DIFFERENTIAL 3D MUELLER-MATRIX MAPPING OF OPTICALLY ANISOTROPIC DEPOLARIZING BIOLOGICAL LAYERS

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ABSTRACT

The paper consists of two parts. The first part is devoted to the short theoretical basics of the method of differential Mueller-matrix description of properties of partially depolarizing layers. It was provided the experimentally measured maps of differential matrix of the 2nd order of polycrystalline structure of the histological section of rectum wall tissue. It was defined the values of statistical moments of the1st-4th orders, which characterize the distribution of matrix elements. In the second part of the paper it was provided the data of statistic analysis of birefringence and dichroism of the histological sections of connecting component of vagina wall tissue (normal and with prolapse). It were defined the objective criteria of differential diagnostics of pathologies of vagina wall.

Keywords: Mueller matrix, biological tissue, diagnostic, correlometry.

1. THEORETICAL BASICS AND EXPERIMENTAL REALIZATION OF DIFFERENTIAL MUELLER-MATRIX MAPPING OF BIOLOGICAL LAYERS

1.1. Brief theory of the method

The theoretical basis of Mueller matrix approach [1-3] to description of the interaction of optical radiation with multiple scattering layers is shown in a series of publications [4-12]. It was shown that depolarization properties of diffusive layer with Mueller matrix $\{M\}$ are described by means of differential matrix of the 2nd order $\{\Delta m^2\}$

$$\{\Delta m^2\} = 0{,}5z^{-2}\left\| \begin{matrix} \ln M_{11} & \ln\left(\dfrac{M_{12}}{M_{21}}\right) & \ln\left(\dfrac{M_{13}}{M_{31}}\right) & \ln\left(\dfrac{M_{14}}{M_{41}}\right) \\ \ln\left(\dfrac{M_{21}}{M_{12}}\right) & \ln M_{22} & \ln(M_{23}M_{32}) & \ln(M_{24}M_{42}) \\ \ln\left(\dfrac{M_{31}}{M_{13}}\right) & \ln(M_{32}M_{23}) & \ln M_{33} & \ln(M_{34}M_{43}) \\ \ln\left(\dfrac{M_{41}}{M_{14}}\right) & \ln(M_{42}M_{24}) & \ln(M_{43}M_{34}) & \ln M_{44} \end{matrix} \right\|. \quad (1)$$

Physically, matrix operator (1) has the meaning of fluctuations ($\overline{\sigma}_i^2$) of polarization properties

Thirteenth International Conference on Correlation Optics, edited by Oleg V. Angelsky, Proc. of SPIE Vol. 10612, 106121I · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2305329

$$\left\{\Delta m^2\right\} = \left\| \begin{matrix} \left(\bar\sigma_4^2+\bar\sigma_5^2+\bar\sigma_6^2\right)_{11} & -0,5\left(\bar\sigma_2\bar\sigma_6-\bar\sigma_3\bar\sigma_5\right)_{12} & -0,5\left(\bar\sigma_3\bar\sigma_4-\bar\sigma_1\bar\sigma_6\right)_{13} & -0,5\left(\bar\sigma_1\bar\sigma_5-\bar\sigma_2\bar\sigma_4\right)_{14} \\ 0,5\left(\bar\sigma_2\bar\sigma_6-\bar\sigma_3\bar\sigma_5\right)_{21} & \left(\bar\sigma_4^2-\bar\sigma_2^2-\bar\sigma_3^2\right)_{22} & 0,5\left(\bar\sigma_1\bar\sigma_2+\bar\sigma_4\bar\sigma_5\right)_{23} & 0,5\left(\bar\sigma_1\bar\sigma_3+\bar\sigma_4\bar\sigma_5\right)_{24} \\ 0,5\left(\bar\sigma_3\bar\sigma_4-\bar\sigma_1\bar\sigma_6\right)_{31} & 0,5\left(\bar\sigma_1\bar\sigma_2+\bar\sigma_4\bar\sigma_5\right)_{32} & \left(\bar\sigma_5^2-\bar\sigma_1^2-\bar\sigma_3^2\right)_{33} & 0,5\left(\bar\sigma_2\bar\sigma_3+\bar\sigma_5\bar\sigma_6\right)_{34} \\ 0,5\left(\bar\sigma_1\bar\sigma_5-\bar\sigma_2\bar\sigma_4\right)_{41} & 0,5\left(\bar\sigma_1\bar\sigma_3+\bar\sigma_4\bar\sigma_6\right)_{42} & 0,5\left(\bar\sigma_2\bar\sigma_3+\bar\sigma_5\bar\sigma_6\right)_{43} & \left(\bar\sigma_6^2-\bar\sigma_1^2-\bar\sigma_3^2\right)_{44} \end{matrix} \right\|. \quad (2)$$

