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# Tapered multicore fibers for energy-scalable fiber laser systems

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**Abstract.** With active multicore fibers (MCFs), many parallel amplifying waveguides can be densely assembled into a common glass cladding. A tapered fiber geometry applied to MCFs enhances the power- and energy scalability of these systems by increasing the doped waveguide volume and reducing peak irradiance while maintaining low output mode order. Recent high-energy experiments have achieved 37 mJ ns-class pulse energies with Yb-doped tapered MCFs, with potential application to a new generation of compact MCF-based coherently-combined laser systems. In this submission, latest experimental results with tapered MCFs and flexible fabrication of taper profiles as a post-draw processing step will be discussed. Numerical analyses of MCF tapers will be presented, using beam propagation method (BPM) and mode-decomposition techniques to study mode coupling and inter-core crosstalk. These simulations are used to guide the tapering of existing fibers and aid the design of future "taper-ready" MCFs.

## 1 Introduction

Coherent beam combination (CBC) of parallel fiber amplifiers has enabled the development of high average power laser sources with near-ideal beam characteristics capable of driving new scientific and industrial applications [1]. The physical size of such a system is determined primarily by the unit size of its constituent lasers, limiting the practical scaling of CBC systems to 1-2 orders of magnitude. This scaling dependency is circumvented with the use of multicore fibers (MCFs) where many parallel amplifying waveguide cores are arranged in a single cladding. Recent ultrafast demonstrations of MCF CBC have achieved 500 W combined and compressed average power [2], and numerical simulations predict scalability to the ~ 10 kW level with several hundred mJ pulse energy [3].

As with single-core fibers, the capability of MCFs to generate and handle high powers and high pulse energies can be improved with mode area scaling techniques. A tapered fiber design can significantly increase the mode area and available doped volume while maintaining near-ideal output beam quality [4]. A tapered MCF amplifier was recently demonstrated, achieving 37 mJ total energy in ns-class pulses with improved beam quality in comparison to an untapered fiber (see Fig. 1), with a proposed application in CBC systems [5]. In this context, where the MCF cores are intended to be used as independent parallel amplifiers, the design and fabrication of a tapered MCF presents unique constraints in addition to those encountered with standard tapered gain fibers. Numerical simulations can analyze mode evolution and inter-core crosstalk in MCF tapers to produce optimized taper designs for a given MCF. These designs can be flexibly realized using a flame or $CO_2$ laser tapering system as a post-draw processing step.

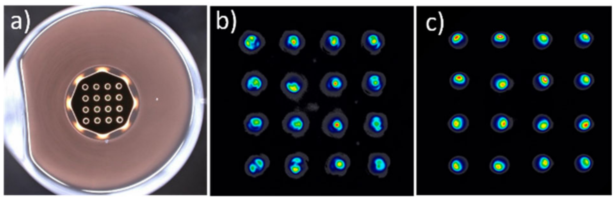


**Fig. 1.** a) Polished MCF facet. b) Beams of untapered MCF with 50-micron core diameter. c) Beams of tapered MCF with 19 micron input core diameter and 50-micron output diameter.

## 2 High energy tapered MCF experiment

A primary benefit of a tapered fiber geometry is the fiber's greater doped volume, and thus higher extractable energy, per unit fiber length. This and the lower peak intensity due to the larger mode field area lead to lower accumulated nonlinear effects and increased damage threshold. While fiber lasers are typically considered low pulse energy/high average power systems, tapered MCF systems can extend the working range of fiber systems into a higher energy regime.

A recent experiment to demonstrate the energy handling capability of a tapered MCF is depicted schematically in the upper portion of Fig. 2. A Q-switched MCF oscillator seeded a counter-pumped tapered 4x4 MCF amplifying stage. The tapered fiber had a total

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length of 98 cm with a ~20 cm taper from 19-micron core diameter to 50-micron core diameter. The amplified energy is plotted in the lower portion of Fig. 2, reaching a maximum of 37 mJ before damage due to a defect in the fiber. An untapered version of the fiber reached a pump-limited 49 mJ without damage. The output beams of both amplifying MCFs are shown in Fig 1 b), c), with the tapered fiber achieving an average single-beam $M^2 = 1.5$ vs. $M^2 = 2.1$ in the untapered fiber. With further taper refinement, combinable beams with pulse energies >10 mJ from a single fiber are likely feasible.

