Fourier-Stokes Polarimetry Of Fields Scattered By Birefringence Biological Tissues

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***Abstract* - The optical model of polycrystalline networks of histological sections of rectum wall is suggested. The results of investigating the interrelation between the values of statistical (statistical moments of the 1st-4th order) parameters are presented. They characterize the coordinate distributions of the fourth parameter of Stokes vector of Fourier transforms of laser images of rectum wall histological sections and oncological changes. The diagnostic criteria of rectum cancer are determined.**

***Index Terms* - Fourier-stokes polarimetry, microscopic images, polycrystalline networks, polarizationally sensitive optical coherent tomography, histological sections of rectum wall biopsy.**

1. INTRODUCTION

A new direction of optical physical diagnostics [1-8] – laser polarimetry of microscopic images of polycrystalline networks of biological tissues histological sections [9-12] has been developed in recent years. This approach is focused on *in vitro* measurements of coordinate distributions of Stokes vector parameters of biological tissues laser images with further complex (statistical, correlation, fractal, singular, wavelet, etc.) analysis on the basis of the obtained data arrays [13-24].

Another diagnostic biomedical laser technique – polarizationally sensitive optical coherent tomography – also became widely spread [25-28]. It is based on measuring the parameters of Stokes vector in the remote (Fourier) diffraction zone of the field of scattered laser radiation.

That is why the task of combining the information potentiality of the above mentioned techniques of optical diagnostics basing on the development of new methods of analysis and processing of polarizationally inhomogeneous images of biological tissues in the Fourier plane [29] of scattered radiation field proves to be topical.

This research is focused on the development of experimental technique of polarization investigation of coordinate distributions of Stokes vector parameters of the laser field in the Fourier plane for diagnostics and differentiation of the severity of pathological changes in rectum tissue biopsy.

2. BASIC ANALYTICAL RELATIONS

It was determined for the fields of scattered laser radiation that polarization state in every point with (n,m) coordinates is formed by the mechanisms of statistical interference and is determined using the following relations [15, 19, 30]

$$\alpha(n,m) = 0{,}5\arcsin\left[\frac{\sin 2\Theta(n,m)}{\cos\delta(n,m)}\right]; \quad (1)$$

$$\beta(n,m) = 0{,}5arctg\left[\frac{\sin\delta(n,m)}{\cos 2\Theta(n,m)}\right], \quad (2)$$

where $\Theta = arctg\dfrac{E_y}{E_x}$ – the phase angle, δ – phase shift between the orthogonal components E_x, E_y of laser radiation amplitude determined from relations [26]

$$\begin{gathered} E_x e^{i\delta_x} = e^{i\delta_{0x}} E_{0x}\left[\left(\cos^2\rho + e^{-i\varphi}\sin^2\rho\right)\sin^2\theta\right] + \\ + e^{i\delta_{0y}} E_{0y}\left[\cos\rho\sin\rho\left(1-e^{-i\varphi}\right)\cos^2\theta\right]; \end{gathered} \quad ; (3)$$

$$\begin{gathered} E_y e^{i\delta_y} = e^{i\delta_{0x}} E_{0x}\left[\cos\rho\sin\rho\left(1-e^{-i\varphi}\right)\sin^2\theta\right] + \\ + e^{i\delta_{0y}} E_{0y}\left[\left(\cos^2\rho + e^{-i\varphi}\sin^2\rho\right)\cos^2\theta\right]. \end{gathered} \quad . (4)$$

Here δ_{0x} , δ_{0x} – phases of orthogonal components (E_{0x}, E_{0y}) of the amplitude of the laser image probing polycrystalline network; ρ φ θ $\delta = \delta_x - \delta_y = \varphi + \theta$.

Expressions (3) and (4) are "input" parameters for diffraction integrals [31] determining further diffraction-interferential process of evolution of amplitude-phase distributions of object field.

