doi: 10.4302/plp.2010.1.xx PHOTONICS LETTERS OF POLAND, VOL. **2** (1), XX-XX (2010)

Spectroscopic analysis for polarization sensitive optical coherent tomography

Marcin R. Strąkowski[*], Jerzy Pluciński, and Bogdan B. Kosmowski

Department of Optoelectronics and Electronic Systems, Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology, Narutowicza 11/12, 80-233 Gdańsk, Poland

Received June 15, 2009; accepted June 26, 2009; published June 30, 2009

Abstract— Polarization Sensitive Optical Coherent Tomography (PS-OCT) is a novel optical method for examination of a broad range of scattering materials. PS-OCT is an extension of OCT systems, which enables a cross-sectional visualization of device inner structure, as well as analysis of polarization state of light backscattered from particular points inside the tested device. Polarization sensitive analysis is a very useful tool in OCT measurements, however it brings a number of problems referring to measurement signal processing, birefringence changes of the investigated sample over the spectral width of the broadband light source. In this paper these problems have been discussed and possible solution have been given.

Optical coherence tomography (OCT) is an interferometric method for two and three-dimensional imaging of surface and subsurface structure of scattering materials with micrometer resolution. The OCT measurements are performed in non-contact and non-destructive way, therefore, this method is totally safe for the tested object [1][2]. Presently, the main applications of OCT cover medical diagnosis in the field of ophthalmology, dermatology and also dentistry [3][4]. However, the usefulness of OCT in beyond medical applications has been noticed. Nowadays, the OCT is used in industry and science for material characterization, surface and subsurface defect detection, strain fields mapping inside polymer materials, ceramic materials examination, as well as art conservation [5]-[9].

The OCT is based on the interference of the light beams, which have a low temporal coherence (WLI – White Light Interferometry or LCI – Low-Coherence Interferometry). Thereby, the light backscattered from the particular scattering points inside the investigated object can be selectively detected, which is needed for tomography imaging [1][2][10]. There are several types of OCT systems. Our research has been concentrated on Polarization Sensitive Optical Coherent Tomography (PS-OCT). Polarization sensitive analysis provides unique benefits to OCT measurements, which allow studying phenomena occurring in a tested sample that cannot be investigated by conventional OCT methods. This measurement method gives structural information about an investigated sample and also enables selective visualization of an optical anisotropic structure [1][2][7]. Hence, we apply this method to investigate birefringent complex structures like liquid crystals cells, polymer retarders, as well as polymer and ceramics composites. The PS-OCT system, which has been designed in Gdańsk University of Technology (Department of Optoelectronics and Electronic Systems), has been shown in Fig. 1 and Fig. 2.

Usunięto: short

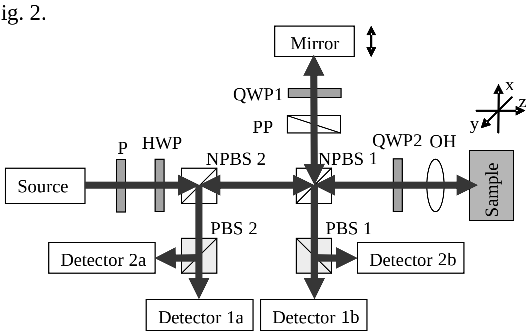

Fig. 1. The PS-OCT system setup; NPBS 1÷2 – non-polarizing beamsplitter, PBS 1÷2 - polarizing beamsplitter P – polarization plate, QWP 1÷2 – quarter-wave plate, HWP – half-wave plate.

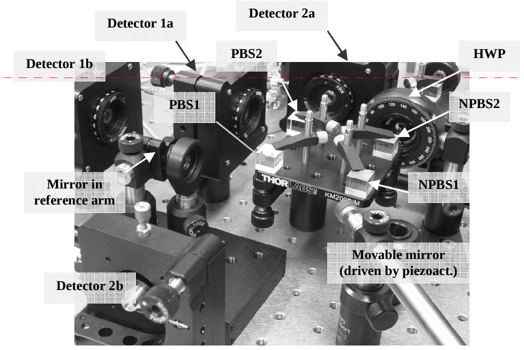

Fig. 2. The optical part of the PS-OCT system.

