ELECTRODYNAMICS OF DNA AND ARTIFICIAL DNA-LIKE STRUCTURES

Igor Semchenko, Sergei Khakhomov, Alexei Balmakov

Dept. of Optics, Dept. of General Physics, Gomel State Univ., 104 Sovetskaya Str., Gomel, Belarus 246019

ABSTRACT

Investigations of polarization properties of DNA molecules are considered to be of primary importance due to mirror asymmetry of the shape of DNA. Preliminary theoretical calculation has shown that the shape of DNA is optimum for its radiation of a circularly electromagnetic wave under the resonance condition when the wave length is approximately equal to 10 nm. The molecule of DNA takes a special place among other chiral objects owing to the property of polarization selectivity. The effect of polarization selectivity of interaction of the DNA molecule with right-circularly and left-circularly waves in a vacuum ultraviolet range can reach 100 per cent. This statement has been proved by the example of metal DNA-like helices in a microwave range following to the principle of scaling. The effect of polarization selectivity of DNA-like helices which means that left-handed circularly polarized microwaves interact with right-handed DNA-like helical elements more efficiently than right-handed circularly waves has been proved experimentally. These results are of interest in connection with the opportunity of producing artificial 2D and 3D structures on the basis of DNA molecule branches. Such structures can be into a basis of new type metamaterials.

Keywords: Helix, ellipticity, polarization

1 INTRODUCTION

It is known in biology that such elementary molecules of life as amino acids and nucleotides are chiral (have a mirror asymmetrical shape) and optically active [1]. If we analyse large biological polymers that consist of these elementary blocks, we can see that most of vitally important biological molecules of living nature such as deoxyribonucleic acid (DNA) [2,3], ribonucleic acid (RNA) [4], proteins and carbohydrates (their secondary structure) [5] have the shape of a helix. It seems to be very important that overwhelming majority of these helices have the same sign corresponding right-handed helix.

Molecules which are especially important for life of all living beings, such as DNA or proteins are met in nature only in one of their mirror form – mostly the right-handed helix – whereas other molecules which are less important, can exist in nature in both forms (racemic mixture) at the time. Thus we can assume that this factor may play a very important role in the cell processes which involve DNA. We also assume that there are displacements of valence electrons along a chain of DNA atoms which cause to excitation of a very weak electromagnetic field around the chain. The electron displacement can take place due to chemical processes inside a cell. However, the intensity of these fields is too week to be registered by existing receivers of radiation and moreover the fields have narrow resonance for each of the polymer molecule.

External electromagnetic waves influence upon living beings (their tissues and separate cells) in various ways and it depends on a number of factors of molecule internal structure (periodicity, anisotropy, asymmetry etc) and this influence is difficult to study. Artificially created electromagnetic fields affect different parts of biological cells of living beings and especially their DNA [6,7]. It is generally known, that absorption of electromagnetic fields by biological organisms is due to electron transitions in a molecule which differ in their types as each molecule has its resonance frequency. Nevertheless, many biological objects and endocellular structures are ordered enough, so it is possible to apply already known methods of physics of anisotropic and periodic media to them [8].

2. OUTLOOK ON THE PROBLEM

In work [9] it is proved that molecules of amino acids interact in different ways with the light waves which are circularly polarized to the right or to the left. However selectivity of such interaction is insignificant and the relative distinction of the light waves influence is only of some percent.

At the same time, it has been experimentally demonstrated by several researchers that under some conditions even low frequency electromagnetic waves are capable to produce essential effect leading to changes in DNA of cells of living beings [10]. In the cases when cells are influenced by electromagnetic fields generated by similar cells excited by chemical reactions or UV radiation [11] the influence effect takes place and can lead to cell damage. It is quite probable that the fields first influence DNA which further leads to destruction of all cells.

Therefore, it is important to find specific properties of a weak electromagnetic field capable to influence DNA with maximum efficiency. First of all, we would like to find out in what way electromagnetic waves affect DNA depending on their polarization properties. Since any DNA molecule in nature has the universal geometrical form of double helix in all organisms and it is of great biological importance, this research is regarded by us as very promising.

At first approximation the quantum properties of the intercellular DNA interaction are not taken into account because of the following reasons: DNA polymers are enormous molecules containing millions of nucleotides. For instance, the largest human chromosome is approximately 220 million base pairs long (approx. 73 mm). One coil of helix of DNA is 8 nm long, it contains 10 pairs of nucleotides and it contains 20 atoms of phosphorus and 120 atoms of oxygen that make up the double right-handed helix. So even one coil of helix can be considered as a macroscopic structure which has to display both quantum and classical properties. So for investigation of a long molecule of DNA it is possible to use general classical principles of electrodynamics.

