3C Yb-doped Fiber Based High Energy and Power Pulsed Fiber Lasers

Thomas Sosnowski*[a], Andrey Kuznetsov[a], Robert Maynard[a], Xiuquan Ma[b], Cheng Zhu[b], I-Ning Hu[b], Almantas Galvanauskas[b], Joona J. Koponen[c], Timothy S. McComb[c]

[a] nLight Corporation, 251 Jackson Plaza, Unit A1, Ann Arbor, MI 48103; [b]Center for Ultrafast Optical Science, University of Michigan 2200 Bonisteel Blvd., Ann Arbor, MI 48109; [c] nLight Corporation, 5408 NE 88th Street, Building E,Vancouver, WA 98665

ABSTRACT

3C fiber technology advances the performance frontier of practical, high-pulse-energy fiber lasers by providing very large core fibers with the handling and packaging benefits associated with single mode fibers. First-generation fibers demonstrate scaling to > 240 W average power coincident with 100-kW peak power in 1-mJ, 10-ns pulses while maintaining single-mode beam quality, polarized output, and efficiencies > 70%. Peak powers over 0.5 MW with negligible spectral distortion can be achieved with sub ns, near-transform-limited pulses. In-development second-generation 3C Yb-fiber based on core sizes around 55 μm[1] have produced >8 mJ, 13 ns pulses with peak powers exceeding 600 kW.

Keywords: Fiber Laser, Peak Power, 3C, CCC, Power Scaling, Pulsed Laser

1. INTRODUCTION

A principal advantage of fiber laser technology is its compatibility with monolithic integration, enabling practical, compact, and robust systems. Conventional fiber lasers are limited to pulse energies and peak powers that are insufficient for many important materials processing applications, such as processing of semiconductors, glasses, and ceramics. Power scaling of pulsed fiber sources beyond these limits generally requires fiber formats that preclude monolithic integration (e.g., micro-structured fiber rods[2]). Specifically, these fiber types:

- are difficult to splice, thereby requiring free-space optics, with the associated increase in complexity, reduction in efficiency, and susceptibility to contamination, damage, and misalignment;
- cannot be coiled tightly or at all, leading to large and unwieldy packages; and/or
- are incompatible with fused-fiber components, such as combiners and other all-fiber structures.

Laser developers have thus been forced to make tradeoffs between performance and practicality. Achieving MW peak power, multi-mJ energy pulses with practical, integration-compatible fibers remains a critical frontier for enabling widespread adoption of pulsed fiber lasers.

1.1 Demonstrated Performance of 3C Fibers

3C fiber technology is closing the performance gap between practical fiber lasers and those producing the highest peak powers. 3C fibers combine robust single-mode performance in large cores (up to 60 μm demonstrated), environmentally-stable polarized output, and under specific conditions, stimulated Raman suppression while retaining the handling and packaging benefits associated with single mode fibers. Amplifiers based on first generation ~28-μm-MFD 3C Yb fibers are commercially-available. These fibers demonstrate average-power scaling to greater than 240 W coincident with peak powers greater than 100 kW, pulse energies around 1 mJ and with pulse durations in the range of 10 ns, while maintaining single mode beam quality, a high PER and a net optical efficiency greater than 70%. When amplifying sub-ns pulses, these fibers generated negligible spectral distortions at peak powers greater than 500 kW. Second-generation 3C Yb-fiber technology, based core sizes around 55 μm that are still effectively single-mode, is currently in development, but has so far produced ~8 mJ energy, 13 ns duration pulses with peak powers exceeding 600 kW.

1.2 3C Fiber Basics

3C fibers permit single-mode-only propagation in very large cores, without any need for conventional mode-management techniques, such as fiber coiling or single-mode excitation. 3C fibers are also distinctly different from single-mode photonic-crystal fiber designs, such as rod-type PCF, as well as conventional LMA fibers in that they can be managed in exactly the same way as conventional telecom-type single-mode fibers. They can be coiled or remain straight as required for packaging, spliced together, built into fiber-based components such as fused fiber combiners or used for pigtailing bulk optical components such as optical isolators. 3C structures are implemented in conventional index-guiding fibers enabling use of standard, simple and easily-accessible fusion splicing procedures.

Single mode operation in 3C fibers is achieved by effectively suppressing higher-order-mode (HOM) propagation while preserving a low-loss fundamental mode. More specifically, 3C fiber exploits mode symmetry differences to select only the LP_{01} mode for propagation through a process of quasi-phase matching. The 3C fiber structure, depicted in Figure 1, consists of a large on-axis signal-carrying central core with one (or more) smaller helical side core(s) "wound" around it. The side helix-core is designed to achieve (i) highly mode-selective coupling of HOMs from the "straight" central core into the helical side core, and (ii) to radiate all the optical waves coupled into this side core into the cladding.

