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Simulating optical memory effects and the scanning of foci using wavefront shaping in tissue-like scattering media

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ABSTRACT

Wavefront shaping could enable focussing light deep inside scattering media, increasing the depth and resolution of imaging techniques like optical microscopy and optical coherence tomography. However, factors like rapid decorrelation times due to microscale motion and thermal variation make focusing in living tissue difficult. A way to ease the requirements could be exploiting prior information provided by memory effects. For example, this might allow partially or wholly scanning a focus. To study this and related ideas, a computational model was developed to simulate the generation and correlations of foci formed by WFS in scattering media. Predictions of the angular memory range were consistent with experimental observations. Furthermore, correlations observed between optical phase maps required to focus at different positions suggested correlation-based priors might enable accelerated focussing. This work could pave the way to faster optical focussing and thus deeper imaging in living tissue.

Keywords: Wavefront shaping, memory effect, computational simulation, T-matrix, scattering, biological tissue

1. INTRODUCTION

Biological tissue strongly scatters visible and near-infrared light, resulting in attenuated intensity and a loss of coherence with depth, constraining many optical methods to imaging only a few millimetres deep. However, by spatially modulating the wavefront of the incident light, the field inside or through a scattering medium can be shaped to constructively interfere and produce arbitrary fields such as optical foci at depth. This process, known as wavefront shaping (WFS)[1] (see Figure 1), has been successfully used to generate foci deep inside scattering media[2]. This has been used to improve the resolution and imaging depth of techniques such as multiphoton microscopy,[3] light sheet microscopy,[4] optical coherence tomography,[5] endoscopy,[6] and photoacoustic microscopy[7].

Unfortunately, focusing light in living tissue via WFS is stymied by the dynamic nature of biological tissue, in which even microscale tissue motion and temperature fluctuations cause the scattering matrix to shift and any shaped light to decorrelate[8]. This results in a prohibitively short time window (<50 ms) in which to shape light[8]. The problem is further exacerbated if a large number of input modes are required, e.g. in the case of focusing light into multiple output modes or generating foci with high enhancement.

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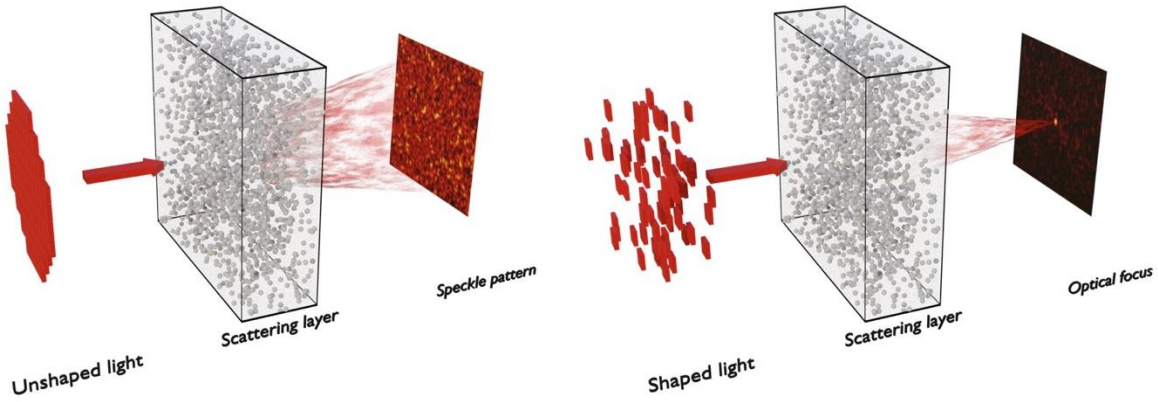

Figure 1. Light incident upon a highly turbid medium is strongly scattered. However, appropriately structured light propagates through the same medium in such a way that the transmitted field constructively interferes within a target region, producing (in this example) an optical focus. Depicted speckle patterns are physically realistic simulation data generated by shaping light through a titanium dioxide (TiO2) medium.

One way to reduce the time needed to generate a focus in a scattering medium could be to exploit correlations present in the medium. For example, the angular memory effect (AME) - a small tilt invariance of scattered light that is present even in strongly scattering media - has been exploited to image through turbid media[9] and rapidly focus light onto dynamic targets[10]. Interestingly, the strength of these AME correlations are known to be particularly strong in highly anisotropic materials such as biological tissue[11]. Furthermore, if, owing to the AME, correlations exist between the input modes (e.g. phase values on a spatial light modulator (SLM)) required to generate foci at different (e.g. adjacent) locations, then this could provide a route to using prior information to accelerate focussing at one or more of these locations. Such possibilities provide significant motivation to study memory correlations and related phenomena in optically scattering media.