The latest articles on DNA write about the creation of new composite nanomaterials from branches of DNA, in particular, about an attachment by the complementary principle of nanometer particles of gold to a branch of DNA. It is also said about palladium metallization DNA molecules and also about zinc, cobalt or nickel insertions in the DNA nitrogenous bases that allow them to increase the conductivity of these DNA branches. Thus, it looks like the perspective application to use the branches of DNA as molecular nanowire. It is possible to expect, that for such structures the properties of polarization selectivity can become considerably essential in a far UV range.

We wonder whether it is possible to investigate polarization properties of the DNA molecule based on the established data about its shape and the sizes, without direct resorting to molecular researches.

At the first stage it is important to carry out the research on models of DNA-like helical structures for example in a microwave range on the principle of electrodynamic similarity (scaling). And then we shall pass to the experiment on molecules of DNA being based on obtained results and analogies [12]. This idea is realized in the presented paper. It is obvious that the model under consideration is rough enough and it only approximately reflects the essence of the phenomenon of interaction of DNA with the polarized wave of a UV range. However, it has the right for existence, since it is capable to describe qualitatively the essence of the phenomenon.

The main reason for us to use the rough model is a theoretical conclusion about the character of electric current in DNA proved earlier in [13-19]. This means that for appearance of the considered effect of polarization selectivity of DNA under the main resonance condition the presence of any electron displacement along a helical path is necessary. It is also necessary that the helix be double and the helix pitch angle be equal to 24.5 degrees. Other characteristics play a secondary role. In this respect, the modeling of real DNA by the DNA-like metal helices is quite justified, taking into account the DNA metallization possibility as it was written above.

3. BASES OF THE THEORETICAL MODEL

The theoretical model of DNA interaction with electromagnetic fields was investigated within the limits of the theory of dipole radiations [20]. As it is known, the molecule of DNA is a macroscopic periodic structure: it consists of numerous joined molecules – nucleotides, the size of which is much smaller than the size of DNA chain. The electromagnetic excitation arising in the DNA chain under the influence of external fields or due to some other reasons can be characterized by electric current. This current is not a conduction current, but a molecular current, which is caused by the displacement of electrons from its "equilibrium positions" along the helical paths [21]. Due to the periodicity of DNA the electric current is also a periodic function.

We should note that separate nucleotides in structure of DNA are characterized by various polarization properties and can display its own selective-frequency properties. The helical current causes simultaneous occurrence of the electric dipole moment $\vec{p}$ and the magnetic moment $\vec{m}$ in the double helix. As we will see below, these moments are interconnected.

It was shown, the electric dipole moment and the magnetic moment, which is not less important, are induced simultaneously in the DNA molecule under the main resonance. These moments make equal contributions in their absolute values into the electromagnetic field radiated by the molecule. The specified circumstance leads to the polarization selectivity effect in the case of interaction of electromagnetic radiation with the molecule of DNA.

It is known, that the double helix of DNA [2] has the radius *r*=1,0·10-9 m and the pitch *h*=3,4·10-9 m. Geometrical parameters of the double helix of DNA measured in many experiments are close to the specified values *r* and *h*.

The following expression has been obtained for components of the electric dipole moment of the helix:

$$p_x = \frac{i}{\omega}\int_{x_1}^{x_2} I(x)dx \tag{1}$$

here the axis x is directed along the axis of the helix, x_1 and x_2 are coordinates of the origin and the end of the helix's half-coil, i is the imaginary unit.

We assume the existence of a harmonious dependence of the electric current I on time (proportionate to $e^{-i\omega t}$), where ω is the cyclic frequency. Moreover, taking into consideration geometrical parameters of the helix, we have calculated x-component of the magnetic moment:

$$m_x = \frac{1}{2}r^2 q\int_{x_1}^{x_2} I(x)dx \tag{2}$$

where $q = \pm 2\pi/h$ is the specific torsion of the helix, the signs «+» and «-» correspond to the right-handed helix and the left-handed helix accordingly.

Relationship between the projections of moments onto the axis of the helix is expressed by the formula

$$p_x = \frac{2i}{\omega r^2 q} m_x \tag{3}$$

This relationship is universal, since it does not depend on the distribution of an electric current along the helix and remains valid at any sequence of the nitrogenous bases in the DNA chain. Components of the moments along the axis of the helix play the main role at radiation of circularly polarized wave in the direction which is perpendicular to the helix's axis.

We have considered a helical oscillator with an arbitrary distribution of the electric current. The condition, at which the helix radiates the electromagnetic circularly polarized wave orthogonally to helical axis direction, was obtained:

$$|p_x| = \frac{1}{c}|m_x| \tag{4}$$

where c is the electromagnetic constant.

