Analysis of the Cross-Sectional Width of the Optical Phase Conjugation Refocusing of Light Multiply Scattered Through Macroscopic Random Media

Snow H. Tseng, *Member, IEEE*

***Abstract*—The pseudospectral time-domain (PSTD) technique is employed to accurately simulate the optical phase conjugation (OPC) refocusing phenomenon of light propagating through a macroscopic scattering medium. The effect of medium thickness is analyzed by means of numerical solutions of Maxwell's equations. Simulation findings show that the OPC refocused light width is insensitive to optical thickness.**

***Index Terms*—Electromagnetic wave propagation in random media, optical phase conjugation (OPC), scattering.**

I. Introduction

OPTICAL wavelengths are beneficial for medical diagnosis purposes but in general do not penetrate deep into biological tissues. The inhomogeneities of the biological tissues cause incoherent scattering and distort light propagation, preventing biological tissues from being transparent [1]. Thus, it is difficult to utilize optical wavelengths for biomedical applications deep within biological tissues.

Lately, much research effort has been placed on guiding optical waves into turbid medium. With a special choice of phase, it is possible to construct the illumination in such a way that it interferes constructively at a targeted position within a scattering medium [2]. Other than choosing the required phase distribution of wavefront via optimization, another approach is by utilizing the optical phase conjugation (OPC) of a phase conjugate mirror (PCM). The OPC phenomenon provides a means to suppress turbidity and enable guiding light into turbid medium. As shown in Fig. 1, by inverting the phase of the light field, the OPC phenomenon causes light to propagate in reversed directions, back-trace its previous trajectories, and refocus at where it originated.

Experimental effort to realize the OPC phenomenon of a PCM has been reported in [1], showing that the scattering effect caused by scattering media can be *undone* by the OPC phenomenon. The OPC phenomenon inverts the poynting vector of light; after OPC, multiply scattered light propagates in reversed directions—similar to a time reversal process Thus, the OPC effect of PCM enables focusing light through turbid media via multiple scattering. In addition to the OPC refocusing of light, experiments also exhibited phenomena that are yet to be understood. One of the interesting phenomena is that the OPC refocused light cross-sectional width is observed to be approximately the same regardless of thickness of the scattering medium. "What are the factors that affect the cross-sectional width of the OPC refocused light?" This is a fundamental question that needs to be answered in order to utilize the OPC phenomenon for practical applications.

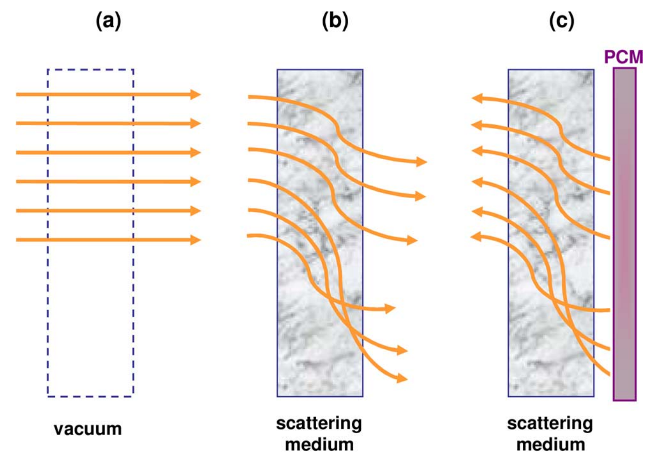

Fig. 1. Schematic of optical paths distorted by the presence of a scattering medium and refocused by a phase conjugate mirror (PCM). (a) Uniform incident light propagates straight through vacuum. (b) Optical paths of uniform incident light distorted by the scattering medium. (c) After incident upon PCM, the OPC effect causes light to propagate in reversed directions.

II. Methods

The Pseudospectral time-domain (PSTD) technique is capable of rigorously simulating light scattering problems of *macroscopic dimensions*. A schematic of the OPC simulation using the PSTD technique is shown in Fig. 2. Our goal is to analyze the OPC phenomenon for scattering media of various thicknesses. Since the scattering effect in biological tissue typically dominates over absorption by an order of magnitude or more [1], we investigate the effect of scattering on the OPC refocusing phenomenon by simulating a scattering medium without absorption. The PSTD technique [3] is implemented to simulate the OPC phenomenon of a 2-D PCM. Based on Maxwell's equations, the PSTD method is a grid-based technique capable of simulating light scattering by arbitrary

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The author is with the Graduate Institute of Photonics and Optoelectronics, and Department of Electrical Engineering, National Taiwan University, Taipei 10617, Taiwan (e-mail: snow@cc.ee.ntu.edu.tw).

