Imaging through specialty optical fibers

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ABSTRACT

Transmission matrix measurements relating the electric field at the ends of standard step-index and graded-index multimode fibers promise to enable next generation miniaturized endoscopes. Relatively few measurements of specialty fibers and components have been demonstrated. Here, we present transmission matrix measurements and distal control through a variety of specialty fibers, including fibers for harsh environments, a polarization maintaining fiber, coreless fibers, a rectangular core fiber, multicore fibers, and a pump signal combiner. The calibration of these fibers and structures enables their dual-use for imaging and their original design application and allows control of the spatial profile of the light used in sensing, power delivery, and amplification.

Keywords: Transmission Matrices, Multimode Fibers, Imaging

1. INTRODUCTION

The output electric field from a multimode fiber (MMF) is typically a speckle pattern comprised of a complex superposition of the many modes supported by the fiber. The transmission matrix (TM) has proven to be a powerful tool for quantifying the propagation of the light through the fiber.[1–6] Once the TM is known, it can be used to determine the specific input field required to produce a desired output field.

Most of the published TM measurements and subsequent distal control have been demonstrated in standard step index and graded index MMFs. Here, we demonstrate distal control through a variety of OFS specialty optical fibers, showing the general applicability of these techniques and paving the way to integrate imaging into the original design application space of these fibers. We highlight results from harsh environment fibers, a polarization maintaining (PM) fiber, coreless fibers, a rectangular core fiber, multicore fibers, and a pump-signal combiner using a tapered fiber bundle.

2. EXPERIMENT

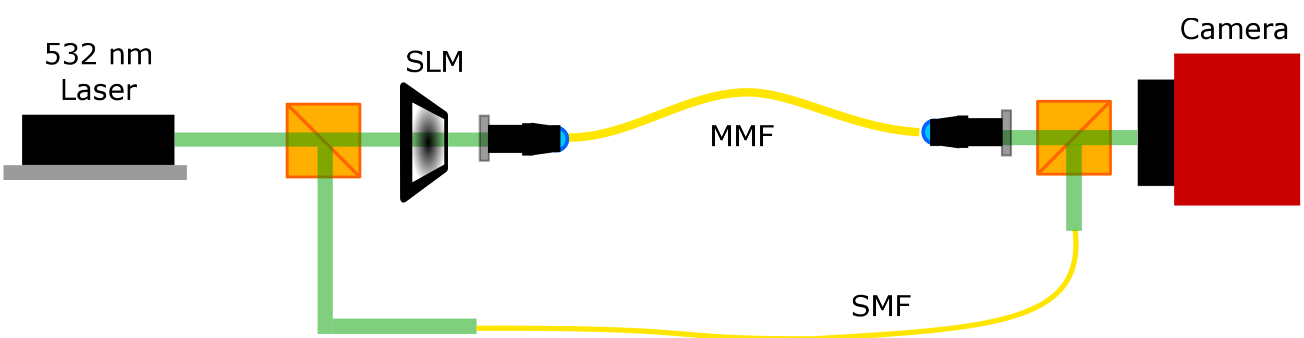

Figure 1. Schematic of experimental set-up for conducting scalar transmission matrix measurements using a spatial light modulator and phase-shifting interferometry for the electric field measurements. SLM: spatial light modulator; MMF: multimode fiber; SMF: single mode fiber.

Our experimental set-up is depicted in Figure 1. A 532 nm laser (CrystaLaser CL532-100-S) is used in conjunction with a spatial light modulator (SLM; Meadowlark Optics HSP1920-532) to measure the transmission

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matrix. A series of linear phase gratings is displayed on the SLM to produce a scanned spot at the input facet of the fiber, which is placed in a Fourier plane of the SLM. Similar quality data are achieved when using the same linear phase gratings to produce angled plane waves by placing the fiber input facet at the image plane of the SLM. The phase of the speckle pattern produced by each input spot is measured using phase-shifting interferometry with a static reference beam derived from the same laser.[3] Once measured, the TM is constructed and used to calculate the complex superposition of the input gratings needed to produce a desired distal pattern. The gratings are multiplexed using the technique presented by Davis and coworkers,[7] or one based on constructive and destructive interference of neighboring regions of the SLM.[8] A Gerchberg-Saxton algorithm[4] is sometimes used to improve the signal-to-noise ratio of the extended (non-spot) distal images.

