Prognosis of NEM development and practical implementation

Analytical review

Table of contents

Abstract

Rapid progress in the synthesis of various nanostructures and their amazing physical and chemical properties different from the properties of macroscopic bulk samples, led to a significant and potentially long-term growth of the investments of human and financial resources to this area around the world. Not any other area in materials science unites to such an extent the progress in basic research with rapid offer of realization for new equipment and products that have both a great social value and significant commercial potential. Such a potential of nano-sized elements and nanostructured materials for management and control of electromagnetic fields caused the recent introduction of a new research discipline - nanoelectromagnetics - that is, conceptually, a synthesis of classical electrodynamics and modern methods and approaches of condensed matter physics. To be kept in line with the main directions of development of nanoscience and nanotechnology, nanoelectromagnetics as any new interdisciplinary research direction, needs an intensive exchange of knowledge between different scientific communities: basic and applied electromagnetics, chemistry and technology of nanostructures and nanostructured materials, physics of nanostructured systems etc.

The purpose of the prognosis is to discuss the following issues:

- ✓ electromagnetic effects in nanostructures: simulation and experiment,
- ✓ carbon nanotubes, graphene and other forms of nanocarbon in electromagnetics,
- ✓ nano-resonators, -antennas, -transmission lines,
- ✓ optical nonlinearity at the nanoscale,
- ✓ nanostructured composite materials and thin films: synthesis and physico-chemical properties,
- ✓ nanostructured composite materials for electromagnetic protection and protection against ionizing radiation,
- ✓ ordered nanostructures and metamaterials to control electromagnetic fields,
- ✓ biomedical applications of metal nanoparticles and nanocarbon,
- ✓ operation of quantum light and single-photon devices.

Nanoelectromagnetics as a research discipline and a concept was introduced quite recently, 6-7 years ago. And, thus, its subject is just beginning to attract the attention of the research community. Especially such interest becomes apparent so far as the publications on nanoelectromagnetics pass from the physics journals such as Physical Review and Journal of Applied physics, to the engineering IEEE magazines. Plenty of applied articles in electromagnetic applications of

nanostructures and composites were published, but often the features specified by prefix nano are ignored. It was organized a number of international events to overcome this problem such as the special sessions on nanoelectromagnetics at the annual major events of IEEE antenna and propagation society in 2008 and 2010, etc. In May 2011, a special session on nanoelektromagnetizms was organized at the International Conference on Physics, Chemistry and Applications of Nanostructures (Nanomeeting 2011), that attracted much attention from the international nano-community. The success of the session was one of the main motivations for organizing within the framework of By-NanoERA project the international conference Fundamental and Applied Nanoelectromagnetics FANEM'12.

This paper presents an analytical review and defines the development trends of nanoelectromagnetics - a new field of science that represents a synthesis of classical radio physics and electrodynamics with quantum theory of solids, statistical physics, physical kinetics, quantum chemistry, computational mathematics. In the paper there are presented the main types of nanostructures (carbon nanotubes, quantum walls, quantum wires, quantum dots, plasmonic nanowires, etc.), the theoretical methods of nanoelectromagnetics, connections to other fields of science (materials science, nanotechnology, biophysics and medicine). The main applications of nanoelectromagnetics in nanoelectronics and nanophotonics are described (circuits, nanoresonators and nanoantennas, amplifiers and generators microwaves of terahertz and optical frequency), materials science (synthesis of composite metamaterials for radar absorbing coatings). The probable ways of development of nanoelectromagnetics and its future applications in various fields of science, technology and medicine are analyzed.

Chapter 1. Nanoelectronics: Analytical review

1.1. Introduction

Before we start to review the specific elements and nanoelectronics devices, we should make one general observation. For several years, the development of radio physics followed the way of increasing of the operating frequency: from microwaves - to mm-and submm-waves. Due to the technological limitations, the realization of passive components, the dimensions of which are comparable to the wavelength, becomes problematic. This has led to the refusal to use electrical circuits with lumped constants and transmission lines with TEM - waves. The realization of hollow single-mode waveguides and resonators was problematic: surface treatment with the required purity class was impossible, that was leading to

unacceptably high level of heat loss during the scattering of working modes on the randomly irregular surfaces.

Objectively the dimensions of the main elements were significantly higher than the wavelength, which led to a multimode nature of the electromagnetic field. It caused difficulties in frequency tuning, limited range of operating frequencies, high sensitivity of the elements to errors of their setting. Therefore Radiophysics of mm- and submm-range borrowed the principles of the field formation in optics of visible light. Wave beams of Gauss-Hermite and Gauss-Laguerre types appeared as working fields. Accordingly, lens and aperture lines were used as the transmission lines, and Fabry-Perot interferometers with flat or focusing mirrors were used as resonators.

The appearance of nanotechnologies and the elements based on them has fundamentally changed the trend: in mm-, submm-, terahertz and even optical fields appeared the elements which dimensions were much smaller than the wavelength, or comparable to it. It has changed the trend to the opposite: the principles of the field formation typical for low-frequency radiotechnics started to move to the higher-frequency ranges. In particular, single-mode components (photonic crystals, long lines, microcavities) and elements with the lumped constants (electrical capacitors, inductors, resistors) became possible for terahertz and even optical ranges.

Below, we will consider a number of distributed nanoelements, the structure of field in which has a single-mode nature. When using them, it occurs a potential problem of transforming their operational fields (so-called near-fields) to a freely propagating electromagnetic radiation that is not associated with the effect of any guiding surfaces (radiated field). Such a transformation is performed by antennas. At the moment the development of nanotechnologies has led to the implementation of different types of nanoscopic antennas in the terahertz and optical ranges. Below, we will also consider their main varieties.

1.2. Types and characteristics of microresonators.

All types of microcavities are based on the ability of different surfaces to reflect electromagnetic waves with high efficiency [1]. The elementary are two-mirror resonators with focusing mirrors (Figure 1.1). Let the angle of arrival of a plane wave on a single mirror is Θ, then the tangential component of the wave vector is $k_{\perp} = k\cos\theta$. Given that there are two parallel mirrors the resonance condition is as follows: $k_{\perp}L = m\pi$, where m is integer, L is the distance between the mirrors. As a result, the spectrum of eigenmodes is determined by the frequencies

$$\omega = \frac{m\pi c / L}{\sqrt{\bar{n}^2 - \sin^2\theta}}, \qquad (1.1)$$

$\bar{n}$ is the refractive index of the mirrors material.

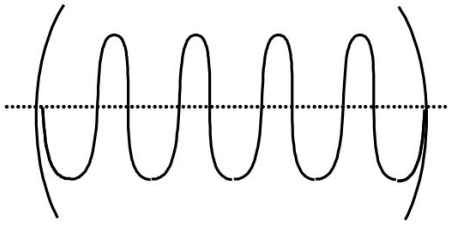


Figure 1.1 Two-mirror resonator with focusing mirrors.

The essential peculiarity of the modes under consideration is their discrete spectrum and full allocation in the space between the mirrors. The situation is conditional on a significant idealization of the task (infinite length of the mirrors and an absolute reflection at them). Objectively to excite a microresonator one of the mirrors is supplied with the aperture and the excitation of the resonator is performed by a focused wave beam falling from outside on the aperture. The existence of the aperture changes significantly the structure of the spectrum: the modes that are essentially localized in the vicinity of the aperture appear (Airy modes [1]).

Another possibility for the excitation of a planar microresonator is to use metal mirrors [1]. The most important physical characteristics of microresonators are the quality factor of a given mode and the frequency difference between two adjacent modes. The quality factor (Q-factor) is defined as

$$Q = \frac{\omega_0}{\delta\omega_0}, \qquad (1.2)$$

where ω_0 is the resonant frequency, $\delta\omega_0$ is the width of the resonance line. The density of the frequency spectrum of the resonator is conveniently characterized by the dimensionless parameter

$$F = \frac{\Delta\omega_0}{\delta\omega_0}, \qquad (1.3)$$

where $\Delta\omega_0$ is the difference between adjacent frequencies of the spectrum. It should be noted that the microresonators are characterized by the following condition $\Delta\omega_0 \sim \delta\omega_0$, that is why Q~F. The situation is different for the bulk microwave resonators of big size where $\Delta\omega_0 << \delta\omega_0$ and, correspondingly, Q>>F. For planar microresonators with metallic mirrors the typical values in the optical range are Q~500 (for comparison, the superconducting microwave resonators can have a quality factor of $Q \sim 10^8 - 10^9$).

Another possibility of implementing high-performance mirrors is the use of dielectric Bragg reflectors [1]. A single mirror is a planar structure of N dielectric or semiconductor layers with alternating thicknesses value and refractive index. It

appears an effect of Bragg diffraction in the system (partial waves reflected from different layers are added in phase). As a result, the frequency intervals in which there exists a very strong reflection are formed. The use of two of these reflectors (Figure 1.2) generates a spectrum of eigenmodes. Such structures are characterized by the values of $Q \sim 10^6$.

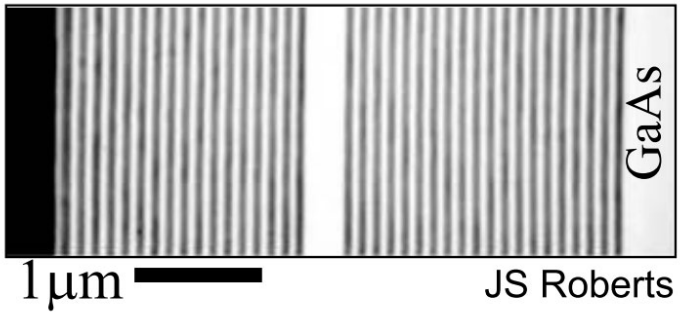


Figure 1.2 Microresonator with Bragg reflectors.

A wide class of microresonators is characterized by non-planar geometry, the spherical reflectors (Figure 1.3).

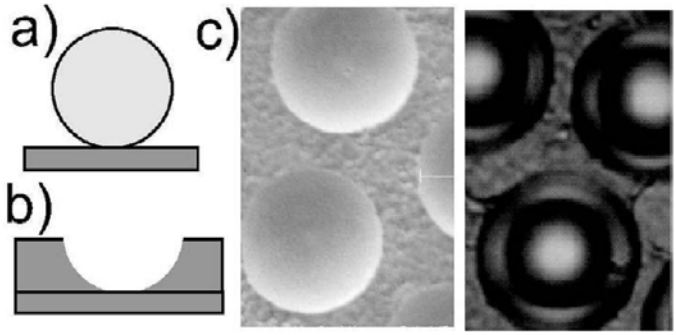


Figure 1.3 (a,b) The gold spherical mirrors generating process, (c) SEM- and optical images of mirrors with the diameter of 5 mm.

Physical implementation: dielectric spheres, micron air bubbles in the cool glass, etc. [1]. Attention to such structures is defined by the presence of specific mechanisms of reflection of light from the curved surfaces. In particular, for gold spherical mirrors with a radius of ~ 100 microns with an appropriate quality of the surface treatment the reflection coefficient R~ 0.9999984 [1], which corresponds to $Q \sim 10^8$, is achievable. For radii of ~ 1 micron, – $Q \sim 10^8$.

The theory of spherical microresonators is based on the Mie electromagnetic wave diffraction theory on the dielectric body. The diffraction problem is solved by

the method of separation of variables in the spherical coordinate system [2]. The desired solution is presented in the form of expansion in associated Legendre polynomials. In the limit of no external field the diffraction problem may also have non-trivial solutions that meet the eigenmodes of the spherical resonator. Their spectrum is discrete, and the natural frequencies are complex even in the absence of losses in the medium. Physically, this corresponds to the radiation losses.

It results from Mie theory that the effect of total internal reflection is also possible for curved surfaces (the geometry schematically is shown in Figure 1.4). The reflection coefficient is then determined by the expression

$$\ln(1-R) = -\frac{4\pi\rho}{\lambda} h \left[\ln\left(h + \sqrt{h^2 - 1}\right) - \sqrt{1 - \frac{1}{h^2}} \right], \qquad (1.4)$$

where $h=n\cos\alpha$, where α is an angle of arrival on a curved surface, ρ is the radius of curvature. It results from (1.4) that the reflection at the curved surface at grazing incidence ($\alpha \geq \pi/2$) for the sphere may be more effective than for the planar structure. The grazing incidence corresponds to the existence of a set of specific modes (so-called "whispering gallery" mode). These modes are characterized by the location of the field close to the surface and by an extremely high quality factor. We should point that the whispering gallery modes also exist in two-dimensional structures such as microresonators in the form of discs. Thus, for the disc with a diameter of 2 micron of AlO_x, located in GaAs, the values $Q>10^4$ are obtained.

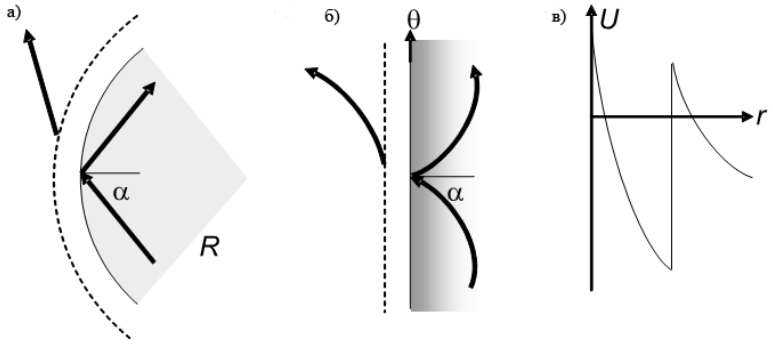


Figure 1.4 (a) The tunneling at full internal reflection, (b) a conformal mapping, and (c) the optical potential

From the other types of microresonators we should point out the resonators on the surface plasmons. Such plasmons exist in metal nanofibers made of precious metals and are distributed along the plane boundary of the metal with dielectric or semiconductor. Given the strong reflections at inhomogeneities the plasmons

generate resonance modes. The field of resonant modes is localized close to the surface, but the nature of the localization is different from the whispering gallery waves. The localization for plasmons is not connected to the influence of the curvature, but is conditional on the strong slowdown inside the metal.

In conclusion, it should be noted that the well-known types of microresonators are characterized by a wide range of physical principles and technical characteristics. One of the fundamental differences from the macrosystem is the possibility of geometric resonances even when the cavity size is small comparing to the wavelength in the surrounding medium (or vacuum). The reason is the high specific polarizability of many types of nanostructures that is not typical to other materials and media.

1.3. Nanostructured transmission lines. The theory of long lines in nanoelectronics.

In this section we will discuss the nanostructured transmission lines. They are characterized by a wide variety of technical solutions: metal wires with surface plasmons [3], semiconductor nanowires with exciton-polaritons [4], single-walled and multi-walled carbon nanotubes [5, 6] etc. Theoretical apparatus for the analysis of transmission lines in the classical radiotechnics is a theory of long lines and telegraph equations. It is essential that it was extended to the nanostructured lines, so different in their physical principles. In this section, we will illustrate it on the example of single-walled carbon nanotubes, and will point the most fundamental features.

It must be emphasized that an attempt to mechanically extend the experience of classical radiotechnics to nano-objects is not successful. The reason is that the macroscopic conductors and conductive nano-elements interact with the electromagnetic radiation by different laws. Indeed, the macroscopic metal samples in the super frequency electromagnetic field behave like perfect conductors. This means that the electromagnetic radiation is reflected almost completely at the metal edge. The radiation that has come inside the metal is concentrated in a thin surface layer, and therefore is characterized by a very low absorption level (such interaction of electromagnetic radiation with the matter is called the skin effect [7]). Therefore, during the transmission of electromagnetic radiation through a wire or through two wires (two-wire line) the movement of the main part of the electromagnetic energy takes place in the free space, though is headed by the wires. The speed of movement of the wave is close to c, and the matched impedance of such transmission lines is close to $Z_0 = 120\pi$ Ом, that makes their alignment with free space relatively simple.

The position for nano-objects is different. The skin effect is impossible in principle (the radius of a nanowire is significantly less than the thickness of the skin layer for almost any material). As a result the wave propagation is accompanied by a strong slowdown and significant absorption. It can be said that such a wave is not purely electromagnetic - the particles of condensed matter are significantly involved in its formation (the conduction electrons in metals, electron-hole pairs in semiconductors). In fact, in a condensed medium it is formed bound states of charged particles and photons. These states are of a quantum nature; in particular, they are characterized by discrete energy values (these states are often referred to as quasi-particles [8]).

The possibility of existence of different types of quasiparticles is a feature of nano-objects. Plasmons in nanowires of noble metals [8] and exciton-polaritons in semiconductor nanowires [8] can be named as examples. Such quasiparticles exist in carbon nanotubes. They represent bound states of photons and π-electrons of carbon atoms.

Let's consider a conducting carbon nanotube of diameter d, located above the ground half-plane parallel to the latter at a distance a from it (Figure 1.5a). Let the nanotube is located under the alternating electric potential. As a result, an alternating electric current flows in the nanotube. If the frequency of the applied voltage is high enough (at about ~ 100 ÷ 10000 Hz), the electromagnetic field when propagating along the nanotube axis is experiencing a significant delay. That means that between the current (and voltage) at different points along the axis of the nanotube exists a phase shift, which depends on the frequency.

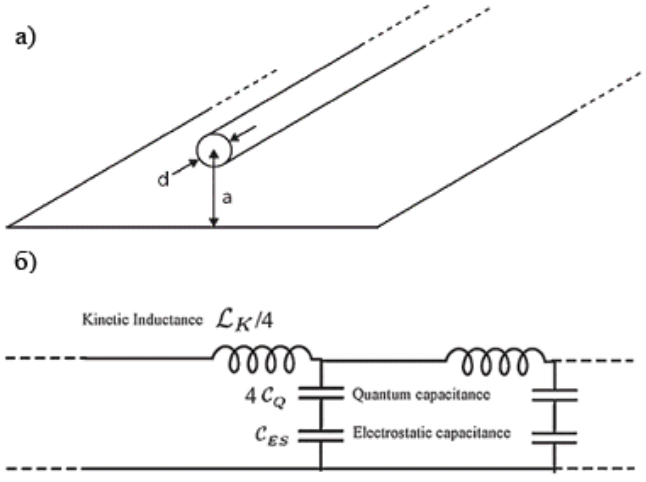


Figure 1.5 Carbon nanotube above the ground plane (a) and equivalent circuit for a single nanotube above the ground plane (b).

