PSTD Simulation of optical phase conjugation of light propagating long optical paths

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Abstract: The phenomenon of Optical Phase Conjugation (OPC) can be rigorously simulated using the pseudospectral time-domain (PSTD) technique. However, with finite computational memory, it is infeasible to simulate light propagating long optical paths. We report a robust OPC simulation technique that can account for long optical path lengths by sequentially inverting the electromagnetic fields. Specifically, the ideal efficiency of OPC refocusing of light through scattering medium can be accurately determined.

OCIS code: (290.4210) Multiple scattering; (290.7050) Turbid media

References and links

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1. Background

Due to the *non-invasive* nature of optical wavelengths, optical techniques are assuming greater importance in medicine. However, optical wavelengths in general don't penetrate deep into biological tissues. As light propagates through turbid medium (e.g., biological tissues), the amplitude and phase become distorted and incoherent due to scattering effect of the inhomogeneities within the turbid medium. The scattering effect of light prevents biological tissue structures from being transparent [1]. Thus, it is difficult to utilize optical wavelengths for biomedical applications in deeper tissue.

Recent research has shown that the scattering effect cause by turbid medium can be *undone* by the optical phase conjugation (OPC) phenomenon—similar to a time reversal process. Though light propagation through scattering medium may appear random and stochastic, it is actually a deterministic process. By inverting the phase of the light field, the OPC phenomenon causes light to propagate in the reverse direction, back-trace its previous trajectories, and refocus at where it originated. With a particular arrangement of phase and

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amplitude, it is possible to cause light to interfere constructively at a targeted position within a scattering medium. In other words, the undesired scattering effect caused by scattering medium can be undone by means of OPC, and light can potentially be guided deep into biological structures. Experimental progress to utilize OPC for biomedical application has been reported [1]. However, the characteristics of OPC phenomenon is not yet well understood, further analysis is required. To analyze the optical characteristics of OPC, a simulation that can yield accurate electromagnetic field information is desired.

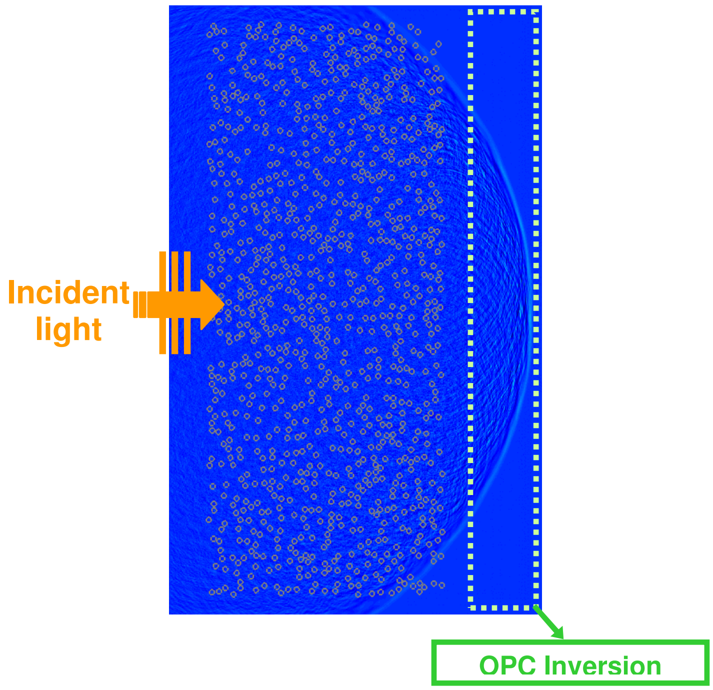

Fig. 1. Schematic of the serial OPC simulation. Incident light multiply scatters through a scattering medium consisting of N dielectric cylinders. To account for light traveling long optical paths before undergoing OPC, the electric field and magnetic field in the OPC inversion region is sequentially recorded. The recorded field information is later inserted sequentially to simulate OPC phenomenon while accounting for light propagating long optical paths.

In this paper, we report an innovative OPC simulation technique that can handle light propagating long optical paths that was not feasible before. Light propagating long optical paths needs to be taken into account in order to accurately simulate the OPC phenomenon. However, with the previously reported simulation method [2], a very large simulation grid is required to account for long optical paths. Hence, the previously reported method is only applicable to optically thin scattering media; for optically thick scattering media, an enormously large computational grid is required to account for long propagating light and is therefore infeasible. In this paper, we propose an advanced OPC simulation technique that can account for light propagating long optical paths. The proposed OPC simulation technique enables determining the ideal OPC refocusing efficiency of light through *macroscopic optically-thick*, scattering medium that was not possible to simulate with previously reported methods.