Taking into consideration the relationship between geometrical parameters of the helix, expressed as

$$P\cos\alpha = 2\pi r \tag{5}$$

where P is the length of one coil of the helix, measured along the helical chain of atoms, and also the condition of the main resonance, we obtain the following trigonometrical equation for the helix with the pitch angle α :

$$\sin^2\alpha + 2\sin\alpha - 1 = 0 \tag{6}$$

Taking the positive root of the quadratic equation (6), we can find the optimum pitch angle of the helix for any number of coils $\alpha_{opt} = 24.5^\circ$.

The obtained theoretical value of the optimum pitch angle differs from the pitch angle $\alpha_{exp} = 28.4^\circ$, corresponding to the experimental data presented above for the radius r and the pitch h of the helix, approximately by 15 %.

The optimum shape of the helix implies that at any electric current in the helix, the electric dipole moment and the magnetic moment are induced simultaneously. They are directed along the helix's axis and are equivalent to each other. Such optimum helix is activated much more efficiently by the circularly polarized wave which propagates perpendicularly to its axis. Then the sign of polarization of the efficiently influencing electromagnetic wave is opposite to the sign of the helix. Hence, circularly polarized wave influencing right-handed helix DNA draw a left-handed screw in space. For the circularly polarized wave with the opposite sign the optimum helix is absolutely transparent. This property of polarization selectivity also plays an important role under radiation of electromagnetic waves by the helix. DNA-like helices have optimum properties when activated by both electric and magnetic fields, *i.e.* at any orientation of polarization plane of an incident wave.

In the dipole approximation the electric vector of the radiated wave is expressed:

$$\vec{E}(\vec{R},t) = \frac{\mu_0}{4\pi R}\left(\left[\left[\ddot{\vec{p}} \times \vec{n}\right] \times \vec{n}\right] + \frac{1}{c}\left[\vec{n} \times \ddot{\vec{m}}\right]\right) \tag{7}$$

where $\vec{R}$ is the radius-vector passing from the considered half-coil of the helix to the observation point, $\vec{n}$ is the unit vector with the same direction as vector $\vec{R}$, μ_o is the magnetic constant. Dots over the vectors mean differentiation in time.

In the equation (7) the derivatives of the electric dipole moment and the magnetic moment are calculated at the previous moment of time to take into consideration the delay of the waves propagating from the source to the observation point.

We have shown, that orthogonal components of the electric vector of the radiated wave are related between themselves by an expression

$$E_x = -iE_y \tag{8}$$

Thus, we can conclude, that under the resonance conditions DNA radiates a left-handed circularly polarized electromagnetic wave in the direction perpendicular to the helix axis. This polarization of the radiated wave remains unchanged for any distribution of electric current in DNA, *i.e.*, for any sequence of nitrogenous bases in DNA.

Ellipticity of a wave, radiated by the activated fragment of DNA perpendicularly to its axis (the axis of helix is directed along the axis Ox), can be calculated by the following formula:

$$\gamma = -i\frac{E_y}{E_x} \tag{9}$$

The time-varying electric dipole moment of any half-coil of the helix excites the electromagnetic field. The electric vector of this field is oriented along the helix's axis. The electric vector of the field excited by the harmonically varying magnetic moments of all half-coils is directed perpendicularly to the helix's axis. Taking into account the propagation times delays of the electromagnetic waves radiated by different half-coils, we can find the expressions for the components of the resulting electric field and then find the ellipticity of the wave:

$$\gamma = \frac{1}{R_o}\sum_{k=-N}^{N}(-1)^k \frac{\exp\left(i\omega\frac{R_k}{c}\right)}{R_o^2 + (k\frac{h}{2})^2}\left(\sum_{k=-N}^{N}(-1)^k \frac{\exp\left(i\omega\frac{R_k}{c}\right)}{\left(R_o^2 + (k\frac{h}{2})^2\right)^{3/2}}\right)^{-1} \tag{10}$$

Here, R_0 is the distances from the central half-coil of the helix to an arbitrary point in space, R_k is the distances from the half-coil of the helix with the number k to the same point, and k is the index ranging from $-N$ to N. Hence, the considered DNA section contains $2N+1$ half-coils.

The ellipticity is very close to +1, that means the radiated wave has a circular polarization and the electric vector circumscribes a left-handed screw in space.

4. EXPERIMENTAL VERIFICATION

An electromagnetic wave of a microwave range reflected from 2D array, consisting of helical conductors, has been investigated. Each helical metallic element is geometrically similar to the helix of DNA. The ellipticity of the reflected electromagnetic wave has been investigated depending on the frequency near the main resonance. On the basis of the principle of electrodynamic similarity (scaling) the results, obtained earlier theoretically, have been experimentally proved.