The dependence of the induced current on the applied voltage determines the characteristics of the nanotube as an electrical conductor. From different perspectives this problem was reviewed in works [9-18]. First, we should note that the conductivity of the nanotube is determined not by classical but by quantum laws of π-electrons motion. The process of charge transfer under the influence of the applied voltage is carried out on a number of independent channels that have different quantum nature. First, the conduction electrons can have the oppositely directed spins (spin degeneracy). Next, for each spin orientation the nanotube band structure at the Fermi level is doubly degenerate. Thus, in the conductive nanotube there are four parallel channels, each of which makes an identical contribution to the total current, and this should be taken into account during the construction of an equivalent circuit diagram of the nanotube (Figure 1 b). According to [11-18], a nanotube can be considered as an electrical circuit of the infinite length, the unit interval of which is characterized by three electrical parameters L_k, C_Q, C_{EC}, that are called, correspondingly, the kinetic inductance, quantum capacitance and electrostatic capacitance. They are of a different physical nature and below they will be examined independently.

The energy of the charge carrier in the nanotube with the length L_{nt} is quantized. Quantum of energy $\delta E = h\upsilon_F / L_{nt}$, where υ_F is the speed of electrons in the Fermi-point of the nanotube. The current value $I = 2e\delta E / h$ [16] corresponds to the quantum of energy δE . In classical magnetostatics the reserve energy of the magnetic field W is associated with the current flowing through a conductor equal to $W = LI^2 / 2$ [7]. The coefficient of proportionality L is called the inductance and is defined by the geometry of the conductor and the magnetic properties of the material. Inductance describes the ability of the system to store magnetic energy. Quantum of energy δE , the current value and the kinetic inductance L_k are connected by the equality $\delta E = L_k I^2 / 2$. The value L_k plays in respect to the nanotube a role of inductance L for ordinary macroscopic conductor. It is easy to see that the kinetic inductance is proportional to the length of the nanotube, so it is convenient to characterize the ability of nanotubes to store energy through specific kinetic inductance per unit length:

$$\mathrm{L}_k = \frac{L_k}{L_{nt}} = \frac{h}{2e^2\upsilon_F}. \qquad (1.5)$$

Kinetic inductance is defined by the electronic structure of the material through the Fermi velocity, but does not depend explicitly on the nanotube radius. Formula (1.5) refers to the single channel conductance. However, as mentioned

above, there are four parallel channels. Full inductance herewith differs from (1.5) by the factor 1/4, shown in Figure 1.5b.

Voltage applied to the nanotube brings to it the surface charges accumulating electrical energy. This energy is related to the amount of charge Q with the equation $W = Q^2 / 2C_{EQ}$, where C_{EQ} is the coefficient of proportionality called the electrostatic capacity [7]. For an infinitely long nanotube it is convenient to introduce the energy and the charge per unit length. Then C_{EQ} will characterize the ability of a single nanotube area to store the electrical energy. The value C_{EQ} is expressed by the equation [16]:

$$C_{EQ} \cong \frac{2\pi}{\ln(a/d)} \mathrm{E}_d, \qquad (1.6)$$

where E_d is the dielectric capacitivity of the environment. The equation (1.6) provides the accuracy of ~ 1% at $a > 2d$.

The concept of electrostatic capacity refers to the classical conductor the charge of which (and, respectively, the energy) can be changed by an infinitesimal amount. A nanotube is a quantum conductor, the energy of which is measured by quanta of entity δE. A single electron with a charge e corresponds to the energy δE. Therefore, the true electric capacitance of the nanotube represents a series connection of the electrostatic capacitance C_{EQ} and quantum capacitance C_Q. Quantum capacitance is defined by the equality $e^2 / 2C_Q = \delta E$ [16]. For the quantum capacitance per unit length, we obtain:

$$C_Q = \frac{8e^2}{h\upsilon_F}. \qquad (1.7)$$

Value (1.7) refers to the single channel conductance. The record of four paralleled channels leads to a fourfold increase in the total quantum capacitance, as shown in Figure 1.5b.

So, the carbon nanotube in microwave and terahertz range can be considered as a transmission line, equivalent circuit of which is shown in Figure 1.5b. The line parameters of the transmission line are determined by formulas (1.5) - (1.7). These statements make it possible to introduce the linear charge *Q(z)* and linear current *I(z)*, which are connected by the differential equations

$$\begin{cases} (j\omega L_t + R_t)I = -\dfrac{1}{C_t}\dfrac{\partial Q}{\partial z} \\ j\omega Q = -\dfrac{\partial I}{\partial z} \end{cases}, \qquad (1.8)$$

where $L_t=L_k+L_m$, $R_t=\nu L^k$, $C^{-1}{}_t=C^{-1}{}_E+C^{-1}{}_Q$, ν is a phenomenological parameter that determines the dissipative loss in the line and is called the relaxation frequency [19]. It is easy to see that (1.8) have the form of the ordinary telegraph equations. However, the nature of linear parameters is significantly different from the ordinary electrical parameters, which leads to a number of fundamental differences.

First, along the tube can be extended the electromagnetic wave with the phase velocity

$$\upsilon \approx 1/(\mathrm{L}_k C_Q)^{1/2} \cong \upsilon_F ,$$

and the value υ_F is by two exponents smaller than the light speed c in the free space. This makes the nanotube fundamentally different from ordinary macroscopic cables used in radioelectronics (single-wire, two-wire, coaxial, microstrip lines, hollow waveguides, etc. [2]). In the transmission lines of radio-frequency range the phase velocity is close to c, and in the hollow waveguides exceeds it. Slowdown of an electromagnetic wave by the nanotube was predicted in the works [11-15, 18-21]. It should be emphasized that the slowdown of the wave comparing to the free space is necessarily accompanied by a concentration of the electromagnetic field inside the nanotube and on its surface [11, 12]. This means that the nanotubes could form the basis of the nanoscale circuits with very high levels of integration: closely spaced wires will experience no significant parasitic interactions and require special protective measures.

The characteristic impedance of the electromagnetic wave in a carbon nanotube is defined by the equation $Z_0 \cong 4(\mathrm{L}_k/C_Q)^{1/2} \cong h/2e^2 = 12.5$ kohm. This value of the characteristic impedance is much higher than that of the classical types of radio waveguides.

The equations similar to (1.8), obtained in [22] for plasmonic nanowires. At first glance, the applicability of the telegraph equations to nanowires may seem unexpected. Indeed, in classical radiotechnics they are applied to the transmission lines with TEM- and quasi-TEM waves (two-wire, coaxial, microstrip, etc.). It is well known that the waves in the nanowires differ dramatically by the presence of the significant longitudinal components. Here we must make a significant statement of methodological nature. The applicability of the telegraph equations does not require TEM-structure of the field, it requires low frequency dispersion.

Electrodynamic analysis (see, e.g., [11]) shows that such modes do exist in the nanowires in a wide frequency range. For comparison, in the operating range of hollow waveguides (bands of single-mode operation), the dispersion is significant, and this determines the ambiguity and the inability of correct introduction of linear parameters.

1.4. Nanoantennas

Free electromagnetic radiation represents a transverse field, in which the strength of electric and magnetic fields **E** and **H** , and the unit vector of the direction of propagation **m** form an orthogonal triple of vectors. In this case, can be applied the equality $\mathbf{E} = Z_0[\mathbf{m}, \mathbf{H}]$, where the value Z_0 defines the quantitative relationship between the strength of electric and magnetic fields and it is called the impedance of the medium [23]. For vacuum $Z_0 = 120\pi$ ohms and represent a fundamental physical constant. On the other hand, the electronic devices with dimensions of at about the de Broglie wavelength of the electron have the constant current resistance of at about the quantum resistance $R_Q \cong h/e^2 = 25$ kohms [24]. The ratio of these values $\alpha = Z_0 / R_Q = e^2 / 2\pi\hbar c = 1/137$ (c is the speed of light) represents a fundamental physical quantity called in quantum electrodynamics the fine structure constant [25]. The smallness of this value is one of the cornerstones of modern quantum electrodynamics. In fact, it means the smallness of the interaction of the electron-positron and electromagnetic fields (more precisely, the possibility of division of a single quantum field on electromagnetic and electron-positron fields). The equality of ratio of two characteristic impedances to this value is certainly not a coincidence. It means fundamentally different structure of free (i.e. far) and near (i.e. connected to quantum particles) electromagnetic fields.

This indicates that the impedance of free space for electromagnetic radiation and impedance of typical nanoelectronic circuits are mismatched. Therefore, the radiation of the currents flowing in them is inefficient. On the other hand, the reverse situation is also true: free electromagnetic radiation with the low efficiency excites electric currents in nanocircuits. That is why in nanoelectronics it is necessary to take special measures to harmonize external sources of electromotive forces (emf) with nanocircuits and nanocircuits with free space. The problem of such harmonization, in general, has been successfully solved in classical radiotechnics. The elements that convert near (quasisteady) field of electrical circuits to the far field of the electromagnetic radiation are called transmit antennas [26]. Accordingly, the elements, making an inverse transformation are called the

receiving antennas [26] (in some cases they are also called "rektennas"). The elements that connect the various electrical circuits are called interconnects.

At the moment the physics and technology of nanoantennas has turned into a wide research area with a variety of perspectives for practical applications. Based on them there were published fundamental reviews representing a subject from different angles (see, e.g. [16, 27, 28]). Nanoantennas cover a wide frequency range - from the terahertz to the visible optical. They are characterized by a great variety of technical solutions (their examples are shown in Figure 1.6), in the following we shall discuss them in more detail.

From a conceptual point of view it is important to note that it was possible to establish a correspondence between the theory of nanoantennas and macroscopic radiofrequency antennas.

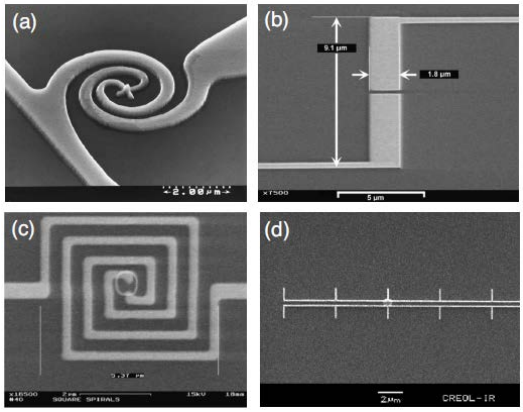


Figure 1.6 Examples of IR and optical antennas made by Boremann and his employees: a) asymmetric spiral antenna [29], b) microstrip dipole antenna [30], c) a square spiral antenna [31], d) phased-array antenna [32].

It is conveniently to describe the field in the far field of antenna in the spherical coordinate system (ρ, φ, θ), connected with the center of the antenna. It is characterized by the components

$$E_\theta = iZ_0 \frac{\exp(ik\rho)}{4\pi\rho} kF(\theta,\varphi), \qquad H_\varphi = E_\theta / Z_0 \tag{1.9}$$

where $F(\theta,\varphi)$ is the fundamental characteristic of the antenna, called the directional diagram. In case of dipole antennas can be applied the equality [26]:

$$F(\theta) = \sin\theta \int_{-L_{nt}/2}^{L_{nt}/2} I(z)\exp(ikz\cos\theta)dz\,, \qquad (1.10)$$

where $I(z)$ is the distribution of the surface current.

It results from (1.10) that the field in the far field of antenna is polarized, and the structure of the field does not depend on the distance ρ between the antenna and the observer. The directional diagram $F(\theta)$ (as, indeed, all the other parameters of the antenna) is completely determined by the distribution of the current density $I(z)$.

Of the other parameters that characterize antennas, the effectiveness of the antenna (antenna efficiency) should be indicated, it is defined as

$$\eta = \frac{P_{рад}}{P_{рад} + P_{погл}}, \qquad (1.11)$$

where $P_{рад}$, $P_{погл}$ are correspondingly the radiated power and the power absorbed by the antenna. Another important parameter, called the directivity factor (DF), is defined as

$$D(\theta,\varphi) = \frac{4\pi}{P_{рад}} P(\theta,\varphi), \qquad (1.12)$$

where $P(\theta, \varphi)$ is the partial power radiated in the direction (θ, φ). The DF describes the ability of the antenna to concentrate the radiation energy in a particular direction (along with (1.12) is also used as the amplification constant, defined as $\eta D(\theta, \varphi)$).

For the characteristics of the antenna is significant the radiation resistance, which is introduced based on the definition

$$R_{\Sigma} = \frac{2P_{рад}}{|I|^2}, \qquad (1.13)$$

where I is the peak value in a fixed point, usually at the peak of the distribution. Along with (1.13), is also introduced the input resistance of the antenna, defined as

$$R = \frac{2P}{|I|^2}, \qquad (1.14)$$

where $P = P_{рад} + P_{погл}$ is the full power of the antenna.

In the classical theory of antennas the reciprocity theorem [2] is widely used. This leads to the conclusion about the identity of all the parameters (1.11) - (1.14), respectively, for receiving and transmitting antennas. Therefore, the theory is built for the transmitting antennas, and the results obtained on the receiving antennas are transferred automatically. It is essential that the reciprocity theorem under fairly general assumptions is proved in nanooptics that allows to use similar correspondence for nanoantennas. However, the use of the reciprocity theorem for nanoantennas should be treated with caution. It, in its usual form, can be violated for fields, having the quantum nature. In this case, the stated correspondence between the transmitting and receiving antennas will not take place. A detailed analysis of this issue is the subject of future research.

As a simple example of nanoantennas of optical spectrum, consider a spherical particle of silver or gold, in which there exists a surface plasmon [33-37]. The experimental scheme is shown in Figure 1.7: metal particle is placed on the edge of a glass needle and it is excited by a single molecule (the inset shows the image of a sample obtained from a distance of 80 nm

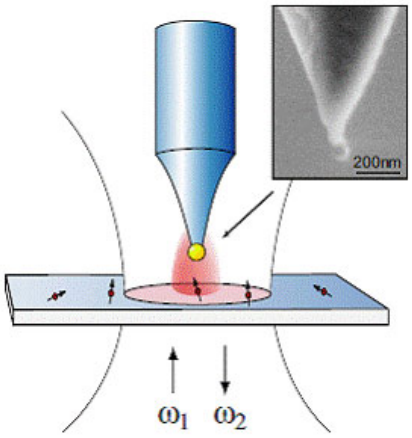


Figure 1.7 The optical antenna in the form of gold or silver nanoparticles placed on the edge of a glass needle.

from gold particles with the help of a scanning electron microscope). The experiments have shown that the efficiency of the antenna depends significantly on the distance between a molecule and a particle, as well as on the quantum yield of the molecule η_0. At large distances $\boldsymbol{r}$ the interaction between the molecule and the antenna decreases rapidly (as r^{-3}), at short distances all the energy is absorbed by the antenna. At the optimal distances the increase of the intensity is $10^4 \div 10^6$. The search for the optimal distances represents a difficult task that requires a joint application of theoretical and experimental methods. For DF the following dependence takes place:

$D(\theta, \varphi) = (3/2)\sin^2\theta$ [26]. This helps to conclude that the radiation properties of this antenna are identical to the properties of the ideal electric dipole.

It is possible to manage the radiation characteristics by changing the geometry of the antenna. Thus, for this type of antennas it was implemented antennas in the form of elongated spheroids and wires, that make it possible to realize very complex directional diagrams [26]. The hoop-type antennas generates radiation close to the ideal magnetic emitter [26]. Another possibility to increase DF is to use multiunit antennas Udo-Yagi (for example, three identical coaxial vibrators, only the central one of them is excited, and the other two are passive and adjust the radiation [26]). Antennas based on this principle are used in macroscopic electrical engineering. They are called "wave channel" [26]: the number of vibrators may be 10÷12, and the lengths may be non-identical.

Carbon nanotubes are promising in use as a terahertz antennas. To some extent, the antenna properties of nanotubes are similar to those of macroscopic wire radiofrequency antennas, although there are a number of important qualitative differences. To discuss them graphically, let's consider a simple scheme proposed in [15] and shown in Figure 1.8. The field radiated by any antenna system is determined by the distribution of currents and voltages in it. A semi-infinite open-loop line of two nanotubes is shown in Figure 1.8.A. If the tubes are identical, the current in each tube is equal in magnitude and opposite in direction. The field in the far field is a superposition of the fields produced by individual tubes. Because of the opposite directions of the currents these fields almost completely compensate each other, so the radiated power of this structure is close to zero.

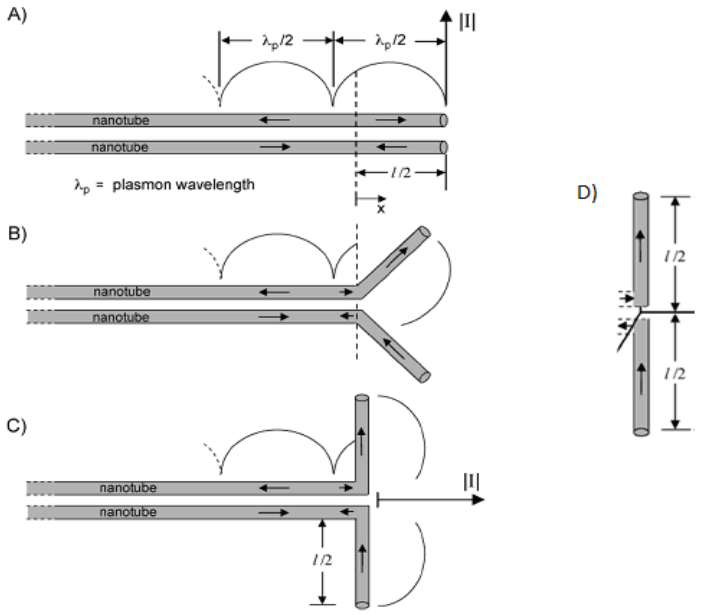


Figure 1.8. A semi-infinite open-loop line of two nanotubes (A); if the edges of open-loop nanotubes are bent, the system will emit electromagnetic energy (B); dipole antenna (C); generalized antenna scheme (D). Here λ_p is the length of the surface wave that is different from the wavelength in free space.

