Published in final edited form as:

J Opt. 2017 October ; 19(10): . doi:10.1088/2040-8986/aa84dc.

Interleaved segment correction achieves higher improvement factors in using genetic algorithm to optimize light focusing through scattering media

Runze Li^{1,2,3}, Tong Peng^{1,3}, Yansheng Liang^{1,3}, Yanlong Yang¹, Baoli Yao¹, Xianghua Yu¹, Junwei Min¹, Ming Lei¹, Shaohui Yan¹, Chunmin Zhang², and Tong Ye⁴

¹State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China

²School of Science, Xi'an Jiaotong University, Xi'an 710049, China

³University of Chinese Academy of Sciences, Beijing 100049, China

⁴Department of Bioengineering, Clemson University, Clemson-MUSC, Bioengineering Program, Charleston, South Carolina 29425, USA

Abstract

Focusing and imaging through scattering media has been proved possible with high resolution wavefront shaping. A completely scrambled scattering field can be corrected by applying a correction phase mask on a phase only spatial light modulator (SLM) and thereby the focusing quality can be improved. The correction phase is often found by global searching algorithms, among which Genetic Algorithm (GA) stands out for its parallel optimization process and high performance in noisy environment. However, the convergence of GA slows down gradually with the progression of optimization, causing the improvement factor of optimization to reach a plateau eventually. In this report, we propose an interleaved segment correction (ISC) method that can significantly boost the improvement factor with the same number of iterations comparing with the conventional all segment correction (ASC) method. In the ISC method, all the phase segments are divided into a number of interleaved groups; GA optimization procedures are performed individually and sequentially among each group of segments. The final correction phase mask is formed by applying correction phases of all interleaved groups together on the SLM. The ISC method has been proved significantly useful in practice because of its ability to achieve better improvement factors when noise is present in the system. We have also demonstrated that the imaging quality is improved as better correction phases are found and applied on the SLM. Additionally, the ISC method lowers the demand of dynamic ranges of detection devices. The proposed method holds potential in applications, such as high-resolution imaging in deep tissue.

Keywords

turbid media; scattering; wavefront control; Genetic algorithm; memory effect

1. Introduction

Turbid media, such as the atmosphere or biological tissues, scatter light in a random fashion and adversely affect focusing and imaging quality. Considering light propagates as a wave, traditional adaptive optics measures distortion of the wavefront and actively corrects it to minimize the scattering effect. This wavefront correction approach has been successfully used in astronomical observations to minimize the effect of the turbulent atmosphere [1]. However, for strongly scattering media, such as opaque tissues, the complete scrambling of the scattered field requires much more freedoms of phase control to correct the wavefront distortion in high spatial resolution [2]. Phase only spatial light modulators (SLMs), such as liquid crystal on silicon (LCOS) devices, commonly possess over millions of phase control elements (pixels) and are choice of devices for such high-resolution correction of the wavefront; as such, sharper light focusing can be achieved after scattering media and imaging quality can be improved owing to the improved point spread function. For high-resolution wavefront shaping, three major approaches have been developed: optical time reversal [3–6], transmission matrix measurement [7–9] and iterative optimization [10–22] methods. The optical time reversal approach is a fast method for focusing through scattering media with high enhancement factor of the focusing intensity [3–6]; however, a time reversal system is difficult to implement, for light field measurement and phase control devices have to achieve a strict pixel-to-pixel match [3]. The transmission matrix measurement approach obtains a medium's transmission matrix so that a precise wavefront correction is achieved to maintain a high fidelity imaging after the medium [7–9]; however, an extremely large set of data required in this approach make it challenging to handle the measurement properly. Easy to be implemented, the iterative optimization approach is perhaps the most practical approach and its usability has been demonstrated in wide-field imaging through scattering media [13, 16] and deep-tissue fluorescence imaging [20].

In iterative optimization methods, the optimization starts with an initial guessed or random phase mask and continuously searches for a best possible phase value over every correction element (also called *segment*, the smallest patch of the wavefront) to ensure constructive interference forming at targets behind scattering media. The searching procedure involves a feedback tuning loop [10–22] that decides if the optimization proceeds to the next step and what the next trial will be. Among all the iteration optimization algorithms, adaptive learning algorithms, such as genetic algorithm (GA), stand out for their fast and robust convergence owing to optimizing all segments in parallel, and for their high stability in noisy environment [17]. Using GA and a phase only SLM, Silberberg and coworkers [13] successfully refocused the light field from a point source after passing through a strongly scattering medium. They further demonstrated that, once the correction phase mask was found for focusing the light, the “memory effect” [23, 24] would allow an object placed close to the point source to be imaged through the scattering medium.