Here

$$\sigma_i = \begin{pmatrix} \sigma_1 = \sqrt{D_{LD}} \\ \sigma_2 = \sqrt{D_{CD}} \\ \sigma_3 = \sqrt{D_{LD'}} \\ \sigma_4 = \sqrt{D_{LB}} \\ \sigma_5 = \sqrt{D_{CB}} \\ \sigma_6 = \sqrt{D_{LB'}} \end{pmatrix}, \quad (3)$$

where

- LD and LB – linear dichroism and birefringence for the direction of the optical axis $\gamma = 0^0$;
- $LD^/$ and $LB^/$ – linear dichroism and birefringence for the direction of the optical axis $\gamma = 45^0$;
- CD and CB - circular dichroism and birefringence;
- M_{ik} - Mueller-matrix elements [13-22];

Such a parameters are in particular investigated for optically thin (non-depolarizing) layers of the histological sections of biological tissues and films of biological liquids [23-39]. For depolarizing layers such data is not obtained.

Thus, the use of ideology differential analysis of Mueller matrix mapping data allowed us to obtain a set of algorithms of polarization reconstruction of average values of флуктуаций phase and amplitude anisotropy parameters of polycrystalline component of biological layer.

The analysis of expressions (2)-(3) reveals the following physical content of the partial elements of the depolarization component of the Mueller matrix of the optically thick biological layer with fluctuations of the linear and circular birefringence and dichroism parameters. The diagonal elements $\left\{\Delta m^2\right\}_{ii}$ are determined by combinations of dispersion D_i of the parameters fluctuations of various mechanisms of phase and amplitude anisotropy.

1.2. Experimental results of the method differential mapping

We obtain an expression for calculating elements of differential matrix of the 2nd order

$$\left\{\Delta m^2\right\} = 0,5z^{-2} \times \left\| \begin{matrix} \ln 0.5(V_1^0+V_1^{90}) & \ln\left(\frac{(V_1^0-V_1^{90})}{V_2^0+V_2^{90})}\right) & \ln\left(\frac{V_1^{45}-0.5(V_1^0+V_1^{90})}{0.5(V_3^0+V_3^{90})}\right) & \ln\left(\frac{V_1^{\otimes}-0.5(V_1^0+V_1^{90})}{0.5(V_4^0+V_4^{90})}\right) \\ \ln\left(\frac{V_2^0+V_2^{90})}{(V_1^0-V_1^{90})}\right) & \ln 0.5(V_2^0-V_2^{90}) & \ln\left(\left(V_2^{45}-0.5(V_2^0+V_2^{90})\right)0.5(V_3^0-V_3^{90})\right) & \ln 0.5(V_4^0-V_4^{90})\left(V_2^{\otimes}-0.5(V_2^0+V_2^{90})\right)\big) \\ \ln\left(\frac{0.5(V_3^0+V_3^{90})}{V_1^{45}-0.5(V_1^0+V_1^{90})}\right) & \ln\left(0.5(V_3^0-V_3^{90})(V_2^{45}-0.5(V_2^0+V_2^{90})\right) & \ln\left(V_3^{45}-0.5(V_3^0+V_3^{90})\right) & \ln 0.5\left(V_3^{\otimes}-0.5(V_3^0+V_3^{90})(V_4^0-V_4^{90})\right) \\ \ln\left(\frac{0.5(V_4^0+V_4^{90})}{V_1^{\otimes}-0.5(V_1^0+V_1^{90})}\right) & \ln 0.5(V_4^0-V_4^{90})\left(V_2^{\otimes}-0.5(V_2^0+V_2^{90})\right)\big) & \ln 0.5\left(V_3^{\otimes}-0.5(V_3^0+V_3^{90})(V_4^0-V_4^{90})\right) & \ln\left(V_4^{\otimes}-0.5(V_4^0+V_4^{90})\right) \end{matrix} \right\| \quad (4)$$

