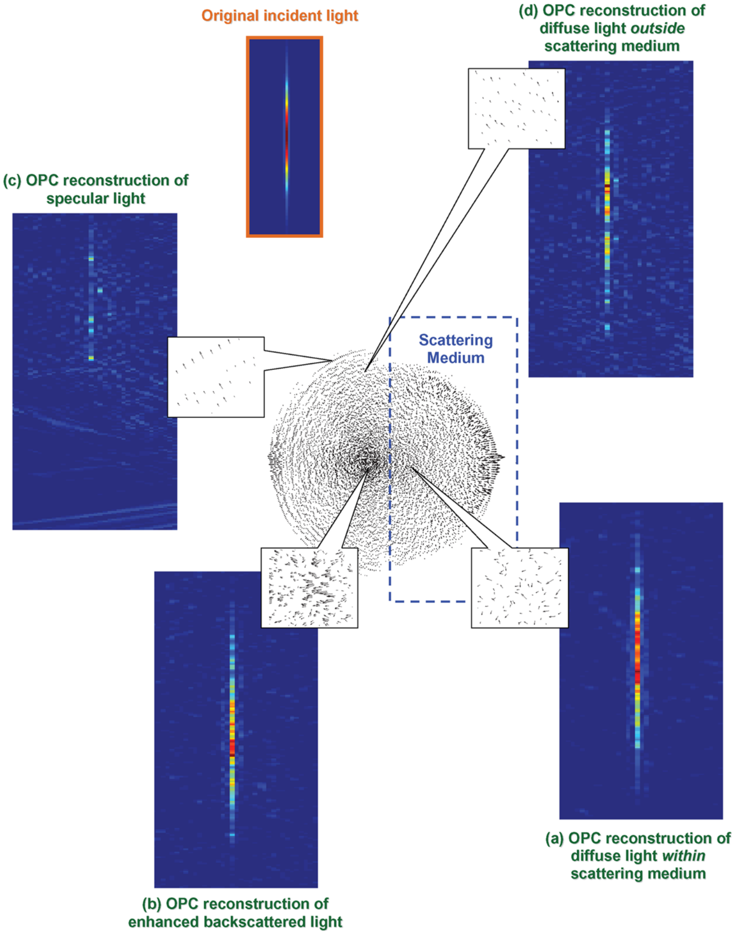
IEEE Photonics Journal
An IEEE Photonics Society Publication

Investigating the Optical Phase Conjugation Reconstruction Phenomenon of Light Multiply Scattered by a Random Medium

Volume 2, Number 4, August 2010

Snow H. Tseng, Member, IEEE



DOI: 10.1109/JPHOT.2010.2055555
1943-0655/$26.00 ©2010 IEEE

Investigating the Optical Phase Conjugation Reconstruction Phenomenon of Light Multiply Scattered by a Random Medium

Snow H. Tseng, ***Member, IEEE***

Graduate Institute of Photonics and Optoelectronics, and Department of Electrical Engineering,
National Taiwan University, Taipei 106, Taiwan

DOI: 10.1109/JPHOT.2010.2055555
1943-0655/$26.00 ©2010 IEEE

Manuscript received June 9, 2010; revised June 18, 2010; accepted June 20, 2010. Date of publication June 28, 2010; date of current version July 19, 2010. This work was supported by the Taiwan National Science Council Grant NSC-96-2112-M-002-028-MY32. Corresponding author: S. H. Tseng (e-mail: snow@cc.ee.ntu.edu.tw).

Abstract: The optical phase conjugation (OPC) phenomenon of light multiply scattered through a macroscopic scattering medium is simulated using the pseudospectral time-domain (PSTD) technique. We investigate the OPC reconstruction from scattered light at various positions in space. Specific results show that the original incident light *cannot* be reconstructed from singly scattered light. To reconstruct the original incident light, an "unbiased" selection of scattered light is required.

Index Terms: Electromagnetic wave propagation in random media, optical phase conjugation, scattering.

1. Introduction

Optical techniques are assuming greater importance in medicine. Due to the opacity of biological tissues, optical wavelengths are in general limited to shallow applications. For turbid media such as biological structures, scattering is the dominating factor that prevents transparency [1]. As light propagates through turbid media, the amplitude and phase become distorted and incoherent due to scattering of inhomogeneities, resulting in blurred images or even opacity. By suppressing the scattering effects, transparency of turbid media can be enhanced. In principle, the optical phase conjugation (OPC) phenomenon enables *undoing* the scattering effect, therefore providing a means to enhance transparency of biological tissues or turbid media in general. An effort to implement the OPC reconstruction and deliver light through turbid media for practical applications are currently being pursued [2].

