Single-Fiber Based Endoscopic Imaging: Methods and Characteristics

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Abstract: Different from imaging an object through a multimode optical fiber (MMF) directly, it is much more challenging to use a single MMF for practical endoscopic imaging in which the light wave has been distorted twice: on the way in for the illumination and on the way out for the detection. In this paper, based on obtaining the optical transmission matrix (TM) of the MMF working in the reflective mode, we demonstrate that, via the measured optical TM, the object can be reconstructed directly from its round-trip distorted output speckle fields. Compared with other single-fiber based endoscopic imaging methods, our method doesn't involve any scanning operation during the imaging process. Such an efficient method might have potential applications for wide-field and ultrathin fiber endoscopic imaging.

Keywords: Single-fiber imaging, Transmission matrix, Endoscopic imaging, Computational imaging.

1. INTRODUCTION

Optical endoscope is a very efficient tool for imaging the interior of the human body in a minimally invasive manner. However, the diameters of typical commercial endoscopes (e.g. fiber bundles and/or GRIN lenses) are a few millimeters [1-3], which may lead to much invasive damage during imaging. To solve this problem, recently, the MMF has drawn interest owing to its advantage of a small cross-section down to tens of microns and the ability of parallel information transporting because of thousands of independent spatial propagation modes [4]. However, due to the mode coupling and dispersion in the fiber, the MMF cannot be used for imaging directly. To solve this problem, some computational imaging strategies have ever been proposed. Such as the wavefront shaping [5-9] and the optical transmission matrix (TM) [10-13]. Unfortunately, the wavefront shaping method involves a complete point-scanning process, which will be very time-consuming to the real-time imaging. Relatively speaking, the TM method has an inherent superiority for its ability of wide-field imaging. Once the relationship between the input wave and the output wave of the MMF is characterized by the TM in advance, the information of the object can then be reconstructed directly from its distorted output wave.

Nevertheless, the TM method has only be studied to overcome the one-way distortion for the transmission imaging, but not for the endoscopic imaging where the illumination light wave has also been seriously distorted. In order to overcome the input distortion simultaneously, some extra technologies are usually adopted to work together with the TM scheme. For example, the speckle imaging technology has ever been widely adopted for this purpose, but this technology involves an average process of large numbers of speckle images [12,14]. It will inevitably make the experiment procedure complicated and unstable.

In this paper, in order to achieve the endoscopic imaging using a single MMF directly, we propose and establish a round-trip imaging scheme based on measuring the round-trip TM of the system. This round-trip TM can overcome the on-the-way-out distortion and eliminate the influence of the on-the-way-in distortion simultaneously. The experiment procedure to acquire the TM of the system is introduced and the object recovering results from the distorted output speckle fields with this TM are also demonstrated.

2. IMAGING METHOD AND EXPERIMENT

To demonstrate that the round-trip TM can reconstruct the object $O(\xi,\eta)$ through the MMF directly from its round-trip distorted output speckle field $E(x,y)$, we built an experimental setup as shown in Figure **1**, where a He–Ne laser with a wavelength of 632.8 nm is

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expanded and split into two beams by a beam splitter (BS). The reflected beam by BS is modulated by the spatial light modulator (SLM) to produce the reference wave, while the transmitted beam through BS experiences the distortion via the MMF and illuminates the digital micromirror device (DMD) on the way in; then, the reflected wave by DMD is distorted again by the MMF on the way out to produce the output wave. Finally, the interference image of these two waves is recorded by a CMOS camera.

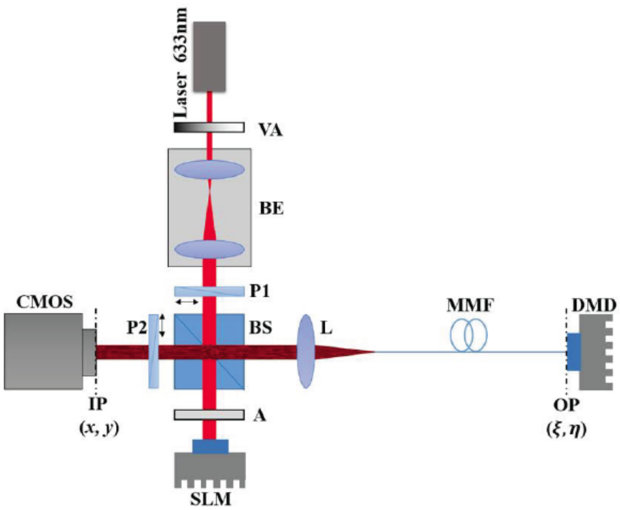

Figure 1: Experimental setup. VA: variable attenuator; A: attenuator; BE: beam expander; P1, P2: linear polarizer; BS: beam splitter; L: lens; MMF: multimode optical fiber (polymer optical fiber with a numeric aperture (NA) of 0.5, the fiber core diameter of 980 μm and the fiber length of 0.5 m); DMD: digital micromirror devices (ViALUX, V-7001VIS, the pixel size is 13.68 μm×13.68 μm); SLM: spatial light modulator (Meadowlark Optics, P1920-0635-HDMI); CMOS: CMOS camera (Hamamatsu, C13440-20CU, the central 256×256 pixels are used for imaging); OP: object plane; IP: image plane.

