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Utilizing optical conjugate plane to enhance 3D focusing and forming shapes behind turbid media

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ABSTRACT: Inner diffraction phenomenon is known as the major obstacle of light transmission through scattering media such as ground glasses, skin or biological tissue. Recently, the most effective and convenient solution is wave-front shaping technique which modulates the field profile of incident light by using a spatial light modulator (SLM). For practical and advanced biomedical applications, requirement of speedy response, high accuracy and large energy delivery are necessary. In our previous work, we presented a wave-front shaping technique and utilized optical memory effect for swiftly drawing various 2 dimensional (2D) shapes or contours through a scattering medium without any mechanical movement. However, with process of scanning angle phase profile and shifting phase pattern on SLM, the accuracy and beam energy utilization are still very much restricted. Here, we present an exceeding improvement from previous technique by establishing optical conjugate planes between SLM and scattering medium surface, which is also known as 4F system. With only one phase profile for creating a focus spot behind scattering medium, we are able to swiftly move focus spot in 3D space or draw any 3D contours through turbid medium without scanning or shifting process. The new approach allows us to deliver laser energy through a scattering medium to any spot within 3D memory effect space with very fast response, high accuracy and more importantly, fully utilized laser beam energy. Our approach demonstrates a practical method to control light through scattering media for prominent applications such as opto-genetic excitation, minimal invasive laser surgery and other related fields.

- Key words: Optical Memory Effect, spatial light modulator, biomedical application, scattering media, focus point, wave front shaping.
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1. INTRODUCTION

Controlling light propagation through any medium is important because it introduces a lot of distortion to the optical information. The information is usually lost by the scattering effect in turbid or disorder media such as ground glass or biological tissues. Such strong scattering effect distorts the directionality, phase and intensity of transmitted light. Hence, focusing light inside biological tissues, through skin or common translucent media is also restricted. The solution to overcome this limitation could provide a useful approach for many significant applications in biomedical and manufacturing field. To work towards this goal, one can directly measure the transfer matrix of turbid medium then control the incident light to reverse the scattering effect and produce desired images behind it [1-8]. Because of the time reversal property of light, the field that is phase conjugated with output field can travel backward through the scattering medium and generate the focus point [9-16]. Controlling the incident light can be done by using wave front shaping devices such as Spatial Light Modulator (SLM) or Digital Micro-mirror Device (DMD) [8, 17]. In this phase conjugation – time reversal method, the precision requirement of alignment for pixel by pixel matching and the complexity of experiment set up will consume a lot of time and effort which strictly limit the possibility for applications.

Another powerful approach to create a point behind the scattering medium is via optimization technique, which treat the scattering medium as a black box [16-19]. There is no strict requirement for optical alignment. With the help of a guiding star on the other side of scattering media, we can build a feedback loop to optimize the

incident phase pattern. In our experiment, we utilize the feedback wave-front shaping method [17] to create a focus point behind the scattering medium by optimizing the pattern on the phase-only SLM. Our work emphasize on the method to swiftly move the focusing point, generate multiple points simultaneously, and draw any desired contours/shapes on the other side of turbid medium. In principle, one can do multiple optimizations, then record the phase patterns in the memory and use it accordingly [20]. However, multiple-optimization process approach is not practical for most applications because it's time consuming, especially for complex turbid media. Here, we utilize the optical memory effect [21, 22] to use only a single optimized phase pattern for generating various complex shapes on the other side of turbid medium. In our previous work [23], with Memory Effect, we have demonstrated a technique of moving focus spot in 2D plane by digitally tilting and shifting original phase pattern which requires no mechanical movement. However that technique still requires a pre-scanning for moving spot to a specific position which limit technique's ability for speedy applications. Beside, shifting process, even digitally on SLM will always make a mismatch with incident reference beam which will reduce the quality of focus spot later. Therefore, here we will show a significant enhancement to implement for Memory Effect by utilizing a simple 4F optical system. With this implement, there is no requirement for multi-scanning, shifting as well as it improves the quality of focus spot by matching continuously phase pattern with reference beam. Therefore, our new technique will allow drawing swiftly contours in 3D space by moving focus spot sequentially or creating multiple spots simultaneously. In consequence, our proposed approach can open a wide range of applications in related fields.

2. PRINCIPLE AND EXPERIMENT SETUP

As widely known, wave-front shaping technique with use of SLM is the most common and efficient tool to overcome the random scattering effect which allows modulating incident light field digitally. However, for practical applications, there is essential requirement to enhance it with other principles and techniques. For creating a focus spot behind a scattering medium, here the wave-front shaping technique is enhanced with Genetic Algorithm (GA)[18]. In principle, a laser beam with phase profile modified digitally by SLM plays as changing input for GA. The output pattern also known as feedback for the algorithm which targets for achieving a sharp focus spot, is acquired by a camera behind the scattering medium. Although the optimizing time is quite short in range of dozen minutes, however running repeatedly optimization process is not practical for speedy moving spot in space or drawing any shape. Therefore, Optical Memory Effect partakes in to help swiftly moving focus spot with only one optimized phase pattern.