2. Serial OPC simulation

A schematic of the serial OPC simulation is shown in Fig. 1. The pseudospectral time-domain (PSTD) technique [3, 4] is implemented to simulate the OPC phenomenon of a 2-D phase

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conjugate mirror (PCM). Based on Maxwell's equations, the PSTD method is a grid-based technique capable of simulating light scattering by arbitrary geometries. 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 consisting of randomly-positioned dielectric cylinders is placed adjacent to a PCM in vacuum. 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. The scattering medium is illuminated by a light pulse; the light pulse scatters through the scattering medium via complex optical paths and impinges the PCM.

The OPC phenomenon of a PCM is simulated by sequentially inverting the electromagnetic field within the OPC inversion region at constant time intervals. When light impinges a PCM, the poynting vector is inverted and light then propagates in reversed directions. To simulate OPC, the **H**-field and **B**-field are manually inverted:

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

with the **E**-field and **D**-field kept unchanged. Thus, the phase conjugated light then propagates in reversed directions. To account for light propagating long (and short) optical paths before reaching the OPC inversion region, the optical field in the OPC inversion region is sequentially inserted into the simulation grid. Details of the simulation are described as follows.

3. Storing the electromagnetic fields for sequential OPC inversion

As shown in Fig. 2, the E- and H- fields of the scattered light within the OPC inversion region are stored every T timesteps. For the simulations reported in this paper, $T = 4000$ timesteps is chosen, corresponding to a temporal duration of 0.2 ps. T cannot be too large where light transpasses the OPC inversion region without being recorded. An appropriate T is chosen so that all light entering the OPC inversion region is stored before exiting the OPC inversion region. In addition, there should be overlap of the stored field of the OPC inversion region; the overlapped fields are essential for connecting the stored OPC inversion fields. The stored OPC electromagnetic fields are later sequentially inserted to reconstruct the OPC phenomenon of light.

4. Sequential OPC inversion of scattered light

As depicted in Fig. 3, the previously stored E-field and H-field [Fig. 3(a)-(d)] are OPC inverted and sequentially inserted into the simulation grid. The OPC phenomenon inverts the poynting vector and causes light to propagate in reversed directions. Each insertion of the OPC inverted fields is equally spaced in time by T timesteps, the same as storing the E-field and H-field (as shown in Fig. 2).

By sequentially stitching together the OPC inverted field, the OPC inverted electromagnetic field of light propagating various long optical paths can be reconstructed. As shown in Fig. 4. (Media 1), the OPC inverted field at various timesteps are sequentially stitched together to reconstruct the OPC reversed propagation of light. In Fig. 4(a): the light pulse propagates in the reverse direction (towards left). Notice that the profile of the wavefront is imperfect—the middle section breaks apart with an opening. This defect is a result of OPC inversion of incomplete optical wavefront. As shown in Figs. 4(b) and 4(c), T timesteps later, the next OPC inverted field is inserted to cover up and replace the erroneous artifacts caused by OPC of incomplete field. After sequentially "*stitching*" all OPC inverted fields together, all the artifacts are sequentially replaced by correct field values to reconstruct the OPC refocusing of light propagating long optical paths.

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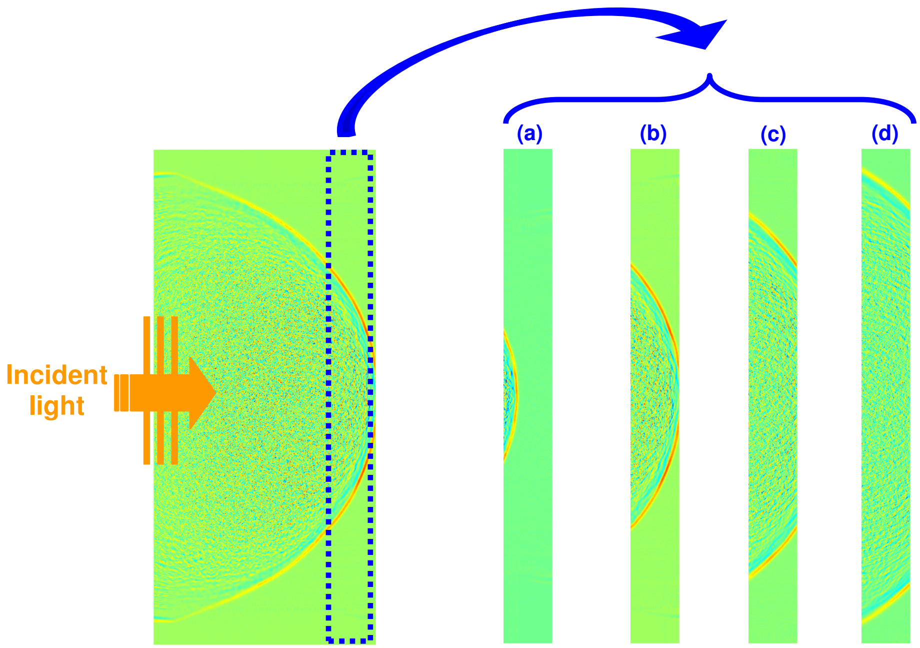