A variety of specialty fibers and structures are tested in this experimental set-up. The transmission matrix of each is measured and a variety of goal images, consisting of both distal spots and extended images, are produced. Results for a variety of the fibers tested will be shown in the next section. Multiple distal images and focused spots are shown for each fiber to illustrate success over a variety of goal images and spot locations.

3. RESULTS

3.1 Harsh Environment Fiber

OFS TCU-ME050H is a 50 μm graded-index MMF with a pure-silica core and a specialty coating designed for application in harsh environments, such as those with high temperature and hydrogen concentration. The successful TM characterization of this fiber and subsequent distal control allows for imaging to be implemented in areas where such a fiber is deployed. Figure 2 shows illustrative distal goal images and spots created through this fiber.

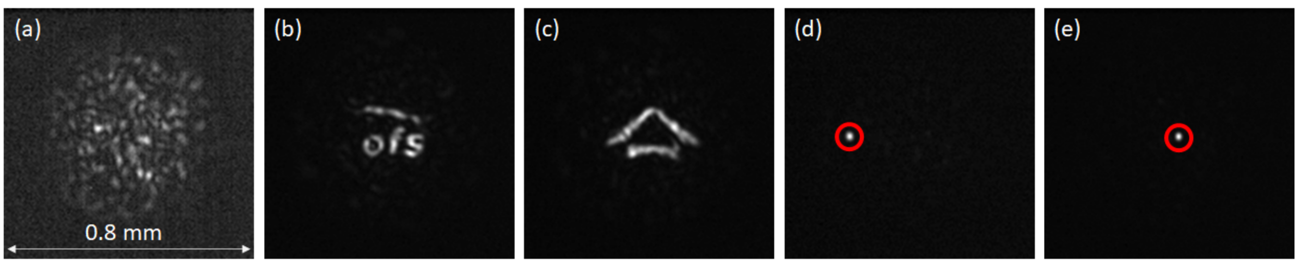

Figure 2. (a-e) Goal images produced at the distal end of OFS TCU-ME050H fiber calibrated with 45x45 spots. Images show the fiber core at approximately 13x magnification. Panel(a) shows the distal result when all launch conditions are multiplexed together with constant amplitude to indicate the core size and location within the image frames.

3.2 Pedestal Fibers

The TM is successfully measured in higher-order mode pedestal fibers, including one that is polarization-maintaining[9,10] at 1 μm wavelengths. The use of PM MMFs in imaging may provide a simplification of the distal optics as the two linear polarizations will not need to be separated prior to calibration and use of the fiber as an imaging waveguide.

Figure 3 shows a variety of goal images achieved in standard and PM versions of this pedestal fiber of approximately 1 m lengths. The quality of the goal images is comparable between the two, indicating that the presence of the panda-style stress rods does not negatively impact the calibration of the PM MMF.

3.3 Coreless Fibers

We have measured the TM of a variety of coreless fibers, which can serve as power delivery fibers in medical and machining applications. We investigate 125 μm and 200 μm hard-clad silica (HCS®) fibers and show that even sparse sampling of the TM allows for high quality distal spot formation, indicating that calibration times and data set sizes may not need to be dramatically increased to integrate imaging into these larger fibers.

