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Swiftly moving focus points and forming shapes through the scattering media

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ABSTRACT

Propagation of light through scattering media such as ground glass or biological tissue limits the quality and intensity of focusing point. Wave front shaping technique which uses spatial light modulator (SLM) devices to reshape the field profile of incoming light, is considered as one of the most effective and convenient methods. Advanced biomedical or manufacturing applications require drawing various contours or shapes quickly and precisely. However, creating each shape behind the scattering medium needs different phase profiles, which are time consuming to optimize or measure. Here, we demonstrate a technique to draw various shapes or contours behind the scattering medium by swiftly moving the focus point without any mechanical movements. Our technique relies on the existence of speckle correlation property in scattering media, also known as optical memory effect. In our procedure, we first modulate the phase-only SLM to create the focus point on the other side of scattering medium. Then, we digitally shift the pre-optimized phase profile on the SLM and ramp it to tilt the beam accordingly. Now, the incoming beam with identical phase profile shines on the same scattering region at a tilted angle to regenerate the focus point at the desired position due to memory effect. Moreover, with linear combination of different field patterns, we can generate a single phase profile on SLM to produce two, three or more focus points simultaneously on the other side of a turbid medium. Our method could provide a useful tool for prominent applications such as opto-genetic excitation, minimally invasive laser surgery and other related fields.

- Key words: optical memory effect, spatial light modulator, optimization, scattering media, focus point, wave front shaping.

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 direction, phase and intensity of transmitted light. Hence, focusing light inside biological tissues, through skin or common translucent media is also challenging. 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 [1-7]. 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 [8-15]. 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) [7, 16]. 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 [15-18]. 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 [16] to create a focus point behind the scattering medium by optimizing the pattern on the phase-only SLM. Our work emphasizes 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 them accordingly [19]. 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 [20, 21] to use only a single optimized phase pattern for generating various complex shapes on the other side of turbid medium. With memory effect, we only need to change the incident angle to tilt the direction of the output, which is equivalent to move the focusing point. We digitally shift the optimized phase pattern then appropriately apply a ramping phase on SLM to holographically generate the same optimized field coming to the same scattering region at different angle. There's no mechanical movement, no further optimization process involved in this step, allowing us to swiftly move the focus point to any position within memory effect region. In addition, we also linearly combine multiple fields and deduce one phase pattern to produce multiple points simultaneously. Our proposed approach can improve the works done by Psaltis group [9, 12] and open a wide range of applications.

Figure 1: Schematic diagram of experiment setup; SLM: Phase-only Spatial Light Modulator; PL: Polarizer; L1-L2: Lenses; OBJ1-OBJ2: Objective lenses.

2. Experiment

The Fig. 1 represents the experimental setup. A He-Ne laser source with wavelength of 632.8 nm is shined on the surface of the phase-only SLM (HOLOEYE Pluto-2 reflective phase-only SLM) with a small incident angle. After being modified by the pattern on the SLM, the laser beam passes through a linear polarizer to eliminate

Figure 2: The diagram of tilting and shifting phase pattern to utilize the memory effect. 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.

undesired light. Then with a lens (L1) and 60X microscope objective lens (OBJ1, NA 0.85), the modulated beam is transmitted to a small area of scattering medium (Thorlabs ground glass diffuser 220 grids). The scattered pattern behind the diffuser is observed by a camera (A2080 monochrome 12bits Photonfocus CMOS camera) through a lens L2 and 20x microscope objective lens (OBJ2, NA 0.4). The distance between the observed plane and the surface of scattering medium is about 2 mm. The image on camera provide feedback signals to modify the phase pattern on SLM accordingly.

Among recent optimization methods to achieve focus point, we choose the Genetic Algorithm (GA), which has been proven to have many advantages [16-18]. In the experimental setup, the phase pattern on SLM combines with Gaussian laser beam to form the input field for the GA and the image on the camera as the output intensity target. The final target of the optimization here is to achieve a sharp focus point with size range from 3 to 5 pixels and high contrast intensity on camera (camera pixel $8 \times 8 \mu\text{m}$). The illuminated area on SLM covers a rectangular of 700×700 pixels with pixel size of $8 \times 8 \mu\text{m}$. This area corresponds to a matrix of size 70×70 , which is optimized by GA to achieve the focus point on the other side of the turbid medium. After getting the focus point, our aim is to swiftly move the focus point around without knowing the characteristics of the turbid medium. To do that, we apply the knowledge of optical memory effect with scanning mechanism.

