Electrophysics and optics in topological quantum nanophotonics of low-dimensional systems

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Abstract. This work has been carried out on the basis of the fundamental areas of optics and electrophysics of topological nanoscale objects with an emphasis on demonstrating the work of the developed prototypes of the corresponding practical devices and on their test tests.

1. Introduction

In the aspect of fundamental research, we are talking about solving a specific problem on a controlled nanostructured localized dynamic modification of a solid-state surface in different time ranges – from continuous laser exposure and in a millisecond (10^-3 sec) time scale to a femtosecond (10^-15 sec) range with different excited mechanisms for such modification and treatment of the target surface. This will be realized both as a result of laser ablation and before its onset threshold with the development of non-stationary laser-plasma complex processes with, respectively, on the one hand, the removal of a substance of different composition from the surface of the samples and its subsequent deposition in the required configuration on the surface of another object, or, on the other hand, a given rearrangement of the electron-phonon and/or other bound collective quantum states excited in the medium. In this case, structural phase transitions occur in the medium, which depend on the size of nanoparticles and their combination into clusters, which are induced by laser radiation on the surface of the irradiated sample. A new, predictable, phase state of the medium arises here under the corresponding control parameters of the problem – for a certain size and shape of nanoparticles and/or a characteristic scale of their spatial association into nanoclusters on the surface of a solid. Under certain conditions, it becomes possible to excite in such a structure quasiparticles of different nature and control their quantum state, which dramatically expands the options for using such systems in applications.

In the aspect of applied exploratory research, the emergence of such micro- and nanostructures (with a certain spatial arrangement and/or periodic and which are topologically stable granular objects with control of their development in time under laser action), as well as the excitation of multistable stochastic dynamic quantum states (including the formation of fractal spatial nonlinear structures) should allow in the future to develop devices with the required/necessary functional and structural characteristics in the final product.

In the case of laser action on a medium with such a controlled induction of its different dimensional phase states, many new (in comparison with standard phenomenological approaches for monolithic samples) effects and states appear, first of all, quantum-dynamic and nonlinear bound states of light and a medium with unique kinetics and modified composition of elemental composition in the presence of vacancies with different active centers. Special emphasis will be placed on the quantum statistical characteristics (in terms of quantum stochastic resonance) of the photon radiation of a microcavity with
exciton mode nonlinearity in its model with a quantum well at various frequency detunings of the microcavity eigenfrequency from exciton resonance and from the laser pumping frequency. In addition, this should make it possible to determine a number of directions for the development of methods based on new physical principles for controlling the quantum states of objects in the required mode.

All these listed problems are the subject of fundamental and exploratory research and their novelty in this paper.

2. Modern challenges and background in the field

Metallic, hybrid and semiconductor island nanostructures of various compositions on a solid surface are widely used in nanoelectronics and optoelectronics, and are also used as luminescent labels for supersensitive detection of biochemical reactions and for visualizing the structure of various biological objects, and in other applications, in particular, as substrates for directed growth of carbon nanotubes (see, for example, [1-5] in the list of references cited in this section of the application).

Of particular importance is the development of methods and models/algorithms for controlling the electrophysical and optical characteristics in the required direction for nanostructured island films formed when the target is exposed to laser radiation and in the process of deposition of substances with different elemental / chemical compositions on the surface of solid substrates.

At the same time, the use of island cluster nanofilms makes it possible to solve such a fundamental problem as the transition to miniaturization, high reliability and durability for a modern component base of computing systems with a simultaneous significant increase in their performance, throughput and information capacity of communication channels with a significant reduction in the level of energy consumption and cooling requirements [6, 7]. At the same time, the sensitivity of digital sensor devices is increasing, and it also becomes possible to create a new class of electronic devices with high performance in various tasks of their use in the context of wide digitalization.

The existing methods of precision/atomic transfer of matter are technologically complex and expensive (molecular beam epitaxy, atomic lithography, atomic force methods); they are also very limited in the choice of source material. In this regard, methods of laser controlled synthesis of thin island nanofilms with the deposition of a substance on a solid substrate from colloidal systems preliminarily obtained by laser ablation of various targets have become one of the most rapidly developing tools in this field, allowing one to obtain a wide class of nanostructured materials with the required topology arrangement of nanoparticles/nanoclusters on a solid surface due to various schemes of laser experiments with a corresponding trajectory of the laser beam in the process of affecting the irradiated surface.