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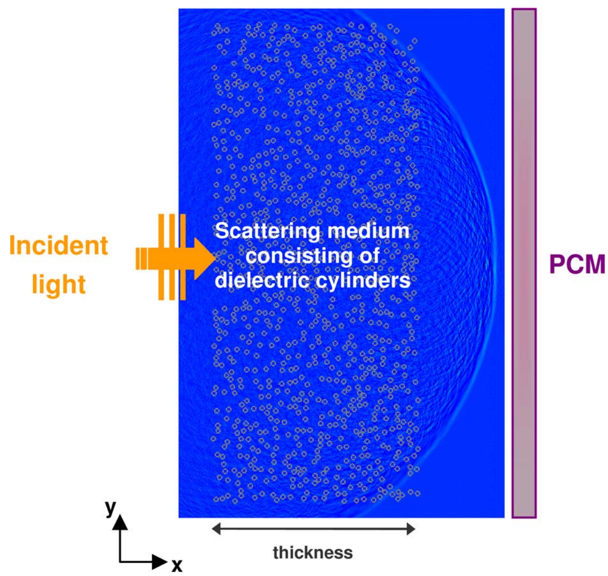

Fig. 2. 2-D PSTD simulation of the OPC phenomenon. Incident light undergoes multiple scattering as it propagates through scattering media. After incident upon a PCM, the OPC phenomenon causes light to propagate in reversed directions, back-trace its previous optical path, and return to where it originated.

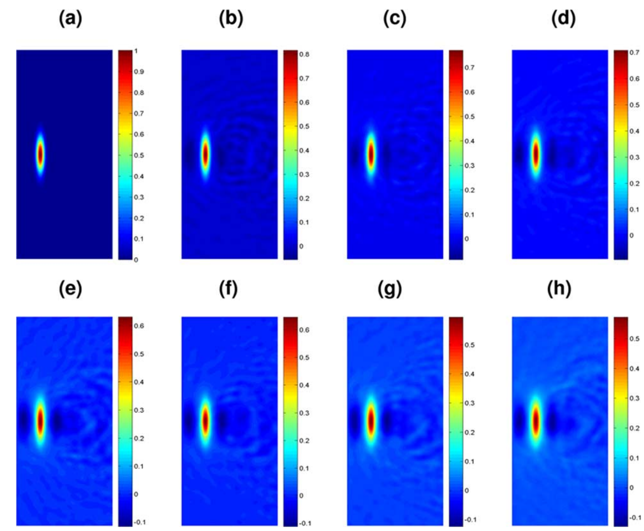

Fig. 3. OPC refocused light pulse of various thicknesses of scattering medium. The initial incident light pulse with a FWHM of 9.3 μm is shown in (a). The thickness of the scattering medium is varied between 80 and 320 μm. (b) 80 μm, (c) 120 μm, (d) 160 μm, (e) 200 μm, (f) 240 μm, (g) 280 μm, and (h) 320 μm, respectively.

geometries. More importantly, the PSTD method is computationally economic [4] and enables simulating light interaction with a large-scale scattering medium. The simulation reported in this paper is performed with a spatial resolution of 0.33 μm and temporal resolution of 0.05 fs. A scattering medium is positioned adjacent to a PCM in vacuum. The scattering medium is illuminated by an incident light pulse; the light pulse scatters through the scattering medium via complex optical paths. For light impinging the PCM, the $\mathbf{H}$-field and $\mathbf{B}$-field components are manually inverted

$$\mathbf{H} \rightarrow -\mathbf{H}, \mathbf{B} \rightarrow -\mathbf{B} \tag{1}$$

while keeping the $\mathbf{E}$-field and $\mathbf{D}$-field unaltered. As a consequence, the inverted light continues to propagate in reversed directions, simulating the OPC refocusing effect of a PCM. Since the 2-D OPC phenomenon obeys essentially the same principle as the 3-D OPC phenomenon, the 2-D OPC simulations provides important information to understanding the optical characteristics of the OPC phenomenon in 3-D. Initial simulations show results consistent with 3-D experiments; a detailed description of the PSTD simulation of OPC has been reported earlier [5].