The experimental investigation of memory correlations is difficult due to the challenging nature of measuring the light field inside scattering media. In contrast, computational methods could allow predicting these fields, aiding validating theory and interpreting experimental data. Unfortunately, existing tractable computational methods are too incomplete to model the underlying deterministic scattering and interference processes that characterise physically realistic light transport. This leads to inaccurate predictions. For example, AME predictions made by random phase screen simulations have been shown to differ significantly from measurements in highly anisotropic media[11]. Unfortunately, at the same time, more accurate methods such as those that directly solve Maxwell's equations are typically too computationally expensive to study optical phenomena deep in tissue. This renders it challenging to study WFS and memory effects using existing computational tools.

To address this challenge, a full-wave discrete-particle model of scattering media was coupled with a T-matrix method of calculating light fields[12]. This full-wave approach directly solves Maxwell's equations (and as such can accurately simulate the physics of light scattering), without requiring a computationally expensive subwavelength discretisation of the simulation medium, and as such is both relatively time and memory efficient. It is found that the proposed method can be used to model memory correlations in scattering media. For demonstration, the model is used to simulate angular memory effect ranges and investigate how correlation-based priors might enable accelerated focussing via WFS.

2. METHODS

Mie theory was used to design a $100\mu m^3$ tissue-like discrete particle medium. Embedding particles with a radius of 1.72μm and a refractive index of 1.6 in a medium with a refractive index of 1.33 at a concentration of 0.0077 by volume produces a tissue-like medium with a scattering coefficient of $10mm^{-1}$ and an anisotropy of 0.9 when the wavelength of incident light is 1064nm. The scattering coefficient and anisotropy were verified by simulating transmission and reflection measurements and applying the Inverse Adding Doubling technique[13], and found to be as intended (within ~3%).

Using the T-matrix method, an angular spectrum of 441 different optical plane waves were propagated one at a time through the medium, with the polar and azimuthal angles of the incident waves varying from -10 to 10°. The field on a 50x50μm^2 plane behind the medium was evaluated for each angle. Simulations were performed using CELES[14]. To enable studying the memory effect, the cross-correlation coefficient was calculated for each generated speckle pattern relative to the field produced from a directly incident plane wave.

To study the correlation between the phase patterns required to form different foci, WFS was used to form foci at two different locations behind the medium. To do the WFS, a stepwise sequential algorithm was used to optimise the phase of each the incident plane waves (which thus constituted the input modes)[1]. Correlation coefficients were calculated between the phase maps resulting for different foci.