The uniqueness of the electronic - transport and spectral - properties of cluster nanostructures is due to the fact that their spatial characteristics correspond to the nanometer range in all three dimensions. This leads to the effects of dimensional quantization of the energy levels of electrons for such structures, controlled localization and delocalization of charge carriers, and makes it possible to control their characteristics in a given direction over a wide range, including the appearance of quantum bound states of electrons with other collective motions in a medium and under conditions their transport in low-dimensional structures of various types.

On the other hand, quantum nanoclusters can be represented as nanocrystals of various spatial structures and shapes with a special distribution of charged particles over the surface. In this case, such nanoclusters consisting of many atoms can be considered in certain cases as single isolated atoms within the framework of the standard shell model, when, for example, the electronic spectrum of a nanocluster in the form of an ideal quantum dot (0D object) corresponds to the energy levels of a single atom [8].

Therefore, depending on the distance between such quantum dots (islands/clusters) and the boundary conditions on the sample surface, various mechanisms of electrical conductivity are realized, for example. In particular, at relatively large distances (~ 10 nm), we are talking about the thermionic mechanism / thermal activation, and at small (~ 2-5 nm) - about the tunneling effect of charge carrier transfer [2, 9]. In this aspect, it is of interest to obtain and study nanostructures in which regions with variable distances between nanoclusters will be observed, which will make it possible to implement
various mechanisms of electron transfer with their localization and delocalization in one structure, including hopping electrical conductivity. This is of fundamental importance when designing trigger quantum systems for various purposes operating under external control, for example, by optical radiation.

Moreover, the fundamental phenomena of the physics of the condensed state of matter, which are of fundamental importance (superconductivity, BEC, various mechanisms of the development of phase transitions, etc.) require special conditions (control parameters - low temperatures, high pressures, vacuum insulation, etc.), which are strongly limit their widespread use in practice in specific devices. On the contrary, stable nanocluster systems are easily obtained under ordinary conditions, and a change in their topological parameters, which are controlled control parameters of the system, should make it possible to achieve the realization of these quantum states much more easily and in easily accessible schemes.

At present, in the development of new physical principles for the creation of practical devices on nanostructures with given/controlled functional characteristics, which include the surface cluster nanofilms considered in this Project, various laser experimental schemes are used for obtaining surface topological objects on a solid. An integral condition of these methods is mathematical and computer modeling, with the help of which the observed features and key parameters for the directed synthesis of such structures should be predicted and adequately described. Finding the optimal solution to these problems within the framework of predictive modeling requires the development of algorithms and models with a prediction of the required elemental/chemical composition, characteristics and properties of synthesized nanoobjects on the surface of samples for their possible use in practical devices.

The presented Project also corresponds to this research area with planned competitive advances in determining the necessary procedures for controlled laser synthesis/deposition of nanoscale cluster structures on the surface of a solid substrate. In this case, the emphasis will be placed on the study of the modification of the functional properties of such systems, in particular, for electrophysics, depending on the specific topology created in a controlled manner: the density of the arrangement of nanoclusters on the surface, the size and shape of individual clusters, as well as their elemental composition and boundary conditions on the substrate. ... This makes it possible, in a single complex, for the first time to outline the ways and perform experimental demonstrations for the creation of photonics/optoelectronic devices on new physical principles with the required functional characteristics using various experimental schemes for laser action on a substance, taking into account the preliminary modeling of the influence of the control parameters of the system under consideration on the developing dynamic processes in it.

In this case, the quantum properties of light interacting with a nonlinear medium are of particular importance, which is a fundamental problem of modern quantum technologies in terms of the excitation of collective states - exciton-polariton states - in systems with a reduced dimension in microcavity circuits [10]. Of fundamental interest here is the statistical description of the quantum behavior of radiation, which makes it possible to develop photon sources based on non-classical statistics with single photons in the Fock state, which find practical application in problems of quantum informatics and cryptography [11, 12]. We are talking about the effects that determine the efficiency and optimal operating modes of real practical quantum devices [13, 14]. A fundamental phenomenon here is the possibility of the appearance in a medium of such quasiparticles as exciton-polaritons (bosons), which can form an equilibrium Bose-Einstein condensate - BEC, in a high-temperature region with a single coherent wave function of such a state even when it propagates in an inhomogeneous medium with defects [15-17].