Goal images for the two 1 m length HCS® fibers are shown in Figure 4. The fiber with the 125 μm diameter (panels (a-e)) supports over 30,000 modes at the 532 nm wavelength used in these experiments. We measure

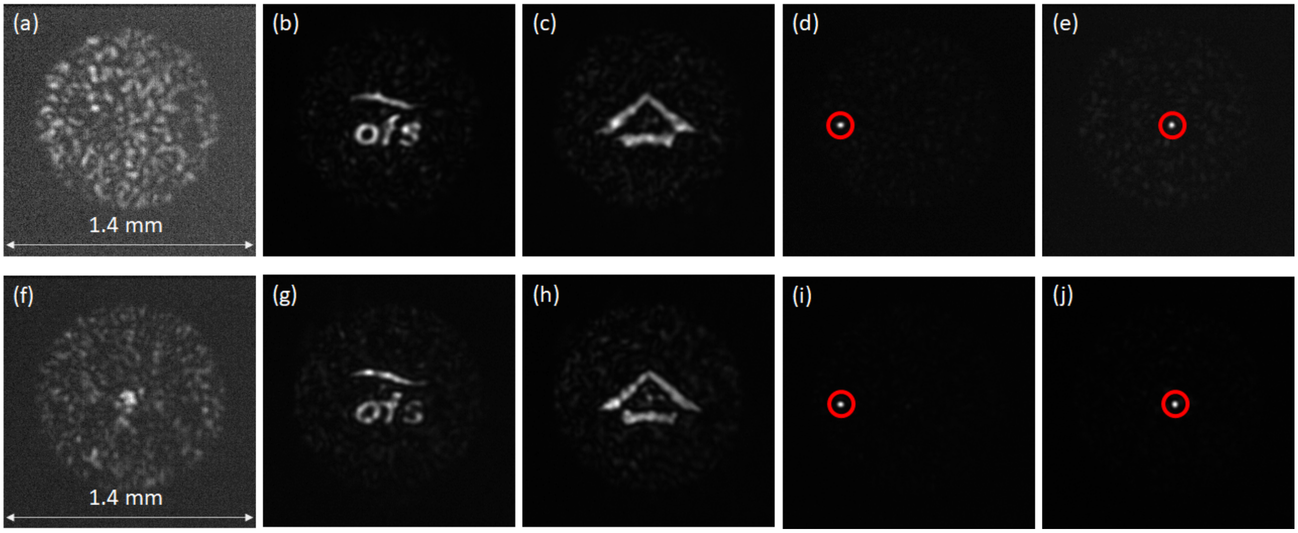

Figure 3. (a-e) Goal images produced at the distal end of around 1 m of higher-order mode pedestal fiber with a 70 µm core diameter from a TM calibrated with 45x45 spots. Images show the fiber core at approximately 13x magnification. Panel(a) shows the distal result when all launch conditions are multiplexed together with constant amplitude to indicate the core size and location within the image frames. (f-j) Goal images produced at the distal end of polarization-maintaining higher-order mode pedestal fiber from a TM calibrated with 45x45 spots. Images show the fiber core at approximately 13x magnification. Panel(f) shows the distal result when all launch conditions are multiplexed together with constant amplitude to indicate the core size and location within the image frames.

the TM using a grid of 45x45 scanned spots, so we are undersampling the TM by over a factor of 15 (number of fiber modes per basis function). Despite this undersampling, we are able to produce extended images with high fidelity (panels (b) and (c)) and focused spots with excellent SNR (panels (d) and (e)). In the 200 µm fiber, over 80,000 modes are supported. We measure the TM with an expanded 55x55 grid of scanned spots, which results in an undersampling of over 26. In the results for this fiber, the extended images show some degradation, but the focused spots still remain with high SNR. The quality of the images can be improved by further increasing the number of launch conditions used to measure the TM (data not shown).

