Improved Spot Formation through Flexible Multimode Fiber Using a Partial Reflector

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Abstract: A drawback of multimode fiber (MMF) endoscopes is that imaging quality degrades substantially as the MMF is perturbed. We describe a method for improving the formation of a spot of light at the distal end of a perturbed MMF by attaching a partial reflector to the distal end of the MMF. The perturbation of the light reflected from the partial reflector is highly correlated with the perturbation of the light transmitted through the MMF, and exploiting this correlation enables formation of spots at the distal MMF end with higher power confinement.
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1. Introduction

Single-fiber endoscopes are a new type of rigid endoscope that use only a single optical fiber to transmit images and offer a better trade-off between diameter and spatial resolution than existing commercial fiber bundle endoscopes. Various methods for imaging through a flexible single fiber endoscope have been proposed, such as imaging through a graded-index MMF by using multi-photon excitation endoscopy [1]; imaging through a single mode fiber by encoding spatial information in different wavelengths [2]; imaging through a flexible multicore fiber by encoding image information in the different cores of a MCF [3]; and compensation for mode coupling in MMF using a perturbation-invariant basis [4]. In this paper, we experimentally demonstrate a method first described in [5] for measuring mode mixing in a flexible MMF by placing a structured partial reflector on the distal end of the MMF, which makes it possible to measure mode mixing without observing the distal end, allowing more accurate imaging.

2. Experimental apparatus

The linearly-polarized (LP) mode coefficients of light entering a MMF at the proximal facet ($\mathbf{m}_{in,p}$), exiting at the distal facet ($\mathbf{m}_{out,d}$), and reflecting from a partial reflector back to the proximal facet ($\mathbf{m}_{out,p}$), are given by:

$$\begin{aligned} \mathbf{m}_{out,d} &= \mathbf{TCm}_{in,p} & \mathbf{m}'_{out,d} &= \mathbf{P_t TCm}_{in,p} \\ \mathbf{m}_{out,p} &= \mathbf{ROm}_{out,d} & \mathbf{m}'_{out,p} &= \mathbf{P_r ROm}'_{out,d} \end{aligned} \tag{1}$$

where $\mathbf{m}$ and $\mathbf{m}'$ are vectors of the mode coefficients before and after perturbation of the MMF, $\mathbf{T}$ and $\mathbf{R}$ describe mixing of the modes due to travel of light forward and backwards through the MMF, $\mathbf{C}$ describes mode coupling into the MMF, $\mathbf{O}$ describes mode coupling back into the MMF (due to the partial reflector), and $\mathbf{P}_\mathrm{t}$ and $\mathbf{P}_\mathrm{r}$ are perturbation matrices. These quantities were measured for various perturbation strengths (0 to 5 cm) using the setup in Fig. 1, and $\mathbf{P}_\mathrm{r}$ was used to compensate for $\mathbf{P}_\mathrm{t}$ to experimentally create grids of spots at the distal end of MMF2.

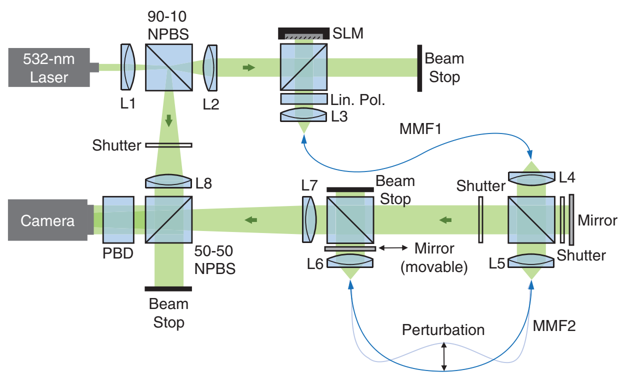

Fig. 1. Experimental setup for forming spots through a perturbed MMF (MMF2). Laser (200 mW, 532-nm), phase-only nematic liquid crystal-on-silicon reflective SLM (Meadowlark HSP256-0532), MMF1 and MMF2 (Thorlabs, 1 m long, 25 µm core diameter, 0.1 NA), 99% reflectivity silver reflector (approximating a partial reflector), camera (QImaging Retiga 4000R), polarizing beam displacer (2.7 mm displacement).

3. Results

We experimentally found that bending the MMF results in perturbation matrices $\mathbf{P}_t$ and $\mathbf{P}_r$ that are strongly diagonal, their transposes are correlated as predicted by reciprocity, and most perturbation occurs in the lower-order modes while higher-order modes are unaffected, a more optimistic result than the worst case predicted in [5] (Fig. 2.a). Using $\mathbf{P}_r$ to compensate for $\mathbf{P}_t$ thus results in the same or substantially better spots, depending on the perturbation strength (Fig. 2.b). For example, for one specific perturbation strength (Fig. 2.c), when averaged across all spots, perturbation compensation results in 30% more power contained inside the spot as compared to no compensation.

