

Layer-by-layer phase scanning of polycrystalline blood facies laser induced images for determination thyroid gland cancer and tissues injury necrosis

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ABSTRACT

The methods of layer-by-layer interference phase scanning with digital holographic reproduction of azimuth and ellipticity polarization maps for differential diagnosis of benign (nodular goiter - NG) and malignant (papillary thyroid - PT) thyroid tumours are presented. All studies in representative groups of histological sections M and AC were conducted using a circular laser beam. This ensured the azimuthal invariance and repeatability of measurements of polarization maps NG and PT. Integrated, and layer-by-layer polarization maps of NG and PT were received. Values of statistical moments of 1st - 4th order, which characterize NG and PT samples coordinate distributions of azimuth and ellipticity polarization have been determined and systematized. A set of statistical parameters - diagnostic markers most sensitive to changes in the polycrystalline structure NG and PT has been determined. The results of information analysis - determination of accuracy of vector-parametric and polarization-interference methods of differentiation of benign and malignant thyroid tumours are presented.

Keywords: polarization, interference, holography, microscopic image, optical anisotropy, thyroid, statistical moments

1. INTRODUCTION

Polarimetric studies have formed a separate direction in the biological tissue's optics^{1,2}. Analysis of the scattered radiation polarization characteristics makes it possible to obtain qualitatively new results on the biological tissues morphological and physiological state. In particular, cataract of the lens; glucose concentration in the tissues of diabetic patients; malignant changes^{1,3-7}. A new step in the development of such methods was the successful combination of polarimetric and interferometric methods⁸⁻¹¹ for mapping laser object fields and creating new computer processing¹²⁻¹⁶ for the foundations of 3D polarimetry techniques on this basis.

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However, at present, only the first, but already promising, studies are known in the framework of using this technique of biomedical diagnostics¹⁷⁻²⁴. Our work is aimed at the development and experimental testing of 3D polarimetry methods for thyroid diffuse layers multiple scattered fields in order to search opportunities for different scattering multiplicity components layer-by-layer digital holographic selection to improve the differential diagnosis of benign (nodular goiter - NG) and malignant (papillary thyroid - PT) thyroid tumours²⁵⁻²⁹.

2. A BRIEF THEORY

We will briefly consider (without reducing the completeness of the analysis) within the framework of the linear birefringence **LB** approximation^{3-7,17-24}, the main theoretical provisions of our work. We chose a right-circularly ($\otimes$) polarized laser beam as the radiation illuminating biological tissues. This condition is necessary when measuring a series of samples of biological tissues. For other states of polarization, the result of its object transformation will be azimuthally dependent on the rotation of the sample relative to the direction of irradiation. The following analytical relationships are known between the elements of the Mueller matrix $(\{\mathbf{M}\})^{j=1}$ of a birefringent network of fibrils and its optical-geometric parameters - the orientation of the optical axis ε and the phase shift θ ¹⁷:

$$\begin{aligned} m_{11} &= 1; \\ m_{12;13;14} &= 0; \\ m_{21;31;41} &= 0; \\ m_{22} &= (\cos^2 2\varepsilon + \sin^2 2\varepsilon \cos \theta); \\ m_{33} &= (\sin^2 2\varepsilon + \cos^2 2\varepsilon \cos \theta); \\ m_{44} &= (\cos \theta); \\ m_{23;32} &= (\cos 2\varepsilon \sin 2\varepsilon (1 - \cos \theta)); \\ m_{24;42} &= (\cos 2\varepsilon \sin \theta); \\ m_{34;43} &= (\sin 2\varepsilon \sin \theta). \end{aligned} \quad (1)$$

Here m_{lk} - Mueller matrix partial elements.