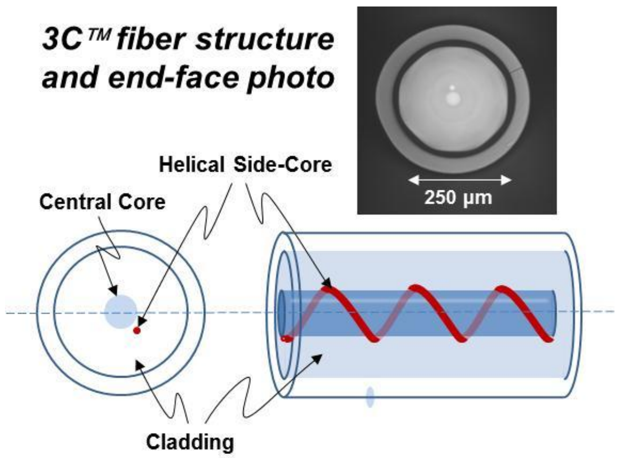

Figure 1. 3C fiber structure

Both passive and Yb-doped 3C fibers with 33 µm cores have been fabricated by several vendors with higher order mode suppression greater than 25-dB/m and fundamental-mode losses in the range of 0.1 dB/m. These fibers have been spliced together without modal quality degradation and with splicing losses in the 0.1-0.2 dB range. 3C fibers are able to maintain linear polarization states and high-power linearly-polarized amplifiers have been fabricated and proven to robustly maintain polarization even when strongly perturbed by environmental changes. 3C dual-clad Yb-doped fiber lasers and amplifiers operating at the commercially-important wavelength of 1064 nm have been demonstrated with high optical-optical efficiency (>75%) and high gain (>30 dB) and with diffraction-limited beam quality at power levels up to 500 W and with peak powers in excess of 500 kW.

More recently, low-loss single mode operation has been demonstrated in 3C fibers with core sizes 55 µm and larger. Figure 2 is an end-face picture of a 55 µm core passive fiber with 8 side cores. An image of a 125 um fiber is also shown for reference. Figure 3 illustrates that the mode quality at the output of this 3C fiber is maintained as the input coupling is walked off from optimal – in stark contrast to LMA fibers of this size that under identical tests deliver beams with highly distorted shapes.

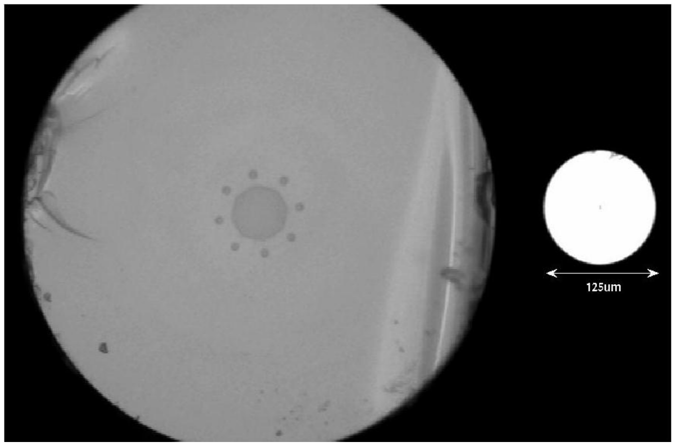

Figure 2. 55 µm core 3C fiber with 8 side cores. A standard 6/125 µm fiber is shown for reference.

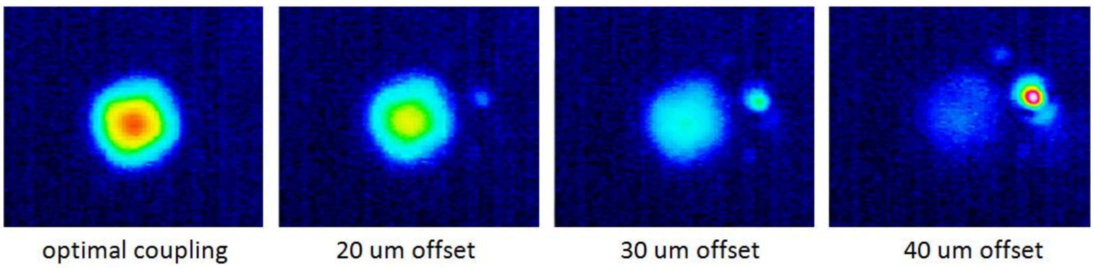

Figure 3. Output mode from 55 µm core 3C fiber as the input is misaligned. There is no distortion of the central core mode even as the signal input misalignment becomes larger than the core radius of 25 µm.

2. HIGH AVERAGE POWER AND HIGH-ENERGY PULSES

High-energy, short-pulse fiber lasers require highly-doped, large-core fibers with a large core-to-clad diameter ratio. Large cores support large modes reducing the optical intensities in the fiber and increasing the threshold for SBS and SRS. A large core also increases the amplifier's saturation energy enabling amplification to higher pulse energies without any temporal distortion. The high doping and the large core-to-clad ratio ensure a short pump absorption length and signal gain length even with the large cladding diameters required for coupling high average power pump lasers. These design factors enables efficient amplifiers that employ very short fiber lengths, again increasing the thresholds for SRS and SBS. Fiber length constraints in single-mode amplifiers operating at high pulse energy and >100 kW peak powers are such that the W/m thermal loads on the gain fiber can be significantly higher than those in kW class fiber lasers for average powers just in the 100-200 W range. Therefore the design of these high average power pulsed systems requires not only advanced fiber designs such as 3C fiber, but also careful engineering for safe and reliable handling of the high thermal loads.