III. Results

Based upon Maxwell's equations, we simulate the OPC phenomenon for scattering media of various thicknesses. Recent tomographic phase microscopy measurements have shown that typical refractive index of biological cells is on the order of $n \sim 1.36$ [6]. Considering the scattering effect caused by refractive index mismatch between different biological structures and surround medium, we simulate light scattering by a cluster of randomly-positioned, *non-absorbing* dielectric cylinders with a refractive index of $n = 1.2$. The number density of the cluster geometry is 0.0186 ($1/\mu\text{m}^2$), and the anisotropy factor is $g = 0.85$; for wavelength of $\lambda = 1\ \mu$m, the reduced scattering coefficient μ_s' is 0.0194 ($1/\mu$m). While fixing the number density, the thickness of the scattering medium is varied from 40 μm up to 320 μm—six times the transport mean free path for wavelength of $\lambda = 1\ \mu$m.

In Fig. 3, the PSTD-computed amplitude profiles of the OPC refocused light pulse for various thicknesses of the scattering medium are shown. Consistent with experimental findings [1], our simulations show that the amplitude of the OPC refocused pulse decreases as the thickness of the scattering medium increases. Also, for thicker scattering medium, increased reverberations of the light field trailing behind the OPC refocused pulse is shown. The trailing reverberations show that the OPC refocused light was not perfectly in phase; some light was scattered away and never undergone OPC.

As shown in Fig. 4, we further analyze the cross-sectional width of the OPC refocused light pulse. The cross-sectional widths of the OPC refocused light pulse corresponding to scattering media of various thicknesses are depicted. Simulation results show that the OPC refocused peak intensity decreases as the thickness of the scattering medium increases. Nevertheless, simulation results show that the profile of the OPC refocused light remains unchanged—the OPC refocusing of light is insensitive to the specific thickness of the scattering medium.

Next, we simulate incident light pulses of various cross-sectional widths. In Fig. 5, the cross-sectional width of the OPC refocused light pulse is plotted versus $\mu_s' \times L$, where L is the thickness of the scattering medium and μ_s' is the reduced scattering coefficient (corresponding to wavelength $\lambda = 1\ \mu$m); thus, $\mu_s' \times L = 1$ corresponds to a single transport mean free path. Width of the OPC refocused light remains constant for various thicknesses. The simulation results show that, for a scattering medium with an optical thickness up to six times the transport mean free path, the cross-sectional width of the OPC

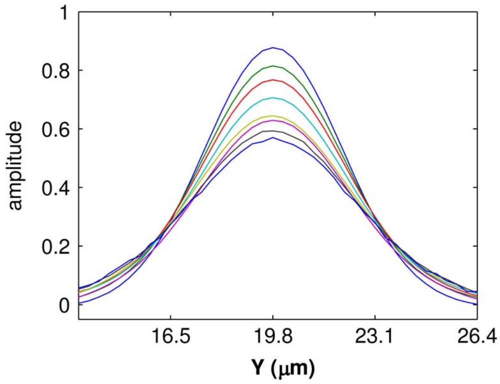

Fig. 4. Amplitude of the OPC refocused light pulse for various thicknesses of the scattering medium. The top to bottom curve corresponds to a scattering medium with thickness of 40, 80, 120, 160, 200, 240, 280, and 320 μm, respectively.

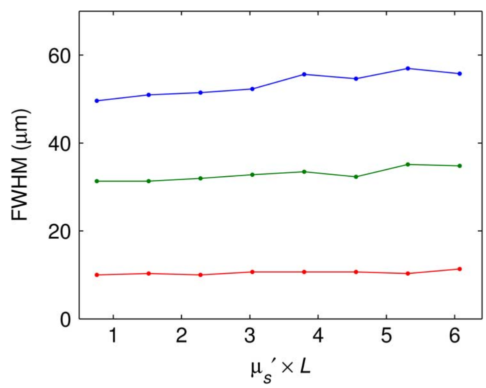

Fig. 5. Cross-sectional width of the OPC refocused light. Incident light of three different cross-sectional widths are shown (bottom to top): 9.32, 29.97, and 47.3 μm. The FWHM for various incident light pulses are plotted versus transport mean free path $(\mu_s' \times L)$. [L: thickness of the scattering medium; μ_s': reduced scattering coefficient corresponding to wavelength $\lambda = 1$ μm].

refocused light pulse is insensitive to the thickness of the scattering medium.

