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ANALYSIS OF METHODS AND SYSTEMS FOR MULTIWAVELENGTH POLARIMETRIC DIAGNOSTICS OF BIOLOGICAL LAYERS

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Анотація. Проаналізовано сучасні методи та засоби багатохвильової лазерної поляриметрії біологічних шарів, визначено їх переваги та недоліки. На основі проаналізованих даних сформульовано підходи до удосконалення систем лазерної поляриметричної діагностики.

Ключові слова: методи та системи багатохвильової поляриметрії, біологічна тканина, оптична діагностика, мюллер-матричне зображення.

Abstract. The modern methods and means of multiwavelength laser polarimetry of biological layers are analysed, their advantages and disadvantages are determined. On the basis of the analysed data, approaches to the improvement of laser polarimetric diagnostics systems are formulated.

Key words: methods and systems of multiwavelength polarimetry, biological tissue, optical diagnostics, Mueller matrix images.

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INTRODUCTION

The modern methods of laser polarimetry and Mueller matrix mapping [1-5] reflect the trends in the development of advanced optical information technologies for the automated measurement of the anisotropy of biological tissues (BT). The principal benefit of these techniques is their capacity to discern even slight alterations in the configuration of protein molecules at the earliest stages of cancer and degenerative-dystrophic diseases. Laser polarimetry enables the identification of pathological alterations in histological tissue sections and films of biological fluids at the micrometre level, that is not available for other methods of medical diagnostics. These technologies have been effectively employed for the diagnosis of oncological pathologies and inflammatory processes, particularly in the early detection of tumours of the female reproductive organs [6-8].

The development of functional capabilities of polarimetry methods is associated with the use of statistical, correlative, fractal and wavelet analysis [3, 5, 6] of the reproduced distributions of biological tissue anisotropy parameters to form a feature vector for automated data classification based on the results of analysis [6, 8, 9]. Intelligence analysis of the distributions of azimuth maps, ellipticity and phase shifts of polarization images, Mueller matrix images (MMI) allowed to improve the reliability of diagnostic methods of laser polarimetry to some extent.

On the other hand, an increase in the reliability of pathology assessment by multiparametric laser polarimetry can be achieved through conducting multiwavelength measurements of the anisotropy parameters of biological tissues, providing reproduction of Mueller matrix images of BT at two wavelengths – of 632 nm and 487 nm (or 405 nm) [10-12].

Therefore, the expansion of the range of modern laser polarimetric methods and systems for the diagnosis of biological sections due to the multiwavelength approach and the existing need for further improvement in the reliability of assessment of pathological changes in the BT with their help, necessitates a more detailed analysis.

The purpose of this paper is to analyse the known approaches to multiwavelength methods and systems of laser polarimetric biomedical diagnostics, as well as to determine their advantages and disadvantages in order to formulate requirements for new developments.

ANALYSIS OF METHODS, SCHEMES AND CHARACTERISTICS OF MULTIWAVELENGTH POLARIMETRY SYSTEMS FOR BIOLOGICAL LAYERS

The relevance of video-polarimetry in biological and clinical studies of biological layers has led to the development of a wide range of different methods and systems based on the measurement of the vectorial properties of light or vectorial transformations imposed on light by objects.

One of the most complete classifications of methods and means for polarimetric diagnostics of biological tissues and liquids is given in [13]. In this classification of biological tissue polarimetry devices, the following classification features are used: a type of polarization object field registration, a degree of measurement automation, a type of measurement circuit, a type of radiation modulation, a method of controlling the parameters of polarization transducers, and functionality. The advantage of these devices is the achievement of a high level of reliability in assessing pathological changes in biological tissues in accordance with evidence-based medicine standards. In particular, the accuracy of diagnosing the structure of biological tissues in the context of ‘norm’ - ‘pathology’ when using these methods ranges from 71% to 95,3% [13].

At the same time, one of the possible factors influencing the improvement of the reliability of polarization diagnostics of biological tissues and fluids is an increase of the information content of the respective polarization systems by performing polarization measurements at several wavelengths with subsequent intelligent analysis of the data obtained. Therefore, below, we are going to analyse in more detail the known multiwavelength systems of BT imaging laser polarimetry in the diagnosis of pathological conditions.

