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ABSTRACT

The feedback-based wavefront shaping method can be used to focus light behind or inside strongly scattering media. In this study, we investigated several characteristics of the focus after optimization to evaluate the enhancement effect of the wavefront shaping method, including the spot size, the intensity, and two types of enhancement factor. In addition, we studied the influences of various experimental parameters on these characteristics, including the number of controlled segments N, diameter of the irradiated area at the front of the scattering medium D, and distance between the expected focusing spot and scattering medium Z. A larger N and smaller Z provided a smaller focus spot. For a brighter focus spot, a larger N and smaller D and Z were required, while for a high-resolution focus spot, larger N, D, and Z were required.

I. INTRODUCTION

Light scatters during propagation through turbid media such as white paint, ground glass, milk, and biological tissue. These media are usually regarded as obstacles in many optical applications. The amplitude and phase of the incident light become disorganized and generate speckle patterns. The light scattering through a weak scattering medium, e.g., in the atmosphere, has been reconstructed by adaptive optical techniques.[1] However, these techniques are inadequate for scattering in a strongly turbid medium, which could generate speckle patterns with no simple correlations to the incident light. In 2007, in a pioneering study, Vellekoop et al. demonstrated that wavefront shaping of the incident light is helpful to focus light behind the scattering medium.[2] Using a spatial light modulator (SLM), the incident light was modulated to form a perfect wavefront matched to the transmission eigenmode of the scattering medium, which can be used to focus the incident light through or inside the scattering medium onto a target area. The method of wavefront shaping has been utilized in various applications, such as polarization control,[3,4] spectral filtering,[5] spatiotemporal modulation,[6,7] enhanced Raman spectroscopy,[8] biological imaging,[9,10] optogenetics,[11] and cryptography.[12,13]

For these applications, a key factor in the wavefront shaping method is the algorithm used for optimization, which could influence the speed of the whole process and enhancement effect. The continuous sequential algorithm and partitioning algorithm were initially used in the wavefront shaping method.[2] To improve the optimization in high-noise environments, the genetic algorithm (GA) has been also used,[14] which rapidly becomes the most practical algorithm. For the fitness function of the GA, the most common figure of merit is the enhancement factor η defined as $\eta \equiv I/I_0$, where I is the intensity in the focus after the optimization and I_0 is the reference intensity.[2] Generally, the reference intensity depends on the optimization process. Some differences in I_0 exist between phase optimization (using a phase-only SLM to control the wavefront of the incident light) and amplitude optimization (using an amplitude-only SLM to control the wavefront of the incident light).[15] In the phase optimization, the SLM controls only the phase of the incident light without changing the amplitude, so that the average energy does not change in the whole optimization process. Therefore,

I_0 is defined as the ensemble average intensity of the target focusing area before the optimization and η represents the enhancement effect. We denote the enhancement factor for phase optimization as η_1. However, in the amplitude optimization, the SLM changes the amplitude of the incident light leading to a variation in the average energy of the output light during the optimization process. In this case, I_0 is defined as the average intensity of the background around the focusing spot after the optimization and η represents the signal–to–background ratio (SBR) after the optimization, denoted as η_2.

Although most researchers in this field use the enhancement factor η to describe the enhancement effect, it may not be the only factor to evaluate the enhancement effect. Recent studies considered the intensity correlations between the reflected and transmitted speckle patterns[16] and width of the focus[17] after the optimization. In this regard, it is necessary to consider other characteristics of the final focus to evaluate the enhancement effect. For example, to excite a two-photon fluorescence in a biological tissue, the intensity of the exciting focus must be sufficient.[6] In this case, the intensity of the focus is one of the most important characteristics in the wavefront shaping method. Simultaneously, to obtain higher resolution and contrast ratio while imaging through a scattering medium, the spot size of the focus should be as small as possible.[18] The spot size of the focus is another important characteristic in the wavefront shaping method. These focus characteristics could be used to evaluate the enhancement effect of the wavefront shaping method.