The given article, the experimental results of investigation of the polarization selectivity of microwaves, reflected from arrays composed of right-handed or left-handed DNA-like helices presents. Parameters of the helices have been chosen according to the theoretical predictions to obtain the high ellipticity of reflected waves.

The lattices composed of copper helices and fixed on the radiotransparent material have been manufactured (fig.1). Each lattice consists of identical helices of one sign (right-handed or left-handed).

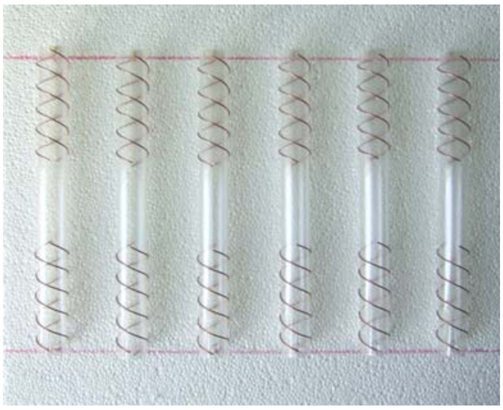

Fig. 1. Photo of the experimental sample of 2D array composed of the double right-handed DNA-like helices.

The helices in the experiment have been activated by a plane incident wave, and each helix is in a uniform field. Therefore, an antinode of an electric current standing wave should take place in the center of each helix. At the ends of the helix the electric current tends to zero. Therefore, the full length of the helix should be multiplied by the half of wave length of an electromagnetic field $L = k\lambda/2$.

The maximal value of a current (antinode) in the center of the helix can arise only under the helix with odd number of half-coils. It means that $k = 2m+1$, where m is an integer. If the helix has an integer number of coils the electric current cannot be produced in it by a uniform field of the incident plane wave.

The first sample was excited by a linearly-polarized incident wave propagating to the sample at the angle of incidence 45° to its plane (fig. 2).

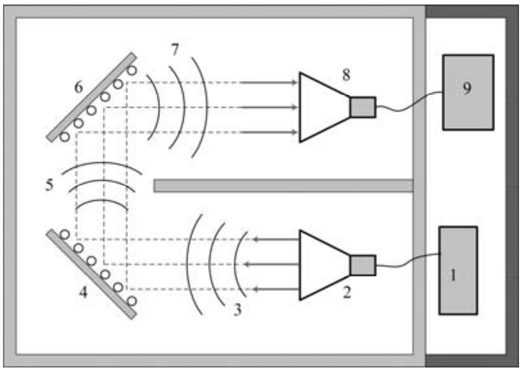

Fig. 2. The scheme of experiment in the anechoic chamber (1 is the generator of microwave signals, 2, 8 are trumpet antennas, 3, 5, 7 are directions of waves propagation, 4, 6 are samples of DNA-like helices, 9 is the receiver of microwave signals)

The wave reflected from the first sample was nearly circularly polarized in the investigated wavelength range and then fell on the second sample (fig. 3). The wave reflected from the second sample had a left-handed circular polarization (the electric vector of such wave draws a left-handed screw in space) if helices of both samples were right-handed. The wave after the second sample got a linear polarization if the helices of the first sample were right-handed and helices of the second sample were left-handed. In the second case, the wave intensity of the reflected wave was much lower.

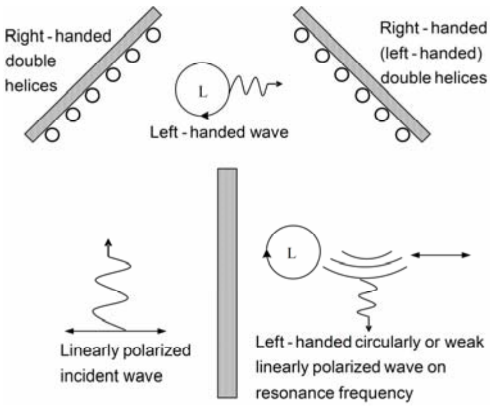

Fig. 3. Process of transformation of an electromagnetic wave by the right-handed and the left-handed DNA-like helices is schematically shown

Ellipticity-frequency diagram that characterized the reflected waves is given in fig. 4 A for the case of the right-handed helices on both samples (the effect of polarization selectivity of radiation arises at the frequency of 2.8 GHz). Fig. 4 B corresponds to the case of the right-handed helices on the first sample and the left-handed helices on the second sample (we can see the absence of the effect of polarization selectivity of radiation).

The electric vector of the linearly polarized incident wave is directed along the helix axis. Cases, when the electric vector has been directed perpendicularly to the helical axes, were also experimentally investigated. Ellipticity-frequency diagrams for these cases have been similar with already specified in fig. 4A and 4B, but the ellipticity maximum has displaced a little.