OPC inverts the poynting vector of the electromagnetic field and causes light to propagate in reverse directions. Preliminary studies of the OPC reconstruction effect have been pursued in various fields. Back in 1966, Leith and Upatnieks reported reversing optical scattering induced by a ground glass slide [3]. In 1986, Chiou and Yeh reported an application employing OPC to eliminate the phase aberration introduced by the photorefractive gain medium [4]. Besides optics, the OPC phenomenon has also been explored in microwaves and acoustics [5], [6]. Regardless of the specific research problem involved, each of these works is based upon phase conjugation of the wave.

Although light scattering through turbid medium may appear random and stochastic, it is deterministic in nature. In theory, if the phase and amplitude of the scattered light field could be completely recorded to reproduce a phase conjugate field, light will back-trace its previous trajectory through the turbid medium and be reconstructed where it originated. Thus, by utilizing the OPC

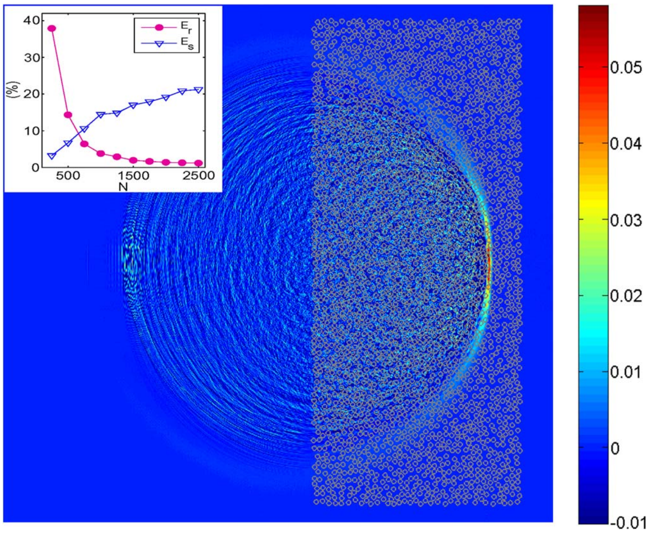


Fig. 1. PSTD simulation of a light pulse impinging a scattering medium consisting of 2500 5-μm-diameter, $n = 1.2$, dielectric cylinders. The PSTD simulation shows a significant amount of energy being scattered away from the scattering medium. The total energy (E_s) scattered away from the scattering medium and the total energy (E_r) of the OPC reconstructed light pulse are calculated and shown in the inset-figure as functions of N. E_s increases as N increases, showing that with increasing scattering coefficient, more energy is scattered away from the scattering medium.

phenomenon, it is possible to *undo* the distortion and incoherence caused by turbid media. Early theoretical analysis of the OPC phenomenon was pioneered by Agarwal *et al.* [7] in the 1980s. Without computers, various assumptions to simplify the problem were inevitable for the theoretical development. These theoretical analyses have provided an important foundation of OPC research today [7], [8].

Experimental effort utilizing static holography to realize the OPC phenomenon has been reported [1]; it is shown that the optical characteristics of OPC may lead to promising applications in biomedical optics and other related fields. A theoretical model for the OPC phenomenon of a phase-conjugation mirror was proposed [9], [10]; based upon the paraxial wave equation, this analysis is applicable to thin random medium where light propagation *within* the random medium is ignored. For practical applications, a general model applicable to random media of *arbitrary thicknesses* is desired. In this manuscript, we report simulation of the OPC phenomenon based upon Maxwell's equations, which can accommodate arbitrary geometry. Specifically, we report contribution analysis of the OPC reconstruction phenomenon from scattered light at various locations in space.

