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Focusing light through random scattering media by four-element division algorithm

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A B S T R A C T

The focusing of light through random scattering materials using wavefront shaping is studied in detail. We propose a newfangled approach namely four-element division algorithm to improve the **average** convergence rate and signal-to-noise ratio of focusing. Using 4096 independently controlled segments of light, the intensity at the target is 72 times enhanced over the original intensity at the same position. The four-element division algorithm and existing phase control algorithms of focusing through scattering media are compared by both of the numerical simulation and the experiment. It is found that four-element division algorithm is particularly advantageous to improve the **average** convergence rate of focusing.

1. Introduction

In many random scattering materials such as ground glass, wood and biological tissues light is strongly scattered. As a result, the propagation of light becomes weak. 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 [1–5]. An typical example for controlling light through scattering materials by wavefront manipulation is stepwise sequential algorithms (SSA) [6], where the optimal phase of a segment, or a group of pixels, also called as an element, is determined by cycling its phase from 0 to 2π while the rest segments keep the optical phase the same with the incident light, or phase of zeros, and the phase at which the target intensity reaches highest is stored as the initial optimal phase for this segment. After the optimization of all the segments, the stored the 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 acquire the optimized phase distribution since the initial optimized phase pattern for each segment after one iteration is the result of the constructive interference of between the segment and the background, which means each segment is in phase with the background, not in phase with each other. The improved algorithm of SSA is continuous sequential algorithm (CSA), in which 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 from both the already optimized segments and the background, which will increase the signal-to-noise ratio in the focal position. Nevertheless, the optimization for the current segment only takes account of the contribution from the previously optimized segments, therefore, additional iterations are still needed. A related phase control algorithm namely partitioning algorithm (PA) is demonstrated by Vellekoop and coworkers [3]. The PA approach maximizes the intensity of target signal by modulating a randomly selected half of the segments during each iteration, which increases the signal-to-noise ratio. This algorithm initially enhances the target signal more quickly than SSA and CSA, which can be used on condition that the number of segments is much larger than the number of iterations performed when the scattering material is dynamic. Other approaches have been developed to compensate for the disorder in the scattering media. Popoff and coworkers measure the optical transmission matrix (TM) of the scattering medium and use it to create a sharp focus [7]. The transmission matrix is measured by monitoring the intensity in the output plane when the incident light is modulated by a set of given input basis such as Hadamard basis [7–10]. The genetic algorithm (GA) is a class of probabilistic optimization algorithms that are inspired by biological evolution process and is can be employed in focusing light through scattering media [11]. This algorithm achieves best performance when the scattering media is in low signal-to-noise environments.

In this paper we introduce a new focusing method based on element phase modulation namely four-element division algorithm (FEDA).

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Instead of optimizing a single segment in the processing, FEDA approach takes all the segments in account during each optimization processing, which will accelerate the focusing procedure and improve the signal-to-noise rate. In the following parts, firstly, our new algorithm namely four-element division algorithm is described in detail. Next, the six approaches for focusing light through randomly scattering media are compared by numeric simulation. Then the validity of the FEDA approach is verified through physical experiment and the six approaches are compared again through experiment. Lastly, the main conclusions are summarized.

2. The four-element division algorithm (FEDA)

Light propagating through random scattering media is described by a transmission matrix which connects the incident and output scattering channels. Scattering channels are the amplitude or phase modes of the propagation light field. At the back of random scattering media the electric field of outgoing light is a linear combination of the electric field of incident light which is related by the transmission matrix of the scattering medium:

$$E_m = \sum_{n=1}^{n} t_{mn} E_n \quad (1)$$

where E_m is the electric field of the mth output channel; E_n is the electric field of the nth input channel; and t_{mn} is the element of transmission matrix of mth row and nth column. The input channels and output channels are the amplitude and phase distributions of incident light and output light.

