Biomolecular Neuronet Devices

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Biomolecular Neuronet Devices

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38.1.1 Bacteriorhodopsin Is an Advanced Material for Molecular Nanophotonics

Bacteriorhodopsin (BR)—light-sensitive protein—is similar to the optic rhodopsin of the human eye. BR is obtained from halo-bacteria containing BR in cellular membranes (so-called purple membranes). During the separation from the bacterial cells, purple membranes save the entire structure (Vsevolodov, 1988; Oesterhelt et al., 1991). The typical size of purple membranes is 500–1000 nm. It is the unique biocrystalline structure capable of saving its permanent properties for a number of years, which consists of dry and polymer films with the thickness from 5 nm (monolayer) up to a few tens of micrometers.

The fundamental BR property is the photochemical cycle availability: after the light quantum absorption, BR molecule passes through the sequence of states and spontaneously returns to the primary form (Figure 38.1). At that point, in compliance with the cycling of BR molecule state, the light-induced cycling
38.2 Some Techniques of Neuro-Molecular and Molecular Information Processing Using Bacteriorhodopsin (Basic Processes, Constructions, Technology)

38.2.1 Basic Process of Classic Optical Neural Network in Bacteriorhodopsin Medium

BR properties listed above allow us to illustrate one of the available basic processes of data transformation in BR-containing media. It is based on reversible light-sensitive changes of absorption index and appears in optical effects considered below.

38.2.1.1 Nonlinear Absorption of Optical Radiation: Medium Bleaching

The absorption of optical radiation in substance is described by some known classic equations. Generalized Bouguer–Beer law associates intensities of the incident light and the light transmitted through the substance layer with the thickness of the layer and molecular concentration of absorption agent:

\[ I = I_0 \cdot e^{-D} = I_0 \cdot e^{-\alpha d} = I_0 \cdot e^{-\varepsilon cd}, \]  

(38.1)

where

\begin{align*}
I & \text{ is the transmitted light intensity} \\
I_0 & \text{ is the incident light intensity} \\
\alpha & \text{ is the absorption index of the substance} \\
D & \text{ is the optical density of the substance} \\
d & \text{ is the thickness of the substance layer} \\
c & \text{ is the molar concentration of absorbing substance molecules} \\
\varepsilon & \text{ is the extinction coefficient, characteristic feature of absorbing substance molecule} \\
\end{align*}

The values of \( \varepsilon, \alpha, \) and \( D \) depend on the wave length of incident light. When the values of coefficients in Equation 38.1 are invariable, the transmitted light intensity is in direct proportion to the incident light intensity.
Nonlinear absorption of optical radiation by BR-containing media is connected to the change of absorption centers concentration (molecules in form BR570) as a result of light quanta absorption by these centers at wave length 570 nm and transformation to M412 with low absorption at wave length 570 nm. Finally, as was mentioned above, absorption in the yellow range ($\lambda = 570$ nm) decreases, medium becomes more transparent—bleached.

38.2.1.2 Indirect Interaction of Optical Radiation Fluxes in Bacteriorhodopsin-Containing Media

Mediated interaction of optical radiation fluxes appears during the sequential or combined transmission through the same part of BR-containing medium and is at its clearest for monochromatic radiation with wave length 412 and 570 nm.

As a result of interaction between BR and the radiation with wavelength 570 nm during the transmission through the medium, the energy of the light flux is absorbed, and in BR-containing medium, the photo-induced allocation of the absorption index forms. The light-induced allocation of the absorption index variation corresponds to energy distribution along the surface of the transmitted light wave front (Figure 38.3A).

Non-modulated along the front surface, the light pulse with the wave length of 570 or 412 nm (as actuating or inhibiting signal) absorbs spatially and nonuniformly in compliance with the changed value of the absorption index (Figure 38.3B and C).

Thus, the energy distribution along the preceding pulse front surface, indirectly, over the BR-containing medium, modulates the energy distribution along the following pulse front surface.

As a result, BR-containing medium is capable of accumulating (summing up) effects signed “+” and “−,” correspondingly, at wave lengths 570 and 412 nm. Predicating upon the indirect interaction of optical radiation in BR-containing media, the method of formal neuron creation in such media is available to offer. At that point, all the main functions can be realized by optical technique.

38.2.1.3 One of the Possible Methods of Formal Neuron Main Functions Realization in Bacteriorhodopsin Medium

Realization of the main operations of neuronet algorithms—weighing of input signal vector according to the matrix of weighing coefficients of synaptic bonds; composition of weighed values of input signals; realization of activation (threshold) function by optical method without optoelectronic buffering—permits to simplify the construction and the technological realization of multilayered optical neuronet, to increase the integration of neuro-like elements in device, and to solve the problem of areal density limitation inherent in microelectronic elements and electric connections.

38.2.1.4 Formation of the Neuro-Like Element

The neuro-like element is formed under the exposure of optical emission with the spectrum, corresponding to the absorption spectrum of BR molecules’ initial state and BR-containing material medium. This element is a part of the BR-containing medium with photo-induced absorption index. The threshold properties of such neurons are defined by the concentration ratio of molecules in primary and photo-induced forms, and the interaction of neuro-like elements is provided by optical emission.

The example of the similar neuronet realization, based on information conversion of basic process in BR-containing media (Figure 38.4), is considered below.

Construction for optical neuronet formation includes the following:

1. The source of the plane light front (transparent for normal incident light flux) providing the signal formation and transfer to neurons.
2. Photo-detecting layer based on BR-containing material for imaging of the input optical information by photoduced variation (according to light energy distribution along the surface of input light front) of absorption/transmission in BR-containing medium.

![FIGURE 38.3](image-url) The indirect interaction of optical radiation fluxes in BR-containing media: (A) green light pulse (modulated along the front surface) acts on a layer of BR-containing medium (nontransparent for green light); (B) modulated allocation of molecules in form M412 (transparent for green light) and BR570 (nontransparent for green light), (C) the action of unmodulated blue light pulse, (D) modulated blue pulse as a result of transmission via the modulated medium (BR-containing medium layer recovered the primary state).
3. Light flux expanding lens.
4. Layer of synaptic bond synthesis (matrix of weighing coefficients) made of BR-containing material.
5. The lens, focusing the light flux on layer 7 and forming the combination of input optical signals based on neuro-like elements in that manner.
6. The source of flat light front (transparent for normal incident light flux) for parallel comparison with thresholds, formation, and transfer to other layers of output neuron signals in layer 7 as light front, modulated by intensity along front surface according to the values of absorption/transmission area of BR-containing medium (corresponding to neuro-like elements).
7. The layer of neuro-like optical elements (being obtained on the basis of BR-containing material) composes input optical signals, traversing matrix 4 and realizing the activation function during the light front traverse from the source 6, and forms thereby output signals.