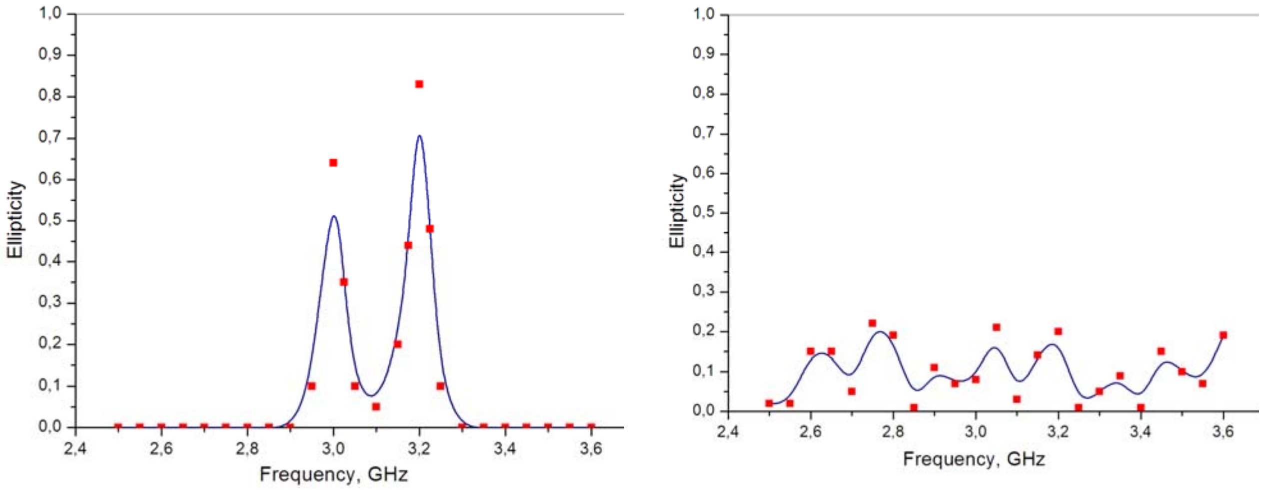

Fig. 4. The plots show the dependence of the ellipticity of the reflected wave on the frequency when the both of samples consist of the right-handed helices (A), and when the first sample consists of the right-handed helices and the second consists of the left-handed helices (B); the electric vector oscillated along the helix axis

The wave intensity of the electromagnetic wave, reflected from the second sample, depending on the frequency was also investigated. Graphs of this dependence are shown in fig. 5A for a case when the right-handed helices are on both samples and in fig. 5B for the case when the right-handed helices are on the first sample and the left-handed helices are on the second one.

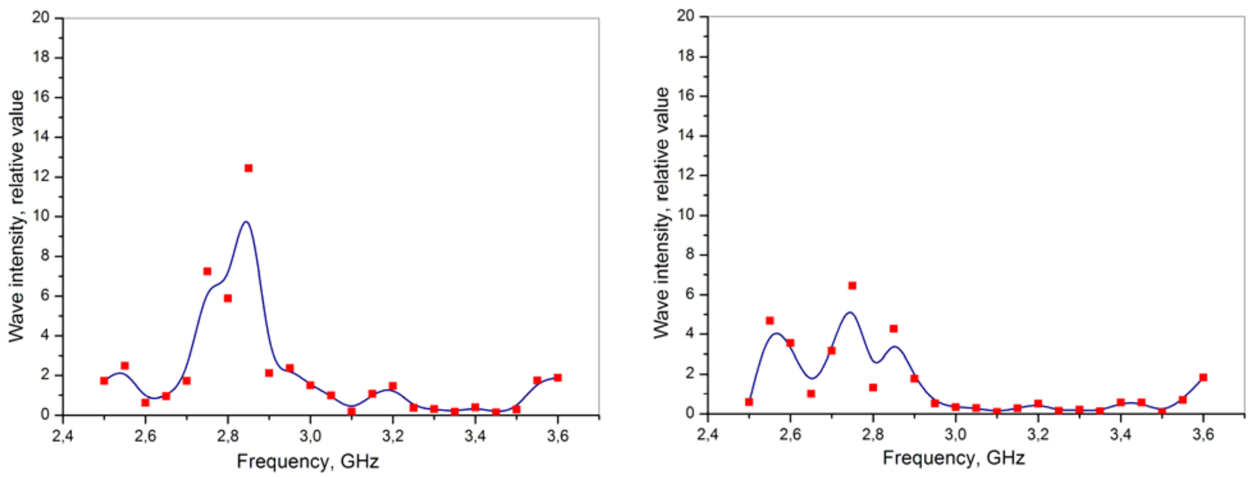

Fig. 5. The plot shows the dependence of the relative intensity of the reflected wave on frequency when the both of samples consist of the right-handed helices (A), and when the first sample consists of the right-handed helices and the second consists of the left-handed helices (B); the electric vector oscillated perpendicular to the axis of helix

