Quantitative single-mode fiber based PS-OCT with single input polarization state using Mueller matrix

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Abstract: We present a simple but effective method to quantitatively measure the birefringence of tissue by an all single-mode fiber (SMF) based polarization-sensitive optical coherence tomography (PS-OCT) with single input polarization state. We theoretically verify that our SMF based PS-OCT system can quantify the phase retardance and optic axis orientation after a simple calibration process using a quarter wave plate (QWP). Based on the proposed method, the quantification of the phase retardance and optic axis orientation of a Berek polarization compensator and biological tissues were demonstrated.

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1. Introduction

Polarization-sensitive optical coherence tomography (PS-OCT) [1] is a functional extension of optical coherence tomography (OCT) [2], which is particularly useful when the nano-scale organization of tissue are difficult to be observed in the intensity images of a regular OCT [3, 4]. It has been used for many important medical applications, including measuring the retinal nerve fiber thickness [5], assessing the collagen content of coronary artery plaque [6], identifying basal cell carcinoma [7], and constructing whole brain micro-tractography [8, 9].

PS-OCT systems can be categorized to two kinds by the number of input polarization states: multi-input polarization state (multi-IPS) and single IPS. In the multi-IPS systems [10–25], sample motion or birefringence changes in the fiber-optics slower than the time interval between successive A lines can be compensated by referencing the polarization measurement from the sample surface. The information from different input polarization states can be obtained simultaneously by depth multiplexing [22, 25] or frequency multiplexing [21]. However, multiplexing requires additional modulation or polarization delay-line unit which may increase the cost and the complexity of system.

In contrast, single IPS system is simpler than the multi-IPS system [26]. However, the cross-talk between orthogonal polarization channels caused by the birefringence variation of the fiber-optics needs to be carefully avoided. There are several different single IPS configurations: bulk optics based system [1, 22, 27–29], polarization-maintaining fiber (PMF) based system [3, 30–34], single-mode fiber (SMF) based system [35] and PMF/SMF mixture system [36]. These systems use the same algorithm [28] to obtain polarization information by assuming that the polarization cross-talk doesn’t happen when light travels in the fibers. In order to fulfill this assumption, SMF components in the system need to be carefully fixed and isolated from the environment.

Bulk-optics system provides minimum polarization cross-talk, but it is difficult to be used in clinics due to the demand of careful light coupling. On the other hand, fiber-based PS-OCT offers easy alignment, compact size, and the possibility of miniaturizing the probe size. PMF-based systems demonstrate great polarization stability and has been used for constructing ex vivo whole brain tractography [8, 9] and performing in vivo retina imaging [30]. However, the “ghost peaks” caused by the cross-talk between the orthogonal polarization channels of PMF needs to be shifted to a position where it doesn’t impact the sample imaging by adding long (20-30m) PMF in the arms of the interferometer and by carefully aligning the angle of PMF components when splicing them together [31, 32]. In general, PMF systems have higher cost than SMF systems.

SMF-based PS-OCT with single IPS has several advantages: low system complexity, no ghost peaks, low cost, and easy conversion to PS-OCT from regular OCT. However, the polarization crosstalk needs to be carefully avoided. With good environment isolation, SMF system demonstrates good long term (two weeks) polarization stability [35]. Thorlabs Inc. produces an all-SMF-based PS-OCT with single IPS (PSOCT1300, Thorlabs) [37] that can provide polarization contrast imaging of biological tissues [38, 39]. However, this system cannot provide quantitative birefringence and optic axis orientation measurement. Lin et al. [36] present a hybrid PMF/SMF based PS-OCT to obtain quantitative birefringence information. In this system, SMF and two polarization controllers (PC) are used in the arms of the interferometer to replace the QWPs typically used in PMF systems. The rest is similar to the PMF-based system. Since the system contains PMF components, the ghost peaks need to be carefully avoided. Trasischker et al. [35] introduce an all-SMF-based PS-OCT, which avoids the problem of ghost peak. However, this method requires a time-consuming process to ensure that the incident light on sample is circularly polarized.

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In this paper, we propose a simple method to quantify the phase retardance and the optic axis orientation of tissue using an all-SMF-based PS-OCT with single IPS. By analyzing the Mueller matrix of the SMF system and sample, we theoretically prove that the SMF-based PS-OCT system can measure the phase retardance and optic axis orientation when the phase retardance of SMF system is calibrated to the integer multiplication of \( \pi \) and the reference power is equally distributed on the orthogonal channels. The system retardance can be adjusted to integer \( \pi \) by using a QWP as a standard sample and by adjusting the polarization controller on the sample arm to make the output Stokes vectors from the front and back surfaces of the QWP \([0, 0, 1]^T\) and \([0, 0, -1]^T\), respectively. It is worth to note that the incident light on the sample is circularly polarized after this adjustment. However, instead of calibrating the polarization state of the incident light as reported in previous PS-OCT systems [35], we calibrate the polarization states at the detector side, which is easier and doesn’t require extra polarization measurement setup. Based on the proposed method, we experimentally test the capability of measuring phase retardance and optic axis orientation using a Berek polarization compensator. In addition, we also present quantitative birefringence imaging of biological tissues.