The input optical information in the form of light flux (input vector) effects the photo-detecting layer 2 that results in the absorption of light flux energy in BR-containing medium of photo-detecting layer and the distribution of the photo-induced absorption index forms.

Distribution of the photo-induced BR-containing medium absorption index along the surface and in depth corresponds to the power distribution along the surface of the effective light front.

Plain light front from the source 1, modulated by intensity according to the contour of absorption index of photo-detecting layer 2 by lens 3, allocates on the surface of weighing coefficients layer 4.

### 38.2.1.5 Realization of Weighing Function

The input vector weighing function comes around during the transfer process of input light signal—the components of input vector—over the matrix of weighing coefficients 4. By the component of input vector, we mean the quantity of the light energy (the intensity multiplied by exposure—exposition) affecting the matrix section.

Weighing coefficient (by which the input vector component is multiplied) is a transmission coefficient of the corresponding section of BR-containing matrix:

\[ I_{wij} = I_{nij} \cdot t \cdot \omega_{ij}, \]  

(38.2)

where

- \( I_{wij} \) is the light intensity transmitted over the \( ij \) matrix section or weighed component of the input vector
- \( I_{nij} \) is the light intensity of the light front section or a component of the input vector
- \( t \) is the exposition time of the corresponding component of the input vector
- \( \omega_{ij} \) is the weighing coefficient or transmission of the corresponding \( ij \)-section of the BR-containing matrix

Transmission of the \( ij \) matrix section is defined according to Bouguer–Beer law

\[ \omega_{ij} = e^{-\varepsilon c_{ij} \delta}, \]  

(38.3)

where

- \( \varepsilon \) is the BR absorption factor
- \( d \) is the thickness of BR-containing layer
- \( c_{ij} \) is the concentration of the BR molecules in the initial state in the \( ij \) matrix section

The properties of the input vector weighed components are formed by lens 5 in a light flux that gets to the inputs of the corresponding neuro-like elements of the layer 7.

### 38.2.1.6 Realization of the Weighed Signals Composition Function

Composition function of the input signals is realized in the BR-containing medium in layer 7 by the converging cylindrical lens 5 as a result of the combined effect at the same area of BR-containing medium of the light energy exposition by the corresponding components of the input vector.

Every component of the input vector contributes to the formation of the molecules ensemble in photo-induced state in proportion to the intensity and exposure time:

\[ \Delta c_{ij} = k \cdot I_{wij} \cdot t, \]  

(38.4)
where
\( \Delta c_{j/p i} \) is the concentration of BR molecules in photo-induced
spectral state
\( k \) is the coefficient of proportionality depending on the
concentration of BR molecules in the initial state, cross-
section interaction, photo response of BR-molecules transition
from the initial to the photo-induced form, and the
effecting light wave length
\( I_{wij} \) is the intensity of the input vector weighed \( ij\)-component
\( t \) is the exposure time of the input vector \( i\)-component

Thus, \( \Delta c_{j/p i} \) contains information about the value of the
weighed input interactions sum on the \( j\)-neuron.

38.2.1.7 Realization of the Activation Function

Magnitude \( \sum I_{wij} \cdot t \) (the total dose of light energy effecting
on the \( j\)-area of BR-containing medium) assigns the point at
the graph (dependence of the transmission value on the sum of
weighed input effects) and defines the transmission of the light
signal over the \( j\)-neuro-like element.

The changed transmission \( \omega_{n/e j} \) value of the BR-containing
medium \( j\)-section according to the \( j\)-neuro-like element assigns
the value of the activation function and the output signal of the
neuro-like element in layer 7, according to Figure 38.5. This
magnitude depends on the number of molecules possessing the
changed spectral properties of the medium section correspond-
ing to the neuro-like element of the layer 7 according to

\[ \omega_{n/e j} = e^{-\delta (t_w ij - \Delta c_{j/p i})}. \]  (38.5)

The graphic chart on the dependence of the BR-containing layer
relative transmission on the emission energy consists of the area
with the initial transmission value (unequal to zero), the area of
almost linear transmission change, and the saturation area (Figure
38.5). In general, the curve corresponds to the activation function
proposed for the neuronet realization by Grossberg (Wasserman,
1989). The similar compressive function automatically provides
the output signal range from 0 to 1 and corresponds to the ne-
cessary requirements for realization of reconversion algorithm
during the neuronet learning, for example, according to scheme
(Wasserman, 1989).

The output signal formation of neuro-like element (threshold
comparison and realization of the activation function) is car-
ried out by the light front of the specified intensity and duration
induced by the source-former 6.

The output signal of the neuro-like \( j\)-element is formed as an
energy portion of the active light signal being transferred over to
the corresponding section of BR-containing medium in the layer
of neuro-like elements 7 (according to the transmission of the
section considered) in conformity with the formula

\[ I_{\text{out } n/e} \cdot I_{\text{active}} = W_{n/e} \cdot I_{\text{active}} \cdot t_{\text{active}}. \]  (38.6)

The minimum value of the output signal is fixed by the trans-
mision of non-firing neuron (the inputs signals sum value is
close to zero) and corresponds to the initial transmission of
photochromic medium, and the maximum value is close to the
value of active front energy and corresponds to the satu-
ration area of the curve (Figure 38.5) and to the maximum
excited state (transmission) of firing neuron. Output signals
of neuro-like elements form the continued light front being
modulated according to the activation function at every point
of BR-containing layer 7. System learning (formation of matrix
weighing coefficients) corresponds to the formation of adequate
values of transmission coefficients of matrix sections based on
BR-containing medium that can be achieved by the inverse
transformation method.

The optical version of the inverse transformation method
can be simply and effectively realized (failing optoelectronic
transformations) by combined presentation of learning pair: the
input image in its usual direction and the ordered output as the
light front in the counter direction. Due to the reversibility of
the light passing, both of light fronts will affect the matrix made
of BR-containing material and will change the matrix transmis-

38.2.2 Neuronets Based on Multilayered
Optical Structures Including Polymeric
Bacteriorhodopsin-Containing Layers

The considered approach of neuro-computer element base for-
mation takes into account the cyclicity of processes in living
systems appearing, for example, in spontaneous activity of pace-
making (assigning the rhythm of functioning) neurons. As was
conclusively shown in Prigogine (1980), the cyclicity proceeds
as a result of the processes’ self-organization in open nonlinear nonequilibrium systems and the origination of stable dissipative structures due to which the coordination of trophic processes (providing cell nutrition) is possible in living systems.