3. THE 3D POLARIMETRY PHASE SCANNING METHOD OF OBJECT FIELD

1. The main idea is to record an interference pattern in the plane of a microscopic image of a biological specimen. For this purpose, a circular polarization state ($\otimes$) is formed in the reference and illuminating arms of the polarization interferometer.
2. The resulting interference distribution is analysed by two rotations of the polarizer-analyser plane.
3. For each polarization projection of the interference pattern, a two-dimensional digital Fourier transform is used, which provides restoration of the field of complex amplitudes of the biological preparation²⁸.

$$\begin{cases} I_x^\otimes(0^0)(m, n) = A_x^\otimes(0^0)(A_x^\otimes)^*(0^0)(m, n); \\ I_y^\otimes(90^0)(m, n) = A_y^\otimes(90^0)(A_y^\otimes)^*(90^0)(m, n) \end{cases} \quad (2)$$

$A_{x,y}^\otimes$ - complex amplitude orthogonal components for different orientation $\Omega = 0^0$; $\Omega = 90^0$; * - denotes the complex conjugation operation; (v, v) are the spatial frequencies and $(m = 1120; n = 960)$ are the CCD camera pixels quantity.

4. Step-by-step phase scanning of the algorithmically reconstructed object field (2) is carried out and the coordinate distributions of the quantity are determined in each phase plane polarization parameters $\beta(\theta_k, m, n)$.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. DIFFERENTIAL DIAGNOSIS OF THYROID ONCOLOGY

Two groups of thyroid histological sections were formed:

- Biopsy of a benign tumour (nodular goiter - NG)– Group 1, 51 samples.
- Biopsy of a malignant tumour (papillary thyroid - PT) – Group 2, 51 samples.

Figure 1 presents the results of a study of integral ((1)-(4)) and phase ((5)-(8) and (9)-(12)) ellipticity polarization maps - PT and NG. The statistical analysis results of ellipticity polarization $\beta(m, n)$ and $\beta(\theta_k, m, n)$ maps are illustrated in

Table 3. Different from normal statistical distributions of ellipticity polarization maps (Group 1 and Group 2) were revealed – all 1st - 4th order statistical moments, that characterize histograms $G(\beta)$ and $G(\theta_k = \pi/4, \beta)$, $G(\theta_k = \pi/8, \beta)$, other than zero – $Z_{i=1,2,3,4}((\beta), (\theta_k = \pi/4, \beta), (\theta_k = \pi/8, \beta)) \uparrow$. Asymmetry and excesses are maximally sensitive to changes in thyroid samples microscopic images polarization ellipticity distributions for both groups. The use of the phase scanning technique provided a reduction in the influence of multiple scattering acts ($\theta_k \downarrow$) and the selection of components of the object field with a small multiplicity of scattering, which statistically turned out to be in a 10-fold increase in the 3rd - 4th orders statistical moments value – $Z_{i=1,2,3,4}((\beta), (\theta_k = \pi/4, \beta), (\theta_k = \pi/8, \beta)) \uparrow$.

