

Polarization Sensitive and Mueller Matrix OCT measurements and data analysis

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ABSTRACT

The present work developed a Polarization Sensitive Optical Coherence Tomography system capable of perform birefringence images and also determine completely the Mueller Matrix of a sample, in depth. In this way many measurements were needed to be done, with different combinations of polarization states of the incident beam on the sample and the reference arm of the interferometer. After calibrating the system, a roll of adhesive tape was used as sample for two main reasons: presents birefringent and has a periodic structure. Firstly the system was set to gather data about the horizontal polarization state and then vertical polarization state of light to construct a birefringence image. The birefringence (δn) of ordinary adhesive tape was evaluated as $4.03(26) \times 10^{-4}$. Latter a system capable of measure any polarization state was implemented and 16 scattering profiles for different polarizations were collected. Software also was developed to solve a linear equations system. As a result a 4x4 matrix of images were calculated. Some of the features, as birefringence were easily indentified in some elements of this matrix, others, more subtle, can be founded in the literature. We also decomposed the matrix as linear combinations of other known optical elements.

Keywords: OCT, Mueller, polarization, coherence

1. INTRODUCTION

Optical interferometry is broadly known as a technology which delivers high precision measurements, and is used in many areas of knowledge, maybe the most famous one it is the Michelson and Morley experiment (1). Optical Low Coherence Interferometry (LCI) can be seen as a derivative form of interferometry in which polychromatic light sources is applied, this kind of interferometry has interesting properties which can provide information about the difference of optical path between the interferometers arms. LCI has being used for location of faults in optical fibers (2) and also in perfilometry (3).

In early 90's another breakthrough of LCI was done when it was applied to perform tomographic images of biological samples by Huang (4). Since then the name Optical Coherence Tomography became established and also the acronym OCT. This first OCT system, designed to detect structures capable of backscatter the light, could not explore information about the light polarization state.

Measure change in polarization in many cases can be considerate relatively simple process, but measure change in polarization as position function (inside a sample) it is not trivial. Using an OCT system it is possible to gather information from different polarizations states and perform not a scattering image, but it is possible to perform birefringence image (5). PS-OCT needs some modification in the setup - a polarized light source, polarization analyzer and a pair of quarter wave plate is needed.

In 1992 the first Polarization Sensitive OCT (PS-OCT) system was reported (5) allowing perform birefringence images, in this way the differences between the refraction indices, ordinary and extraordinary, can be analyzed as an image.

The polarization properties of the light can provide crucial information about the sample structure and composition, in biomedical applications the birefringence is, in many cases, related with tissue health.

Besides PS-OCT images, a more complex, but also more complete way to study the polarization properties of light can be done using the Mueller Matrix theory (6). This matrix, a 4x4 sized, describes how a sample changes the incident light polarization state. For an homogeneous media, like an optical glass, a single matrix can be used to describe it, but to describe inhomogeneous media, like a tissue, each point of the sample (pixel) will generate a matrix, in this way, to represent a tissue are needed 16 images, each of them related to an element in the 4x4 Mueller Matrix. In practice, the Mueller Matrix can be obtained using an OCT setup (MM-OCT) performing several measurements of the sample (7).

The aim of the present work was to implement a PS-OCT and a MM-OCT, perform measurements of a suitable sample and analyze the resulting images.

2. SIGNAL PROCESSING

The collected signal in the frequency domain needs to be processed to form images of interest, i.e., processing the signal will make the signal direct related with the sample morphology.

Although the processing algorithm has in the core the Fourier Transform to retrieve the scattering profile, some mathematical manipulations are necessary on the interferometric pattern due to correction and refinements reasons, aiming images with good quality. Some of these corrections are necessary due to physical limitation of the equipment, for example the limited pixel number, or more basic corrections, like changes of unities, for instance.

Algorithms based on Dorrer et al. work (8) were implemented to perform the processing needed in Frequency Domain OCT systems. Firstly these algorithms were implemented in a computational simulator aiming to study about the pros and cons of each one. The algorithms used are: Direct Fourier transform (DirFT), Interpolation (Int) and Zero-Filling (ZF). The algorithms were implemented following the scheme presented at Figure 1.