In practice, several aspects should be considered to obtain high improvement factors when using GA for optimizing light focusing through scattering media. Firstly, choosing a large number of correction elements should yield a better improvement factor. However, computing resources, such as speeds of processors and accessible memories, limit the number of correction segments that can be used in correction processes. As a matter of fact,

to maintain a reasonable optimization efficiency, not all pixels of a SLM are actually used as independent correction elements, although the SLM provides over several millions pixels and may possibly to achieve perfect corrections. As such, pixels of a SLM are grouped to correction segments, each of which is composed of the same number of pixels applied with a single phase value. The reduced number of correction elements is essential to maintain optimization processes in a high efficiency, however, with a tradeoff of the correction resolution. Secondly, an inherent problem of GA is that its convergence rate is nonlinearly changed with generations of optimization, i.e. the convergence rate starts high in early generations and decreases continuously with later generations. This behavior becomes prominent when the number of correction segments is small or when noise is present in the feedback measurement. The improvement factor eventually reaches a maximum that stops the optimization process. Thirdly, the dynamic range of a CCD camera affects the optimization process. On the one hand, the initial exposure level should be above the noise floor of the camera to ensure that the intensity nuance of different phase mask can be detected. On the other hand, at the final stage of optimization, the focusing is usually much higher than that before the optimization; saturation of the camera may occur before the optimization reaches a preferred improvement factor. This often happens when a large number of segments are used to intend for a high-resolution correction.

To address the abovementioned practical aspects of using GA for high-resolution wavefront shaping, in this report, we propose a new correction strategy, called interleaved segment correction (ISC), to achieve higher improvement factor than the conventional all segment correction (ASC) method under the same number of correction segments. We demonstrate that the ISC method significantly improves focusing quality with high level of noise in the measurement. This method also lowers the demand of dynamic ranges of detection devices. With the improved focusing quality, we demonstrate that virtual amplitude objects, which are generated by the Gerchberg-Saxton algorithm, can be imaged through a scattering medium with high quality. At the end of this report, a bottle shaped beam structure, which is widely used in stimulated emission depletion (STED) microscopy [26], is generated after the scattering medium to demonstrate the ability of scattering correction on focusing beams with complicated three-dimensional profiles.

2. Methods

2.1 Wavefront shaping with GA

An ideal imaging system focuses light from a point object onto an ideal focusing spot (an Airy pattern) in the imaging plane. However, when a scattering medium presents on the light path, the wavefront from the original point object is disturbed and, instead of the Airy pattern, speckles are formed in the imaging plane. In order to get back to the ideal focusing profile, i.e. to improve the focusing quality, one of successful approaches is the wavefront shaping method, in which the wavefront is divided into N incident modes (segments) and the phase of each mode is optimized by maximizing the intensity of the focus. Based on Huygens-Fresnel principle, the scattering field at a given target (where light is expected to focus), E_m , is a linear combination of all incident modes [2] as

$$E_m = \sum_{n=1}^N t_{mn} A_n e^{i\varphi_n}, \quad (1)$$

where A_n and φ_n are the amplitude and phase of mode n respectively; t_{mn} is the transmission matrix which describes the scattering property of a medium. The focusing quality can be improved if phases of all N segments are corrected so that light constructively interferes at the target. Optimization algorithms, such as GA, are employed to find each correction phase by maximizing the intensity at the target.

GA is an optimization algorithm inspired by species evolution [27]. In GA, individual is defined by independent variables and a number of individuals that compose a population. A cost function is used to evaluate every individual in the current population, i.e. the current generation. Then the algorithm iteratively optimizes problems by crossover and mutation operations. In the case of wavefront shaping for light focusing, the variables are the phases of N segments, and the individual is a phase pattern applied on the SLM. The cost function is the intensity at the target point and measures the focusing quality. In one generation, multiple phase patterns are sequentially applied to the SLM and their generated field intensities at the target are measured. A phase mask that generates higher intensity is assigned with a higher rank. A set of top-ranked phase patterns are selected out while the others are eliminated. Operations, known as elite, crossover and mutation, simulate species breeding and are acted on the selected phase masks to populate a new generation of phase masks that participate in the next iteration. After optimization, the correction phase mask is applied to the SLM and expected to refocus scattered speckles at the target with improved profile and higher intensity.

