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Detailed study on the statistical properties of optimized phase distribution in focusing light through turbid media

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It is studied in detail that whether the optimized phase distributions obtained from different approaches have relations in focusing light through turbid media. A view is proposed that there exists a strong correlation among the optimized phase distributions from different approaches. The numeric simulations and experiments indicate that the larger the number of segments is, the greater the correlation coefficient of optimized phase distributions from different approaches will be. This study might give an important insight into the essence of focusing light through turbid media by phase modulation.

1. Introduction

The propagation of waves in turbid media is a very fundamental problem of physics with vast applications in optics, solid state physics, material physics and so on. Light propagating in such media is diffused. However, it has been recently demonstrated that it is likely to control light propagating through scattering materials and form a sharp focus by wavefront manipulation [1–4]. To adjust the refractive aberration, adaptive optics has been widely studied for applications in optical telescope and microscope [2]. The recent researches has demonstrated its potential to adjust aberration in imaging of air samples. As the concentration and the thickness increases, adaptive optics becomes invalid for focusing through scattering media. Multiple scattering becomes a major factor limiting the focusing result. The deterministic essence of elastic light scattering ensures that there is a linear relationship between the input light field and output light field [4]. Thus, by correctly shaping the incident wavefront with a modulator, the random speckle pattern can be modulated into a given target pattern, such as a focal spot. A typical algorithm for controlling light through turbid materials by wavefront shaping is stepwise sequential algorithm (SSA) [1], in which the optimal phase of a segment is determined by cycling its phase from 0 to 2π while the rest segments keep the optical phase the same with the incident light and the phase at which the target intensity reaches highest is saved as the initial optimal phase for this segment. After the optimization of all the segments, the stored phases are employed on the corresponding segments to reconstruct the intensity pattern of the original light field. SSA is successful in reconstructing a field through random scattering media. However, more iterations are needed to obtain the optimized phase distribution since the initial optimized phase pattern for each segment after one iteration is the result of the constructive interference between the segment and background. It means each segment is in phase with the background, not in phase with each other. The continuous sequential algorithm (CSA) is very similar to the SSA except for the fact that the optimized phase is employed on the corresponding segment before moving to the next segment, instead of storing the optimized phase for later use [3]. This approach considers the contribution of both the already optimized segments and the background, which increases the signal-to-noise ratio at the focal position. However, the optimization for the current segment only takes account of the contribution from the previously optimized segments. Therefore, additional iterations are still needed.

On the other hand, the whole element optimization approaches – partitioning algorithm (PA) [3], transmission matrix (TM) approach [5–17] and genetic algorithm [18] (GA) were proposed to focus light through scattering media. The PA approach maximizes the intensity of target signal by modulating half of the elements which is randomly selected during each measurement. The TM approach is proposed to calculate the TM by monitoring the intensity pattern of the output plane when the incident light is modulated by a set of given basis, such as Hadamard basis. The GA is a class of probabilistic optimization algorithm that is inspired by biological evolution process. In these algorithms, all

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elements are employed for the optimization. Thus, the signal-to-noise ratio during the optimization is improved. However, because more random procedures are introduced into the process, optimization takes more time to converge than the single element based approaches.

Recently, we proposed an approach named four-element division algorithm [19–21] (FEDA) to accelerate the convergence rate of focusing and increase the signal-to-noise rate. This approach maximizes the target signal by initially modulating a quarter of incident wavefront, which increases the signal-to-noise rate. Then each quarter of incident wavefront is further divided into four segments and each smaller segment is optimized, while the rest of the segments keep their phases the same with the previous optimized phase values. This procedure can go on, generating 16 × 16, 32 × 32 … optimized phase distribution, until the number of segments equals to the number of pixels of the phase modulator. FEDA approach increases the speed of focusing since it doesn't need to iterate several times, which can be applied to dynamic media, such as biological tissues [22–30].

Focusing light through scattering media has potential in various biomedical applications and the approaches to obtain optimized phase distribution have been widely studied. However, few work has studied the relations among the optimized phase distributions by different approaches, and our analysis indicates that there exists a strong correlation among the optimized phase distributions from different approaches. According to our analysis, it is concluded that the larger the number of segments is, the larger the correlation coefficient of optimized phase distributions from different approaches will be. In this paper, we study this issue in detail.

2. Theory study

First, we define some terminology employed in the context. A 'pixel' of the phase-only spatial light modulator (SLM) is the smallest modulation unit that can be controlled separately. An 'element' is a group of adjacent pixels of SLM, in which these pixels are combined together and their phases change simultaneously. The format '$m \times n$' represents the wavefront in which horizontal number of elements is m and the vertical number of elements is n.