As a next step we consider the structure shown in Figure 1.8.B, in which the edges of open-loop nanotubes of the length $L_{nt}/2$ are bent from each other at a certain angle. The contributions of the bent segments to the far field are no longer compensate each other. This will cause the radiation of electromagnetic energy by the system. The radiation effect is mostly pronounced when the bending angle is equal to 90^{o} as it's shown in Figure 1.8C. The structure represents a simple scheme of dipole antenna. Bent segments of wires are called the the dipole arms. If their lengths are equal the vibrator is called symmetric. Two wire line supply electromagnetic energy to the bent section, i.e. performs the role of the antenna power supply. Electric field at the bent point creates an extraneous voltage. This field is near in the sense that it is being formed and sent by the wires. This statement explains the sense in which antenna transforms the near-field to the far field and back. The currents in the dipole arms, causing the radiation, are created by the tension in a narrow gap between the arms. In this case, the radiative properties of the antenna does not depend on the way in which this tension is created. Two wire line as a power cable is not the only method with the help of which the voltage can be created by unspecified source of the applied electromotive force (emf). Thus, we come to the generalized scheme of the antenna shown in Figure 1.8D. Its two wire

line is removed and replaced by unspecified source emf of arbitrary physical nature, located right in the gap.

All of the above mentioned can be equally applied both to the usual macroscopic radiofrequency antennas and nanoantennas. Now let us stop on the principal differences starting from the physical realization of the antenna circuit power. For makroantenna the driving generator plays the role of emf source (typically is implemented with transistors, semiconductor diodes, electronic tubes, etc.). Some of these principles are transferred to nanoelectronics and can be used together with nanoantennas. However, other principles of essentially quantum nature, that have no analogues in the classical radiotechnics, are also possible. They involve lasers, the sources of spontaneous radiation and resonance fluorescence on the atoms, molecules, semiconductor quantum dots, etc. Both carbon nanotubes and nanowires of other types, such as semiconductor nanowires with excitons, metal plasmonic nanowires, can be used as the conducting cables.

The current density in the dipole arms is usually distributed according to the oscillating law. Optimal from the point of view of the radiation efficiency is the situation when the length of the arm is at about a quarter of the period. Indeed, if a large number of periods is placed on the antenna arms, the currents in some areas of the antennas are oppositely directed. However, their contributions to the far field largely compensate each other. In the opposite case (when the arm length is much smaller than the period), the total current is reduced because of the shortening of the arm at a given current density, which reduces the radiated power. Speaking about the macroscopic antenna dipoles, their period of change of the current density is equal to the wavelength λ, i.e. the optimal length of the antenna is $l = \lambda / 2$. The period of change of the current density for antennas on the carbon nanotubes equals to $2\pi / \tilde{h}$, where $\tilde{h}$ is the wave number of the surface wave. This means that the optimal length of the antenna is $l \sim \lambda \,\mathrm{Re}(\beta) / 2$, where β is the deceleration rate. Thus, we come to a significant qualitative difference between macroscopic dipoles and nanoantennas: due to the large kinetic inductance of the latter their optimal length is significantly (by two exponents!) smaller $\lambda / 2$ [15, 38, 39].

Figure 1.9 shows the results obtained in [38] the results of calculations of $F(\theta)$ for antennas on the carbon nanotubes. They show that the radiation of nanoantennas obtains the directional property.

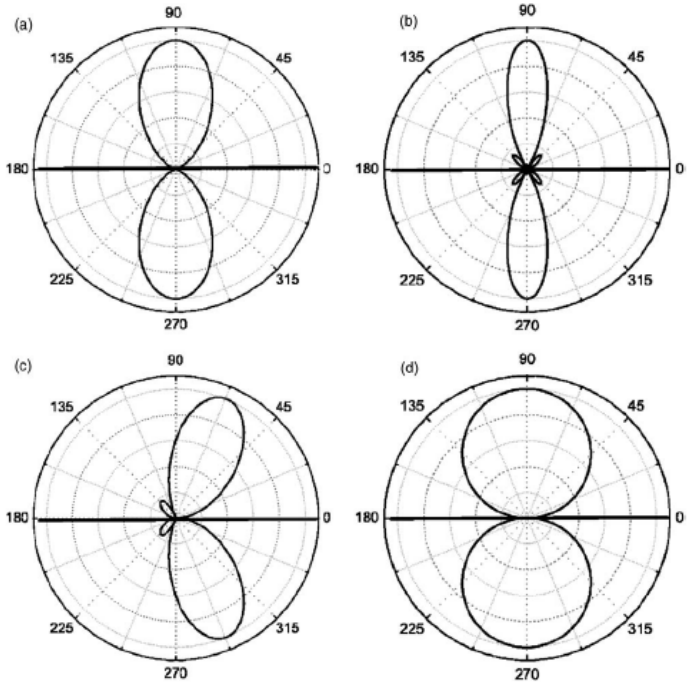
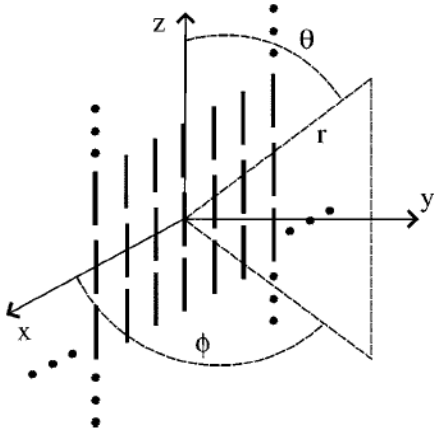


Figure 1.9. The directional diagram for carbon nanotube (9,0) in the visible range of frequencies at λ = 432,4 nm with different lengths of the nanotube and different angles of arrival: a) $L_{nt}=\lambda$, $\theta_0=90°$ б) $L_{nt}=2\lambda$, $\theta_0=90°$, (c)$L_{nt}=\lambda$, $\theta_0=60°$, d) is a low-frequency limit (nanotube is significantly shorter than the wavelength) [38].

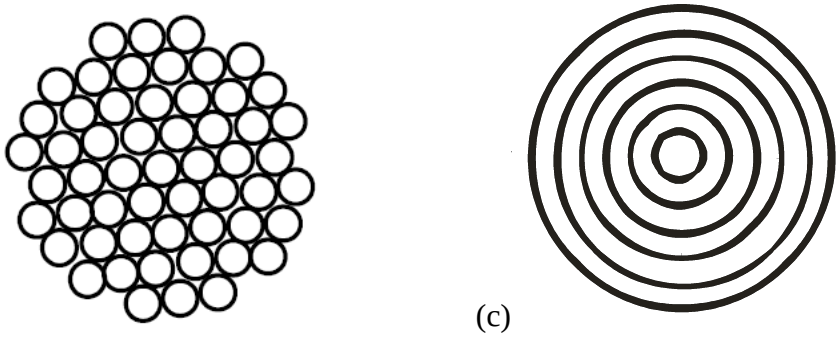
Until now, when considering antenna properties, we neglected the thermal losses in the nanotubes. To account them it is sufficient to replace the kinetic inductance L_k in the equivalent circuit in Figure 1.5 by the serial connection of this inductance and additional ohmic resistance. In fact, this is equivalent to replacing $i\omega L_k \to i\omega L_k + \Re$, where $\Re$ is the nanotube resistance per unit length. The value $\Re$ is usually taken from the experimental data; according to [15] the value is ~10 kohm/micron. To implement high-performance antennas it is necessary to fulfill the condition of small losses, which in this case corresponds to the inequality $\omega L_k >> 4\Re$. This corresponds to the $f > 400\,\text{GHz}$ frequency range, which determines the most promising range for the use of antennas on carbon nanotubes.

The papers [15, 38, 40, 41] are devoted to the calculation of the efficiency of the antenna η and, for example, in [38] are obtained the values $\eta \sim 10^{-5} - 10^{-6}$. It is important to note that this value is significantly smaller than the values η, that are typical for wire makroantennas. This regularity again presents a fundamental property of nanoantennas: strong current waves retardation, specified by the large amount of kinetic inductance.

As in the classical antenna technology, it is possibe to increase the antenna efficiency and to manage the directional diagram in the transition to multi-element antennas. By now there were described three types of multiunit antennas on carbon nanotubes, and Figure 1.10 illustrates the arising opportunities. In particular, for the antenna in the form of a bundle of nanotubes the antenna efficiency can reach values of 0.1 η ~0.1 [40]. Of course, the physics of processes in multiunit nanoantennas and in their macroscopic analogs vary significantly. The reason for this is the availability, along with the ordinary electromagnetic, of electronic interaction between various elements of the nanoantenna. For example, in the antenna on a multilayer carbon nanotube are possible tunneling electron transitions between different layers [41]. In other words, for each π -electron of the nanotubes the probability that they can be found in any layer is different from zero. In fact, you can not declare that a single electron belongs to an individual layer - all the electron states in a varying degree are collectivized. As a result, the current density in each layer is not determined by the field, acting only in the layer, and depends on the fields and in other layers. Along with the conductivity of its own separate layer in the system appear mutual conductances, rapidly decreasing together with the distance between the layers. Optical response of the nanotube obtains a kind of radial non-locality, resulting in the emergence of new types of waves (one of the examples is longitudinal electrostatic waves [41], which differ significantly from the surface ones). Quantum mechanisms of this type must be considered when designing the nanoantennas: they are unique in the classical makroantennas and substantially change the radiative properties.



(a)



(b) (c)

Figure 1.10 The infinite plane latitude of carbon nanotubes of equal length (a), a bundle of nanotubes (b) and a multilyer nanotube (c) as the examples of multiunit nanoantennas.

In conclusion let us briefly stop on the practical applications of nanoantennas. Here, first of all, we should note the new principles of spectroscopy and high-resolution microscopy [42-48]. These applications are based largely on the ability of nanoantennas to concentrate the near field in a bounded region of a space (e.g. in the vicinity of highly curved parts of the surface).

Chapter 2. Nanophotonics: analytical review

2.1. The interaction of the light with semiconductor nanostructures

Semiconductor quantum dots (QDs) are the compound semiconductor crystals (CdSe, PbS, GaAs, InGaAs, etc.), all the transverse dimensions of which are comparable to the exciton Bohr radius of the given material. The movement of charge carriers (electrons and holes) in CT is limited in all directions, that results in a digitalization of their energy spectrum. Similarly, if two of the three dimensions of the crystal are comparable to the exciton Bohr radius, one says about the quantum wire. If one of the three sizes is comparable to the exciton Bohr radius, one says about the quantum wall (quantum well). For the quantum wire and quantum wall the digitalization of their energy spectrum also takes place, but in the space of lower dimension.

The optical properties of nanostructures are currently the subject of intense research. It is connected to the possibility of using of such structures in modern micro-and opto-electronic devices for creation of the innovative displays and lasers, solar cells, devices for the transmission and processing of quantum information, in medicine - as markers and sensors for imaging of malignant tumors at an early stage. Due to their unique optical properties, the nanocomposites based on them are used as active laser media in double heterostructures that have extremely high differential

gain. One of the priorities of modern physics of nanostructures is the study of applicability of CT as logic elements for quantum computation. Great prospects has the use of CT of the metamaterials in creation of the high-efficiency solar cells.

2.2. Nanoelectronic elements as structured photonic reservoirs

In classical electronics the activity of external sources comes to the action of external currents and external electromotive forces (emf). In this case, the opposite effect of the electric circuit at the light source is completely absent. Mathematically, this is reflected in the fact that the sources appear as given right-hand sides of the dynamics equations. In this situation, the properties of the electronic components are completely characterized by the scattering matrices (S-Matrices), connecting the complex amplitudes of the incident and reflected waves [49]. Due to the single-mode nature of the used fields, it is sufficient to confine oneself with the record of the propagating waves, considering S-matrix is of the order of 2×2. Another approach is based on the introduction of the transfer matrix (T-matrix), which connects the fields and currents in two randomly selected sections (defined respectively as the input and output). Essentially two approaches are equivalent; the choice of one of them in particular cases is determined by the convenience considerations.

Another situation occurs in nanoelectronics, as the impact of external sources is of the quantum nature It is accompanied by the exchange of virtual particles through quantum tanks and excitation of quantum fluctuations that can significantly change the observed values of [50]. At the same time some other characteristics of the elements become important. One of them is the density of photon states, which we will discuss below.

The density of photon states at a given point of the space $\vec{r}$ at a frequency ω is the number of photon modes in the interval of between ω and $\omega+\Delta\omega$, classified as the value of $\Delta\omega$ [51]. It can be shown that this value is expressed by

$$\rho_0(\boldsymbol{r},\omega)=\frac{2\omega}{\pi c^2}\mathrm{Im}\{Tr[\vec{G}(\boldsymbol{r},\boldsymbol{r};\omega)]\}, \qquad (2.1)$$

where $\vec{G}$ is the Green tensor of wave equation for the electric field, *Tr* is the trace of tensor. Along with (2.1) one also introduce the partial density of photonic states (e.g. the number of modes of a certain polarization etc.).

It is remarkable that in nano-elements a number of principle quantum effects is possible, that are characterized by the value $\rho_0(\boldsymbol{r},\omega)$ (below we will discuss them in detail). In this case it is essential, that the nano-elements (microrsonators,

photonic crystals, nanoantennas) are able to control the density of photonic states and, in particular, to make it spatially inhomogeneous. This means that these elements referes to a class of structured photonic reservoirs, the fundamental theory of which is presented in the monograph [50].

Let us consider a randomly selected two-level quantum system (for brevity, we shall call it an atom), which has two steady states: lower (ground) and higher (upper); the energy difference between two states is denoted as $\hbar\omega_0$. Suppose that at the time $t = 0$, for example, an atom is brought to excited state by optical pumping. During the interaction of the atom with the photon vacuum, the excited state is not stable. The probability of finding an atom in an excited state decreases with time according to the law $W(t) = \exp(-\Gamma t)$, where Γ is constant. In other words, the atom moves from an excited state to the ground state. Therein lies the effect of spontaneous decay [4, 25].

By spontaneous decay the excess of energy $\hbar\omega_0$ is released in the form of a photon of frequency ω_0, so the effect is also called the spontaneous emission of a photon [4]. The value Γ characterizes the rate of spontaneous decay, and the time $\tau = \Gamma^{-1}$ is interpreted as the lifetime of the atom in the excited state, so that the lifetime of the excited state is defined by the probability of photon emission, which depends on the density of photonic modes associated with the atom (the modes connected with the atom in a dipole way are modes with nonzero component of the electric field in the direction of the dipole moment of the quantum transition of an atom). In this case can be applied the equality [51]:

$$\Gamma = \frac{(2\pi\mu)^2 \omega_0 \rho_0(\omega_0)}{3\hbar}, \qquad (2.2)$$

where μ is the dipole moment of the quantum transition in an atom, which characterizes the strength of the atom connection with the electromagnetic field. It follows from (2.2) that the rate of spontaneous decay is proportional to the photon state density $\rho_0(\omega_0)$ at the frequency of the resonant transition ω_0.

As we have already mentioned, the presence of condensed matter changes the density of photonic states in comparison with the vacuum. Any microresonator which is characterized by a discrete spectrum of modes and is different from the free space can be given as a simple example. As a result, the density of photonic states of the microresonator represents a set of narrow peaks located in the vicinity of the resonance frequencies. Widths and amplitudes of the peaks are determined by dissipative processes (in the absence of dissipation they move to the Dirac delta function).

Thus, we come to the fact that the rate of spontaneous decay Γ of the excited state of the atom is changing comparing to the vacuum, if the atom is located close or inside the nanoelectronic elements. The value Γ depends on the optical characteristics of the body, and also on their configuration. For example, if the atom is located in the antinode of the microresonator eigenmode, and the frequency of the atomic transition ω_0 is close to its natural frequency, the estimation takes place

$$\Gamma \cong \Gamma_0 Q ,$$

where Q is a parameter called the quality factor of microresonator, that characterizes the level of losses in the microresonator. Practically $Q >> 1$ (in real situations $Q \cong 10^4 - 10^5$ (see [1]). As a result, the lifetime of the excited state of the atom inside the microresonator is significantly reduced comparing to the vacuum case. This is the essence of the Purcell effect [51, 52], which is one of the fundamental research subjects of nanophotonics.

Otherwise the Purcell effect is manifested in photonic crystals [4, 53]. Due to diffraction effects for certain energy photons such an environment becomes opaque in all directions of propagation. In other words, for photons of certain frequencies the restricted areas arise, the density of photon states in which is equal to zero. Thus, if the excited atom is located inside the photonic crystal, and the frequency of the optical transition is located within the band gap, the excess energy $\hbar\omega_0$ can not be emitted in the form of a photon. The excited state of the atom will last forever (of course, endless energy time is the result of idealization: photonic crystal is assumed to be infinite). Because of its finite size, the band structure is smeared, and the density of photonic modes in the band gap becomes finite, although much smaller than in free space. The lifetime also becomes finite, but it exceeds the corresponding value for free space by several exponents.

Carbon nanotubes are also able to change the density of photon states (this effect was predicted in [54, 55]). It should be noted that the question is about a partial density of modes polarized along the nanotube axis. Moreover, the concept of "density of photon states", given the presence of nanotubes, requires the clarification. As mentioned above, the delayed waves, the electromagnetic field in which is strongly associated with the conduction electrons, are being distributed in the nanotubes. Strictly speaking, these waves can not be attributed to photons (they are not strictly transverse, as is the case for real photons). Moreover, we should talk about the density of electromagnetic modes, which contains the real photon component and a component associated with the surface waves. We, however,

following the established terminology, the term "density of photon states" will refer to the total density of electromagnetic modes, referring to the above mentioned features.

In the work [55] the spontaneous emission of an atom located within or in the vicinity of the carbon nanotubes is examined. It is shown herewith that in the nanotube a strong Purcell effect takes place. The lifetime of the excited state of the atom, as in the microresonator, is decreased by several exponents under the nanotube action. However, the excess energy can be emitted both in the form of a true photon and a quantum of a surface wave. In the latter case, the [54] indicate a radiationless decay (in contrast to the radiative decay associated with the emission of real photons). The meaning of this terminology is that the surface waves are located close to the nanotube and can not be registered in the far field, like radiation. The value Γ can be expressed as $\Gamma = \Gamma_{rad} + \Gamma_{nonrad}$, where Γ_{rad} and Γ_{nonrad} are components corresponding o the radiative and nonradiative decay. In this case $\Gamma_{nonrad} >> \Gamma_{rad}$, that is under the spontaneous decay the probability of emission of a photon of the surface wave is much higher than the probability of emission of a real photon.

Another fundamental effect on which we would like to stop is the thermal radiation of nanoelements. Under the black thermal radiation we mean electromagnetic radiation, that is at thermal equilibrium [56]. It can be considered as an ideal gas, consisting of photons which do not interact with each other. The mechanism ensuring the establishment of equilibrium consists of the absorption and emission of photons by the matter at finite temperature. In this case the matter uniformly fills the space, and its temperature does not depend on the coordinates.

