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V.V. SHOLOTA

METHOD AND INTELLECTUALIZED SYSTEM OF LASER CORRELATION-POLARIZATION DIAGNOSTICS OF BIOLOGICAL LAYERS

Vinnytsia National Technical University, 21021,
95 Khmelnytske Shosse, Vinnytsia, Ukraine, e-mail: vladislava.sholota@gmail.com

Анотація. Удосконалено метод та систему поляризаційно інваріантної діагностики біологічних шарів шляхом комплексного вимірювання азимутально незалежних азимутів, еліптичностей поляризації зображень об'єктів і модуля та фази комплексного ступеня взаємної поляризації, доповненого їх статистичним та нечітким аналізом. Показано зростання достовірності методу диференціації патологічних станів біологічних шарів в розробленій системі.
Ключові слова: метод, інтелектуалізована система, біологічний шар, кореляційно-поляризаційна діагностика, нечіткі моделі.
Abstract. The method and system of polarization-invariant diagnostics of biological layers has been improved by comprehensive measurement of azimuthally independent azimuths, ellipticities of polarization of object images and the modulus and phase of the complex degree of mutual polarization, supplemented by their statistical and fuzzy analysis. The increase in reliability of the method of differentiation of pathological states of biological layers in the developed system is shown.
Key words: method, intellectualized system, biological layer, correlation-polarization diagnostics, fuzzy models.

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INTRODUCTION

The development and application of tissue laser polarimetry methods and systems in biological and clinical research during the last decade contributed to increasing the informativeness of the diagnosis of cancerous tissues of various human organs (breast cancer [1-4], cervical cancer [3, 4], stomach cancer [5, 6]), differentiation of inflammatory and autoimmune states of biological tissues (differentiation of Crohn's disease and intestinal tuberculosis [7]) and detection of other diseases, including Alzheimer's disease [8].

Taking into account the optical anisotropy of most biological layers (BL), which manifests itself when interacting with polarized laser radiation in polarimetry systems, methods of "single-point" polarization mapping of azimuths and polarization ellipticities of microscopic images of BL have become widespread [3–5]. They are based on a multi-parameter analysis of the relations between the characteristics of the transformed polarized radiation and the anisotropy parameters of the experimental sample determined at their points of the same name. The main disadvantage of the "one-point" approach was the insufficient reproducibility of the measured distributions, caused to the dependence of the azimuth and ellipticity maps of the BL images on the angle of rotation of the sample during its irradiation.

The development of azimuthal-invariant methods and systems of "single-point" laser tissue polarimetry in combination with statistical, correlation and fractal analysis of polarization maps of the BL [4, 9, 10] have led to the improvement of the diagnostic capabilities of the specified group of methods.

The further development of azimuthal-invariant methods of laser tissue polarimetry was facilitated by the use of the "two-point" or correlation-polarization approach to the evaluation of the structure of the coherent fields transformed by the biological sample at neighboring points. Measurement and analysis of the distribution parameter of the complex degree of mutual polarization (CDMP) [11, 12] of laser fields in the systems of correlation-polarization diagnostics of BL allowed increasing the accuracy of data reproduction.

Thereby, it is relevant to expand the functional capabilities of the laser tissue diagnostics system, focused on the use of correlation two-point and azimuthally invariant polarimetric approaches with the improvement of the quality of diagnostics of biological tissues when using the advantages of artificial intelligence technologies in the analysis of measured BL parameters [10, 13].

The goal of the work is to increase the reliability of diagnostics in the system of laser diagnostics of biological layers due to the development of the correlation-polarization method of diagnostics in combination with methods of intellectual analysis and decision support.

IMPROVED METHOD AND ARCHITECTURE OF THE SYSTEM OF CORRELATION-POLARIZATION DIAGNOSTICS OF BIOLOGICAL LAYERS

It is known that azimuthally invariant maps of azimuths $\alpha(x,y)$ and ellipticities $\beta(x,y)$ of BL`s polarization images are obtained during its probing by a laser beam with a circular polarization type [14] according to the measured parameters of the Stokes vector.