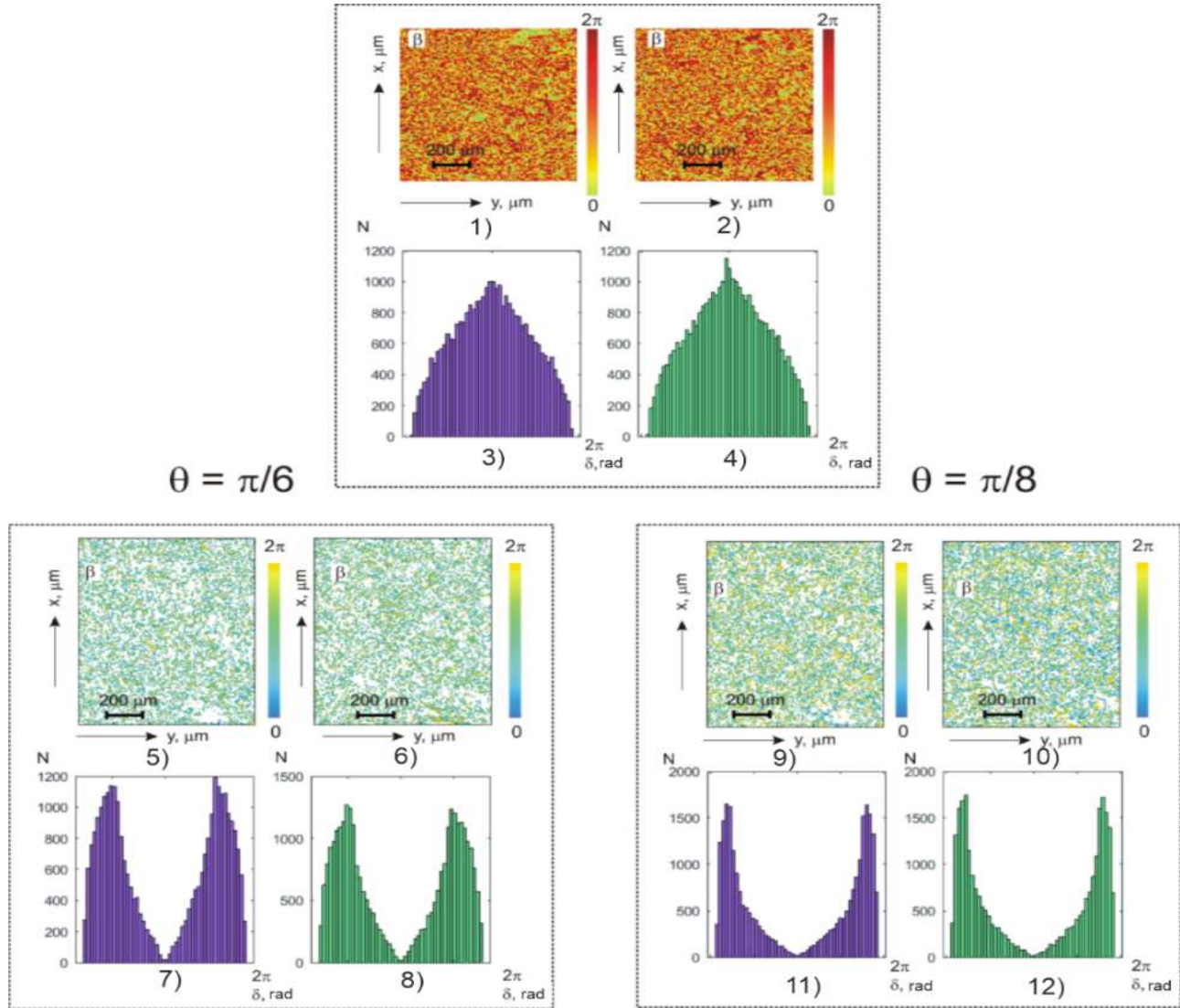


Figure. 1. Ellipticity polarization maps and histograms. PT (left column, blue colour) and NG (right column, green colour).

From a physical point of view, for the plane $\theta_k = \pi/8$, fibrillar meshes necrotic changes ($\theta \downarrow$) for due to PT lead to a smaller phase modulation ($\theta(m, n)$) between the orthogonal components U_x and U_y . Accordingly, realized to small values of mean $Z_1(\beta, \theta)$ and variance $Z_2(\beta, \theta)$ of the distributions $\left(D^{j=1}(\beta^{j=1}(R, \theta))\right) + \left(D^{j=p}(\beta^{j=p}(R, \theta))\right) + \left(D(I)^{j=p}(\beta(I)^{j=p}(R, \theta))\right)$ in comparison with similar this polarization parameter distributions, which are formed by

thyroid samples of deceased NG. Inverse changes occur for higher - order statistical moments $Z_{3,4}(\beta, \theta)$ - $\left(Z_{i=1,2}(PT, (\beta), (\theta_k)) < Z_{i=1,2}(NG, (\beta), (\theta_k)) \right)$ $\left(Z_{i=3,4}(PT, (\beta), (\theta_k)) > Z_{i=3,4}(NG, (\beta), (\theta_k)) \right)$.