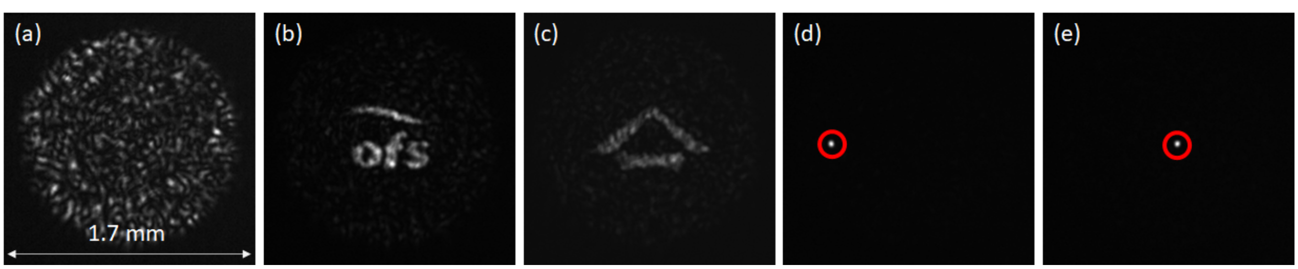

Figure 4. (a-e) Goal images produced at the distal end of 1 m of 125 µm HCS® from a TM calibrated with 45x45 spots. Images show the fiber core at approximately 13x magnification. Panel(a) shows the distal result when all launch conditions are multiplexed together with constant amplitude to indicate the core size and location within the image frames.

3.4 Rectangular Core Fiber

We also characterize the undersampled TM of 1 m of an OFS rectangular core fiber with dimensions 43.5 x 96.7 µm, showing that the same measurement technique is applicable to non-circular geometries. In certain situations, this would allow the geometry of the fiber to better match the region of interest. Results are shown in Figure 5.

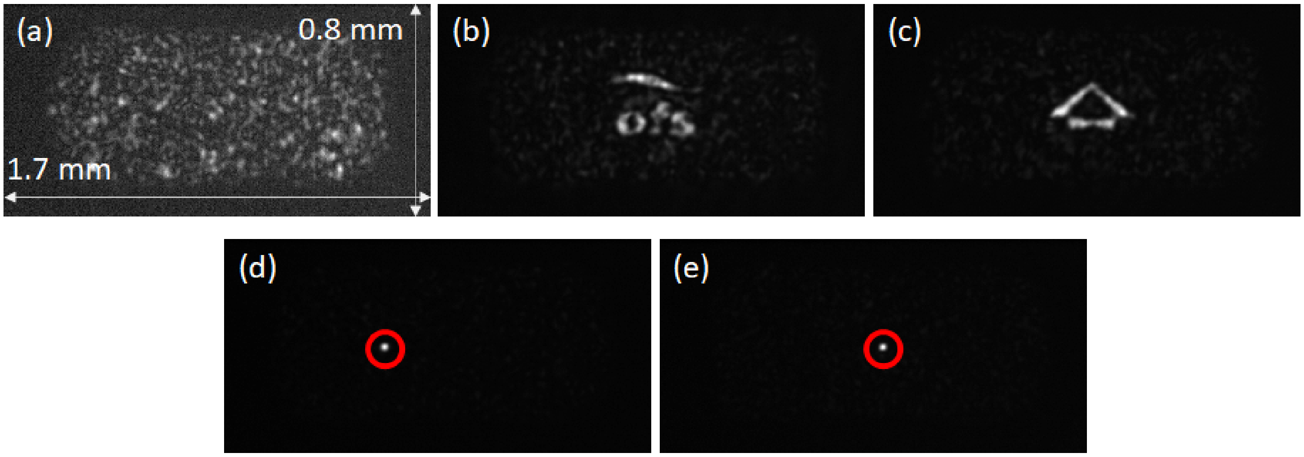

Figure 5. (a-e) Goal images produced at the distal end of rectangular fiber calibrated with 45x45 spots. Images show the fiber core at approximately 13x magnification. Panel(a) shows the distal result when all launch conditions are multiplexed together with constant amplitude to indicate the core size and location within the image frames.

3.5 Multicore Fibers

We measure the TM of cores within two different OFS multicore fibers. The first (Fig. 6(a-c)) contains two 50 µm cores, and the second (Fig. 6(d-f)) contains three 50 µm cores and one core that is single mode at the 1550 nm design wavelength. Figure 6 shows a few example distal goal images from these fibers on a log scale to highlight the presence of the additional cores, which are not visible on a linear scale. The TM of different cores can be measured and controlled separately (data not shown), allowing for spatially distinct information channels in the same fiber.

