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Deeply focusing light at 1550 nm through strongly scattering media

Xiaoming Cheng, Biqi Li, Bin Zhang, Qi Feng, Chengyou Lin *, Yingchun Ding *

College of Science, Beijing University of Chemical Technology, Beijing 100029, China

A R T I C L E I N F O

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A B S T R A C T

Wavefront shaping is a mainstream technique of focusing light through strongly scattering media. The usage of near infrared (NIR) source in wavefront shaping attracts attentions due to its promising applications for deeply focusing light. In this paper, we experimentally demonstrate that the light at 1550 nm wavelength focus through a strongly scattering media (ZnO) by controlling DMD and using genetic algorithm (GA). As deep as 456 μm focusing depth is realized when focusing 1550 nm light through a ZnO layer. In addition, focusing one or multiple spots in arbitrary positions through a ZnO layer is also achieved by using 1550 nm light.

1. Introduction

Multiple scattering happens in some non-transparent materials such as papers, eggshells and human tissues. In these materials, multiple scattering twists incident light in random directions so strongly that all spatial coherence is lost. However, scattering in static media is a linear process, so it can be reversed. In 2007, Vellekoop et al. demonstrated focusing of coherent light through opaque scattering materials by control of incident wavefront, which was referred to wavefront shaping later [1].

Iterative optimization is a common-used method of wavefront shaping in present. It can update a wavefront after each single step according to a feedback signal. Vellekoop et al. investigated three iterative algorithms (stepwise sequential algorithm, continuous sequential algorithm, and partitioning algorithm) for focusing through strongly scattering media both in theory and in experiment [2]. In 2012, Conkey et al. introduced genetic algorithm (GA) for wavefront control to focus light through strongly scattering media, and demonstrated that GA were particularly advantageous in low signal-to-noise environment [3]. Zhang et al. have demonstrated the use of genetic algorithm with binary amplitude modulation of light through turbid media in 2014 [4] and introduced a transmission matrix algorithm that works with only binary amplitude control and intensity measurements. In 2015 [5], Huang et al. have demonstrated focusing through scattering media by using particle swarm optimization [6].

In early iterative experiments, the speed of the optimization process is limited by the updating speed of phase modulator [1]. To explore a fast way of wavefront shaping, Akbulut et al. utilized a digital micromirror device (DMD) to focus light through strongly scattering media by binary amplitude modulation [7]. DMD enables the optimization process at a rate of 23 kHz, much faster than the speed of the spatial light modulator (SLM) [1,8]. Besides iterative speed, the focusing depth is also a very important parameter in wavefront shaping. Various scattering samples have been verified for light focusing, however the large focusing depth of those samples are still limited, such as 80 μm thick ZnO layer [9,10] and 11.3 μm thick ZnO layer [11]. Horton et al. compared the imaging depth achieved with 775 nm excitation to that achieved with 1280 nm excitation and found deeper penetration was achieved with longer wavelength both in vivo and ex vivo blood vessels [12]. M. Balu et al. presented comparative study of imaging in turbid media at 800 nm and 1300 nm, and 50%–80% increase in scattering length was also observed by using 1300 nm light than 800 nm light [13].

In this paper, we applied a 1550 nm laser for focusing light through a strong scattering media (ZnO). GA was employed to realize binary amplitude optimization for wavefront shaping. The ZnO samples of different thickness was tested for focusing light, and up to 456 μm focusing depth was realized.

2. Experiment setup

The experimental setup is shown in Fig. 1. A 1550 nm laser beam is amplified by erbium doped fiber amplifier to 60 mW. The beam coming out from optical fiber laser is expanded and collimated by beam expander (Daheng GCO-2505) first, and then reflected by mirrors M1, M2 and M3. After that, the light is shaped by DMD (TI DLP6500FYE), which is a reflecting device consisted of millions of micro-mirrors.

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* Corresponding authors.
E-mail addresses: cylin@mail.buct.edu.cn (C. Lin), dingyc@mail.buct.edu.cn (Y. Ding).

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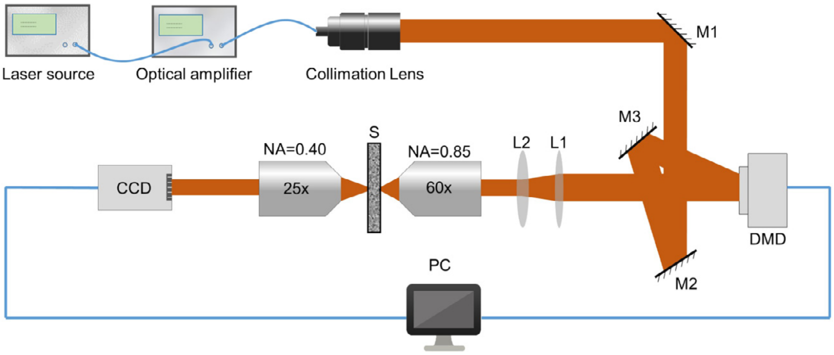

Fig. 1. Experiment setup.