Basically, Optical Memory Effect is described as spatial correlation of light with turbid media [21, 22]. That effect, in case of thin and stable turbid medium, shows that if the incident light field is shifted, tilted or both tilted and shifted, then the output light field behind the scattering medium will be similarly affected accordingly. Normally, the mechanism of utilizing memory effect is demonstrated in the Fig.1 for moving focus spot in 2D plane behind scattering medium. In our previous work [23], we have introduced a method of utilized the memory effect without any mechanical movement as showed in Fig.1. Firstly, the optimized phase pattern on SLM is tilted digitally by ramping method. Then to retain the shined area on scattering medium, the new phase pattern is shifted on SLM surface a distance according to the tilting angle. However, to find precisely the relationship between

Figure 1: The diagram of tilting and shifting phase pattern to utilize the memory effect.

shifting distance and tilting angle, it still requires a quick scanning process for each phase profile. Besides, with incident beam is fixed on surface of SLM, shifting phase pattern will reduce the intensity as well as the quality of focus spot. Therefore, here we enhance the introduced memory effect by establishing a 4F optical system between the planes of SLM and scattering medium's surface which will no longer require scanning and shifting process to move focus spot.

Consider a free space is between the SLM and the surface of a scattering medium as in Fig.1. Spectrum at SLM's plane is denoted as $U(x, y, 0)$ and spectrum at observation plane is $U(x, y, z)$ in which z is the distance between two planes. Then the relationship between the fields at two planes can be expressed by diffraction calculation with direct and inverse Fourier Transform $F\{\}$ and $F^{-1}\{\}$ in the equation below []:

$$U(x, y, z) = F^{-1} \left\{ F\{U(x, y, 0)\} \exp \left[j \frac{2\pi}{\lambda} z \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} \right] \right\} \quad (1)$$

Where λ is the wave-length of used laser beam, f_x and f_y are spatial frequencies. Follow the diagram in Fig.1, it suggests that to create two spots at point A and B, the two wave-front on surface of the scattering medium $U_A(x, y, z_A)$ and $U_B(x, y, z_B)$ are different due to adding ramping phase to the original phase pattern and shifting it at original plane. Hence, to achieve the spot at B position without scanning angle and shifting pattern, it will require modulation for both phase and amplitude of $U_A(x, y, 0)$ to create $U_B(x, y, z_B)$ at turbid medium's surface. This modulation could be done with Fresnel diffraction calculation to find required spectrum at SLM plane for creating focus spot at B. However, the diffraction calculation is only an approximation and modulation of both phase and amplitude by SLM also requires strict optical alignment for a complex setup. To simplify those problems, we present a solution which establishes a 4F optical systems with two convex lenses between SLM and turbid medium's surface. The ideal 4F system which equals to two times Fourier Transform with Fraunhofer approximation, will transfer the wave-front at SLM's plane to turbid medium's plane without changing phase or amplitude. Therefore, from optimized wave-front $U_A(x, y, 0)$ for creating focus spot at A, we only need to modify the phase by adding a ramping phase to move the spot to B.

The experiment setup with 4F system is demonstrated in Fig.2. A laser beam with wavelength of 632.8nm is guided by a beam splitter to shine at the center of a SLM. The laser beam after reflexing on SLM, passes through a system of two convex lenses with focal length of 150mm and 50mm respectively. A ground glass diffuser (Thorlab, N-BK7) is used as turbid medium, is placed at the focal length of L2. With system of L1 and L2, the SLM's plane and diffuser's plane are conjugate with magnification of 1/3 to reduce number of degree of freedom for optimization process. A monochromic CMOS camera is set behind the diffuser as observation plane. At the

Figure 2: Experiment setup. BS: Beam Splitter. L1, L2: Convex lenses with focal length $f_1 = 150\text{mm}$ and $f_2 = 50\text{mm}$ respectively. D: distance between diffuser and camera

first step of experiment, image acquired by camera is used for feed-back wave-front shaping method with GA. Then an optimized phase pattern on SLM is obtained corresponding to creating a focus spot at camera plane.

Let consider position of original focus spot as origin of a Cartesian coordinate in which X-axis is along the horizontal axis and Y-axis is along vertical axis. Then to move the focus spot to a position (x, y) on the camera, based on Memory Effect, wave-front on diffuser's surface needs to be tilted digitally around X-axis and Y-axis by an angle α_y and α_x , respectively:

$$\tan(\alpha_x) = x/d \quad (2)$$

$$\tan(\alpha_y) = y/d \quad (3)$$

Where d is the distance between camera plane and the diffuser. Because camera surface is a discrete plane of which smallest fraction is a pixel, then the position x and y can be expressed by: $x = n_x \times p$ and $y = n_y \times p$ where n_x and n_y are number of pixel moving in X-axis and Y-axis, p is the pixel size of camera. Because the magnification from SLM plane to diffuser plane is 1/3, hence the real angles for tilting digitally phase pattern on SLM are $\beta_x = \alpha_x/3$ and $\beta_y = \alpha_y/3$. Based on Memory Effect, correct angle tilted will give brightest spot at corresponding position on camera. Therefore, by a quick scanning process with a range of tilted angle, the distance d can be estimated precisely. From knowing exactly d, phase profile for moving focus spot in 2D plane which is a combination of original optimized phase pattern and ramping phase pattern, can be calculated easily without any further scanning process.