The effect of radiation polarization selectivity was also observed in relation to the intensity of the wave, reflected from samples with the right-handed helices at the frequency of 2.8 GHz (the maximum of the ellipticity). At the same time for the samples composed of helices with the opposite sign, the maximal intensity of the wave after the double reflection has decreased approximately twice at the frequency near to 2.8 GHz.

We have also investigated the dependence of the reflected wave ellipticity on the density of the helices on the sample. We reduced the number of helices on the sample, deleting each second row of the helices. Thus it has appeared that the form of the graph of the reflected wave ellipticity remained constant. The signal intensity has decreased only. Thus, the registered wave reflected by the sample as a whole, allows us to estimate about the ellipticity of the wave radiated by the separate double helix. This conclusion is made because of the circumstance, that in our experiment the waves radiated by the separate helices are coordinated on a phase.

So the experimental data, confirming the theoretical researches of the polarization selectivity in case of electromagnetic radiation interaction with DNA-like helices, have been produced.

Speaking about the polarization selectivity of objects that are similar to DNA, we stress the necessity to use the double helix and to reach the optimum pitch angle of the helix. In the case of electromagnetic wave reflection from single DNA-like helix this wave has a linear polarization regardless of the type of polarization of the incident wave.

And the density of helices on the sample has no essential importance. The effect takes place even in the case of one helix. The distribution of electric currents in each helix can have an absolutely arbitrary type since the relationship (3) does not depend on the type of the current.

5 POLARIZATION SELECTIVITY OF DNA AT WAVELENGTH Λ=266 NM

After the theoretical investigation of the polarization selectivity effect it is important to prove it directly in ultraviolet range by using a solution of DNA. Approaching to the main resonance for DNA and having the appropriate equipment we tried to observe the above-mentioned effect at the wavelength of 4[th] harmonic of YAG-Nd laser which is λ =266 nm. Spectra of absorption of radiation have been obtained by means of spectrophotometer in which the mercury lamp was used as a radiating element. Knowing that DNA has an absorption band near this wavelength we can count to see the different absorption for linearly, left- and right-handed polarized waves. Of course the polarization selectivity effect for λ =266 nm will be expected much weaker than predicted one for $\lambda \sim 10$ nm due to the resonance condition.

In the experiment it was used the classic scheme for making circularly polarized waves. The Glan prism served as an analyzer and polarizer of the ultraviolet waves. A quarter-wave plate for 266 nm transformed the linearly polarized radiation to circularly polarized one when the angle between the plane of polarization and quarter-wave plate axis was $\varphi = \pm 45°$, if the angle was $\varphi = 0°$ the linearly polarized wave produced.

The graphs of dependences of the DNA absorption of radiation on the wavelength are represented in the figures below. A graph, which is corresponding the case $\varphi = 0°$, is given in the fig. 5. Graphs, which are corresponding the cases $\varphi = \pm 45°$, are given in figures 6, 7.

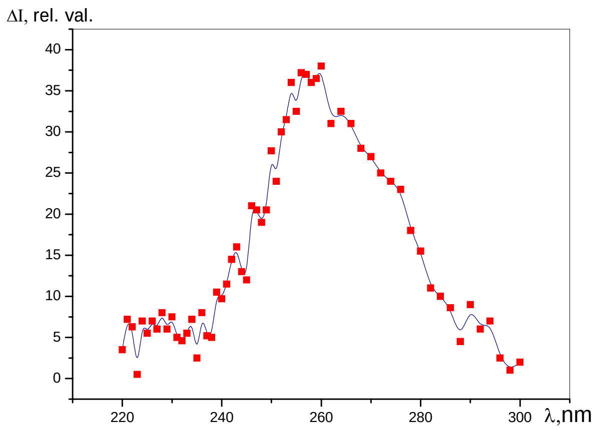

Fig. 6. Dependence of the DNA absorption of radiation on the wavelength (incident radiation was linearly polarized)