2.1 Experimental Setup

The system front end consisted of a 0.5 W 1.06 µm wavelength pulsed diode seed source, a 3C fiber preamplifier and a 3C fiber final stage amplifier as depicted in Figure 4. The seed laser enabled pulse width and repetition rate tuning from 10 ns to 250 ns and single-shot to 500 kHz. In some respects this seed source was not ideal for investigating high peak power capabilities of the 3C amplifier because its output spectrum consisted of many, rapidly-varying, narrow longitudinal-mode spectral lines inside of a broad spectral window. These characteristics lead to rapid broadening of the spectral envelope in the final amplifier, which in turn lowered the peak power for which significant Raman broadening was observed. Nonetheless the compact, rugged and inexpensive seed source is potentially useful for OEM integration in fiber laser systems deployed for applications that are not overly sensitive to the pulse bandwidth, and the broad spectrum did allow operation at peak powers above 100 kW with no SBS for 10-50 ns pulse durations. The preamplifier design was based on a 33 µm core 3C fiber pumped with 915 nm diodes and was configured to amplify the 0.5 W seed laser input to 4W that then served as the input for the final amplifier stage. The final amplifier was counter pumped by 7 non-wavelength-locked 976 nm laser diodes that were combined in a 7:1 pump combiner. The net power available from the 220 µm core, 0.22 NA combiner output fiber was 338 W. The final amplifier fiber assembly consisted of both Yb-doped and passive 33 µm core, 250 µm clad 3C fibers with a 0.46 NA cladding. The fiber assembly was terminated on both ends with ferrules that allowed for appropriate heat sinking and rigid and stable fixturing of the fibers to optomechanical assemblies.

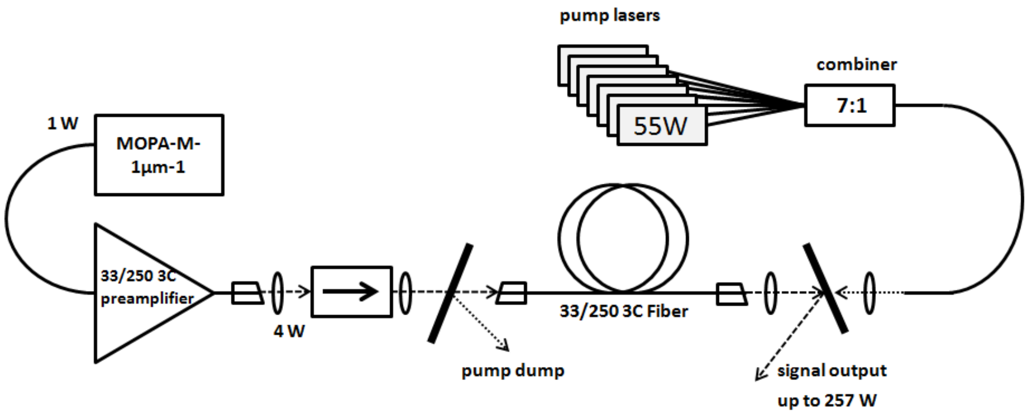

Figure 4. Diagram of experimental setup for high average power, large pulse energy 3C fiber amplifier characterization

2.2 Results

The seed laser was operated at the 10-ns pulse duration setting at 200 kHz repetition rate. Its output was amplified to 4W average power in the 3C pre-amplifier. The temporal and spectral properties of the pulses out of the final amplifier were characterized as its output power was varied from 14 W to 246 W by adjusting the pump power. This power range corresponds to pulse energy range from 0.07 mJ to 1.2 mJ and peak powers from 8kW to 140kW. The effective duration of the output pulse used for peak power calculations was 8.5 ns. The difference from the 10 ns setting was due to the seed laser's pulse shape and the effects of gain saturation.

The 33 µm 3C fiber has a high slope efficiency of 86%. The amplifier output as a function of pump power is shown in Figure 5. The maximum output power achieved is 257 W at 338 W of pump power for a net optical-to-optical efficiency of 76%, calculated as a ratio of the in-core signal power to the 7:1 combiner output power.

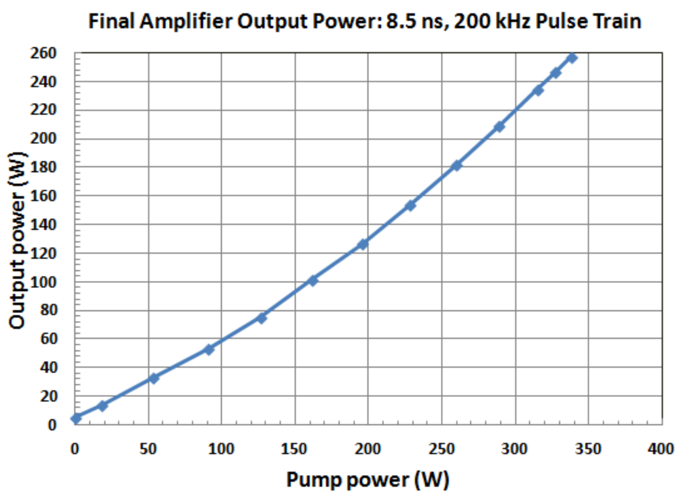

Figure 5. In-core signal output power versus 976 nm pump power.

