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Multiple-channel Mueller-matrix optical coherence tomography in biological tissue

Shuliang Jiao[1], Wurong Yu[1], George Stoica[2] and Lihong V. Wang[1]
[1]Biomedical Engineering Program, Texas A&M University, College Station, TX 77843-3120
[2]Department of Pathobiology, Texas A&M University, College Station, TX 77843-5547
Email: LWang@tamu.edu; URL: http://oilab.tamu.edu

Abstract: **A multiple-channel polarization-sensitive system based on optical coherence tomography was built to measure the Mueller matrix of scattering biological tissue. The Jones matrix of a sample can be determined with a single scan and subsequently converted into an equivalent Mueller matrix. As a result, the system can be used to measure the polarization contrast of any kind of biological sample, such as soft tissue.**

***Keyword*: Optical coherence tomography; Jones matrix; Mueller matrix; polarization; burn depth.**

1. INTRODUCTION

Polarization-sensitive optical coherence tomography (PS-OCT) can reveal important polarization information about biological tissue, which is unavailable in conventional OCT [1]. The best way to ascertain the optical polarization properties of a sample is to measure its Mueller matrix [2], [3]. The combination of polarimetry and OCT makes it possible to acquire the Mueller matrix of a sample with OCT resolution. Jiao *et al* demonstrated that the degree of polarization of the back-scattered light measured with OCT remains unity—indicating that the measured Mueller matrix is non-depolarizing [3]. This conclusion allows the use of the Jones matrix in OCT. The relatively time-consuming process of the previous measurements of Mueller matrices limited the technique to use with stable samples such as bones. To measure unstable samples such as soft tissues, we developed a system that can determine the Jones matrix with a single depth scan (A scan) [4]. The Jones matrix **J** can be transformed into an equivalent non-depolarizing Mueller matrix by $\mathbf{M} = \mathbf{U}(\mathbf{J} \otimes \mathbf{J}^*)\mathbf{U}^{-1}$, where $\otimes$ represents the Kronecker tensor product and **U** is the 4×4 Jones–Mueller transformation matrix [1, 0, 0, 1; 1, 0, 0, −1; 0, 1, 1, 0; 0, *i*, −*i*, 0], which is written row by row [5]. The Jones matrix has four complex elements, in which seven real parameters are independent.

2. METHODS

The schematic of the experimental setup is shown in Fig. 1. Two superluminescent diodes (central wavelength λ = 850 nm, FWHM bandwidth $\Delta\lambda$ = 26 nm) are employed as low-coherence light sources and are amplitude modulated at 3 and 3.5 kHz. The two source beams are merged by a polarizing beam splitter, filtered by a spatial filter assembly, and then split into the reference and sample arms by a non-polarizing beam splitter. The sample beam passes through a quarter-wave plate (λ/4 plate) oriented at 45°, and is focused into the sample by an objective lens (L1: f = 15 mm and NA = 0.15). The reference arm consists of a λ/4 plate oriented at 22.5°, a lens (L2), and a mirror. After double passing through the λ/4 plate, the horizontal polarization (*H*) of the incident light is converted into 45° polarization, and the vertical polarization (*V*) of the incident light is converted into −45° polarization. The reference beam combines with the back-scattered sample beam through the non-polarizing beam splitter. The combined light is split into two orthogonal polarization components by polarizing beam splitter PBS2. The two components are coupled into two single-mode optical fibers, which are connected to photodiodes PDH and PDV, respectively. A data-acquisition board sampling at 50,000/s digitizes the two signals. A Doppler frequency of ~1.2 kHz is generated by the linear scan of the reference mirror. The carrier frequencies are the beat and harmonic frequencies between this Doppler frequency and the modulation frequencies of the light sources.

The incident Jones vectors, $\mathbf{E}_i$, to the sample arm is transformed to the detected Jones vector, $\mathbf{E}_o$, as follows:

$$\begin{aligned}\mathbf{E}_o &= \mathbf{J}_{NBS}\mathbf{J}_{QB}\mathbf{J}_{SB}\mathbf{J}_M\mathbf{J}_{SI}\mathbf{J}_{QI}\mathbf{E}_i \\ &= \mathbf{J}_{NBS}\mathbf{J}_{QB}\mathbf{J}\mathbf{J}_{QI}\mathbf{E}_i = \mathbf{J}_T\mathbf{E}_i\end{aligned} \quad (1)$$

where $\mathbf{J}_{QI}$ and $\mathbf{J}_{QB}$ are the Jones matrices of the λ/4 plate for the incident and the backscattered light, respectively; $\mathbf{J}_{SI}$ and $\mathbf{J}_{SB}$ are the Jones matrices of the sample for the incident and the backscattered light, respectively; $\mathbf{J}_M$ is the Jones matrix of single backscattering—the same as the one for a mirror; $\mathbf{J}_{NBS}$ is the Jones matrix of the reflecting surface of the non-polarizing beam splitter; **J** is the combined round-trip Jones

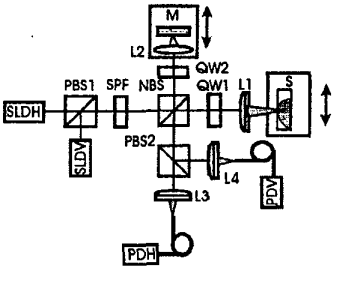

Fig. 1. Schematic of the multiple-channel polarization-sensitive OCT system: SLDH and SLDV are superluminescent diodes, horizontally (*H*) and vertically polarized (*V*), respectively; PBS1, PBS2, polarizing beam splitters; SPF, spatial filter assembly; NBS, nonpolarizing beam splitter; QW1, QW2, zero-order quarter-wave plates; M, mirror; L1–L4, lenses; S, sample; PDH and PDV are photodiodes for *H* and *V*

matrix of the scattering media; and $\mathbf{J}_T$ is the overall round-trip Jones matrix. As a result of the reciprocal constraint [6], the matrices $\mathbf{J}$ and $\mathbf{J}_T$ are transpose symmetric.