2. Method

2.1 Principle of quantitative phase retardance and axis orientation measurement using Mueller Matrix

Figure 1 shows a SMF-based PS-OCT system with a single IPS. The tunable wavelength range of the swept laser source is 100 nm centered at 1325 nm (Thorlabs Inc., SL1325-P16). The wavelength-swept repetition rate is 16 kHz with 19 mW output power. A Mach-Zehnder interferometer (MZI) receives 3% of the laser output power and generates an \( f \)-clock signal with uniformly spaced optical frequency to trigger the sampling of the OCT signal during data acquisition. The sample and reference arms of a Michelson interferometer receive equal portions of the remaining 97% of the laser power. The axial resolution is 12 \( \mu \)m (in air). The transverse resolution is 15 \( \mu \)m (in air). The imaging speed is about 16 frames per second with 1000 A-lines per frame. The imaging objective is a scan lens with 36 mm focal length (Thorlabs Inc., LSM 03). The length of SMF in the sample and reference arms is 3 m. The field of view (FOV) is 3.4 mm \( \times \) 3.4 mm. A polarization diversity detector (PDD, Thorlabs Inc., INT-POL-1300) is used to detect the light in orthogonal polarization channels. The detector contains two SMF-based polarization beam splitters and two balanced photodetectors. The 3-dB bandwidth of PDD is 15 MHz that is corresponding to the frequency of the inference fringe at 2 mm imaging depth. The PDD includes an low-passing filter to suppress the generation of aliasing frequencies in the digitized fringe signal, which improves the quality of the OCT image within 2 mm depth range [40]. The data acquisition rate of this system is 50 M samples/s. After collimation, the incident light is scanned by a pair of galvo mirrors (Cambridge Technology Inc.) and focused onto the sample by a microscope objective. The polarization controller (PC1) aligns the polarization from the light source along with the polarizer to ensure maximum power transmission through the polarizer. Other polarization controllers (PC2-PC5) allow us to adjust the polarization of the SMF-based system. The details will be described later.
In SMF-based system, as the polarization information of SMF and SMF-based components in the system are unknown, the polarization information of the system and sample are mixed. Here, we investigate a simple method to extract the polarization information from the sample.

Before we get into the details of our method, we will briefly introduce how to measure the Stokes vector using the interference fringes from the horizontal and vertical (H & V) channels of the PDD. The complex interference fringes $H(z)$ and $V(z)$ come from a specific depth $z$ that can be expressed as:

$$
H(z) = 2H_r H_s \exp[i\psi(z)]
$$

$$
V(z) = 2V_r V_s \exp[i\psi(z) + \varphi_s - \varphi_r],
$$

where $H_r$ and $H_s$ are the amplitudes on the horizontal channel of the reference and sample arm, respectively. Similarly, $V_r$ and $V_s$ are the amplitudes on the vertical channel from reference and sample arm. $\psi(z)$ is the phase difference coming from optical path difference between reference and sample arm. $\varphi_s$ and $\varphi_r$ are the phase difference between the H and V channels from sample and reference arm respectively. The output Stokes vectors $S_{out}$ can be calculated by using the interference fringes $H(z)$ and $V(z)$ and can be expressed as [19]:

$$
S_{out} = 
\begin{bmatrix}
S_1 \\
S_2 \\
S_3
\end{bmatrix} = 
\begin{bmatrix}
H(z)H^*(z) - V(z)V^*(z) \\
H(z)V^*(z) + H^*(z)V(z) \\
i[H(z)V^*(z) - H^*(z)V(z)]
\end{bmatrix}.
$$

Substituting Eq. (1) into Eq. (2), $S_{out}$ can be expressed as:

$$
S_{out} = 
\begin{bmatrix}
S_1 \\
S_2 \\
S_3
\end{bmatrix} = 
\begin{bmatrix}
4H^2_r + 4V^2_s \\
4H_r V_r V_s \cos(\varphi_s - \varphi_r) \\
4H_r V_r V_s \sin(\varphi_s - \varphi_r)
\end{bmatrix}.
$$