The pulse temporal shape and spectrum are shown in Figure 6 and Figure 7 for amplifier power levels of 14, 56,133 and 246 W, corresponding to 0.07, 0.28, 0.67 and 1.23 mJ pulse energies. The temporal profile and spectrum plotted for the 14W power level are similar to those directly from the seed laser.

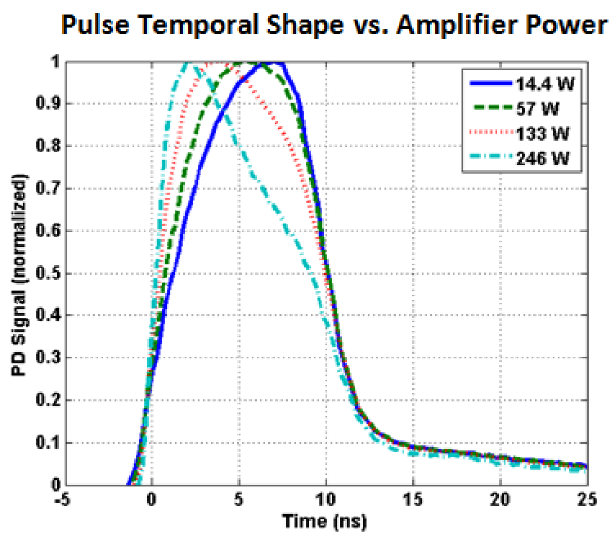

Figure 6. Pulse temporal shape vs. amplifier in-core signal output power. Gain saturation steepens the leading edge of the pulse as the power increases.

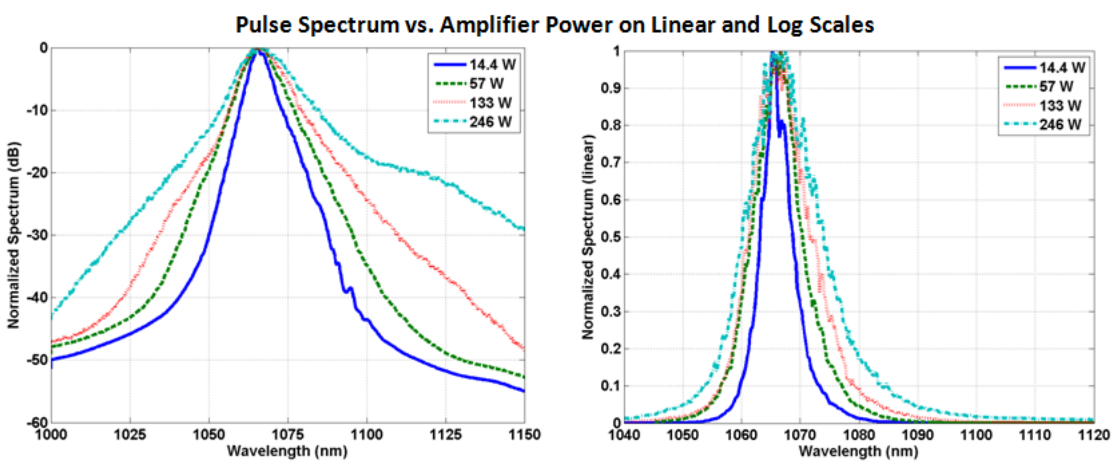

Figure 7. Pulse spectrum vs. amplifier in-core signal output power. The large bandwidth of the MOPA-M results in significant spectral broadening in the final amplification stage. The pulse energy associated with each average power curve is: 0.07mJ (14 W), 0.28 (57 W), 0.67 (133 W) and 1.23 mJ (246 W).

2.3 Discussion

The saturation energy of the final amplification stage is ~0.35 mJ, close to one quarter of the pulse energy at the 246 W power level. This leads to some distortion of the output pulse shape such as a steepening of the front edge, but the overall pulse width does not change significantly. Significant spectral broadening is observed as the output power increases, progressing from 6 nm at low powers and pulse energies to 14 nm at maximum power. The broad spectrum seeds the Raman process resulting in 5-10% of the output power occurring around the Raman shifted wavelength of 1120 for the maximum pulse energies.

Attention to engineering details such as thermal management and the design of the fiber terminations enable long-term stable operation at these power, energy and peak-power levels. In fact, 3C amplifier prototypes with 100W average power and 1 mJ pulse energy capabilities have been sold and successfully deployed for micromachining applications in manufacturing environments.

3. HIGH PEAK POWERS

A high-quality narrow-bandwidth pulsed laser diode seed source enables scaling the output pulses to much higher peak powers with significantly reduced spectral broadening. For pulse durations shorter than 1 ns there is no risk of SBS. The performance of 3C fiber amplifiers in this parameter regime was examined with a 150 ps narrow linewidth seeder module developed internally at nLIGHT Photonics.