The effect of nano-elements on the thermal radiation, in general, is determined by two different mechanisms. First, it at the final temperature generates its own heat radiation. Secondly, it scatters black radiation that exists in the environment. If the environment is cold compared to the nano-elements, the second factor is absent. (In this case nano-elements, of course, are not at thermal equilibrium with the environment).

The spectrum of thermal radiation $W_\omega(\vec{r},\omega)$ is determined by the so-called fluctuation-dissipation theorems [56]. In our case it is convenient to write it in the form

$$W_\omega(\boldsymbol{r},\omega) = \left[\frac{\hbar\omega}{2} + \frac{\hbar\omega}{e^{\hbar\omega/kT} - 1}\right]\rho_0(\boldsymbol{r},\omega), \qquad (2.3)$$

where $\rho_0(\boldsymbol{r},\omega)$ is defined by the equality (2.1).

For example, in the work [55] is built a theory of thermal emission of carbon nanotubes in the terahertz frequency range. Let us briefly enumerate its main provisions. First of all, because of the anisotropy of the high-frequency conductivity the thermal radiation becomes partially polarized and directional. Figure 2.1 shows the frequency spectrum of the conductive nanotube of finite length together with a linear (Figure 2.1a) and logarithmic (Figure 2.1b) scales. For comparison, the dashed line in Figure 2.1b also denotes Planck's blackbody spectrum.

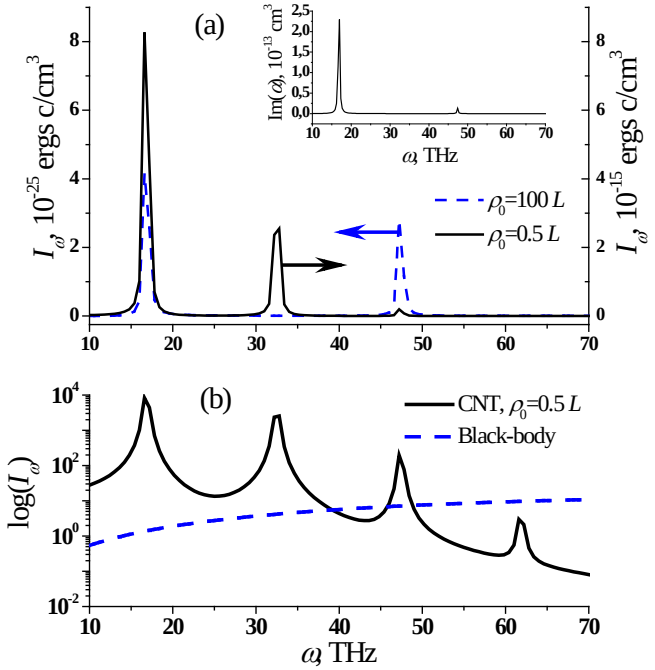


Figure 2.1. (A) The spectrum of thermal radiation of the metallic carbon nanotube (15.0) in the cross section z0=0 at the distance of 100 Lnt from the axis (dotted lines, left axis) and at the distance of 0,5 Lnt (solid line, right axis). The inset shows the frequency spectrum of the polarizability of the nanotube. (B) Thermal radiation from the carbon nanotube in the near field (solid line) in comparison with the radiation of a black body. Lnt = 1 micron, T = 300 K. Electron relaxation time in the calculation of the conductivity of the nanotube τ=3·10-12s.

You can also see that in the spectrum of thermal radiation of the nanotube present narrow discrete lines by which it is radically different from the Planck scale. The appearance of these lines is connected to the nature of the density of photon states in the nanotube. Specifically, these lines correspond to the geometric resonances, that have already been discussed above in detail. The intensity of the line decreases with the increase of the number of resonance. Thus, the thermal

radiation of the nanotube is partially coherent (concentrated in the narrow frequency intervals).

Above mentioned ability of the nanotube to control the spectrum of the thermal radiation is determined by its belonging to the class of structured photonic reservoirs. Such behavior of thermal radiation was also predicted for photonic crystals and systems with surface plasmons [57]. From a fundamental point of view is important to note that the above mentioned quantum effects are determined by the classic characteristic $\rho_0(\boldsymbol{r},\omega)$ (expression (2.1) does not contain the Planck constant). It shows that the correspondence between the classical and quantum physics is much more profound than the passage to the limit $\hbar\to 0$ in the equations of dynamics.

2.3. The strong coupling regime in the interaction of light with the nanostructures

One of the fundamental phenomena in quantum optics is the Rabi oscillations (RO), the periodic system transitions between its stationary states under the action of an external field (see, e.g. [51, 58]). Theoretically predicted by I. I. Rabbi in 1937 [59], RO was firstly experimentally observed in 1949 by Torrey at the nuclear spins in the radio frequency magnetic field [60]. Later this phenomenon was discovered in many other systems, such as atoms in an electromagnetic field [61], semiconductor quantum dots (QDs) [62, 63], Josephson qubits [64] etc.

Theoretically RO may be observed at any intensity of the external field, but really for their observations, the oscillation frequency should be bigger than all the characteristic speeds of the relaxation of the system. If this condition is satisfied, then one talks about the strong connection regime with the field or the regime of strong control field [51].

Since the oscillation frequency is proportional to the amplitude of the external field, then when changing it, it is possible to exercise control over the processes of transition between levels, i.e. to perform basic qubit operations [62, 63] (logical NOT, AND, OR, etc.). So in addition to the fundamental interest in them, the RO are important as a means of realizing of the binary logic and optical control in quantum informatics and quantum computing.

The increasing complexity of physical systems that exhibit RO, results in the appearance of new features that are absent in the classical carting [51] of the phenomenon. The quality changes of the PR picture in the interaction with the field, the frequency of which varies with time [65], phonon-induced dephasing [66] and the effects of local fields [67-69] can be viewed as the samples. New effects appear in the systems with the broken inversion symmetry [70] and in the systems of two coupled oscillators Rabi [71-77].

2.4. The role of local fields in the interaction of nanostructures with the quantum light

The resonant interaction of nonclassical light with QDs is implemented through two different mechanisms. The first of them is semiclassical and is associated with the macroscopic polarization of the medium in an external electromagnetic field. This mechanism provides the depolarization shift of the resonance frequency, the blue is for QDs in the ground state and the red is for an excited QDs. The shift of the exciton resonance is observed for the states of light that generate macroscopic polarization of the medium, i.e., for the classical light, and any other states with non-fixed number of photons. The magnitude of the shift depends on the geometry of QDs and its electronic properties. The second mechanism of the interaction of light with QDs is of QED origin and can not be interpreted within limits of classical electrodynamics. This mechanism leaves the resonant frequency unbiased and is implemented in the fields with a given number of photons, such as the spontaneous emission and absorption of a single photon. Thus, it arises a fine structure of the exciton line in QDs interacting with a quantum light (see Figure 2.2). The component of intensity of the fine structure is determined by the statistics of the quantum light.

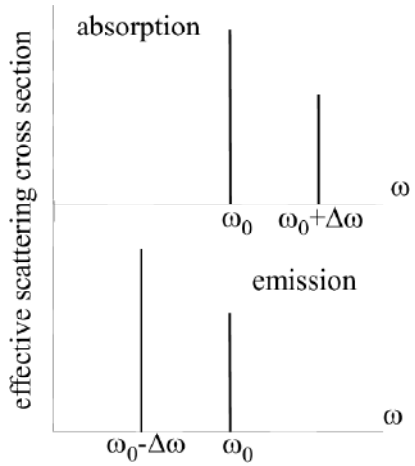


Figure 2.2 The fine structure of the electromagnetic response of QDs in the quantum light [78]. Top figure corresponds to the case of absorption, and the lower - to the emission of light.

In semiconductor physics was established the concept of the exciton gas as a system of freely moving quasi-particles in an infinite semiconductor environment - excitons. In the quantum dot the exciton movement is limited by its size. In such circumstances, it is useful to introduce the concept of the exciton composite [79] - the medium of QDs. Unlike the ordinary composite materials, the exciton composite

is formed by the resonance active inclusions, which determines the characteristics of the electromagnetic response. In this case most of the standard procedures for spatial averaging, adopted in the effective medium theory, remain applicable to the exciton composites. Such approach allows us to develop the electrodynamics of layered heterostructures with quantum dots based on the well known methods of the description of the quantum wells [80, 81].

2.5. Optical nonlinearities of nanostructures

Linear and nonlinear optics corresponds to the optics of small and high light intensity. Linear optics describes the propagation of low-intensity light in the transparent media. The laws of linear optics are violated at high light intensities, which are achieved with the help of laser radiation: (for example, a standard pulsed laser with an intensity of at about 10^{10} W/cm2). We can point out two main reasons for the difference of the results of interaction with the light matter of small and large intensity. First, in addition to single-photon processes that determine the interaction with the light matter of low intensity, a major role at high intensity play the multiphoton processes, when in the elementary act of interaction of light with the matter a few photons are absorbed. Second, at high intensity arise the self-action effects consisting in the change of the original properties of the matter under the influence of light propagating in it. For these reasons, the principle of superposition [82] is violated: the field generated by independent sources acting simultaneously is not equal to the sum of the fields produced by these sources separately.

However, in this case, the contribution of non-linearity can often be viewed as a perturbation of the linear case, and the polarization $\mathbf{P}$, induced in a nonlinear medium by monochromatic field $\mathbf{E}(t) = \mathbf{E}_0 \exp(i\omega t)$ of frequency ω, can be represented as a decomposition [82]:

$$\mathbf{P} = \chi_1 \mathbf{E} + \chi_2 \mathbf{EE} + \chi_3 \mathbf{EEE} + \ldots, \qquad (2.3)$$

where χ_i are the tensors of the $(i+1)$ rank, which are determined by structural properties of the environment and are called optical susceptibilities; and the index i is called the period of optical susceptibility. Optical susceptibilities decrease rapidly with the order increase, and in most environments the nonlinearities of the exponent $i \geq 4$ are negligible.

Many types of nanostructures have pronounced nonlinear optical properties, and nonlinear optics provides a highly efficient tool for the study of their structure and identification. On the other hand, the use of nonlinear optical properties of nanostructures opens new opportunities for controlling the properties of light to

solve the problems of nanooptics and nanophotonics. Below we illustrate some of the general trends by the example of carbon nanotubes.

The effects of generation of higher harmonics in the carbon nanotubes is theoretically studied in [67, 83-86]. The uniqueness of the nonlinear optical properties of the nanotubes is caused by the high mobility of π-electrons and one-dimensional conduction type, and is characterised by the fact that, even at relatively low intensities there is a strong interaction between the nonlinearities of different orders. In fact, it means that the high-order harmonics play an important role in the nanotubes, as in the equation (2.3) the higher-order nonlinearity cannot be omited. In general, in the spectra of the nanotubes one can observe both odd and even harmonics, but in the non-chiral nanotubes such as "zigzag" and "chair" types there exists a center of inversion, and therefore the non-linearity of even orders is equal to zero; while the lowest is the nonlinearity of the third order, which in itself helps to distinguish chiral and Non-chiral nanotubes. (The appearance of even harmonics is possible also in the tubes with an inversion center by the addition of a constant field which lowers the symmetry of the system).

A number of recent theoretical and experimental studies [83-89] have confirmed that the nanotubes are highly nonlinear optical media with the high potential of applied use in nanoscale control devices and the control of optical radiation. To illustrate this statement, let us consider the third-harmonic generation process in the nanotubes, irradiated by an intense electromagnetic pulse, linearly polarized along the nanotube axis and having a Gaussian shape. To determine the density of the axial current, induced in the nanotube, the numerical solution of the quantum kinetic equations [87] is obtained.

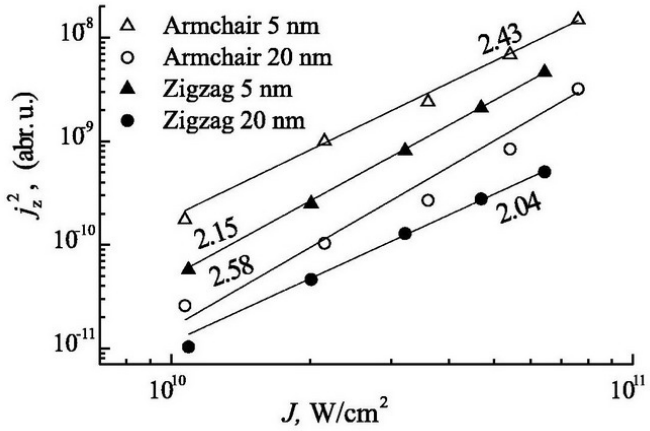


Figure 2.3. Approximation of the parameter p in the equation (2.4) [85].

Third-harmonic generation in the non-resonant excitation in crystals or gases can generally be described by the third-order polarizability even for the rather high intensities, in which the destruction of the matter does not happen under the influence of the irradiate field. For the low intensities, the current amplitude of the N harmonic is proportional to the amplitude of the incident field of N degree. It is natural to expect the similar behavior of the third harmonic in the nanotubes. However, even for a pump pulse intensities of less than 10^{10} W/cm^2, the expected power law breaks down:

$$| j(N\omega) | \sim E_0^p, \tag{2.4}$$

and $p \neq N$. This indicates that there is a saturation of the nanotubes interaction with intense laser pulses, and therefore the power series expansion is no longer valid. For a more detailed study of this effect and its comparison with the experimental data [85] was calculated $| j_z |^2$ as an intensity function of incident ultrashort pulse. It was found out that in a narrow band of low intensity the parameter p in the equation (2.4) can be approximated by a number lying in the range from 2.04 to 2.58, for different types of nanotubes (see Figure 2.3). Experimental results for the third harmonic [85] confirm this conclusion. At higher intensities of the irradiating field the numerical simulation predicts a more significant deviation from the power law $p = N$. Figure 2.4 shows the saturation of the third harmonic of the induced current at the increase of the amplitude of the pump pulse in a wide range of amplitude parameters.

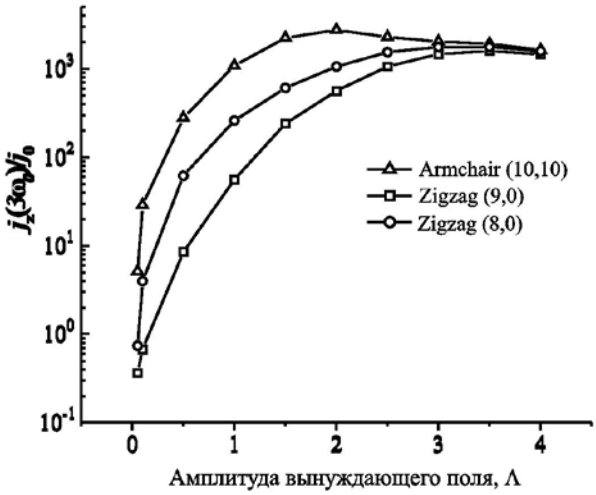


Figure 2.4. The current amplitude of the third harmonic as a function of the intensity of the incident field for different types of nanotubes [85]; $j_0 = e\gamma_0 / 2\pi^2 \hbar R_c$.

In the case of electromagnetic fields of sufficiently low intensity the nonlinear response of the nanotubes can be described by the cubic susceptibility. To this end,

quantum kinetic equations are solved analytically by successive approximations method, which allows to determine the components of the cubic susceptibility tensor $\chi^{(3)}_{zzzz}(-3\omega;\omega,\omega,\omega)$. The results of the calculations [87] are in good fit with the experimental data [88, 90]. The comparison is shown in Table 2.1.

$\hbar\square\square$ (eV)	$\mathrm{Im}\left[\chi^{(3)}\right]$, esu experiment [88,90]	$\mathrm{Im}\left[\chi^{(3)}\right]$, esu theory
0.8	-1.9×10^{-8}	-3.7×10^{-8}
1.47	-10^{-9}	-6.5×10^{-9}

Table 2.1 The comparison of the experimentally measured values of the cubic susceptibility [88, 90] with those calculated theoretically [87].

Chapter 3. Synthesis of nanoelectromagnetics with other sciences

3.1. General comments

The last two decades of the development of science and technology were marked by the rapid progress in the synthesis of various types of artificial media and materials, posessing the nanoscale patterning and properties that are substantially different from those of natural environments. In essence, it happens a fundamental change in the physics and chemistry of condensed matter, that expands greatly our understanding of the nature of solids and our ability to control their properties, a it was made decisive step towards the creation of materials, devices and systems with the new unique features. The phrases prefixed with nano-: Nanoelectronics and nanooptics, nanomechanics, nanosensoris, nanomaterials - define the entire areas of modern physics, chemistry, materials science, instrument engineering.

The development of nanoelectronics - the electronics on the deep sub-micron level, that is, with the linear dimensions of circuit elements of less than 0.1 microns - creates the prerequisites for a new step in the solution of the problem of miniaturization of the transmission, reception and of the information processing devices. The term covers both traditional microelectronic devices and technologies with a higher degree of miniaturization, and the latest advances in molecular electronics, which is manipulating single atoms and molecules. The monomolecular logical schemes are being developed. They can become the basis for a new generation of computers, distinctive by its sub-miniature size at a unique performance. The new nanotechnology materials such as fullerenes [5, 6] and carbon nanotubes (CNTs) [5, 6] are quasione-dimensional carbon macromolecules, organic polymers, the structures based on quantum wells, quantum wires and quantum dots (QDs) - localized nanoscale inclusions into the semiconductor [91],

providing the spatial quantization of the motion of charge carriers in one or more directions, provide the basis for this. Thus, they represent a potential for application of such structures as the active medium of semiconductor lasers. Wide review of the research works on QDs lasers is presented in the monograph [91]. The recent studies have demonstrated the emergence of hybrid carbon forms - peapods - based on the introduction of various fullerenes in CNTs, such as C_{60}, C_{70}, C_{80}, and C_{84}, and metal fullerenes such as $Gd@C_{82}$ and $Sc_2@C_{84}$. Optical and electronic properties of QDs attract attention by its promising possibilities for the storage, transmission and processing of quantum information [92, 93]. In particular, it was achieved a significant progress in the development of single-photon light sources [94].

The solid-state nanostructures represent nanoscale heterogeneity of different natures and configurations inside of the semiconductor and dielectric media. Despite the different physical nature of these objects, they are united by a very small size in one or more directions, they are just by 1-2 orders of magnitude greater than the typical interatomic distance. Under these conditions, the de Broglie wavelength of an electron is comparable to the size of the system, and the quantum nature of the charge carriers is shown in full extent. In particular, the spatial limitation of the charges movement leads to a digitalization of the energy spectrum with the energy levels determined by the size and shape of the nano-object.