The direct Fourier transform (DirFT) method could be considered as the simpler one, consequently the more fast and robust. It perform just a change of unity, that is because spectrometers are calibrated in wavelength, and as OCTs gives information of depth (m), we need to change from wavelength to wave number ($k=2\pi/\lambda$). This process makes the spectrum, originally organized in crescent order in wavelength to a reversed order array, so the vector must to be inverted. After that the vector Fourier transform is done, resulting the scattering profile. The schematic diagram represents the process Fig. 9 (a). But this process, i.e., $1/x$, cause unequal sized bins, resulting in issues in the Fourier transform, leading to broadening of the structures and asymmetry of the peaks in respect to the it center. A method to avoid this problem is to perform an interpolation. After the changing of unities, the interpolation is done to retrieve equally sized bins, and then submitted to the Fourier transform, this process is schematically represented in the Figure 1 (b). The last method (Figure 1 (c)), Zero-Filling (ZF) is a more elaborated technique when compared with the two discussed previously, consequently more expensive computationally. The Zero-Filling technique is based in a mathematical gimmick, used to increase sampling without increase the data collection. In practice the (ZF) it is preformed applying the Fourier transform on the collected spectrum, then, in the reciprocal space, empty arrays (Zero-Filling) are added at the ends of the original array, Figure 2, the increased sampling of the original data will, according to the Nyquist theorem, allow to process higher frequencies resulting in less computational errors (9).

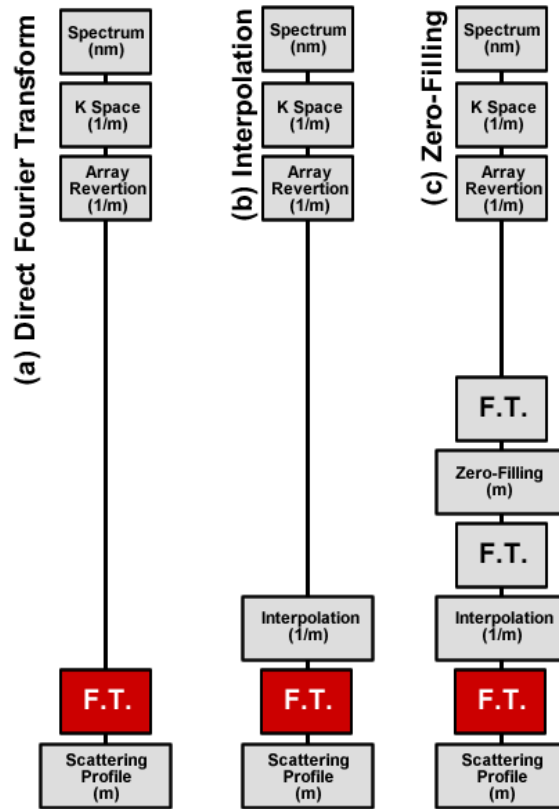


Figure 1: Flowchart representing the three algorithms used in this study.

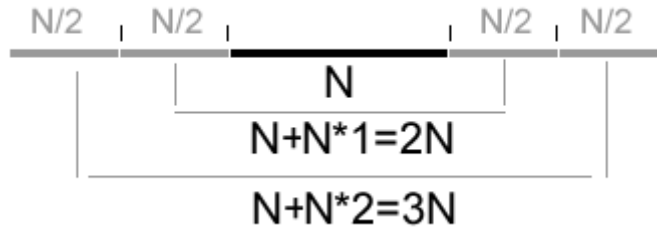


Figure 2: Schematic representation of Zero-Filling process.

The first step was to compare qualitatively the shape of the resulting peaks for the same input spectrum (Figure 3), we were looking for the narrower and tallest peak, and also for high signal/noise ratio. The processing time of each one were studied too (Figure 4).