2.2 Simulation of GA optimization process

Numerical simulation provides a reliable and convenient way to study the behavior of the GA optimization process. In the simulation, the imaging process is modeled with a simple lens based imaging system, in which a scattering medium is placed at the object focal plane and the diffused light forms speckles at the image focal plane. The scattering medium is modeled as a random phase mask. The field of the scattered light propagating to the image focal plane is simply calculated by Fast Fourier Transformation (FFT). In the image focal plane, the pixel at the center of the field of view is selected as the target and its intensity is measured and used as feedback (cost function) for the optimization procedure. The GA algorithm is implemented by using callback functions provided in Global Optimization Toolbox of Matlab (MathWorks, USA). The GA callback function uses the following parameters: 30 for population size, 8 for elite count, 0.8 for crossover fraction, and 0.01 for mutation rate. Population size is the number of individuals. A larger population size ensures greater diversity of individuals, but spends longer time in calculation; 30 is chosen empirically for a good balance. Elite count specifies the number of individuals that survive and move on to the next generation. We choose 8 to reduce the influence of noise. As the major part of the operation that drives the optimization process, crossover combines two individuals to form two new ones for the new generation; we choose 80% for the crossover

fraction. Mutation makes random and small genetic changes to form a new individual; mutation rate is usually set to a small number. Peak to Background Ratio (PBR), which defined by $PBR = I_{focus}/I_{average}$, is used as a measure to evaluate the final focusing quality. I_{focus} is the focusing intensity and $I_{average}$ is the averaged background intensity before the optimization.

2.3 Wavefront shaping with interleaved segment correction (ISC)

To improve the convergence rate and to overcome the prematurity when using a larger number of correction segments so that a higher improvement factor can be achieved, we propose a new correction strategy with the GA based algorithms, the interleaved segment correction (ISC). ISC divides the correction segments of a SLM into interleaved groups and performs correction on each group with GA individually. The principle of ISC is illustrated in figure 1 by using 60×60 segments and 4 groups of interleaved segments as an example. In this case, 1080×1080 pixels of the SLM are grouped to 60×60 correction segments, each of which is composed of 18×18 pixels. For the ISC method, we divide 60×60 segments into four groups of interleaved 30×30 segments, as shown in figure 1(b), with each interleaved group labeled with different number and gray colors. Instead of optimizing the 60×60 segments altogether, we first perform GA optimization with each correction group independently as shown in figure 1(c)–(f) and then merge the four resulting correction masks to form the final correction phases. For each individual correction, GA optimization starts with zero phases for all segments in the group being optimized and updates those values to yield higher intensity at a selected target, which is usually a speckle (bright spot on a CCD camera) located at the center of the field of view in the imaging plane. Once every individual group has been corrected, a combined phase masks is applied to the SLM and a higher improvement factor is proposed to achieve. During the optimization with one group, the other three non-correcting groups are maintained at zero phases on all their segments to provide a common reference for interference. Thus, the optimization processes with the four individual groups are performed under the same reference so that a constructive interference will be warranted at the target when the final combined phase is applied. This ISC method can be implemented with more groups of interleaved segments, such as 9, 16 or more with squared number. The number of correction generation for ISC is the total generations of every group.

2.4 Experimental Setup

The schematic of the experimental setup for studying focusing and imaging through scattering media is shown in figure 2. A horizontal polarized 632.8 nm He-Ne laser beam is spatially filtered and expanded by a Galilean telescope which is composed of a $25\times$ microscope objective, a $25\ \mu\text{m}$ pinhole, and an 150 mm doublet lens. The collimated beam is reflected by a mirror and is incident onto a SLM (PLUTO NIR-II, Holoeye Photonics AG, Germany) in an angle approximately 6° . A telescope constructed by a 200 mm doublet lens and a $10\times$ microscope (NA 0.3, Nikon Inc., Japan) images the surface of the SLM onto a ground glass diffuser (DG05-600-MD, Thorlabs Inc., USA). The SLM and the diffuser are conjugated and so are all the correction segments and their projected areas on the diffuser. The speckles after the diffuser (5 mm after the diffuser) are imaged on a CCD camera (DCU224M, Thorlabs Inc., USA) by a $20\times$ microscope (NA 0.45, Nikon Inc., Japan) and a