Here $V_{i=1;2;3;4}^{0;45;90,\otimes}$ - Stokes vectors of differently polarized beams [1-3, 13-16]

The results of experimental approbation of the method of differential mapping of depolarizing component of polycrystalline structure of diffuse biological layer for optically thick layer of rectum ($z = 100\mu m; \tau = 1{,}36; \Lambda = 83\%$, z - geometrical thickness; τ - extinction coefficient; Λ - depolarization degree) are illustrated by a series of dependencies (maps and histograms of m_{ik} distributions), which are shown in Fig. 1 and Fig. 2

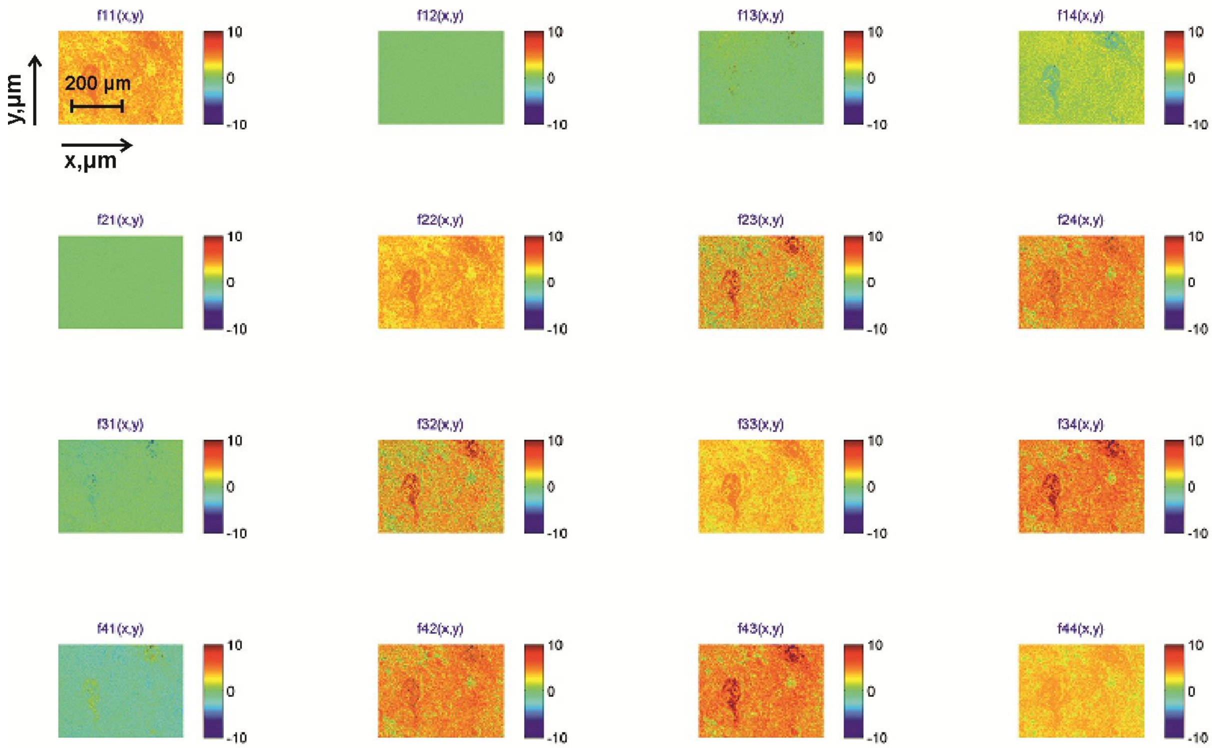

Fig. 1. Maps of elements of the 2st-order differential matrix of a histological section of rectum wall ($z = 100\mu m; \tau = 1{,}36; \Lambda = 83\%$).

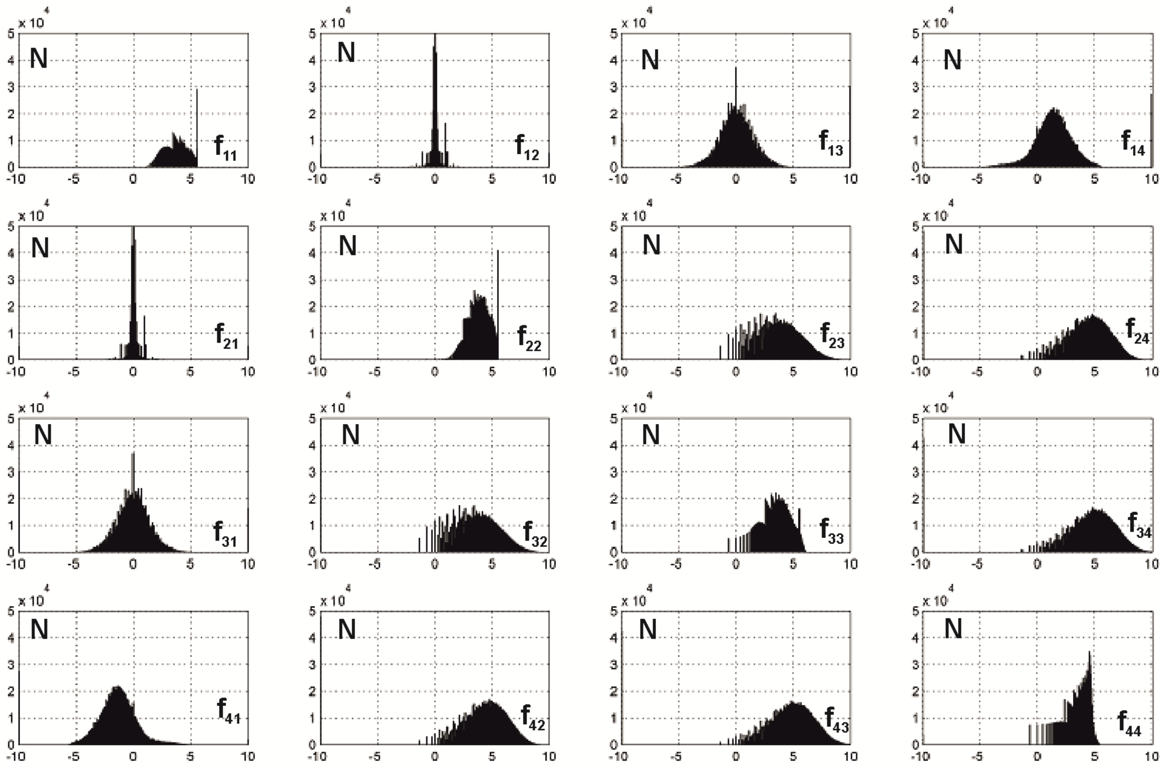

Fig. 2. Histograms of distribution of values of the 2st-order differential matrix elements of a histological section of rectum wall tissue ($z = 100\mu m; \tau = 1{,}36; \Lambda = 83\%$).