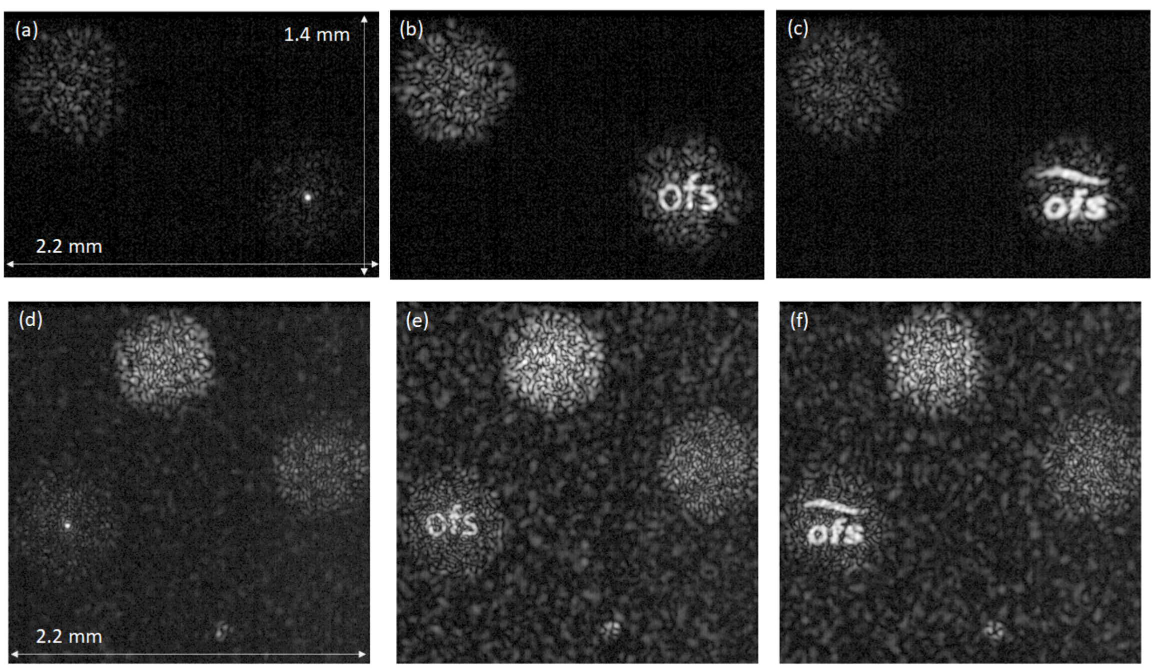

Figure 6. (a-f) Goal images produced at the distal end of 1 m lengths of multicore fibers calibrated with 35x35 plane waves. Images show the fiber core at approximately 13x magnification. Images plotted on a log scale to highlight the presence of the non-calibrated cores.

3.6 Pump-Signal Combiner

There have been a few demonstrations of TM measurements of gain fibers,[11,12] which are used to control the performance of fiber amplifiers and lasers. However, these results still rely on bulk-optical coupling to the gain fiber. We measure the transmission matrix of a pump signal combiner consisting of a tapered fiber bundle, which would allow TM control of a more fiber-integrated amplifier or laser. Calibration light is launched into a random lead fiber (110/125 μm), and the distal images are created at the output fiber (220/240 μm). Calibrations are also performed operating in the reverse direction. In addition to its use in fiber amplifiers and lasers, this shows that TM measurements can be successfully performed through tapered fiber structures. Data from this device will be highlighted in a future publication.

4. CONCLUSION

We have successfully measured the transmission matrix of a variety of specialty OFS fibers. This demonstrates that the measurement technique, and the distal control it enables, is widely applicable across different fibers and structures. This will enable imaging to be integrated within the broad application space of these fibers.

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