tube lens ($f=200$ mm). The intensities of five cross pixels at the center of the field of view are averaged to provide the feedback used in GA optimization. Averaged intensity is chosen for reducing the influence of noise. Note that the results shown in figure 7 were acquired by using another camera (8050M-GE-TE, Thorlabs Inc., USA) with higher dynamic range (16 bit), which allowed to reveal the divergence behavior of GA with more generations. A blazed grating is superimposed on all the phase masks applied on the SLM to shift the non-diffracted component off the imaging path.

3. Results and discussion

3.1 Convergence behaviors of GA optimization in wavefront shaping with and without noise in feedback measurement

Previous studies have shown that, in wavefront shaping, GA optimization have outstanding performance over other optimization algorithms for its fast and robust convergence in noisy environment [17]; on the other hand, the optimization “plateaus” with GA have been noticed and considered as a limitation [16–17, 21]. However, the convergence behaviors of GA have not been studied systematically in respect of the number of correction segments and the amount of noise. Here we took advantage of the simulation method to study the convergence behaviors of GA optimization processes with different number of correction segments without or with the noise is present in the system. Figure 3 shows the results with no noise in the system. As shown in figure 3(a), for all cases, the convergence rates are high and not much different within first 150 generations. After 150 generation of optimization, the focusing intensity reaches 0.081, 0.086 and 0.09 respectively with the number of segments at 20×20 , 30×30 and 60×60 . At higher generations, the convergence rate continuously decreases during the course of optimization—a nonlinear behavior typical to GA. For fewer number of correction segments, such as 10×10 and 20×20 , the intensity reach an apparent plateau and the optimization is matured. For larger segment numbers, the plateau is not reached even after a very large number of generations, indicating that it will take more generations to reach, of course, a better correction. The simulation study clearly shows that larger number of correction segments achieves higher improvement factors with the same number of optimization generations and yields better focusing quality as shown in figure 3(c). To study the optimal improvement factor that can be achieved for different number of segments, we performed exceedingly large number of generations of optimization to achieve a convergence plateau, which is defined as the moment when increase of PBR was smaller than 0.2 in 50 generations. As shown in figure 3(b), the optimal PBR increases approximately linearly with the number of correction segments. This result is consistent with the theoretical predication (the blue line in figure 3(b)), which states that, with any given N number of modes, the PBR follows a linear relation as $\pi(N+I)/4$. In figure 3(c), the final correction phase patterns and corresponding focus images are shown for the number of correction segments chosen at 10×10 , 20×20 , 30×30 and 60×60 and after about 1300, 4000, 5000 and 10000 generations of optimization, respectively. These results suggest that larger segment numbers provide higher resolution correction and achieve higher improvement factors; however, it takes longer time (as indicated with the number of generations) for optimization with larger segment numbers to reach the optimum. Considering that the time expense on each generation varies little with different number of correction segments, in

practice, these simulation results implicate that more correction segments is better. However, using too many correction segments may cause the improvement factor to increase so little during one generation and the noise present in the measurement may lead to a collapse of the optimization.

We then investigate how the noise level present in the intensity affects the optimization behavior. The simulation results are shown in figure 4, where 30×30 correction segments were used and Gaussian noises at the level of 0.05, 0.10, 0.15 and 0.20 of average intensities were added to the cost function measurement. It clearly demonstrates that the noise level adversely affect the improvement factor; higher level of noise causes optimization to reach the plateau earlier, yielding lower improvement factor ultimately.