Optical memory effect or also known as spatial correlation in turbid medium has been exploited to do imaging through scattering media [22, 23] [24]. In principle, there are three types of spatial correlation in turbid media: "tilt", anisotropic "shift" and the combination of both [21]. In our experiment, the tilting and shifting processes are made digitally on the SLM. The process of tilting and shifting phase pattern is described in the Fig.2. To holographically tilt the direction of the incident field on the surface of scattering medium, we modulate the optimized phase pattern by adding a ramping phase according to the formula:

$$\text{Ramping Phase} = 2\pi x S \alpha / \lambda, \quad (1)$$

where x is co-ordinate of the pixel in X axis; S is pixel size; α is tilting angle; λ is the wavelength of the light source. We do the same way for tilting in Y axis. Then, to satisfy the requirement of memory effect that the beam has to be shined on the same region, the new phase pattern has to be shifted on the SLM by a distance d which is equivalent to number of pixel shifted n ($d = n \times S$). The relationship between the tilting angle and the shifted distance is: $\tan(\alpha) = d/L$, where L is the optical distance between SLM and the scattering medium. Since L is hard to be measured precisely, a scanning method is used to obtain the accurate value for L . The mechanism of scanning method is: with a shifted distance d , by adjusting the distance $L = d/\tan(\alpha)$, there will be an angle α which give the brightest focus point on the camera. This scanning method runs automatically and produces result quickly, which also gives us the information about the relative position between the plane of scattering medium and the plane of SLM. The scanning is done separately in X and Y axis one at a time, which is then combined to achieve ramping in both X and Y directions. With the profile of tilting angle α and the shifting distance d for every pixel, it is capable to create the point at any position in X-Y plane behind the scattering medium with minor loss of intensity. For moving the point in Z direction (forward and backward), we digitally add in a calculated phase pattern which represents the diffraction effect for electric field to propagate through a distance z . Therefore the whole process for tilting and shifting pattern could be done digitally and precisely on the SLM without any mechanical movement. More importantly, from the profile of phase pattern to create focus points, we deduce a single phase pattern which can simultaneously produce more than one focus point by using the formula (2). However, the decrease of intensity for each point is directly proportional to the number of created focus points.

$$P = \arg \left[\sum_{j=1}^n (E \times \exp(iP_j)) \right], \quad (2)$$

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, the intensity of each point is inversely proportional to the number of created focus points n .

3. Result and Discussion

In the Fig.3, the result of using GA to focus light through turbid medium is shown with optimized phase pattern at the center of SLM. The optimized phase pattern is a matrix of 70×70 of which value from 0 to 1

Figure 3: a. Optimized input-phase pattern on SLM has a size of 700×700 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

represents for the added phase range from 0 to 2π . This matrix is magnified 10 times to display on SLM which is equivalent to a matrix of 700×700 with pixel size of $8 \times 8 \mu\text{m}$. The contrast between the focus point and the background is used as a main factor in optimization process and measured in the expression as

$$C = I_S / \bar{I}_B, \quad (3)$$

where C is contrast value; I_S is maximum intensity of focus point; $\bar{I}_B$ is the mean value of background intensity. In the experiment, the contrast value for the final point is achieved as 6×10^5 , which is clear enough to distinguish the point as shown in the Fig.3. Certainly, the contrast as well as the intensity of focus point could be improved more by giving more iterations or more pixel elements to the optimization algorithm. However, the improvement costs more and more time, which is unnecessary in our case. Besides, the quality and time consuming of method are also affected by other factors such as the illuminating area on scattering medium, the magnification factor on SLM and the response time of SLM.