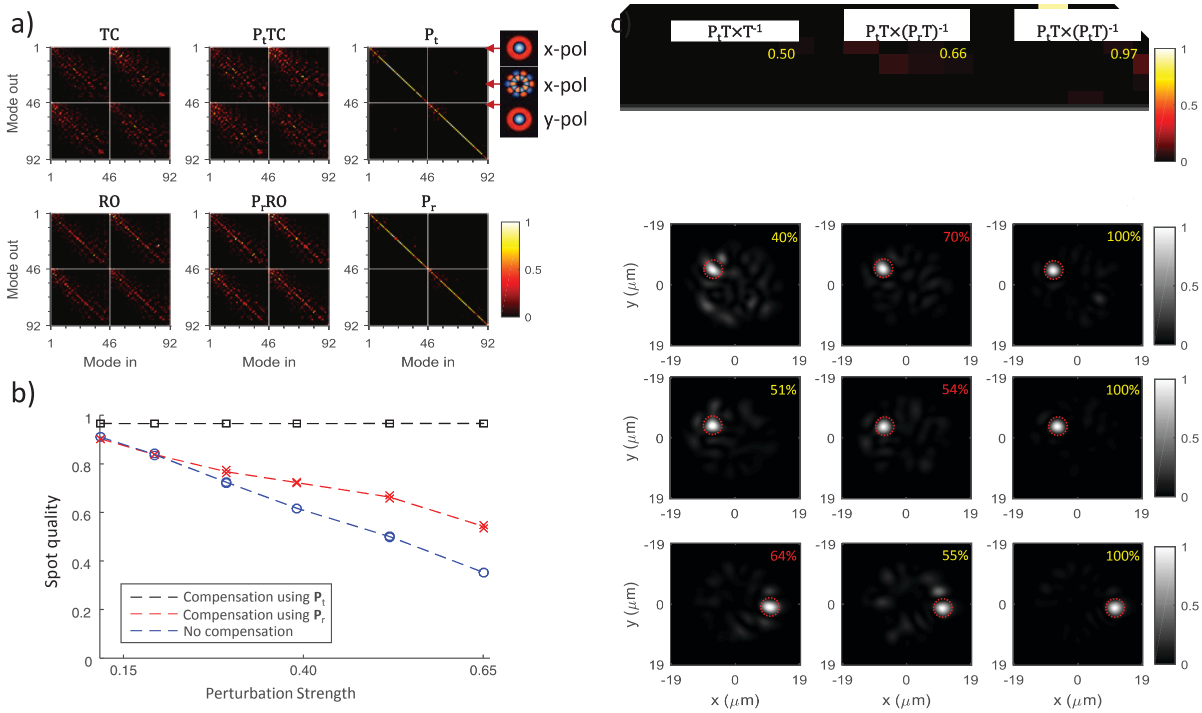

Fig. 2. a) Matrices corresponding to eq. (1) for one perturbation strength. Matrix entries correspond to power. b) Quality of spot formation vs. the perturbation strength. Each plot includes two points per perturbation corresponding to exciting spots in the x- and y-polarizations. Spot quality is parameterized by the percent of power (of the theoretical maximum) contained in a spot. Perturbation strength is parameterized by the one minus the correlation coefficient between $\mathbf{P}_t$ and the identity matrix. Note that compensation using $\mathbf{P}_t$ would only be achievable by observing the distal end of the MMF. c) Representative spots formed for one specific perturbation strength. Different columns correspond to no compensation, compensation using $\mathbf{P}_r$, and compensation using $\mathbf{P}_t$. The correlation coefficient between each matrix and the identity matrix and the amount of power contained in the spot (relative to perfect compensation) are indicated. Row 1 shows a spot that is substantially better with compensation, row 2 shows a spot that is about the same with or without compensation, and row 3 shows a spot that is better without compensation.

Though this method doesn't allow perfect compensation since spot quality still decreases, the results suggest that more advanced algorithms might be able to achieve this; for example, a method that measures **T** and **R** for a large number of perturbations and then interpolates for $\mathbf{P}_t$ by measuring $\mathbf{P}_r$, instead of assuming that the two are the same, which should lead to close to perfect compensation. Perturbation compensation should also work as well for a MMF with higher number of modes N, as it is likely possible to substantially increase the NA of the MMF and thus N without affecting the strength of mode coupling [6].

To summarize, we have experimentally verified a method to obtain information about the transmission matrix through a perturbed step-index MMF using only a partial reflector attached to the distal end of the MMF, allowing measurements of the matrix without observing the distal end of the MMF. This allows spots to be created with higher quality and hence better imaging through a MMF compared to methods that assume no change in the MMF.

4. References

[1] S. Rosen et al., "Focusing and scanning through flexible multimode fibers without access to the distal end," arXiv:1506.08586 (2015).
[2] S. M. Kolenderska et al., "Scanning-free imaging through a single fiber by random spatio-spectral encoding," Opt. Lett. **40**, 534–537 (2015).
[3] S. C. Warren et al., "Adaptive multiphoton endomicroscopy through a dynamically deformed multicore optical fiber using proximal detection," Opt. Express **24**, 21474–21484 (2016).
[4] M. Plöschner, T. Tyc, and T. Čižmár, "Seeing through chaos in multimode fibres," Nat. Photonics **9**, 529–535 (2015).
[5] R. Y. Gu, R. N. Mahalati, and J. M. Kahn, "Design of flexible multi-mode fiber endoscope," Opt. Express **23**, 26905–26918 (2015).
[6] D. Loterie, D. Psaltis, and C. Moser, "Bend translation in multimode fiber imaging," Opt. Express **25**, 6263-6273 (2017).