In addition, in such exciton-polariton systems, many other fundamental and fundamental phenomena are found, such as bistability [18, 19], formation of quantum vortices [20], soliton propagation regime [21-23], superfluidity [24], etc. On the basis of such exciton-polariton states, models of logic gates [25, 26], polariton transistors [26-28], qubits [29] and components of quantum computing devices [30, 31] have already been developed.
In particular, the influence of noise (classical and quantum) on the bistable regime of exciton–polariton states was considered in [32–34]. It was found that the region (in terms of the pump intensity parameter) of the bistable response of exciton-polaritons is more localized than the theoretical width of the bistable loop for this system in the classical limit [35]. In this case, a dependence of the width of the bistability region on the parameters of laser pumping is observed with the possibility of compressing the bistable loop, which is associated with the influence of noise. Quantum effects such as antibunching and compression of polariton photons (radiation of a microcavity/microproillar at polariton frequencies) were also discovered [36–38]. The antibunching of radiation recorded in this case, when the normalized second-order two-particle correlation function is less than unity, may indicate the so-called quantum blockade, when the emission of photons in pairs is suppressed, and therefore they are emitted one after another one by one in states close to the Fock states (sub-Poisson statistics radiation). In the context of polaritonics, we can speak of the so-called polariton blockade effect [39], when the emission of polariton photons in pairs is suppressed. On the other hand, under certain conditions, the bistability effect is observed and dissipative quantum phase transitions with the effect of stochastic resonance appear (cf. [40]). At the same time, the presence of noise in the system at a certain frequency of the external signal and noise power provides a transition from one state to another, which becomes possible even with a weak external signal, although under normal conditions this requires a signal with sufficient power to overcome the threshold - a potential barrier (in the phase space of different states) with the transition of the system from one stable state to another. This is of fundamental importance in the development of practical logic devices and their components with a small amount of external control signal power.

At the present search stage of these works and fundamental and applied research in this area, adequate methods for diagnosing emerging states in such hybrid complex systems are needed - both in topology and in elemental/chemical composition. For these purposes, the SERS methods are relevant and are used as a stand-alone instrument for highly informative spectroscopy. They are optimal and preferable because of their record sensitivity and accuracy for the determination of ultralow concentrations of substances for a number of problems of interdisciplinary scientific direction (physics, chemistry, biology, medicine) [41]. In this case, the use of nanosized silicon particles is of particular importance [42].

For example, for physics problems, recent research has shown that plasmon enhancement of absorption of visible light is a way of concentrating low-intensity visible light energy in a desired direction onto specially lined up adsorbed molecules. The physics of this phenomenon is based on nonradiative damping of excitation from Landau levels, which leads to high-energy carriers (for electrons above the Fermi energy of the metal and / or for holes in the region below the Fermi energy) [43, 44]. This provides new opportunities for the use of quantum technologies in various applications.

In addition, the interest in SERS spectroscopy is explained by the efficiency of the analysis of trace amounts of substances, which is in demand in many fields, such as biology, medicine, forensic science, ecology, etc.

For medical problems, the effect of SERS can be combined with existing biosensing and bioimaging methods to confirm the diagnosis and/or determine the effectiveness of drug delivery [45].

The main advantages of the SERS method include simplicity of sample preparation, high sensitivity, the ability to detect ultra-low concentrations of test substances down to single molecules, qualitative determination of the composition of a substance/molecules, and obtaining detailed information about their structure and orientation from characteristic spectra [46–48]. The peculiarity of SERS, which makes it a unique and versatile tool in relation to other methods that are also capable of detecting low concentrations of substances, is determined by the availability of data on vibrational transitions in a molecule over the entire spectrum, which determines a much greater informativeness of this approach in comparison, for example, with fluorescence spectroscopy. The individuality of the vibrational spectra and the sensitivity of the SERS methods lead to its great advantages also in comparison with the currently popular SPR biosensors (sensors based on the surface plasmon resonance effect) both in the development of highly sensitive biosensors and electroanalysis, and in the study of interphase processes. On this basis, it is possible to carry out environmental analyzes, create fiber-optic sensors, etc. One of
the principal trends in the application of SERS spectroscopy is the analysis of living cells [49, 50]. In various studies of living cells, a number of significant and still unresolved problems arise associated with the search for effective non-invasive and well-reproducible research methods with high selectivity and information content. The SERS methods make it possible to significantly advance in solving these problems in the very near future, especially when using nanostructured templates of various types. Such their targeted nanostructuring is a separate line of research, which will be the focus of this work.

This Project will provide theoretical and experimental exploratory research on a number of the above fundamental problems for the specific requirements of the problems being solved. At the same time, in a single complex, such works are being implemented for the first time and include, firstly, obtaining in a laser experiment surface structures of different elemental/chemical composition with the required topology with appropriate procedures for their analysis, modeling and diagnostics, which make it possible to control dynamic processes during their synthesis. Second, the study of quantum and nonlinear states (electrophysics + optics) in such granular systems and control of their characteristics based on new physical principles, including under conditions of excitation of bound quantum states of radiation and collective motions in a medium with a reduced dimension (in microcavities) with the development of appropriate algorithms and procedures for numerical analysis, including the emerging stochastic resonance states of exciton-polaritons and the proposal of possible model schemes for practical trigger-type devices. Third, the implementation of unique schemes of highly sensitive methods for recording ultra-low concentrations of substances at the level of individual molecules in the background environment using modified SERS methods with specially created nanostructures on a solid-state substrate (templates) with hybrid nanoclusters with a topology optimal for practical problems.