Fig. 1. SMF-based PS-OCT schematic with a single IPS. SS, swept laser source; PC, polarization controller; BPD, balanced photo-detector; PBS, polarization beam splitter. DAQ, data acquisition. OBJ, objective; $f$-clock is a signal with uniformly spaced optical frequency to trigger the sampling of the OCT signal in DAQ.
As shown in Eq. (3), the information from the sample arm is mixed with the reference arm in the Stokes vector measured at the detector. We need to equalize the H and V amplitudes from the reference arm for isolating the sample arm information. This can be achieved by disconnecting the sample arm and then using PC2, PC4, and PC5 to equalize the reflected reference power on the H and V channel of the PDD. When \( H_r = V_r \), Eq. (3) can be rewritten as:

\[
S_{\text{out}} = 4H_r^2 \begin{bmatrix}
H_r^2 - V_r^2 & 2H_rV_r \cos(\phi_s - \phi_r) \\
2H_rV_r \cos(\phi_s - \phi_r) & 2H_rV_r \sin(\phi_s - \phi_r)
\end{bmatrix}.
\] (4)

If we further expand the phase term in Eq. (4), we can obtain this:

\[
S_{\text{out}} = 4H_r^2 \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(\phi_r) & \sin(\phi_r) & 2H_rV_r \cos(\phi_r) \\
0 & -\sin(\phi_r) & \cos(\phi_r) & 2H_rV_r \sin(\phi_r)
\end{bmatrix}.
\] (5)

In Eq. (5), the first term \( 4H_r^2 \) is an amplitude term. It doesn’t influence the polarization analysis and thus can be neglected. The second term of Eq. (5) is the reference arm’s phase retardance matrix which can be expressed as \( M_r \). The last term of Eq. (5) is the Stokes vector of the sample arm which can be expressed as \( S_{\text{sample}} \). Equation (5) can be simplified as:

\[
S_{\text{out}} = M_rS_{\text{sample}}.
\] (6)

Equation (6) gives the relation between the Stokes vector measured at PDD and the Stokes vector from the sample arm while the reference power is equally distributed among the orthogonal channels. Our goal is to extract the information from the sample, which is mixed in the system information in \( S_{\text{sample}} \).

We set the surface of the sample as an interim parameter. We assume that the Stokes vectors of the incident light on the sample is \( S_{\text{in}} \), the round-trip cumulative Mueller matrix at a specific depth of the sample is \( M_{ST} \) and the Mueller matrix from the sample surface to PDD is \( M_{SA} \). The relation of \( S_{\text{sample}} \) and \( S_{\text{in}} \) can be expressed as:

\[
S_{\text{sample}} = M_{SA}M_{ST}S_{\text{in}}.
\] (7)

Substituting Eq. (7) into the relation between the measured Stokes vector \( S_{\text{out}} \) and the sample arm vector \( S_{\text{sample}} \) in Eq. (6) will lead to:

\[
S_{\text{out}} = M_rM_{SA}M_{ST}S_{\text{in}}.
\] (8)
We set the local effective system Mueller matrix from the surface of the sample to the PDD Mueller matrix equal to be $M_{\text{out}} M_{\text{st}}$ ($M_{\text{out}} = M_{\text{st}}$). From the concept charts shown in Fig. 2(a), Eq. (8) can be simplified as:

$$S_{\text{out}} = M_{\text{out}} M_{\text{st}} S_{\text{in}}.$$  \hspace{1cm} (9)

From Fig. 2(b), the output vector from the sample surface on PDD, $S_{\text{front}}$, can be expressed as:

$$S_{\text{front}} = M_{\text{out}} S_{\text{in}}.$$  \hspace{1cm} (10)

Please note that we do not change the coordinate orientation for back reflected light. Thus, the surface back reflection light can still be expressed as $S_{\text{in}}$. Rearranging Eq. (10) to obtain $S_{\text{in}}$, and substituting it into Eq. (9) will provide us this relation:

$$S_{\text{out}} = M_{\text{out}} M_{\text{st}} M_{\text{out}}^{-1} S_{\text{front}}.$$  \hspace{1cm} (11)

Equation (11) shows $M_{\text{out}}$ is mixed with $M_{\text{st}}$ in the measurement. In order to extract the information from $M_{\text{st}}$, we will analyze the general form of $M_{\text{out}}$, which is the multiplication of $M_{\text{c}}$ (the reference arm phase retardance matrix) and $M_{\text{st}}$ (the Mueller matrix from sample surface to PDD). If the SMF on the sample arm is short (1~2m), $M_{\text{st}}$’s diattenuation can be neglected. In theory, $M_{\text{st}}$ can be expressed as a Mueller matrix product of a rotator (circular birefringence) $M_{\phi}$ and a linear retarder (linear birefringence) $M_{\delta}$ [15, 41]:

$$M_{\text{out}} = M_{\phi} M_{\delta} = \begin{bmatrix} \cos 2\phi & \sin 2\phi & 0 \\ -\sin 2\phi & \cos 2\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos 2\theta & -\sin 2\theta & 0 \\ \sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos 2\theta & \sin 2\theta & 0 \\ -\sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 1 \end{bmatrix},$$  \hspace{1cm} (12)