IV. Discussions

A simplified model for the OPC phenomenon was proposed by [7], [8]. The model is derived based upon various approximations: for example, the Huygens–Fresnel approximation is employed to calculate light propagation; in addition, the scattering medium is assumed to be a very thin phase screen, only considering the phase variations of light. Thus, this phase-screen model is in principle suitable only for infinitely thin phase screen whereas the amplitude and direction of propagation are unaltered by the scattering medium.

To analyze the OPC characteristics for practical applications, a research approach capable of handling the OPC phenomenon of thick scattering medium is required. The PSTD technique is a grid-based simulation that can model the OPC phenomenon for arbitrary geometry. Based upon Maxwell's equations, the OPC simulation reported in this paper is practically a virtual experiment yielding accurate information of the electromagnetic field that is in general not accessible experimentally. Specifically, the OPC simulations provide important information to explore innovative OPC applications, e.g., guiding light through thick biological tissue structures for medical treatment purposes.

OPC simulation provides important information to determine the cause of phenomenon observed in experiments. Experimental results show that the OPC refocused intensity decreases with increasing thickness of the scattering medium; however, whether this intensity decrease is due to absorption or scattering effect of the turbid medium is unknown. Since the information of the electromagnetic field is in general not accessible, this question is difficult to answer experimentally. On the other hand, the scattering effect and absorption effect can be controlled independently in the OPC simulation. We simulate only the scattering effect (with no absorption) and observe the same intensity decrease as observed in experiments [1]; hence, it is clear that the observed intensity decrease is due to scattering rather than absorption.

Why is the OPC refocused light width unchanged for thicker turbid medium? This phenomenon can be understood as follows. As light propagates through random media, light is multiply scattered into arbitrary directions. For thicker scattering medium, more light is scattered into all possible directions without preference. Thus, light impinging the PCM consists of a uniform sample of the initial incident light profile. As a result, the OPC refocused light is a replicate of the original incident light pulse, but with amplitude only a fraction of the incident energy. In other words, the OPC refocused light width is determined by the incident light; thicker scattering medium decreases the OPC refocused light intensity, but does not change the OPC refocused light pulse profile.

V. Conclusion

In this manuscript, we simulate and analyze the OPC refocused phenomenon where the light intensity decreases with increasing thickness of the scattering medium, whereas the OPC refocused cross-sectional width remain unchanged. Simulation results show that the OPC refocused intensity decrease is a consequence of scattering rather than absorption effect of the turbid medium. Furthermore, we show that the cross-sectional width of the OPC refocused light pulse is insensitive to the optical thickness of the scattering medium, even for scattering medium as thick as six times the transport mean free path.

The OPC phenomenon enables *undoing* the light scattering effect which is the dominating factor causing biological tissues to be opaque. Undoing the scattering effect enables light to be guided deeper into human body. This can potentially enable new treatment or diagnosis applications using optical techniques. For example, Photodynamic therapy (PDT) [10] requires delivery of light to the photosensitizer in order to activate the drug for treatment. With the proper phase and amplitude profiles as determined by the OPC phenomenon, light can be delivered deeper into biological tissues to activate the PDT photosensitizer, extending the applicability of PDT treatment to deeper organs located within the biological body. To realize such applications, it is important to understand the optical characteristics of OPC for thick scattering medium. The simulation results reported in this manuscript is rigorous and generally applicable to scattering medium of finite thicknesses. Based upon Maxwell's equations, the OPC phenomenon for arbitrary geometry can be accurately analyzed by means of the reported PSTD simulation.

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Snow H. Tseng (M'98) received the B.S. degree in physics from National Taiwan University (NTU), Taipei, Taiwan, in 1994, the M.S. degree in physics from the University of Chicago, Chicago, IL, in 2001, and the Ph.D. degree in electrical engineering from Northwestern University, Evanston, IL, in 2005.

In 2006, he became an Assistant Professor in the Graduate Institute of Photonics and Optoelectronics and Department of Electrical Engineering, NTU. Based upon rigorous solutions of Maxwell's equations, he utilizes the pseudospectral time-domain (PSTD) technique to investigate optical characteristics of macroscopic random medium, including biological tissues and turbid media in general.