(2+1)D Spatiotemporal Characterization of Nonlinear Interactions between Selectively Excited Spatial Modes of a Few-Mode Fiber

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Abstract: We present a novel approach to measure nonlinear interaction between selectively-excited modes of few-mode fibers. Selective excitation is achieved by end-facet patterning; spatiotemporal measurements are performed by raster-scanning a near-field probe coupled to high-speed detection. © 2020 The Author(s)

1. Introduction

Nonlinear optics in multimode fibers (MMFs) has gathered considerable interest over the past few years. Kerr and Raman nonlinearities in multimode fibers give rise to rich phenomena such as supercontinuum generation [1] and spatial beam self-cleaning [2]. These phenomena arise from complex collective nonlinear interactions between a large number of modes. However, the fundamental interactions between a small number of modes have been relatively understudied. Further, while these interactions are intrinsically spatiotemporal in nature, most reported measurement techniques have been limited to using CCD/CMOS cameras and optical spectrum analyzers, both of which average over many pulses. As a result, many interesting dynamics that occur within the duration of a single pulse are missed, thereby not capturing their spatiotemporal nature. In this paper, we demonstrate an approach to not only control the number of modes taking part in the nonlinear interaction, but to also to resolve the effects of the interactions in both space and time.

2. Experimental Setup

We achieve selective mode excitation by patterning the input end-face of a 20 μm step-index few-mode fiber. The patterning is done by milling a pre-determined shape in the SiO_2 of the FMF core by using a high energy, focused, Ga^+ ion beam (Ga^+ FIB). The geometrical shape of the milled region is carefully designed to excite a desired linear combination of the LP_{lm} modes (in this case LP_{01} and LP_{03}) when illuminated by a Gaussian beam at the input face. Figure 1A shows a schematic of the pattern milled on the FMF core region, and also a scanning electron microscopy (SEM) image taken of the whole fiber end-facet (including cladding) after patterning. The laser used for these experiments is a Nd:YAG microchip laser (λ_0 = 1064 nm) that emits 700 ps (FWHM) pulses at 1 kHz rep. rate. The beam power incident on the FMF is adjusted to be 9 kW (peak power). The beam is then focused down to a spot size of about 16 μm on the patterned FMF input end-face. (See Figure 1B).

At the output end of the FMF, as shown in Figure 1C, an NSOM tip/probe that is coupled to a 0.5 meter long single-mode fiber (SMF) is brought in close proximity to the FMF output facet in order to collect light from a small, sub-wavelength region. The NSOM probe is then raster-scanned along a 20 μm × 20 μm grid on the FMF

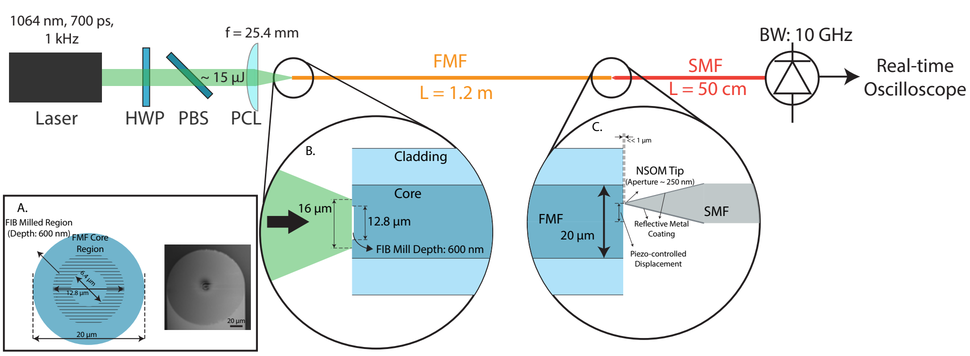

Fig. 1. Experimental Schematic: **A**. Pattern milled on the FMF input end-face by FIB, **B**. Input beam of 16 μm diameter illuminating the end-face, exciting LP_{01} and LP_{03} modes, **C**. Raster-Scanning NSOM Probe for (2+1)D Spatiotemporal Measurements