Table 1 presents the results of statistic analysis (statistical moments of the 1st-4th orders $Z_{i=1;2;3;4}$) of coordinate distributions of the values of diagonal elements of differential Mueller matrix of the 2nd order.

Table 1. Statistical moments $Z_{i=1;2;3;4}$ of the distributions of anisotropy parameters of depolarizing layer of rectum wall tissue

$Z_{i=1;2;3;4}$	Δm_{11}^2	Δm_{22}^2	Δm_{33}^2	Δm_{44}^2
$Z_{i=1}$	1,87	1,79	2,02	1,65
$Z_{i=2}$	1,37	1,55	1,29	1,42
$Z_{i=3}$	0,45	0,73	1,18	0,61
$Z_{i=4}$	0,78	1,27	1,85	0,94

It was defined the individual sensitivity of the value of $Z_{i=3;4}$ to the peculiarities of coordinate distributions of fluctuation of optical anisotropy parameters of partially depolarizing layer of rectum wall tissue.

Such a fact was chosen as the basic for applied biomedical usage of statistic analysis of coordinate distributions of fluctuation of both birefringence and dichroism values on diffusive layers of rectum wall tissue.

2. CLINICAL APPLICATION OF MUELLER-MATRIX MAPPING OF BIOLOGICAL LAYERS IN DIFFERENTIAL DIAGNOSTICS OF VAGINA WALL TISSUE WITH PROLAPSE

2.1. Objects of investigation

It was investigated two groups of samples of biopsy of vagina wall tissue:

- healthy donors - control group 1 (30 samples);
- affected by prolapse - investigated group 2 (30 samples).

Histological sections were produced due to the standard technique on the freezing microtome.

2.2. Experimental results

The set of Figs. 3, 4 presents the results of Mueller-matrix mapping of the distributions of diagonal elements of differential matrix of the 2nd order of diffusive layers of vagina wall tissue of donors (Fig.3) and with prolapse (Fig.4).

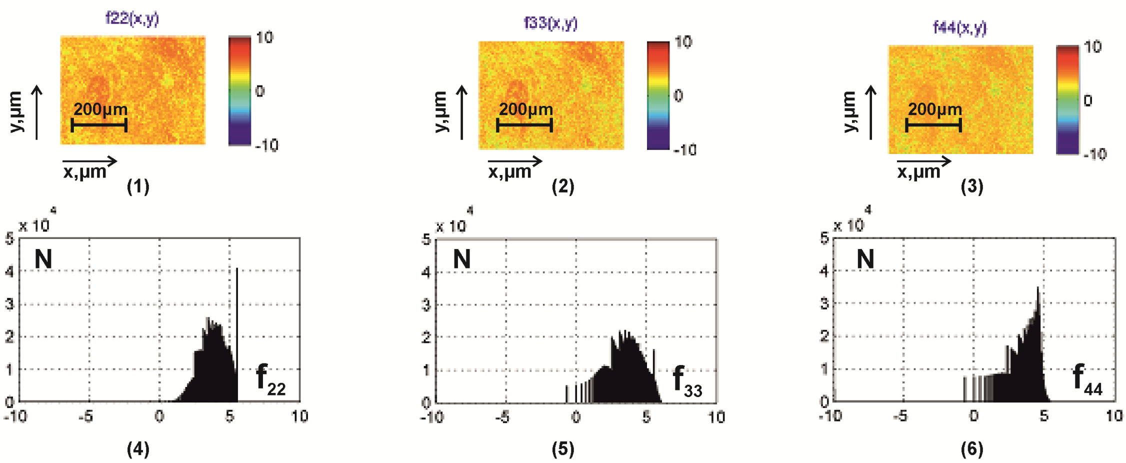

Fig. 3. Maps (upper line) and the histograms (bottom line) of the distribution values of diagonal elements Δm_{ii}^{2} of the histological sections of biopsy of vagina wall of donors.

