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Towards Multimode-fiber-based Two-photon Endoscopy

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Multimode fibers (MMFs) show great promise in imaging applications where space is limited, due to their small diameter, yet high NA [1,2]. One such application is endoscopy, where a multimode fiber can be used as a thin and flexible probe. Unfortunately, the perturbation sensitive mode mixing in a multimode fiber makes it difficult to reconstruct an image that is transmitted through the fiber [3]. Methods to overcome this difficulty, such as spatial wavefront shaping, still need re-optimalization after significant fiber perturbations. Such methods are also usually based on linear imaging. However, nonlinear imaging can provide increased resolution, reduced background and the ability for 3D imaging [4]. Combining ultrashort pulses with MMFs is challenging because of the complex spatiotemporal response of an MMF. So far, only methods based on spatial domain wavefront shaping have been used to selectively focus an ultrashort pulse through an MMF [5], which are still perturbation-sensitive.

Here, we pave the way towards a new MMF-based nonlinear imaging method based on time-domain wavefront shaping [6]. By shaping an ultrashort pulse in *time*, we can control the position of a temporally focussed beam in *space* on the output face of an MMF. By shaping only in time, the influence of spatial perturbations of the single-mode channel leading up to the piece of MMF can be avoided. In principle, our method allows grid scanning of an ultrashort pulse at the output of an MMF.

We demonstrate this by imaging the output face of a square-core MMF with a nonlinear method based on two-photon fluorescence. A position on the facet is selected, after which our time-domain wavefront shaping optimizes the nonlinear signal there by shaping the input pulse in time with a pulse shaper. Fig. 1 shows the result of the time-domain wavefront procedure at 25 different locations. If the MMF is short and kept rigid, the optimizations for each location can be saved and re-used later for a grid scan. The input pulse is delivered to the MMF through a single spatial mode, which is insensitive to perturbations.

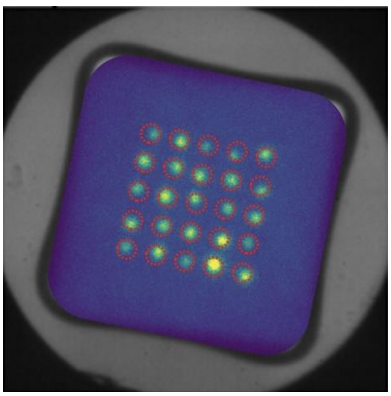

Fig. 1 Composite image of a grid of 25 different wavefront shaping results, overlaid on the square core fiber geometry. The red circles indicate the optimization region for each point. The core measures ~ 70 μm × 70 μm.

In summary, we have shown a new nonlinear imaging method based on multimode fibers, where the shaped pulse is delivered through a single mode channel which is insensitive to perturbations. This paves the way towards two-photon endoscopy.

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