Fig.4 shows different tilted and shifted phase patterns on the whole SLM to create focus points at different positions on the camera, respectively. Here, the effective distance for moving the point is defined till the limit where the peak intensity of point reduces by half. Therefore, the effective size of area on camera for moving point is 64×64 pixel, which is centered at the position of original optimized focus point. The magnification in distance between movement of the point on the camera plane and movement of the phase pattern on the SLM plane is 8.75 in our optical setup. The maximum intensity of focus point while it is being moved in X and Y direction, is shown in the figure 5. In the figure 5, the maximum intensity is at the position (0, 0) in X-Y plane on camera, which is the position of the optimized point. By moving the point around with tilting and shifting the optimized phase pattern the focus point intensity decreases, which is already known from memory effect. However, this decrease is also affected by the small mismatch in position of intensity and phase between the new wave-front and the reference beam, which is fixed during tilting and shifting process. Besides, the difference of intensity slopes in negative and positive direction reveals the relative position between the SLM plane and the surface of scattering medium. In

Figure 4: The phase pattern on SLM according to focus point on camera at different positions. The original point is considered as origin (0, 0). The shined phase pattern on SLM has size of 700×700 pixel while the size of SLM is 1080×960 . To avoid light from unmodified part, the whole SLM is ramped with added phase as in equation 1. a: The point is moved down 4 pixels and 15 pixels to the right; b: The point is moved up 4 pixels and 6 pixels to the left (pixel size of camera $8 \times 8 \mu\text{m}$).

principle, if the plane of SLM is parallel with the scattering surface, the moving points which are symmetric with the origin (0, 0) should have the same intensity. In other word, we expect a symmetric graph in Fig.5 if the SLM surface is perfectly parallel with the scattering surface. Therefore, the scanning method with memory effect here could be also useful for measuring precisely the distance between two planes in some applications.

Figure 5: The normalized intensity of moving focus point along X axis (a) and Y axis (b). The position (0, 0) represents for the position of original optimized focus point.

Figure 6: Creating a desired contour by multiplexing point images; a. 9 different points in a set of 125 points; b. Drawing contour from the set of focus points by multiplexing.

From the profile of scanning method which takes few minutes, we are able to create focus points at any position in effective area behind the scattering medium. In consequence, it is possible to draw any contour or image through an unknown scattering medium by knowing the phase profile for a single focus point. In Fig.6, an example of creating a word “NTU” is demonstrated by laying 125 focus point images on top of each other. Due to the point size of 3×3 pixel, the shape of desired contour is blurred. By adding the background, the contrast of image is decreased but still gives a clear contour. To eliminate the background noise, it requires a larger illuminating area on the turbid medium to be optimized, which will consume more time. The reason for decreasing illuminating area on the turbid medium is to decrease the number of degree of freedom, which will help to reduce optimization time and. Apart from the phase profile of moving point, another way for creating multiple points is that, we numerically superimpose the field of various points and deduce one phase as stated in equation 2. This phase pattern will produce the number of points according to the number of phase patterns used. The images of creating two points simultaneously is shown in the Fig.7. Obviously, the quality of simultaneously created points is usually worse than multiplexing the points due to the conservation energy and also the interference of beam from creating each point. The mean value of back ground intensity increases double for creating simultaneously two points.

Figure 7: Creating multiple points simultaneously, the position of points are the same with points created separately by the each used phase pattern in the combination. The origin $(0, 0)$ is at the original optimized point; a. Image of the first point at $(-4, -2)$ with its phase pattern; b. Image of the second point at $(-4, 7)$ with its phase pattern; c. Image of creating simultaneously two points at $(-4, -2)$ and $(-4, 7)$ with combined phase pattern

4. Conclusion

We have successfully established a simple experimental set up to focus light through scattering medium by using feedback wave-front shaping method with GA and demonstrate quickly the memory effect of light propagating through scattering medium. By utilizing the memory effect and the use of SLM, the tilting and shifting process are digitally done by controlling through the computer. In consequence, moving swiftly focus point with high accuracy enables drawing any contours or images behind the scattering medium. In addition, drawing image could also be done by creating simultaneously multiple points by a simple calculation from a pre-optimized pattern for a single point. With these achievements, our techniques could deliver prominent applications for opto-genetic excitation, also minimal invasive laser surgery and other related fields.

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