The similarity of cyclic processes in the living cell membranes (including neurons) and the processes under optical emission exposure in isolated purple membranes is obvious, particularly, taking into consideration that in that case one of the halobacterial trophic cycles is reproduced.

If the neuron is represented as a structure population (purple membranes) allocated in media and the interactions between the neurons are carried out by light fluxes, the “neuralike medium” in question can be considered as the alternative to the net of neuro-like elements (Grebennikov, 1997).

In the interpretation being stated, the problem of neuronet formation is in simulation of nonequilibrium nonlinear systems in BR-containing media with allocated parameters by optical emission of two different wave lengths corresponding to the absorption maxima of two “long-living” intermediates. It can be solved in the following consequence:

1. Using the spectral sensitivity of BR in optical range to initiate the cyclic light-dependent processes by the light flux and to control the processes by the application of emission with various wave lengths.

2. Stationary and dynamic structuring of BR-containing films by modulated light fluxes to create the conditions of formation and development of neuro-like relations in neuro-like medium and to correlate the multitude of cyclic processes.

Data input and processing in that case is “deformation” of the correlated cyclic processes in BR-containing medium, and the commands of system behavior control are the transient processes originating in the organized neuro-like medium.

On the other hand, analyzing the development tendencies of neuronet technology, the best perspective can be emphasized, and their combination in the same device can provide essential expansion of neuronet data processing:

1. Optical mechanism of data transmission and processing, which will allow to construct three-dimensional nets that function simultaneously at high speed. The problem of wide application is in large dimensions, peculiar to optical systems, and the inevitable efficiency losses due to multiple intermediate optoelectronic conversions and the finite size of the optoelectronic elements.

The application of continuous photochromic media with high resolution close to molecular level of data representation and processing can become a solution to the problem. BR is the most available and well-investigated (at present) photochromic material with sufficiently high cyclization (>10⁵) and is suitable for the considered purposes. Using BR enables to carry out data processing in optical mode without intermediate optoelectronic conversions and to increase the areal density of neuro-like elements value comparable to the native neuron systems.


BR application can solve the problem of substance transfer that complicates the construction and limits the continuous working life of neuro-like media processing. Light-dependent properties of that material allow the open nonlinear allocated dissipative systems to simulate effectively. Optical exposure in the range of 520–650 nm is like the input flux and dissipative properties, and in that case can be provided by the component of trophic cycle that remains invariable in composition of artificial medium (for example, in polymeric matrix) and also by emission exposure in blue light range (λ = 400–420 nm).

3. Element base adaptability to losses of some elements during the preparation and exploitation compensated by self-organizing and self-modification of neuro-like structures. Application of continuous media based on BR in conjunction with optical methods permits to form neuro-like elements, and the bonds between it suit requirements according to the light energy allocation.

Classic methods of the light fluxes formation by lens systems result in the loss of advantages expected from significant density of neuro-like elements and dimension restrictions of elements and systems, peculiar to optical computers. Moreover, when the volume of BR-containing medium is greater, the probable process integration is higher. However, the emission access to all the molecule groups is more unfavorable as the medium absorption increases.

In the field of optoelectronic technology, efforts are made to deflate the construction dimension of optical neuro-computers by the application of multilayered structures. Multilayered structures forming neuronets and containing the layer of spatial light modulators as the liquid crystal matrix, the layer of photoconducting material (Engel, 1990) or material with the photovoltaic effect (Akiyama et al., 1995), and the layer of electric transducer-amplifiers (forming and transducing the commands to liquid crystal panels) are proposed.

Essential disadvantage of the proposed constructions is the facility of intermediate conversion of light exposure to electric current or voltage used for the following changes of optical transmission modulator. Furthermore, neuronet function realization requires the application for these purposes of optoelectronic and microelectronic elements. Consequently, the application of metallic conductors in inter-cell links for realization of neuro-systems with a great number of neurons results in delays in communication lines and neuronet processing deceleration due to the capacity influence of inter-cell communication lines. The existing areal density restrictions of optoelectronic elements and electrical bonds inevitably limit the spatial resolution of constructions.
38.2.2.1 Multilayered Constructions, Including Bacteriorhodopsin-Containing Films

We proposed multilayered structures including layers based on the BR for the realization of neuronet medium in nonequilibrium nonlinear dynamically allocated dissipative systems.

Supposedly, the multilayered structures would allow the data processing to continue at the level of BR molecules groups by forming neuro-like elements using optical methods in BR-containing media.

The basic processes in BR medium are defined by light-dependent changes in absorption index allocation profile along the surface of BR-containing polymeric films. In multilayered structures, many light fluxes circulate without interaction. This property is usually proved as an advantage of optical methods enabling data processing and transmission in the three-dimensional space. At the same time, the information arrays in the form modulate indirectly by intensity light fronts over the reciprocal fluctuation of absorption index local value of BR-containing media sections, and the local intensity value of the light front sections realize concurrent information interactions in the three-dimensional space of the multilayered structure.

We would like to consider a possibility of neuro-like element net organization in BR medium by optical method using multilayered structures (Figure 38.6) including BR-based layers, wave guide layers, and reflecting layers. To allocate light fluxes, the system of waveguides, transparent in the optical range, is formed in BR-containing medium. It is possible to input the controlled emission in the form of light front in BR-containing medium, activating at that point the groups of neuro-like elements, by producing the sections with the disturbed conditions of total internal reflection in waveguides.

It is expected that the multilayered structure will provide not only functioning and interaction of neurons and their ensembles but also the generation of new neurons and links (emission output from one layer and penetrating to the other layers) between single neurons and neuronets, and will permit, according to the information (image) at system output, to connect and to correlate the cyclical processes originating in BR medium. At that point, the process of self-organization of data processing system will continue.

The adaptability principles realization of data processing elements and system self-organization will permit to essentially reduce the requirements of the elements and facility as a whole to provide reliable functioning in case of the single-element failure.

Reduction of technological requirements is achieved by that neuro-like elements and links that are formed in continuous (uniform, i.e., not divided into constructive matrix elements) transparent (without optical dispersion) layer of photochromic material according to the light energy allocation.

38.2.2.2 Expected Parameters of the Element Base

According to the traditional criteria, it is acceptable to evaluate the number of the neuro-like elements in medium containing BR at area 10 mm³ in quantity not less than 10⁴. At the area in question, not less than 10¹¹ bonds per second are realized (circuit time 0.1 ms, coefficient of bond formation 10).

38.2.2.3 The Basic Elements of the Multilayered Structures

The multilayered structures (Figure 38.6) for the realization of the basic neuronet data processing include: the system of flat waveguides, the elements of optical emission input as gitter, and the devices of the surface light front formation (Figure 38.7).