$M_{c}$ is the first matrix in Eq. (12) and $\phi$ is the rotation angle of circular birefringence. $M_{\delta}$ is the product of the last three matrices in Eq. (12). $\theta$ is the fast axis orientation of linear birefringence in $M_{\text{out}}$ and $\delta$ is the phase retardance in $M_{\text{out}}$. The detailed matrix elements of $M_{\text{out}}$ can be found in Appendix A. $M_{\text{out}}$ is an orthogonal matrix and thus $M_{\text{out}}^{-1} = M_{\text{out}}^{T}$. Equation (11) can be rewritten as:

$$S_{\text{out}} = M_{\text{out}} M_{\text{st}} M_{\text{out}}^{T} S_{\text{front}}.$$  \hspace{1cm} (13)

For $M_{\text{st}}$, its general expression can be expressed as [29]:

$$M_{\text{st}} = \begin{bmatrix} \cos^2 2\theta_{s} + \sin^2 2\theta_{s} \cos \delta_{\text{st}} & \cos 2\theta_{s} \sin 2\theta_{s} (1 - \cos \delta_{\text{st}}) & -\sin 2\theta_{s} \sin \delta_{\text{st}} \\ \cos 2\theta_{s} \sin 2\theta_{s} (1 - \cos \delta_{\text{st}}) & \sin^2 2\theta_{s} + \cos^2 2\theta_{s} \cos \delta_{\text{st}} & \cos 2\theta_{s} \sin \delta_{\text{st}} \\ \sin 2\theta_{s} \sin \delta_{\text{st}} & -\cos 2\theta_{s} \sin \delta_{\text{st}} & \cos \delta_{\text{st}} \end{bmatrix},$$  \hspace{1cm} (14)

where $\theta_{s}$ is the fast axis orientation in the sample and $\delta_{\text{st}}$ is the round trip cumulative phase retardance in the sample. It is worth to note that the circular birefringence of the sample is not considered in Eq. (14).

If we adjust the polarization controller in the sample arm (PC3) so that the phase retardance of system is equal to an integer number times $\pi$ ($\delta = n\pi, n = 0, 1, 2, 3...$) (detail will be provided in the next section) and the output Stokes vector from the sample surface is $[0, 0, 1]^T$, we can obtain the following results by substituting Eqs. (12) and (14) into Eq. (13):
From Eq. (15), the third row of \( S_{out} \) equals \( \cos \delta_{ST} \). Based on this relationship, the round-trip accumulative phase retardance of the sample at a specific depth \( \delta_{ST} \) can be measured and expressed as:

\[
\delta_{ST} = \arccos(S_3).
\]  

(16)

The fast axis orientation \( \theta_S \) of the sample is mixed with the SMF system’s \( \phi \) and \( \theta \) in the first and second rows of Eq. (15). If the SMF system is stable, namely \( \phi \) and \( \theta \) remain unchanged, \( \theta_S \) also can be determined by:

\[
\theta_S = \begin{cases} 
-\frac{1}{2} \arctan \left( \frac{S_1}{S_2} \right) + \phi, & \delta = 2n\pi, n = 0,1,2,... \\
\frac{1}{2} \arctan \left( \frac{S_1}{S_2} \right) - \phi + 2\theta, & \delta = (2n+1)\pi, n = 0,1,2...
\end{cases}
\]  

(17)

Since there is sign ambiguity and unknown offset, we can only obtain relative optics axis measurement from \( S_1 \) and \( S_2 \).

Both Eqs. (16) and (17) show that if we can adjust the system polarization so that the output Stokes vectors from the sample surface \( S_{front} \) is \([0, 0, 1]^T\) and the system retardance is equal to multiple integers of \( \pi \), we can then measure the optical axis orientation and round-trip cumulative phase retardance from the sample with single IPS. In the next section, we will describe how we fulfill the prerequisites using a QWP. In addition, when the prerequisites are fulfilled, the incident light on the sample \( S_{in} \) is circular polarized based on Eq. (10) and (23). The proof is provided in Appendix C.

