# Imaging Applications of Time-Domain Wavefront Shaping

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**Abstract:** We demonstrate grid scanning of an ultrashort pulse at the output of a multi-mode fiber by temporally shaping the input pulse in a single spatial mode. Our method has applications in nonlinear endoscopic imaging. 

## 1. Introduction

Endoscopic imaging via an optical fiber bundle or with a camera at the remote end already sees widespread use in life sciences and medicine. Multimode fibers (MMF) combine the smallest footprint with the highest NA and stand out as a unique imaging tool for minimally-invasive high-resolution microscopy *in vivo* [**?**]. Different MMF-based imaging methods have been investigated, such as spatial wavefront shaping [**?**, **?**] and compressive sensing [**?**]. Most of the current techniques are solely used to detect linear processes (scattering or fluorescence). In contrast, nonlinear imaging with ultrashort pulses is well-established in free-space microscopy: it reduces out-of-focus background and provides optical sectioning that results in higher sensitivity and 3D imaging ability [**?**]. Combining ultrashort pulses with MMF imaging is non-trivial, as the modal interference and modal dispersion in an MMF results in a complex spatiotemporal output field. Light focusing and 3D imaging through an MMF have been recently demonstrated using phase conjugation and spatial wavefront shaping [**?**, **?**]. Unfortunately, these methods still use ~~of~~ spatial light modulation meaning that imaging can be easily distorted by fiber perturbations.

Here, we demonstrate a method that ~~exploits the complex output field and~~ enables grid scanning an ultrashort pulse over the output facet of a stiff piece of MMF. Our system thus allows control over the position of a nonlinearly focused beam *in space* by shaping an input pulse only *in time* within a single spatial mode. This new way of light control at the MMF output also helps to avoid the perturbation sensitivity of MMF-based imaging probes.

## 2. Experimental details

We use a 1 m long 70 x 70 μm$^2$ square-core MMF in our experiment (Ceramoptec, 0.22 NA). Compared to round-core MMFs, we found that square-core MMFs have a flatter output intensity profile and higher order modes are easier to excite. With a pulsed and focussed Gaussian input beam, the output field is spatially speckled due to modal interference, and also wavelength and time dependent due to modal dispersion [**?**]. For our fiber, the output speckle pattern decorrelates after a wavelength shift of 0.04 nm. Because the output speckles each have a different temporal profile, one of them can selectively be compressed in time. The input light consists of 13 nm bandwidth

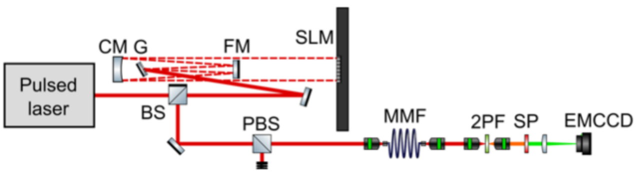


Fig. 1. Schematic of the experimental setup. The pulse shaper consists of (polarizing) beam splitters ((P)BS), a grating (G), a cylindrical mirror and folding mirror (CM/FM), and a spatial light modulator (SLM). The output facet of the multimode fiber (MMF) is imaged with a two-photon fluorescent screen (2PF), a short-pass filter (SP) and an electron-multiplying CCD camera (EMCCD).

femtosecond pulses of a Ti:Saph oscillator (Spectra Physics Tsunami, 80 MHz), centred at 800 nm, which are shaped in time with a 640-pixel $4f$ pulse shaper (0.064 nm/pixel resolution).

To detect temporal compression, the output speckle pattern is focused inside a two-photon fluorescent screen (Rhodamine 6G in ethylene glycol) and an EMCCD camera detects the resulting fluorescence. This nonlinear imaging method is required to see temporal compression of the speckles. To selectively compress a single output speckle, its nonlinear intensity is optimized by iteratively optimizing the phases of the pulse shaper pixels [**?**].

## 3. Results

Fig. 2 shows nonlinear images of the output speckle pattern before (a) and after (b) optimization of the input pulse shape. A single speckle can be selected and temporally compressed by enhancing its nonlinear intensity, while the other speckles with a different temporal response remain dark. Fig. 2 (b) shows a composite nonlinear output image for 25 different input pulse optimizations. The input pulse shapes for each speckle can be saved and reused for a stiff MMF, as the pulse shape is delivered in a single spatial mode and is therefore not sensitive to spatial perturbations. This allows for robust, deterministic grid scanning of an ultrashort pulse at the output facet of a stiff MMF, which can be applied to nonlinear endoscopic imaging.

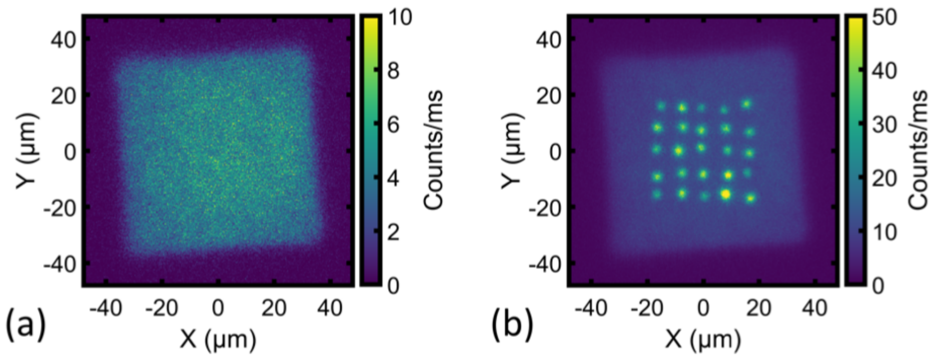


Fig. 2. (a) Nonlinear image of the output speckle pattern before optimizing the input pulse shape. (b) Composite nonlinear image of the output speckle pattern after selectively optimizing the input pulse shape for each of 25 speckles. This demonstrates grid scanning of an ultrashort pulse at the MMF output facet.

## 4. Conclusion and discussion

We have demonstrated spatial grid scanning an ultrashort pulse at the output facet of a square-core multimode fiber by only changing the temporal shape of an ultrashort pulse at the input facet. Delivery of the pulse is done in a single spatial mode, which is insensitive to spatial perturbations. Our method has applications in nonlinear endoscopic imaging, as the pulse delivery and corresponding response readout can be done via the same fiber.