2. Methods

To analyze the OPC effect on light multiply scattered through a macroscopic scattering medium, we employ the pseudospectral time-domain (PSTD) technique [11] to simulate the optical characteristics of a phase-conjugate mirror in 2-D. The PSTD simulation yields numerical solutions of Maxwell's equations; it is a grid-based technique capable of simulating light scattering by arbitrary geometries. Space and time are discretized into grid points that are imposed to satisfy Maxwell's equations. The PSTD method is computationally economic [11] and can simulate a much larger electromagnetic interaction region than the finite-difference time-domain (FDTD) [12] method. Hence, the PSTD technique enables simulating OPC phenomenon of light interaction with a scattering medium of *macroscopic dimensions* that is difficult to achieve using other simulation methods.

Here, we investigate the effect of scattering on the OPC reconstruction phenomenon. The entire optical field is simulated and shown in Fig. 1: A 2-D PSTD simulation of light multiply scatters through a *macroscopic* scattering medium and undergoes OPC. The physical dimensions of the simulation region are 640 μm by 600 μm with a spatial resolution of 0.33 μm. The simulation is performed with a temporal resolution of $\Delta t = 0.05$ fs. A macroscopic random medium consisting of a cluster of randomly positioned dielectric cylinders is placed in space. The scattering medium consists of N randomly positioned, infinitely long, dielectric cylinders. Considering the scattering effect caused by refractive index mismatch between different biological structures and surround medium, a typical refractive index of $n = 1.2$ is assigned to each dielectric cylinder. Light propagating through the aggregate of dielectric cylinders is randomly scattered by the inhomogeneity of the scattering medium. A detailed description of the PSTD simulation of the OPC phenomenon can be found in [13].

The OPC phenomenon of a phase-conjugate mirror causes light to propagate backwards, similar to a time-reversal process. In our simulation, the OPC phenomenon is simulated by manually inverting the phase of the optical field. A Gaussian light pulse from the left impinges and scatterers through the scattering medium and undergoes OPC within a selected region (hereby named the “OPC inversion region”), simulating the effect of a phase-conjugate mirror. The optical characteristics of a phase-conjugate mirror are simulated by manually inverting the magnetic field **H** and magnetic induction **B**: $\mathbf{H} \rightarrow -\mathbf{H}$, $\mathbf{B} \rightarrow -\mathbf{B}$ within the OPC inversion region, whereas the electric field **E** and electric displacement **D** are kept unchanged. After OPC, the backward propagating light interferes coherently and reconstructs where the initial incident pulse originated. Details of the PSTD simulation of the OPC phenomenon have been previously reported [13].

3. Results

Experimental results show that the OPC reconstruction effect deteriorates as the optical thickness increases [1]. We simulate the effect of optical thickness on the OPC reconstruction phenomenon by simulating scattering without absorption. A schematic of the simulation is shown in Fig. 1. Since the optical thickness $[\text{optical thickness} \equiv (\text{geometrical thickness})/(\text{scattering mean free path})]$ of a cluster of dielectric cylinders is proportional to the number N of dielectric cylinders, the optical thickness of the scattering medium can be increased by increasing N. A quantitative analysis of the OPC reconstructed energy as related to N is shown in the inset-figure of Fig. 1. We calculate the total energy (E_s) scattered away from the scattering medium and the total energy (E_r) of the OPC reconstructed light pulse. E_s represents the energy that never reaches the phase conjugate mirror and, therefore, is not reconstructed by the OPC phenomenon. E_r is the energy of the OPC reconstructed light, which is determined by integrating the total energy of the OPC reconstructed light pulse. Both E_s and E_r are plotted versus N. For $N = 2500$, the total energy of light scattered away by the scattering medium amounts to approximately 20% of the total incident energy—a significant fraction of the total energy loss of the OPC reconstruction effect. As N increases, E_s increases, and E_r decreases, indicating that more energy is scattered away by the increased number of scatterers and never undergoes OPC; as a consequence, the OPC reconstructed light intensity decreases. Simulation findings show consistent characteristics as the reported experimental findings [1]. Since no absorption is allowed in the simulations, our simulation results clearly show that deterioration of the OPC reconstruction effect observed in experiments can be accounted for by the scattering effect of the scattering medium. In addition, the simulation results of Fig. 1, based upon numerical solutions of Maxwell’s equations, show that the assumption of negligible backscattering of light imposed in the early OPC theoretical analyses by Gbur and Wolf [14] does not generally hold.