For the case of finding the biological tissue layer in the focal plane of the objective the following can be written

$$U_x\left(m^*,n^*\right)=\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_x(m,n)\exp\left[-i\frac{2\pi}{\lambda f}\left(nn^*+mm^*\right)dndm\right] \tag{5}$$

$$U_y\left(m^*,n^*\right)=\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_y(m,n)\exp\left[-i\frac{2\pi}{\lambda f}\left(nn^*+mm^*\right)dndm\right]. \tag{6}$$

Here f – focus distance of the objective; λ – wave length of laser radiation; n,m and n^*,m^* – coordinates of the points in the image plane and Fourier plane respectively.

Diffraction integrals (5) and (6) enable to determine the asymmetry degree of Fourier spectrum in two mutually transverse directions

$$\Delta(\nu)=\frac{U_x\left(m^*\right)+U_y\left(m^*\right)}{U_x\left(n^*\right)+U_y\left(n^*\right)}, \tag{7}$$

where

$$U_x\left(m^*\right)=\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_x(m)\exp\left[-i\frac{2\pi}{\lambda f}mm^*\right]dm= =\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_x(m)\exp\left[-i2\pi m\nu_m\right]dm \tag{8}$$

$$U_x\left(n^*\right)=\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_x(m)\exp\left[-i\frac{2\pi}{\lambda f}nn^*\right]dn= =\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_x(m)\exp\left[-i2\pi n\nu_n\right]dn \tag{9}$$

$$U_y\left(m^*\right)=\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_y(m)\exp\left[-i\frac{2\pi}{\lambda f}mm^*\right]dm= =\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_y(m)\exp\left[-i2\pi m\nu_m\right]dm \tag{10}$$

$$U_y\left(n^*\right)=\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_y(n)\exp\left[-i\frac{2\pi}{\lambda f}nn^*\right]dn= =\frac{A}{i\lambda f}\int_{-\infty}^{+\infty}E_y(n)\exp\left[-i2\pi n\nu_n\right]dn \tag{11}$$

Thus, taking into account relations (1)-(6) the following expressions for the Stokes vector parameters can be written [31]

$$\begin{aligned}S_1\left(m^*,n^*\right)&=E_xE_x^*+E_yE_y^*;\\ S_2\left(m^*,n^*\right)&=E_xE_x^*-E_yE_y^*;\\ S_3\left(m^*,n^*\right)&=E_xE_y^*-E_yE_x^*;\\ S_4\left(m^*,n^*\right)&=i\left(E_yE_x^*-E_xE_y^*\right),\end{aligned} \tag{12}$$

and asymmetry degree of $S_{k=1;2;3;4}\left(m^*,n^*\right)$ distributions can be determined and to determine the degree of asymmetry (relations (7) – (12)).

For objective (quantitative) estimation of distributions $S_{k=1;2;3;4}\left(m^*,n^*\right)$ the statistical, correlation and spectral approaches were used.

3. DIAGNOSTIC POTENTIALITY OF FOURIER STOKES POLARIMETRY OF LASER FIELDS OF BIOLOGICAL TISSUES HISTOLOGICAL SECTIONS *IN VITRO*

Histological sections of rectum wall biopsy with benign (group of samples 1-9) and malignant (group of samples 2-10) were used as objects of investigation.

This research is confined to the analysis of distributions structure of the 4th Stokes vector parameter most vividly characterizing the changes in optical anisotropy of polycrystalline biological networks.

The coordinate (left parts) and probability (right parts) distributions of the values of the 4th Stokes vector parameter of optically realized Fourier spectrum of laser radiation scattered by histological sections of rectum wall biopsy of group 2 (Fig. 1) and group 2 (Fig. 2) are presented in Fig. 1 and Fig. 2.