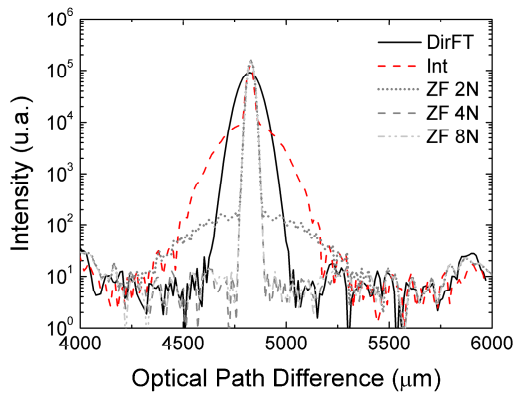


Figure 3: Profile characteristics of each processing type.

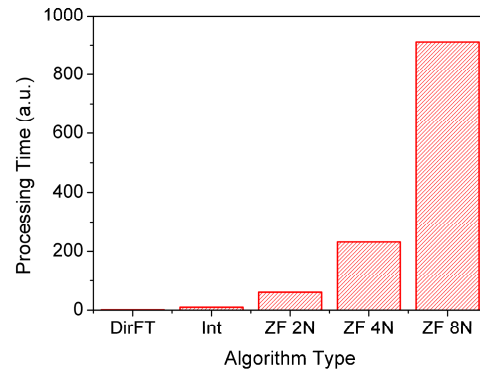


Figure 4: Processing time of each algorithm

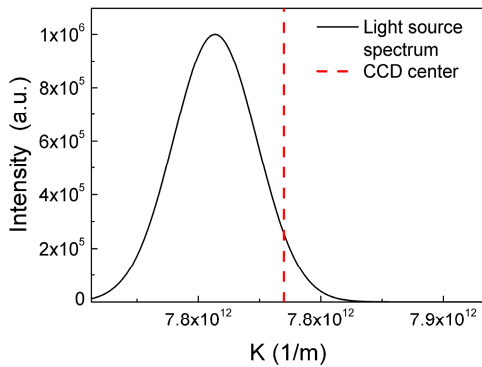


Figure 5: Simulated Gaussian spectrum and its asymmetry in respect to the CCD center.

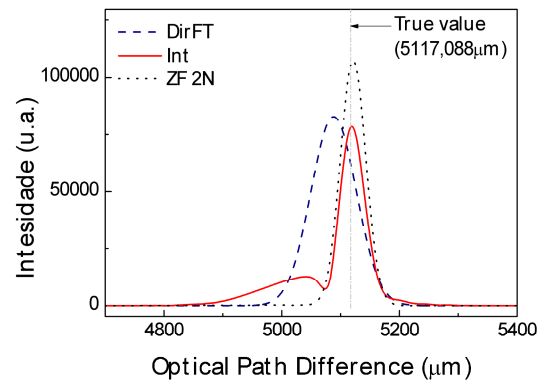


Figure 6: Error and peak shape analysis.

An issue, concerning the Interpolation (Int) algorithm, was verified when the spectrum peak is not near of the CCD center (Figure 5) a false structure appears for great optical path differences (high frequencies), see Figure 6 where doublet like structure can be seen for the Int algorithm. We attributed this behavior to issues due to, besides minimal, the abrupt cut of the tail of the Gaussian curve.

Due to robustness, accuracy and processing time, the algorithm ZF 2N was used in this study.

3. EXPERIMENTAL SETUP

Both setups used Ti:Sapphire mode-locked laser with ~ 35 nm FWHM (Coherent® MIRA), one Czerny-Turner spectrometer with 0.027 nm of spectral resolution (Princeton® Acton 2500i) and a XY scanning system (GSI Lumonics®). Both systems, PS-OCT and MM-OCT, were air based (without optical fibers). The schematic representations of the systems are shown in the Figure 7 and Figure 8, respectively.