To further investigate the energy propagation of the OPC phenomenon, we calculate the poynting vector field and compare the contribution from singly and multiply scattered light. Specifically, four inset-figures are shown, i.e., Fig. 2(a)–(d), each depicting diffuse light within the scattering medium, enhanced backscattered light, specular light, and multiply scattered light exiting the scattering medium, respectively. In Fig. 2(a), as light multiply scatters through the scattering medium, the poynting vectors lose their original orientation and point in random directions. In Fig. 2(b), poynting vectors anti-parallel to the incident light propagation direction is observed where the incident light impinges upon the scattering medium. The late emergence of these anti-parallel poynting vectors

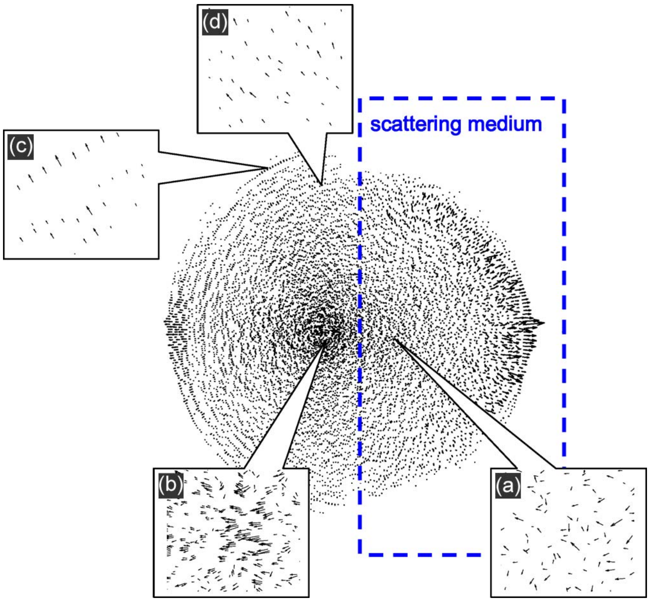


Fig. 2. Poynting vector field of light multiply scattering through a scattering medium. Four inset-figures (a), (b), (c), and (d) each show a zoomed-in region of the poynting vector field. As light scatters through the scattering medium, the poynting vector field in each region bears different characteristics: (a) randomly oriented, (b) in general pointing away from the scattering medium and anti-parallel to the incident light, (c) uniformly pointing away from the scattering medium, and (d) pointing away from the scattering medium but not as uniform as in (c).

shows that the scattered light has traveled long, sinuous optical paths, which is typical of the enhanced backscattering (EBS) phenomenon. Furthermore, we have verified that regardless of the angle of incidence, the EBS poynting vectors always align anti-parallel to the incident light direction—a definite characteristic of the EBS phenomenon. (Fig. 2(b) shows a snapshot of the EBS phenomenon in the time domain that has not been reported before.) In Fig. 2(c), the farthest wavefront of scattered light is shown. The light field in this region is from specular reflection, whereas the poynting vectors uniformly point radially outward with respect to the location where incident light impinges the scattering medium. In Fig. 2(d), light multiply scattered and exited the scattering medium is shown. Without further scattering, light propagates away from the scattering medium in free space. The poynting vector field helps decipher singly and multiply scattered light of the problem.

Next, we determine the OPC contribution from various portions of the scattered light field by applying OPC only to scattered light within a selected 40 μm-by-40 μm area, as shown in Fig. 2: Four regions of the scattered light field are arbitrarily chosen and phase conjugated to determine its contribution in the OPC reconstruction. Each of these four regions corresponds to a 40 μm-by-40 μm rectangular area as pinpointed by the four inset-figures of Fig. 2. The phase-conjugated light field of each of the four regions is achieved by manually inverting the magnetic field. The OPC reconstructed light from each selected area corresponding to Fig. 2(a)–(d) is shown in Fig. 3(a)–(d), respectively: In Fig. 3(a), the OPC reconstructed light from diffuse light within the scattering medium, in Fig. 3(b), the original incident light pulse reconstructed via OPC of the EBS light, in Fig. 3(c), the original incident light pulse *cannot* be reconstructed via OPC of the specularly reflected light, and in Fig. 3(d), the original incident light pulse reconstructed via OPC of diffuse light propagating outside of the scattering medium. Cross-correlation analysis shows that, for each local scattered light field [see Fig. 2(a), (b), and (d)] consisting of *multiply* scattered light, the original incident light can be reconstructed, where diffuse scattered light within the scattering medium [see Fig. 2(a)] is the most effective. As shown in Fig. 2(c), for *singly* scattered, specularly reflected light, the original incident light profile cannot be reconstructed [see Fig. 2(c)].