This noise effect along with the nonlinear convergence behavior of GA can be understood by using Equation (1). In the GA optimization process, the intensity at the target is contribution of all the phase segments, only part of which are actually modified in a GA iteration to search for a better intensity at the target while the rest are kept unchanged. All the segments are thus separated to two categories: one with varying phases designated by S and the other with stationary phases designated by $\bar{S}$. The output field at the target after the SLM then can be written as:

$$\begin{aligned} E_m^{out} &= \sum_{n=1}^N t_{mn} E_n^{in} e^{i\theta_n} \\ &= A_S e^{i\varphi_S} + A_{\bar{S}} e^{i\varphi_{\bar{S}}} \end{aligned} \quad (2)$$

where A_S and $A_{\bar{S}}$ are the overall amplitude contributions resulted from segments with variable or stationary phases at the target, respectively; their corresponding phase values are φ_S and $\varphi_{\bar{S}}$. The intensity at the target after a scattering medium is calculated as follows:

$$\begin{aligned} I_m^{out} &= |E_m^{out}|^2 \\ &= A_S^2 + A_{\bar{S}}^2 + 2A_S A_{\bar{S}} \cos(\varphi_S - \varphi_{\bar{S}}) \\ &= I_S + I_{\bar{S}} + 2\sqrt{I_S I_{\bar{S}}} \cos(\Delta\varphi) \\ &= I_0 [1 + M \cos(\Delta\varphi)] \end{aligned} \quad (3)$$

where,

$$I_0 = I_S + I_{\bar{S}}, \text{ and } M = \frac{2\sqrt{I_S I_{\bar{S}}}}{I_S + I_{\bar{S}}}. \quad (4)$$

M is the depth of the interference modulation. Although S and $\bar{S}$ are randomly chosen in each iteration due to crossover and mutation operations, during the course of GA optimization, as more and more segments are in-phase, less and less segments will have dramatic phase changes, meaning that the range for ϕ to be modified is getting smaller. $I_{\bar{S}}$ can be view as the already achieved focusing intensity and I_S is the tuning segments' intensity. As the GA going on, the achieved focusing intensity getting higher and M is reduced. I_m^{out} is thus getting less sensitive to the modified segment phases in each iteration—GA's nonlinear convergence behavior. If the measurement of the target intensity has noise from various sources, such as readout of CCD, shot noise, output fluctuation of laser sources and other factors in the environment, the noise may overwhelm the minute improvement caused by modification of ϕ . The optimization process reaches a plateau earlier than that without noise; the higher noise level causes the optimization ended with lower improvement factor. In the proposed ISC method, $I_{\bar{S}}$ are maintained in low level, thus I_m^{out} keeps sensitive to the modified segment phases.

3.2 ISC for focusing and imaging through scattering media

Using 60×60 segments in the simulation, we first compared three different methods to perform the GA optimization: (a) dividing all segments to four quarters and correcting each quarter separately; (b) dividing all segments to four interleaved groups and correcting each group separately (the ISC method); (c) correcting segments altogether (the ASC method). For method (a) and (b), the final correction phase masks were merged from the four individual corrections. For a fair comparison, each individual optimization in method (a) and (b) was performed with $1/4$ numbers of generations in method (c) so that in total all methods used the same number of generations. As shown in figure 5(a)–(c), the ISC method clearly has the best PBR. After 4000 generations, the PBR of the ISC method reaches 1657 while that of the ASC method reaches 1360. The quarterly correcting method can also reach a higher PBR than ASC. However, as shown in figure 5(a), the focusing quality in single quarterly correction is not as good as that in single group correction of ISC as shown in figure 5(b). Thus ISC is a better grouping method with higher PBR. GA optimization processes are shown in figure 5(g), in which the normalized intensity of ISC exceeds that of ASC after 400 generations. The ISC maintains higher convergence rate than the ASC. We then introduced different levels of noise to the simulation to compare the performance of the ISC and ASC methods in the noisy environment. In the simulation, 0.05, 0.10, 0.15 and 0.20 of average intensities of Gaussian noise were added to the cost function measurement. The normalized intensity vs the optimization generation are plotted in figure 6(a)–(d) for each noise level respectively. As expected, the focusing intensities in two correction methods are all much lower than those without noise. Since the modulation depth of the interference at the target decreases when the focusing intensity is being improved during the optimization, noise eventually overwhelms the modulation depth as well as the feedback signals. As such, noise causes ASC to reach the improvement plateau at earlier generations; this convergence behavior is improved significantly in the ISC as a higher convergence rate is maintained even in much later generations. Furthermore, as shown in insets of figure 6, the four individual correction processes (G1-G4) reach very low level of intensity, indicating that the

ISC has lower demand for the dynamic range of feedback. Note that, all simulation results shown here were averages of 10 independent optimization processes.