In [14], the study of features from the measured values of the elements of the Mueller matrix was used to differentiate normal and pathological unfixed human pancreatic tissue ex-vivo. Experimental studies of pancreatic biopsy specimens from 11 patients were carried out and 4x4 Mueller matrix images with the resolution of 36 pixels/mm were obtained. In the study, an imaging Mueller polarimeter scheme to visualise biological layers with the geometry of backscattered light was used (Figure 1).

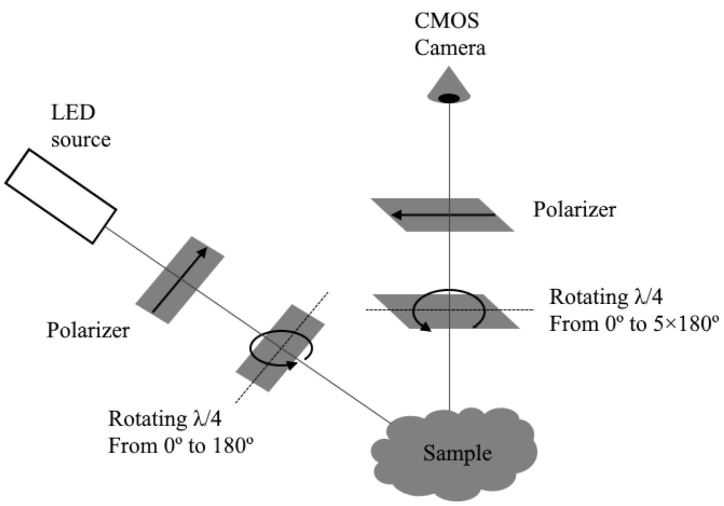

Figure 1 – A schematic representation of a polarimeter with a double rotating retarder [14]

In particular, in the system [14], a polarimeter with a double-rotating retarder for sample imaging was used. The polarimeter consists of a light source, a filter wheel, a polarization state generator, and a polarization state analyzer. Samples are exposed to light waves of five wavelengths (450 nm, 470 nm, 500 nm, 540 nm, and 625 nm) and interact with the polarization generator and analyser. The polarimeter performs the rotation of the wave plates at harmonic frequencies and makes a series of measurements with a fixed colour filter to build up pixel-by-pixel Mueller matrices, that show the response of the samples to different polarization states over the selected wavelength range. This process is repeated for each filter, allowing for the reconstruction of the polarization spectrum with low resolution. The identification of abnormal tissues was automated by performing classification using machine learning techniques. In particular, a multi-layer perceptron was used to classify each pixel of the Mueller matrix image as both normal and abnormal. The reliability of detecting such abnormal tissues in the system shown in Figure 1 reached 91%, and the sensitivity (true positive rate) and specificity (true negative rate) were above 80% [14].

A significant drawback of the polarimetry system [14] is the lack of automated control of the micropolarimeter while measuring and analysing the data obtained. This leads to the significant time spent on research and limits the hardware flexibility when setting up the installation for performing the selected measurement mode or parameter analysis.

PRACTICAL REALIZATION OF MULTIWAVELENGTH SYSTEMS FOR IMAGING LASER POLARIMETRIC DIAGNOSTICS OF BIOLOGICAL LAYERS

The paper [15] describes the use of Mueller polarimetry for the diagnosis of precancerous lesions of the cervix. The polarimeter shown in Figure 2 is based on ferroelectric liquid-crystal polarization modulators and uses a polarization state generator (PSG) and a polarization state analyser (PSA). The PSG generates four different polarization states projected sequentially onto the PSA, which, in turn, also realises four polarization states. After the precise calibration of the polarization states of the PSG and PSA, the 16 images obtained allow the reconstruction of Mueller matrices for each pixel of the sample under investigation.