---

[*] E-mail: marcin.strakowski@eti.pg.gda.pl

The PS-OCT system (Fig. 1, Fig. 2) is based on the Michelson interferometer where the movable mirror driven by a piezo actuator is placed in the reference arm. The interferometer is illuminated by the broadband supercontinuum light source. The backscattered light beams from the sample and light reflected from the mirror are recombined and subsequently separated by a polarization beam splitter into orthogonal components which are recorded by two pairs of photodetectors (in Fig. 1: Detector 1a and 1b, Detector 2a and 2b). These detectors provide polarization diversity detection with excess noise elimination. The details of developed system has been described in [2][10][11]. In this system, as well as others such PS-OCT systems, the polarization state analysis is based on Jones formalism. The birefringent parameters of the investigated sample are calculated from the magnitude and phase of a received interference signal. These calculations are based on equations (1) and (2):

$$\Gamma(z) = a\tan\left(\frac{|I_H(z)|}{|I_V(z)|}\right), \qquad (1)$$

$$\Theta(z) = \frac{\pi - \Delta\varphi(z)}{2}, \qquad (2)$$

where: $I_H(z)$ and $I_V(z)$ – recorded interference signals at detector 1 and detector 2 respectively, $\Delta\varphi(z)$ – phase difference between recorded interference signals, $\Gamma(z)$ – depth (z) profile of retardation angle changes inside tested device, $\Theta(z)$ – depth profile of optical axis orientation of the device.

This method of polarization sensitive analysis has been developed for the PS-OCT systems where the light source fulfills the condition (3):

$$\lambda_0 >> \Delta\lambda, \qquad (3)$$

where: λ_0 – central wavelength and $\Delta\lambda$ – bandwidth of the light source.

In this particular case the both $\Gamma(z)$ and $\Theta(z)$ characteristics are calculated for central wavelength with sufficient accuracy. However, the range of measured values of retardation angle and fast axis orientation is limited to 90° for $\Gamma(z)$ and 180° for $\Theta(z)$. For high birefringent materials like liquid crystals cells or grass-fiber reinforced polymers the absolute values of $\Gamma(z)$ can be difficult to calculate [6]. Great progress in ultra-broadband light sources results in obtaining not only a better resolution of OCT measurements but also opens up new possibilities to apply spectroscopic analysis with success. Based on those well known methods the new method for ultra-high resolution PS-OCT systems can be developed [11]. This is new approach in PS-OCT, which enables the polarization sensitive analysis to be performed over the spectral range of the broadband light source. The method is based on spectroscopic analysis of the spectral characteristic of the light, which is backscattered from the particular points inside investigated device. One of the most important problems, which must be solved, is the selective reconstruction of the spectral characteristics from recorded interference signals. Consider the equation:

$$\begin{aligned} S_D(k) &= (\mathrm{DC}) + \\ &+ 2\cdot\sum_{n=1}^{N} |S_{Rn}(k)| \cdot \cos\left(2k\cdot(z_R - z_n) + \arg\{S_{Rn}(k)\}\right) + \qquad (4), \\ &+ (\text{auto - correlation terms}) \end{aligned}$$

which describes the OCT measurement signal in spectral domain. The $S_{Rn}(k)$ is the cross-spectral density of the interfering beams. It depends on the spectral characteristics of the light from the measurement and reference arm of the low-coherent interferometer. By the use of Fourier transform (FT) it is possible to transfer the $S_D(k)$ function to time domain, which has been shown as the relation (5).