All this confirms the relevance and competitiveness of the presented Project, both in a fundamental aspect and in the aspect of using the expected results in various applications on the general landscape of work carried out in world science in this area.

3. Obtained results

The results deals with fundamental dimensional phenomena of topological quantum nanophotonics in surface solid-state structures, and the possible prospect of using these effects in various applications.

A number of exploratory studies is carried out in a uniform complex:

(a) on the consideration of dynamic models for the development and implementation in a laser experiment of topological surface nanostructures of different elemental/chemical composition in the controlled synthesis of nanostructured samples with specified functional characteristics (optics + electrophysics) – see Figs. 1-3;

(b) on the study of the development of nonlinear and quantum processes in low-dimensional structures, including in microcavity systems and one-dimensional wires, upon excitation of quantum collective states with the participation of exciton-polaritons in a medium, and possible schemes for creating practical devices based on them – see Figs. 4,5.

![Fig.1. AFM-images of various modifications of PbTe cluster structures deposited on a substrate with an epitaxial film by different mechanisms: the mechanism of Brownian motion (a); the appearance of a dendritic structure (b); the mechanism of a percolation process (c); the appearance of a granular/labyrinth structure (d).](image-url)
Fig. 2. AFM-image of the PbTe surface after exposure to 8W laser radiation. In the lower left corner – an ensemble of nanoparticles within the irradiation region; in the upper right corner – unirradiated film surface. The size of nanoparticles decreases with approaching the boundary between the irradiated and non-irradiated zones (a). Experimental normalized histogram of the lateral size distribution of nanoparticles – bimodal distribution (b).

Fig. 3. Temperature dependence of the natural logarithm of the resistance lnR of films obtained under different deposition modes with the same activation energy for all samples equal to 0.3 eV: up to temperature ~ 33°C the thermos-activation mechanism works; for temperature more than ~ 33°C the tunneling effect occurs.

Within the framework of this approach, we write the Hamiltonian $\hat{H}_C$ of exciton-polaritons, in terms of secondary quantization in the photon-exciton basis, which has the form:

$$\hat{H}_C = \hbar \Delta_{ph} \hat{\phi}^+ \hat{\phi} - \hbar \Delta_{ex} \hat{x}^+ \hat{x} + \hbar \omega_p (\hat{x}^+ \hat{\phi} + \hat{\phi}^+ \hat{x}) + \hbar \alpha \hat{x}^2 + i \hbar E_d (\hat{\phi}^+ - \hat{\phi}),$$  (1)

where $\hat{\phi}(\hat{\phi}^+)$ and $\hat{x}(\hat{x}^+)$ are the production operators of photons and excitons, respectively, $\alpha$ is the Kerr-type nonlinearity parameter, and $E_d$ – is the laser pumping amplitude at the frequency $\omega_d$.

Fig. 4. Proposed experimental set-up. (a) Design of a micropillar as a 0D polariton object implemented in a columnar microcavity; (b) Schematic diagram of a polariton quantum gate "AND"; (c) Formation of a stable soliton solution for condensate in a microwire.

The following detunings are introduced in Hamiltonian (1): $\Delta_{ph} = (\Delta - \Omega) = \omega_{ph} - \omega_d$ – is the detuning of the photon mode frequency from the pump frequency, $\Delta_{ex} = (\Delta + \Omega) = \omega_{ex} - \omega_d$ – is the detuning of the exciton mode frequency from the pump frequency, $\Delta = (\omega_{ph} - \omega_{ex})/2$ – is half of the exciton-photon detuning, $\Omega = \omega_d - (\omega_{ph} + \omega_{ex})/2$ – is the pump frequency detuning from the middle between the frequencies of eigenstates of the exciton-photon system (laser detuning).
Fig. 5. (a) Region of existence of the bistability effect; (b) the number of photons $n_{\text{ph}}$ in the semiclassical and quantum approximations for the frequency parameters (in inverse units of picoseconds): $\Delta = 3.12 \text{ ps}^{-1}$, $\Omega = -4.92 \text{ ps}^{-1}$ (orange curve), $\Omega = -4.91 \text{ ps}^{-1}$ (blue loop), $\Omega = -4.9 \text{ ps}^{-1}$ (red loop), $\Omega = -4.89 \text{ ps}^{-1}$ (green loop); these points correspond to points on the image (c). The curves in the image (b) correspond to the graphs of the second moment of photons in the image (d). The results of numerical simulation of quantum jumps between stationary states on the bistability loop are shown in images (e), (f) for the cases corresponding to the red double arrow and red single arrow shown in the image (b), respectively.