For further applications of the wavefront shaping method, we should understand the effects of different experimental parameters on these characteristics during the optimization. One of the most important experimental parameters is the number of controlled segments N, corresponding to the degrees of freedom. Although the influence of N on the enhancement factor η had been reported,[2,19,20] no extensive studies have been reported on the influences of N on other characteristics such as the spot size. The influence of the irradiated area at the front of the scattering medium on η was also demonstrated.[21] However, when the diameter of the irradiated area at the front of the scattering medium D was changed, the distance between the expected focusing spot and scattering medium Z also changed; Z might also influence the optimization. Therefore, the influences of D and Z should be studied. These characteristics of the focus after the optimization and influences of various experimental parameters on the characteristics have not been systematically studied. Such studies are required owing to their significance for applications.

In this paper, we discuss the characteristics of the focus to evaluate the enhancement effect, including the spot size, intensity, and two types of enhancement factor. In addition, we systematically analyze the influences of some experimental parameters on these characteristics, including the number of controlled segments N, diameter of the irradiated area at the front of the scattering medium D, and distance between the expected focusing spot and scattering medium Z. We also study the influences of the polarization of the incident light on the characteristics of the focus.

II. EXPERIMENT

We experimentally analyze the influences of various experimental parameters on the characteristics of the final focus using the phase optimization method. The experimental setup is shown in Fig. 1(a). An expanded laser beam (expanded by a 4-f imaging system) of λ=671 nm is reflected off the surface of phase-only SLM (Holoeye PLUTO-VIS). A half-wave plate and polarizer are placed at the output of the laser to control the intensity of the laser beam. The modulated light is then expanded by an extender lens (EL, GCO-2505; Daheng Optics) and focused behind a scattering medium (DG10-120-MD; Thorlabs) by a focusing lens (f = 4 cm). The magnification of the EL can be controlled from 2 to 6. A quarter-wave plate is placed behind the EL to control the polarization of the laser. An observation system including an objective and charge-coupled device (CCD) camera is placed behind the scattering medium. The observation system is used to monitor the intensity of the expected focus area and provide feedback to a PC for optimization. The algorithm here used for the optimization is GA, and the fitness function is the intensity of the target area. The pattern before the optimization is a random speckle pattern, while after the optimization the speckle pattern transforms to a sharp focus. The scattering medium and lens could be combined as an equivalent scattering lens,[17] shown in Fig. 1(b). The equivalent focal length f_e is the distance between the scattering medium and focal plane, while the equivalent aperture D_e can be regarded as the diameter of the diffuse spot at the back of the scattering medium that would change during the optimization process.

In our experiment, it is necessary to obtain the limited focusing spot, so that the magnification of the observation system should be as large as possible and the expected focus size should be as small as possible. However, if the monitoring area is too small, the system stability will be reduced. To obtain the smallest focusing spot and high system stability, we consider the size of the feedback signal as well as the system magnification. We change the radius R of the monitoring area (circle area) on the CCD camera; R also represents the radius of the expected focus in our algorithm. The unit of R is the number

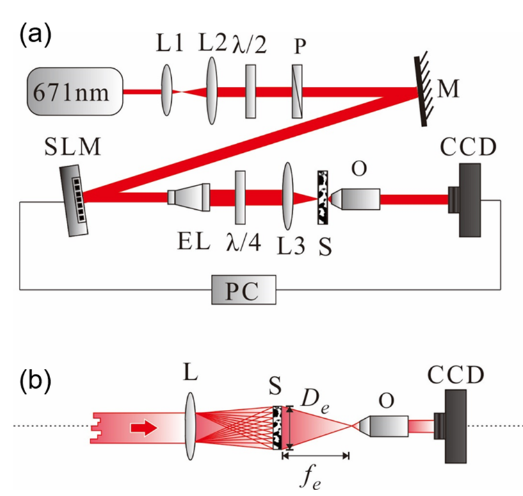

FIG. 1. Light focusing through the scattering medium. (a) Experimental setup; L1, L2, L3: focusing lens; λ/2: half-wave plate; λ/4: quarter-wave plate; P: polarizer; EL: extender lens; S: scattering sample; O: objective. (b) Schematic of the light focusing through the scattering medium. The lens and scattering medium can be regarded as an equivalent lens L_e. D_e is the equivalent aperture and f_e is the equivalent focal length.