The system presented at Figure 7 was based on the work performed by (5). The purpose of the optical polarization elements is to promote a linear polarization state at $+45^\circ$ at the spectrometer by the reference arm, and induce a circular polarization at the sample. In this way the former avoid alignment of a linear polarization with an optical axis of the sample, and the latter gives projections that allow interference pattern to both polarizations states of interest: vertical and horizontal.

To perform MM-OCT images a more versatile system were mounted, Figure 8. Optical compensators were put in the laser output and in the reference arm, in this way any combination of polarization could be set in both arms. The polarization states were gauged using a polarimeter (TXP by Thorlabs®).

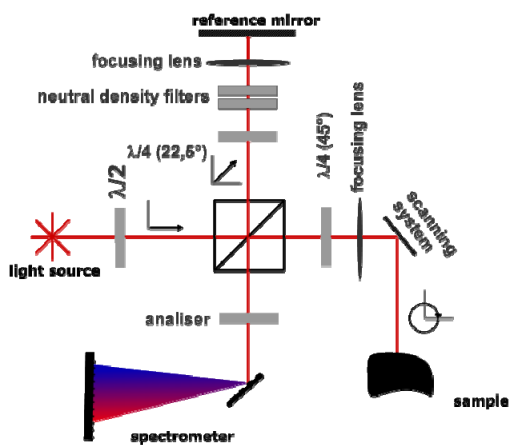


Figure 7: PS-OCT setup.

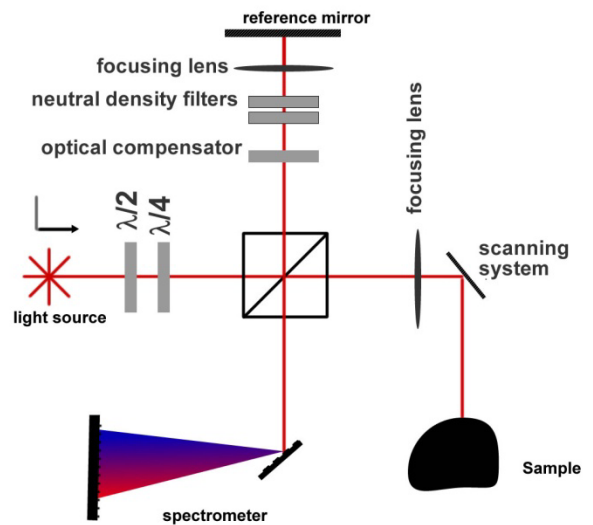


Figure 8: MM-OCT setup.

As sample, a roll of adhesive tape (scotch tape like) was chosen due to its physical and optical properties: the adhesive tape presents birefringence, is quite transparent to near infrared radiation and also presents a periodic and scattering structure, also has low cost and is present in any laboratory.

4. RESULTS AND ANALYSIS

The PS-OCT was able to perform birefringence images, Figure 9, and using the equation 1 (10):

$$\delta n = \frac{\pi}{k_0 z} \quad (1)$$

where z is the spatial period of the birefringence fringes, allowed us to calculate the difference between the ordinary and extraordinary refraction indices (δn) of the adhesive tape as $4.03(26) \times 10^{-4}$.