Fig. 2. The electric fields and magnetic fields of the OPC inversion region are recorded every T timesteps (corresponding to 0.2 ps). Electromagnetic fields at equal time intervals (T = 4000 timesteps) are stored in series: (a): $1\times T$, (b): $2\times T$, (c): $3\times T$, and (d): $4\times T$. The interval T is chosen so that the OPC inversion fields overlap each other. The recorded field information is later inserted sequentially to simulate OPC reversed light propagation.

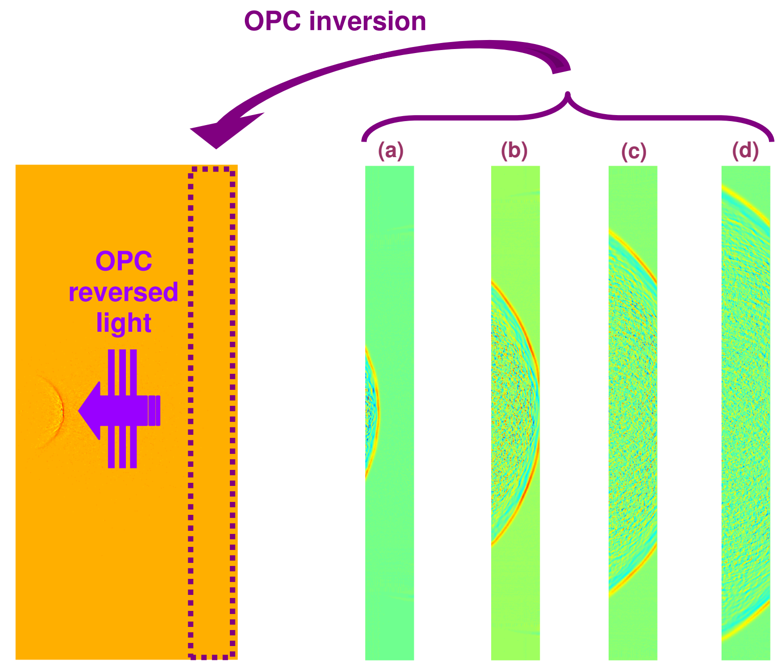

Fig. 3. The recorded electric fields and magnetic fields are sequentially inserted into the OPC inversion region every T timesteps to simulate light propagating long optical paths.

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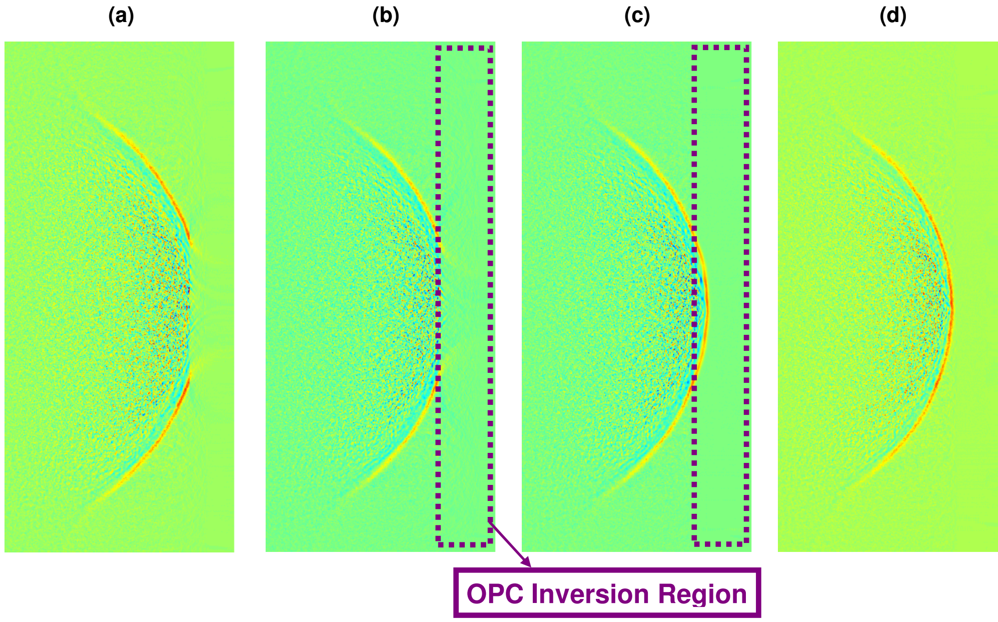

Fig. 4. (Media 1) Sequentially stitching the OPC inverted field to reconstruct the OPC reversed propagation of light. The E- fields of the OPC inverted field at various time steps are shown: T = (a) 59001, (b) 60000, (c) 60001, and (d) 61000 timesteps. (a): after OPC, light propagates in the reverse direction (towards left); defect of the reconstructed wavefront is a result of OPC inversion of incomplete electromagnetic field. Later, as shown in (b) and (c), the next OPC inverted field is inserted to replace the artifacts, resulting in (d): a perfect OPC reversed propagation of light.