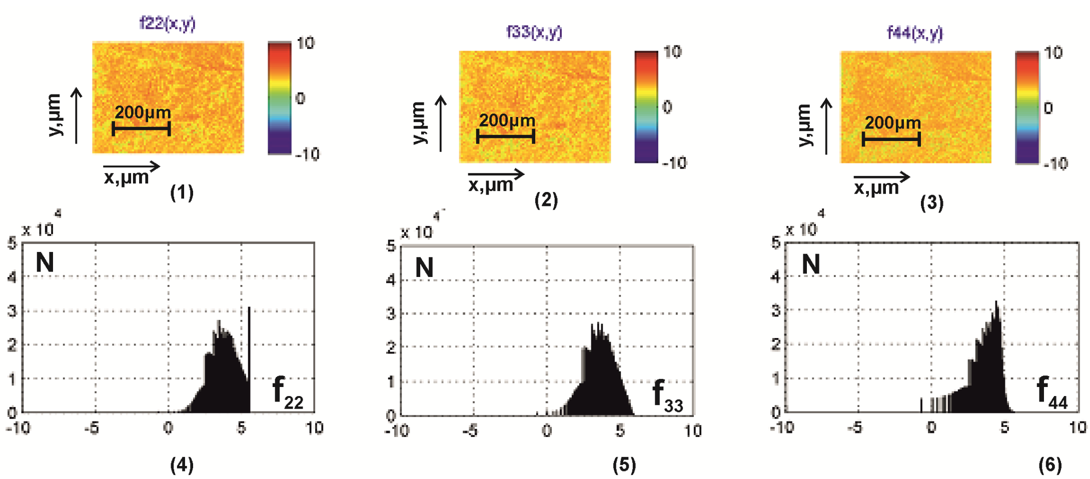

Fig. 4. Maps (upper line) and the histograms (bottom line) of the distribution values of diagonal elements Δm_{ii}^{2} of the histological sections of biopsy of vagina wall of patients with prolapse.

For the possible clinical application of the Mueller matrix mapping method for each group of samples the operating characteristics, typical for evidence-based medicine[37-39] that determine the diagnostic power of the method are determined, namely – sensitivity ($Se = \frac{a}{a+b} 100\%$), specificity ($Sp = \frac{c}{c+d} 100\%$) and balanced accuracy ($Ac = \frac{Se + Sp}{2}$), where a and b – the number of correct and incorrect diagnoses within group 2; c and d – the same within group 1 – Table 2.

Table 2. Balanced accuracy of method of differential Mueller-matrix mapping

$Ac,\%$	Δm_{22}^2	Δm_{33}^2	Δm_{44}^2
$Z_{i=1}$	61%	67%	64%
$Z_{i=2}$	72%	74%	71%
$Z_{i=3}$	88%	92%	93%
$Z_{i=4}$	93%	95%	96%

It was reached a good ($Ac\left(\Delta m_{22}^2\right) = 88\% - 93\%$) and excellent ($Ac\left(\Delta m_{33;44}^2\right) = 95\% - 96\%$) level of balanced accuracy of differential diagnostics of the biopsy samples of vagina wall tissue from donors and patients with prolapse.

CONCLUSIONS

Short theoretical basics of the method of differential Mueller-matrix mapping of the distribution of fluctuation of parameters of polycrystalline structure of depolarizing biological layers were provided. It was demonstrated the results of experimental approbation of such method and defined the parameters of differential Mueller matrix of the 2nd order of rectum wall tissue. The differential diagnostics of connecting component of vagina wall tissue was realized by means of statistic analysis of coordinate distribution fluctuation of the parameters of linear birefringence and dichroism of the diffusive samples of donors and patients with prolapse. It was reached a good and excellent levels of balanced accuracy of differential diagnostics of such samples.

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