The development of electrodynamics is always closely connected to the practical problems that arise at the solution of the tasks of two-way transmission and processing of signals by various systems in different environments. For example, the problem of radiolocation has led to the development of methods for the solution of the problems of electromagnetic waves scattering by the bodies of arbitrary shape [49], and the necessity of realization of the long-range radio communications has led to the creation of the theory of scattering by statistically heterogeneous surfaces [95]. The formation of quantum electronics has required a creation of the theory of open quasi-optical resonators [96]. The synthesis of high-quality optical fibers made it real the optical fiber communication, that has led to the development of the theory of open dielectric waveguides [97, 98]. The development of microelectronics has stimulated the works on the electrodynamics of microstrip and other planar structures [99]. The modern stage of development of the electrodynamics involves the creation of highly efficient methods of description of diffraction by bodies with an arbitrary spatial configuration and energy dissipation [49]. Given the advances in technology of synthesis of new types of nanostructured objects and materials and the necessity of their applications in the information and sensory systems, one can confidently say that the ***modeling of the nanostructures and nanoscale circuit elements and systems is one of the main directions of the development of modern***

electrodynamics. Therefore, there arise new formulations of problems and well-known techniques and methods are filled with the new content. This process can be viewed as the formation of a new interdisciplinary academic discipline, which we call nanoelectromagnetics.

It can be said without exaggeration that nanoelectromagnetics is located at the crossroad of many sciences. This is determined by many factors. One of them is the fact that the objects of study are the structures that can be referred to macromolecules (their form may vary considerably: Carbon nanotubes are the macromolecules that are strongly elongated in one direction; semiconductor quantum dots - macromolecules of a quasi-physical form, etc.). Due to the above mentioned the electronic properties are determined by a complex synthesis of quantum and quasiclassical effects.

In addition to the effect of the spatial limitation of the charge carriers movement, the spatial heterogeneity inherent to the nanostructures creates in them nanoscale heterogeneity of electromagnetic fields. In many cases, they generate a considerable spatial dispersion, which as it is well known plays a fundamental role in the classical crystal optics [100]. If the first factor lies in the focus of modern physics research of nanostructures, the role of the second of them is often underestimated. Therefore, we will dwell on it in detail in different sections of this review.

It is essential also that the electronic properties of a nano-object depends on its configuration (for example: the carbon nanotube depending on the folding of the graphene sheet into a cylinder can be either metal or semiconductor). This makes it impossible to transfer the standard macroscopic electrodynamics to the nanoscale objects: constitutive equations and material parameters are meaningless. The problem of quantum electrodynamics and kinetics should be solved concordantly: the motion of the particles is determined by the fields established by them.

In most of the cases, these factors are not limited to small perturbations. It raises a number of complex mathematical problems (boundary value problems for integro-differential equations in the field of complex configurations, differential equations with special nonlinearity laws, inverse problems of mathematical physics, the theory of superoperators etc.)

If to talk about practical applications of nanostructures, one of the major classification directions should include the use of them in the process of sending, receiving and processing of the information. One of the main problems in this case is a selection of signal on the background of random noise. This problem for many years has been the subject of studies in classical radiotechnics. The experience

gained is useful for nanoelectronics, but its automatic use is not possible: a nontrivial adaptation to the quantum systems is necessary.

Even these brief remarks show how great and diverse are the possibilities of synthesis of nanoelectromagnetics with other sciences. Below, we will discuss them in more details. Here we should point out only that the synthesis is interrelated: nanoelectromagnetics is not only based on the fundamental positions of the other sciences, but also sets up new challenges that are needed to be addressed in the future.

3.2. Nanoelectromagnetics and Theoretical Physics

3.2.1. The concept of quasi-particles

One of the foundations of nanoelectromagnetics is a quantum many-body problem. It is clear that its direct solution for physical models of nano-objects is not possible. The processes of the carriers transfer in nanostructures is accompanied by their interaction, leading to cross-correlations. These interactions are not limited to small perturbations - they significantly modify the energy spectrum. It means that to describe the quantum transfer is fruitful the concept of quasi particles - bound states of real particles [8]. The intercorrelations tend to weaken over the time, and therefore the quasiparticles are characterized by a finite lifetime. This alone means that the application of the Schrodinger equations to them is not correct - in the latter there are no factors of relaxation ("real" particles exist forever).

It should be noted that the concept of quasi-particles was formed in theoretical physics for a long time ago - before the appearance of the nanostructures. As an example can be named the Cooper pairs in superconductors, photons and rotons in the liquid helium [8], Frenkel excitons and Wannier excitons in crystals [8], etc. The appearance of nanostructures required further development of physics of quasiparticles: it appeared the new types of them (the examples are polaritons, plasmons, and etc.) The existence of the interactions between the particles leads to the entanglement of quantum states. Let there be two particles 1 and 2, each of them is characterized by the quantum states $\left|a_{1,2}\right\rangle$ and $\left|b_{1,2}\right\rangle$. The effect of entanglement means that, considering the interaction, the quantum state of the quasiparticle is not limited to the factorization of the states of individual particles; the wave function exists only on the two-particle basis:

$$\left|\Psi\right\rangle = c_1\left|a_1a_2\right\rangle + c_2\left|a_1b_2\right\rangle + c_3\left|b_1a_2\right\rangle + c_4\left|b_1b_2\right\rangle, \qquad (3.1)$$

where $c_{1,2,3,4}$ is just some coefficients satisfying the normalization condition.

The fundamental importance of entanglement states has been recognized in theoretical physics (in particular, for quantum computers and quantum computations

[92]). The emergence of entanglement states initially occasioned to bring into question the quantum mechanics (Einstein-Podolsky-Rosen paradox [92]). The existence of the nanostractures has turned the problem of synthesis of entanglement states into applied physical problem - non-trivial, but not related to the category of unique physical experiments.

An important special case of entanglement states are bound states of condensed matter and phonons - the so-called atoms, wearing the radiation [58]. The use of this type of quasi-particles is especially effective for description of the interaction of light with the matter at the strong coupling regime - the problem that is very significant for nanoelectromagnetics, that we pointed out in Chapter 2.

In general, the quasiparticles should be divided into two types. The first, when the interaction tend to zero, split into individual particles (for example: Cooper pairs move into free electrons). The second, when the interaction tend to zero, cease to exist (for example: phonons in crystals). The most important characteristic of both types of quasi-particles is their dispersion low ε(**p**) - dependence of the energy ε on the pulse **p**. It is essential that the form of the law can vary significantly from the square - typical for usual particles. The knowledge of it let in many cases to consider the nanoobject as ideal (or close to ideal) gas of quasiparticles and to use the standard methods of kinetic theory (Boltzmann equation [101]).

From the point of view of synthesis of nanoelectromagnetics and theoretical physics, the remarkable is a fact that the latter often manipulates with the models of quasiparticles (at first glance, quite abstract), which have a universal character and lead to the manifestation of the same mechanism in different physical situations. We confine ourselves here only to one example: we are talking about a degenerate almost ideal Bose gas. His theory was developed by N.N. Bogolyubov in connection with the problem of superfluidity of liquid He, and led to the prediction of the Bose-Einstein condensation [56]. Quasiparticle dispersion law in this model is:

$$\varepsilon(\boldsymbol{p}) = \sqrt{\frac{U}{m}\boldsymbol{p}^2 + \left(\frac{\boldsymbol{p}}{2m}\right)^2}\,, \qquad (3.2)$$

where m is the mass of the electron, and U is the coupling parameter of two-particle interactions. For small $\boldsymbol{p}$ (3.2) gives a linear law $\varepsilon(\boldsymbol{p}) = U\frac{|\boldsymbol{p}|}{m}$, which for large $\vec{p}$ returns to the normal square law for free particles. Namely a linear section $\varepsilon(\mathbf{p})$ corresponds to Bose-Einstein condensation and, in principle, describes the superfluidity.

It should be pointed out that this model was not sufficient for description of the superfluid liquid helium. However, this is a fundamental physical model, arising in different physical situations. Her first successful application was made at the polarized vapor of alkali metals, held in the "magnetic traps". At the moment it is used in nanoelectromagnetics to describe the optical properties of semiconductor quantum walls: the base is the introduction of a polariton Bose-liquid and rpresentation of the superfluidity of the latter [1].

3.2.2. Physics of open quantum systems

The basis for the synthesis of this theory with the nanoelectromagnetics is the ability of correct description of the attenuation in quantum processes. The general idea is based on the assumption that the object being examined is associated with a "large" system (referred to as the reservoir). The term "large" means that it contains a lot of modes; all of these modes are associated with the object, and the connection of each of the modes is weak. Due to the above mentioned, the reservoir is in a state of thermodynamic equilibrium: the inverse effect of the object to the reservoir is negligible. The reservoirs can be of different physical nature. Example: photonic reservoir is the vacuum state of the electromagnetic field, in which the number of photons equals to zero. The interaction of the excited object with a photon reservoir can lead to a spontaneous decay of the excited state [4].

The formalism of the description of the object link to the reservoir is based on the following considerations. The system of "object + reservoir" is characterized by a full density matrix $\rho_{\text{tot}}(t)$, provided in the form $\hat{\rho}_{tot}(t) = \hat{\rho}(t) \otimes \hat{R}_0$, where $\hat{\rho}(t)$, $\hat{R}_0$ are the partial matrix of density of the object and the reservoir, respectively (and $\hat{R}_0$ does not depend on t). The starting point is the Liouville equation for $\hat{\rho}_{tot}$, in which it was made an average over the degrees of freedom of the reservoir (the connection of the object to the reservoir is described in the Born approximation taking into account the Markov approximation). The result is the equation for $\hat{\rho}_{tot}$ in the form

$$\frac{\partial \hat{\rho}}{\partial t} = -\frac{i}{\hbar}\left[\hat{H}, \hat{\rho}\right] - \frac{1}{\hbar}\sum_{n,m} h_{nm}\hat{L}_{nm} + h.c., \qquad (3.3)$$

where $\hat{H}$ is the Hamiltonian of the object, h_{nm} are the constant coefficients, and $\hat{L}_{nm}$ are special operators (called the linblad forms - n.a. B. Linblad), having the form of $\hat{L}_{nm} = \hat{\rho}\hat{L}_n\hat{L}_m + \hat{L}_n\hat{L}_m\hat{\rho} - 2\hat{L}_n\hat{\rho}\hat{L}_m$, $\hat{L}_{n,m}$ - where a number of operators that characterize the object. In the simplest cases $\hat{L}_0, \hat{L}_1$ are the creation and annihilation operators of the two states of the object, and the rest equal zero.

The availability of linblad forms makes the equation (3.3) non-Hermitian, which corresponds to the dissipation. It is remarkable that the type of linblad forms does not depend on the nature of the object and the reservoir - the operators $\hat{L}_{nm}$ and numbers h_{nm} can only be changed. This means that the physics of open quantum systems provides a unified approach to the description of the decay processes in nanoelectromagnetics. This approach eliminates the involvement of phenomenological models, which often lead to a number of fundamental questions bigger than the number of really obtained answers.

3.2.3. The principles of the secondary quantization and nanophotonics

In many cases at the interaction of nanostructures with the light the quantization of the latter plays a crucial role. In this case, we are led to the necessity of development of *the quantum optics of nanostructures and nanostructured composites*. It should be emphasized that the application of general principles of the quantization of electromagnetic field [1, 4, 25, 101] to the nanostructures is not trivial. Here, there exist various ways, and they are not alwaysfundamentally equivalent. Meanwhile, the problem is particularly important in quantum optics: the violation of some general conditions for the constitutive equations immediately leads to physical contradictions in the quantization of the field [76]. Example: the automatic application of the secondary quantization in absorbing media leads to the attenuation in time of the correlators of creation and annihilation photons. The above mentioned means that the quantum fields over the time in interaction with the matter should become classical, i.e. disappear. It is evident that there is nothing of the kind in the experiment, which means that the incorrectness of the applied technique of quantization.

The most credible and effective way here, in our opinion, is based on the introduction of the refractive index of the amplitude of scattering of a single diffuser at the zero angle. It should be emphasized that this approach is applicable not only for photons, but also for quantum particles of another physical nature (atoms, atomic nuclei, nucleons, etc.), which allowed to put it in the basis of the nuclear optics of the polarized media [102].

3.2.4. Quantum Thermodynamics.

The processes of heat conduction in nanostructures have attracted much attention due to their fundamental and applied importance. The absorption of electromagnetic waves by the nanostructures generates the heating of them and the heat distribution. At the first stage, there were a lot of attempts in the literature, causing the confusion, to analyze them. They were based on the application of the

Fourier law and the classical equation of thermal conductivity; the specifics of a nanoobject reflects only the numerical values of its geometrical dimensions.

Of course, it is clear that such attempts are physically inadequate. The concept of temperature is meaningless in relation to the single atom, or a system with a not large enough number of particles. Nontrivial question: where is located the boundary on which the classical thermodynamics laws come into force [103-106]. It is reasonable to assume that this boundary is located exactly in the nanoregion where micro- and makroconformities intertwine in a very complex way. The correct thermodynamics should be built on quantum principles for "large" systems [106]; in this case the usual thermodynamic concepts are subject to revision.

Due to the considerable complexity of quantum thermodynamics, the ordinary phenomenological models, that have a clear physical meaning [103,105], are also attractive. They number in a lot; and they are developing intensively. As an example, let us mention [103]: in some cases, a nanoobject can be regarded as being in a global thermodynamic equilibrium and being characterized by the spatial average temperature. However, there is no local thermodynamic equilibrium, i.e. the spatial fluctuations of the temperature are fundamental. The thermal conductivity equations include both the temperature and the correlator describing such fluctuations. In the result we obtain a generalized thermal conductivity equation, which has the form of

$$\tau \frac{\partial^2 T}{\partial t^2} + \frac{\partial T}{\partial t} = \alpha \nabla^2 T, \qquad (3.4)$$

where α is the diffusion coefficient, τ is a constant factor, which describes the local fluctuations. In the limit of local thermodynamic equilibrium$\tau \to 0$, and (3.4) becomes the classical equation of Fourier.

3.2.5. The instability theory.

This theory originates from plasma and electron beams physics [101]. Usually it is applied to the homogeneous infinite media. The field being examined is represented as a superposition of the stationary state and the small fluctuations. Due to this smallness the equations for the fluctuations are being linearized, and their particular solutions are in the form of a traveling wave $\exp(j(hz - \omega t))$. In the result we obtain the dispersion equation $\Delta(h, \omega) = 0$, which is the subject of analysis. If at the real ω the field increases in space, one say about the convective instability; if at every point of the space the field grows exponentially with time, one say about the

absolute instability. The case of convective instability should be distinguished from the non-transmission counter wave - there exist special criteria [101]for this.

The instability theory applied to the nanostructures is being filled with the new content. Spatial heterogeneity of nano-objects leads to reflection and scattering fluctuations. These processes can both inhibit and stimulate the development of instabilities - depending on the specific properties of the scattering matrices. The development of sufficiently rigorous universal criteria is the subject of the future research.

Chapter 4. The forecast of development of nanoelectromagnetics.

The problems that are described in this section can be divided into basic and applied. Of course, such a division is conventional, especially since the development proceeds in strong interrelation. Below we will provide a brief description of both of them, based on their analysis of the current state, described in chapter 1.2.

4.1. Nanocircuits and nanoantennas

4.1.1. Reciprocity theorem for nanoantennas

As it was described in Chapter 1, the identity of the characteristics of such antenna in the "transfer" and "reception" regimes follow from the theorem of reciprocity. The latter is a direct consequence of Maxwell's equations. In the case of quantum fields, it can be easily proved for the field operators: $\hat{\mathbf{I}}_1\hat{\mathbf{E}}_2 = \hat{\mathbf{I}}_2\hat{\mathbf{E}}_1$, where $\hat{\mathbf{I}}_{1,2}$, $\hat{\mathbf{E}}_{1,2}$ are the operators, respectively, both of the current and the field in two given points of the space. However, the antenna characteristics are determined by the observed values. If the question is about a pure state, then the fields and currents averaging is performed independently and provides the reciprocity theorem for the mean:

$$\left\langle \hat{\mathbf{I}}_1 \right\rangle \left\langle \hat{\mathbf{E}}_2 \right\rangle = \left\langle \hat{\mathbf{I}}_2 \right\rangle \left\langle \hat{\mathbf{E}}_1 \right\rangle \qquad (4.1)$$

where the angle brackets denote the averaging over the quantum state.

For the mixed states (4.1) it does not result directly from the corresponding operator equality: the average of the products is not equal to the products of the average. This means that the electron-photon quantum correlations can lead to a violation of the reciprocity theorem, even in the absence of non-reciprocal optical

media. Therefore, in general, the bond of characteristics of receiving and transmitting antennas is non-trivial and requires additional analysis.

4.1.2. The spectral characteristics of the signals.

In classical radiotechnics the problem is trivial: the spectrum is defined by the transformation of the Fourier signal. In quantum systems, we are dealing with fluctuating signals, and the spectrum is defined by the Fourier transformation of the two-time correlation function of the first order $K(t_1,t_2)$ (Wiener-Khinchin theorem (BX) [51, 56]). However, this theorem is valid only for stationary processes, where $K(t_1,t_2) = K(\tau)$, $\tau = t_1 - t_2$. Attempts to automatically shift it to the general case lead to physical inconsistencies and errors.

It is convenient to illustrate the situation by example of the spontaneous emission of two-level atom. In this case $K(t_1,t_2) \propto e^{j\omega_0\tau}$, where ω_0 is the transition frequency. The spectrum according to VK-theorem represents $\delta(x)$ is Dirac delta function. However, the infinitely narrow spectral line is unphysical - it is the result of a certain idealization. If we take into account the finite lifetime of the excited state in the calculation of the correlation function, we will obtain

$$K(t_1,t_2) \propto e^{j\omega_0\tau} e^{-2\Gamma T} \qquad (4.2)$$

where Γ is the frequency of the spontaneous transition and $T = (t_1 + t_2)/2$. The dependence of the correlator on $\boldsymbol{T}$ means the non-stationarity of the process, and hence the inapplicability of VK-theorem. Probably, for small Γ one can introduce the concept of "quasi-stationarity" and modify the concept of spectrum. In any case, the concept of the spectrum must be properly entered, so the problem is mostly principal than computing.