We then performed experiments to implement the ISC for focusing light through scattering media and to confirm if we could see the same effect shown in the simulations. Again, 60×60 segments were divided into four interleaved groups, each of which consisted of 30×30 segments. GA optimization adopted a population size of 30, elite count of 8, crossover fraction of 0.8, and mutation rate of 0.01. The intensity of the central pixel of the CCD was set as the cost function. The results are shown in figures 7. The noise of the system was characterized by measuring the fluctuations of the targeted speckle before the correction process was performed. As shown in figure 7(a) and (b), the normalized intensity (to the saturation level of CCD) can be well characterized with a Gaussian distribution with the maximum at 0.59 and the Gaussian width ($1/e$) at about 0.10, corresponding to a noise level of 0.0847. As shown in figure 7(c), the ISC converges significantly faster than the ASC. After 800 generations of optimization, the PBR of ISC reaches 690 and in comparison the ASC reaches 582. While the optimization process is not shown here, we also performed the ISC by using 270×270 segments and 9 sets of interleaved segments in experiments. The result showed that the PBR of 1556 was achieved after 900 generations. The final correction phase mask and focusing profile are shown in figure 8(a) and (c) respectively.

Using ISC we realized imaging through scattering media with high quality. Experimental results are shown in figure 8. Because of multiple scattering, the CCD images are speckles when no wavefront correction is performed, as shown in figure 8(b). After optimization with 900 generations, the light is refocused to a sharp spot (shown in figure 8(c)) on the CCD with a PBR of 1556. This PBR has already exceeded the dynamic range of the 8bit CCD camera, which demonstrates that this method can tolerate low dynamic ranges of CCDs. The correction phase pattern is shown in figure 8(a). Such a high PBR is essential for imaging through scattering media with high quality. We used virtual objects and the “scattering lens” to generate images after the strongly scattering medium. A ring of points and a letter “E” were imaged. Their phase patterns were calculated by Gerchberg-Saxton algorithm and are shown in figures 8(d) and 8(e). By addressing the superposition of these phase patterns with the one in figure 8(a) on SLM, the designed patterns were successfully imaged on the CCD behind the scattering medium with high quality as shown in figures 8(d) and 8(e). Note that the CCD shows random speckles as in Figure 8(b) if no correction phase is applied.

We also demonstrated that the focusing quality of a relatively complicated beam, such as a bottle shaped beam with 3D structure, could be also improved after passing through the scattering medium, which showed the 3D imaging capability of “scattering lens” [13]. A little difference of this experimental setup from figure 2 was that we corrected the scattering medium into a lens with focal length about 1mm and NA about 0.45. After correction and superimposition of the annular phase profile with the correction phase pattern (phase for focusing through the scatter), we were able to image the bottle shaped beam through the scattering medium. The 3D distribution of the image shown in figure 9(d) is obtained by scanning the imaging system along optical axis. Generation of bottle shaped beam behind scattering media may have its potential use in deep-tissue STED microscopy [26].

The simulation and experimental results indicate that dividing SLM into interleaved groups for correction can improve converging rate comparing to all segments GA optimization and is not limited by dynamic range of CCD, thus can achieve a more perfect correction. However, dividing into too many interleaved groups may affect the parallel processing of GA then increase the optimization time. The SLM can correct the aberrations introduced by turbid scattering media and transforms the scattering media into a “scattering lens” for imaging. Increasing the degree of measurement and the number of controlled segments can improve the focusing and imaging quality. Based on reversibility of optical path, the object behind scattering media can be imaged in front, i.e. we can see the object behind the scattering media. This is very useful in deep tissue imaging which we will demonstrate this ability later.

4. Conclusion

In summary, we have proposed and demonstrated an interleaved segment correction method to yield a greater improvement factor than the traditional all segment correction for focusing and imaging through turbid media. This method has shown a greater tolerance to the noise of an imaging system and less demanding of dynamic ranges of detectors. With all these advantages, a larger number of correction segments are allowed to use to yield even better correction. The improvement of the light focusing may help in many applications such as two-photon fluorescence excitation, STED super-resolution microscopy, phototherapy and optical manipulation in deep tissue, allowing us to acquire high contrast images behind the scattering media with the help of “memory effect”.