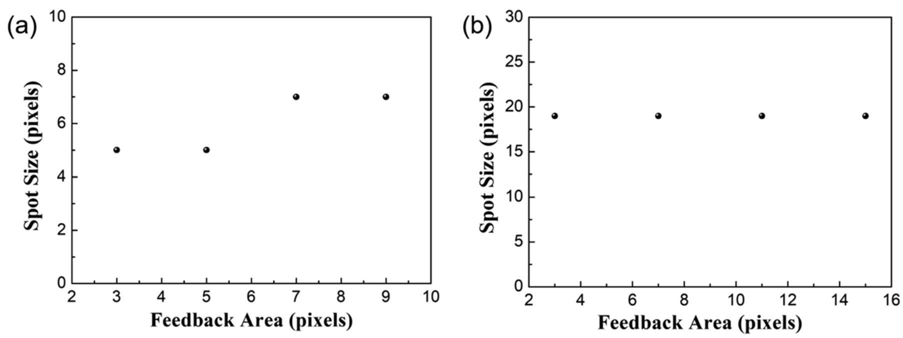

FIG. 2. Spot sizes of the focus as functions of the size of the feedback signal *R*. Spot sizes as functions of the feedback area in systems (a) 1 and (b) 2.

of CCD pixels. We then measure the spot size of the focus after the optimization in two different systems. The system with a smaller system magnification uses a 10× objective and CCD camera to collect the light behind the scattering medium. One pixel of the CCD camera corresponds to 0.435 μm at the position of the expected focus; this system is denoted as system 1. In the other system using a 20× objective, one pixel of the CCD camera corresponds to 0.125 μm at the position of the expected focus; this system is denoted as system 2. The result of system 1 is shown in Fig. 2(a). When $R < 5$, the spot size of the focus is 5. The limited spot size in this system is 5. Similarly, as shown in Fig. 2(b), the limited spot size in system 2 is approximately 19. In our experiment, the limited spot size may be changed owing to variations in the experimental parameters. Considering possible variations in the limited spot size, to obtain a high system stability, we choose system 2 as our experiment setup.

III. RESULTS AND DISCUSSION

We vary the number of controlled segments *N* to investigate its influences on the characteristics. We change the controlled segments by combining the pixels of the SLM (i.e. we obtain smaller segments when *N* increases); the other parameters of the experimental system are fixed. We measure the spot size of the focus after the optimization; the result is shown in Fig. 3(a). With the increase in *N*, the spot size of the focus decreases. To explain this behavior, we regard the focusing lens and scattering medium as an equivalent lens, shown in Fig. 1(b). We experimentally measured that D_e would increase with N. In addition, the limited spot size can be calculated by $1.22\lambda f_e/D_e$. The spot size of the focus should reduce with increasing N, consistent with the experimental results. From the discussion above, we can infer that the spot size of the focus is greatly influenced by D_e and f_e. f_e is related to the distance between the scattering medium and the focal plane. D_e may be related to the properties of the incident light (e.g. the number of the sub-sources on SLM) and the scattering medium (e.g. scattering angle). These effects to D_e are required to be studied systematically in the future research. We then measure the background intensity before the optimization, the intensity of the focusing spot *I*, and η. Their relations to *N* are shown in Fig. 3(b). We only reprogram the algorithm, so that the background intensity before the optimization remains constant. The trends of η_1 and *I* are identical; both of them increase with *N*, which is consistent with the previous study.[20] η_2 increases with *N*, which indicates that we can obtain a higher resolution ratio at a larger *N*. This can be explained as when *N* increases, the intensity of the focus increases. However, the total energy of the transmitted light does not change, leading to the increase of the SBR. We can obtain a brighter focus with a higher resolution if we choose a larger *N*.

