/dielectric interface, which causes electrons to oscillate in resonance with the light wave (figure 1). The oscillations lead to the formation of an electromagnetic field propagating along the surface until complete attenuation in the material. The magnitude of the antenna electric field depends on the type of metal used, the spatial geometry, the width of the gap between the nanostructures, the radius of curvature of the surface. Thus, changing the parameters of antenna interfaces allows to control the position of the frequencies at which the maximum amplification of the local field strength is observed, which determines the working emission spectrum and the target applications of the created elements.

At present, a number of scientific works have been published, describing the successful use of nanoschemes elements on the basis of SPPs for performing classical electronic circuits tasks, such as information transfer and logical calculations [1, 2]. Such elements have proven the ability to operate in the wavelength range, including the infrared region of the spectrum, which allows them to be used both for broadband signal transmission and for integration into silicon chips. Taking into account the diversity of sources and detectors of highly localized fields (groups of atoms, molecules, luminescent cells, quantum dots, etc.), it can be argued that the area of practical applicability of nanoantennas in the near future is comparable with their classical counterparts. Currently, nanoantennas are already successfully used in near-field microscopy, Raman spectroscopy, high-resolution biomedical sensors [3].

2. Direct laser writing technology
There are many methods of micro- and nanoscale technologies for producing and processing thin-film elements. The undeniable advantage of thin-film technology is their flexibility, which is reflected in the possibility of selecting materials with optimal characteristics and obtaining virtually any desired configuration of elements. At the same time, tolerances with which individual parameters are maintained can reach units of percent.

The following methods are most actively used to form the topology of the conductive, resistive or dielectric layers of thin-film elements: masking (the coating materials are deposited onto the substrate through removable masks) and photolithographic (the film is applied to the entire substrate surface, then etched from certain areas) [4]. Despite the relatively high efficiency of traditional methods, these technological approaches have very significant drawbacks, the main of which is the need to use templates. The complexity and long duration of multi-stage processing operations make this approach inapplicable for the rapid production of various geometric configurations of elements.

In view of the foregoing, the most relevant solution to the problem of nanoscale elements fabrication, in particular, nanoantennas, is the use of femtosecond laser writing technology for the formation of the topological structure of elements on the substrate surface. Unlike pulses of longer duration, where the main mechanisms are thermal evaporation and explosive boiling-up, for femtosecond radiation, the desorption of excited particles from the target surface, nonlinear absorption, development of avalanche ionization, non-equilibrium electronic and vibrational excitation of the target material, as well as effects associated with overheating of the substance above the thermodynamic point becomes important components. Characteristic features of laser pulses with a duration of less than picoseconds are the ultrafast transfer of radiation energy to the material being processed and extremely low heat removal from the impact zone, which allows to minimize the occurrence of thermal distortion. These conditions allow the use of a much lower average radiation power and pulse energy for the removal of material areas, due to localization in a strictly limited area of the laser spot. Thus, the technology of selective laser ablation by ultrashort pulses offers an excellent solution for precision controlled processing of thin-film coatings and the formation of micro- and nanoscale elements.
3. Experimental setup

The development of the nanoscale thin-film elements formation technique is carried out using a hardware-software complex of femtosecond laser micromachining (figure 2), working under the control of the developed software. The setup is based on Yb: KGW laser system, radiation wavelength \( \lambda = 1030 \) nm (with the ability to work on the second (\( \lambda = 515 \) nm) and fourth (\( \lambda = 257 \) nm) harmonics), the maximum pulse frequency \( f = 10 \) kHz, pulse energy \( E \approx 150 \) mJ, pulse duration \( \tau \approx 280 \) fs. The complex is equipped with the Aerotech ANT130-XY nanopositional sample transfer system (displacement range 110 mm, minimum movement increment 1 nm, exposure accuracy for the working area length \( \pm 250 \) nm), which allows achieving extremely high spatial positioning resolution required for writing of geometrically complex structures. The system was tested on the example of performing the tasks of controlled micromodification of transparent solid media [5], as well as selective laser ablation of thin-film coatings [6-7].

![Figure 2. Femtosecond laser micromachining complex: 1 – camera, 2 – portal periscopic system, 3 – variable attenuator, 4 – XYZ-coordinate stages system, 5 – femtosecond laser, 6 – PC, 7 – joystick.](image)

The presented setup allows to form basic types of plasmon nanoantenna interfaces (with a flat tip, a tapered tip, a «bow-tie») [8-9], and combined experimental interfaces of complex geometry (figure 3). Separate geometrical parameters of elements can reach the nanometer order. Thus, in [10-11], the possibility of obtaining structures of sizes much smaller than the diffraction limit of the optical range of the processing radiation was demonstrated.

The following types of metals are used as the material of the conducting layer of a bicomponent sample: gold, silver, copper. Studies of the formed nanoscale structures characteristics are carried out by scanning electron and atomic-force microscopy.
Figure 3. Plasmon nanoantenna interfaces: a – with a tapered tip; b – with a flat tip; c – «bow-tie»; d – interface of experimental geometry.

4. Conclusion
The use of ultrashort laser pulses for selective removal of thin film coatings offers a unique approach for rapid prototyping and testing of various geometric configurations of optical antennas interfaces. Properly selected exposure mode allows to avoid physical and thermal damage of surrounding areas, and occurrence of negative changes in dielectric substrate morphology.

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