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An optical target to eliminate impinging light in a light scattering simulation

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ABSTRACT

Based on the Convolutional perfectly matched layers (CPML) absorbing boundary condition algorithm that is implemented at the outer boundary of a light scattering simulation, we propose a numerical target that can eliminate light impinging upon it from arbitrary directions. To model light propagation through random media to a specific position, elimination of light reaching the target position is necessary to prevent further reverberation through the simulation space and become a source of noise. Various factors that affect the performance of the optical target are analyzed, including shape of the wavefront and alignment of the impinging light. Simulation results show that incident light can be most effectively eliminated for incident wavefront normally impinging upon the optical target.

1. Introduction

Biomedical techniques utilizing optical wavelengths such as Photodynamic therapy (PDT) and Optical coherence tomography (OCT) are attracting more attention nowadays. However, due to the scattering of light propagating through macroscopic random media (e.g. biological tissue structures), light penetration is typically limited to the surface and cannot penetrate deep into the bulk. The shallow penetration depth poses a limitation for practical medical applications, both for delivering light through turbid media to a specific target (medical treatment techniques), and detecting light coming through turbid media from a specific source (medical diagnosis techniques). If light can be delivered deeper into a biological medium, optical techniques can potentially be applied to deeper problems rather than just at the surface (epithelial level). Recently, much research effort [1–3] is being devoted to enhancing the delivery of light through macroscopic random media (e.g. biological tissues) to a target position. However, light propagation through macroscopic random media is a complex problem that is difficult to systematically analyze through experiments. A rigorous simulation that can model light propagation through random media of macroscopic dimensions is desired.

The complex problem of light scattering through random media can be rigorously simulated by means of numerical solutions of Maxwell's equations, e.g. the finite-difference time-domain (FDTD) technique or the pseudospectral time-domain (PSTD) technique [4,5]. To simulate an optical phenomenon involving continuous-wave (CW) light propagation through random media to a specific location, two key simulation components are required: (i) a CW light source: to generate a CW light beam and (ii) an optical target: to eliminate light reaching the target position. A simulation technique that can generate a CW light beam has been developed [6]. For CW light continuously impinging into a macroscopic scattering medium such as a biological tissue, light is scattered into all directions and reverberate throughout the simulation space. Without an absorbing optical target, light impinging upon the target position continues to scatter through the simulation space and becomes a major source of noise. In order to quantitatively determine the propagation of light to a specific target position, a numerical optical target that can eliminate incident light from arbitrary directions is required. In this manuscript, we propose an implementation of an optical target that can absorb incident light from all directions to drain out the CW impinging energy of light; the implementation and performance analysis are reported in the following sections.

2. Methods

An ideal optical target absorbs impinging light from all directions and causes no scattering or reflection. Intuitively, one may suggest using a strongly absorbing material to accomplish such task. However, strongly absorbing material causes significant reflections due to the abrupt impedance mismatch relative to the

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surrounding space. Thus, a strongly absorbing material falls short to serve as an ideal optical target that can absorb incident light without causing disruption to the neighboring field. In the past two decades, much effort has been placed on developing a non-reflective, perfectly absorbing boundary condition (ABC) enclosing the simulation space to eliminate all outgoing wave without artificial reflection [4]. Such ABC has been an important yet challenging topic of electromagnetic simulation for many years. Typically an ABC is implemented at the surrounding edge of the simulation to absorb outgoing wave—if all outgoing wave is absorbed and never re-interact with the system, the simulated system can be considered isolated in free space with no boundary.

Various ABCs have been reported to minimize the numerical error caused by the simulation boundary, including Higdon, Liao, Mei–Fang, Bayliss–Turkel, Engquist–Majda, Trefethen–Halpern, and Mur [4]. These ABCs minimized error to 0.5%–5.0% for typical FDTD simulations. In 1994, Berenger reported the Perfectly Matched Layers (PML) ABC [7] that revolutionized the performance of ABC to achieve a reduction of grid noise to 10^{-7} and surpassed the performance of existing ABCs by orders of magnitude [4]. Afterwards, several variant PMLs were developed [8–11]. With these PML ABCs, simulation boundary is no longer the limiting factor for the accuracy of electromagnetic simulations.

The Berenger PML is based on a split-field algorithm in the absorbing boundary region with assigned losses to the individual split field components. Each vector field component is split into two orthogonal components in the PML formulation of Maxwell's equations. By choosing a loss parameter with its conductivity and impedance consistent with the boundaries of a dispersionless medium, a planar PML ABC is employed at the simulation boundary to absorb outgoing waves. The net effect is to create a nonphysical, absorbing medium adjacent to the outer FDTD simulation grid with impedance independent of the angle of incidence and the frequency of outgoing scattered waves. The PML ABC can absorb impinging light most effectively for near-normal incidence, thus PML is typically implemented at a distance from the optical system, so that outgoing light reaches the PML with a near-normal incident angle.