Table 1. 1st - 4th orders statistical moments that characterize ellipticity polarization maps.

Thyroid			
Parameters	Group 1	Group 2	Ac, %
Z_3	0.12 ± 0.007	0.18 ± 0.0095	87.5
Z_4	0.16 ± 0.009	0.21 ± 0.011	87.5
Thyroid (phase section $\theta = \pi/4$)			
Z_3	0.75 ± 0.031	1.09 ± 0.053	91.2
Z_4	1.29 ± 0.064	1.62 ± 0.094	91.2
Thyroid (phase section $\theta = \pi/8$)			
Z_3	0.71 ± 0.049	1.29 ± 0.069	95.8
Z_4	1.01 ± 0.071	1.94 ± 0.105	95.8

Information analysis revealed an increase in the accuracy of differential diagnosis of PT – NG cases (Table 3) compared to phase scanning of polarization azimuth distributions (Table 2):

- polarization ellipticity integral maps are good $Ac(Z_{3,4}(\beta)) = 87.9\%$;
- polarization ellipticity layer – by-layer phase maps are good $Ac(Z_3(\beta, \theta_k = \pi/4)) = 87.5\%$, very good $Ac(Z_4(\beta, \theta_k = \pi/8)) = 91.7\%$, and excellent $Ac(Z_{3,4}(\beta, \theta_k = \pi/8)) = 95.8\%$.