4. Modelling and computer simulation

The algorithms and procedures for numerical modeling and computer simulation are developed to solve these problems, as well as the implementation of special schemes for laser experiments, will allow, firstly, to synthesize nanostructured surface layers and thin-film cluster objects with a variable elemental/chemical composition and with a certain/required topology – variable dimensional parameters, as well as hybrid particles with semiconductor cores and their coating with metal nanoparticles in the form of an inhomogeneous shell – see Fig. 6, 7.

Within the framework of fractal geometry, when modeling well-formed dendritic specimens, we used the diffusion-limited aggregation (DLA) model [51]. It is based on solving a two-dimensional diffusion equation:

$$ \frac{\partial C(x,y,t)}{\partial t} = D(t) \nabla^2 C(x,y,t), \quad (2) $$

where $C(x,y,t)$ is the concentration of wandering particles; $D(t,T)$ is the normalized diffusion coefficient for a Brownian particle; $T$ is the temperature of the system at time $t$; $x,y$ are surface coordinates.

Second, to reveal the fundamental features of the development of nonlinear and quantum effects in exciton-polariton low-dimensional microcavity semiconductor systems of various configurations (columnar microcavities and microwires) – see Fig. 8, 9.

Fig. 6. Model images of nanocluster/island films: by Diffusion Limited Aggregation (DLA)-Cellural Automata (CA) model. Spacecraft with the von Neumann neighborhood (a): seed particles – on the left, the resulting film – on the right; spacecraft (with the Moore neighborhood) is shown in Fig. (b).
Fig. 7. (a) The most likely mechanism of formation of the hybrid NPs is due to the electrostatic attraction of their constituents. The golden NPs are negatively charged as confirmed by the z-potential measurement. The silicon particles are electrically positive due to surface breaking of chemical bonds under non-radiative recombination of optically generated free carriers. (b) The optical density of colloidal solutions which contain Si NPs 100 nm (blue curve), 200 nm (green curve) and hybrid gold–silicon NPs with the silicon core with diameter (100 nm-red and 200 nm-black curves).

To study the quantum statistics of microproillar radiation, we use the second moment – the autocorrelation function $g_{ph}^{(2)}(0)$ in the range of such detunings $\Delta_{ph}$ and $\Delta_{ex}$, where there is no bistability. In this region, the effect of photon antibunching is observed when $g_{ph}^{(2)}(0) < 1$. The result near the triple resonance $\omega_p = \omega_{ph} = \omega_{ex}$ is shown in Fig. 8a as an image $g_{ph}^{(2)}(0)$ for different parameters $\Omega$ and $\Delta$.

Fig. 8a demonstrates the effect of giant photon bunching $g_{ph}^{(2)}(0) >> 1$ (while excitons are in an almost coherent state: $g_{ex}^{(2)} \sim 1$) for the region near $\Omega \approx -\Delta$ (noticeable light stripe in Fig. 8a). In this region, the number of photons is much less than the number of excitons $|\chi|^2/|\phi|^2 >> 1$ (Fig. 8b).

Near the region of giant bunching, in the region of negative exciton-photon detuning $\Delta$, the effect of photon antibunching is observed. It is shown in Fig. 8d. Figure 8c shows slices of the second moment of photons from Fig. 8a shown on it by dash-dotted lines with the corresponding detunings: $\Delta = -0.75$ ps$^{-1}$, $\Delta = 0$ ps$^{-1}$, $\Delta = 0.75$ ps$^{-1}$.