Further, we consider the influence of the diameter of the irradiated area at the front of the scattering medium *D*. We operate the EL to change the irradiated area at the front of the scattering medium; the other parameters of the experimental system are fixed. As shown in Fig. 4(a), the spot size of the focus changes slightly with the increase in *D*. The possible reason may be that the increase in the diameter of the irradiated area at the front of the scattering medium *D* can slightly affect the D_e of scattering lens after optimization. In this case, the spot size of the focus changes little. As shown in Fig. 4(b), with the increase in *D*, the intensity of the focus and background before the optimization decrease, while η_1 and η_2 increase. The decreases in the intensity of the focus and background before the optimization with the increase in *D* can be explained as

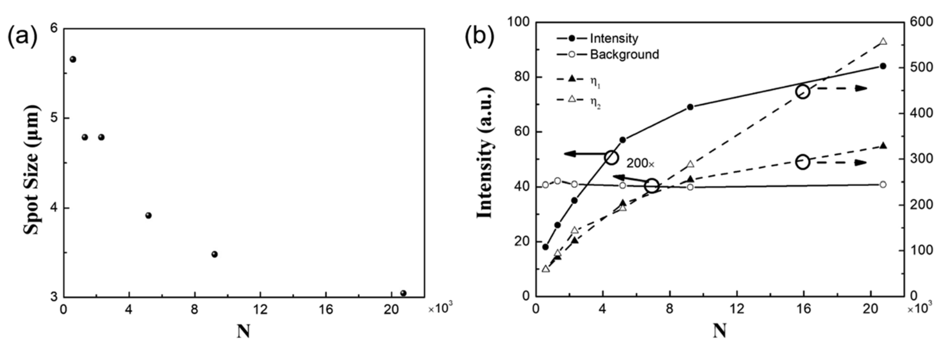

FIG. 3. Characteristics as functions of the number of controlled segments *N*. (a) Spot size of the focus as a function of *N*. (b) Intensity of the focus (solid line with filled dots) and background before the optimization (200×, solid line with hollow dots as functions of *N*, presented on the left vertical axis. η_1 (dashed line with filled dots) and η_2 (dashed line with hollow dots) as functions of *N*, presented on the right vertical axis. These lines simply connect the data points.

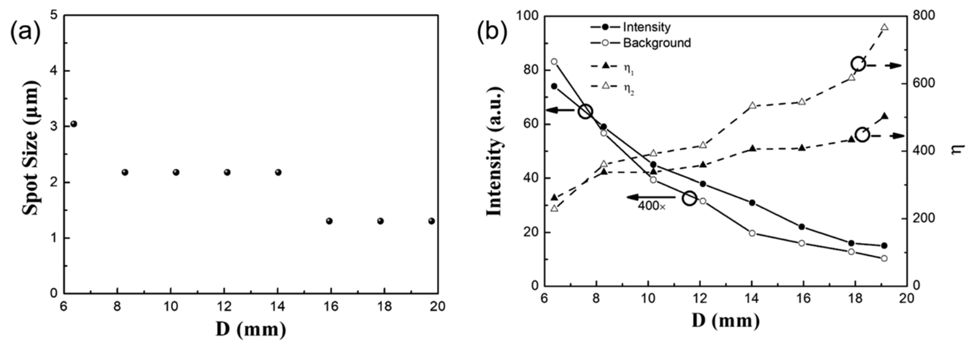

FIG. 4. Characteristics as functions of the diameter of the irradiated area at the front of the scattering medium *D*. (a) Spot size of the focus as a function of *D*. (b) Intensity of the focus (solid line with filled dots) and background before the optimization (400×, solid line with hollow dots) as functions of *D*, presented on the left vertical axis. η_1 (dashed line with filled dots) and η_2 (dashed line with hollow dots) as functions of *D*, presented on the right vertical axis. These lines simply connect the data points.