BR-containing polymeric films are meant for neuro-like elements formation by the change of the absorption/transmission media sections, and the local intensity value of the light front sections realize concurrent information interactions in the three-dimensional space of the multilayered structure.

The angles of radiation input and output depend on different layer indexes and glitter spacing; therefore, those angles can be different for various multilayered waveguides.
The device for surface light front formation (Figure 38.7) generates directed light fluxes for effective allocation of the light energy in BR-containing polymeric films for neuro-like elements concurrent formation, their concurrent interaction, and output of the data processing results in neuro-like element medium as optical signals.

38.2.2.4 Requirements of BR-Containing Polymeric Films

The following are the requirements of optical and geometrical properties of BR-containing polymeric films.

For photochromic effects (induced changes of refraction and absorption indexes) to significantly appear during functioning process, high optic density and consequently substantial BR concentration in polymeric films are needed. Optical density of such films should be 0.8–1.3. In those conditions, basic characteristics of BR-containing media are utilized under optimum light flux density so that the media could be used for technical purposes. Exposure to light of the fluxes with radiation density equal to 10–100 mW/cm² induces the films to experience changes in their absorption and transmission characteristics as much as 10%–50% from the original indexes in as long as 0.1–10 s.

Functioning of films under induced changes in absorption level requires quite homogeneous distribution of BR concentration, as optical heterogeneity infringes the conversion of optical information.

Besides, we must ensure repeatability of the main structural parameters: film thickness, surface finish, homogeneous BR distribution throughout film surface (1–10 cm²), etc.

Requirements to physical and chemical properties of polymeric matrix. Selection of matrix material.

To minimize the influence of diffraction divergence on information conversion processes, the thickness of BR-containing films must be 6–14 μm. To reach the specified optical density with that thickness, the volume of BR content in polymeric films should be 40%–50%. Far from all, the polymers transparent in optical range can meet the requirements above. Moreover, only water-soluble polymers can be used to form BR-containing polymeric films.

The comparative studies held to form polyvinyl alcohol- and gelatine-based BR-containing polymeric films have proved that gelatin-based polymeric matrixes have obvious advantages.

Gelatin-based films could apparently have the highest possible BR concentration (up to 50 vol. %) without aggregation of PM fragments due to thermodynamic peculiarities of gelatin polymerization process. Gelatin properties allow us to avoid destruction of BR protein structure while making polymeric mixture and further polymerization.

PM fragments embedded into a gelatin matrix are long-lasting and resistant to many technological factors. Polymerized gelatin creates optimum conditions for BR to function while retaining enough water needed for photochromic cycle. For the same reason, gelatin matrices make it possible to place environment-modifying water-soluble components and to change the photo cycle time frame.

38.2.2.5 Obtaining of Bacteriorhodopsin-Containing Polymeric Films for Multilayered Structures

It is important for processing and conversion of optical information to take into consideration the dispersion of optical emission in BR-containing media conditioned by purple membranes size (500–1000 nm)—comparable to the wave length of the optical range emission. Therefore, the primary suspensions of PM and BR-containing films based on them are optically nonhomogeneous, which results in the functional properties loss.

The dispersion demagnification is reached consequently: at the step of preparation of purple membranes suspension—by PM fragments separation; at the steps of polymeric mixture preparation and polymerization—by elimination of the aggregation process of the purple membranes fragments.

38.2.2.5.1 Preparation of Bacteriorhodopsin Suspension

For the preparation of PM suspension, the triple centrifugal purification (3000 rpm, 5 min) was carried out; pH value and BR concentration in suspension were measured. The pH value is significant for the following polymeric solutions and film obtaining, since the investigations showed that at pH less than 4.1 PM aggregated, the optical transparency of the suspension was not achieved. It was determined that the ultrasound exposure results in the decrease of pH value in suspension at 0.2–0.4. The control of pH value was managed by the addition of 0.01 M borax buffer solution Na₂B₄O₇·10H₂O, pH = 9.18. During the ultrasound treatment, the suspension temperature must not exceed 36°C.

As the result of technological investigations of ultrasound treatment, optically transparent homogeneous BR suspensions were obtained without detergent addition. The side effect can be the partial melting of protein. Optically transparent PM suspensions were obtained with BR concentration up to 15 mg/mL.

Size evaluation (8.7 ± 0.5 μm) of PM fragments in treated suspensions was carried out by the intensity of Rayleigh scattering and showed that the applied technological mode of suspension treatment permits to separate PM into naturally minimum fragments—trimers without BR protein destruction and the principle possibility of BR-containing medium optical resolution at the level of a few thousand lines per millimeter can be considered.

38.2.2.5.2 Preparation of Bacteriorhodopsin-Containing Mixture

During the preparation of polymeric mixture based on BR, the last exhibited the property of aggregation on the polymer molecules that lead to optical heterogeneity of films. As the result of technological experiments combining thermal parameters and operating pH of components, the conditions selected under that aggregation were not observed and transparent optically homogeneous BR-containing polymeric mixtures were obtained.

At the step of polymeric mixture preparation, pH control of gelatine solution was carried out because pH value in gelatine solution depends either on the obtaining method or on gelatine concentration. The component stirring in the mixture was also carried out by the ultrasound exposure. All the modifying components were put into the polymeric mixture at the last step.
under condition: the final pH value of the polymeric mixture had to be >4.1.

**38.2.2.6 The Properties of BR-Containing Polymeric Films for Multilayered Structures**

According to the elaborated technology, there are transparent and optically homogeneous BR-containing polymeric films (thickness 6–14 μm with optical density 0.8–1.3 D at λ = 570 nm) on substrates of glass K-8 and fused quartz (area up to 60 × 48 mm²) and also on Si plates (76 mm in diameter).

**38.2.2.6.1 Evaluation of PM Size Embedded to Film**

Since during the film polymerization from the polymeric mixture fragment aggregation is possible, the evaluation of PM fragments size is being embedded into film. The placement of films with the embedded PM fragments in detection system between crossed polarizers resulted in no changes in the initial zero signal of photodetector. It means either no rotation of polarization in the light-pass direction, or no significant dispersion that confirms the PM fragments size to be much less than 0.63 μm.

Optical heterogeneity specified by surface geometry and allocation of BR concentration to the film surface is given below.

The distribution of optical absorption heterogeneity coefficient of BR-containing films is specified by the product of two values: the allocation heterogeneity of BR bulk concentration to the film surface and quality of the film surface as the local dilatation from the average thickness value. In the aggregate it results in the local dilatation of so-called surface concentration and, correspondingly, the optical density.

The optical homogeneity of the film being specified only by the surface quality is provided comparatively easily both for the films being realized by glazing method and for the films being obtained by centrifugation method. It was determined that the typical thickness deviation of BR-containing films being obtained equals less than 50 nm at length 10 mm, that, for example, at film thickness >5 μm equals <1%.