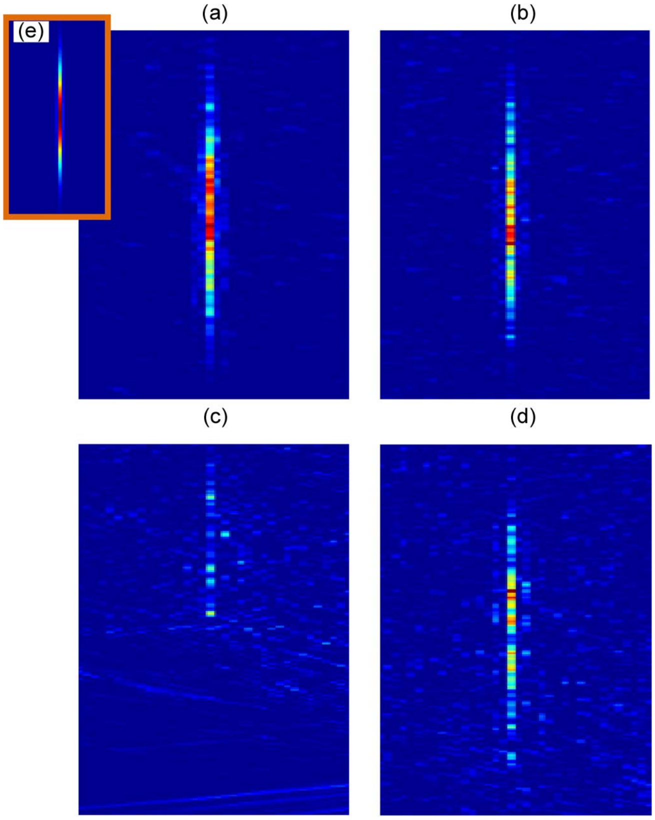


Fig. 3. OPC Refocused light from selected local regions shown in Fig. 2(a)–(d). A cross-correlation of each OPC reconstructed light and the original incident light profile is calculated. (a) Diffuse light within the scattering medium, correlation coefficient $cc = 2.6 \times 10^{-4}$, (b) enhanced backscattered light, $cc = 4.2 \times 10^{-5}$, (c) specularly reflected light, $cc = 4.3 \times 10^{-6}$, (d) diffuse light outside the scattering medium, $cc = 3.2 \times 10^{-5}$. (The original incident light profile is depicted in (e) for comparison.) (c) has a much smaller cc value and falls short to reconstruct the original incident light profile.

4. Discussions

The OPC phenomenon causes light to propagate in reverse directions, similar to a time-reversal process; by inverting the optical phase, scattered light propagates backwards through the scattering medium and reconstructs the original incident light at its originating position. If all scattered light is phase conjugated, the original incident light can be ideally reconstructed. For practical situations, only a portion of light impinges upon the phase conjugation mirror and undergoes OPC. Hence, only a small fraction of scattered light contributes to reconstruction of the original light. Thus, if the contributing light consists of a uniform sampling of the original incident light, a statistical replicate of the original incident light profile would be reconstructed; on the other hand, if the scattered light does not consist of a large enough or uniform sampling, the OPC reconstruction of original incident light is skewed. In Fig. 2(a), (b), and (d), OPC reconstruction is possible since the selected OPC region consists of a random sampling of scattered light; as for the specularly reflected light [see Fig. 2(c)], light only undergoes a single scattering event and strongly depends on the specific surface geometry of the random media, rather than a uniform sampling of the incident light. As a result, the original incident light cannot be reconstructed by OPC of a small chunk of specularly reflected light [see Fig. 2(c)].

5. Conclusion

Research on OPC phenomenon enables new possibilities in biomedical optics, as well as in other fields. By specific manipulation of the phase properties of light, it is possible to guide light deep into turbid medium (e.g., biological tissue) and focus light onto a narrow region. However, the optical characteristics of phase-conjugate mirror are not yet well understood.

In this manuscript, we report analysis of the OPC reconstruction phenomenon of scattered light. The OPC reconstruction of incident light is accomplished by reversing the propagation of a statistical sampling of the scattered light. Simulation results show that even with a significant amount of energy scattered away that never reaches the phase conjugate mirror, the original incident light can be reconstructed with a statistical sampling of the original incident light.