2.2 Principle of calibration using a QWP

A quarter wave plate is placed as a sample and the output Stokes vectors of the front and back surfaces of the QWP measured at PDD are adjusted to \([0, 0, 1]^T\) and \([0, 0, -1]^T\) by the PC3 on the sample arm. Assuming that Mueller matrix of round-trip QWP is \( M_{QWP} \), based on Eq. (13), a new relationship can be expressed as:

\[
[0\ 0\ -1]^T = M_{out}M_{QWP}M_{out}^T[0\ 0\ 1]^T.
\]  

(18)

Both sides of Eq. (18) are multiplied by \( M_{out}^+ \) and \( M_{out}^+ = M_{out}^T \) are substituted into Eq. (18):

\[
M_{out}^T[0\ 0\ -1]^T = M_{QWP}M_{out}^T[0\ 0\ 1]^T.
\]  

(19)

Assuming that \( M_{out}^+ = [C_1\ C_2\ C_3] \) where \( C_{1,2,3} \) are column vectors, Eq. (19) can be simplified to:

\[
M_{QWP}C_1 = -C_3,
\]  

(20)
Substituting $M_{QWP} = \begin{bmatrix} \cos 4\theta_q & \sin 4\theta_q & 0 \\ \sin 4\theta_q & -\cos 4\theta_q & 0 \\ 0 & 0 & -1 \end{bmatrix}$ ($\theta_q$ is fast axis orientation of a QWP) and

$$C_3 = \begin{bmatrix} \sin 2\theta \sin \delta & -\cos 2\theta \sin \delta & \cos \delta \end{bmatrix}^T$$

(see Eq. (23)) into Eq. (20) results in an equation set:

$$\begin{align*}
\sin \delta \sin(2\theta - 4\theta_q) &= -\sin 2\theta \sin \delta \\
\sin \delta \cos(2\theta - 4\theta_q) &= \cos 2\theta \sin \delta \\
-\cos \delta &= -\cos \delta
\end{align*}$$

(21)

When $\theta_q \neq \theta + k\pi/2$ ($k$ is integer), $\delta = n\pi(n = 0, 1, 2, 3, \ldots)$, the prerequisites are fulfilled. When $\theta_q = \theta + k\pi/2$ ($k$ is integer), $\delta$ can be any arbitrary number. In this case, the prerequisites may or may not be fulfilled. This issue is easily solved by rotating the QWP at a small angle ($< \pi/2$). If the system retardance $\delta$ is equal to an integer number times $\pi$, the front and back surface polarization will remain as $[0, 0, 1]^T$ and $[0, 0, -1]^T$ after rotation. However, if $\delta$ is not equal to $n\pi$ (in the case that the system axis was accidentally set on the fast or slow axis of the QWP), the polarization state of the surfaces will be changed after rotation. In conclusion, if we set the output stoke vector of the front ($S_{f,\text{out}}$) and back ($S_{b,\text{out}}$) surface of a QWP equal to $[0, 0, 1]^T$ and $[0, 0, -1]^T$ at two different azimuthal angle by adjusting PC3, the system’s retardance will become $n\pi$ and the output Stokes vectors of any other sample’s front surface ($S_{f,\text{out}}$) will remain as $[0, 0, 1]^T$ because the light is not perturbed by the sample. These two conditions are important for quantifying the sample polarization with a single input polarization state.

In addition, the PDD output Stokes vectors of the front and back surfaces of the QWP can also be adjusted to $[0, 0, -1]^T$ and $[0, 0, 1]^T$ by PC3 on the sample arm. The system’s retardance after this calibration will also be the integer number times $\pi$. The details are included in Appendix B.

3. Experimental results and discussion

3.1 Calibration steps

Several prerequisites need to be fulfilled before quantifying the sample birefringence and optic axis. The following are the calibration steps for fulfilling the prerequisites:

1) Use PC1 to project the polarization of the swept source laser to the pass axis of the polarizer for obtaining maximum output power. The function of the polarizer is to stabilize the polarization input from the laser. If the polarization state of the light source is stable, PC1 and the polarizer can be removed.

2) Disconnect the sample arm and use PC2, PC4, and PC5 to equalize the reference power going into the orthogonal polarization channels, H and V. This step allows us to obtain the Stokes vectors from the sample arm through the PDD measurement.

3) Connect the sample arm and use a QWP as the sample. Adjust PC3 to make the PDD output Stokes vectors of the QWP’s front and back surfaces $[0, 0, 1]^T$ and $[0, 0, -1]^T$. Rotate the QWP with a small angle ($< \pi/2$) to check if the stoke vectors from the front and back surface change. If the polarization doesn’t change, the system retardance $\delta$ has been aligned to an integer $\pi$ and is then ready to quantify the birefringence and optic axis orientation of the sample.