The support of the optical homogeneity being concerned with the allocation of BR bulk concentration along the film surface is hampered by the molecules migration in polymeric solutions during the polymerization process to the area of increased surface tension. Nevertheless, the attained deviation from the average value for allocation of BR bulk concentration does not exceed 3% since the changes of surface concentration and optical density lie in the same range.

**38.2.2.6.2 The Structure of Bacteriorhodopsin-Containing Films**

It is ascertained that the structure of BR-containing polymeric films surface depends on the obtaining conditions. Depending on pH, the surface is either smooth (Figure 38.8A) or it has punctual (100–300 nm) and rectilinear (400–1000 nm lengthwise, 100–200 nm wide) protuberances (Figure 38.8B and C). The cutting of the surface geometry elements is observed (Figure 38.8B). These investigations confirmed the necessity of pH value maintenance higher than 4.1.

Surface roughness (step height Rₛ of surface geometry) of the film with particle size of BR phase <10 nm amounts to Rₛ = 0.1 μm, with particle size of BR phase ~100–1000 nm Rₛ ~ 0.6–3.8 μm.

The analysis of the films with thickness 20 μm (containing BR-phase cutting) by Roentgen diffractometry led to the missing crystalline phase. Only amorphous gallo is observed on roentgenograms of BR-containing polymeric films, being formed under various conditions in the range of Bragg angles 2θ = 5°–8° (α —copper emission).

Clearly defined diffraction maximum appears on roentgenograms of some samples for angles 2θ = 7.5°–7.8° (Figure 38.9) corresponding to interplanar spacing d/n = 1.179–1.133 nm. For a number of samples, diffraction maximum appears on roentgenograms for angles 2θ = 18°–19° (d/n = 0.467–0.493 nm). That indicates the ordered placement of protein complexes in polymeric (gelatinous) matrix. Apparently, the axial texturing of lamellar protein complexes exists by the axis normal to the surface of BR plates.

**38.2.2.6.3 Refraction Index of BR and BR-Containing Polymeric Films**

Information about refraction index in literature (Hampp, 2000) is inconsistent and not exact enough to solve the problem of the multilayered structure construction. Therefore, we made our own measurements.

![FIGURE 38.8](A) (B) (C)

**FIGURE 38.8** The structure of BR-containing polymeric film surface being formed from the polymeric mixture: (A) pH = 4.2–4.5; (B) pH = 3.8–4.0 (the enlarged surface fragment is presented at the insertion); (C) pH = 3.5–3.7.
The refraction index measurement was carried out using refractometer IRF-454B capable of measuring the refraction index in the range from 1.2 to 1.7 in reflected and transmitted light. BR-containing film was formed on the surface of measuring prism by the method of suspension glazing (concentration 15–20 mg/mL) and the following drying at 22°C temperature, relative 60% humidity. The film thickness reached 20±5 μm.

The value 1.534±0.002 of refraction index was obtained in the white light. This result is well reproducible on every one of the samples being prepared from the three different halobacteria strains and conforms to the results of the following refraction index measurements in polymeric BR-containing films. The value of the refraction index in that case is defined by BR concentration in the film.

The refraction index measurement of gelatin was held in order to predict the parameters of the polymeric BR-containing films under construction depending on BR concentration in the film. The refraction index value of polymeric film based on gelatin without BR (formation by the glazing method on the surface of the refractometer measuring prism) got equal to 1.543±0.001. Refraction index was measured at 22°C temperature and relative 60% humidity.

The refraction index value of BR-containing gelatinous film with thickness 50±10 μm lies in the range of 1.539–1.542 depending on BR concentration in gelatin.

### 38.3 Nanostructuring of Bacteriorhodopsin-Containing Molecular Media

Functional parameters of BR-based multilayered structures on the base of BR (the increase of photochromic sensitivity, management of photocycle duration) can reach their maximum capacity in use by additional nanostructuring of molecular media. Enhancement of functional properties of multilayered structures is caused by introduction of new functional elements—nanostructures—making it possible to further realize a new class of optical information systems based on self-organizing oscillatory and auto wave hierarchical processes in BR-containing nanocomposites.

Both nanotechnological and nanotechno-systematic approaches are described below.

While developing BR-based media used to process information with neural network methods, two ways of material structuring are applied. The first way means introduction of modifying organic and nonorganic additives into the system to improve functional characteristics of BR. Modification is done on molecular level that is why such material is a molecular one. The second way means building of hybrid functional structures with every component performing its own function. In this way, structuring goes at nanometric range instead of molecular level. Hybrid nanostructures are systems made of three components—colloidal nanoparticles (metal or semiconductor structures based on transition element [TM] chalcogenide), bridge molecules (spacers) with various linear dimensions, and BR molecules.

#### 38.3.1 Procedure of Complex Estimation of Functional Characteristics of Bacteriorhodopsin-Containing Materials

To characterize and compare functional characteristics of BR-based films made by various methods and difference in thickness, optical absorption, structure, and content (including concentration of BR molecules), it is convenient to apply the designated factor for quantity estimation of photochromic sensitivity. For optimization of experimental investigations, we developed the simulator of photo-dependent processes and designated factor of photo-induced transitions of BR molecules from the primary state BR570:

$$ k_{570}(t) = \frac{N_1(t)}{N_0} = \frac{N_0 - N_1(t)}{N_0}, $$

where

- $N_1$ is concentration of BR570
- $N_2$ is the concentration of BR412
- $N_1 + N_2 = N_0$ is the total concentration of BR molecules

That factor $k_{570}(t)$ named by us as the coefficient of photo-induced transition of BR molecules from basic state BR570 was determined from experimental data of changing optical absorption at wavelength 570 nm under the influence of active inducing radiation. This complex parameter takes into consideration the temporary characteristics of excitation and relaxation processes, quantum efficiency, and cross-section of BR molecules contained in the nanocomposite nanostructured films (media).

While studying the influence of technological formation processes on properties of BR-containing materials, it is very labor-consuming to measure each of the above specified characteristics. Therefore, we use a model to describe photo-dependent processes that pass in BR-based materials under radiation.
We have also designed a method to assess the functional characteristics of those media after one measurement. To carry out all necessary measurements, we can use a soft- and hardware complex (Figure 38.10), making it possible to combine light exposure with two wavelengths in the band of main intermediate absorption (at 570 and 412 nm, respectively).

