Focusing Images through Large-Core Multimode Fibers and a Multimode Fiber Endoscope

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Abstract: In a referenceless imaging setup with coherent light control based on a transmission matrix approach, an endoscope, composed of multimode fibers, is implemented in order to set focus at specific targets and enable structured illumination. © 2020 The Author(s)

The cylindrical symmetry of optical fibers and their small dimensions make them a convenient tool for *in vivo* imaging of biological samples. Their application as endoscopes has been explored in past years and brought about promising results not only in expanding imaging depths in tissues, but also in enhancing image resolution. However, experiments with single mode fibers suffer from a severe limitation because high resolution is only achieved when a large number of fibers is used [1]. In addressing this issue, multimode waveguides have attracted interest due to their multiple modal channels and the possibility to manipulate each one of them independently [2]: by properly shaping their wavefront, they can overcome the resolution of microscope objectives and generate sharp focusing spots, even in the visible range. Large-core multimode fibers (MMFs) [3] and bundles can play an important role in expanding the focus reach and push the resolution limits even further, because the large number of modes they support even more degrees of freedom for wavefront shaping. Thus, by exploiting their applications, non-invasive and *in vivo* imaging measurements with high resolution will become a reality.

Furthermore, imaging with a conventional rod lens endoscope can result in bright central regions, whereas the periphery of the image is quite darker. The uneven intensity causes deficiency in the resolution of these dark regions. A usual solution for this issue consists on increasing light intensity, which, in turn, can cause degradations in the resulting image, such as saturation of the charge-coupled device (CCD), contrast loss, and undesirable reflections from the imaged surface [4].

Different methods have been developed to manipulate wavefronts in order to achieve focus either in a dispersive medium or in a multimode waveguide [5, 6]. Most employed techniques rely on interferometric setups and holograms, whose experimental complexity and strict stability requirements impose practical challenging problems. Alternatively, a formulation based on convex optimization is capable of determining the transmission matrix (TM) of the endoscope system without the need of a reference signal by monitoring only the output intensity profile (no phase information is necessary) [7]. The simplicity of such experimental setup also eliminates calculations in digital phase conjugation methods [8].

In this paper we propose and experimentally demonstrate the use of a MMF bundle for controlled focusing at target locations. Besides focusing, the controlled excitation can be further used to addressing the issue of uneven image brightness by providing a straightforward technique for structured illumination. By employing a simple and robust setup, the system can be readily applied as a non-invasive endoscope for *in vivo* biological imaging.

In this technique, illustrated in Fig. 1a, a 633 nm laser beam is expanded and phase-modulated at a Holoeye Pluto-VIS spatial light modulator (SLM) with several random trial patterns. The modulated beam excites a 61.5 μm MMF and the output is captured by a 3.5 μm pitch CCD through an imaging objective. Then, a quadratic optimization is performed to find the phase pattern that generates a focused beam at a target location at the fiber output. By performing the calculation for every position at the output, the full TM of the system can be derived. Hence, we show that not only is advantageous to use large-core MMF for imaging purposes, but also that the increase in the number of degrees of freedom directly impacts the achievable imaging resolution.

By using the aforementioned convex optimization method, it is possible to choose focal points at the end of the fiber and, therefore, compensate for mode coupling and dispersion that are intrinsic to large waveguides. The convex problem approach employs reduced matrices instead of full-size images, for both the input field and output pattern, i.e, each element in those matrices corresponds to a region of the SLM and the CCD pixel matrices. Seven matrix dimensions were tested for the imaging experiments with the MMF, with element sizes ranging from 12.25 μm to 4.90 μm, which correspond to matrices with dimensions from 4×4 to 10×10.