By creating a focus spot at distance d from diffuser, we can consider the linear combination of wave-front on diffuser's surface and the diffuser as a convex lens with focal length d. Then to move the focus spot to a distance d' from diffuser, it only requires adding phase difference between lens phases with focal length d and d' to the optimized phase pattern on SLM. With this idea, our setup is also able to swiftly move focus spot along Z-axis. In consequence, ability of moving focus spot in 3D space is easily achieved.

Moreover, from phase profile for moving focus spot in 3D space, it is able to produce a single phase pattern on SLM which can simultaneously create more than one focus spot by using an expression below:

$$P = \arg \left[\sum_{j=1}^m (E \times \exp(iP_j)) \right] \quad (4)$$

where P is calculated phase for creating simultaneously multiple points; P_j is the j-th phase pattern for creating single point; E is the amplitude of reference beam. However, restricted by conservation energy law, intensity of each spot is inversely proportional to the number of created spots m.

3. RESULT AND DISCUSSION

The result of feedback wave-front shaping with GA for creating focus spot behind scattering medium is illustrated in Fig.3. There are 540×540 elements for optimizing phase pattern on SLM. Size of focus spot at FWHM is $20\mu\text{m}$. Valuated value for optimization is the contrast between intensity at desired position and average value of background:

$$C = I_s / \bar{I}_B \quad (5)$$

where C is contrast value; I_s is maximum intensity of focus point; $\bar{I}_B$ is the mean value of background intensity. With 8bit CMOS camera, the final contrast value is 112, therefore the contrast could be increased dramatically by using better camera. However, the purpose of this experiment is to quickly achieve a sharp focus spot despite of using normal camera. The quality of focus spot can also be improved by utilizing more elements for optimization and extending optimizing iteration which in trade-off will cost more processing time. As mentioned, with a quick scan, the distance from camera's plane to diffuser is obtained as 3.91cm.

Figure 3: a. Optimized input-phase pattern on SLM has a size of 540×540 pixel with pixel size of $8 \times 8 \mu\text{m}$; b. output image on camera has size of 540×480 pixel with cross section of 64×64 pixel and same pixel size with SLM

Moving focus spot based on Memory Effect gives the distribution of spot intensity in X-Y axis as showed in Fig.4. Due to imperfect parallelism between SLM's plane, diffuser's surface and camera's plane, the intensity of focus spot is fluctuated more as it moves further from original position. The effective radius for moving spot in which the intensity reduces by half is about $100 \mu\text{m}$. The intensity of moving spots along X and Y axis are illustrated in fig Fig.5.

Fig. 4: Focus spots in different positions along X-Y axes

Fig. 5: Intensity distribution of moving spot along X-Y axes. (a) Intensity distribution of moving spot along X axis. (b) Intensity distribution of moving spot along Y axis

In Fig.6, the quality of focus spot in Z-axis is demonstrated. The images of spot are captured by moving camera on a moving stage. Similar to X-Y plane, the intensity distribution in Z-axis is also not symmetric. This phenomenon is explained as the moving direction of camera is not along the same axis with moving focus spots. Efficient radius of moving spot here is about 3.5mm which is much longer than in X-Y plane. However, the range of moving spot in X-Y-Z axes are suitable with memory effect range for used diffuser

Therefore in principle, with the ability of moving focus spot in X-Y-Z direction, our setup is able to swiftly draw any contours in 3D space. By capturing spot in each position in space, a 3D shape could be form using time multiplexing.

Fig. 6: Intensity distribution of moving spot along Z axis.

On the other way of creating 3D shapes, from equation (4), it's possible to create multiple spots simultaneously by combining phase patterns of corresponding each single spot. However, as the number of created spot increases, the quality of the 3D shape will decrease rapidly due to energy conservation. By using 4F

system, the quality as well as number of sharp spots could be increase much more due to a same amplitude E of reference beam used for each spot.

4. CONCLUSION

By using a well know method – feedback wave-front shaping with GA, we have achieved a sharp focus spot. However, the novelty of our method focuses on enhancing that method with Memory Effect and 4F optical system to bring out an efficient approach for practical applications. With obtained results, we have been successful in moving focus spot to different positions in 3D space. More important, the process of moving spot has been performed from only one pre-optimized phase profile which reduces a lot of processing time and error for optimization. Besides, the enhancement of 4F system to Memory Effect has shown the quality improvement and less time processing for creating focus spots without any mechanical movement or long time scanning. To swiftly draw 3D contours, we have given a discussion about two methods with their pros and cons. Therefore, with simple design and speedy processing method, our technique could deliver prominent applications for opto-genetic excitation, also minimal invasive laser surgery and other related fields.

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