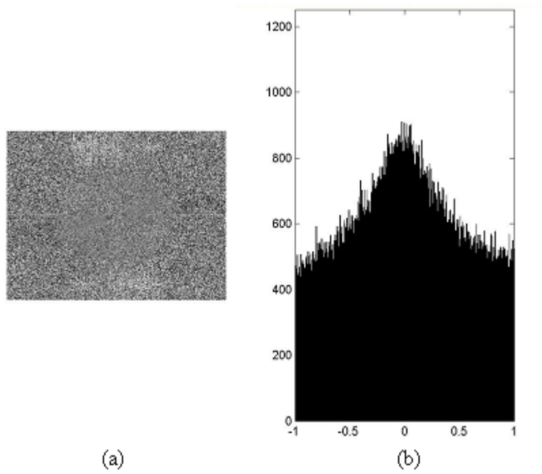

Fig. 1. Coordinate structure and histogram of values distribution of the 4th parameter of Stokes vector scattered by histological section of group 1 in Fourier plane

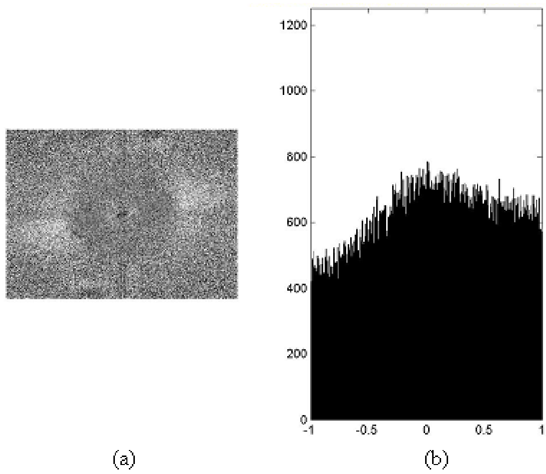

Fig. 2. Coordinate structure and histogram of values distribution of the 4th parameter of Stokes vector scattered by histological section of group 2 in Fourier plane

The results of the 1st-4th order moments calculation characterizing the coordinate distributions in Fourier plane of the field of laser radiation transformed by histological sections of rectum wall with benign (group 1) and malignant (group 2) tumors are presented in Table 1.

TABLE 1. STATISTICAL MOMENTS OF THE 1ST-4TH ORDERS OF FOURIER SPECTRUM S_4

Parameters	Benign changes	Malignant changes
R_1	$0{,}28 \pm 0{,}0012$	$0{,}07 \pm 0{,}021$
R_2	$0{,}11 \pm 0{,}008$	$0{,}39 \pm 0{,}014$
R_3	$1{,}14 \pm 0{,}009$	$0{,}59 \pm 0{,}016$
R_4	$2{,}47 \pm 0{,}017$	$0{,}79 \pm 0{,}027$

It was determined that the difference between the statistical parameters $R_{j=1;2;3;4}$ for both groups of histological sections amounts to: mean R_1 – 4 times; dispersion R_2 – 3.8 times; asymmetry R_3 – 1.9 times; excess R_4 – 3.1 times. On the basis of this the following parameters of sensitivity and specificity in differentiation of benign and malignant changes of rectum wall:

Group 1 ($q = 9$)

State	Benign changes	Malignant changes
Parameters	$b = 7$	$d = 2$

Group 2 ($q = 10$)

State	Benign changes	Malignant changes
Parameters	$c = 3$	$a = 6$

Thus, sensitivity Se and specificity Sp equal to: $Se(dQ_2) = 78\%; Sp(dQ_4) = 77\%.$

4. CONCLUSIONS

1.The complex technique of estimating polarizationally inhomogeneous field of scattered laser radiation in Fourier plane is suggested. It is based on determination of values and range of changes of statistical moments of the 1st-4th orders, characterizing the probability, coordinate and spatial-frequency structure of Stokes vector parameters coordinate distributions.

2. The ensemble of diagnostically urgent statistical (statistical moments of the 1st-4th orders), parameters of coordinate distributions of the 4th Stokes vector parameter of Fourier image of polarizationally inhomogeneous image of optically anisotropic component of histological sections of stomach wall tissue is determined. By means of these parameters differentiation of benign and malignant tumor with high sensitivity and specificity levels is realized for the first time.

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