At the same time, introducing the parameter of the CDMP to the consideration of informative parameters of polarization diagnostics of biological layers, we also note the established property of azimuthal independence to the angle of rotation relative to the irradiating beam of the real and imaginary parts of the CDMP [11, 12, 15].

Thereby, we will obtain an improved method of laser correlation-polarization diagnostics of biological layers by combining azimuthally invariant methods of measuring the parameters of the object field $\alpha(x,y), \beta(x,y)$ and the real and imaginary parts of the CDMP with their subsequent information analysis and methods of forming a diagnostic solution.

The following sequence of actions is the essence of the improved method, which is implemented by an appropriate system of correlation-polarization diagnostics of biological layers.

1. We irradiate the biological layer under study with a circularly polarized laser beam of a certain wavelength.

2. The azimuth ς of the analyzer is changed sequentially by the values of four angles ($0;90;45;135$) of linear polarization and two states of circular polarization ($\otimes -$ right circulation, $\oplus -$ left circulation). We register the six intensity distributions $I_{\varsigma}^{\otimes}(x,y)$ formed in this way, transformed by the biological sample and polarized filtered, one by one with a digital camera with a resolution of (MxN) pixels.

3. We calculate the distributions of the parameters of the Stokes vector transformed by the biological layer of polarized radiation using the formulas:

$$\begin{aligned} S_2^{\otimes}(x,y) &= I_0^{\otimes}(x,y) - I_{90}^{\otimes}(x,y), \\ S_3^{\otimes}(x,y) &= I_{45}^{\otimes}(x,y) - I_{135}^{\otimes}(x,y), \\ S_4^{\otimes}(x,y) &= I_{\otimes}^{\otimes}(x,y) - I_{\oplus}^{\otimes}(x,y), \\ S_1^{\otimes}(x,y) &= I_0^{\otimes}(x,y) + I_{90}^{\otimes}(x,y), \end{aligned} \qquad (1)$$

where $x=\overline{1:M};\ y=\overline{1:N}$.

4. We determine the elements of azimuthally independent maps of azimuths $\alpha(x,y)$ and ellipticities $\beta(x,y)$ and phase shifts by the ratios:

$$\begin{aligned} \alpha(x,y) &= 0,5 arctg(S_3^{\otimes}(x,y) / S_2^{\otimes}(x,y)), \\ \beta(x,y) &= 0,5 \arcsin(S_4^{\otimes}(x,y) / S_1^{\otimes}(x,y)), \\ \delta(x,y) &= arctg(\frac{tg(2\beta(x,y))}{tg(\alpha(x,y))}). \end{aligned} \qquad (2)$$

5. We set the angles of rotation of the linear analyzer θ alternately 0° and 90° and register with the camera transformed by the biological layer and filtered by polarization corresponding distributions of intensities $I_X(r)$ and $I_Y(r)$, where $r-$ number of the image point in $(M \times N)$ resolution.

6. We determine the modulus $\left|V(r_1, r_2)\right|$ and phase $\psi(x_1, x_2)$ of the complex degree of mutual polarization for each first r_1 and second r_2 point of the image with $(M \times N)$ resolution with the phase shift $\delta_{12}(r_1, r_2)$ according to well-known formulas[15]:

$$\begin{aligned} \left|V(r_1, r_2)\right| &= \frac{1}{C(r_1, r_2)}(A(r_1, r_2)^2 + B(r_1, r_2)^2 + 2A(r_1, r_2)B(r_1, r_2)\cos\delta_{12}(r_1, r_2)), \\ \psi(r_1, r_2) &= arctg(\frac{B(r_1, r_2)\sin\delta_{12}(r_1, r_2)}{A(r_1, r_2) + B(r_1, r_2)\cos\delta_{12}(r_1, r_2)}), \end{aligned} \tag{3}$$

where such designations are used [15]:

$$\begin{aligned} A(r_1, r_2) &= (I_x(r_1)I_x(r_2) - I_y(r_1)I_y(r_2))^2, \\ B(r_{1,}r_2) &= 4I_x(r_1)I_x(r_2)I_y(r_1)I_y(r_2), \\ C(r_1, r_2) &= (I_x{}^2(r_1) + I_y^2(r_2))(I_x^2(r_1) + I_y^2(r_2)). \end{aligned}$$

