Evaluation of the magneto-optical effect in biological tissue models using optical coherence tomography

David Pereda-Cubián,[a,b,*] Miloš Todorović,[b] José Luis Arce-Diego,[a] and Lihong V. Wang[b]

[a]University of Cantabria, TEISA Department, Applied Optics Techniques Group, Av. Castros s/n, 39005 Santander, Spain

[b]Texas A&M University, Department of Biomedical Engineering, Optical Imaging Laboratory, College Station, Texas 77843-3120

Abstract. For the first time to our knowledge, an experimental evaluation of the Faraday effect–induced polarization rotation in a biological tissue phantom is reported. The rotation of the polarization plane produced in the optical beam propagating through an Intralipid solution was evaluated using polarization-sensitive optical coherence tomography (PS-OCT), and the experimental results closely matched the theoretical values. The angle of rotation is proportional to the traversed path length along the magnetic field and can potentially be used to estimate the actual penetration depth. [DOI: 10.1117/1.2818103]

Keywords: tomography; polarization; magneto-optics; fiber optics.

Paper 07162LR received May 5, 2007; revised manuscript received Aug. 9, 2007; accepted for publication Sep. 5, 2007; published online Dec. 11, 2007.

The Faraday effect is a magneto-optical effect that produces the rotation of the polarization plane of light propagating along an optical material subjected to an external parallel magnetic field. It is a nonreciprocal effect that happens in all media, and it is caused by the difference in the refractive indices of the two orthogonal circularly polarized components of light. The rotation angle θ can be expressed as follows:

$$\theta = \frac{\pi}{\lambda}(n_r - n_l)l \Rightarrow \theta = V \int \vec{H} \cdot \mathrm{d}\vec{l}, \tag{1}$$

where n_r and n_l are the refractive indexes of the right-hand and left-hand components, l is the path length, λ is the center wavelength, H is the magnetic field, and V is the Verdet constant, a coefficient whose value depends on the material, wavelength, and temperature.[1] The value of the Verdet constant is inversely proportional to the wavelength, it being desirable to keep a short wavelength, close to the absorption band, to maximize the magnitude of the Faraday effect. The Verdet constant is considered to be homogeneous (constant) in the sample.

The Faraday effect has been used in many applications, such as optical isolators, current sensors, and semiconductor devices.[2,3] However, it has never been experimentally evaluated in biological studies, as the susceptibility of biological tissues to this effect is extremely low, and therefore, the polarization rotation is very small. The sensitivity of modern polarization-based detection systems has improved lately (1 to 10 μm) and is good enough to detect even small variations in polarization. The polarization rotation resulting from the Faraday effect can be measured using measurement systems such as polarization-sensitive optical coherence tomography (PS-OCT), which obtains both the Jones and Mueller matrices of an optical sample. Moreover, since PS-OCT works in reflection configuration, the optical activity, which is a natural and reciprocal effect, is cancelled, so the variations in the phase introduced by an external magnetic field can be experimentally evaluated and the value of the polarization rotation extracted without any distortion introduced by the intrinsic optical activity. This magnetic field–induced polarization rotation can be used as a parameter for the determination of the real penetration depth of light into the sample. In samples such as an Intralipid solution, it could be useful to determine the density of the solution. In more complex biological tissues, its value could be used to determine the true penetration depth of light into a biological tissue.

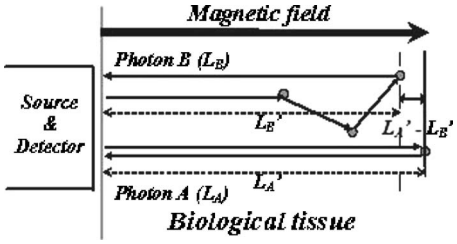

Fig. 1 Two photons A and B simultaneously arriving at the detector travel the same optical path lengths ($L_A = L_B$) but traverse different path lengths (L_A', L_B') in the direction of the external magnetic field, thus encountering different polarization rotations.

Two different photons A and B propagating along a scattering medium can travel two completely different trajectories, reaching the detector at the same time, so no difference between the corresponding path lengths can be established based on the time of detection. However, each can have a different polarization rotation if the length of its optical path projected onto the direction of an external magnetic field is different (Fig. 1). If a constant magnetic field is assumed, the magnetic field–induced rotation angles θ_A and θ_B will be given by:

$$\theta_A = 2VHL_A'; \quad \theta_B = 2VHL_B'. \tag{2}$$

The difference between the rotation angles can provide a tool for differentiating photons arriving at the detector simultaneously but with different paths through the scattering medium. This is possible only for quasi-ballistic photons, where the polarization information of light is kept. The degree of polarization (DOP) is 1 for time $t=0$ and decreases exponentially with time, depending on the class, geometry, and density of the particles producing the scattering. However, if the time of flight $t < 100$ ps, a significant part of light remains polar-