In a one-dimensional coordinate system, the complex Ginzburg-Landau equation for wave function $\psi$ takes the form:

$$i\hbar \frac{\partial \psi}{\partial t} = \left[ -D \partial_{xx}^2 + h g_c |\psi|^2 + h g_d n + \frac{i\hbar}{2} \left( R n - \gamma_c \right) - \beta_1 n |\psi|^2 - \beta_2 n^2 |\psi|^4 \right] \psi, \quad (3)$$

where $D = (1 + i\Gamma_c) \frac{\hbar^2}{2m_{lp}}$, $\Gamma_c$ – a small value of the parameter that takes into account the relaxation of the condensate, n – the population of excitons; $\beta_1 = 2\tilde{a}_0^2 R_s$; $\beta_2 = \tilde{a}_o \beta^2 R^2$; R – the rate of decay of hot excitons; $\tilde{a}_0 = 1.325 \cdot 10^{-3}$ meV/K$^2$ (being magnitude for GaAs-semiconductor); $m_{lp}$ – effective mass of polariton; $\hbar g_c$ – energy of polariton-polariton repulsion (cubic nonlinearity); $\hbar g_R$ – the same but for polaritons and excitons.
We renormalize the stimulated scattering rates in the condensate and the interaction coefficients for the one-dimensional case: 
\[ \left( R^{(1D)}, g^{(1D)} \right) = \left( R^{(2D)}, g^{(2D)} \right) / \sqrt{2 \pi d^2} \]. We assume that the transverse profile of the wave function has a Gaussian shape with width d. In the case of a one-dimensional microwire, the profile width d will be of the order of its diameter; in our case, we consider the beam width d = 240 μm.

Figure 9. Dynamics of polariton condensate. a) Homogeneous stationary solution. b) Soliton solution (Eq. (3)), when the sink soliton is formed. c) Profile of a homogeneous solution corresponding to image (a). d) Profile of the soliton solution corresponding to image (b).

5. Conclusion
The priority original results that are obtained during the implementation of this paper, and characterizing its scientific novelty, can be summarized as follows in two blocks.

On the first block.
1. Development of numerical methods and approaches to planning and experimentally implementing laser methods for the controlled production of nanocluster structures / island nanofilms and metal complexes (Ag, Au, their compounds), as well as semiconductor (PbTe) samples, hybrid metal
compounds with carbon and silicon objects promising for the creation of components and systems of
topological photonics and optoelectronics based on new physical principles.

2. Creation of dynamic models and algorithms for calculating the characteristics of nanocluster
structures / island nanofilms with controlled topology, induced by laser action on a solid surface,
including fractal objects and low-dimensional structures with quantum dimensional states.

3. Revealing the conditions for the realization in the experiment of various mechanisms and processes
of electrical conductivity of nanocluster systems (tunneling, hopping between different clusters
- neighboring and distant, thermal activation) depending on their topological features, created in a
controlled manner in a laser experiment under the appropriate boundary conditions and selected
geometries of surface inhomogeneities.

4. Quantitative agreement of the results of the simulation of the electrophysical parameters of
inhomogeneous nanostructures with the experimental data obtained for laser-induced surface structures
with different topology, with the required mutual adaptation when choosing the appropriate conditions.

5. Consideration of the prospects for the creation on new physical principles of components and
systems of topological photonics and optoelectronics using the developed / experimental methods of
controlled production and modeling of the dynamic development of such structures for specific tasks of
their application.

On the second block.

1. Demonstration of the effect of quantum fluctuations on the bistable states of an exciton-polariton
system formed in a microcavity, with a detailed analysis of the quantum statistics of the microcavity
radiation in a wide range of variation of the parameters of the exciton-photon and laser detunings from
the resonance frequencies of the microcavity to find the optimal modes for exciting different quantum
bound states.

2. Obtaining non-trivial statistical properties of photon radiation of a microcavity and predicting the
effects of giant bunching and antibunching of photons in certain conditions and modes with the
appearance of a quantum phase transition under bistability conditions under hard and soft modes of
excitation / bifurcation.

3. Revealing the conditions for detecting the self-localization effect - the manifestation of the soliton
dynamics of the polariton condensate under the influence of thermal expansion of a one-dimensional
lattice with a quantum well in a microwire due to heating of the system by laser radiation with a certain
selection of the control parameters of the problem.

4. Development of a model of a quantum polariton logic gate of the trigger type operating in a bistable
mode and controlled by both classical and quantum external signals / noises, the physical basis of which
is the effect of quantum stochastic resonance in a bistable polariton system with quantum noise.

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References
[1] Arakelian, S.M. Introduction to Femtonanophotonics: Fundamentals and Laser Methods
for Controlled Production and Diagnostics of Nanostructured Materials / S.M.
Arakelian, A.O. Kucherik, V.G. Prokoshev, V.G. Rau, A.G. Sergeev - M .: Logos,
2015. - 743 p.
[2] Dragunov, VP Fundamentals of nanoelectronics: textbook. allowance / V. P. Dragunov,
V. A. Gridchin, I. G. Unknown - M .: Logos, 2006. -- 496 p.
[3] Feng, W. Luminescent nanomaterials for biological labeling / W. Feng, W. Tan, Y.
Zhang, F. Xianping & W. Minquan // Nanotechnology. –2005. - Vol 17. - No. 1. DOI:
https://doi.org/10.1088/0957-4484/17/1/R01.