5. Effectiveness of the OPC refocusing of light through scattering medium

We employ the proposed serial simulation technique to analyze the effectiveness of the OPC refocusing of light through scattering medium. The effectiveness of OPC refocusing phenomenon depends mainly on two factors: i) OPC efficiency of the PCM, and, ii) percentage of incident light reaching the PCM. Depending on the specific mechanism of the PCM, the OPC efficiency varies [5-9]. For practical applications to focus light within turbid medium, it is important to accurately determine the percentage of light reaching the PCM. By employing the proposed simulation technique, we can simulate the OPC phenomenon for a PCM with ideal efficiency and determine the effectiveness of OPC refocusing of light multiply scattering through a scattering medium.

Next, we analyze the contribution of light propagating through the scattering medium via various optical path lengths. The OPC refocusing of light consists of light propagating short and long optical paths. The contribution of light propagating different optical path lengths can be determined by running the serial OPC simulation for various temporal durations. The physical thickness of the scattering medium is 240 μm. We employ the serial OPC simulation for various durations: from 0.8 to 32 ps (in 32 ps, light propagates a distance of 9600 μm in vacuum). As shown in Fig. 5, the energy of the OPC refocused light energy converges. For a typical scattering medium with optical thickness of 4.65 (for wavelength $\lambda = 1$ μm), a simulation of temporal duration 8 ps is required to account for all light propagating long and short optical paths. Furthermore, the simulation results show that the ideal OPC refocusing efficiency of light through a typical scattering medium is ~15%; energy loss occurs in the forward propagation before impinging the PCM. Though only a fraction of light undergoes

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OPC, the OPC effect causes light to propagate in reversed directions *through* the scattering medium and refocus without loss.

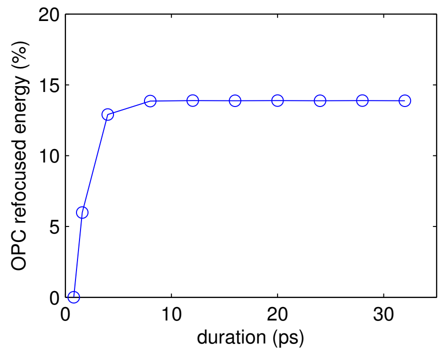

Fig. 5. The total OPC refocused energy vs. duration of the serial OPC simulation. Light traveling long optical paths before reaching the OPC inversion region is accommodated by long duration of the serial OPC simulation. Ideally, the total OPC refocused energy is the total energy of light that impinges the PCM.

6. Discussions

To accurately model the OPC phenomenon of light propagating long optical paths through a *large-scale* scattering medium, the previously reported simulation technique [2] falls short as it requires an enormous amount of computations. For example, with an 8-core Xeon Woodcrest 3.0GHz processor, a typical OPC simulation as shown in this paper accounting for optical paths of as long as 9,600 μm would require a runtime of ~1,600 hours. With the proposed serial simulation technique reported in this paper, the runtime is reduced to ~167 hours. Therefore, the proposed serial simulation technique dramatically reduces the computer requirements for simulating the OPC phenomenon of light propagating long optical paths.

As shown in this paper, the reported serial OPC simulation technique is achieved by storing and later sequentially stitching the OPC inversion fields together. Based on the mathematical characteristics of Maxwell's equations, electromagnetic field values are affected only by local field derivatives and depend little on remote field values; thus, the OPC stitching of electromagnetic field enables reconstructing the macroscopic scattered light field with some artifacts due to discontinuities of the sequential OPC field inversion. The simulation artifacts only affect local field values and are later corrected by sequentially inserted OPC inversion field values. After sequentially inserting all OPC inverted fields, the OPC inverted propagation of light is reconstructed without error.

In summary, by sequentially stitching together the electromagnetic fields, the OPC phenomenon of light multiply scattering through optically thick scattering medium can be simulated with limited computational memory. The proposed simulation technique enables OPC simulation of light propagating *long, sinuous* optical paths that is not possible otherwise. Furthermore, the ideal efficiency of OPC refocusing of light through scattering medium can be accurately determined.

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