4.1.3. Synthesis of macroscopic and microscopic electrodynamics.

Macroscopic electrodynamics is based on averaging of the field over the physically infinitesimal volume. It is clear that it is valid when the sizes of bodies are much bigger than the sizes of atoms and interatomic distances. Otherwise, the constitutive equations and material parameters have no sense, macroscopic Maxwell equations become inapplicable.

It is easy to understand that the applicability conditions of macroscopic averaging for a number of nano-objects are not fulfilled. The structures for a stronger concentration of the fields used in high-precision spectroscopy and microscopy, and having the configuration of sharpened needles, can be given as an example. However, the cancelation of macroscopic averaging and the transfer to the

microdescriptions will make the task extremely difficult. Therefore the synthesis of both approaches, which is not quite a trivial problem, is topical.

In principle, this synthesis might look like in the following way. The field in the vicinity of the needle is described microscopically without any spatial averaging. At some distance from the edge of the needle the macroscopic average is introduced. To pair the macroscopic Maxwell's equations and a microscopic description, it will be necessary to approximate the description of the field in certain transition layers, or to introduce specific boundary conditions. It should be noted that the problem can not be considered as purely physical. It can be expected that it will lead to new types of differential or integrodifferential equations. The study of their mathematical properties will require the involvement of specialists in basic and applied mathematics (functional analysis, operator theory, numerical methods).

4.1.4. Computer simulation of the electromagnetic field in the vicinity of edges and sharp points.

Structures such as edges are always appearing in the microwave microelectronics: typical example is the microstrip transmission line [99]. Normal idealization is infinitely thin perfectly conducting surface. Such idealization creates a fundamental problem: correct description of the field in the vicinity of edges. The point is that on the edge the direction of the normal becomes uncertain, which is why the usual boundary conditions become inapplicable . In fact, if you put on the edge an arbitrary point source, Maxwell's equations, boundary conditions and radiation conditions are not violated, although the solution of the problem has changed radically.

This means that the introduction of edges violates the uniqueness theorem, and requires the introduction of additional conditions that allow to discard non-physical solutions. The principle of the additional condition is that the energy of the field of any finite volume, containing the edge, must be finite. This condition implies the laws of the behavior of various components of the field close to the edge [49]. For example, the current density flowing along the edge is of the form $j \sim x^{-1/2}$, where x is the distance from the edge to the point of observation. A similar situation occurs for structures such as the wedge, cone, etc. The behavior of the field at the edge is changing dramatically with the introduction of dissipation [49].

The problem remains when passing to the nanostructures, namely, to the graphene nanoribbons, edges of carbon nanotubes and nanowires with surface plasmons, etc. The solution of it is absent, and without it the development of mathematically correct computational algorithms for the field computation is impossible. The situation is complicated by the fact that in the nanostructures due to

the needs of microscopy a special interest represents a differential spatial structure of the field, while in microelectronics the main interest represented its integral characteristics (wave impedance, the scattering matrix elements, etc.).

The behavior of the field close to the edge in a macroscopic electrodynamics was studied with the help of two approaches (that led to the same results). The first is the analysis of exact general solutions of the model problems deduced by the Wiener-Hopf-Fock method (e.g. half-plane). The other approach is the use of special representations of the field close to the edge (rows Meixner) [49]. In principle, both approaches can be applied, for example, a to the graphene half-plane. The fundamental problem, however, is that in macroscopic electrodynamics the model of a perfect conductor (i.e. of the averaged field) is extrapolated to the infinitesimal neighborhood of the edge. At the same time, the description of the graphene conductivity based on a surface Drude conductivity is hardly adequate in the vicinity of the edge without any amendments, taking into account its atomic structure. Thus, we again face the problem of synthesis of macroscopic and microscopic electrodynamics (see 4.1.3).

4.1.5. Electrical and nanocircuits and nanoantennas on flat graphene layers.

It should be noted that the use of planar structures in electronics has several advantages compared to the bulk ones. One of the main reasons is extremely high fabricability of planar structures, the possibility of the integralization and miniaturization. This trend is, in general, is quite common: classical microwave radiotechnics has passed it (integrated circuits for microstrip transmission lines [99]).

The possibilities of a graphene monolayer (ribbon) in this respect are largely determined by its ability to direct electromagnetic waves of a particular spatial structure in the terahertz frequency range. There are two types of such waves: the first type is characterized by the structure of the field, distributed over the whole area of the graphene sheet. The waves of the second type are characterized by the field concentration in the vicinity of edges. Both types of waves are characterized by a strong slowdown. The first type, to some extent, is a flat analogue of the surface wave in the carbon nanotube, predicted in [11, 12]. The waves of the second type reflect the specifics of the graphene sheet and have no analogues in the nanotubes.

In principle, the waves of both types are suitable for creation of a passive element base (interconnectors, matching transformers, directional couplers, etc.) of the terahertz range. We can expect that to a certain extent these elements are similar to the corresponding microstrip devices of the centimeter range. This means that the

accumulated experience of their design can be helpful and should be taken into account.

4.2. Applied nanoelectromagnetics and nanophotonics

4.2.1. Electromagnetic compatibility in nanophotonics.

The urgency of the issue is conditional on a tendency to achieve a new level of integration in the electronics that becomes possible in transition to the nanoscale electronic components. In this case then the manifestation of new mechanisms of the mutual influence of the elements for different purposes, of different frequency ranges and power levels, becomes necessary. These mechanisms are of a quantum nature and do not have analogues in the modern electronics of sub-micron scale. These mechanisms will largely determine the interference immunity of the radioelectronic equipment of new generation. Without the research the modification of the rules of integration, set in the classical electronics and applied to the electronics of the nanoscopic level, is impossible.

At the moment the principles of modeling of the electromagnetic interaction of the lumped and distributed components of electronic circuits (including integrated circuits for microwave in the microstrip lines and their modifications) are elaborated. These principles are based on the computer solutions of boundary value problems for Maxwell's equations in the domains with complex geometry by direct numerical methods (finite element method, finite difference method, the method of integral equations, etc.). At the moment because of the development of nanoelectronics, is going an intensive development of the physics of quantum interaction of nanoelements through tanks of different physical nature (phonon, photon, exciton, etc.). The application of these developments to the problems of electromagnetic compatibility of elements in the submicron and nanoscale integrated circuits is absent.

The result of the application of nanophotonics to the problems of electromagnetic compatibility in submicron and nanoscale integrated circuits should be an establishment of a fundamental limit of integration conditional on the quantum mechanical mechanisms of interaction of both active and passive electronic components. Therefore it is necessary to revise the basic theory of EMC, which is expected in the near future. Such a theory will be based on Maxwell's equations together with many quantum equations of motion. In the result of such review a set of recommendations for the optimum in terms of EMC nanotechnique synthesis will appear.

4.2.2. Quantum computing and quantum information science

This direction has great prospects for development and can be attributed to the most promising. We are talking about the application of physics of open quantum systems to encoding, storage, processing and the transmission of the information. It is significant that this trend will not only be based on the electromagnetic processes, but also on the stimulation of another nature (mechanical, spin, etc.). The basis here is the elements with two stable states - qubits. It is important that the excitation of different natures can exist in nanostructures simultaneously; and their influence on each other is a controllable factor. A special role here is played by an entangled quantum state, the synthesis of which is a fundamental problem. We will have to identify the best principles of the qubits building - now the superconducting (Josephson), spin, charge ones, etc. is being studied. The result of this trend will be the creation of new types of computers, distinguished by the increased efficiency at small sizes and high reliability.

4.2.3. Nanostructures in optoelectronics and solar energy.

The problem of energy resources, without exaggeration, is the most important for the mankind. A big role has always been assigned to the solar energy; its attraction in addition to the economic efficiency is supported by the ecological cleanliness. The use of solar energy to the last time was quite narrow due to the low efficiency of the solar cells based on the conventional p-n transitions in semiconductors. The fundamental change in the situation should be expected due to development of the physics of nanostructures, in particular, plasmonic wires and carbon nanotubes. Due to a strong optical nonlinearity, the structures of a beam arrays of vertical type of the parallel nanotubes grown orthogonally to a flat substrate, can become the basis for the receiving photovoltaic antennas (rektennas), that convert the sunlight into direct current with the efficiency of 30-50%. In this case, the solar energy is going to be the main source of energy resources.

4.2.4. Heat nanoantennas.

Belonging of the nanostractures to the structured photonic tanks, as mentioned above, provides an opportunity to control their heat radiation (spectrum, direction, polarization). This effect was predicted for structures with surface plasmons and carbon nanotubes (see Chapter 2). It opens the possibility of excitation of nanoantennas by Joule heating - i.e. creating of a so-called thermal nanoantenna.

It is noteworthy, that at the moment the experiments with thermal nanoantennas on carbon nanotubes have already started. The main result is a significant transformation of the spectrum of thermal nanoantenna compared to the

spectrum of a black body. The attempt of unique interpretation of measurements based on the existing theory proved to be problematic - the specific details of the experimental data differ from the theoretical predictions. But it should be taken into account that the measurements refer to the arrays of nanotubes, but the theory - to single nanotubes. It means that it is necessary to continue both theoretical and experimental research in close contact with each other. Due to the exceptional scientific and applied interest to this issue, there is no doubt that they will be continued.

4.2.5. Rabi-waves.

The increasing complexity of physical systems in which PR is observed, lead to new features, absent in the classical picture of the phenomenon. The quality changes of the PR picture in the interaction with the field, the frequency of which varies with time, phonon-induced dephasing and the effects of local fields can be viewed as the samples. New effects appear in the systems with the broken inversion symmetry and in the systems of two coupled oscillators Rabi.

In spatially extended 3D samples containing a large number of oscillators, the mechanism causing the PR also leads to a number of transient coherent optical phenomena such as free induction decay, photon echo, self-induced transparency, etc. This is connected to the fact that in the samples, the sizes of which are much longer than the wavelenth, the propagation effects are significant. In low-dimensional systems, the propagation effects also occur, but their character changes qualitatively.

The subject of several works was the theoretical studies of the PR in QDs metamaterials, especially in the one-dimensional excitonic composite based on QDs. It was built the theoretical model PR in the system shown in Figure 1 and was predicted the distribution of Rabi oscillations in space (Rabi-waves).

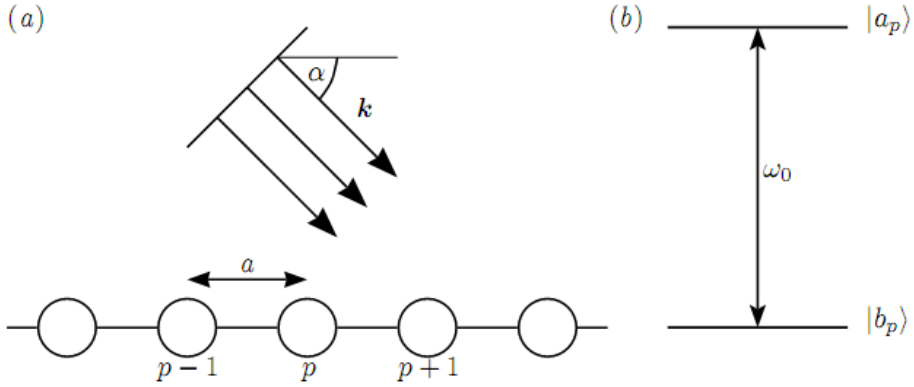


Figure 4.1. Schematic illustration of the QDs-chain, interacting with a single-mode electromagnetic field (a) and the energy level scheme of *p*-th QDs (b).

To spread the Rabi-wave the wave vector of the external field must have non-zero component along the chain; the Ruby-waves features strongly depend on the ratio between the electron-phonon interaction, the frequencies of tunneling through the potential barriers for both levels and the frequency detuning of the external field. In case of plane Rabi-waves for each value of the photon number, there are two eigenmodes. The mode frequency range is limited to a critical value, that is different for each of the modes. The composite is transparent for the Rabi-waves with a frequency of less than critical. Critical frequencies, as well as the dispersion curves in general, depend on the number of photons in the mode.

Each of the modes represents an electron-photon complicated state, the probability amplitude of which oscillates both in time and in space. They can be interpreted as a state of "dressed" by radiation QDs chain. They represent a generalization of the "dressed" states of a single atom in case of a spatially distributed systems. The qualitative difference of this case is the space-time modulation of the "dressing" parameter: it is distributed along the chain, according to the law of a traveling wave $\exp[i(kx-\omega t)]$. The complexity and "dressing" are conditional to the interaction of light with a QDs chain.

In fact it is a new type of wave motion - wave propagation of quantum transitions. We can expect the further development in the direction of spatially inhomogeneous structures. In this case the effects of reflection and scattering of Rabi waves will occur. To describe them it is necessary to formulate the boundary conditions for the corresponding wave equations. The creation of new types of nanoantennas and microcavities of the fundamental quantum nature, can be expected as the practical applications. The latter opens the possibility of electrical control of their characteristics, that are absent at classical analogues.

4.2.6. Dispersion of photon states in exciton composites.

The dispersion of light is one of the most important effects of the interaction of light with the matter. The classic example is the frequency dispersion: the refractive index of the light depends on the frequency. During the distribution process the frequency spectrum of the light is changing. The dielectric capacitivity of the environment is an integral operator in time. Another example is the spatial dispersion [100]: the refractive index of the environment depends on the direction of the light propagation. During the distribution process the spatial structure of the wave beam is being transformed. The dielectric capacitivity of the environment is an integral operator in the space. Anisotropy can be considered as one of the types of dispersion: the refractive index depends on the polarization of light. During the

distribution process the polarization structure of the light is being transformed; the dielectric constant represents a tensor.

In a number of works it was predicted a new type of optical dispersion, which occurs in the nanostructured composite media (excitonic composites) for the quantum light. The refractive index of such light depends on the quantum statistics of the light. At the propagation of the light in such a medium, the quantum statistics of light is being transformed. The dielectric capacitivity of the medium represents an operator in the space of photon states.

The constitutive equation of the exciton composite for the operators of the electromagnetic field is

$$\hat{\mathbf{D}} = \frac{1}{2}\left(\hat{\varepsilon}\,\hat{\mathbf{E}} + \hat{\mathbf{E}}\hat{\varepsilon}\right), \tag{4.3}$$

where $\hat{\varepsilon} = \hat{n}^2$ is the dielectric constant. The constitutive equation (4.3) is fundamentally different from the usual cases of quantum optics of continuous media: it does not match in show with the corresponding equation for the mean values. The operator $\hat{\varepsilon}$ does not commute with the operator of tension and non-Hermitian, even without dissipation (the above mentioned is not a physical contradiction, since the dielectric constant is not the observed value). It is easy to see that all of the selected properties of the operator dielectric constant are conditional to the fine structure of the electrodynamic response of QDs: at $\Delta\omega \to 0$ $\hat{\varepsilon}$ moves to the C-number, which coincides with the dielectric constant of the medium from independent two-level oscillators.

This effect provides a unique possibility to manage the quantum statistics of the light. However, their use requires the fundamental research of the processes of diffraction on the bodies of the exciton composite with the constitutive equation (4.3). This creates new mathematical problems: boundary value problems for operator equations in partial derivatives with operator coefficients. In this case both general theorems on the solution existence and its uniqueness and the computer-based solution methods are necessary. One can assume that such studies will soon become the subject of research in the theoretical and applied mathematics.

4.3. Composite materials and disordered structures

4.3.1. Metamaterials

At the moment there is a process of artificial synthesis of metamaterials - of the composite media with special electrical and mechanical properties. It can be

certainly predicted that in the future, this process will be intensively continued. Several major trends can be pointed out. First of all, we should distinguish between the ordered and unordered metamaterials. The ordered environments are characterized by the high level of anisotropy of the optical properties and by the natural optical activity (the dependence of the refractive index on the direction of the rotation of the circular polarization vector). We can expect from them a high level of transparency at the certain frequency ranges and at the certain directions of the radiation propagation. The metal particles with the plasmon-polariton excitations are used as an elementary diffuser for such materials (example - photonic crystals, Veselago environments, etc.). One can expect the application of such media as high-efficiency shielding materials of the microwave, terahertz and infrared ranges. Unordered metamaterials are characterized by the scattering of the radiation in its dissemination, its spatial localization of the Anderson type, etc. Such materials can be widely used as the absorbing medium. It should be expected that such medium will be notable by the low cost level, low weight, resistance to the weather conditions, etc. As a basis, in particular, can be used carbon nanoparticles (fullerenes, nanotubes, carbon anions, etc.) embedded into the radar-transparent medium (e.g. rubber).

4.3.2. The synthesis of unordered composite materials based on the carbon.

The structures are based on carbon and play an important role in the development of coatings that absorb and shield the electromagnetic fields [107-128], due to their light weight and special electrical properties. The graphite particles, various soots and the carbon fibers, produced from polymers, should be noted as the widely used materials.

At the moment it is known several types of nanoscale carbon materials, which differ significantly in their structure. They include:

-Nanodiamonds (ND) with a mean particle size of less than 5 nm;

-sp2/sp3 composites obtained by surface graphitization of ND and representing the diamond particles of the varied size coated with the graphene flakes;

-Onion-like carbon (OLC) [110], whose main elements are interleaved continuous fullerene-like shells with a variable type of defect. OLC has a unique structure (intensively defective shell with the pores) [111-113] and matches the criteria of the hierarchical ensemble. It was found a pronounced frequency dependence of the conductivity of the OLC [114] and the ability to absorb the broadband EMP [115-118]. In this case, the change of the properties of the OLC can be achieved by the varying of the size of the aggregates, the ND annealing

temperature on the ratio sp2/sp3 of the carbon forms, as well as the type and number of defects [119].

-Carbon nanotubes (CNTs), which represent the rolled up graphene sheets (it is important to note the possibility of changing the number of layers, the tube diameter and the length, accompanied by a significant change in their electronic properties);

—Catalytic carbon-fibers (CCF), in which the changes of the properties can be achieved by changing the orientation of the graphene layers with respect to the fiber axis; the varying of the ratio of the diameter to their length and degree of the defectiveness change.

For future applications it is necessary to change the properties of the CCF and the CNTs over a wide range. We can expect that this is achievable by varying the structure. For the fiber it is the change of the orientation of the graphene layers with respect to the fiber axis, the diameter of the fibers, the changes of defectiveness degree by varying the annealing temperature. For the nanotubes it is the change of the number of layers, for the single-wall tubes - of a chirality factor, geometric parameters (diameter, ratio of length to diameter).