[4] Postnov, V.N. Nanosensors in biology and medicine: principles of operation and application prospects / V. N. Postnov, D. V. Korolev, M. M. Galagudza, D. V. Postnov // Biotechnosphere. - 2013. - 26 (2). - S. 18-27.

[5] Chen, X.H The formation conditions of carbon nanotubes array based on FeNi alloy island films / X.H Chen, S.Q Feng, Y Ding, J.C Peng, Z.Z Chen // Thin Solid Films. - 1999. - Vol. 339.1-2. - PP 6-9.

[6] Gulyakovich, G.N. Prospects and problems of semiconductor nanoelectronics / G.N. Gulyakovich, V.N. Severtsev, I.O. Shurchkov // Engineering Bulletin of the Don. - 2012. - 2 (20). - C. 315-319.

[7] Rizzo, N.D. Nanoelectronics to improve energy efficiency / N.D. Rizzo // Everspin Technologies. - 2009. - 11.

[8] Rogach, A.L. Semiconductor Nanocrystal Quantum Dots. Synthesis, Assembly, Spectroscopy and Applications / A.L. Rogach. - Wien: Springer-Verlag, 2008. - 372 p. DOI: http://dx.doi.org/10.1007/978-3-211-75237-1.

[9] Tkalich, V.L. Physical foundations of nanoelectronics: textbook. allowance / V.L. Tkalich, A. V. Makeeva, E. E. Oborin. - SPb: SPbGUITMO, 2011. - 83p.

[10] Alexey Kavokin, Jeremy J. Baumberg, Guillaume Malpuech, Fabrice P. Laussy Microcavities. - Oxford university press, 2017.

[11] Santori, Charles, et al. "Triggered single photons from a quantum dot." Physical Review Letters 86.8 (2001): 1502.

[12] Lohrmann, A., et al. "A review on single photon sources in silicon carbide." Reports on Progress in Physics 80.3 (2017): 034502.

[13] Brassard, Gilles, et al. "Limitations on practical quantum cryptography." Physical Review Letters 85.6 (2000): 1330.

[14] Knill, E., Laflamme, R., & Milburn, G. J. (2001). A scheme for efficient quantum computation with linear optics. Nature, 409 (6816), 46-52.

[15] Kasprzak, Jacek, et al. "Bose – Einstein condensation of exciton polaritons." Nature 443.7110 (2006): 409-414.

[16] Ballili, R., et al. "Bose-Einstein condensation of microcavity polaritons in a trap." Science 316.5827 (2007): 1007-1010.

[17] Sun, Yongbao, et al. "Bose-Einstein condensation of long-lifetime polaritons in thermal equilibrium." Physical review letters 118.1 (2017): 016602.

[18] Sarkar, D., et al. "Polarization bistability and resultant spin rings in semiconductor microcavities." Physical review letters 105.21 (2010): 216402.

[19] Baas, A., et al. "Optical bistability in semiconductor microcavities." Physical Review A. 69.2 (2004): 023809.

[20] Lagoudakis, Konstantinos G., et al. "Quantized vortices in an exciton – polariton condensate." Nature physics 4.9 (2008): 706-710.

[21] Sich, M., et al. "Observation of bright polariton solitons in a semiconductor microcavity." Nature photonics 6.1 (2012): 50-55.

[22] Walker, P. M., et al. "Ultra-low-power hybrid light – matter solitons." Nature communications 6.1 (2015): 1-7.

[23] Walker, P. M., et al. "Dark solitons in high velocity waveguide polariton fluids." Physical Review Letters 119.9 (2017): 097403.

[24] Amo, Alberto, et al. "Superfluidity of polaritons in semiconductor microcavities." Nature Physics 5.11 (2009): 805-810.
[25] Espinosa-Ortega, Tania, and Timothy Chi Hin Liew. "Complete architecture of integrated photonic circuits based on and and not logic gates of exciton polaritons in semiconductor microcavities." Physical Review B 87.19 (2013): 195305.

[26] Ballarini, D., De Giorgi, M., Cancellieri, E. et al. All-optical polariton transistor. Nat Commun 4, 1778 (2013).

[27] Zasedatelev, Anton V., et al. "A room-temperature organic polariton transistor." Nature Photonics 13.6 (2019): 378-383.

[28] Shelykh, I. A., et al. "Optically and electrically controlled polariton spin transistor." Physical Review B 82.15 (2010): 153303.