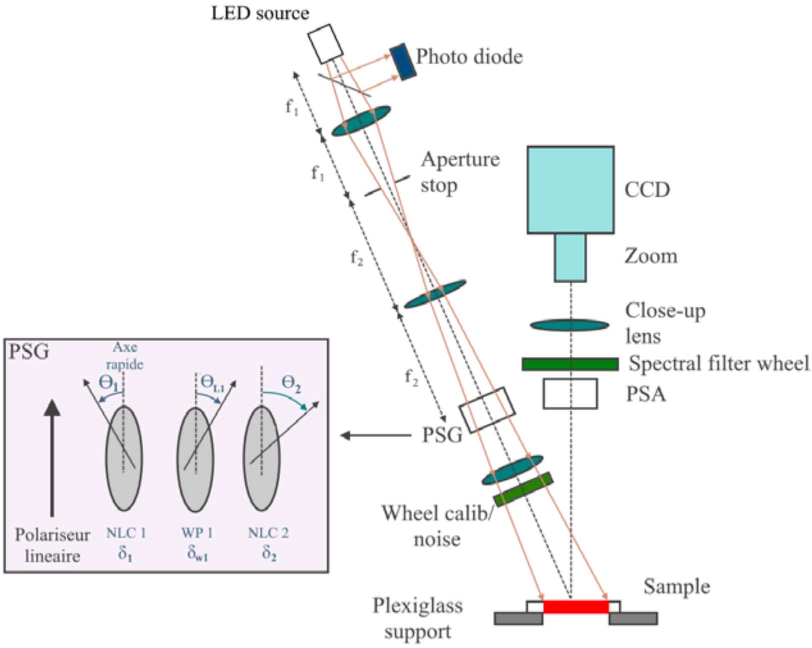

Figure 2 – A scheme of an optical three-wave polarimeter based on ferroelectric liquid crystal modulators [15]

Polarimetric images were obtained for seventeen cervical conization specimens and compared with the results of the histological diagnosis, which is considered to be ‘the gold standard’. The sensitivity and specificity of the method were calculated for images at the wavelengths of 450, 550 and 600 nm. The optimal sensitivity and specificity values, approximately 83%, were achieved for images obtained at a shorter wavelength of 450 nm [15]. Since precancerous transformations of the epithelium primarily affect the collagen layer limited to a shallow area under the epithelium (~300 – 500 µm), further changes in deeper tissue layers can be taken into account when examining a sample with a longer wavelength of light.

Polarimetric analysis allows us to accurately identify morphological changes in tissues, which is critical for the early detection of pathologies. In particular, studies have shown that birefringence is an important parameter for detecting precancerous lesions of the cervix. Healthy tissue demonstrates strong birefringence, while pathologically altered tissue has significantly lower values of this parameter [15].

In [16], a method of an automated Mueller polarimetry system for assessing the anisotropic structure of histological sections of biological layers of the cervix was improved and the architecture of this system was developed (shown in Figure 3). The system has two lasers with wavelengths of 634 nm and 435 nm, which form two separate laser radiation channels. Their outputs are connected through a collimator and a light combiner to the input of a multichannel polarizing irradiator, which, in turn, consists of polarizing linear filters and a right-circular filter.

The image of the samples placed in the object block is projected onto the digital camera plane using a 4x magnification lens. Additionally, the polarization filtering of the generated polarization image is performed in front of the digital camera using a multi-channel polarization analyser containing six channels: four channels with linear polarization filters and two channels with circular filters. The automatic control of the rotary mechanisms of the polarization irradiator and the analyser unit is realised by means of a control unit and stepper motors 1 and 2. The system software includes modules for image capture and storage, as well as the main software module that interacts with the units for determining orientation, phase and orientation-phase Mueller matrix images. This architecture makes it possible to implement an improved method of dual-wavelength Mueller polarimetry for evaluating histological sections by their Mueller matrix images.