2.1. Physical model of light propagating through turbid medium

In a vacuum, a plane wave propagates freely and its wave vector remains invariant. However, a plane wave incident on a random photonic medium induces a random output field, which is called as speckle pattern. The distribution of speckle pattern is different for different random photonic media. For a linear scattering medium, the propagation of an electromagnetic wave is characterized by Green function [20]. Scalar quantity diffraction theory can be used on condition that the light source is linearly polarized and the detector is received on the same polarization. The Green function $\mathrm{G(r,r',t,t')}$ characterizes the relation between the optical field on a surface S which contains light sources and the optical field of observation surface. For a surface S containing several light sources, the optical field at the position r at time t is written as [5,6]

$$\mathrm{E(r,t)} = \iiint_{-\infty}^{\infty} \mathrm{G(r,r',t,t')E(r',t')dt'd^2r'} \tag{1}$$

where $E(\boldsymbol{r},t)$ is the optical field at the position r at time t, $E(\boldsymbol{r}',t')$ is the optical field on the surface S containing all the light sources at position r' at time t'. From Eq. (1) it can be seen that the scalar Green function $G(\boldsymbol{r},\boldsymbol{r}',t,t')$ can describe the influence of the electrical field at position r' at time t' on the optical field at position r at time t. Eq. (1) can be written in the spectral domain [5,6]:

$$\mathrm{E(r,\omega)} = \iint_{s} \mathrm{G(r,r',w)E(r',w)d^2r'} \tag{2}$$

where $E(\boldsymbol{r},\omega)$ is the Fourier transform of $E(\boldsymbol{r},t)$ and $G(\boldsymbol{r},\boldsymbol{r}',\omega)$ is the Fourier transform of $G(\boldsymbol{r},\boldsymbol{r}',t,t')$. In actual experiments, the light sources and detectors have finite sizes and quantities. Therefore, Eq. (2) can be written as [1,2]

$$\mathrm{E_m^{out}} = \sum_{n=1}^{N} \mathrm{t_{mn}E_n^{in}} \tag{3}$$

where E_m^{out} is the output field at the mth detector, E_n^{in} is the input field at the nth source (the number of light sources and detectors are denoted by N and M, respectively) and t_{mn} are the elements of TM. The TM of an optical system for a given wavelength of complex numbers connects the optical field (in amplitude and phase) at the mth output element to the one at the nth input element. In this paper, the amplitude and phase of the input and output field are defined as scattering channels, which includes input channels and output channels. It can be seen from Eq. (3) that the output optical field is the result of interference of all the input elements of the sources. Eq. (3) is the physics principle of the propagation process with coherent light illumination. Constructive interference of incident channels after the linear optical system determines the intensity distribution of the output channels.

2.2. The theoretical enhancement of the focus

The enhancement of the target signal is defined as the ratio between the optimized intensity and the average intensity of target area before optimization, which can be expressed as

$$\eta = \frac{\mathrm{I_{opt}}}{\langle \mathrm{I_0} \rangle} \tag{4}$$

where η is the enhancement, I_{opt} is the target intensity after optimization and $\langle I_0 \rangle$ is the average initial intensity of speckle pattern. Assuming that the modulator is illuminated homogeneously, all the input channels have same amplitude. The amplitude is written as $A_n = 1/\sqrt{N}$ for normalizing the total incident intensity. The nth input channel E_n in Eq. (3) is $E_n = \frac{1}{\sqrt{N}}\exp(i\phi_n)$, where ϕ_n is the phase of the nth input channel. Since our purpose is to focus light at a predefined position, we need to consider a single output channel, E_m. The intensity of this output channel is given by

$$|\mathrm{E_m}|^2 = \frac{1}{\mathrm{N}} \left| \sum_{n=1}^{N} \mathrm{t_{mn}exp(i\varphi_n)} \right| \tag{5}$$

From Eq. (5) it can be seen that, since SLM is a phase-only modulator, the intensity $|E_m|^2$ achieves its global maximum when the phase modulator exactly compensates the phase distortion caused by the scattering medium for each scattering channel [3], that is to say, $\phi_n = -\arg(t_{mn})$. At that point the contributions of the all channels are in phase with each other. The contributions from all elements interfere constructively and the target intensity is at its global maximum. The average intensity of speckle pattern ($\langle I_0 \rangle$) and the intensity after an ideal optimization ($I_{\max}$) are given by

$$\langle \mathrm{I_0} \rangle = \frac{1}{\mathrm{N}} \left| \sum_{n=1}^{N} \mathrm{t_{mn}} \right|^2 \tag{6}$$

and

$$\mathrm{I_{max}} = \frac{1}{\mathrm{N}} \left(\sum_{n=1}^{N} |\mathrm{t_{mn}}| \right)^2 \tag{7}$$