To measure the round-trip TM $T(x,y;\xi,\eta)$, we select the central 8×8 pixels of the DMD for imaging. We turn on only one pixel of the DMD in sequence (as shown in Figure **2a**) and change the phase of the reference wave by the SLM, the output wave is measured by using the phase-shifting digital holography technology [15]. The typical elements of $T(x,y;\xi,\eta)$ are shown in Figure **2b** and **c** for the amplitude part and the phase part, respectively. Obviously, both the amplitude and the phase are strongly speckled. It should be pointed out that the measured $T(x,y;\xi,\eta)$ actually has the ability to eliminate the influence of the round-trip distortion, this is owing to the fact that the distorted illumination optical field has already been additionally recorded in this round-trip TM.

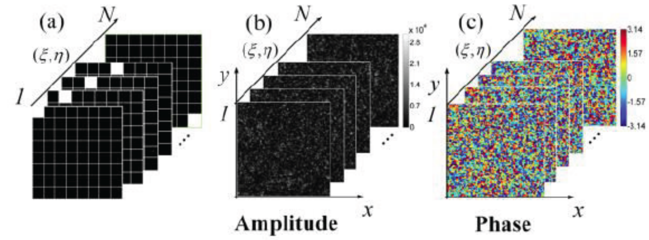

Figure 2: Typical measured TM elements of the MMF. (**a**) the input channels of DMD are switched on in sequence; (**b**) the amplitude and (**c**) the corresponding phase of the TM, respectively.

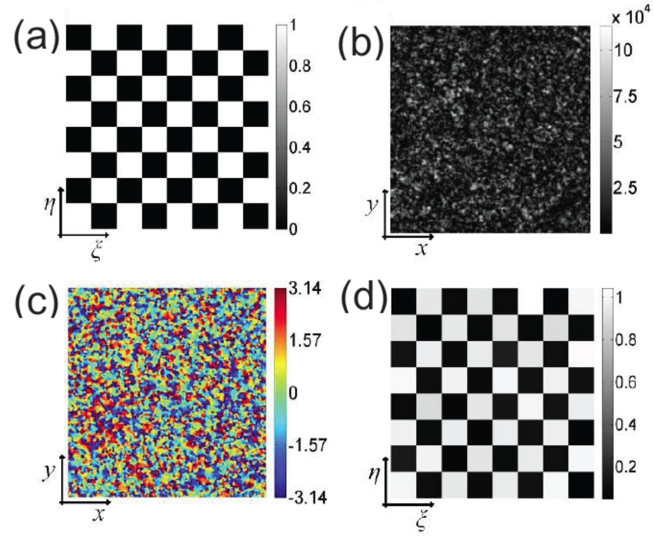

Figure 3: Reconstruction of the object image. (a) a binary amplitude object $O(\xi,\eta)$; (b) the amplitude and (c) the phase of the output speckle optical field $E(x,y)$, respectively; (d) the reconstructed the object image $O_r(\xi,\eta)$.

After the optical system is calibrated, we can reconstruct the target image directly from its distorted output speckle fields, using the TM that calibrated previously. To verify the imaging strategy, we construct a binary amplitude object (Figure **3a**) using the DMD and acquire its output complex optical field, whose amplitude part and phase part are shown in Figure **3b** and **3c**, respectively. The result indicates that due to the random modulation from the MMF, the output optical field has already been seriously distorted. At last, using the calibrated TM $T(x,y;\xi,\eta)$, the target object $O(\xi,\eta)$ can be recovered directly from its distorted output speckle field $E(x,y)$ by using the phase conjugation operation [16]:

$$O_r(\xi,\eta) = \left| \frac{\sum_{x,y} T^*(x,y;\xi,\eta) * E(x,y)}{\sum_{x,y} T(x,y;\xi,\eta) * T^*(x,y;\xi,\eta)} \right|. \quad (1)$$

Here $T^*(x,y;\xi,\eta)$ is the complex conjugation of the transmission matrix $T(x,y;\xi,\eta)$. The recovered result is shown in Figure **3d**, which indicates that our imaging strategy is indeed efficient.

CONCLUSIONS

In conclusion, we propose a novel MMF-based wide-field endoscopic imaging method to avoid scanning and reduce image acquisition time during the process of image capture. The advantage of this method is that the two distortions of the optical field (on-the-way-in and on-the-way-out distortions) can be eliminated simultaneously when reconstructing the object. Experimental results demonstrate that, via the measured optical TM of the optical system including the MMF, the image of the object can be reconstructed directly from its output speckle field. Such an efficient method might have potential applications for wide-field and ultrathin fiber endoscopic imaging.

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