THE OPTOELECTRONIC SENSOR CREATININE AND UREA

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ABSTRACT

In paper the concept of interaction of cholesteric liquid crystals (CLC) with creatinine and urea to designing the active medium material for optical sensor of biological substances are presented. It is shown that there is a general tendency to reduce the pitch of supramolecular helical structure versus of increasing of concentrations of aqueous solutions for all investigated substances. A decision to designing the scheme of signal converter of optical sensors with frequency selection is proposed. In basis of the proposed decision is impedance converter provided the inductive nature of the impedance circle of load photodiode and therefore suppressing of direct component of the photocurrent.

Keywords:

1. INTRODUCTION

The forming of information signal by means of optical methods is widely used in modern sensors [1,2]. In this case the information signal is formed by selective transmission of optical radiation of active medium [3, 4]. These sensors can be used for detection and quantification of biological substances [4].

In applied optical research of biological systems the liquid crystal (LC) materials are widely used. We propose to use the LC as the material of active medium for biological objects detection. The spiral structure of the CLC is sensitive to external factors, including the biological agents [5]. The optical properties of CLC are changed under the influence of biological agents. The optical properties consist of the position of transmittance minimum and integrated bandwidth of the spectral line. The changes of these optical properties are taken in to the basis of designing of active element of biological optical sensors.

The spectral characteristics of the active medium are measured by means of optocouple. The optocouple consist of the controlled pulse sources of optical radiation and photosensitive element. As usual, as the source of optical radiation the group of LEDs with shifted spectral characteristics, lasers, photoluminescent oscillators etc. and as photosensitive elements the photodiode and phototransistor photo matrix are used. In optical sensors, relatively simple and effective way of information signal formation is color measurement. For implementation of this method uses color RGB (red-green-blue) signal transducers [6, 7].

In case of the choosing of the research objects, we took into account such factors as the prevalence of these substances in biological organisms and their functionality. Today for rapid analysis of the quantity of urea and creatinine in blood the biosensors designing is an urgent problem [8-10].

In biological liquids the determination of creatinine concentration is a common general clinical test used to evaluate the muscle state and kidney failure. For determining the creatinine presence the most promising analytical method is a biosensor methods based on the use of both natural enzymes and synthetic analogs of biological receptors capable to selective recognition of this metabolite [11].

In biological objects the analysis of the urea concentration is widely used in medical practice, agricultural and food industries as well as for environment monitoring. In clinical laboratory diagnostics to determine the level of urea and creatinine are one of the most important tests to detect abnormalities in muscle and excretory systems. The importance of urea investigation due to the fact that higher concentrations of standard urea is toxic to the body, so it is urgent the real time monitoring.

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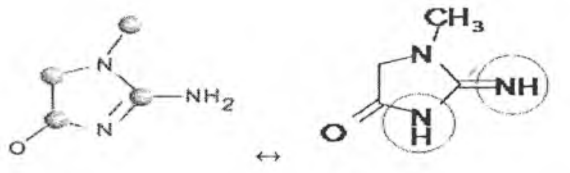
2. EXPERIMENT AND RESULTS

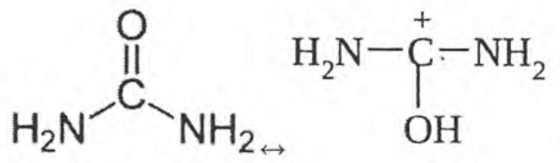
Creatinine and urea used for research were artificially synthesized compounds.

Creatinine C4H7N3O (2-imino-1-methyl-4-okosoimidazolidyn) – nitrogen-contained compound is a product of protein metabolism. The level of creatinine in blood serum and urine are used in clinical diagnosis as a marker of kidney disease and muscle damage. The structural formula creatinine is shown below.



At the dissociation of proton the creatinine molecule can form the amino group -NH_2 or = NH group. This causes the creation of a partial positive charge on the functional groups of creatinine with formation of ionic interactions.

Urea $CO(NH_2)_2$ - dyamid carbonate acid. Urea is the final and main product of protein metabolism. The urea level provides information on the metabolism of nitrogen compounds and removing toxic ammonia from the body. Moreover, urea is a marker of wide range of low- and middle molecular toxic substances. These toxic substances accumulated in the body of patients with impaired renal function, as well as a diagnostic indicator of liver function. The structural formula of urea is shown below.



Urea exists in two tautomeric forms by the accession of a proton H^+ in aqueous solution and formation of partial charge. In aqueous solution besides the hydrogen bonds, molecules of urea are forming the ionic interactions as well.