The pervious method [35] needs to calibrate input light onto the sample to a circularly polarized light. This calibration process needs to rotate a polarizer with a full circle carefully.
and measure the optical power at every point after changing the polarization controller’s paddle position, which is inconvenient and time-consuming. Our method uses a QWP as the standard sample and adjust the polarization controller on the sample arm to make the output Stokes vectors of the front and back surfaces of the QWP \([0, 0, 1]^T\) and \([0, 0, -1]^T\), respectively. Our method only needs to use PDD in the system to measure the output Stokes vectors of the QWP, which will be simpler and more convenient than the previous method.

### 3.2 Verification of phase retardance and optic axis orientation

![Verification Results](image)

Fig. 3. (a) Verification results of different phase retardance range from 0 to 180°, when the optic axis is fixed; (b) different optic axis orientation range from 0 to 180°, when the phase retardance is fixed.

To evaluate the capability of measuring the phase retardance and optic axis orientation of sample by the proposed method, we put a Berek polarization compensator (New Focus Model 5540) on a reflective surface as the polarization testing target. This device allows for an arbitrary and independent setting of the optic axis orientation and phase retardance for a wide range of wavelengths.

![Schematic Diagram](image)

Fig. 4. Schematic diagram of the tracking path on Poincaré sphere of the output Stokes vectors of verification results when \(\delta\) of \(M_{\text{out}}\) is multiple \(\pi\) (a) and not multiple \(\pi\) (b). The red dash line is phase retardance changing and the blue dash line is optic axis changing.
Different phase retardances range from 0 to $\pi$ (180°) of the polarization compensator are measured when the optic axis is fixed as shown in Fig. 3(a). The step of phase retardance variation is not uniform due to the non-linear relationship between the indicators on the compensator and the phase retardance. We have transformed the indicator values to the phase retardance in the Fig. 3(a) using the equation provided by the manufacturer’s manual. Different optic axis orientations also range from 0 to 180° and are measured when the phase retardance is fixed as shown in Fig. 3(b). The step of axis orientation variation is 10°.

From Fig. 3, we see that the phase retardance and optic axis measurement results agree well with the expected data, but there are some deviations. The reason of these deviations is that the phase retardance of the system is not exactly equal to multiple $\pi$. Namely, the output Stokes vectors of the front and back surfaces of the QWP are very difficult to be exactly adjusted to $[0, 0, 1]^T$ and $[0, 0, -1]^T$ (or $[0, 0, -1]^T$ and $[0, 0, 1]^T$). The measured Stokes vectors of the front and back surfaces of the QWP are $[-0.96482, -0.07224, 0.24523]$ and $[0.97718, 0.18614, 0.07547]$, respectively. We can only make them as close to the ideal value as possible. We use the Poincaré sphere to express the Stokes vectors in Eq. (15). In the ideal case, when the optic axis of the system $\theta$ and the circular birefrigence of the system $\phi$ are fixed, the PDD Stokes vectors will be located on the median plan of the Poincaré sphere and rotate along with the sample phase retardance when it changes from 0 to $\pi$ (red line in Fig. 4(a)). On the other hand, if the sample phase retardance is fixed, the vector will rotate on a plan parallel to the equatorial plane ($S_1S_2$ plane) when the axis orientation changes from 0 to 180° (blue line in Fig. 4(a)). However, if $\delta$ of $M_{out}$ is not equal to $n\pi (n = 0, 1, 2, 3,...)$, the tracking path of the output Stokes vectors (Fig. 4(b)) will deviate from the plane shown in Fig. 4(a). If we use Eq. (16) and Eq. (17) to calculate the phase retardance and optic axis orientation when the system retardance is not a multiple of $\pi$, it will introduce a deviation between the measurement values and the expected values. Figure 5 shows the measured...

Fig. 5. Tracking path on Poincaré sphere of the output Stokes vectors of the measured results shown in Fig. 3. The red spots are the Stokes vector with a fixed optics axis but different phase retardance. The blue spots are the Stokes vector with a fixed phase retardance but different optics axis orientation.
tracking path on the Poincaré sphere of the output Stokes vectors of the results shown in Fig. 3. The measured tracking path does not perfectly match with the ideal track shown in Fig. 4(a), because the system retardance is not perfectly aligned to a multiple of \( \pi \).

To reduce these errors, we can use the calibration curves shown in Fig. 3 to correct the phase retardance and optic axis orientation measurement from the sample. The calibration curves in Fig. 3 is consistent for a long time when the SMF system is well isolated from the vibration or temperature variation. To reduce the calibration error, in the future, we can utilize electronic polarization controllers to fine tune the system polarization to a multiple of \( \pi \). Moreover, we can also implement the Mach-Zehnder interferometer configuration, which provides another degree of freedom for alignment as \( M_{in} \) and \( M_{sl} \) are independent. The extra degree of freedom may allow the system retardance to get closer to a multiple of \( \pi \). We will also put the SMF system in an isolation box for improving the stability.

