Time-resolved propagation of polarized light in turbid media: experiment and theory

Xueding Wang, Chia-Wei Sun, Yean-Woei Kiang, Chih Chung Yang, Lihong V. Wang

Xueding Wang, Chia-Wei Sun, Yean-Woei Kiang, Chih Chung Yang, Lihong V. Wang, "Time-resolved propagation of polarized light in turbid media: experiment and theory," Proc. SPIE 4617, Laser Tissue Interaction XIII: Photochemical, Photothermal, and Photomechanical, (27 June 2002); doi: 10.1117/12.472526

Event: International Symposium on Biomedical Optics, 2002, San Jose, CA, United States

Time-resolved propagation of polarized light in turbid media: experiment and theory

Xueding Wang[1], Chia-Wei Sun[2], Yean-Woei Kiang[2], C. C. Yang[2], and Lihong V. Wang[1]
1. Optical Imaging Laboratory, Biomedical Engineering Program, Texas A&M University, TX 77843-3120, USA.
URL: http://oilab.tamu.edu; Email: LWang@tamu.edu
2. Department of Electrical Engineering and Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C.

Abstract

This paper presents our study of time-resolved propagation of polarized light in scattering media. Monte Carlo simulated time-resolved Stokes vectors of transmitted light were compared with the experimental results. A satisfying match has been obtained.
Keywords: Light propagation in tissues; Polarization

1. Introduction

Recently, there has been increasing interest in the propagation of polarized light in randomly scattering media because of its potential applications, especially in noninvasive optical diagnosis in biological tissues. Multiple scattering of light in a turbid medium randomizes the state of polarization and a wave propagated in such a medium loses its initial polarization rapidly. Several techniques have been studied to differentiate between weakly scattered photons and multiply scattered photons. Because multiply scattered photons usually have greater path lengths than weakly scattered photons, they can be rejected by time gating [1]. Since weakly scattered light preserves its original polarization better than multiply scattered light, polarization gating can be used as an alternative technique [2,3].

The propagation of polarized light in turbid media is a complex process. Such parameters as the size, the shape, the refractive index and the concentration of the scattering particles, the polarization state of incident light, and the birefringent characteristics of the medium all play important roles. More study is needed to fully understand the evolution of polarization in turbid media. Monte Carlo (MC) simulation offers a flexible and accurate approach to this problem [4,5] because it can deal with complex geometries in both forward and backward manners, and can score multiple physical quantities simultaneously. We used a time-resolved MC technique to analyze the propagation of polarized light in randomly scattering turbid media. The time-resolved Stokes vectors and the degree of polarization (DOP) of transmitted light that were obtained by simulation were compared with our measurements.

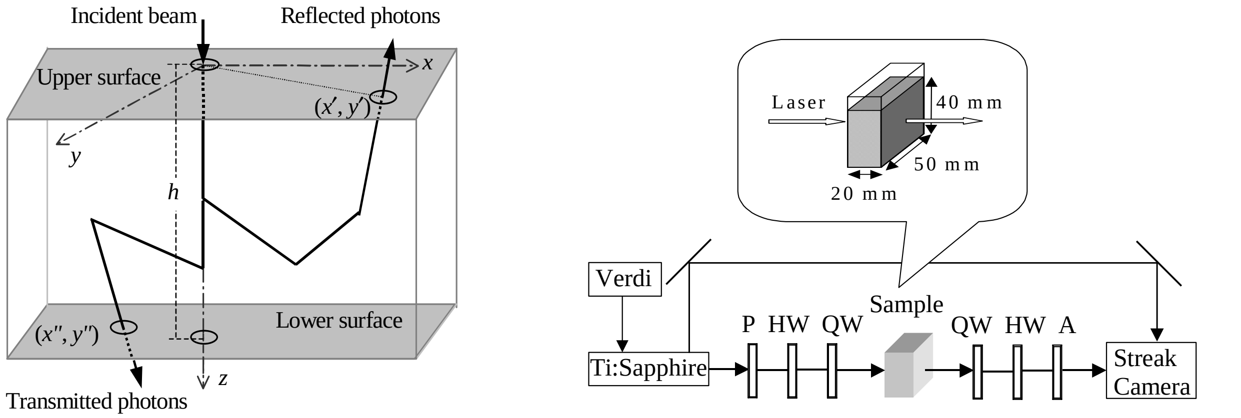
2. Methods

The Monte Carlo simulation that describes the multiple scattering events of photons in turbid media is based on radiative theory, which assumes that the scattering event is independent and has no coherence effects. The geometry of multiple scattering events in a birefringent turbid medium is shown in Fig. 1(a). A narrow pencil beam propagates into a plan-parallel turbid medium downward along the z axis. Photons are scattered in the medium by spherical particles before exiting the upper or lower surface. At each scattering event, the scattering angles of the photon are selected statistically according to the Mie theory. Between two adjacent scattering events, the photon either takes a free path or is affected by the linear birefringence (or chiral materials) in the background medium. The basic Stokes-Mueller formalism for tracing the propagation of each polarized photon packet in turbid media has been described in Refs. 4 and 5. We briefly express the Stokes vector of a transmitted photon packet after it has been scattered n times by spherical scattering particles in a turbid medium as

$$\mathbf{S}_n^{\mathrm{fs}}(x'', y''; \mu_s, \mu_a, \delta) = [\mu_s / (\mu_a + \mu_s)]^n \times \mathbf{R}(\phi_L)\mathbf{M}(\Theta_n)\mathbf{R}(\phi_n)...\mathbf{M}(\Theta_1)\mathbf{R}(\phi_1)\mathbf{S}_0 , \quad (1)$$