*Tel: +34942201545; E-mail: dpcubian@teisa.unican.es

1083-3668/2007/12(6)/060502/3/$25.00 © 2007 SPIE

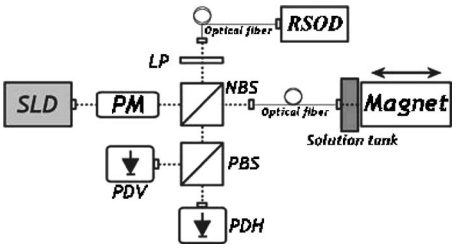

Fig. 2 Schematic of the PS-OCT setup. SLD—superluminiscent diode; PM—polarization modulator; NBS—nonpolarizing beamsplitter; PBS—polarizing beamsplitter; LP—linear polarizer; RSOD—rapid scanning optical delay line; PDH—horizontal detector; PDV—vertical detector.

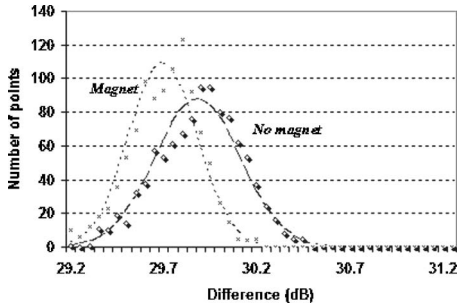

Fig. 3 Histograms of the ratios D_{dB} and D'_{dB} (log scale) for the two orthogonal components in the presence (crosses) and the absence (rectangles) of the magnetic field, and Gaussian functions fitting those histograms.

ized, and polarization studies can be carried out.[4–6] This condition is satisfied in the PS-OCT system since the propagation is basically ballistic, and therefore, light traversing the biological sample can be considered polarized.

We used a PS-OCT system for imaging the cuvette containing an intralipid solution both with and without a magnet in the system.[7–9] The schematic of the PS-OCT system is shown in Fig. 2. A 1300-nm superluminescent diode (SLD) is used as a broadband optical source. The light passes through a polarization modulator (PM) working as a linear polarizer with fixed orientation, thus setting the polarization state to linear vertical. A nonpolarizing beamsplitter (NBS) diverts light into both the reference and sample arms. A rapid scanning optical delay (RSOD) line is used in the reference arm to increase the image acquisition speed. In the detection arm, two detectors PDH and PDV are used to obtain both the horizontal and vertical components, respectively.[10] Due to the configuration setting, the PDV will detect a much higher signal than the PDH, so the ratio of the intensities detected in two channels, $D=I_V/I_H$, will be very high (ideally, infinite).

In our study, a 2% intralipid solution (reduced scattering coefficient, $\mu_S'=3.0\pm0.1\ \mathrm{mm}^{-1}$) contained in a 1.25-mm-thick glass tank is used to simulate the optical behavior of biological tissues, which are mainly composed of water (more than 80%). The refractive index and Verdet constant of the solution are assumed to be those of water[1] for $\lambda=1300$ nm ($n=1.32$, $V\approx0.585\ \mathrm{rad/T\cdot m}$) and homogeneous in the sample. The intralipid solution was placed in the magnetic field generated by the permanent magnet. In order to observe any changes in the phase of light propagating through the solution that are induced by the presence of the magnetic field, two sets of measurements, with and without the magnet in the sample arm, were performed. It is worth noting that the wavelength is not optimal, which reduced the sensitivity to the Faraday effect.

A good solution combining both low price and relatively high field for the external magnetic field source is a permanent magnet. In this experiment, a commercial neodymium iron boron (NdFeB, sintered) permanent magnet providing a residual induction B_r of 1.2 Tesla was used. This is a cylindrical magnet with both a diameter and a length of 25.4 mm (1 in.). A plastic enclosure was designed and built to hold the magnet and position it into the experimental setup. The magnetic field on the external axis of the cylinder (H_C) is given by:

$$H_C=\frac{B_r}{2}\left\{\frac{(l+L)}{[(l+L)^2+d^2/4]^{1/2}}-\frac{l}{(l^2+d^2/4)^{1/2}}\right\}, \qquad (3)$$

where B_r is the residual induction, L the length of the magnet, d its diameter, and l the distance from the surface of the magnet. Any rotation of the polarization state will result in an increase of the PDH and a reduction of the PDV intensities, therefore reducing their ratio D. Supposing very small rotation angles, this reduction can be related to the polarization rotation by the following approximated expression:

$$\frac{1}{D'}=\frac{1}{D}+\tan(\theta), \qquad (4)$$

where D' is the new ratio, and θ is the negative polarization rotation, which reduces the value of D. The tank with the Intralipid solution was placed in the sample arm with the magnet 3 mm behind the inner wall surface closest to the magnet (cumulative thickness of the tank wall and plastic enclosure). Since the expected polarization rotation is very small, 1000 measurements were carried out to minimize the influence of noise (variations of polarization, vibrations, and other random variations). These measurements were obtained both in the presence and the absence of the external magnetic field. The intensities of both orthogonal components was compared on a logarithmic scale, and thus the ratio of the orthogonal intensities was converted to a difference between the corresponding logarithmic values (D_{dB} and D'_{dB}). We considered the nonuniform distribution of the magnetic field along the solution tank to obtain more accurate results. Every measurement set was represented by the mean value of the Gaussian function fitting the experimental data.

Based on the tank dimensions and the magnetic field characteristics, the theoretical polarization rotation of the light propagating along the solution tank was calculated to be $\theta_{th}=-0.0365$ deg. The measurements in the absence of the magnetic field yielded the difference between the orthogonal components $D_{dB}=29.88\pm0.23$ dB. Introduction of the magnetic field reduces this difference to $D'_{dB}=29.69\pm0.18$ dB. If the number of points within a small range of the difference in logarithmic scale is compared for the 1000 measurements carried out per sample, a Gaussian distribution is obtained for both with and without magnetic field. Both Gaussian functions fitting the data points can be observed in Fig. 3. As expected, a reduction of the parameter D was produced and

the experimental polarization rotation corresponding to this reduction is $\theta_{exp}=-0.0397$ deg± 0.0109 deg. This result is in agreement with the theoretical value, and the difference can be explained by the noisy intensity measurements and the small inaccuracies in the tank dimensions and the position of the magnet.

In conclusion, we have experimentally demonstrated that the presence of an external magnetic field induces polarization rotation of light propagating through a 2% intralipid solution. This rotation is small, around a theoretical value of $\theta_{th}=-0.0365$ deg for the given sample geometry and system parameters, but it can be detected using a PS-OCT system. Several improvements such as the reduction of the optical wavelength and the increase of the magnetic field strength would boost the polarization rotation so that biological tissues could be analyzed. However, the validity of the theoretical approach has been confirmed and possible future applications include the estimation of the real penetration depth of light in complex biological tissues.

Acknowledgments

This project has been sponsored in part by the Fulbright Commission through a Spanish Fulbright/MEC (Ministerio de Educación y Ciencia) scholarship, as well as by the National Institutes of Health Grant No. R01 CA092415 and the Spanish MEC project TCE2006-06548/TCM.

References

1. A. B. Villaverde and D. A. Donatti, "Verdet constant of liquids; measurements with a pulsed magnetic field," *J. Chem. Phys.* **71**, 4021–4024 (1979).
2. J. L. Arce-Diego, R. López, J. M. López, and M. A. Muriel, "Model of an openable Faraday-effect hybrid-current optical transducer based on a square-shaped structure with internal mirrow," *Appl. Opt.* **36**, 6242–6245 (1997).
3. D. Pereda-Cubián, M. Haddad, R. André, R. Frey, G. Roosen, J. L. Arce-Diego, and C. Flytzanis, "Photoinduced magneto-optic Kerr effects in asymmetric semiconductor cavities," *Phys. Rev. B* **67**, 045308 (2003).
4. S. Demos and R. R. Alfano, "Temporal gating in highly scattering media by the degree of polarization," *Opt. Lett.* **21**, 161–163 (1996).
5. E. Munin, "Picosecond magneto-optical phenomena in turbid media: Toward magneto-optical characterization of highly scattering biological samples," *Appl. Opt.* **36**, 2990–2994 (1997).
6. E. Munin, V. R. Giancarlo, A. Blain, and M. T. Tavares, "Analysis of the picosecond magneto-optical phenomena in scattering media of biological interests," *Phys. Med. Biol.* **47**, 1519–1534 (2002).
7. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schumann, W. G. Stinson, W. Chang, M. R. He, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, *Science* **254**, 1178 (1991).
8. S. Jiao, W. Yu, G. Stoica, and L. V. Wang, "Optical-fiber based Mueller optical coherence tomography," *Opt. Lett.* **28**, 1206–1208 (2003).
9. M. Todorović, S. Jiao, L. V. Wang, and G. Stoica, "Determination of local polarization properties of biological samples in the presence of diattenuation by use of Mueller optical coherence tomography," *Opt. Lett.* **29**, 2402 (2004).
10. 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).