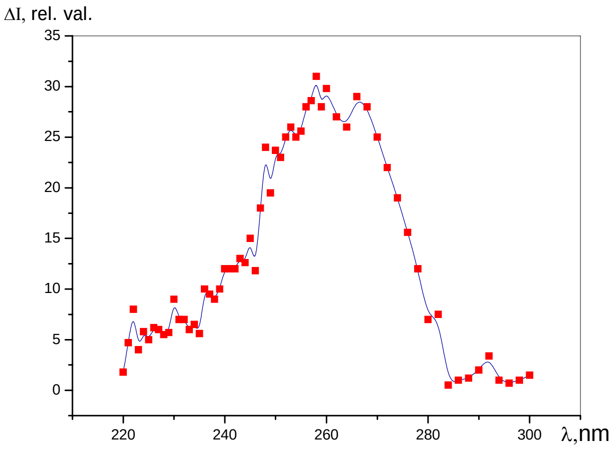

Fig. 7. Dependence of the DNA absorption of radiation on the wavelength (incident radiation was left-handed circularly polarized)

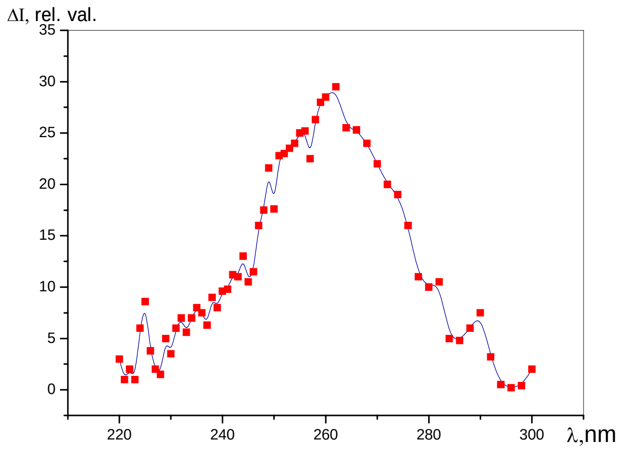

Fig. 8. Dependence of the DNA absorption of radiation on the wavelength (incident radiation was right-handed circularly polarized)

As a result of experiment it was found out, that absorption of the ultraviolet radiation by samples of DNA did not vary depending on the kind of circular polarization of radiation (fig. 7, 8). If we compare the graph in fig. 6 for linear polarization absorption by DNA with graphs in fig. 7, 8 for circularly polarized wave absorption one can see approximately 20% difference in the intensity of the wave which DNA has absorbed. This analysis of the figures let us to conclude that circularly polarized ultraviolet waves interact with DNA solution more weaker then linearly polarized wave in the same range. It doesn't mean the same effect will take place at the resonance condition for wavelength $\lambda \sim 10$ nm. The given experimental result corresponds with predictions of the theory since the circularly polarization selectivity effect for DNA can be shown at the resonance wavelength. The wavelength of 266 nm is approximately at 30 times more than resonance wavelength, therefore DNA absorption of radiation for circularly left- and right-handed waves is almost equal.

6 CONCLUSION

According to the principle of electrodynamic similarity (scaling), the effect of polarization selectivity, observed in the microwave wave range for DNA-like helices, can take place for the molecule of DNA in a nanometer range. The attempts to find any distinction in the absorption of polarized electromagnetic waves have been made, of course, before, for instance in [22] and in some others works. It has been found that under the action of right-handed circularly polarized synchrotron radiation with wave length 182 nm the 2.5% surplus of D-leucine is produced from an initial racemic mixture. We suppose that there is an essential difference between the interaction of electromagnetic waves with amino acids that are in a mixture, and those ones when amino acids compose a DNA molecule, as an effect of their collective excitation can take place. According to the principle of the main resonance the greatest effect of amino acids collective excitation will take place at the wave length $\lambda \sim 10$ nm. In the work [23] it has been shown that the oscillation strength of dry film of DNA is increasing at the wave length within the range from 120 to 15 nm which means that majority of the loosely bound electrons participate in the optical transition above 15 nm.

This effect plays a very important role for DNA (probably as for other helical objects too) and it is directly connected with infringement of mirror symmetry among natural structures and phenomena. The polarization selectivity of electromagnetic interaction can be of importance at genetic preservation of distinctions between right-handed and left-handed forms of objects and animate nature subjects.

The optimum shape of objects of nature has been always a subject of the study and an example for use in technologies. From the point of view of classical electrodynamics a DNA molecule has also the optimum shape. It means that electric dipole moments and magnetic moments, directed along a helical axis and induced in each half-coil of DNA under the action of electromagnetic radiation with the wave length $\lambda \sim 10$ nm, are equivalent. The identical significance of these moments is caused, first, by the fact that the helix pitch angle of DNA is equal to 24.5 degrees, and secondly, by the equality of a wave length of an influencing electromagnetic field to the length of a coil of the DNA helix. And finally

DNA has the shape of a double helix. This additional symmetry leads to the absence both of the electric dipole and the magnetic moments directed perpendicularly to the helical axis. All three specified circumstances lead to the selectivity in the interaction of a DNA molecule with left-handed circularly polarized wave in the extreme ultraviolet radiation or in the “soft” X-ray wave range. The electric vector of such wave, which is predominantly absorbed and radiated by a molecule of DNA, draws a left-handed screw in space.