As LC active material the mixture of BLO-61 heat stable CLC and 5CB nematic liquid crystal (NLC) are used. In case of using of the LC mixture as the active medium makes it possible to significantly increase the sensitivity of optical sensor. At room temperature the cholesteric-nematic mixture (CNM) possesses a transmittance minimum at 508 nm of wavelength. The dependence the wavelength of transmittance minimum versus of 5CB concentration is shown in Fig. 1.

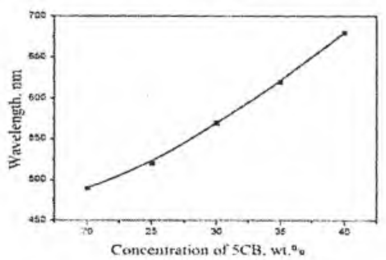


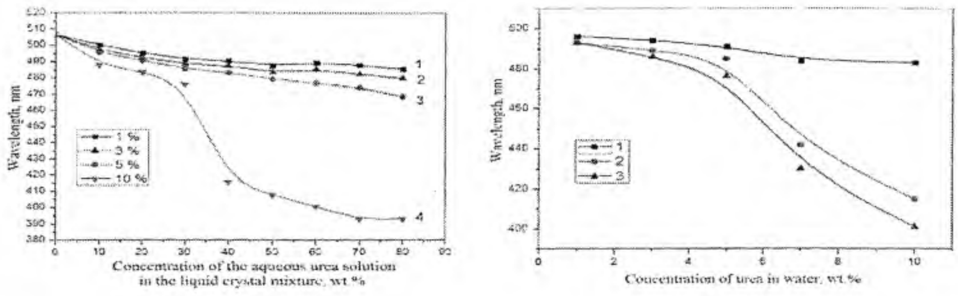
Figure 1. Dependence of wavelength of a long-wave transmission minimum versus of concentration of 5 CB NLC in CNM

To CNM the aqueous solutions of creatinine and urea was added at 1, 3, 5, 7, 10 % concentrations. In LC the aqueous solutions concentration was 10-80 %. Spectral decencies were obtained by means of USB-2000 spectrophotometer in the 200-1000 nm range.

Treatment of experimental results carried out by using the OriginPro 8 software. The obtained spectral dependence approximated by Gaussian function for determination of minimum position of wavelength of light transmittance.

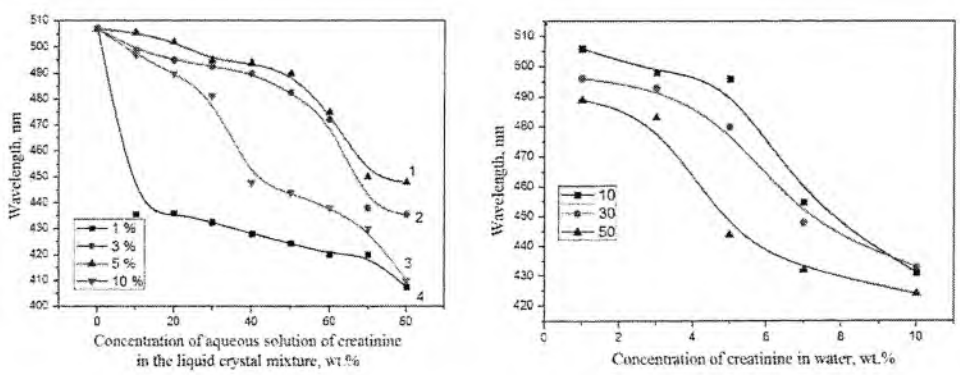
CNM is the basis of active medium of optical sensors of creatinine. The optical characteristics of CLC are changed as the result of contact with biological substances. The change of transmittance minimum and integrated wide spectrum is in basis of operation of optical sensor of biological objects.

The dependence of wavelength transmittance minimum versus of concentration of aqueous solutions of creatinine and urea in the LC mixture are shown in Fig. 2, 3.



a) b)

Figure 2. Dependencies of wavelength transmittance minimum versus of concentration of aqueous solution of urine in LC: 1 – 1% aqueous solution; 2 – 3% aqueous solution; 3 –5% aqueous solution; 4 –10% aqueous solution (a); Dependencies of wavelength transmittance minimum versus of concentration of aqueous solution of urine: 1 – 20 % aqueous solution in LC; 1 – 40 % aqueous solution in LC; 1 – 60 % aqueous solution in LC (b).



a) b)

Figure 3. Dependencies of wavelength transmittance minimum versus of concentration of aqueous solution of creatinine in LC:1 – 1% aqueous solution; 2 – 3% aqueous solution; 3 – 5% aqueous solution; 4 – 10% aqueous solution (a); Dependencies of wavelength transmittance minimum versus of concentration of aqueous solution of creatinine: 1 – 10 % aqueous solution in LC; 1 – 30 % aqueous solution in LC; 1 – 50 % aqueous solution in LC (b).