7. We determine statistical moments from the 1st to the 4th order for $i = \overline{1:4}$ $SM_i(\alpha(x, y)), SM_i(\beta(x, y)), SM_i(V(x, y)), SM_i(\psi(x, y)),$ according to known formulas [13, 16] and form a vector of informative features from them for further making a diagnostic decision.

$$FV(\alpha, \beta, \left|V\right|, \psi) = (SM_1(\alpha) \quad SM_2(\alpha) \quad SM_3(\alpha) \quad SM_4(\alpha) \quad SM_1(\beta) \quad ... \quad SM_4(\psi)). \tag{4}$$

8. We form a diagnostic solution based on the principles of fuzzy logic [13], analyzing the maxima of membership functions $\eta^{d1}_{\alpha,\beta,V,\psi}; \eta^{d2}_{\alpha,\beta,V,\psi}$ in the following form:

if $\eta^{d1}_{\alpha,\beta,V,\psi} > \eta^{d2}_{\alpha,\beta,V,\psi}$, then we accept the diagnostic decision d1,

if $\eta^{d2}_{\alpha,\beta,V,\psi} > \eta^{d1}_{\alpha,\beta,V,\psi}$, then we accept the diagnostic decision d2.

The architecture of the system of laser correlation-polarization diagnostics of biological layers (Fig1), which implements the improved method of diagnostics, is obtained by modifying the well-known architecture of the multi-parameter system of polarization-phase diagnostics [10, 19].

The measuring channel of the system with an automated control unit has a traditional structure that contains a laser, a polarization irradiation unit, a polarization analyzer, an object unit with projection optics, and a registration camera.

The registered two-dimensional distributions of intensities from the camera are recorded in the computer memory and processed using the corresponding software blocks $F1-F5$, obtaining a map of azimuths $\alpha(x, y)$, a map of ellipticities $\beta(x, y)$, a map of phase shifts $\delta(x, y)$, a map of the modulus $\left|V(r_1, r_2)\right|$ and the phase $\psi(x_1, x_2)$ of the complex degree of mutual polarization of the image of the biological layers under study. The software analysis block $F6$ determines the estimates of the statistical moments of the measured distributions of azimuths, ellipticities, phase, modulus and phase of the CDMP.

The structure of the decision making support subsystem (DMSS) is shown in Figure 2. It has a knowledge base, fuzzy term membership function setting blocks, and a fuzzy rule base. At the output of the subsystem, a recommended diagnostic solution is formed. The doctor can make the final decision based on the recommended decision.

RESULTS OF EXPERIMENTAL RESEARCH

Two groups of optically thin native frozen biological layers of the myocardium, unstained and deparaffinized with verified diagnoses of patients "myocardial infarction" and "asphyxia" in the amount of 51 samples in each group (total 102 samples), were processed using a laser diagnostic system.