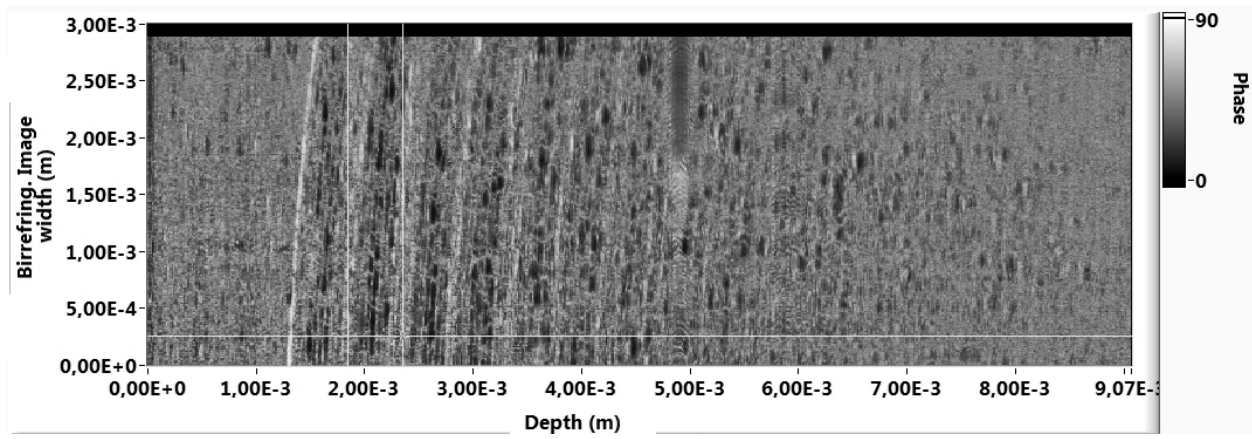


Figure 9: Birefringence image of the adhesive tape.

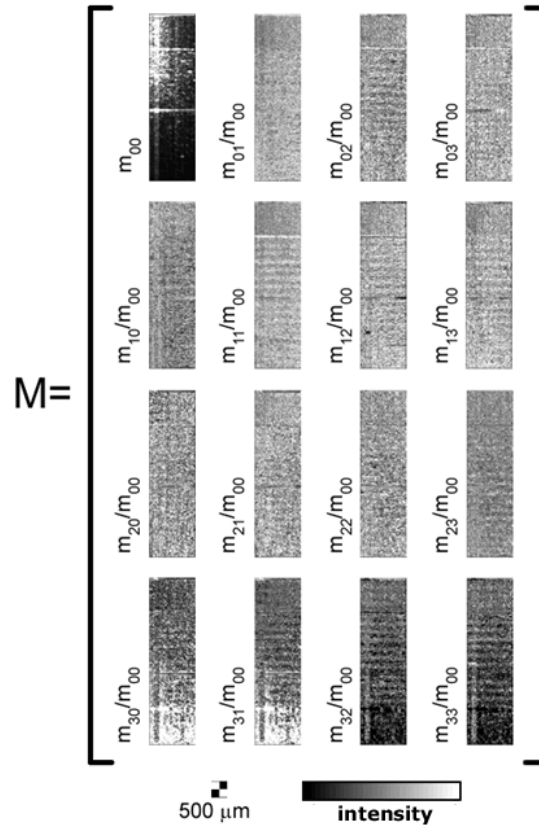


Figure 10: Mueller matrix of adhesive tape

The MM-OCT also performed the images of the same sample, and the Mueller Matrix was calculated, Figure 10, with software developed for this purpose, programmed in LabVIEW® environment, applying the method described by (7). As attempt to better understanding the Muller Matrix, mainly because the complexness of it, an approach to decompose it as a linear combination of four other Mueller Matrices:

$$M_{Sample} = a \cdot M_1 + b \cdot M_2 + c \cdot M_3 + d \cdot M_4 \quad (2)$$

Where, $M_{1,2,3,4}$ are predefined matrices, and in this study we have chose the matrices of: horizontal aligned polarizer, vertical aligned polarizer, $+45^\circ$ aligned polarizer and right handed circular polarizer. Other developed software was programmed to perform de decomposition. In this way the images are now the coefficient matrix a, b, c and d . The resulting images are presented in the Figure 11.