From analysis of obtained results can suggested that increasing of concentration of the aqueous solution of biological objects in the LC mixture the transmission wavelength minimum are shifts into shortwave region. Moreover there are areas with maximum values of coefficient of spectral sensitivity.

Thus, for 1% aqueous solution of creatinine the maximum value of coefficient of spectral sensitivity (10.5 nm/%) are observed at aqueous solution concentration range from 0 to 10% of creatinine in the LC mixture. For 9 % aqueous solution of creatinine the maximum value of coefficient of spectral sensitivity (3.6 nm/%) are obtained at concentration aqueous solution range from 30 to 40% of creatinine in the LC mixture. For aqueous solution concentration of 3, 5, 7% creatinine the maximum value of coefficient of spectral sensitivity (2.1 nm/%) observed in aqueous solution concentration of 55-70% of creatinine in the LC mixture. The behavior of the dependences of wavelength versus of aqueous solution concentration of urea in the LC mixture is similar. For a 10 % aqueous solution of urea the maximum values of coefficient of spectral sensitivity (5.4 nm /%) was observed at aqueous solution concentration range 30-40% in the LC mixture.

The behavior of obtained characteristics can be explained on the basis of such considerations. Creatinine and urea are readily soluble in water. Solubility coefficient is 8.7 at 16°C. In aqueous solutions both substances was hydrated.

Hydration shell formed by the accumulation of water around the dipoles of polar groups such as $-NH_2$, -C=O. When these compounds are dissolved in water the orientation of dipoles around water molecules and caused the ion-dipole interaction. Hydrates formed via dipole-dipole interaction (Fig. 4).

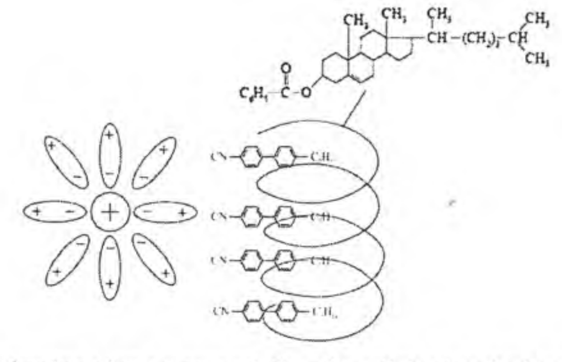


Figure 4. Schematic drawing of an aqueous solution of creatinine (urea) with a CNM molecules

In systems aqueous solution creatinine and urea with LC the stable structures of molecules creatinine or urea and strongly polar component of LC mixtures are formed. Therefore, the increasing of concentration of such structures leads to a reduction of pitch of supramolecular structures due to tearing of 5CB polar molecules from CLC structure.

At high concentrations of aqueous solutions of creatinine or urea the phase separation are observed, namely the separation of LC on separate islands located in aqueous solutions of urea or creatinine. Therefore, when the concentration of the aqueous solution of LC does not exceed 80% the using of CLC as an active medium optical sensor of creatinine or urea are possible.

Molecules of 5CB NLC can form hydration shell of water molecules through a partial positive charge arising on the nitrogen atom CN-group. In contradistinction to polar groups the hydrocarbon radicals can be solvated by molecules of nonpolar solvent molecules, but 5CB molecules without specific enzymes cannot enter into chemical interaction with creatinine or urea.

A major problem of optoelectronic sensors is the significant impact of extraneous parasitic optical radiation and electromagnetic interference. In this paper the circuit decision of designing of optical sensors signal converter with frequency selection based on impedance converter are shown [13-16].

Block diagram of the optical sensor device are shown in Fig. 5. To determine the spectral characteristics of the active medium, namely, liquid crystal modulator (LC modulator) three light-emitting elements are used: LED_R (red), LED_G (green), LED_B (blue) and common photosensitive element is PHD photodiode.

Control modes of the LED driver circuit are performing by LED Driver, and photodiode signal (photocurrent) converted, amplified and digitized via the signal converter circuit NIST (Noise Immune Signal Transduceer). It consists of IMC impedance converter, AMP amplifier, SD synchronous detector, ADC analog-to-digital converter. Informative signal S represents three consistently received RGB components - S_R, S_G and S_B, the ratio between them define the spectral characteristics of the active medium.