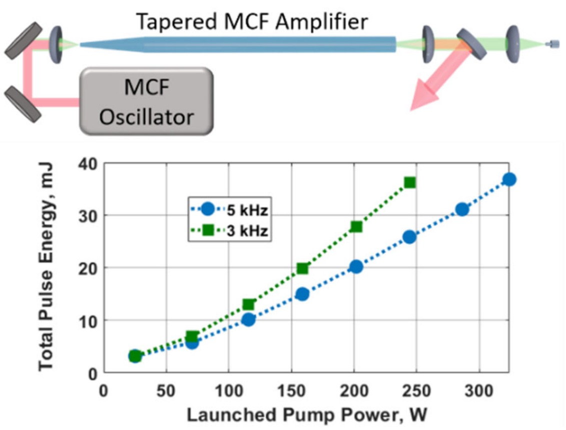


**Fig. 2.** (Top) schematic of MCF energy extraction experiment. (Bottom) extracted pulse energies at 3 kHz and 5 kHz repetition rate.

## 3 MCF taper analysis

Taper designs can be modelled and optimized for a given fiber design using numerical techniques such as beam propagation method (BPM). As an example, a facet image of a double-clad Yb-doped MCF produced by Fraunhofer IOF is shown in Fig. 1a). The core separation is 2.5x the core diameter and the doped cores have a low NA of 0.04. Cross-talk may occur between adjacent cores, depending on the drawn core diameter and chosen fiber length and is strongest in the strictly-single-mode regime in which tapers typically begin. This motivates a short taper length and a large taper angle to minimize crosstalk through the taper. A short taper also benefits laser operation by maximizing dopant volume and mode field diameter through the remainder of the fiber. In the case of single-core tapers, the minimum length is theoretically given by the adiabaticity criterion for axiosymmetric tapers [6]. With MCFs, additional losses and perturbations occur due to the off-axis arrangement of cores. Final intensity distributions of linear tapers simulated with BPM based on the fiber described above are shown in Fig. 3. The core diameters are tapered from 15 µm to 25 µm (single-mode to few-mode). Fig. 3 a) shows bend loss and mode distortion in a 5 mm taper, and Fig. 3 b) shows a 50 mm taper with noticeable power coupled from the two initially seeded cores into adjacent cores. Within this range of taper lengths, a working interval which minimizes crosstalk and mode distortion can be found.

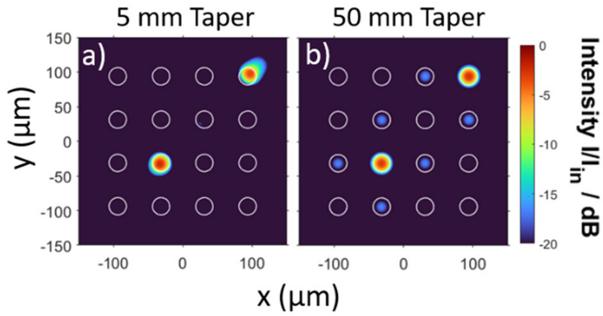


**Fig. 3.** Final intensity distributions of a) a 5 mm MCF taper and b) a 50 mm MCF taper.

Tapers with length scales of ~10-100 mm as in Fig. 3 can be fabricated using a flame-brush or CO2 laser tapering system after fiber drawing. Such systems are also capable of generating arbitrary longitudinal profiles [7]. This may be applicable to MCFs, for example, to accomplish a rapid initial taper for minimized core-to-core coupling, followed by a more gradual taper to minimize mode coupling in the multimode region.

## 4 Conclusion

Using numerical simulation techniques and post-draw processing, optimized designs for tapered multicore fibers can be realized which enable independent operation of large multimode waveguides with single-mode beam characteristics. While CBC with MCFs is already proving to be an attractive format for compact laser system scaling, applying a tapered fiber geometry extends and optimizes energy handling potential for a given MCF. Recent demonstrations have achieved ~50 mJ of output energy in ns-class pulses, and further refinement may enable Joule-class operation and fundamental mode output from highly multimode large core MCFs. These advances can enable CBC systems with power and energy scaled by multiple orders of magnitude.

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