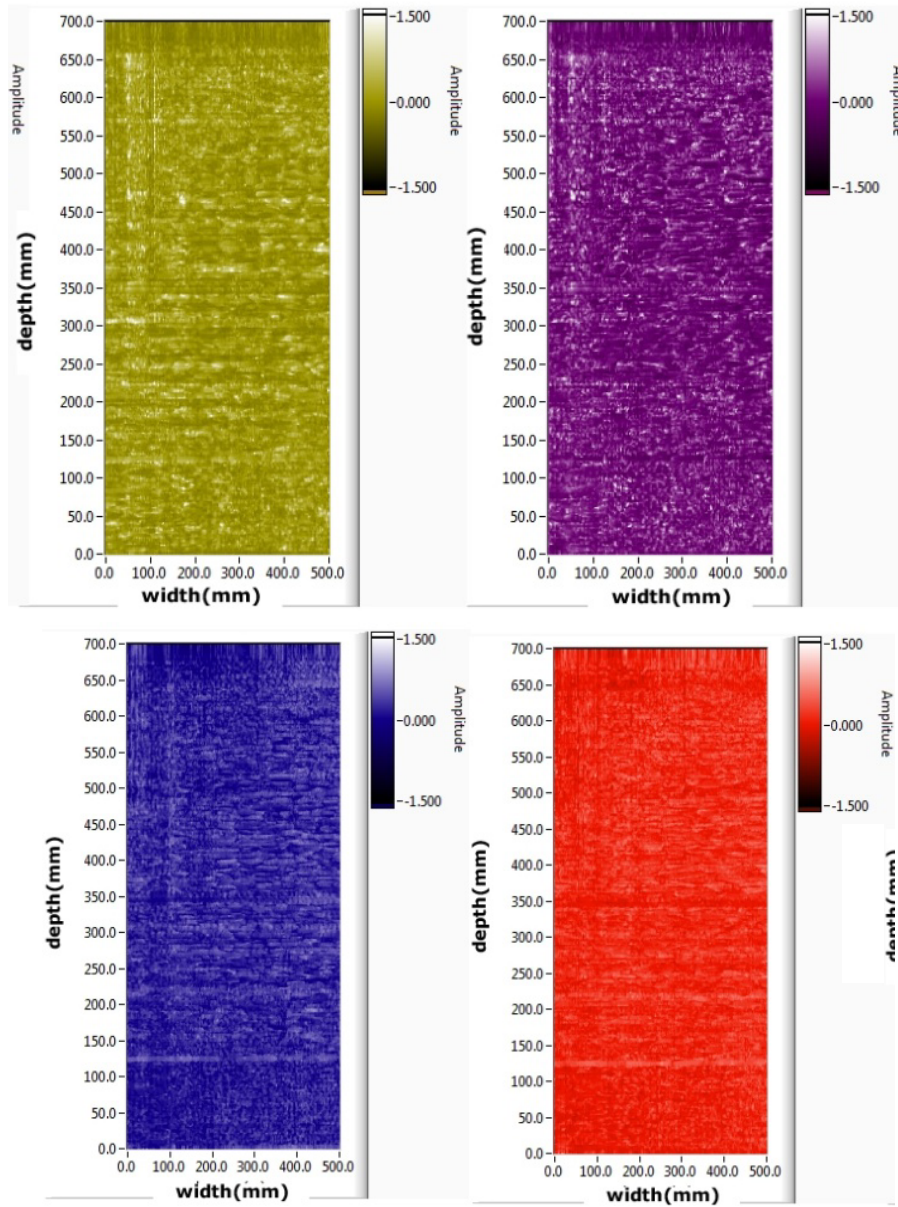


Figure 11: Coefficients images of the linear decomposing.

5. CONCLUSIONS

Finally, was possible to conclude that the both systems were able to perform the desired images. Although, due to the slowness of the spectrometer system, the longitudinal laser modes were able to change during the measures, resulting in a false structure near of 5 mm deep (Figure 9).

The adhesive tape has, indeed, perfect characteristics to be used as a test sample in PS/MM or even the regular scattering OCT systems, and could be used as a reference to compare results between researches groups, aiming that exist a lack of materials to use as a comparison standard.

The linear decomposing of the Mueller matrix promoted images that carry visually comprehensive optical properties, although a more established standard would be a better sample to understanding more deeply the results of this proceeding. The goal of this step, in a near future, is to decompose a Mueller matrix images in other images that can be more directed understood, even using Mueller Matrices experimentally measured ($M_{1,2,3,4}$) in a way that we could relate a sample as a linear composition of any other Mueller matrices.

ACKNOWLEDGEMENTS

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