Acknowledgments

This research is supported by the National Basic Research Program (973 Program) of China under grant No. 2012CB921900 and the Natural Science Foundation of China under the grant No. 81427802, 61275193 and 61377008. TY is grateful for the supports from National Institute of General Medical Sciences (R21GM-104683 and P20GM-103499) and a grant from the National Science Foundation (1539034).

References

1. Babcock HW. The possibility of compensating astronomical seeing. Publications of the Astronomical Society of the Pacific. 1953; 65:229–236.
2. Vellekoop IM, Mosk AP. Focusing coherent light through opaque strongly scattering media. Opt. Lett. 2007; 32:2309–2311. [PubMed: 17700768]
3. Hsieh CL, Pu Y, Grange R, Laporte G, Psaltis D. Imaging through turbid layers by scanning the phase conjugated second harmonic radiation from a nanoparticle. Opt. Express. 2010; 18:20723–20731. [PubMed: 20940968]
4. Papadopoulos IN, Farahi S, Moser C, Psaltis D. Focusing and scanning light through a multimode optical fiber using digital phase conjugation. Opt. Express. 2012; 20:10583–10590. [PubMed: 22565684]
5. Zhou EH, Ruan H, Yang C, Judkewitz B. Focusing on moving targets through scattering samples. Optica. 2014; 12:27–232.
6. Ma C, Xu X, Liu Y, Wang LV. Time-reversed adapted-perturbation (TRAP) optical focusing onto dynamic objects inside scattering media. Nat. Photonics. 2014; 8:931–936. [PubMed: 25530797]
7. Popoff SM, Lerosey G, Carminati R, Fink M, Boccarda AC, Gigan S. Measuring the transmission matrix in optics: an approach to the study and control of light propagation in disordered media. Phys. Rev. Lett. 2010; 104:100601. [PubMed: 20366410]

8. Popoff S, Leroosey G, Fink M, Boccaro AC, Gigan S. Image transmission through an opaque material. *Nat. Commun.* 2010; 1:81. [PubMed: 20865799]
9. Yoon J, Lee KR, Park J, Park Y. Measuring optical transmission matrices by wavefront shaping. *Opt. Express.* 2015; 23:10158–10167. [PubMed: 25969058]
10. Vellekoop IM, Mosk AP. Phase control algorithms for focusing light through turbid media. *Opt. Commun.* 2008; 281:3071–3080.
11. Vellekoop IM, Lagendijk A, Mosk AP. Exploiting disorder for perfect focusing. *Nat. Photonics.* 2010; 4:320–322.
12. Katz O, Small E, Bromberg Y, Silberberg Y. Focusing and compression of ultrashort pulses through scattering media. *Nat. Photonics.* 2011; 5:372–377.
13. Katz O, Small E, Silberberg Y. Looking around corners and through thin turbid layers in real time with scattered incoherent light. *Nat. Photonics.* 2012; 6:549–553.
14. Katz O, Small E, Guan Y, Silberberg Y. Noninvasive nonlinear focusing and imaging through strongly scattering turbid layers. *Optica.* 2014; 1:170–174.
15. Nixon M, Katz O, Small E, Bromberg Y, Friesem AA, Silberberg Y, Davidson N. Real-time wavefront shaping through scattering media by all-optical feedback. *Nat. Photonics.* 2013; 7:919–924.
16. He H, Guan Y, Zhou J. Image restoration through thin turbid layers by correlation with a known object. *Opt. Express.* 2013; 21:12539–12545. [PubMed: 23736472]
17. Conkey DB, Brown AN, Caravaca-Aguirre AM, Piestun R. Genetic algorithm optimization for focusing through turbid media in noisy environments. *Opt. Express.* 2012; 20:4840–4849. [PubMed: 22418290]
18. Cui M. A high speed wavefront determination method based on spatial frequency modulations for focusing light through random scattering media. *Opt. Express.* 2011; 19:2989–2995. [PubMed: 21369123]
19. Cui M. Parallel wavefront optimization method for focusing light through random scattering media. *Opt. Lett.* 2011; 36:870–872. [PubMed: 21403712]
20. Tang J, Germain RN, Cui M. Superpenetration optical microscopy by iterative multiphoton adaptive compensation technique. *PNAS.* 2012; 109:8434–8439. [PubMed: 22586078]
21. Wang F, He H, Zhuang H, Xie X, Yang Z, Cai Z, Gu H, Zhou J. Controlled light field concentration through turbid biological membrane for phototherapy. *Bio. Opt. Express.* 2015; 6:2237–2245.
22. Thompson JV, Throckmorton GA, Hokr BH, Yakovlev VV. Wavefront shaping enhanced Raman scattering in a turbid medium. *Opt. Lett.* 2016; 41:1769–1772. [PubMed: 27082341]
23. Freund I, Rosenbluh M, Feng S. Memory effects in propagation of optical waves through disordered media. *Phys. Rev. Lett.* 1988; 61:2328–2331. [PubMed: 10039084]
24. Judkewitz B, Horstmeyer R, Vellekoop IM, Yang CH. Translation correlations in anisotropically scattering media. *Nat. physics.* 2015; 11:684–689.
25. Mosk AP, Lagendijk A, Leroosey G, Fink M. Controlling waves in space and time for imaging and focusing in complex media. *Nat. Photonics.* 2012; 6:283–292.
26. Klar TA, Jakobs S, Dyba M, Egner A, Hell SW. Fluorescence microscopy with diffraction resolution barrier broken by stimulated emission. *PNAS.* 2000; 97:8206–8210. [PubMed: 10899992]
27. Haupt RL, Haupt SE. *Practical Genetic Algorithms.* 2. John Wiley & Sons; 2004.