3. RESULTS AND DISCUSSION

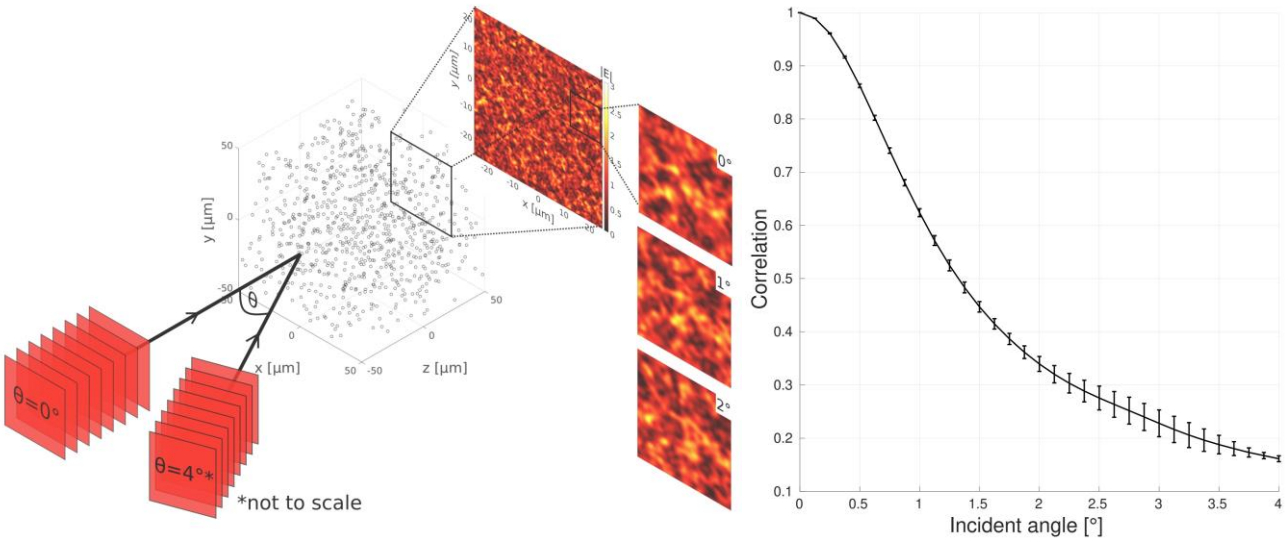

Figure 2. Using the T-matrix method to simulate the AME through scattering tissue-like media, and calculating the correlation coefficient of the scattered light as a function of the angle of the incident light.[15] (a) Light incident on a tissue-like discrete particle medium is scattered and a speckle pattern is generated on a plane behind the medium. As the incident angle is shifted, the speckle begins to decorrelation. (b) The decorrelation of a speckle pattern as a function oof the angle of incident light can be calculated by determining the cross-correlation coefficient.

Figure 2 shows the results of the memory range simulation experiments. As expected, the plane waves that propagated through the medium were scattered, producing speckle patterns behind the medium (Figure 2a). As the incident angle was varied, the speckle decorrelated. The cross-correlations between the speckle patterns were plotted in Figure 2b. To provide error bars, the whole simulation experiment was repeated 5 times (with different stochastic re-creations of the medium). The decorrelation curves show the bell-shaped curve characteristic of the angular memory effect. The experiment was repeated using media of different degrees of anisotropy (results not shown). The results showed differences in the memory range consistent with existing experiments[11].

Figure 3 shows the results of the focussing simulations. As expected, WFS enabled intense foci to be generated behind the medium, and shifting the location of the focus caused a change in the optimised phase map. The phase patterns required to form the foci were found to decorrelate in a way emblematic of the memory effect range. The phase maps decorrelated quickly, with total decorrelation occurring after a few μm of spatial translation of the focus.

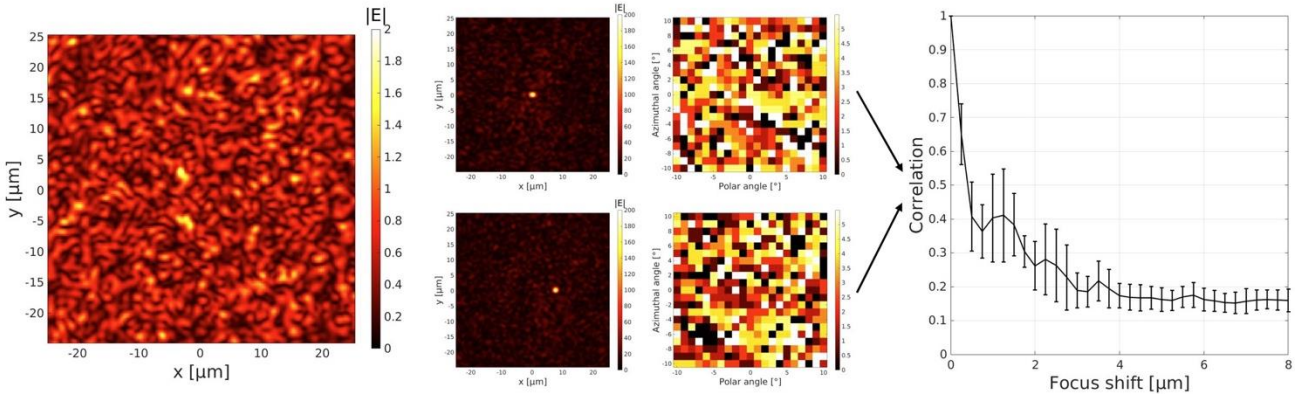

Figure 3. A plane wave propagating through a tissue-like medium is scattered and a speckle pattern is generated. A stepwise sequential algorithm is used to optimise the phase of the incident light to produce an optical focus at an arbitrary location within the imaging plane. The correlations between the phase maps used to optimise a focus at a given location along the x-axis are calculated and plotted.

4. CONCLUSIONS

We computationally modelled light propagation through scattering media using a discrete-particle medium and a T-matrix method. Using this method, we performed optical simulations that allowed quantifying the AME and the correlation between phase maps required to produce foci at different locations via WFS. This approach could help researchers understand if and how memory correlations could be exploited to enhance optical focussing and scanning in tissue.

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