### 3.2 Imaging of biological tissues

The capability of the system is demonstrated by imaging human foot nails, human finger nail folds, pig muscle tissues, chicken breast tissues, and mouse brain. The cross-section of the polarization images of the human foot nails, human finger nail fold, pig muscle tissues and chicken breast tissues are shown in Fig. 6. Figure 6(a), 6(d), 6(g), 6(j) are the intensity images. Figure 6(b), 6(e), 6(h), 6(k) are round-trip accumulative phase retardance. The retardance on the top of the tissue surface is zero (blue) and it varies as light propagates deeper into the tissues with clear polarization birefringence. Figure 6(c), 6(f), 6(i), 6(l) are optic axis orientation that also reflects distinct layered patterns.

The en-face polarization images of a mouse brain are shown in Fig. 7. The photograph of the cross-section of mouse brain is shown in Fig. 7(a). The region of interest (ROI) is indicated by the red dashed line box in Fig. 7(a). Figure 7(b) is the 3-D volumetric image of the ROI in mouse brain that contains 800 cross-sectional frames (B-scan) with 800 A-lines in each frame. Figure 7(c) is the en-face intensity images created from the coronal view (Media 1). Figure 7(d) and 7(e) are the en-face phase retardance and optic axis images, respectively (Media 2 and Media 3). In the intensity image shown in Fig. 7(c), the white matter (nerve fiber) appears brighter than the gray matter. The phase retardance image shown in Fig. 7(d) highlights the nerve fiber tracts due to the fact that gray matter lacks birefringence and white matter has strong birefringence. Comparing Fig. 7(c) with (d), the phase retardance image can provide better contrast between gray matter and white matter than the intensity image. More importantly, optics axis orientation image shown in Fig. 7(e) enables us to map the orientation of nerve fiber, which could be used to generate brain tractography [42]. Direction variation of the nerve fiber is expressed as smooth color transitions in the optic axis orientation image. Similar phenomenon has been observed in previously published papers [8, 9], which verifies the effectiveness of our method. The cross-sectional images of intensity, phase retardance and optic axis orientation are shown in Fig. 7(f), 7(g) and 7(h). Again, the white matter tracks with significant phase variation can be easily identified in the phase image (Fig. 7(g)). Also, Fig. 7(h) shows the two fiber bundles have very different orientation.
Fig. 6. Images of human foot nail (a)(b)(c), (d)(e)(f) human finger nail fold, (g)(h)(i) pig muscle, (j)(k)(l) chicken breast using SMF-based PS-OCT with single IPS; (a)(d)(g)(j) intensity in grayscale; (b)(e)(h)(k) round-trip phase retardance (blue, 0°; red, 180°); (c)(f)(i)(l) optic axis orientation (blue, 0°; red, 180°).
4. Conclusion

We present a simple but effective method to quantitatively measure the birefringence and optical axis orientation of tissue by an all-SMF-based PS-OCT system with a single IPS. We analyze the Mueller matrix of the SMF system with a sample, and find that the phase retardance and optic axis orientation can be measured after the phase retardance of SMF-based system is calibrated to multiple integers of $\pi$ using a QWP. Based on the proposed method, we experimentally test the capability of measuring phase retardance and optic axis orientation using a Berek polarization compensator. The feasibilities of quantitative birefringence and optics axis imaging of biological tissues are also demonstrated.

5. Appendix A: detailed matrix elements of $M_{\text{out}}$

$$M_{\text{out}} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \quad (22)$$

The element in the matrix can be expressed as:
\[ m_{11} = \cos 2\varphi (\cos^2 2\theta + \sin^2 2\theta \cos \delta) + \sin 2\varphi \cos 2\theta \sin 2\theta (1 - \cos \delta) \]
\[ m_{12} = \sin 2\varphi (\sin^2 2\theta + \cos^2 2\theta \cos \delta) + \cos 2\varphi \cos 2\theta \sin 2\theta (1 - \cos \delta) \]
\[ m_{13} = -\cos 2\varphi \sin 2\theta \sin \delta + \sin 2\varphi \cos 2\theta \sin \delta \]
\[ m_{21} = -\sin 2\varphi (\cos^2 2\theta + \sin^2 2\theta \cos \delta) + \cos 2\varphi \cos 2\theta \sin 2\theta (1 - \cos \delta) \]
\[ m_{22} = \cos 2\varphi (\sin^2 2\theta + \cos^2 2\theta \cos \delta) - \sin 2\varphi \cos 2\theta \sin 2\theta (1 - \cos \delta) \]  \hspace{1cm} (23)
\[ m_{23} = \sin 2\varphi \sin 2\theta \sin \delta + \cos 2\varphi \cos 2\theta \sin \delta \]
\[ m_{31} = \sin 2\varphi \sin 2\theta \cos \delta \]
\[ m_{32} = -\cos 2\varphi \sin 2\theta \sin \delta \]
\[ m_{33} = \cos \delta \]