Figure 1.

An illustration shows that an array of phase segments is divided into four interleaved groups. The intensity of focus has been improved by combining the four correction phases. (a) 60×60 segments of the SLM are divided into four interleaved groups labeled in different gray colors and each has 30×30 segments. (b) A set of 4×4 segments is shown with each segment contains 18×18 pixels. (c)–(f) An individual section is optimized with the active segments labeled with gray colors. Each of the individual optimization yields an improved intensity at the target. (g) The combined final correction phase yields a higher intensity at the target. Images at the bottom row illustrate the corresponding intensity profiles of the focuses behind the scattering media when applying the correction phases obtained from each individual group correction and the final combined correction.

Figure 2.
Experimental set up for focusing and imaging through scattering media

Figure 3. Simulation results of the relationship between the number of controlled SLM segments and the PBR of the focus. (a) GA optimization process under segments of 10x10, 20x20, 30x30 and 60x60; (b) The PBR as a function of the number of segments. (c) Optimal correction phase pattern for 10x10, 20x20, 30x30 and 60x60 segments and corresponding focus images.

Figure 4.
Simulation results of GA process with different noise levels. The number of correction segments is 30×30 .

Figure 5.

Simulation results of comparison between different correction strategies with 60×60 segments. (a) Dividing all segments to four quarters and correcting each quarter separately, and the four quarter are combined to a final correction phase; (b) Dividing all segments to four interleaved sets (the ISC method); (c) Correcting segments altogether (the ASC method); (d) GA optimization processes. The inset shows the correction processes of the four groups in ISC.

Figure 6.

Simulation results of comparison of ISC with ASC under controlled segments number 60×60 . (a)–(d) Optimization processes of ISC and ASC optimizing with noises of 0.05, 0.10, 0.15 and 0.20 respectively. The insets show the correction processes of the four groups.

Figure 7.

Experimental results of comparison of ISC with ASC. (a) Normalized target intensity variation by time before correction; (b) The intensity distribution of the target intensity in (a); (c) The optimization process of ASC and ISC. The inset shows the correction processes of the four groups.

Figure 8.

Experimental results of focusing and imaging through scattering media. (a) The optimized correction phase pattern for refocusing the scattering light into a spot; (b) Speckles image without correction; (c) Refocus behind the ground glass after optimization; (d)(e) The phase map of the virtual object calculated by Gerchberg-Saxton algorithm and corresponding images through the ground glass. The scale bar is $40\mu\text{m}$.

Figure 9.

Experimental results of imaging a bottle shaped beam through the scatter. (a) Annular phase profile for generating the bottle shaped beam; (b) and (c) Transverse intensity distributions of the bottle shaped beam at different axial planes of 1 and 2 in (d); (d) 3D intensity distribution of the bottle shaped beam.