3.1 Experimental Setup

The nLIGHT seeder module contains a narrowband gain-switched laser diode and a single mode fiber preamplifier chain that produced 150 ps duration, 0.13μJ energy pulses at a repetition rate of 300 kHz for an average power of 40 mW. The output of the single-mode seeder module was mode-matched to the 33 μm core of a Yb-doped 3C fiber amplifier. A 976-nm VBG wavelength-locked nLIGHT Pearl fiber coupled pump laser capable of providing 120 W in a 200 μm, 0.22 NA fiber was coupled into the 250 μm, 0.46 NA cladding to counter pump the fiber. A diagram of the experimental setup is shown in Figure 8. The pump power was varied to characterize the amplified pulses' temporal and spectral characteristics over a range of pulse energies and peak powers.

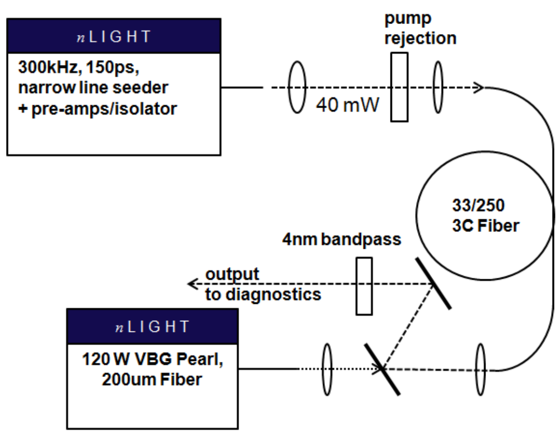

Figure 8. Experimental setup for characterizing 3C amplifier operation for high peak power sub-nansecond pulses.

3.2 Results

The amplifier in-core signal output power increased linearly with pump power up to the maximum tested pump power of 55W. Figure 9 plots the pulse energy and peak power as a function of pump power with the peak powers reaching above 500 kW.

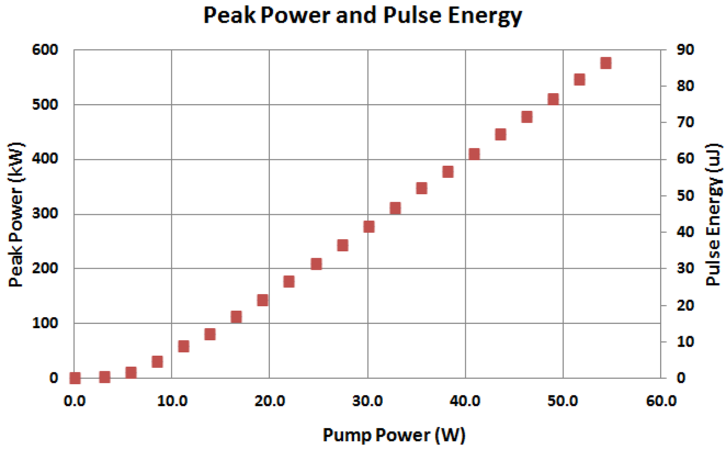

Figure 9. Pulse energy and peak power as a function of pump power.

There is no significant change in the pulse temporal shape within this range of peak power as shown in Figure 10.

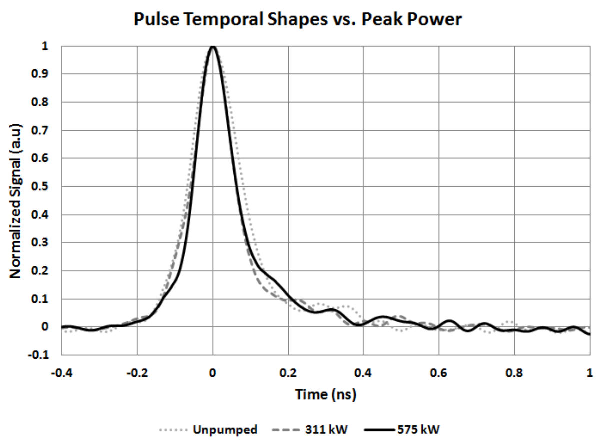

Figure 10. Pulse temporal shapes through an un-pumped amplifier (<0.07 nJ), at 311 kW peak power (46.5µJ), and 575 kW peak power (86.5µJ). The pulse shape and duration remain largely unchanged. Pulses were measured with a 12GHz real-time oscilloscope and >15GHz bandwidth photodiode.

The SPM-induced broadening of the pulse spectrum as a function of peak power is shown on the left side of Figure 11, and the right side shows the spectrum of the 575 kw peak power pulses over a much wider spectral window. Figure 12 plots the 10 dB spectral bandwidth versus peak power. The bandwidth increases linearly with peak power up to 450 kW. Above 450 kW the spectral shape is modulated to an extent that the 10 dB bandwidth is no longer a good metric for the spectral content. Spectral broadening due to SPM is less severe for longer pulse durations, due to its dependence on the rise and fall times of the pulse edges. Therefore it is expected that 0.5-1 ns duration pulses from the same amplifier would exhibit only minimal spectral broadening.