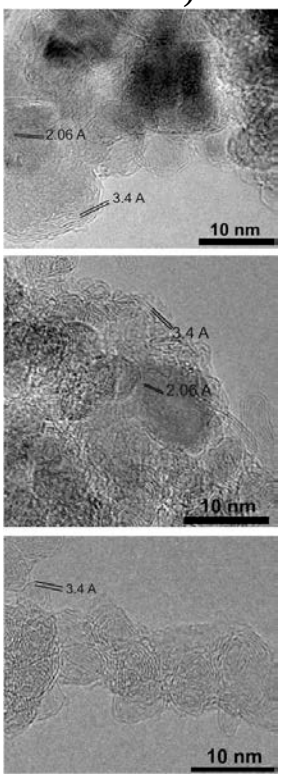


Figure 4.2. HTEM image of the OLC, produced at different annealing temperatures (from top to bottom: 1400, 1650 и 1800K) [126].

The synthesis of new ultrafine nano-carbon materials, the design of nanocomposites based on them, having unique physical and chemical properties, the study of the structure and characteristics of the obtained nanosystems are nowadays one of the promising directions of the world science and the subject of many research centers. In the Republic of Belarus it is the Institute of Heat and mass transfer of the NAS of Belarus, the Institute of Powder Metallurgy of NAS of Belarus, the Institute of Physics of NAS of Belarus, BSUIR and BSU, and abroad: Physical-Technical Institute n.a. Academician A.N. Ioffe RAS, St. Petersburg, the Institute of Catalysis n.a. G.K.Boreskov and the Institute of Inorganic Chemistry n.a. Nikolaev S.O. RAS, Novosibirsk; Federal Research and Production Association "Altai" (Biysk, Russia), Production center "Almaz" (St. Petersburg, Russia), Swiss Federal Institute of Technology, (Lausanne, Switzerland), Gothenburg University and Chalmers University Of Technology (Gothenburg, Sweden), Advanced Technologies Centre (Angler, Belgium), Laboratoire de Physique du Solide, Facultes Universitaires Notre-Dame de la Paix, (Namur, Belgium), Pennsylvania State University (University Park, the U.S.A), International Technology Center (Raleigh, the USA), etc.

It can be expected that this trend for a long period of time stays a priority. It is important that it requires the cooperation of the specialists of different fields (physics, chemistry and technology).

4.3.3. The experimental study of the electromagnetic response of polymer composites based on various forms of nanocarbon in X (8-12 GHz), Ka (26-37 GHz) and W (78-118 GHz) frequency ranges.

In the work [124] it was made an experimental study of the electromagnetic response of polymer composites based on carbon nanotubes and amorphous carbon in X (8-12 GHz), Ka (26-37 GHz) and W (78-118 GHz) frequency ranges. It was conducted a restoration of the composites dielectric constant on the scattering data.

Carbon nanotubes, used as a filter, were obtained with the help of CVD method by Heji Company (http://www.nanotubeseu.com/nano/products/s4402/ main.html, http://www.nanotubeseu.com/nano/products/M4907/ main.html). The presence and the concentration of impurities in the samples were monitored by spectroscopic methods. The characteristics of the samples of carbon nanotubes (single wall - SWCNTs and multi wall - MWNTs) are presented in Table 4.1. :

	SWCNTs	MWNTs
Absolute density	-	2,1 g/cm^3
Bulk density	0,3 g/cm^3 at 25 ^{0}C	0,05 g/cm^3

Length	10-20 mkm	0.5-200 mkm
Outer diameter	1-2 nm (HRTEM)	20-40 nm
Inner diameter	0.8-1.6 nm (KR - spectrum)	5-15 nm
The composition	SWCNTs> 90%	MWNTs > 95%

Table 4.1. Characteristics of the samples of nanotubes.

Amorphous carbon was produced by Evonik Degussa (http://www.evonik.com/). The average particle size is 20-30 nm. The obtained samples of carbon nanotubes and amorphous carbon were added to a solution of the epoxy resin and hardener in acetone (EPIKOTE^{TM}Resin 828). The control of the uniformity of dispersion by the volume was performed with the help of a transmission electron microscope Nova™ NanoSEM 630 (Scanning Electron Microscope). The average thickness of the samples was as follows: 0.750 mm for MWNTs/epoxy resin, 0.678 mm for SWCNTs/epoxy resin, 0.685 mm for amorphous carbon / epoxy resin, 0.686 mm for epoxy resin.

The measurement of the electromagnetic properties of the samples in the Ka-frequency range (26-37.5 GHz) was performed with the help of the panoramic measurement device of the standing wave ratio (SWR) and the weakening P2-408 P, which is designed to measure the modulus of the reflection and transmission (S_{11}, S_{21} respectively), SWR and attenuation of guided microwave devices in the frequency range of 25.95-37.5 GHz in the section of the waveguide 7.2x3.4 mm. The device provides the frequency stability with the accuracy of up to 0^{-6}, the level of output power is 7.0 mW±10 mW.

The measurements in the X-range (8-12GGts) and W-range (78-118GGts) were conducted in the laboratory of the measurement instrumentation of the millimeter-wavelength in the Belarusian State University of Informatics and Radio Electronics. The laboratory is accredited as a measurement and calibration laboratories in the Belarusian system of accreditation. The accuracy was achieved by repeated measurements at different orientations of the sample.

The results of measurements in the microwave range are shown in Figure 4.3.

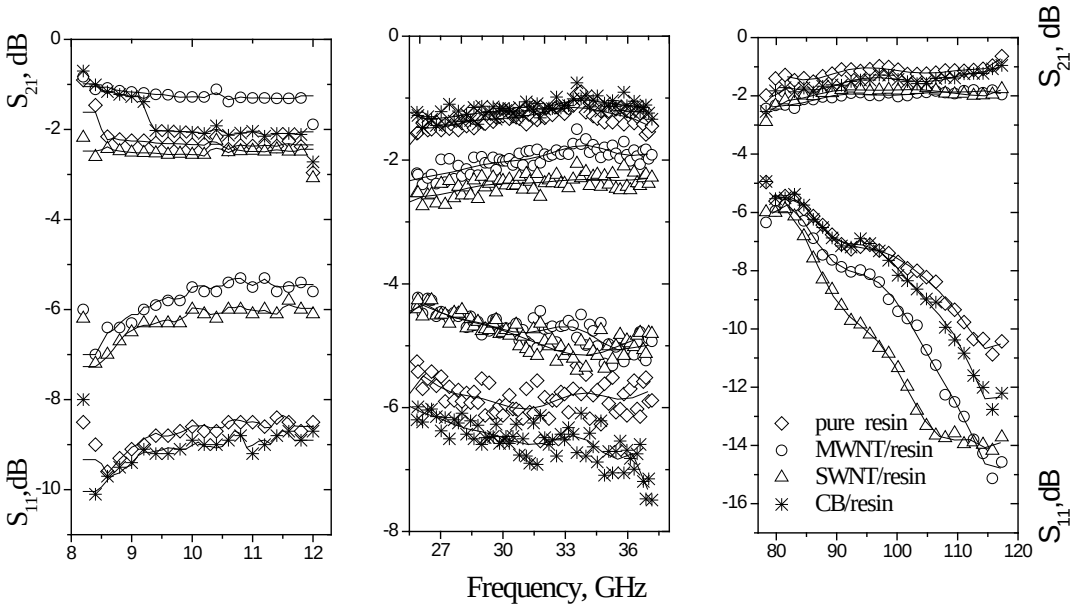


Figure 4.3. The frequency dependence $S_{11,}$ S_{21}.

To enhance the screening capacity of the composite one can increase the concentration of nanotubes in the composite from 0.5% to 1.5%. Such a change should reduce the passage of an electromagnetic signal in half (see Figure 4.4.)

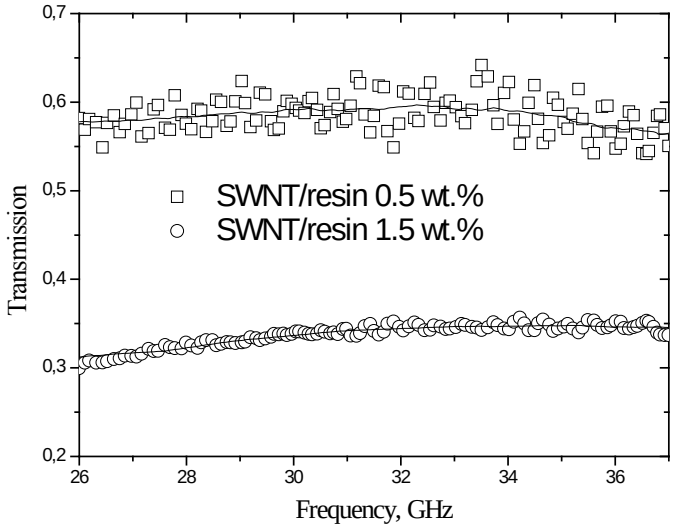


Figure 4.4. Signal passing through the sample on the basis of SWCNTs with a concentration of 0.5 and 1.5 %.

It should be noted that the nanotubes obtained by CVD method are cheap, and can be easily injected into the polymer and are a promising material for the solution of problems of electromagnetic screening.

To improve the screening properties it can be offered to use carbon nanotubes with metallic conductivity. In particular, it is possible to use the chemically modified CNTs (doped with boron or nitrogen) [129].

4.4. Nanostructures in biophysics and medicine.

At the moment one can expect the widespread adoption of various types of nanostructures in biophysics research and medical practice. This forecast is based on a number of their unique physical and chemical properties. For example, carbon nanotubes are easily filled with various substances that can form the basis for the delivery of drugs inside the body. Another their quality is: the possibility of highly efficient heating by infrared and terahertz radiation. This quality is promising in clinical oncology for the thermal destruction of cancer-causing cells without any damage to the healthy tissues (the introduction of the nanotubes in the infected cells, followed by the electromagnetic heating). However, the widespread introduction of carbon nanomaterials in medical practice requires caution because of their specific toxicity.

References

1. A. Kavokin, J. Baumberg, G. Malpuech, and F. Laussy, *Microcavities*. Oxford University Press, 2007.
2. L.A. Weinstein, Electromagnetic waves. Radio and svyaz, 1988.
3. M. J. Kelly, *Low-dimensional semiconductors: materials, physics, technology, devices*. Oxford University Press, 1995.
4. S. Gaponenko, *Optical Properties of semiconductor nanocrystals*. Cambridge Univ. Press, 1998.
5. M. S. Dresselhaus, G. Dresselhaus, and P. C. Eklund, *Science of fullerenes and carbon nanotubes*. San Diego: Academic Press, 1996.
6. M. S. Dresselhaus, G. Dresselhaus, and P. Avouris, *Carbon nanotubes*. Springer, Berlin, 2001.
7. L. D. Landau and E.M. Lifshitz, Electrodynamics of continuous media. Moscow: «Nauka», 1992.
8. N.B. Brandt and V.A, Kulbachinsy, *Quasiparticles in condensed matter physics*. Moscow: "Fizmatlit", 2005.
9. O. Yevtushenko, G. Slepyan, S. Maksimenko, A. Lakhtakia, and D. Romanov, "Nonlinear Electron Transport Effects in a Chiral Carbon Nanotube", *Phys. Rev. Lett.*, 79: 1102–1105, 1997.
10. G. Slepyan, S. Maksimenko, A. Lakhtakia, O. Yevtushenko, and A. Gusakov, "Electronic and electromagnetic properties of nanotubes", *Phys. Rev. B* 57: 9485-9497, 1998.
11. G. Slepyan, S. Maksimenko, A. Lakhtakia, O. Yevtushenko, and A. Gusakov, "Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation." *Phys. Rev. B* 60: 17136-17149, 1999.
12. S. Maksimenko and G. Slepyan, *Electrodynamic properties of carbon nanotubes, in "Electromagnetic Fields in Unconventional Structures and Materials", pp. 217-255;*, O. Singh and A.Lakhtakia, Eds. New York: John Wiley & Sons, Inc., 2000.
13. S. Salahuddin, M. Lundstrom, and S. Datta, "Transport effects on signal propagation in quantum wires", *IEEE Trans. Electron Device*. 52: 8, 2005.
14. P. Burke, "An RF circuit model for carbon nanotubes," *IEEE Trans on Nanotechnology*, 2(1): 55, 2003.
15. P. Burke, S. Li, and Z. Yu, "Quantitative theory of nanowire and nanotube antenna performance," *IEEE Trans. Nanotechnology*, 5: 314-334, 2006.
16. C. Rutherglen and P. Burke, "Nanoelectromagnetics: Circuit and Electromagnetic Properties of Carbon Nanotubes", *Small*, 5 (8): 884-906, 2009.
17. M. Hagmann, "Isolated carbon nanotubes as high-impedance transmission lines for microwave through terahertz frequencies", *IEEE Trans. on Nanotechnology*, 4 (2): 289, 2005.

18. A. Maffucci, G. Miano, and F. Villone, “Performance comparison between metallic carbon nanotube and copper nano-interconnects”, *IEEE Trans on Advanced Packaging*, 31 (4): 692, 2008.
19. G. Miano, C. Forestiere, A. Maffucci, S. Maksimenko, and G. Slepyan, “Signal propagation in carbon nanotubes of arbitrary chirality,” *IEEE Trans. Nanotechnology*, 10(1): 135-148, 2011.
20. S. Maksimenko and G. Slepyan, *Nanoelectromagnetics of low-dimensional structures, in "The Handbook of Nanotechnology: Nanometer Structure Theory, Modeling, and Simulation"*, A. Lakhtakia, Ed. SPIE Press, 2004.
21. S. Maksimenko, G. Slepyan, K. G. Batrakov, A. Khrushchinsky, P. Kuzhir, A. M. Nemilentsau, and M. V. Shuba, *Electromagnetic waves in carbon nanostructures, in: "Carbon Nanotubes and Related Structures"*, V. Blank and B. Kulnitskiy, Eds. Research Signpost Publisher, 2008.
22. K. Song and P. Mazumden, “Equivalent circuit modeling of nonradioactive surface plasmon energy transfer along the metallic nanowire,” *IEEE Trans on Nanotechnology*, 2011.
23. M. B. Vinogradova, O.V. Rudenko and A.P.Suhorukov, *Wave Theory*. Moscow: "Nauka", 1990.
24. M. Di Ventra, *Electrical transport in nanoscale systems*. Cambridge University Press, 2006.
25. V.B. Berestetskii, E.M. Lifshitz, L.P. Pitaevskii, *Quantum Electrodynamics*. Moscow: "Nauka", 1989.
26. C. Balanis, *Antenna theory: analysis and design, 2-nd edition*. New York: Wiley, 1997.
27. P. Bharawaj, B. Deutsch, and L. Navotny, “Optical antennas”, *Advances in Optics and Photonics*, 1: 438-483, 2009.
28. L. Navotny and N. van Hulst, “Antennas for light”, *Nature Photonics*, 5: 83-90, 2011.
29. C. Fumeaux, G. Boreman, W. Herrmann, H. Rothuizen, and F. Kneubuhl, “Polarization response of asymmetric-spiral infrared antennas,” *Appl. Opt.*, 36: 6485-6490, 1997.
30. I. Codreanu and G. D. Boreman, “Infrared microstrip dipole antennas—fdtd predictions versus experiment,” *Microwave Opt. Technol. Lett.*, 29: 381-383, 2001.
31. J. Alda, J. Rico-Garcia, J. Lopez-Alonso, and G. Boreman, “Optical antennas for nano-photonic applications,” *Nanotechnology*, 16: S230–S234, 2005.
32. C. Middlebrook, P. Krenz, B. Lail, and G. Boreman, “Infrared phased-array antenna,” *Microwave Opt. Technol. Lett.*, 50: 719-723, 2008.
33. P. Anger, P. Bharadwaj, and L. Novotny, “Enhancement and quenching of single molecule fluorescence,” *Phys. Rev. Lett.*, 96: 113002, 2006.
34. S. Kuhn, U. Hakanson, L. Rogobete, and V. Sandoghdar, “Enhancement of single-molecule fluorescence using a gold nanoparticle as an optical nanoantenna,” *Phys. Rev. Lett.*, 97: 017402, 2006.
35. P. Bharadwaj and L. Novotny, “Spectral dependence of single molecule fluorescence enhancement,” *Opt. Express*, 15: 14266-14274, 2007.

36. T. Kalkbrenner, U. Hakanson, A. Schadle, S. Burger, C. Henkel, and V. Sandoghdar, "Optical microscopy via spectral modifications of a nanoantenna," *Phys. Rev. Lett.*, vol. 95, p. 200801, 2005.
37. P. Bharadwaj, P. Anger, and L. Novotny, "Nanoplasmonic enhancement of single-molecule fluorescence," *Nanotechnology*, 18: 044017, 2007.
38. G. Y. Slepyan, M. V. Shuba, S. A. Maksimenko, and A. Lakhtakia, "Theory of optical scattering by achiral carbon nanotubes and their potential as optical nanoantennas," *Phys. Rev. B* 73: 195416, 2006.
39. G. Hanson, "Fundamental transmitting properties of carbon nanotube antennas," *IEEE Trans. Anten. Propagat.*, 53: 3426, 2005.
40. M. Shuba, S. Maksimenko, and A. Lakhtakia, "Electromagnetic wave propagation in an almost circular bundle of closely packed metallic carbon nanotubes," *Phys. Rev. B* 76: 155407, 2007.
41. M. Shuba, G. Slepyan, S. Maksimenko, C. Thomsen, and A. Lakhtakia, "Theory of multiwall carbon nanotubes as waveguides and antennas in the infrared and the visible regimes," *Phys. Rev. B* 79: 155403, 2009.
42. L. Novotny and S. J. Stranick, "Near-field optical microscopy and spectroscopy with pointed probes," *Annu. Rev. Phys. Chem.* 57: 303-331, 2006.
43. L. Novotny and B. Hecht, *Principles of Nano-Optics*. Cambridge Univ. Press, 2006.
44. L. Novotny, "Effective wavelength scaling for optical antennas," *Phys. Rev. Lett.* 98: 266802, 2007.
45. A. Hartschuh, M. R. Beversluis, A. Bouhelier, and L. Novotny, "Tip-enhanced optical spectroscopy," *Philos.Trans. R. Soc. London*, Ser.A 362: 807-819, 2003.
46. A. Hartschuh, "Tip-enhanced near-field optical microscopy," *Angew. Chem., Int. Ed.* 47: 8178-8191, 2008.
47. E. Bailo and V. Deckert, "Tip-enhanced raman scattering," *Chem. Soc. Rev.* 37: 921-930, 2008.
48. E. Fort and S. Gresillon, "Surface enhanced fluorescence," *J. Phys. D* 41: 013001, 2008.
49. Slepyan G. Ya. Ilyinsky A. S. and Slepyan A. Ya. *Propagation, scattering and dissipation of electromagnetic waves. London,* Peregrinus, London, 1993.
50. D.S. Mogilevtsev and S.Y. Kilin. *Methods of Quantum Optics of structured reservoirs*. Belorusskaya nauka, Minsk, 2007.
51. M. O. Scully and M. S. Zubairy. *Quantum Optics*. Cambridge: Cambridge Univ. Press, 2001.
52. E.M. Purcell. *Phys. Rev.* 69: 681, 1946.
53. E. Yablonovich. "Inhibited Spontaneous Emission in Solid-State Physics and Electronics", *Phys. Rev. Lett.* 58: 2059, 1987.
54. I.V. Bondarev, G.Ya. Slepyan, and S.A. Maksimenko. "Spontaneous decay of excited atomic states near a carbon nanotube", *Phys. Rev. Lett.* 89 (11):115504, 2002.