The ability to focus the output speckle pattern of the fiber in different positions was evaluated according to the optical contrast of the focus [9]. A contrast value close to unit indicates a speckle with a uniform intensity distribution, whereas higher values correspond to cleaner focus targets. Focal spots were successfully generated, independently of the initial output intensity distribution, as shown in the examples in Fig. 1. Images in Figs. 1b

and 1e exhibit different initial patterns at the output of the fiber, with a 10×10 matrices. Targets, at positions $(4, 7)$ and $(5, 6)$ (resp. Figs. 1d and 1g), were set for each of these measurements and the experimental results, after the optimization, are shown in Figs. 1c and 1f, showing successful focus control. The highest optical contrast is approximately 2.60 and it corresponds to an element size of $8.50\,\mu m$, while the respective maximum energy concentration improvement is 12.5 times over the initial pattern. Experiments also showed that the focus can reach any point within approximately $16\,\mu m$ radius.
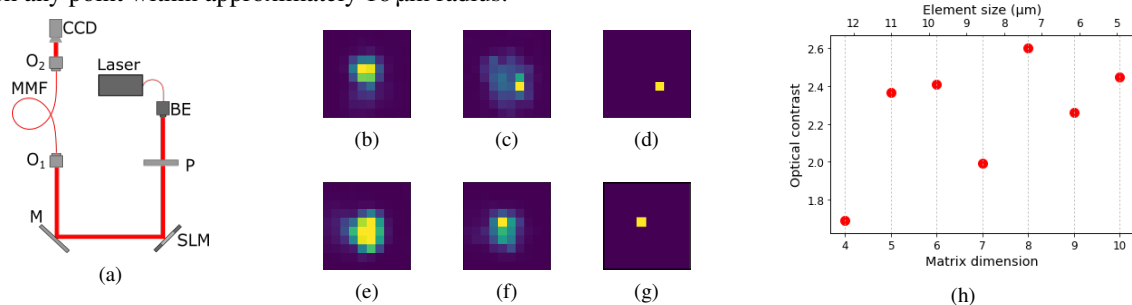

Fig. 1: Focus control in a single large-core MMF. (a) Experimental setup: BE stands for beam expander, P for polarization controller, M for mirror, and O for $5\times$ objective lenses. (b, e) Initial illumination patterns. (c, f) Controlled focus at target locations. (d, g) Focus targets. (h) Optical contrast for different matrix dimensions.

The average optical contrast of, at least, five repetitions of imaging measurements with different resolutions are presented in Fig. 1h. It is possible to observe that the imaging confinement improves with resolution;the highest value we observed was with an 8×8 matrix. We note that low resolutions, *e.g.* 4×4, result in poor enhancements. However, the optimization for higher resolutions, *e.g.* 10×10, takes a longer time due to the increased problem dimension. This makes the experiment more prone to instabilities which might impair the overall focus optimization. Thus, a balance between optical contrast and resolution can be found in order to optimize focus enhancement.

Once the technique was characterised for a single MMF, we replaced it by a MMF bundle with approximately 130 fibers gathered in a rigid 15 cm-long tube, which gives mechanical stability for the setup, besides being a robust instrument when it comes to imaging biological samples. Despite the enormous increase in number of supported modes, Focus optimization was successfully achieved, as shown in Fig. 2. The optical contrast obtained was up to 1.38 and, as proposed, it is possible to tune the endoscope and excite single targets in the structure, which configures a feasible solution to brighten specific dark regions of the sample to be imaged.
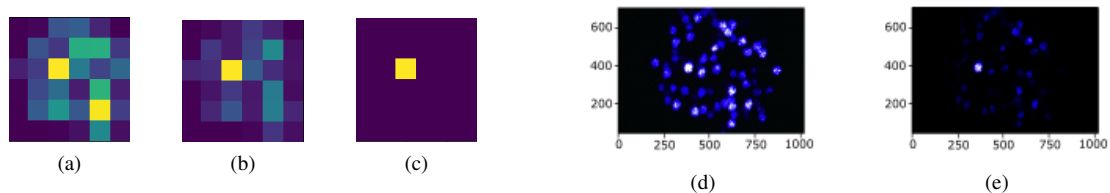

Fig. 2: Focus control in a MMF bundle: the initial pattern of the fiber endoscope (a) is optimized to provide focusing (b) at a target location (c). The full-resolution images from the CCD of the initial pattern (d) and the focused spot (e) clearly show the success of the technique for the large number of modes supported by the bundle.

Thus, the proposed endoscope represents a preferable imaging device to samples in turbid media, which is the case for most biological applications that care for minimum invasive methods. Moreover, because focus can be optimized regardless of the waveguide length, the fiber bundle can be as long as required by the application, allowing the endoscope to perform imaging deep into the sample. *In vivo* measurements can also become a reality due to the simple referenceless technique to obtain the transmission matrix of the proposed multimode fiber endoscope.

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