$$\begin{aligned} FT\{S_D(k)\} &= I_D(z) = (\text{DC terms}) + \\ &+ \sum_{n=1}^{N} G_{Rn}(z) \otimes \left(\delta\left(z \pm 2(z_R - z_n)\right)\right) + \qquad (5) \\ &+ (\text{auto - correlation terms}) \end{aligned}$$

where: $G_{Rn}(z)$ – cross-correlation function of the light from reference arm and backscattered from particular n point inside the investigated sample, $(z_R - z_n)$ determines the optical delay between interfering beams. The cross-correlation function $G_{Rn}(z)$ and cross-spectral density $S_{Rn}(k)$ are related to each other by the pair of Fourier transforms. Therefore, if the $G_{Rn}(z)$ function can be obtained, the $S_{Rn}(k)$ will be determined. According to (5), the $G_{Rn}(z)$ function is separated in time domain, which facilitates its extraction from $I_D(z)$ characteristic. Based on the described relations the measurement signal procedure can be developed in order to obtain the complex spectral characteristic of the backscattered light [12]-[14]. An example of the signal processing, which has been described in details in [12][13], has been shown in Fig. 3.

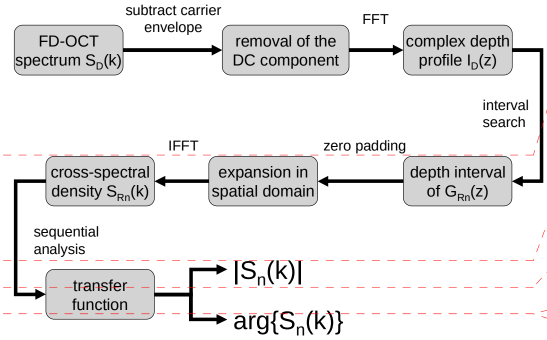

Fig. 3. The diagram of the measurement signal processing in optical coherence tomography with spectroscopic analysis; $S_n(k)$ – complex spectral characteristic of backscattered light from n point inside the device under tests.

Usunięto: -[12

Usunięto: is

Usunięto: suitable

Usunięto: ,

Usunięto: in which utilized broadband light source fulfills

Usunięto: 3

Usunięto: 5

Usunięto: 3

Usunięto: 4

Usunięto: However, if the light source does not satisfy the condition (3), the measurement error may reached even more than 20% of the maximum range of measured quantities.

Usunięto: The problem becomes very significant if the ultra-broadband source like supercontinuum are used. Therefore,

Usunięto: of measurement signal processing should be developed

Usunięto: 2

Usunięto: ¶
From our research and studies we propose novel application of spectroscopic analysis based on Fourier transform principles.

The presented algorithm can be easily adopted to our time domain PS-OCT system. The real part of $I_D(z)$ is proportional to time domain OCT measurement signal. Therefore using Hilbert transform and continuing the procedure for $I_D(z)$ it is possible to obtain the spectral information. This algorithm was used for $I_H(z)$ and $I_V(z)$ signals processing. The spectral characteristics of retardation angle changes were calculated based on the equations (1) and (2) performed for each wavelength values. An example of measurement results obtained for optical retarder has been presented in Fig.4.

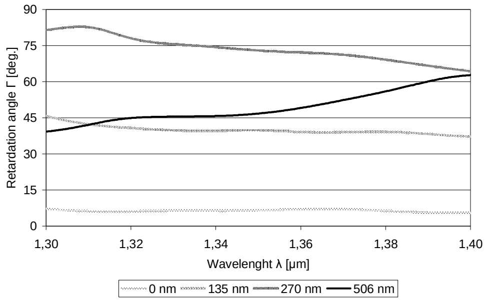

Fig. 4. Measured spectral characteristic of the retardation angle of the optical retarder.

As the device under test the Soleil-Babinet compensator was used. The retardation of the device was set to 0, 135 nm, 270 nm and 506 nm. These values correspond to 0°, 36°, 72° and 135° of the retardation angle for the wavelength equal 1.35 µm. The measurements were carried out using the PS-OCT system presented in Fig. 1 and Fig. 2, and described in [2][10][11]. As was expected the growth of the retardation value caused an increase in a mean value and slope of the measured retardation characteristic. If the retardation angle exceeds the 90° the direction of the slope of the measured characteristics is changing. Moreover, with the continuous growth of the retardation value the measured mean value of retardation angle decreases. Therefore, by the analysis of the slope and mean value of the retardation angle spectral characteristic it is possible to determine the absolute values of the investigated sample retardation.

