# Focusing Light through Turbid Media: Methods and Imaging Applications

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Wavefront shaping has proven to be a powerful tool for imaging in strongly scattering media. We present a combined setup which is able to use this technique as well as to perform OCT measurements. Both capabilities are experimentally demonstrated.

## 1 Introduction

Imaging through highly scattering media remains one of the great challenges of modern optics. While propagating through the medium the light's wavefront gets strongly distorted and thus the quality of illumination or imaging of a hidden sample becomes corrupted.

In recent studies optical wavefront shaping has proved to be a powerful tool to overcome this limitation [1, 2]. It uses a liquid-crystal spatial light modulator (SLM) to shape the optical wavefront of a beam incident to a sample e.g. to create an optical focus deep inside of the scattering layer. Typically some sort of feedback-signal to optimize the incident wavefront is needed for this procedure. Optical coherence tomography (OCT) is promising in this respect since OCT provides high-resolution non-destructive backward-mode imaging in scattering media. For OCT applications wavefront shaping methods might be able to significantly increase the system's signal-to-noise ratio or imaging depth since the light distribution deep inside the sample can be shaped.

In this paper we demonstrate an optical setup which is able to focus broadband light through a scattering layer. The same setup can also be used to perform OCT depth scans.

## 2 Experimental Setup

The combined wavefront shaping and OCT setup is presented in figure 1. A supercontinuum source (Fianium FemtoPower1060, NKT Photonics, Denmark) whose spectrum is restricted to the range of 500-550 nm provides broadband light for both applications. The spectral range was chosen such that wavefront shaping, which is bandwidth-limited [3], is still possible with the presented samples while sufficient OCT resolution can be achieved. To shape the wavefront incident at a sample a reflective liquid crystal spatial light modulator (HEO1080P with NIR11 display, Holoeye, Germany) is used. The beam reflected from the SLM is demagnified by a telescope and focused onto the scattering sample.

At the intermediate plane of the telescope a spatial filter is used to individually switch on and off light reflected from single SLM segments [4]: Light diffracted from a segment to which a linear phaseramp is applied will be blocked by the spatial filter. Thus this segment can be considered to be inactive. Accordingly light diffracted from a segment with a flat phase is transmitted through the filter, which makes this segment active.

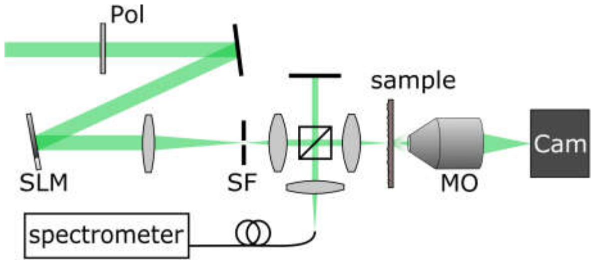

***Fig. 1 Experimental Setup*** *Abbreviations: Pol: polarizer; SLM: spatial light modulator; SF: spatial filter; MO: microscope objective; Cam: camera*

A 10x finite objective with an *NA* of 0.25 (B. Halle Nachfl., Germany) images the light which is transmitted through the sample to a CMOS-camera (DCC1545M, Thorlabs, USA). The camera provides the feedback-signal which is needed for the focusing algorithms used in this work.

For OCT measurements, the wavefront shaping setup was extended to a standard Michelson-type spectral domain OCT setup. The recombined sample and reference beam are coupled in an optical fiber and analysed by a spectrometer (AvaSpec-ULS2048L, Avantes, Netherlands).

## 3 Focusing of Light

To illustrate the wavefront shaping capability of our setup, we demonstrate focusing through a single sheet of lens-cleaning tissue (MC-5, Thorlabs, USA). The optimized wavefront for focusing is determined by using a continuous sequential algorithm [5]. This algorithm iterates the phase of all active SLM segments individually and chooses the phase which results in a maximum intensity at a given target area at the camera.

The intensity distribution at the camera for a plain

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and for an optimized wavefront is illustrated in figure 2. As can be seen from the figure the algorithm is able to create a focal spot from the broadband light whose size is comparable to the observed speckle dimensions.