55. A. M. Nemilentsau, G. Ya. Slepyan, and S. A. Maksimenko. “Thermal radiation from carbon nanotube in terahertz range” *Phys. Rev. Lett.* 99:147403, 2007.
56. L.D. Landau and E.M. Lifshitz. Statistical Physics, Part 1. Nauka, Moscow, 1982.
57. L. Novotny and B. Hecht. *Principles of Nano-Optics*. Cambridge Univ. Press, 2006.
58. C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg. *Atom-Photon Interactions: Basis Properties and Applications*. Chichester: Wiley, 1998.
59. I. I. Rabi. “Space quantization in a gyrating magnetic field”, *Phys.Rev.*, 51:65, 1937.
60. H.C. Torrey. “Transient nutations in nuclear magnetic resonance”, *Phys.Rev.*, 76:1059, 1949.
61. G.B. Hocker and C.L. Tang. “Observation of the optical transient nutation effect”, *Phys. Rev. Lett.* 21:591, 1968.
62. T. H. Stievater, X. Li, D. G. Steel, D. Gammon, D. S. Katzer, D. Park, C. Piermarocchi, and L. J. Sham. “Rabi oscillations of excitons in single quantum dots”, *Phys. Rev. Lett.* 87:133603, 2001.
63. H. Kamada, H. Gotoh, J. Temmyo, T. Takagahara, and H. Ando. “Exciton Rabi oscillation in a single quantum dot”, *Phys. Rev. Lett.* 87:246401, 2001.
64. A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf. “Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation”, *Phys. Rev. A.* 69:062320, 2004.
65. C.K. Law and J.H. Eberly. “Arbitrary control of a quantum electromagnetic field”, *Phys. Rev. Lett.* 76:1055, 1996.
66. J. Forstner, C. Weber, J. Danckwerts, and A. Knorr. “Phonon-assisted damping of rabi oscillations in semiconductor quantum dots”, *Phys. Rev. Lett.* 91:127401, 2003.
67. G. Ya. Slepyan, A. Magyarov, S.A. Maksimenko, A. Hoffmann and D. Bimberg, Strong light-matter coupling in a quantum dot: local field effects**,** *phys. stat. sol. C 2* (2): 850–853, 2005.
68. E. Paspalakis, A. Kalini, and A.F. Terzis. “Local field effects in excitonic population transfer in a driven quantum dot system”, *Phys. Rev. B* . 73:073305, 2006.
69. G.Ya. Slepyan, A. Magyarov, S. A. Maksimenko, and A. Hoffmann. “Microscopic theory of quantum dot interactions with quantum light: Local field effect”, *Phys. Rev. B* . 76:195328, 2007.
70. O.V. Kibis, G.Ya. Slepyan, S. A. Maksimenko, and A. Hoffmann. “Matter coupling to strong electromagnetic fields in two-level quantum systems with broken inversion symmetry”, *Phys. Rev. Lett.* 10:023601, 2009.
71. Th. Unold, K. Mueller, C. Lienau, Th. Elsaesser, and A. D. Wieck. “Optical control of excitons in a pair of quantum dots coupled by the dipole-dipole interaction”, *Phys. Rev. Lett.* 94:137404, 2005.
72. J. Gea-Banacloche, M. Mumba, and M. Xiao. “Optical switching in arrays of quantum dots with dipole-dipole interactions”, *Phys. Rev. B* 74:165330, 2006.
73. L. Saelen, R. Nepstad, I. Degani, and J. P. Hansen. “Optical control in coupled two-electron quantum dots”, *Phys. Rev. Lett.* 100:046805, 2008.

74. S. Hughes. “Modified spontaneous emission and qubit entanglement from dipole-coupled quantum dots in a photonic crystal nanocavity”, *Phys. Rev. Lett.* 94:227402, 2005.
75. J. Danckwerts, K. J. Ahn, J. Forstner, and A. Knorr. “Theory of ultrafast nonlinear optics of coulomb-coupled semiconductor quantum dots: Rabi oscillations and pump-probe spectra”. *Phys. Rev. B* . 73:165318, 2006.
76. Ho Trung Dung, L. Knoll, and D.-G. Welsch. „Resonant dipole-dipole interaction in the presence of dispersing and absorbing surroundings”. *Phys. Rev. A.* 66:063810, 2000.
77. A.V. Tsukanov. “Rabi oscillations in the four-level double-dot structure under the influence of the resonant pulse”. *Phys. Rev. B* 73:085308, 2006.
78. G. Ya. Slepyan, S.A. Maksimenko, A. Hoffmann, and D. Bimberg. “Quantum optics of a quantum dot: Local-field effects”, *Phys. Rev. A.*, 66-6:063804(17), 2002.
79. G.Ya. Slepyan, S.A. Maksimenko, A. Hoffmann, and D. Bimberg. Excitonic composites. *Advances in Electromagnetics of Complex Media and Metamaterials, NATO Sci. Ser.: II: Mathematics, Physics and Chemistry*, 89:385–402, 2003.
80. G.Ya. Slepyan, S.A. Maksimenko, V.P. Kalosha, A. Hoffmann, and D. Bimberg. “Effective boundary conditions for planar quantum dot structures”, *Phys. Rev. B.* 64:125326 (8pp), 2001.
81. S.A. Maksimenko and G.Ya. Slepyan. *Quantum Dot Arrays: Electromagnetic Properties In: Encyclopedia of Nanoscience and Nanotechnology*. Marcel Dekker, New York, 2004.
82. I.R. Shen. *The principles of nonlinear optics*. Nauka, Moscow, 1984.
83. G.Ya. Slepyan, S.A. Maksimenko, V.P. Kalosha, J. Herrmann, E.E.B. Campbell, and I.V. Hertel. “Highly efficient high harmonic generation by metallic carbon nanotubes”, *Phys. Rev. A* 61:R777–R780, 1999.
84. G.Ya. Slepyan, S.A. Maksimenko, V.P. Kalosha, A.V. Gusakov, and J. Herrmann. “High-order harmonic generation by conduction electrons in carbon nanotube ropes”. *Phys. Rev. A* 63:053808, 2001.
85. C. Stanciu, R. Ehlich, V. Petrov, O. Steinkellner, J. Herrmann, I.V. Hertel, G. Ya. Slepyan, A. A. Khrutchinski, S.A. Maksimenko, F. Rotermund, E.E.B. Campbell, and F. Rohmund. „Experimental and theoretical study of third-order harmonic generation in carbon nanotubes”. *Appl. Phys. Lett.* 81 (21):4064–4066, 2002.
86. G. Ya. Slepyan, A.A. Khrutchinski, A. M. Nemilentsau, S.A. Maksimenko, and J. Herrmann. ′High-order optical harmonic generation on carbon nanotubes: quantum-mechanical approach′, *Int. J. of Nanoscience*, 3-4:343–354, 2004.
87. A.A. Khrutchinski, S.A. Maksimenko, A.M. Nemilentsau , G.Ya. Slepyan, “Third-order optical nonlinearity in single-wall carbon nanotubes”, *Carbon*, 44(9):2246–2253, 2006.
88. J. S. Lauret, C. Voisin, G. Gassabois, C. Delalande, Ph. Roussignol, O. Jost, and L. Capes. “Ultrafast Carrier Dynamics in Single-Wall Carbon Nanotubes”, *Phys. Rev. Lett.* 90-5:057404(4), 2003.

89. V.A. Margulis and T.A. Sizikova, Theoretical study of third-order nonlinear optical response of semiconductor carbon nanotubes, *Physica B* 245-2:173–189, 1998.
90. J. S. Lauret, C. Voisin, G. Cassabois, C. Delalande, Ph. Roussignol, L. Capes, and O. Jost., "Ultrafast pump–probe measurements in single wall carbon nanotubes", *Physica E* 17 (1):380–383, 2003.
91. D. Bimberg, M. Grundmann, N.N. Ledentsov, *Quantum dot heterostructures*, Chichester, John Wiley & Sons, 1999.
92. S.Y. Killeen, "Quantum Information", UFN. 169 (5): 507-527, 1999.
93. P. Michler (Ed.) *Single quantum dots, Topics of applied physics*, Heidelberg, Springer Verlag, 2003.
94. B. Lounis and M. Orrit, "Single-photon sources", *Rep. Prog. Phys.* 68(5): 1129-1180, 2005.
95. F.G, Bass, I.M. Fuchs, Wave scattering from statistically rough surfaces. Moscow, Nauka, 1972
96. L.A. Weinstein, *Open resonators and open waveguides*. Moscow, Sov. Radio, 1966.
97. M. Adams, *An introduction to optical waveguides*. Moscow, Mir, 1984.
98. V.V. Shevchenko, Continuous Transitions in Open Waveguides. Moscow, Nauka, 1969.
99. E. I. Nefedov, A.T. Fialkovsky, *Striplines*. Moscow, Nauka, 1980.
100. V.M. Agranovich and V.L . Ginzburg, *Crystal optics with spatial dispersion, and excitons*, Moscow "Nauka", 1979.
101. L.D. Landau and E.M. Lifshitz, *Physical Kinetics*. Moscow: "Nauka", 1979.
102. V.G. Baryshevsky, *Nuclear optics of polarized media*, Moscow "Energoatomizdat", 1995.
103. S.G. Volz, "Thermal Insulation Behavior in Crystals at High Frequencies", *Phys. Rev. Lett.* 87: 074301, 2001.
104. G. Chen, "Ballistic – Diffusive Heat – Conducting equations", *Phys. Rev. Lett.* 86: 2297, 2001.
105. Y. Dubi and M. Di Ventra, "Heat flow and thermoelectricity in atomic and molecular junctions", *Rev. of Mod. Phys.* 83.131, 2011.
106. J. Gemmer, M. Michel and G. Mahler, *Quantum Thermodynamics*, Springer, Berlin, 2004.
107. D.D.L. Chung, G. Benedek, P. Milani and V.G. Ralchenko, "Nanostructured Carbon for Advanced Applications", *NATO Science series.* 24: 331, 2001.
108. K.J. Vinoy, R.M. Jha, "*Trends in radar absorbing materials technology*", Sadhana - *Proc. Indian Academy of Sciences* . 20: 815-850, 1996.
109. J.-H. Oh K.-S. Oh, C.-G. Kim, C.-S. Hong, "Radar Absorbing Materials from Theory to Design and Characterization" , *Composites Part B: Engineering*. 35: 49—56, 2004.
110. S.Q. Zhang, C.G. Huang, Z.Y. Zhou, Z. Li, Mater, "Investigation of the microwave absorbing properties of carbon aerogels", *Sci. Engin.* B 90, 38, 2002.

111. V.L. Kuznetsov, A.L. Chuvilin, Yu.V. Butenko, I.Yu. Malkov, and V.M. Titov, *Chem. Phys. Lett.* 222: 343, 1994.
112. E.D. Obraztsova, M. Fujii, S. Hayashi, V.L. Kuznetsov, Yu.V. Butenko, A.L. Chuvilin, *Carbon*, 36: 821, 1998.
113. L.G. Bulusheva, A.V. Okotrub, V.L. Kuznetsov, A.L. Chuvilin, Yu.V. Butenko, and M.I. Heggie, in: S. Komarneni, J.-I. Matsushita, G.Q. Lu, J.C. Parker, R.A. Vaia (Eds), "Topology and Electronic Structure of Onion-Like Carbon and Graphite Diamond Nanocomposites", *Nanophase and Nanocomposite Materials. Mat. Res. Sym. Proc*. 703: 381, 2002.
114. A.I. Romanenko, O.B. Anikeeva, A.V. Okotrub, V.L. Kuznetsov, Yu.V. Butenko, A.L. Chuvilin, C. Dong, and Y. Ni, in: S. Komarneni, J.-I. Matsushita, G.Q. Lu, J.C. Parker, R.A. Vaia (Eds), *Nanocomposite Materials. Mat. Res. Sym. Proc*. 703: 259, 2002.
115. S.A. Maksimenko, V.N. Rodionova, G.Ya. Slepyan, V.A. Karpovich, O. Shenderova, J.Walsh,V.L. Kuznetsov, I.N.Mazov, S.I.Moseenkov, A.V. Okotrub, Ph. Lambin, *Diamond and Related Materials* 16 (4-7): 1231-1235, 2007.
116. I. Mazov, V. Kuznetsov, S. Moseenkov, A. Usoltseva, A. Romanenko, O. Anikeeva, T. Buryakov, P. Kuzhir, S. Maksimenko, D. Bychanok, J. Macutkevic, D. Seliuta, G. Valusis, J. Banys, and Ph. Lambin, Electromagnetic shielding properties of MWNT/PMMA composites in Ka-band, *phys. stat. sol. B* 246 (11): 2662-2666, 2009
117. V. Kuznetsov, S. Moseenkov, A. Ischenko, A. Romanenko, T. Buryakov, O. Anikeeva, S. Maksimenko, P. Kuzhir, D. Bychanok, A. Gusinski, O. Ruhavets, O. Shenderova and P. Lambin, Controllable electromagnetic response of onion-like carbon based materials**,** *phys. stat. sol. B* 245(10): 2051–2054, 2008
118. P.P. Kuzhir, D.S. Bychanok, S.A. Maksimenko, A.V. Gusinski, O.V.Ruhavets, V.L. Kuznetsov, S.I. Moseenkov, C. Jones, O. Shenderova, Ph. Lambin, Onion-like carbon based polymer composite films in microwaves**,** *Solid State Sciences* 11(10): 1762-1767, 2009
119. R Langlet, Ph Lambin, A Mayer, S A Maksimenko and P P Kuzhir, Dipole polarizability of onion-like carbons and electromagnetic properties of their composites, *Nanotechnology*, 19 (11): 115706 (8pp), 2008.
120. J. Macutkevic, R. Adomavicius, A. Krotkus, D. Seliuta, G. Valusis, S. Maksimenko, P. Kuzhir, K. Batrakov, V. Kuznetsov, S. Moseenkov, O. Shenderova, A.V. Okotrub, R. Langlet and Ph. Lambin, Terahertz Probing of Onion-Like Carbon-PMMA Composite Films, *Diamond and Related Materials* 17: 1608-1612, 2008.
121. P. Kuzhir, S. Maksimenko, D. Bychanok, V. Kuznetsov, S. Moseenkov, I. Mazov, O. Shenderova and Ph. Lambin, Nano-scaled onion-like carbon: Prospective material for microwave coatings, *Metamaterials* 3(3-4): 148-156, 2009
122. J. Macutkevic, D. Seliuta, G.Valusis, J. Banys, P. Kuzhir, S. Maksimenko, V. Kuznetsov, S. Moseenkov, A. Usolseva, I. Mazov, A. Ischenko, P. Lambin, Dielectric properties of MWCNT based polymer composites close and below percolation threshold, *Phys. Stat. Sol. C* 6(12): 2814-2816, 2009
123. J. Macutkevic, P. Kuzhir, D. Seliuta, G. Valusis, J. Banys, A. Paddubskaya, D. Bychanok, G. Slepyan, S. Maksimenko, V. Kuznetsov, S. Moseenkov, O. Shenderova, A.

Mayer and Ph. Lambin, Dielectric properties of novel high absorbing onion-like-carbon based polymer composite, *Diamond and Related Materials* 19(1): 91-99, 2010

124. P. Kuzhir, A. Paddubskaya, D. Bychanok, A. Nemilentsau, M. Shuba, A. Plusch, S. Maksimenko, S. Bellucci, L. Coderoni, F. Micciulla, I. Sacco, G. Rinaldi, J. Macutkevic, D. Seliuta, G. Valusis, J. Banys, Microwave probing of nanocarbon based epoxy resin composite films: toward electromagnetic shielding, *Thin Solid Films*, 519(12): 4114-4118, 2011

125. P. Kuzhir, V. Ksenevich, A. Paddubskaya, T. Veselova, D. Bychanok, A. Plusch, A. Nemilentsau, M. Shuba, S. Maksimenko, S. Bellucci, L. Coderoni, F. Micciulla, I. Sacco, G. Rinaldi, CNT based epoxy resin composites for conductive applications, *Nanosci. Nanotechnol. Lett.*, 3(6): 889-894 **(**6pp), 2012

126. P. P. Kuzhir, A. g. Paddubskaya, S. A. Maksimenko, V. L. Kuznetsov, S. Moseenkov, A. I. Romanenko, O. A. Shenderova, J. Macutkevic, G. Valusis, P. Lambin, Carbon onion composites for EMC applications**,** *IEEE Trans. Electromagnetic Compatibility*, 54(1): 6-16, 2012

127. J. Macutkevic, D. Seliuta, G. Valusis, R. Adomavicius, A. Krotkus, P. Kuzhir, A. Paddubskaya, S. Maksimenko, V. Kuznetsov, I. Mazov, I. Simonova, Multi-walled carbon nanotubes / PMMA composites for THz applications, *Diamond and Related Materials*, 25: 13-18, 2012

128. A. Paddubskaya, D. Bychanok, A. Plyushch, P. Kuzhir, A. Nemilentsau, S. Maksimenko, S. Bellucci, L. Coderoni, F. Micciulla, I. Sacco, G. Rinald**i,** Epoxy Resin/SWCNT Shielding Paint for Super-High-Frequency Range, *J. Nanoelectronics and Optoelectronics,* 7(1): 81-86, 2012

129. A.M. Nemilentsau, G. Ya. Slepyan, S. A. Maksimenko, A. Lakhtakia, and S. V. Rotkin, Spontaneous decay of the excited state of an emitter near a finite-length metallic carbon nanotube, *Phys. Rev. B* 82**,** 235411 (9pp), 2010