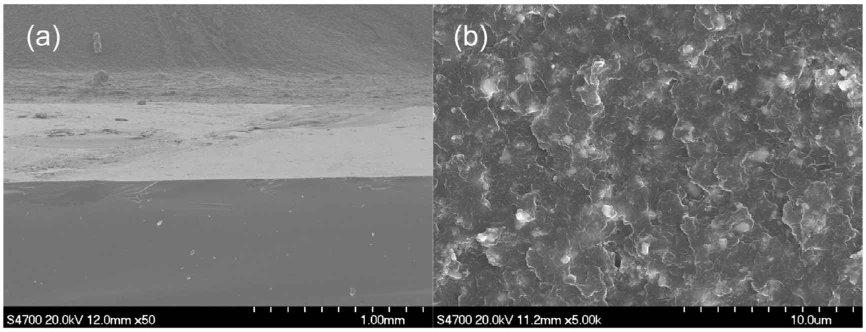

Fig. 2. The SEM image of a ZnO samples with 456 μm thickness. (a) Shows the structure of the samples. (b) Shows the ZnO particles in samples.

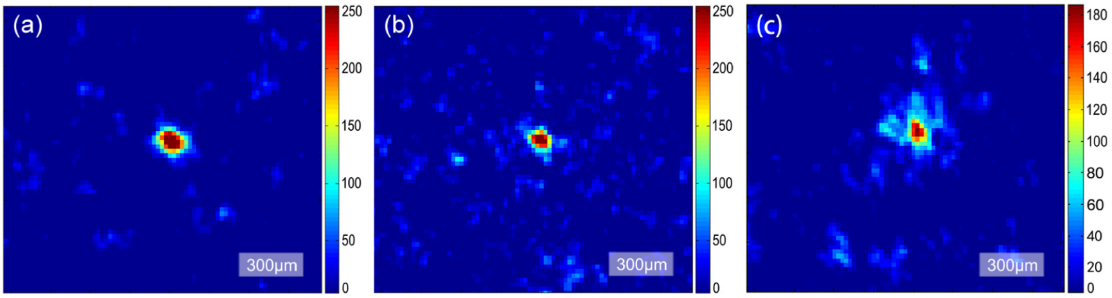

Fig. 3. Focusing 1550 nm light through ZnO samples with the thickness of (a) 102 μm, (b) 190 μm, and (c) 456 μm respectively.

Reflected beam from DMD is narrowed by lens L1 and L2 to a suitable size. The forward-facing 60× objective lens (NA 0.85) is used to focus light on samples, while the back-facing 25× one (NA 0.4) is employed to collect the output intensity speckle image. The scattering samples (S) in our experiment are ground glass diffuser (Edmund, Stock No. #45-635) and ZnO nanoparticles (Aladdin-Z112848) deposited on glass substrates. The ground glass diffuser was used to verify the feasibility of our experiment setup. A CCD camera (HAMAMATSU C14041-10U) monitors speckle pattern and provides feedback to a PC. The PC processes the feedback, and outputs a mask to DMD for next optimization. We use GA to realize a focus through ZnO samples via iteratively modulating the incident wavefront. The size of a pixel on DMD is 7.56 × 7.56 μm^2, and parts of pixels of DMD are grouped into a variable number (N) of square segments, on which the optimized mask is loaded.

3. Experimental results

3.1. Effect of the thickness of ZnO samples on focusing

In our experiments, we prepared a batch of strongly scattering samples, and each of them consists of an opaque layer of ZnO particles. The solution of varnish and ZnO nanoparticles (90 nm) were spin-coated on a glass slip. We controlled the thickness of ZnO samples via adjusting spin speeds. Fig. 2 shows SEM images of a selected ZnO samples. As shown in Fig. 2(a), the white inter-layer in samples is ZnO layer. The thickness of ZnO layer in Fig. 2(a) was measured to be 456 μm by the ruler in SEM image. Fig. 2(b) shows the ZnO particles in samples. The white points in Fig. 2(b) is ZnO particles (90 nm), which are uniform in this samples.

By using the experiment setup described above, we realized focusing of 1550 nm light through ZnO samples with various thickness. Fig. 3 shows the focus effect of different ZnO layers, which all exhibit clear and bright focus. However, with the increase of the thickness of ZnO layer, the focus becomes smaller, and the background becomes worse.

To further investigate the effect of different thickness samples on the focusing of 1550 nm light, we tested a batch of samples. As shown in Fig. 4, the enhancement η, which defined as the ratio of the mean intensity at the focus to the mean intensity of background, decreases with increasing thickness of ZnO layer. The position of focus spot was set in algorithm before each optimization. Light propagate through 27 μm thick ZnO samples, reaching enhancement of about 50, much higher