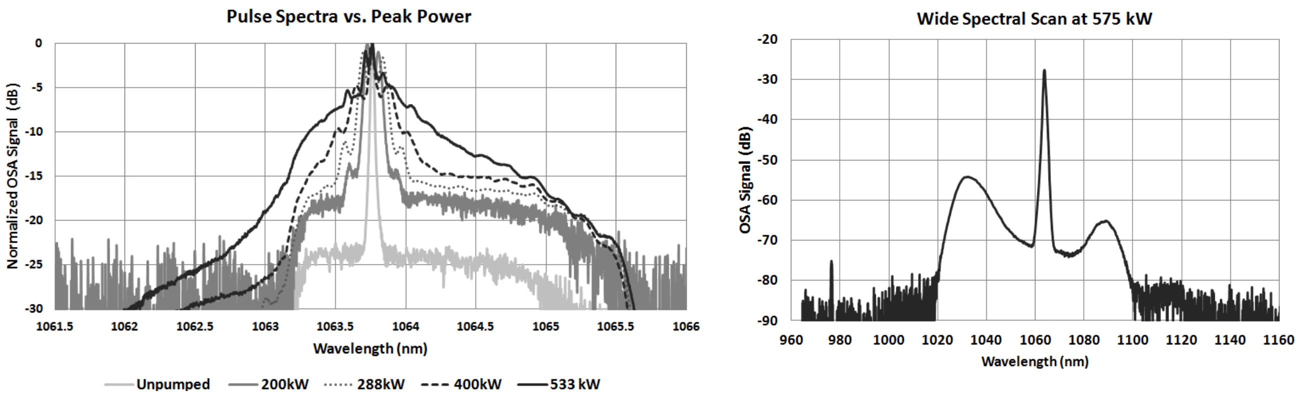

Figure 11. Left - amplified pulse spectrum as a function of the pulse peak power. Right - the spectrum of 575 kW peak power pulses over a wide spectral window.

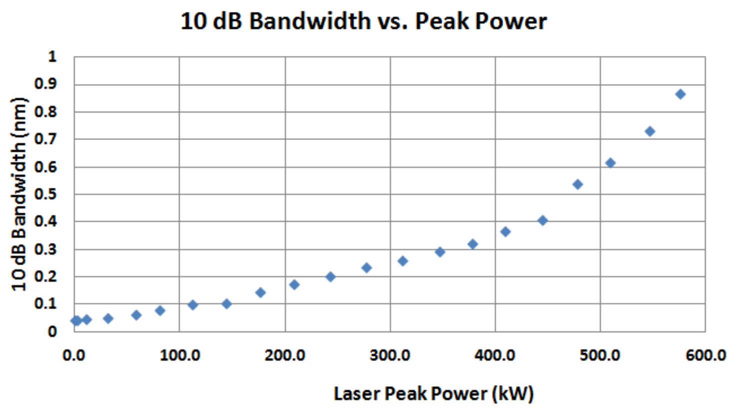

Figure 12. Pulse spectrum 10 dB bandwidth versus peak power.

3.3 Discussion

The pulse temporal shape changes little over this range of peak power and pulse energy, as expected since pulse energies in the 10's of μJ range and are well below the 3C fiber's saturation energy of ~0.35 mJ.

The narrow-band short-pulse spectra in Figure 11 demonstrate that with the correct seed source, 33 μm core 3C fiber amplifiers can produce high quality pulses that have peak powers in the 500 kW range. Self-phase modulation gradually broadens the pulse bandwidth as the peak power increases, but the bandwidth remains sufficiently narrow to enable high efficiency second harmonic conversion at all peak powers and third harmonic conversion for IR peak powers up to around 500 kW. On a wider spectral window, the spectrum of pulses with 575 kW peak powers show two pronounced spectral peaks at 1030 and 1090 nm. (Note that the spectrum is taken before a 4-nm bandpass spectral filter, while all power measurements were taken after the bandpass filter.) We believe these features are likely due to four wave mixing of ASE centered around 1035 nm with the 1064 nm signal. The Raman peak at ~1120 nm is barely observable, a sign that that the peak power could be further increased with a more powerful preamplifier, as gain limited further increase of the amplifier power.

The amplifier gain is 28 dB for the 86 μJ pulse energies, so it is worth considering whether both out-of-band and in-band ASE are a significant issue. If out-of-band ASE, peaking in the 1035-1040 nm range, was a significant issue, the plot of output pulse energy vs. pump power would roll off at the high pump power end as the ASE grew to a significant fraction of the output power but was then reflected by the narrow-band filter. So it does not appear that the out-of-band ASE is significant even for a signal gain of 28 dB.   A second harmonic generation stage was set up, and although it was not optimized for these particular bandwidths and peak powers, the conversion efficiency was above 50% at the full peak power, indicating the IR peak power results are credible and that the in-band ASE power contribution is relatively small, likely less than 10% determined by the preamplifiers which set the signal to in-band ASE ratio.

4. 60 µm CORE 3C FIBER

Larger core 3C fibers enable scaling to even higher peak powers and larger pulse energies. 55 µm core 3C fibers have been utilized to generate pulse energies > 8 mJ with peak powers as large as 640 kW with pulse durations in the 10-20 ns range.