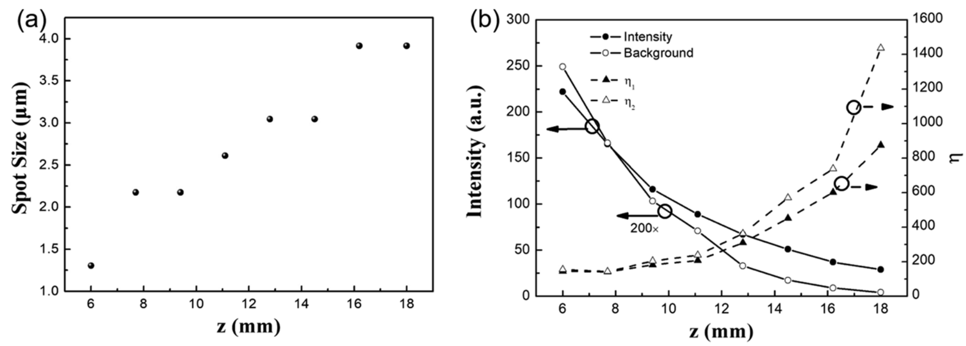

FIG. 5. Characteristics as functions of the distance between the expected focusing spot and scattering medium *Z*. (a) Spot size of the focus as a function of *Z*. (b) Intensity of the focus (solid line with filled dots) and background before the optimization (200×, solid line with hollow dots) as functions of *Z*, presented on the left vertical axis. η_1 (dashed line with filled dots) and η_2 (dashed line with hollow dots) as functions of *Z*, presented on the right vertical axis. These lines simply connect the data points.

the scattering efficiency of the scattering medium for the incident light would be more significant, and thus after the optimization less scattering lights can converge into the focus. Considering the definition of η_1, when the background changes, η_1 is not suitable to describe the enhancement effect. However, η_2 can indicate the SBR after the optimization. Therefore, we can obtain a higher-resolution focus spot at a larger *D*, although the intensity of the focus will be smaller.

Then we consider the influence of the distance between the expected focusing spot and scattering medium *Z*. We move the scattering sample to change *Z* and simultaneously operate the EL to ensure that the irradiated area at the front of the scattering medium *D* does not change; the results are shown in Fig. 5. The spot size of the focus increases with *Z*, shown in Fig. 5(a), a similar effect have been shown recently.[22] As discussed above (Fig. 1(b)), *Z* is equal to f_e. Therefore, the spot size of the focus increases with f_e. As shown in Fig. 5(b), the background before the optimization and intensity of the focus spot decrease with the increase in *Z*, which could be explained as when *Z* increases, the scattering efficiency of the scattering medium may be more significant, hindering the convergence of the diffusing light into the focus. In contrast, η_1 and η_2 increase with *Z*. η_1 cannot describe the enhancement effect owing to the variation in the background. η_2 can also indicate the SBR after the optimization. We can obtain a higher-resolution focus spot at a larger *Z*, although the intensity of the focus will be smaller.

We also studied the effect of the polarization of the incident light. We used a quarter-wave plate to change the polarization of the incident light. The polarization of the incident light had small influences on the considered characteristics. This could be attributed to the isotropy of the scattering sample; the results may be different if the sample is anisotropic. Further studies are required to better understand this effect as well as the influences of the scattering medium on the characteristics.

IV. CONCLUSION

We systematically evaluated the influences of the three main experimental parameters (number of controlled segments, diameter of the irradiated area at the front of the scattering medium, and distance between the expected focusing spot and scattering medium) on the four characteristics of the focus (spot size of the focus, intensity of the focus, and enhancement factors η_1 and η_2). The experimental results demonstrated that the most common figure of merit used in previous studies was not suitable under some conditions owing to the variation in the background intensity; the other characteristics could effectively characterize the optimization.

To obtain a smaller focus spot, a larger number of controlled segments and smaller distance between the expected focusing spot and scattering medium were required. To obtain a brighter focus spot, we should increase the number of controlled segments, reduce the irradiated area at the front of the scattering medium, and decrease the distance between the expected focusing spot and scattering medium. To obtain a high-resolution focus spot, we should increase the number of controlled segments, irradiated area at the front of the scattering medium, and distance between the expected focusing spot and scattering medium. These results could guide further studies to choose different experimental parameters for different applications using the wavefront shaping method.

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