[29] S. S. Demirchyan, I. Yu. Chestnov, A. P. Alodjants, M. M. Glazov, and A. V. Kavokin Phys. Rev. Lett. 112, 196403

[30] Ghosh, Sanjib, and Timothy CH Liew. "Quantum computing with exciton-polariton condensates." npj Quantum Information 6.1 (2020): 1-6.

[31] Berloff, Natalia G., et al. "Realizing the classical XY Hamiltonian in polariton simulators." Nature materials 16.11 (2017): 1120-1126.

[32] Abbaspour, H., et al. "Effect of a noisy driving field on a bistable polariton system." Physical Review B 92.16 (2015): 165303

[33] Rodriguez, S. R. K., et al. "Probing a dissipative phase transition via dynamical optical hysteresis." Physical review letters 118.24 (2017): 247402.

[34] Fink, Thomas, et al. "Signatures of a dissipative phase transition in photon correlation measurements." Nature Physics 14.4 (2018): 365-369.

[35] Werner, Albrecht, Oleg A. Egorov, and Falk Lederer. "Exciton-polariton patterns in coherently pumped semiconductor microcavities." Physical Review B 89.24 (2014): 245307.

[36] Walls D. F., Milburn G. J.: Quantum optics. Springer Science and Business Media. - 2007. - P. 370.

[37] Deng H., Weih G., Santori C. Condensation of Semiconductor Microcavity Exciton Polaritons // Science. –2002. – Vol.298. – 199–202pp

[38] Paul, H. "Photon antibunching." Reviews of Modern Physics 54.4 (1982): 1061.

[39] Delteil, Aymeric, et al. "Towards polariton blockade of confined exciton – polaritons." Nature materials 18.3 (2019): 219-222.

[40] Gammaitoni, Luca, et al. "Stochastic resonance." Reviews of modern physics 70.1 (1998): 223.

[41] Recent progress and perspective of trace antibiotics detection in aquatic environment by surface-enhanced Raman spectroscopy, Volume 16, October 2017, Pages 16-23, https://doi.org/10.1016/j.teac.2017.10.002.

[42] Silicon nanoparticles as Raman scattering enhancers, March 2014 Nanoscale 6: 5666-5670, doi: 10.1039 / C4NR00593G

[43] Heterometallic antenna-reactor complexes for photocatalysis PNAS August 9, 2016 113 (32) 8916-8920;

[44] Aluminum Nanocrystals as a Plasmonic Photocatalyst for Hydrogen Dissociation Nano Lett., 2016, 16 (2), pp 1478-1484, DOI: 10.1021 / acs.nanolett.5b05149

[45] A brain tumor molecular imaging strategy using a new triple-modality MRI-photoacoustic-Raman nanoparticle. Nat Med. 2012 Apr 15; 18 (5): 829-34. doi: 10.1038 / nm.2721.

[46] Kneipp, J. Surface-enhanced Raman scattering: a new optical probe in molecular biophysics and biomedicine / J. Kneipp, B. Wittig, H. Bohr, K. Kneipp // Theoretical
Chemistry Accounts. - 2009. - T. 125. - No. 3-6. - S. 319–327.

[47] Vitol, E. A. Nanoprobes for intracellular and single cell surface-enhanced Raman spectroscopy (SERS) / E. A. Vitol, Z. Orynbayeva, G. Friedman, Y. Gogotsi // Journal of Raman Spectroscopy. - 2012. - T. 43. - No. 7. - P. 817–827. 135.

[48] Bantz, K. C. Recent progress in SERS biosensing / K. C. Bantz, A. F. Meyer, N. J. Wittenberg, H. Im, O. Kurtuluş, S. H. Lee, N. C. Lindquist, S.-H. Oh, C. L. Haynes // Physical chemistry chemical physics: PCCP. - 2011. - T. 13. - No. 24. - P. 11551–67.

[49] Jarvis, R. M. Characterization and identification of bacteria using SERS / R. M. Jarvis, R. Goodacre // Chemical Society reviews. - 2008. - T. 37. - No. 5. - P. 931–936.

[50] Jarvis, R. M. Surface-enhanced Raman scattering for the rapid discrimination of bacteria / R. M. Jarvis, A. Brooker, R. Goodacre // Faraday Discuss. - 2006. - T. 132. - P. 281-292.

[51] Mroczka, J. Algorithms and methods for analysis of the optical structure factor of fractal aggregates / J. Mroczka, M. Woźniak, F.R.A. Onofri// Metrol. Meas. Syst. – 2012. – Vol. XIX, № 3. – PP. 459-470.