The in-development 55 µm core Yb-doped 3C fiber has 8 side cores and is similar in design to the fiber depicted in Figure *2*. The fiber is triple clad with a 330 µm 0.22 NA inner cladding and a 370 µm 0.46 NA outer cladding.

4.1 Experimental Setup

The pulses for the 55 µm core 3C amplifier characterization were generated by a ring cavity regenerative fiber laser developed by the University of Michigan[3]. It produces spectrally-smooth broadband output pulses that do not suffer from stimulated Brillouin scattering (SBS) during amplification, but that are also relatively insensitive to SPM-induced spectral broadening due to the absence of longitudinal mode lines under the spectral envelope. Pulse energies from the regenerative seed laser are in the 0.1 µJ range, significantly reducing the number of amplification stages needed in a fiber MOPA system when compared with pulsed laser diode sources. Operating at 5 kHz, the seed output was amplified in two preamplifiers, the first one constructed with SM fiber and components and the second with 35 µm-core 3C fiber as shown in Figure 13. The 150 µJ, 5 kHz pulse train from the second stage preamplifier was used as the seed for the final stage amplifier based on 55 µm Yb-doped 3C fiber.

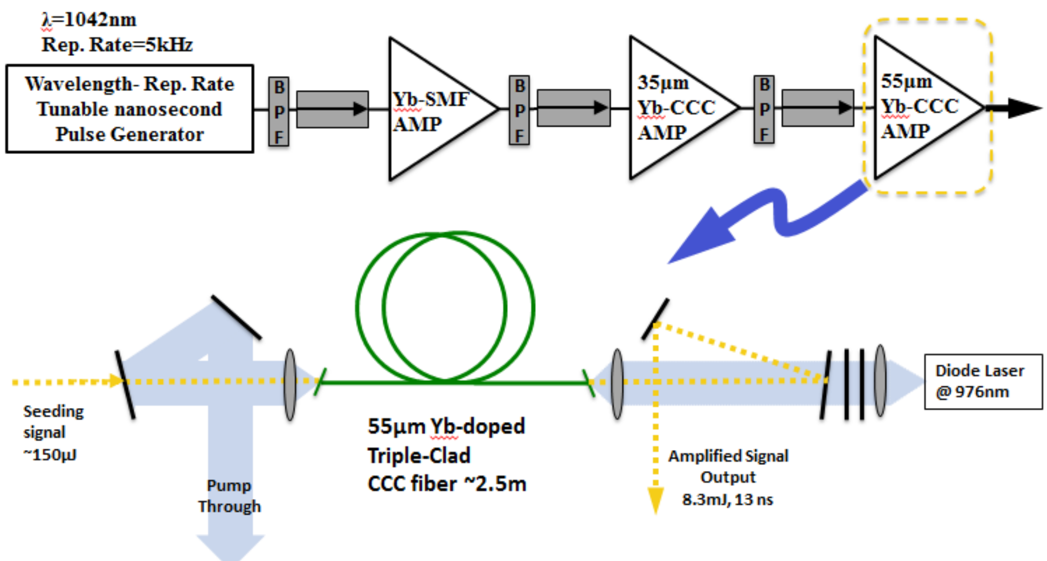

Figure 13. Diagram of experimental setup for pulse amplification in 55 µm core 3C fiber amplifier.

4.2 Results and Discussion

With 183 W of pump power, the final stage amplified the pulse energy to 8.3 mJ, corresponding to a peak power of 640 kW, while maintaining a single-mode quality beam as shown in Figure 14. Although the pulse energy was well above the saturation energy of ~1mJ, Figure 15 illustrates that there is little indication of the pulse reshaping in the time domain. This is a consequence of the Gaussian temporal shape which has a smooth and gradual turn-on and turn-off times and as a result does not change shape as the amplifier gain changes during the pulse duration. On a linear scale the pulse maintains a 2 nm full-width half-max (FWHM) spectrum, while the log scale shows significant broadening in the low energy wings of the pulse, a result of self-phase modulation. There was no measurable power in the Raman wavelength region of 1120 nm at pulse energies up to 8.3 mJ. This indicates that significantly higher pulse energies and peak powers may be achievable and practical for applications that are not particularly sensitive to spectral width.

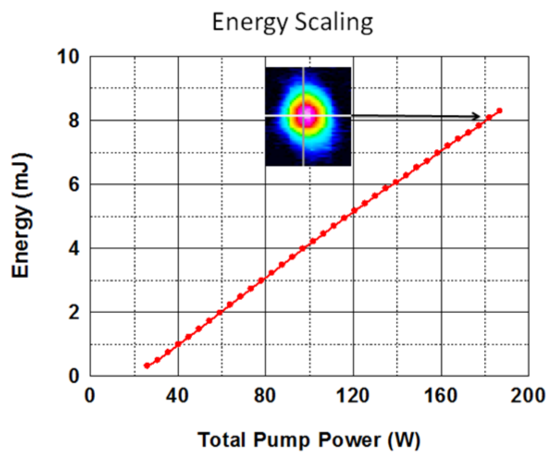

Figure 14. Pulse energy from the final stage 3C amplifier as a function of pump power. A single mode quality beam is maintained up to full power levels.