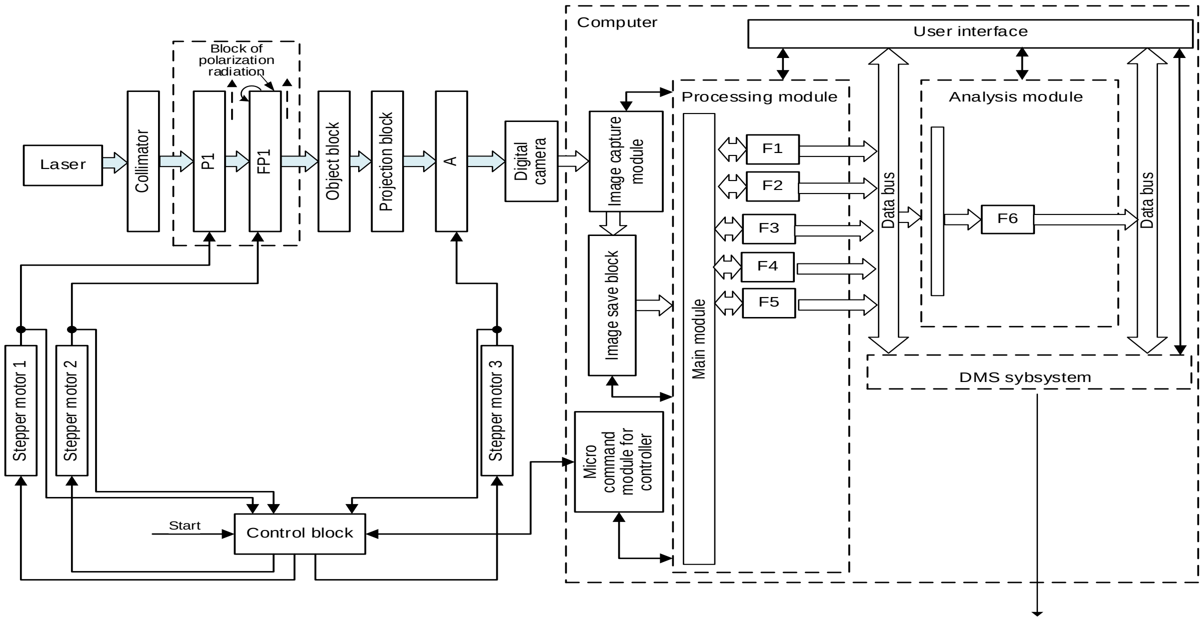

Figure 1 - Architecture of the laser system for correlation-polarization diagnostics of biological layers

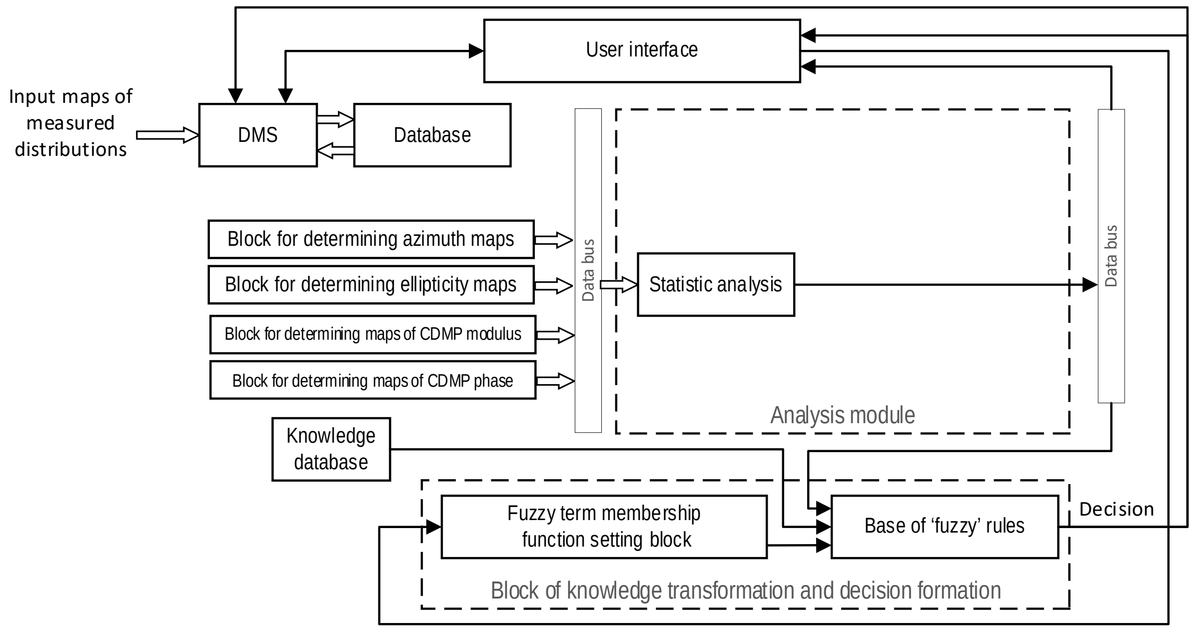

Figure 2 – The structure of the decision making support subsystem for the developed system