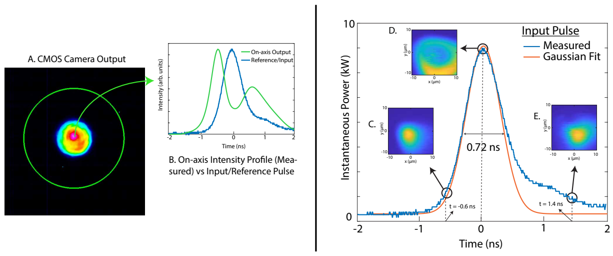

Fig. 2. (2+1)D Spatiotemporal Characterization: **A**. Shows the FMF output captured by a traditional CMOS camera, **B**. The temporal intensity profile measured on-axis by the NSOM probe setup shown above; **C**., **D**., **E**. Reconstructed instantaneous 2D spatial profiles at FMF output at t = -0.6 ns, t = 0 and t = +1.4 ns

output end-face in steps of 0.4 μm, and at each spatial location, the output pulse is measured in the time-domain using a 10 GHz photoreceiver followed by a high-speed real-time oscilloscope. The temporal data collected at each spatial location is processed and used to reconstruct a movie that shows the evolution of the 2D spatial intensity pattern at the FMF output facet as the pulse turns on and turns off.

3. Results and Discussion

Upon neglecting the intermodal dispersion term, and upon recognizing that the four-wave mixing terms average to zero, the analytical solution to the generalized multimode nonlinear Schrödinger equations (GMM-NLSE) [3], for two interacting LP_{0n} modes, can be written as [4]:

$$A_1(z,t) = A_1(0,t)e^{j(\gamma_{1111}|A_1(t)|^2+2\gamma_{1122}|A_2(t)|^2)z} \quad \text{and} \quad A_2(z,t) = A_2(0,t)e^{j\delta z}e^{j(\gamma_{2222}|A_2(t)|^2+2\gamma_{2211}|A_1(t)|^2)z} \qquad (1)$$

where $A_p(z,t)$ is the complex slowly-varying amplitude of mode p, γ_{pppp} and γ_{ppqq} are respectively nonlinear coefficients of SPM and XPM, and δ is the difference in propagation constants. As can be seen from equation 1, the two modes acquire a differential chirp as they propagate through the fiber. As a result, at a spatial location on the FMF output end-face where the two modes overlap, the theory predicts that we see an "interference pattern" in the time-domain.

Figure 2A shows the output of the FMF for the input excitation described above, as recorded on a traditional CMOS camera. The CMOS camera is then replaced by the NSOM probe setup described in Figure 1, and by axially aligning it with the FMF, the on-axis temporal intensity profile is measured on the oscilloscope. As Figure 2B shows, the output on-axis pulse exhibits a non-Gaussian shape in time, which we attribute to power-dependent temporal interference between the two spatial modes. We then perform the raster-scanned measurements, and in Figures 2C, 2D and 2E, we show snapshots of the reconstructed spatial intensity pattern at three time instances. As one can see, at $t = -0.6$ ns, the output beam looks like a gaussian centered on-axis. However, as the pulse reaches its peak the modes acquire different nonlinear phase shifts, and they overlap to produce an annulus-like pattern. Further, on the trailing edge of the pulse, at $t = 0.7$ ns, the output beam shape retreats back to a gaussian on-axis.

By spatially resolving the time-domain output of nonlinearly-interacting modes in an FMF, we are able to resolve the underlying intermodal nonlinear interaction in a way that traditional cameras cannot. In addition, this technique can also be a highly effective tool in the development of high-power spatiotemporally mode-locked fiber lasers where both output spatial beam quality and temporal shape are important. In conclusion, we have demonstrated selective mode excitation by patterning the input end-face using a novel FIB milling method. Our measurement technique serves as a complete (2+1)D diagnostic that can be used to explore and understand a wide variety of spatiotemporal phenomena resulting from nonlinearly interacting spatial modes in multimode fibers.

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