The light radiated by the source of continuous testing radiation with up to 2 mW/cm² intensity passes through the sample and falls onto the monochromator where a narrow spectrum line (at 570 nm) is allocated. The signal goes to the photo-electronic multiplier being adjusted to convert the signal and transfer it to the oscillograph. The sample is exposed to light pulsed by the source of exciting radiation with intensity at least 10 times more than the intensity of testing radiation. The signal registered with the oscillograph goes to the computer for mathematic curve processing as per the below physical and mathematic ratios.

Based on the Buger–Lambert–Beer law, taking into consideration photo-induced changing concentrations N₁ and N₂, the expression has been obtained that allows to calculate the value of k₅₇₀(t) from the experimental data recording testing light λ = 570 nm transmission changing under illumination of exciting radiation:

$$k_{570}(t) = \frac{\lg \frac{I(t)}{I_0}}{\lg \frac{I_1}{I_0}},$$

(38.8)

where

- I₀ is the intensity of the incident test light
- I₁ is the intensity of the transmitted test light in the absence of exciting radiation
- I(t) is the intensity of the transmitted test light under exciting radiation at the time moment t

Also the proposed method of the complex estimation is based on the kinetic equation evaluating concentration distribution of BR molecules between forms of BR570 (N₁) and M412 (N₂):

$$\frac{dN_1}{dt} = -\sigma_1 \cdot A_1 \cdot \frac{P}{h \cdot \nu} \cdot N_1 + \frac{1}{\tau} \cdot N_2,$$

(38.9)

where

- σ₁ is the absorption cross-section of BR570 form (on wavelength of acting light)
- A₁ is the quantum yield of photoreaction
- P is the power density of acting light
- τ is the lifetime of M412 form
- h is the Planck constant
- ν is the acting light frequency

From the same experimental data (Figure 38.11) based on the solution of equation evaluating concentration distribution of BR molecules between forms BR570 (N₁) and M412 (N₂), the estimation of quantum yield of photoreaction A₁ from the value of the derivative at the point t = 0 (the beginning of exciting radiation action) and the estimation of the lifetime of M412 form τ from value of derivative at the point t = t* (the end of exciting radiation action) may be obtained. As time goes by, film transmission value being influenced by the relaxation of excited molecules approaches to the original transmission level.

### 38.3.2 Functional Characteristics of Nanostructured Bacteriorhodopsin Films

To form the effective functional structures out of biomaterials, we need to apply various technological methods. In particular, we can use BR-containing materials to prove the necessity to use...
the additional nanostructuring of functional biomolecular films subject to storage and neural network processing with optical methods.

As a result of non-modified BR films’ investigations, we established that immediately after obtaining the values, \( k_{570}(t) \) are in interval 0.5–0.7 and then decrease to value 0.2 for 3–5 h and demonstrate this value during a few years. In the primary formed films, BR molecules constitute the structure that in time is destroyed in consequence of the heat oscillations, resulting in disordered molecule orientation relative to each other and destruction of hydrogen bonds. To keep the high photochromic sensitivity for the whole period, we can create additional linkages (covalent or hydrogenous) between protein molecules by using chemical reagents.

For example, our use of diamine (1,4-diaminobenzen [DAB]) in the ratio of BR:DAB = 1:3, 1:6 in 1:9 (molecular ratio) has resulted in increased values of factor \( k_{570}(t) \) (0.35–0.5) in comparison with non-modified BR films (0.2–0.25) during 12 days. The stabilization of the primary formed BR structure occurs due to the fact that 1,4-diaminobenzen is an aromatic amine and capable to interact with the carboxyl groups of glutamic and aspartic acids. In our opinion, the high values \( k_{570}(t) \) for BR:DAB films are the result of raising the lifetime of M412 form owing to the fact that 1,4-diaminobenzen screens extract proton groups.

At the same time the use of glutaric dialdehyde (GA) with sodium tetraborate for the alkaline catalysis of the reaction of bonding between amine groups of BR lysine residues and aldehydic groups of GA (the Schiff base) for the samples BR:GA = 1:5 had more high values of factor \( k_{570}(t) \) = 0.55 (Figure 38.12), whereas BR:GA = 1:10 and 1:30 had \( k_{570}(t) \) = 0.4–0.5, which is explained by the high content of GA oxidation products by atmospheric \( \text{O}_2 \) (glutaric acid) that partially destroy BR molecules. The dynamics change of decay factor \( k_{570}(t) \) value was studied during 1 year for BR:GA films (Figure 38.12).

The samples BR:GA = 1:5 kept the high value of factor \( k_{570}(t) \) (20.45) for 120 days. After 330 days for all the samples of BR:GA \( k_{570}(t) \) ≥ 0.3.

Introduction of amino acids in the content of BR-containing films leads to even better results. The films of BR: glycine, BR: isoleucine, and BR: lysine in molecular ratio from 1:1 to 1:25 had been made. The BR: glycine and BR: isoleucine films were first inhomogeneous optically and characterized by the high light scattering, and consequently had low values of factor \( k_{570}(t) \) within the limits of 0.05–0.1. The BR: lysine films were optically transparent and homogeneous. The dynamics of changing value \( k_{570}(t) \) for the films with ratio BR: lysine = 1:10 and 1:25 was shown in Figure 38.13. The samples with the ratio BR: lysine = 1:25 kept stable higher values during not less than

![FIGURE 38.11](image-url)  
Typical curve of photo-induced changes of optical transmission of BR-containing media.

![FIGURE 38.12](image-url)  
Changing values \( k_{570}(t) \) in the operation process for the films. BR:GA = 1:30, 1:10, and 1:5.

![FIGURE 38.13](image-url)  
Changing values \( k_{570}(t) \) in the operation process for the films. BR: lysine = 1:10 and 1:25.
80 days—$k_{370}(t) (0.4–0.55)$—in comparison with the check sample (0.15–0.2). At that optical density and transparency, films did not change throughout that time. The samples with ratio BR: lysine = 1:10 demonstrated higher values $k_{370}(t) (0.35–0.5)$ in comparison with the check sample (0.15–0.2) for 330 days.

The above results prove that there are considerable opportunities to improve functional characteristics of BR-containing materials by nanostructuring (by forming additional bonds between BR molecules).

### 38.3.3 Metal Nanoparticles and Bacteriorhodopsin-Based Hybrid Nanostructures

The other way to expand the functional opportunities of molecular nanophotonic materials is to form hybrid nanostructures. We suggest the system use of some physical phenomena common for nanoscale structures as the basic processes for photonic information systems. In particular, we can use the effect that nano-objects have on the lifetime of excited atoms and molecules located closer than radiation wavelength. This effect is rapidly enhanced near nanoparticles when strong electromagnetic fields locate at plasma resonance frequency. Strong local fields influence the speed of electron transitions (i.e., the processes of light absorption and spontaneous radiation). Such fields can also change spectral characteristics of those processes and lead to substantial enhancement of various nonlinear optical effects. In particular due to strong local fields we can manage tumescence enhancement and effective suppression (depending on the distance), have radiationless energy transition, and manage the quantum efficiency of BR photoreaction and the lifetime of its spectral intermediates. The specified mechanisms could be useful to design photonic devices, which perform basic functions of information systems on the basis of nonlinear dissipative media with distributed feedbacks. It is to be taken into account that the effect nanoparticles have on the excited state of the functional molecule becomes different with the change of the distance between them. This circumstance creates wide opportunities to create hybrid nanostructure-based composition materials with bridge molecules of various lengths.