Statistical estimates of azimuthally independent distributions of azimuths and ellipticities of polarization $\alpha(x,y),\beta(x,y)$ of the images of the studied biological layers of myocardial tissues, as well as the corresponding correlation parameters of the modulus $|V(r_1,r_2)|$ and phase $\psi(r_1,r_2)$ of the complex degree of mutual polarization are given in Table 1.

Table 1

The average and standard value of the estimates of the elements` distributions of modulus and phase of CDMP maps, azimuths and ellipticities of the polarization images of the BL of the myocardium in "myocardial infarction" and "asphyxia"

Measured parameter	$SM_1 \pm \sigma_1$		$SM_2 \pm \sigma_2$		$SM_3 \pm \sigma_3$		$SM_4 \pm \sigma_4$	
	Asphyxia	Myocardial infarction	Asphyxia	Myocardial infarction	Asphyxia	Myocar-dial infarction	Asphyxia	Myocar-dial infarction
Map of polarization azimuths of BL $\alpha(x,y)$	$0{,}08 \pm 0{,}007$	$0{,}065 \pm 0{,}006$	$0{,}16 \pm 0{,}023$	$0{,}11 \pm 0{,}016$	$0{,}51 \pm 0{,}069$	$0{,}58 \pm 0{,}067$	$0{,}25 \pm 0{,}034$	$0{,}37 \pm 0{,}044$
Map of polarization ellipticity of BL $\beta(x,y)$	$0{,}025 \pm 0{,}004$	$0{,}017 \pm 0{,}008$	$0{,}05 \pm 0{,}001$	$0{,}03 \pm 0{,}012$	$1{,}31 \pm 0{,}12$	$1{,}57 \pm 0{,}125$	$1{,}66 \pm 0{,}16$	$1{,}83 \pm 0{,}12$
Map of CDMP modulus $\lvert V(r_1,r_2)\rvert$	$0{,}68 \pm 0{,}098$	$0{,}92 \pm 0{,}11$	$0{,}22 \pm 0{,}034$	$0{,}13 \pm 0{,}018$	$0{,}57 \pm 0{,}072$	$0{,}65 \pm 0{,}084$	$0{,}93 \pm 0{,}12$	$1{,}13 \pm 0{,}15$
Map of CDMP phase $\psi(r_1,r_2)$	$0{,}63 \pm 0{,}088$	$0{,}44 \pm 0{,}056$	$0{,}27 \pm 0{,}036$	$0{,}22 \pm 0{,}034$	$0{,}35 \pm 0{,}041$	$0{,}74 \pm 0{,}098$	$1{,}25 \pm 0{,}15$	$1{,}85 \pm 0{,}18$

The analysis of the distributions` estimates of the relevant characteristics of the myocardium BL`s polarization images, presented in Table 1, made it possible to reveal their differences for various physiological states of the myocardium tissue, which correspond to asphyxia and myocardial infarction.

Thus, the greatest differences in the obtained indicators, considered later as informative diagnostic signs, are observed for the following parameters of the myocardial BL in asphyxia and myocardial infarction:

- statistical moments of the second and fourth orders of the azimuth map differ by 1.38 and 1.47 times, respectively;
- statistical moments of the first and second orders of the ellipticity map differ by 1.47 and 1.8 times, respectively.
- statistical moments of the first and second orders of the CDMP module differ by 1.35 and 1.69 times, respectively.
- statistical moments of the first and third orders of the CSVP phase differ by 1.43 and 2.11 times, respectively.
- The vectors of informative features for each method of polarization laser diagnosis of BL can be considered separately.