Furthermore, we demonstrate transmission matrix focusing of the broadband light-source through the scattering layer. The optical transmission matrix of the sample was measured according to Popoff et al. [6]. The light reflected from individual active SLM segments was used as incident modes in this formalism. The light which was not modulated by the device due to its finite diffraction efficiency served as reference field. After acquisition of the transmission matrix, a focal spot was created behind the sample by using digital optical phase-conjugation. The corresponding intensity distribution at the camera is displayed in figure 2e and yields similar results to iterative focusing.

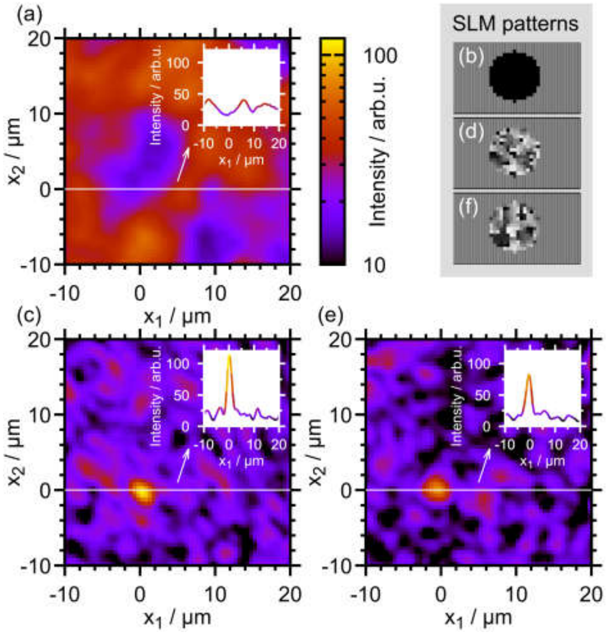

***Fig. 2 Optimized light distribution behind the scattering sample and corresponding SLM patterns*** *(a) Intensity at the camera for an unoptimized wavefront incident at the sample. (b) SLM pattern used for this case. (c) and (d): Camera image and corresponding SLM pattern after the wavefront has been optimized by continuous sequential algorithm. (e) and (f): Camera image and SLM pattern after transmission matrix focusing. The insets present horizontal cross-sections through the camera images. The target for focusing was placed at position (0,0), the imaging plane was located 2 mm behind the sample.*

## 4 OCT A-scan

To prove that our setup is capable of performing OCT measurements, we tested the setup with a sample consisting of a single thin reflective layer (NDUV40A, Thorlabs, USA) which was mounted to a micrometer stage (PT1, Thorlabs, USA). Multiple OCT A-Scans were taken while the sample was displaced in increments of 20 µm along the optical axis. As can be seen from figure 3 the physical displacement can be accurately tracked from the acquired OCT signals.

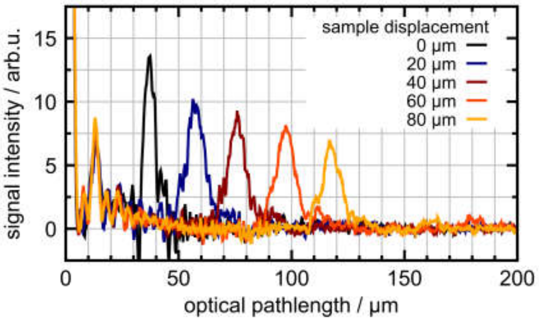

***Fig. 3 OCT A-Scans of a reflective sample*** *Successive depth scans of a reflective sample which was moved in increments of 20 µm with respect to the setup were acquired. The sample's OCT signal shifts accordingly.*

## 5 Discussion

We presented a combined setup which is able to use wavefront shaping and digital optical phase conjugation to focus broadband light through a scattering sample. The same setup is also able to perform OCT depth scans. In later steps the two methods will be combined, e.g., to enhance the OCT imaging depth or signal-to-noise ratio by means of wavefront shaping.

## 6 Acknowledgements

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