The working principle of the algorithm is illuminated in Fig. 1. In our experiment the liquid-crystal spatial light modulator (SLM) is used as phase modulator. A plane wave incident on a random scattering medium is spatially divided into four segments. A segment is a group of adjacent pixels of SLM, which are combined together and their phases change simultaneously. A pixel in phase modulation plane is the smallest phase modulation unit that can be controlled separately by the computer. The optimization processing begins with cycling the optical phase of the first segment from 0 to 2π, which is shown in Fig. 1(a), while the target signal is measured and the phase at which the target intensity gets maximum is recorded and set into this segment before the optimization takes place at the second segment, which is shown in Fig. 1(b). The phase of each segment can be controlled by the computer. The back surface of the scattering media is imaged with a lens and the intensity distribution of output light can be measured by a CCD or CMOS camera. The target intensity is a single output channel selected in advance which is aimed to maximize its intensity. After the optimization, the second segment is set to its optimized phase value, thus the third segment is optimized with the first and second segments kept optimized phase values, as is shown in Fig. 1(c). The fourth segment is optimized with the rest three segments taking their optimized phase values, which is shown in Fig. 1(d). Obviously, in FEDA, the contributions of all segments are considered. In order words, the optimization is obtained by interfering constructively from all the segments, as is shown in Fig. 1(e). The optimized 2×2 format is called 'father' layer of the phase distribution. The format 2×2 means the phase plane of SLM with horizontal number of segments of 2 and the vertical number of segments of 2.

Next, one segment is further divided into four same smaller segments, as is shown in Fig. 1(f). Each smaller segment firstly inherits its 'father's' phase distribution. Optimization takes place for each smaller segment by cycling its phase from 0 to 2π, while the signal at the focal point is monitored and the phase value at which the target intensity reaches the maximum is acquired and set to replace the inherited phase value from 'father' layer before the optimization moving to the second smaller segment, which is shown in Fig. 1(g). The same processing is conducted to the rest smaller segments, which is shown in Fig. 1(h) and (i). The divisions and optimizations are employed to all four segments in the 'father' layer. A 4×4 element phase array with all its segments

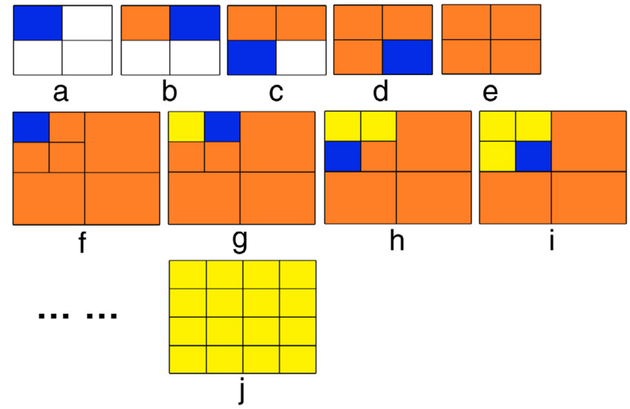

Fig. 1. Principle of the four-element division algorithm (FEDA) to focus coherent light through random scattering media. (a)–(e)Procedure of phase modulation of 4 segments. (f)–(j) Procedure of phase modulation of 16 segments. Blue segment means to modulate this segments cycling from 0 to 2π; White segment represents to keep this part the same with the original wave; Yellow segment means to set this segment the brightest phase of elder generation; Orange segment means to set this segment the brightest phase of filial generation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

optimized is achieved, as shown in Fig. 1(j), which is called as 'son' layer of the phase distribution. The meaning of '4×4' is similar to the format '2×2' expressed above.

The division and optimization can be continued to generate 8×8 optimized phase distribution, which is called 'grandson' layer of the phase distribution. 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 SLM.

FEDA approach greatly improves signal-to-noise of the measurement since it begins with large segments of phase modulation, in which the detector in the imaging plane easily catches the intensity variation when the phase modulation of 0 to 2π at the segment takes place. Furthermore, as is mentioned above, the optimization in FEDA happens on the layer-by-layer basis, in which optimization processing in the new generation layer always inherits the optimal phase distribution of the elder generation. In other words, FEDA itself is an 'iteration' based optimization with segment size reduced at each iteration, which leads to high average converging rate and high enhancement to focus through scattering medium as the SLM is divided into more segments.

3. Numeric simulation

In order to compare FEDA approach and the existing algorithms mentioned above, we define enhancement of the target signal:

$$\eta = \frac{I_{\text{opt}}}{\langle I_0 \rangle} \quad (2)$$

where η is the enhancement of the target signal, I_{opt} is the optimized intensity of the target signal, and $\langle I_0 \rangle$ is the average intensity of the initial speckle pattern.

The concrete simulation process is described as follows. The incident plane wave is represented by a matrix with N elements in which the magnitudes of all the elements are set to 1 with phase of 0. The plane wave is incident on spatial light modulator. The phase-only modulator can be seen as a matrix with N complex numbers in which their modulus are one and phases can be changed. The spatially phase shaped wave is incident on a strongly scattering medium, which is represented by a random matrix with uniform distribution. After propagating through the scattering medium, the scattered light is collected by a lens and a CCD transmits the light intensity distribution to a computer, which could