We propose a numerical optical target that absorbs impinging light from arbitrary directions. Absorption of impinging light is enabled by modifying the Convolution PML (CPML) ABC [8] algorithm: instead of the planar geometry of CPML ABC typically implemented at the outer edge surrounding an FDTD simulation, we implement a localized, round-shaped optical target to be positioned *inside* the simulation space. An optical target that eliminates impinging light [12–14] is necessary to model light delivery to a specific target position in a light scattering simulation. The optical target is designed to eliminate incident light from arbitrary directions to drain out the CW impinging energy. Ideally, light impinging upon the CPML optical target from arbitrary direction is eliminated; without an absorbing optical target, impinging light continues to scatter through the simulation space and becomes a major source of noise.

To enable effective absorption of impinging field from all directions, the electric and magnetic conductivities are tapered down from the center radially outwards. A schematic is shown in Fig. 1. The electric and magnetic conductivities are given by:

$$\begin{Bmatrix} \sigma = \sigma_0 \cdot \left(\dfrac{R-r}{R}\right)^m \\ \sigma_0 \cdot \dfrac{0.8(m+1)}{\eta \Delta} \end{Bmatrix} \tag{1}$$

where R is the radius of the CPML optical target, r is the distance from the center to an arbitrary point in the CPML optical target, η is the impedance of EM waves, m is a constant number between 3 and 4, and Δ denotes the grid size. The CPML formulation of the TMz frequency-domain Maxwell's equations are written as:

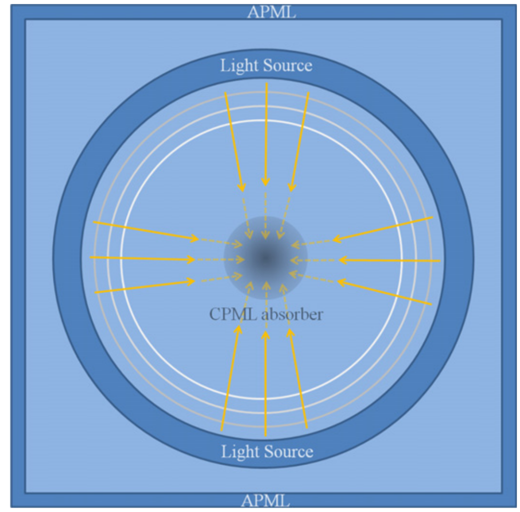

Fig. 1. An ideal optical target absorbs light impinging from arbitrary incident angles.

$$\begin{cases} -j\omega\mu H_x = \dfrac{1}{s_y}\dfrac{\partial}{\partial y}E_z \\ -j\omega\mu H_y = \dfrac{1}{s_x}\dfrac{\partial}{\partial x}E_z \\ (\sigma + j\omega\varepsilon)E_z = \dfrac{1}{s_x}\dfrac{\partial}{\partial x}H_y - \dfrac{1}{s_y}\dfrac{\partial}{\partial y}H_x \end{cases} \tag{2}$$

where s_x and s_y denote the stretched metric coordinates which are given by:

$$S_i = 1 + \frac{\sigma_i}{j\omega\varepsilon_0}, \quad (i = x, y). \tag{3}$$

To implement the CPML frequency-domain formulation in a PSTD simulation, the convolution between the temporal stretched coordinate metrics $S_i(t)$ and $\boldsymbol{E}$- and $\boldsymbol{H}$-fields are calculated in the time domain. The original PML algorithm is typically implemented surrounding the simulated region to absorb outgoing light (most effectively for near-normal incidence), whereas the reported round-shaped CPML optical target can be positioned within the simulated region to absorb light impinging upon it from all directions.

3. Results

To validate the proposed CPML optical target, we first simulate a circular wave converging upon the proposed CPML optical target placed at the center of the simulation space. The proposed numerical optical target is designed to absorb incident light from all directions in a simulation. Though experimentally it may be very difficult to create an optical-frequency spherical wavefront, modeling the elimination of a spherical wavefront by the proposed numerical optical target is most suitable for validation. If no absorber were in place, after the incident light reaches the center, it would further diverge, propagate outwards, and interfere with the incoming wave to form a standing wave—just like the ripple pattern formed when water droplets are constantly dripped onto the water surface of a round bucket. If the outgoing wave can somehow be eliminated, the resulting ripple pattern would be only the incoming wave converging towards the center and then disappears. By implementing the proposed CPML optical target, we simulate this scenario for a converging light wave with the outgoing light eliminated. As shown in Fig. 2, the CPML optical target effectively