Laser Tissue Interaction XIII: Photochemical, Photothermal, and Photomechanical, Steven L. Jacques, Donald D. Duncan, Sean J. Kirkpatrick, Andres Kriete, Editors, Proceedings of SPIE Vol. 4617 (2002)

where μ_s, μ_a are the scattering and absorption coefficients, respectively; δ is the linear birefringence value; and (x'', y'') is the detection point on the lower surface of the turbid medium in the laboratory coordinate. $\mathbf{S}_0$ and $\mathbf{S}_n^{\mathrm{fs}}$ represent the Stokes vectors of the incident and the backscattered photons, respectively. $[\mu_s/(\mu_a+\mu_s)]^n$ denotes the remaining energy after the photon has been scattered n times. $\mathbf{R}(\phi)$ is the rotation matrix that connects the two Stokes vectors that describe the same polarization state but with respect to the two reference planes such that one reference plane coincides with the other after a counterclockwise rotation by angle ϕ around the direction of light propagation. $\mathbf{M}(\Theta)$ is the matrix for each scattering event based on Mie theory, where Θ is the scattering angle. The expression for the diffusely reflected photon packet is similar to Eq. (1).

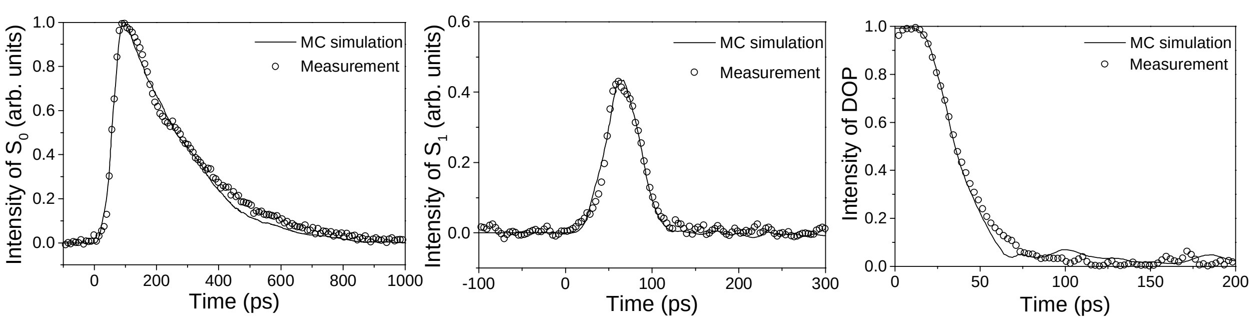


(a) (b)

Fig. 1 (a) Geometry of multiple scattering events in a turbid medium. (b) The experimental setup. P polarizer; HW zero order half-wave plate; QW zero-order quarter-wave plate; A analyzer.

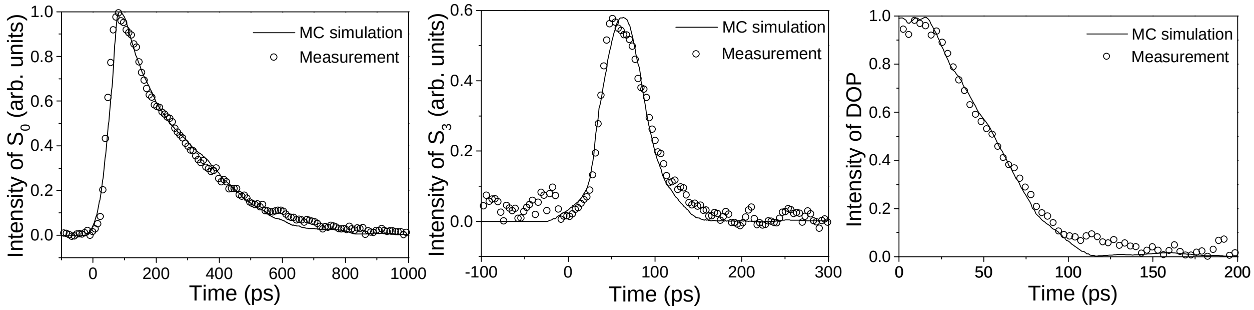
The experimental setup is shown in Fig. 1(b); a Verdi pumped mode-locked Ti:Sapphire laser was used to provide 800 nm laser pulses with a FWHM at 20 ps. The laser output was split into two branches, one for triggering the streak camera and the other for propagating through samples. About 200 mW average power was applied to the samples. The input and output polarization states were controlled with polarizers and waveplates. The transmitted light from a sample were directed to the streak camera with a fiber bundle. The temporal resolution of the operation mode of the streak camera was 4.74 ps. The polystyrene microspheres solution was put in a transparency plastic cubic container with a size of 5 cm×5 cm×2 cm. The sample solution occupied about 4/5 volumes of the container.