In conclusions, the spectroscopic analysis can be useful method in polarization sensitive optical coherence tomography. It brings a unique benefits to PS-OCT measurement delivering full spectral information about backscattered light from the particular points inside the tested device. It enables an investigation of optical anisotropy changes occurring inside the device in the range of broadband light source spectrum. Moreover, combination of PS-OCT and spectroscopic analysis enables to conduct optical anisotropy and spectroscopic measurements simultaneously. Therefore, the polarization sensitive optical coherence tomography with spectroscopic analysis can be interesting tool for the investigation and quality assessment of the complex objects like printed electronics parts or polymer composites materials.

This study was partially supported by the Polish Ministry of Science and Higher Education under the grant No. N N515 335636, and DS programs of the Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology.

References

[1] A. F. Fercher, W. Drexler, and C. K. Hitzenberg, Reports on Progress in Physics **66**, 239 (2003).

[2] M. R. Strąkowski, J. Pluciński, M. Jędrzejewska-Szczerska, R. Hypszer, M. Maciejewski, and B. B. Kosmowski, Sensors and Actuators A **142**, 104 (2008).

[3] A. Szkulmowska, M. Szkulmowski, A. Kowalczyk, and M. Wojtkowski, Opt. Lett **33**, 1425 (2008).

[4] M. Wojtkowski, T. Bajraszewski, P. Targowski, and A. Kowalczyk, Opt. Lett. **28**, 1745, (2003).

[5] D. Stifter, P. Burgholzer, O. Höglinger, E. Götzinger, and C. K. Hitzenberger, Appl. Phys. **76**, 947 (2003).

[6] D. Stifter, Applied Physics B **88**, 337 (2007).

[7] D. Stifter, K. Wiesauer, M. Wurm, E. Schlotthauer, J. Kastner, M. Pircher, E. Götzinger, and C K Hitzenberger, Meas. Sci. Technol. **19**, 074011 (2008).

[8] K. Wiesauer, M. Pirchen, E. Gotzinger, and C. K. Hitzenberger, Composites Science and Technology **67**, 3051 (2007).

[9] P. Targowski, B. Rouba, M. Góra, L. Tymańska-Widmer, J. Marczak, A. Kowalczyk, Appl. Phys. A **92**, 1 (2008).

[10] J. Pluciński, R. Hypszer, P. Wierzba, M. Strąkowski, M. Jędrzejewska-Szczerska, M. Maciejewski, and B. B. Kosmowski, Bulletin of the Polish Academy of Sciences – Technical Sciences **56**, 155 (2008).

[11] M. Strąkowski, *Analiza stanu polaryzacji światła w układach optycznej tomografii koherentnej dla badań struktury materiałów optoelektronicznych i mikroelektronicznych* (PhD Dissertation, WETI PG 2010).

[12] Ch. Kasseck, V. Jaedicke, N. C. Gerhardt, H. Welp, M. R. Hofmann, Opt. Com. **283**, 4816 (2010).

[13] Ch. Kasseck, V. Jaedicke, N. C. Gerhardt, H. Welp, M. R. Hofmann, Proc. of SPIE **7554**, 75542T (2010).

[14] G. Latour, J. Moreau, M. Elias, J-M. Frigerio, Opt. Com. **283**, 4810 (2010).

Usunięto: 3

Usunięto: ···Podział kolumny···

Usunięto: <nr>A. F. Fercher, W. Drexler, and C. K. Hitzenberg, Reports on Progress in Physics **66**, 239 (2003).¶

Sformatowane: Punktory i numeracja

Sformatowano: Polski

Usunięto: Fig. 1¶
¶

Usunięto: Referring to our studies, it improves the polarization sensitive measurement accuracy more than twice [12].