6. Appendix B: Output Stokes vectors of the front and back surfaces of the QWP are adjusted to \([0, 0, -1]^T\) and \([0, 0, 1]^T\)

The PDD output Stokes vectors of the front and back surfaces of the QWP are adjusted to \([0, 0, -1]^T\) and \([0, 0, 1]^T\) using PC3 on the sample arm. We have a relation as

\[ [0 \ 0 \ 1]^T = M_{\text{out}} M_{\text{QWP}} M_{\text{out}}^T [0 \ 0 \ -1]^T. \]  \hspace{1cm} (24)

We multiply \(-1\) by both sides of Eq. (B1) and this results in the same equation as Eq. (18). The system retardance can still be proved to be an integer number times \(\pi\) based on Eq. (18)-(21). As the PDD output Stokes vectors of front surface of the QWP is adjusted to be \([0, 0, -1]^T\), the sample front surface will be \([0, 0, -1]^T\). Equation (15) can then be changed to

\[ S_{\text{out}} = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} = M_{\text{out}} M_{\text{ST}} M_{\text{out}}^T \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} = \begin{bmatrix} -\sin(2\varphi - 2\theta_x) \sin \delta_{ST} \\ -\cos(2\varphi - 2\theta_x) \sin \delta_{ST} \\ -\cos \delta_{ST} \end{bmatrix}, \quad \delta = 2n\pi, n = 0, 1, 2... \]

\[ -\sin(2\theta_x + 2\varphi - 4\theta) \sin \delta_{ST} \\ -\cos(2\theta_x + 2\varphi - 4\theta) \sin \delta_{ST} \\ -\cos \delta_{ST} \]

\[ \delta = (2n+1)\pi, n = 0, 1, 2... \]  \hspace{1cm} (25)

The phase retardance of a sample in Eq. (16) can be changed to

\[ \delta_{ST} = \arccos(-S_3). \]  \hspace{1cm} (26)

The expression of optic axis orientation of a sample is the same as Eq. (17).

7. Appendix C: The polarization state of the incident light on sample \((S_{\text{in}})\) after system calibration.

Based on Eq. (10), we have this relation:

\[ S_{\text{in}} = M_{\text{out}}^{-1} S_{\text{front}} = M_{\text{out}}^T S_{\text{front}} \]  \hspace{1cm} (27)

After applying the calibration steps, the system’s retardance is equal to an integer number multiplies \(\pi\). \(M_{\text{out}}^{-1}\) is equal to:

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\[
M'_{\text{out}} = \begin{bmatrix}
\cos 2\varphi & -\sin 2\varphi & 0 \\
\sin 2\varphi & \cos 2\varphi & 0 \\
0 & 0 & 1
\end{bmatrix}, \quad \delta = 2n\pi(n = 1, 2, \ldots)
\]

\[
\begin{bmatrix}
\cos(2\varphi - 2\theta) & \sin(2\theta - 2\varphi) & 0 \\
\sin(2\theta - 2\varphi) & -\cos(2\varphi - 2\theta) & 0 \\
0 & 0 & -1
\end{bmatrix}, \quad \delta = (2n+1)\pi(n = 1, 2, \ldots)
\]

(28)

On the other hand, the output Stokes vectors of the sample surface \(S_{\text{front}}\) is \([0,0,1]^T\) or \([0,0,-1]^T\)
. Therefore, the input light on the sample \(S_{\text{in}}\) is either left or right circular polarizations:

- When \(\delta = 2n\pi(n = 1, 2, \ldots)\) and \(S_{\text{front}} = [0,0,1]^T\), \(S_{\text{in}} = [0,0,1]^T\).
- When \(\delta = 2n\pi(n = 1, 2, \ldots)\) and \(S_{\text{front}} = [0,0,-1]^T\), \(S_{\text{in}} = [0,0,-1]^T\).
- When \(\delta = (2n+1)\pi(n = 1, 2, \ldots)\) and \(S_{\text{front}} = [0,0,1]^T\), \(S_{\text{in}} = [0,0,-1]^T\).
- When \(\delta = (2n+1)\pi(n = 1, 2, \ldots)\) and \(S_{\text{front}} = [0,0,-1]^T\), \(S_{\text{in}} = [0,0,1]^T\).

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