3. Results and Discussion



(a) (b) (c)

Fig. 2 The experimental (scattered symbols) and MC simulated (solid curves) temporal profiles of (a) S_0, (b) S_1 and (c) DOP of light transmitted through the polystyrene microspheres solution. The incident light was linearly polarized.



(a) (b) (c)

Fig. 3 The experimental (scattered symbols) and MC simulated (solid curves) temporal profiles of (a) S_0, (b) S_3 and (c) DOP of light transmitted through the polystyrene microspheres solution. The incident light was circularly polarized.

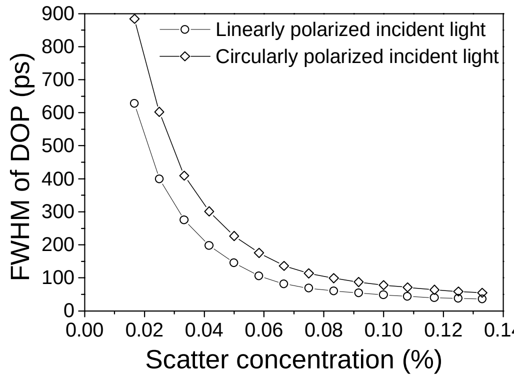


Fig. 4 MC simulated FWHM of DOP as a function of the concentration of a 0.38 μm polystyrene micro-spheres solution. The incident lights were linearly polarized and circularly polarized, respectively.

The results of the polarization propagation in the polystyrene micro-spheres solution obtained from our MC simulation can be proved by the results measured in the experiments. For example, we present the experimental and the MC simulated time-resolved Stokes vectors ($S=[S_0, S_1, S_2, S_3]^T$) as well as the DOP of transmitted light in Figs. 2 and 3 where linearly polarized incident light and circularly polarized incident light were adopted, respectively. The turbid medium was made up of a 0.38 μm diameter polystyrene micro-spheres solution with a concentration of 0.133%. The shape and size of the solution container is shown in Fig. 1(b). In the simulation, the absorption coefficient μ_a was set to be 0; the scattering coefficient μ_s and the anisotropic factor g was simulated to be 9.22 cm^{-1} and 0.65 respectively; and the size parameter ka was calculated to be 1.98. The temporal profiles of the transmitted Stokes vectors and the DOP obtained through the MC simulation fit very well with the experimental results.

The MC simulated FWHM of the DOP as a function of the concentration of 0.38 μm polystyrene micro-spheres is shown in Fig. 4. By comparing the results for linearly incident polarization and circularly incident polarization, we can see that the circularly polarized light preserves its polarization state better than the linearly polarized light after multiple scattering, which agrees with the analysis of Bicout *et. al.* [6] for size parameter $ka>1.23$.

4. Conclusion

The satisfying match between the MC simulation results and experimental measurements proves that MC technique is a powerful tool for analyzing the polarization characteristics of randomly scattering turbid media, which can provide a theoretical basis and explanation for the experimental studies. The time-resolved MC approach presented in this paper should contribute to the understanding of the essential physical processes of polarized light propagation in biological tissues. By adjusting the MC algorithm, we can study samples that are even more complicated, for example, an inhomogeneous turbid medium with a certain distribution of absorption or scattering, or a turbid medium with birefringence or glucose. Some of which will also be reported in the conference.

Acknowledgments

This project was sponsored in part by National Institutes of Health grants R01 CA71980 and R21 CA83760, National Science Foundation grant BES9734491, and Texas Higher Education Coordinating Board grant 000512-0123-1999.

References

1. B. Das, K. Yoo, and R. R. Alfano, “Ultrafast time gated imaging,” Opt. Lett. **18**, 1092–1094(1993).
2. J. M. Schmitt, A. H. Gandjbakhche, and R. F. Bonner, “Use of polarized light to discriminate short-path photons in a multiply scattering medium,” Appl. Opt. **31**, 6535–6546(1992).
3. C. W. Sun, C. Y. Wang, C. C. Yang, Y. W. Kiang, I. J. Hsu, and C. W. Lin, “Polarization gating in ultrafast-optics imaging of skeletal muscle tissue,” Opt. Lett. **26**, 432–434(2001).
4. G. Yao, and L. V. Wang, “Propagation of polarized light in turbid media: simulated animation sequences,” Opt. Express **7**, 198–203 (2000).
5. X. D. Wang, and L. V. Wang, “Propagation of polarized light in birefringent turbid media: time-resolved simulations,” Opt. Express **9**, 254–259(2001).
6. D. Bicout, C. Brosseau, A. S. Martinez, and J. M. Schmitt, “Depolarization of multiply scattered waves by spherical diffusers: influence of the size parameter,” Phy. Rev. E **49**, 1767–1770(1994).