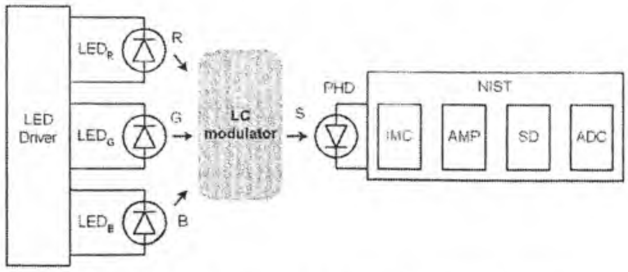


Figure 5. Block diagram of the optical sensor device

High noise immunity of proposed optical sensor device to extraneous light sources and to electromagnetic interference is provided by means of impedance converter. In signal converters of optical sensor the impedance converter are implementing of reactive load of photodiode. In contradistinction to resistive load, impedance converter provides the frequency selection of photocurrent with reduction of the parasitic influence of extraneous light sources and electromagnetic interference.

In fig. 6 the functional scheme of frequency-selective signal converter on the basis of the circuit impedance converter with scheme implementation are shown.

Designed scheme is used to converts the I_{IN} photocurrent of D_{PH} photodiode into V_G output voltage. In contradistinction to traditional resistive load, impedance converter G is forms the inductive load. With aim to form the resonant characteristics in parallel to the impedance G converter the C_P shunt capacitor are plugged. High quality factor of impedance converter circuit is provided for the operational amplifier OA and circuit of frequency selection on R_1, R_2 resistance and C_1, C_P capacitors.

Amplitude-frequency characteristic is in decibels $K = 20\log_{10}(V_G/I_G)$, dB and phase-frequency characteristics Ph is in deg. The scheme of this impedance converter is shown in fig. 7. These characteristics correspond to the parameters: $R_1 = 10^5$ Ohm, $R_2 = 10^2$ Ohm, $C_1 = 3\cdot10^{-8}$ F, $C_P = 1\cdot10^{-7}$ F (curve 1), $C_P = 1\cdot10^{-8}$ F (curve 2), $C_P = 0$ (curve 3). The bandwidth transmittance of operational amplifier is GBW= $2.5\cdot10^6$ Hz.

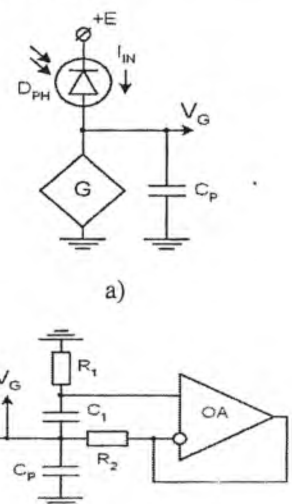


Figure 6. Functional diagram of the signal converter on the basis of impedance converter (a) with circuit implementation (b)

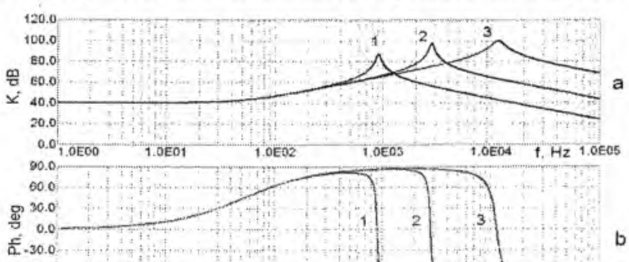


Figure 7. Amplitude-frequency (a) and phase-frequency (b) characteristics of impedance converter

From obtained frequency-selective characteristics of the impedance converter will improve the signal-to-noise ratio up to 60 dB. The resonant frequencies and conversion ratios signal are achieved the maximum highest values at given type of operational amplifier. It provides the high immunity of optoelectronic sensor to spurious light sources and to noise power supply network.

3. CONCLUSIONS

The significant changes of wavelength transmittance minimum are taking place at higher concentration of creatinine or urea in water and at lower concentration this aqueous solution in LC mixture. As follows from these results exactly at higher concentration in system of aqueous solution of creatinine or urea – LC the changes of spiral structures are observed.

The principal advantage of the proposed circuit solutions is the possibility of forming of resonant characteristics. It provides the highest possible for a given type of operational amplifier values of resonant frequencies and conversion ratios signal. Frequency-selective characteristics of the impedance converter can improve the signal-to-noise ratio up to 60 dB.

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