Specifically, the reported simulations show that for specularly scattered light, the incident light pulse cannot be reconstructed. For multiply scattered light, OPC of an arbitrarily selected region of scattered light consists of a uniform sampling of the original incident light and, therefore, can reconstruct the original incident light. The reconstruction is based upon statistical sampling; hence, a better reconstruction of the incident light can be achieved by applying OPC to a larger collection of multiply scattered light. For practical applications, OPC of a wide angular range of scattered light is required; this can be achieved by using a larger phase-conjugate mirror. In this paper, we investigate the feasibility of utilizing the OPC phenomenon to propagate light through random media. The simulation results show that the incoherent multiple scattering characteristics of random media cause opacity. Specifically, to reconstruct the incident light using phase-conjugated light scattered through random media, the scattered light must consist of a uniform sampling of the original incident light.

Acknowledgment

The author thanks C. Yang, E. McDowell, M. Cui, and D. Gauthier for insightful discussions. The author thanks the National Taiwan University Computing Center for providing the computing facilities.

References

[1] Z. Yaqoob, D. Psaltis, M. S. Feld, and C. Yang, “Optical phase conjugation for turbidity suppression in biological samples,” *Nature Photon.*, vol. 2, no. 2, pp. 110–115, Feb. 2008.

[2] M. Cui and C. Yang, “Implementation of a digital optical phase conjugation system and its application to study the robustness of turbidity suppression by phase conjugation,” *Opt. Express*, vol. 18, no. 4, pp. 3444–3455, Feb. 2010.

[3] E. N. Leith and J. Upatnieks, “Holographic imagery through diffusing media,” *J. Opt. Soc. Amer.*, vol. 56, no. 4, p. 523, Apr. 1966.

[4] A. E. Chiou and P. Yeh, “Laser-beam cleanup using photorefractive two-wave mixing and optical phase conjugation,” *Opt. Lett.*, vol. 11, no. 7, pp. 461–463, Jul. 1986.

[5] G. Lerosey, J. Rosny, A. Tourin, and M. Fink, “Focusing beyond the diffraction limit with far-field time reversal,” *Science*, vol. 315, no. 5815, pp. 1120–1122, Feb. 2007.

[6] M. Fink, “Time-reversed acoustics,” *Sci. Amer.*, vol. 281, pp. 91–97, 1999.

[7] G. S. Agarwal, A. T. Friberg, and E. Wolf, “Elimination of distortions by phase conjugation without losses or gains,” *Opt. Commun.*, vol. 43, no. 6, pp. 446–450, Nov. 1982.

[8] G. S. Agarwal, A. T. Friberg, and E. Wolf, “Effect of backscattering in phase conjugation with weak scatterers,” *J. Opt. Soc. Amer.*, vol. 72, no. 7, pp. 861–863, Jul. 1982.

[9] E. Jakeman and K. D. Ridley, “Incomplete phase conjugation through a random-phase screen. 1. Theory,” *J. Opt. Soc. Amer. A, Opt. Image Sci. Vis.*, vol. 13, no. 11, pp. 2279–2287, Nov. 1996.

[10] K. D. Ridley and E. Jakeman, “Incomplete phase conjugation through a random phase screen. 2. Numerical simulations,” *J. Opt. Soc. Amer. A, Opt. Image Sci. Vis.*, vol. 13, no. 12, pp. 2393–2402, Dec. 1996.

[11] Q. H. Liu, “Large-scale simulations of electromagnetic and acoustic measurements using the pseudospectral time-domain (PSTD) algorithm,” *IEEE Trans. Geosci. Remote Sens.*, vol. 37, no. 2, pp. 917–926, Mar. 1999.

[12] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method.* Norwood, MA: Artech House, 2000.

[13] S. H. Tseng and C. Yang, “2-D PSTD simulation of optical phase conjugation for turbidity suppression,” *Opt. Express*, vol. 15, no. 24, pp. 16 005–16 016, Nov. 2007.

[14] G. Gbur and E. Wolf, “Phase conjugation with random fields and with deterministic and random scatterers,” *Opt. Lett.*, vol. 24, no. 1, pp. 10–12, Jan. 1999.