The molecule of DNA with the optimum geometrical shape does not “feel” the influence of the right-handed circularly polarized electromagnetic wave in a nanometer range. Such a wave, for which the right-handed molecule of DNA is "transparent", should propagate orthogonally to the axis of helix and to draw the right-handed screw in space. The wave radiated by the DNA right-handed molecule, orthogonally to its axis, under the resonance, has, accordingly, the left-handed circular polarization.

These distinctive features can be used for developing DNA-like metamaterials and other DNA-like periodic structures [23] possessing polarization selectivity properties, it can be also useful for the explanation of helical objects widespread in living nature and their interaction with polarized light [24].

ACKNOWLEDGEMENT

The research was supported by the Ministry of Education of Belarus, the project “Research of the polarization selectivity effect of the optical radiation absorption by a DNA molecule in the visible and ultraviolet range”.

REFERENCES

[1] H.D. Flack, Acta Crystallographica A 65, 371 (2009).
[2] J.D. Watson, F.H.C. Crick, Nature 171, 737 (1953).
[3] R.E. Franklin, R.G. Gosling, Nature 171, 740 (1953).
[4] W. Saenger, Principles of Nucleic Acid Structure, (Springer, New York, 1984).
[5] D.J. Taylor, N.P.O. Green, G.W. Stout, R. Soper, Biological Science 1 and 2, (Cambridge University Press, Cambridge 1997).
[6] M. Blank, R. Goodman, Journal of Cellular Biochemistry 75 (3), 369 (1999).
[7] J.L. Phillips, N.P. Singh, H. Lai, Pathophysiology 16, 79 (2009).
[8] F. Fedorov, Theory of Gyrotropy, (Nauka i Tehnika, Minsk, 1976). [in Russian].
[9] U.J. Meierhenrich, et al., Origins of Life and Evolution of the Biosphere 33, 257 (2003).
[10] M. Blank, R. Goodman, Pathophysiology 16, 71 (2009).
[11] A.G. Gurvich, Principles of analytical biology and the theory of cellular fields, (Nauka, Moscow, 1991). [in Russian].
[12] A.N. Serdyukov, I.V. Semchenko, S.A. Tretyakov, A.H. Sihvola, Electromagnetics of bi-anisotropic materials: Theory and Applications, (Gordon and Breach Scientse Publishers, Amsterdam, 2001).
[13] I.V. Semchenko, S.A. Khakhomov, A.P. Balmakov, Journal of Communications Technology and Electronics 52 (9), 996 (2007).
[14] I.V. Semchenko, S.A. Khakhomov, A.P. Balmakov, Proceedings of the 1st International Congress on Advanced Electromagnetic Materials in Microwaves and Optics. Metamaterials, Rome, 2007, edited by F. Bilotti and L. Vegni, (Rome, 2007).
[15] A.P. Balmakov, I.V. Semchenko. Proceedings of the 2nd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics Metamaterials, Pamplona, 2008, edited by S. Tretyakov, (Pamplona, 2008).
[16] I.V. Semchenko, S.A. Khakhomov, A.P. Balmakov, Proceeding. of the 3rd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics. Metamaterials, London, 2009, edited by G. Palikaras, (London, 2009).
[17] I.V. Semchenko, S.A. Khakhomov, A.P. Balmakov, Journal of Automation, Mobile Robotics and Intelligent Systems 3 (4), 207 (2009).
[18] I.V. Semchenko, S.A. Khakhomov, A.P. Balmakov, J. Electromagnetic waves and electronic systems 4, 66, (2009). [in Russian].
[19] I.V. Semchenko, S.A. Khakhomov, A.P. Balmakov, J. Biophysics (Biofizika) 55-2, 227, (2010). [in Russian].
[20] L.D. Landau, E.M. Lifshitz, The Classical Theory of Fields, (Pergamon, Oxford, 1973).
[21] W. Kauzmann, Quantum chemistry. An introduction, (Academic Press, New York, 1957).

[22] U.J. Meierhenrich, et al., Angew. Chem. 117, 5774 (2005).
[23] T. Inagaki, R.N. Hamm, E.T. Arakawa, L.R. Painter, J. Chem. phys. 61 (10), 4246 (1974).
[24] N.C. Seeman, Scientific American Reports 9, 30 (2007).
[25] L. Vellus, M. Legrand, M. Grojean, Optical Circular Dichroism, (New York-London, 1960).