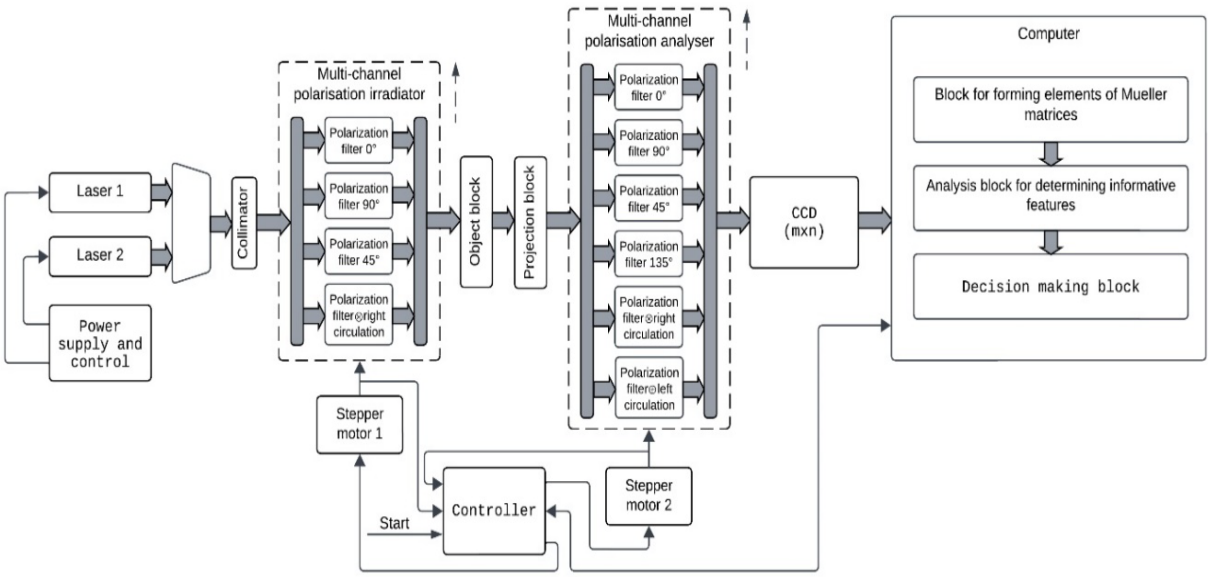

Figure 3 – The architecture of the automated dual-wavelength Mueller polarimetry imaging system for assessing the anisotropic structure of histological sections

Experimental studies of the method and system of automated two-wave Mueller polarimetry were carried out using two samples of cervical muscle tissue samples with verified diagnoses: 21 samples of each control group, ‘norm’ and ‘pathology’. The geometric thickness of optically thin sections was 10 μm.

The analysis of the main reliability indicators of the methods discussed in [16] showed an increase in the accuracy of assessing changes in the anisotropic structure of histological sections due to the presence of pathologies. Thus, in the system of two-wave automated Mueller polarimetry, the reliability of phase Mueller mapping reached 90,5%, and orientation Mueller mapping – 88,1%.

Table 1 below shows the above-mentioned and other multiwavelength video-polarimetric systems and their main technical parameters and characteristics.

The analysis of Table 1 demonstrates high efficiency in diagnosing pathological conditions using the multiwavelength laser polarimetry system, which reaches 91% of abnormal tissue detection.

Each of the systems has its own advantages, disadvantages and specific technical characteristics, which makes their use appropriate in various fields of medical diagnostics. Further research and development in this area should focus on increasing automation, improving analysis methods, and integrating modern machine learning algorithms.

Table 1

A comparison of the main technical parameters of multiwavelength systems for imaging laser polarimetric diagnostics of biological layers with the decision support system (DSS)

System name	Polarimetric diagnostic method	Wavelength range, nm	DSS method/ software implementation	Reliability of diagnostics
Two-wave laser micropolarimetry system [18]	Reproduction of phase and amplitude anisotropy on the basis of 16 MMIs	638 ÷ 405	No DSS	80% (detection of diabetes mellitus by bile films)
Two-wave polarization mapping system for plasma films for breast diagnostics [17]	Measurement of image polarization azimuths and ellipticities	675 ÷ 405	Neural network of perceptron type / MATLAB	90,3% (cancer detection in the analysis of blood plasma films)
System of automated two-wave Mueller polarimetry of histological sections [16]	Method of mapping and analysis of phase and orientation Mueller matrix images of the biological layers	634 ÷ 435	Neural network of perceptron type / MATLAB	90,5% for phase Mueller mapping; 88,1% for orientation Mueller mapping
Mueller matrix polarimetry for the diagnosis of pancreatic tissue [14]	Mueller matrix polarimetry and t-SNE analysis	450 ÷ 470 ÷ 500 ÷ 540 ÷ 625	Neural network, multi-layer perceptron	91% detection of abnormal tissue

CONCLUSIONS

The analysis of modern methods and systems of multiwavelength laser polarimetry and Mueller matrix mapping of biological tissues indicates their prospects in medical diagnostics, in particular for the early detection of cancer and degenerative-dystrophic diseases at the wavelengths from 405 nm to 638 nm.

The directions of further research aimed at improving the reliability of diagnostics of biological layers using multiwavelength laser polarimetry may be: the automation of measurements of new anisotropy parameters of the studied samples with increased measurement accuracy; automated data classification, the integration of machine learning algorithms for automated classification of the obtained images and identification of pathologies.

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ОЛЕГ ШВИДЮК, НАТАЛІЯ ЗАБОЛОТНА

АНАЛІЗ МЕТОДІВ І СИСТЕМ ДЛЯ БАГАТОХВИЛЬОВОЇ ПОЛЯРИМЕТРИЧНОЇ ДІАГНОСТИКИ БІОЛОГІЧНИХ ШАРІВ

Вінницький національний технічний університет