We band-pass filter the interference signals with central frequencies of 4.2 kHz and 4.7 kHz—the harmonic frequencies of the interference signals of source H and source V, respectively—to extract the interference components of each light source. The two orthogonal interference components (H and V) form the imaginary parts of the output Jones vectors, whose real parts are obtained through inverse Hilbert transformation [7]. When the output Jones vectors for the two independent incident polarization states are determined, the elements of the Jones matrix can then be calculated based on (1).

3. RESULTS

The system was first tested by measurement of the matrix of a standard sample—a $\lambda/4$ plate at various orientations in combination with a mirror. The results show that the measured data agree very well with the theoretical values.

The system was then applied to image soft tissue (a piece of rat skin). The sample was mounted in a cuvette filled with saline solution. The sample was transversely scanned with a step size of 10 μm, and multiple A-scan images were taken. For each A scan, the pixels were formed by averaging the calculated elements of the Jones matrix over segments of 1000 points—the resolution of the system. Two-dimensional (2D) images were formed from these A-scan images and then median filtered. The final 2D images are shown in Fig. 2 (a).

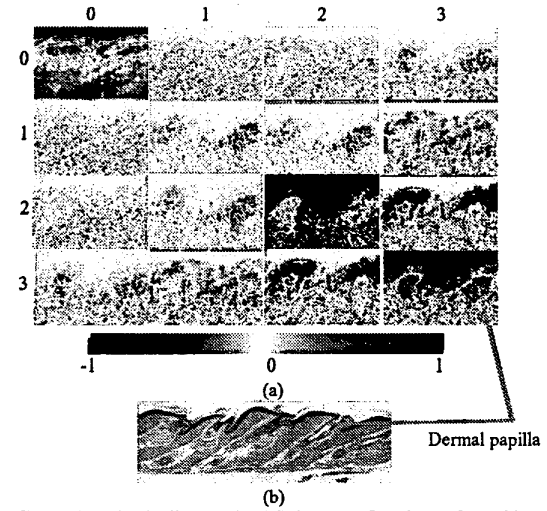

Fig. 2. (a) 2D Mueller-matrix (**M**) images of a piece of rat skin. Each image except M_{00} is pixel-wise normalized with the M_{00} element and shares the same color table. The size of each image is 1.5 mm × 1 mm. (b) routine histologic image.

Clear high birefringent cluster structures can be seen in some of the images. There is no such structure present in the M_{00} image, which is the image based on the intensity of the back-scattered light. In other words, the M_{00} image is free of the effect of polarization. The high birefringent clusters correspond to the dermal papilla of the rat skin, as shown in Fig.2(b), which is composed of collagen, a highly birefringent biological component. The birefringence image and the histology conform to each other very well.

4. CONCLUSION

In summary, we have developed a novel multiple-channel polarization-sensitive OCT imaging technique. The Jones matrix of a sample can be determined with a single scan. This technique permits the acquisition of 2D tomographic Mueller-matrix images of either hard or soft biological tissues. The Mueller matrix can be decomposed to extract important information on the optical polarization properties of a sample. The polarization properties can potentially be correlated with the conditions of biological tissues and thus used for disease diagnosis.

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References

[1]. J. F. de Boer, T. E. Milner, M. J. C. van Gemert and J. S. Nelson, "Two-dimensional birefringence imaging in biological tissue by polarization-sensitive optical coherence tomography", Opt. Lett. **22**, 934 (1997).

[2]. G. Yao and L.-H. V. Wang, "Two-dimensional depth-resolved Mueller matrix characterization of biological tissue by optical coherence tomography", Opt. Lett. **24**, 537 (1999).

[3]. S. Jiao, G. Yao and L.-H. V. Wang, "Depth-resolved two-dimensional Stokes vectors of backscattered light and Mueller matrices of biological tissue measured with optical coherence tomography", Appl. Opt. **39**, 6318 (2000).

[4]. S. Jiao and L. V. Wang, "Two-dimensional depth-resolved Mueller matrix of biological tissue measured with double-beam polarization-sensitive optical coherence tomography", Opt. Lett., 27, 101(2002).

[5]. F. Le Roy-Brehonnet and B. Le Jeune, "Utilization of Mueller matrix formalism to obtain optical targets depolarization and polarization properties", Prog. Quant. Electr. **21**, 109 (1997).

[6]. N. Vansteenkiste, P. Vignolo and A. Aspect, "Optical reversibility theorems for polarization: application to remote control of polarization", J. Opt. Soc. Am. A **10**, 2240 (1993).

[7]. Y. Zhao, Z. Chen, C. Saxer, S. Xiang, J. F. de Boer and J. S. Nelson, "Phase-resolved optical coherence tomography and optical Doppler tomography for imaging blood flow in human skin with fast scanning speed and high velocity sensitivity", Opt. Lett. **25**, 114 (2000).