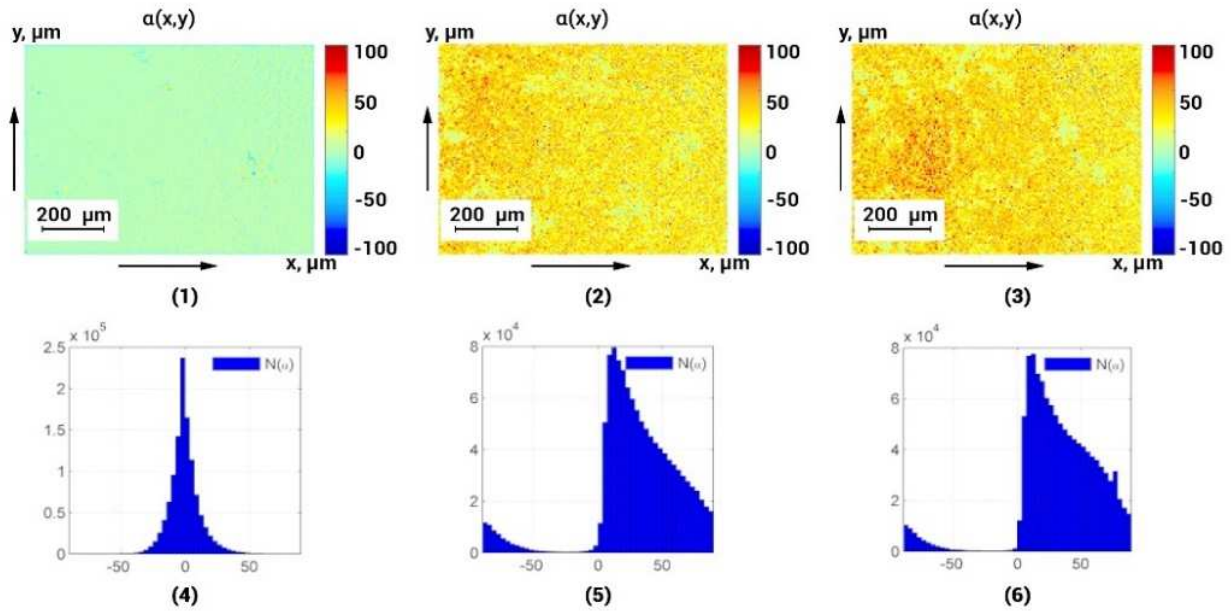


Figure 2. Maps ((1),(2),(3)) and histograms ((4),(5),(6)) of liver histological sections microscopic images polarization azimuth distributions from the control group ((1), (4)), experimental groups (6 hours - (2), (5)) and (18 hours - (3), (6)). Polarization maps (Figure 2, (1)-(3)) of intact and damaged liver histological sections microscopic images are coordinate-inhomogeneous (Figure 2 (4)-(6)) with a slightly smaller spread of the azimuth value, which decreases with increasing age of application damage - 6 hours ((5)) and 18 hours ((6)), respectively (Table 2).

Table 2. Temporal dynamics of changes in statistical moments of the 1st - 4th orders, which characterize the liver histological sections microscopic images azimuth maps.

T, h	1	4	6	12	18
SM_3	0.76 ± 0.036	0.92 ± 0.043	1.11 ± 0.052	1.42 ± 0.068	1.32 ± 0.064
SM_4	0.54 ± 0.026	0.65 ± 0.031	0.78 ± 0.034	1.02 ± 0.042	0.96 ± 0.045
$T, h.$	24	30	36	42	48
SM_3	1.34 ± 0.071	1.38 ± 0.069	1.36 ± 0.073	1.39 ± 0.075	1.38 ± 0.074
SM_4	1.02 ± 0.054	1.06 ± 0.056	1.13 ± 0.063	1.11 ± 0.065	1.14 ± 0.066

Table 3. Time intervals and accuracy of the polarization azimuth mapping method.

Brain				
Statistical moments	Time, h		Accuracy, min	
Magnitude	4x	40x	4x	40x
Asymmetry	12	18	60	55
Kurtosis	12	18	60	55
Myocardium				
Asymmetry	12	18	60	55
Kurtosis	12	18	60	55
Liver				
Asymmetry	12	18	70	60
Kurtosis	12	18	70	60
Lung tissue				
Asymmetry	12	18	70	60
Kurtosis	12	18	70	60

4.2. DIFFERENTIAL DIAGNOSTICS OF DUNT MECHANICAL INJURIES

Figure 2 illustrates the liver histological sections digital microscopic images azimuth polarization maps from experimental ((1), (4)) and two control ((2), (3), (5), (6)) groups. The results of the statistical analysis (Table 3) revealed the diagnostic possibilities of digital polarization histological examination of the age of liver damage in the linear ($p < 0.05$) range of changes in the value of asymmetry (dynamic range 0.66) and kurtosis (dynamic range 0.48), which characterize the microscopic images polarization azimuth distributions at a time interval of up to 12 hours.

4.3. PROSPECTS FOR FURTHER LAYER-BY-LAYER PHASE SCANNING RESEARCH

In order to expand the functionality of the method and increase its sensitivity at the molecular level of polycrystalline architecture, future studies will use phase scanning of laser-induced auto fluorescent images of biological tissue and liquid preparations.

5. CONCLUSIONS

1. A complex polarimetric and interferometric analytical description of the formation of polarizing-inhomogeneous components with different scattering multiplicity in the object laser field of biological diffuse tissues with different optically anisotropic structures is proposed.
2. Experimental testing of polarimetry methods and digital holographic 3D layer-by-layer processing of histological sections of the thyroid reproduction complex amplitudes and maps of the polarization distribution was carried out.
3. The following maximum levels of accuracy were achieved for differential diagnosis of benign and malignant tumours of the thyroid - polarization ellipticity layer-by-layer maps - excellent $Ac(Z_{3,4}(\beta, \theta_k = \pi/8)) = 95.8\%$.
4. A polarimetric technique for determining the duration of blunt mechanical trauma of various internal organs is proposed, which provides an accuracy of 55 minutes at an interval of up to 18 hours.

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