Based on them, a knowledge base was created for derivation DMS rules using fuzzy logic [10, 13, 16–18], as the most successful method of synthesizing diagnostic solutions with small amounts of data samples.

8 models of "fuzzy rules" were developed based on the knowledge base developed by experts and the adjusted membership functions of fuzzy terms, described analytically in [16]. The implemented models made it possible to obtain numerical values $\eta^{d1}_{\alpha,\beta,V,\psi}, \eta^{d2}_{\alpha,\beta,V,\psi}$ (where d1 is the diagnosis of "asphyxia", d2 is the

diagnosis of "myocardial infarction") when measuring the distributions of azimuths, ellipticities of the polarization images of the BL and CDMP modulus and CDMP phase.

By statistical processing of the results of a priori and a posteriori decisions for all 102 samples of biological layers of the myocardium, the reliability of differentiating the states of "asphyxia" and "myocardial infarction" was assessed for each of the measured parameters of the BL (table 2). The choice for the study of such physiological conditions is conditioned to the complication of their differentiation due to the non-specific nature of the macroscopic signs in asphyxia.

In Table 2, classic designations are adopted for the categories of true positive (A) and true negative results (C), false positive (B) and false negative results (D) of automatic solutions.

Table 2

Reliability of differentiating diagnoses of "asphyxia" and "myocardial infarction" in the system of laser correlation-polarization diagnostics with DMS based on fuzzy logic

N	Informative parameter in the diagnostic system	Category and number of decisions				Assessment of reliability, %
		A	B	C	D	
1	Map of azimuthally invariant azimuths $\alpha(x,y)$ of the BL polarization	45	4	46	5	91
2	Map of azimuthally invariant ellipticity $\beta(x,y)$ of the BL polarization	45	5	45	5	90
3	Map of CDMP modulus $\left\|V(r_1,r_2)\right\|$ and CDMP phase $\psi(r_1,r_2)$	46	4	46	4	92
4	Complex measurement and analysis of maps: azimuths $\alpha(x,y)$, ellipticities $\beta(x,y)$, modulus $\left\|V(r_1,r_2)\right\|$ and phase $\psi(r_1,r_2)$ of the CDMP	47	2	48	3	95

Therefore, the differentiation of diagnoses (using the example of "asphyxia" and "myocardial infarction", which caused the death of a person) in the intellectualized system of laser correlation-polarization diagnosis of BL according to the improved method made it possible to increase the reliability of the diagnosis to 95%.

CONCLUSIONS

The method of polarization-invariant laser diagnosis of BL has been improved due to the complex measurement of maps of azimuthally independent azimuths and ellipticities of polarization of BL images, and also maps of the modulus and phase of CDMP with their subsequent statistical analysis and fuzzy rules for making diagnostic decisions.

The functionality of the laser system for polarization-invariant diagnosis of BL has been expanded due to the adding of a unit for measuring the correlation-polarization parameters of BL images with their further statistical analysis and fuzzy DMS models.

As a result of the comparison of the reliability of differentiating the diagnoses of "asphyxia" and "myocardial infarction" in the developed system according to the improved method, an increase in the reliability of differentiation of BL was established to 95%, which is 3% better than for the analogue [15], for which DMS methods were applied.

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VLADYSLAVA V. SHOLOTA, assistant of the Department of Computer Sciences, Vinnytsia National Technical University, 95 Khmelnytske Shose, Vinnytsia, Ukraine, ***e-mail: vladislava.sholota@gmail.com***

В.В. ШОЛОТА

МЕТОД ТА ІНТЕЛЕКТУАЛІЗОВАНА СИСТЕМА ЛАЗЕРНОЇ КОРЕЛЯЦІЙНО-ПОЛЯРИЗАЦІЙНОЇ ДІАГНОСТИКИ БІОЛОГІЧНИХ ШАРІВ

Вінницький національний технічний університет