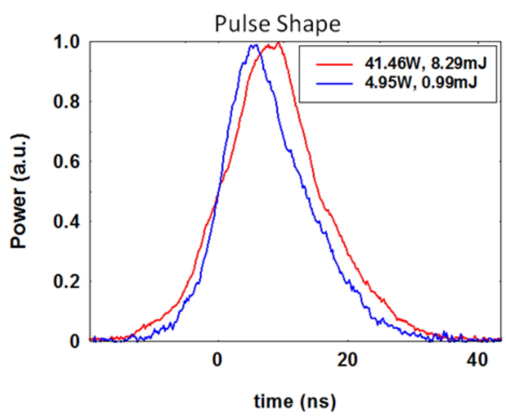

Figure 15. Pulse temporal shape at 0.99 and 8.29 mJ. The smooth spectral shape does not change significantly even at amplification to pulse energies up to 8X the saturation energy.

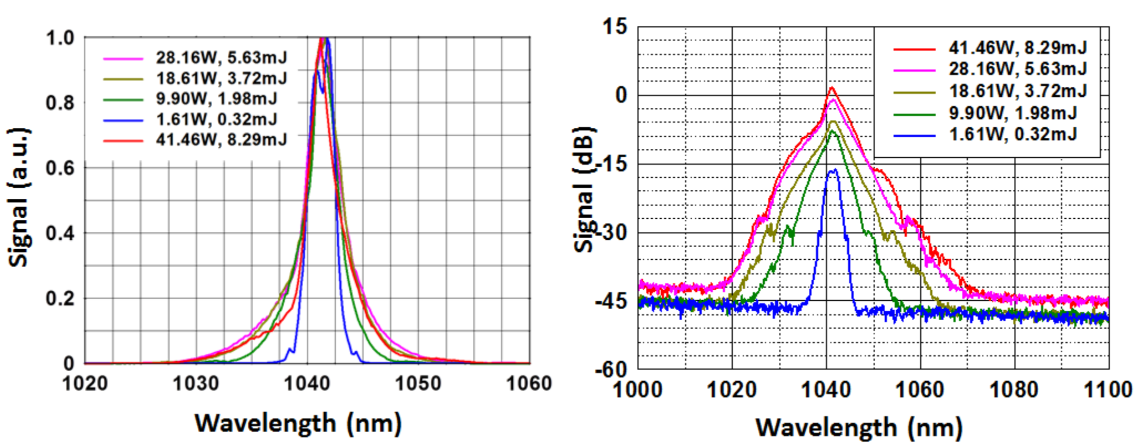

Figure 16. Pulse spectrum on a linear scale (left) and a log scale (right) vs. pulse energy. 8.29 mJ corresponds to a peak power of 640 kW.

5. CONCLUSION

These experimental results demonstrate the promise of pulsed fiber laser systems based on 3C fiber technology. 3C fibers are capable of delivering state of the art performance while maintaining most of the benefits associated with conventional fibers. The large pulse energies (8 mJ), high peak powers (640 kW) and high average powers (> 250 W) reported in this paper are well outside the capabilities of conventional single mode fibers.

Alternative fiber designs that enable scaling of the pulsed performance exist and have been demonstrated for 50 µm and even larger core sizes. However these other larger core fibers generally loose many of the characteristics that make fiber-based technology attractive in the first place. In contrast, 3C fiber maintains these key characteristics:

- It maintains a robust single mode immune to environmental perturbations
- It is spliceable using standard commercial cleaving and splicing equipment
- It operates correctly while being maintained straight, bent or coiled as needed for packaging or pigtailing of components
- It maintains polarization states
- It is compatible with all in-fiber system designs

These characteristics have many practical benefits. The robust nature of the mode and the compatibility with standard fiber splicing equipment make it practical for technicians to assemble 3C fiber based systems. The flexibility in the fiber arrangement (straight or bent) enables flexible packaging options and monolithic integration for compact, robust and reliable systems. It polarization characteristics allow for polarized systems compatible with harmonic conversion - critical for many machining applications. These benefits make 3C an ideal technology for expanding the capabilities of cost-effective commercial pulsed laser systems.

REFERENCES

[1] X. Ma, A. Kaplan, I. Hu, and A. Galvanauskas, "Characterization of Single-Mode Performance of Chirally-Coupled-Core Fibers with Cores Larger than 50µm," in *CLEO:* Science and Innovations, OSA Technical Digest (online) (Optical Society of America, 2012), paper CM1N.7.

[2] C. D. Brooks and F. Di Teodoro, “Multimegawatt peakpower, single-transverse-mode operation of a 100 µm core diameter, Yb-doped rodlike photonic crystal fiber amplifier,” Appl. Phys. Lett. 89, 111119 (2006).

[3] I. Hu, X. Ma, C. Zhu, C. Liu, T. Sosnowski, and A. Galvanauskas, "Experimental Demonstration of SRS Suppression in Chirally-Coupled-Core Fibers," in Lasers, Sources, and Related Photonic Devices, OSA Technical Digest (CD) (2012), paper AT1A.3.