In general, hybrid nanostructures are the systems made of three components—colloidal nanoparticles, bridge molecules (spacers) with various linear dimensions, and functional (photochromic, photoluminescence, electroluminescence, etc.) molecules. Below is the description and diagram (Figure 38.14) to show different aspects of hybrid nanostructures' formation with metal nanoparticles.

Formation of the hybrid nanostructures with adjusted distance between a nanoparticle and a functional molecule includes several key stages:

1. Formation and stabilization of nanoparticles in the polar or nonpolar solvent.
2. Modification of nanoparticle surface in order to functionalize and to ensure selective and self-organizing hybrid nanostructures.

Formation of nanoparticles compatible with BR photochromic protein has its own peculiarities due to the biological nature of the material as water is used as the main solvent.

The number of spacers used to form BR-based hybrid structures is quite limited due to the chemical properties of both components. First, the spacers must be hydrophilic substances, well soluble in water. Second, functional groups are also very limited. As BR is a protein, its structure is based on polypeptide amino acid consequence, including among others asparagic and glutamic acid residues. Those residues have free carboxylate groups taking no part in the formation of peptide bonds. pH area, where BR demonstrates its functional characteristics, is limited to pH > 5. Under those conditions the molecule is negatively charged. Therefore, to bind with BR functional spacer, the groups must be positively charged. The most efficient spacers look like molecules, including free aliphatic positively charged amino acids. Those substances include, for example, symmetrical diamines (1.6-diaminohexane, 1.7-diaminohexane) or lysine (2.5-diaminopentane acid). Besides, in low-molecular compounds, one can use polymers, including amino acids in their structure. Polylysine is one of such polymers.

Gold nanoparticle-based nanohybrid structures are relatively easy to form as gold nanoparticles are chemically inert in aqueous suspensions. At the first technological stage we apply the borohydride method, which makes it possible to get smaller particles with more homogenous size distribution than nanoparticles obtained by using the citrate method. Besides to reach that we do not need to use any additional technological tricks. To apply the borohydride method, add 1 mL 1% HAuCl₄, 0.5 mL 0.1 M K₂CO₃ to 100 mL distilled water. While stirring the mixture vigorously with a magnetic stirrer, add 140 μL 0.1 M NaBH₄ solution (in some 10 μL portions during 10 min).

The technological methods of forming hybrid structures that we are developing are based on mechanisms of special bonding and self-organization activated by interaction of spacers with the appropriate functional groups. To build hybrid nanostructures based on formed gold nanoparticles, we have to modify nanoparticle surface with amino-containing spacers, which are able to actively interact with both BR molecules and the surface of nanoparticle. We have selected symmetrical aliphatic diamines, in particular, 1.6-diaminohexane. The surface of nanoparticles is modified by introducing 1.6-diaminohexane water solution with up to 5000 spacer molecules to 1 nanoparticle. The intensity of spacer molecules bonding with the surface

**FIGURE 38.14** Schematic composition of hybrid nanostructures.
of nanoparticles can be indicated by the fact that after introducing 1.6-diaminohexane, excess gold nanoparticles are quick to aggregate (sometimes with residue). The results of that process can be seen while extracting films out of suspensions by methods of atom microscopic investigation (Figure 38.15).

Comprehensive studies have proved that we need to not only modify the surface of gold nanoparticles but also remove the suspension reacting system components that have failed to react during nanoparticle synthesis as those components destruct BR molecules and obstruct synthesis of hybrid structures. To solve this problem, we have suggested the use of dialyze. Place nanoparticle-containing suspension in the so-called dialysis bag, which is a hollow plastic container with some nanometer-size holes. Sink the dialysis bag into the solution of the substance to be introduced into the system (concentration of the solution should be enough to modify the surface of nanoparticles effectively). The volume of that solution is usually at least 10 times more than the volume of the original suspension.

During the process, small organic and nonorganic molecules migrate through the hollow walls of the dialysis bag, depending on the concentration gradient of the hole. Nanoparticles that are bigger than bag holes stay inside the dialysis bag. Some time (around 2 days) later thermodynamic balance is reached. That means that concentration of organic and nonorganic substances get homogenous throughout the volume. Therefore, the solution inside the dialysis bag experiences dilution due to contaminating impurities to an extent and solution volume relates to the volume of the original suspension. Concentration of the substance to modify nanoparticle surface is the same as that of the original solution. Using this method, we have obtained gold nanoparticles with 1.6-diaminohexane-modified surface. Those suspensions are stable. The studies of spectral characteristics of such suspensions have proved that dialysis has no effect on the spectrum of gold nanoparticles form (Figure 38.16).

We have synthesized hybrid structures with nanoparticles to BR molecules ratio 1:3600. BR suspension (51 mg/mL) is used as an original one. Hybrid structures are formed by vigorously stirring the suspension with a magnetic stirrer for 2 days at the temperature of the reaction mixture equal to 20°C–25°C. Figure 38.17 demonstrates spectral characteristics of the hybrid nanostructures suspension based on gold nanoparticles, 1.6-diaminohexane, and BR. We have to stress that characteristic spectral maximums of certain components do not decompose and therefore make it more complicated to study functional characteristics of those structures. By using extraction, we have obtained films with the surface characterized by atom microscopic investigation (Figure 38.18).

The use of silver nanoparticles providing optimum combination of spectral characteristics in the nanoparticle–BR system is of more interest. At the same time, silver nanoparticles demonstrate substantial chemical and photochemical activity in water suspension and require special stabilization measures.

**FIGURE 38.15** AFM characterization of the surface of gold nanoparticle-based films extracted from (A) a suspension with optimum 1.6-diaminohexane level; (B) from a suspension with excessive 1.6-diaminohexane level.

**FIGURE 38.16** Spectrum of gold nanoparticles after dialysis with 1.6-diaminohexane solution.
To solve this problem, we introduce bridge molecules with various functional groups into the reaction system used to synthesize nanoparticles. This single technological operation includes two stages: formation and stabilization of nanoparticles and modification of their surface.

By using this method, we have obtained water suspensions of hybrid nanostructures based on BR and silver nanoparticles while using cysteine, arginine, lysine, and polylysine as spacers.

To form water colloidal suspension of silver nanoparticles we have used the following original water solutions:

1. Cysteine, arginine, and lysine with concentrations $c = 0.09\%$, $0.118\%$, and $0.122\%$ (weight) correspondingly
2. Polylysine with concentration $c = 0.125\%$ (weight)
3. Silver nitrate with concentration $c = 0.024\%$ (weight)
4. Water solution of sodium boron hydride with concentration $c = 0.4\%$ (weight) (to stabilize particles we have added $2.5\%$ (vol.) 1 M solution of sodium hydroxide)

To form nanoparticles, first we add the specified volume of spacer solution (up to $0.2\%$ total volume) into silver nitrate solution. Then we introduce $120\mu\text{L}$ boron hydride solution (divided into several $30\mu\text{L}$ portions to be introduced every $5\text{min}$) while stirring the mixture vigorously with a magnetic stirrer. Characteristic absorption maximums in the spectrums of silver nanoparticles suspensions stabilized with lysine, arginine, cysteine, and polylysine are at wavelength $390–400\text{nm}$ (Figure 38.19). Comparing the bands of absorption of silver nanoparticles stabilized with monomer amino acids and stabilized with polylysine, we can conclude that nanoparticles stabilized with amino acids are smaller in size than nanoparticles stabilized with polylysine. That conclusion is proved by the fact that the spectral maximum of the polylysine-stabilized nanoparticles is located in a longer wavelength area, at $\lambda = 398\text{nm}$, whereas absorption maximums for amino-acid-stabilized nanoparticles are located at $\lambda = 390–392\text{nm}$. nanoparticles of smaller sizes are likely to occur due to the higher mobility of monomer molecules as synthesis is a quick
reaction, whereas polymer molecules of polylysine are too big to take optimal confrontation that fast. It could also be explained by the fact that silver nanoparticles quite easily form nonspherical structures. This can lead to absorption maximums moving to the long wavelength area (Krutyakov et al., 2008).

The spectral characteristics (location of absorption maximum and absorption intensity) of the silver nanoparticle suspensions also depend on spacer concentration. Nanoparticles of the most homogenous sizes have been formed in suspensions with silver into spacer ratio close to 1:1. The fact is proved by the smaller semi-width of characteristic peaks in the nanoparticle spectrum (Figure 38.20).

Figure 38.19 demonstrates that characteristic maximums in the spectrum of absorption of silver nanoparticles and BR are divided into 160–170 nm to make it easier for the analysis and application of hybrid nanostructure optical properties to form functional nanocomposites to happen.

As mentioned above, the technological methods of forming hybrid nanostructures are based on the mechanisms of special bonding and self-organization activated by selecting appropriate bridge molecules for various functional groups. For example, during formation and stabilization of silver nanoparticle molecules of cysteine, arginine, lysine, and polylysine bond with the surface with the help of thio- (cysteine), guanydo- (arginine), or amino groups (lysine and polylysine). At the same time those molecules are spacers as they include additional amino groups which are able to actively interact with carboxyl groups of glutamic and asparagic acid residues, included in the amino acid consequence of BR. So, by using silver nanoparticles and BR molecules we can obtain hybrid nanostructures.

Such hybrid structures are synthesized with nanoparticles into BR molecules ratio equal to 1:3600. We use 5 mg/mL BR suspension as the original one. The hybrid nanostructures are formed by vigorously stirring the suspension with a magnetic stirrer for 1 day at the temperature of the reaction mixture equal to 22°C–25°C.

Figures 38.21 and 38.22 demonstrate spectral characteristics of hybrid nanostructures using lysine and polylysine as spacers.
While analyzing the technological results of obtaining hybrid nanostructures, we have to pay attention to the following:

The spectral characteristics of hybrid nanostructure suspensions demonstrate two characteristic spectral maxima, corresponding to certain components. It proves that BR and nanoparticle bonding causes no destruction of materials and BR molecules keep their functioning.

1. The characteristic spectral maxima of certain components of hybrid nanostructures may be offset. For example, the suspension of hybrid nanostructures based on silver nanoparticles, lysine, and BR demonstrates absorption maximum offset for silver nanoparticles from 391 to 408 nm (Figure 38.21), whereas the location of absorption maximum for BR stays the same—568 nm. The suspension of hybrid nanostructures based on the silver nanoparticles, polylysine, and BR demonstrates absorption maximum offset for BR from 568 to 560 nm, whereas the location of absorption maximum for the silver nanoparticles stays almost the same 400 nm (Figure 38.22). It could possibly happen because of the different distances between nanostructure components due to various spacer molecules (≈0.75 nm of lysine and ≈1.5 nm of polylysine), the type of bonding with nanoparticle surface, and BR.

2. After measuring the spectral characteristics of hybrid nanostructures, we have found out considerably increased absorption by every component of hybrid nanostructure against the adaptive spectral characteristic calculated by the simple adding of the spectrum of separate components in the same concentration they have in the suspension of hybrid nanostructures. The absorption increase reaches 13% at \( \lambda = 394 \text{ nm} \) (cysteine-stabilized silver nanoparticles) and 26% at \( \lambda = 568 \text{ nm} \) (BR) (Figure 38.23).

Therefore, synthesized hybrid nanostructures demonstrate functionality, mutual influence of certain components on spectral characteristics of each other, as well as an influence on BR photocycle.

38.4 Summary

The use of molecules with conformation-adjusted relative position (distance and angle) of molecular groups including bridge functional groups as spacers can contribute to the development of nanotechnological and nanosystem approaches based on self-organization. Using the above method, we can regulate dipole–dipole interaction of a nanoparticle and a functional molecule. The effect is more obvious for nonspherical particles. Taking into the account that BR molecule performs photo-dependent transit of charge (\( \text{H}^+ \)), the above method of regulating photochromic photoreaction and the lifetime of intermediates must be quite effective. The suggested approach can also be applied for hybrid nanostructures with different composition.

Therefore, we have demonstrated the system and technological aspects of self-organization of functional nanostructures of molecular photonics realizing bionic principles of neural network appliances operation.

The systems designed are expected to have some functional characteristics, making them to sense and analyze like live intelligent neural systems. For example, apart from having distributed and content-addressed memory and the ability to learn and identify steady images, those systems will be able to identify dynamic images, i.e., images of evolving objects. Such abilities are based on new functions built upon self-organization of structures and processes, including: adaptive sensing with feedbacks, regulating activity of various parts of artificial retina; adaptive change of sampling rate and of retina coverage; modeling of tunable retinal receptive fields with spatial filtering; and formation of structures sensitive to the direction and speed of object movements.

References


