REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
03-10-2022	Final Report	20-Aug-2012 - 19-Aug-2020

4. TITLE AND SUBTITLE
Final Report: Fiber Laser Light Engines - A New Platform to Collectively Address Power-limiting Constraints

5a. CONTRACT NUMBER
W911NF-12-1-0450

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
62119-ES-HEL.85

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Rodrigo Amezcua Correa
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RPPR Final Report
as of 06-Oct-2022

Agency Code: 21XD

Proposal Number: 62119ESHEL **Agreement Number: W911NF-12-1-0450**

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Report Date: 19-Nov-2020 Date Received: 03-Oct-2022
Final Report for Period Beginning 20-Aug-2012 and Ending 19-Aug-2020
Title: Fiber Laser Light Engines - A New Platform to Collectively Address Power-limiting Constraints
Begin Performance Period: 20-Aug-2012 **End Performance Period:** 19-Aug-2020
Report Term: 0-Other
Submitted By: Rodrigo Amezcua Correa Email: r.amezcua@creol.ucf.edu
Phone: (407) 823-6800
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 2 **STEM Participants:**

Major Goals: For fiber lasers to reach the 20 kW range several limits must be overcome. We identify three of these as the well-known Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) mechanisms, and the recently identified phenomenon now becoming termed, Thermal Modal Instability (TMI). This instability has thus far not been overcome through advanced mode discrimination techniques. In this research program we are investigating the TMI power-scaling limits through an integrated methodology oriented to circumventing or mitigating these limitations through the development of new fiber design/fabrication methods, new high power components for fiber laser system integration, as well as novel modeling and measurement techniques for the characterization of thermal mode instabilities in the kW regime. Although anecdotal reports of modal instabilities have been circulating for years, TMI has only recently been identified as a fundamental limitation to the increasing single-mode power in fiber lasers. During this project, we are developing advanced optical fiber waveguide designs that mitigate the modal instability going beyond conventional modal discrimination techniques. To do this we are studying the onset threshold with detailed high-fidelity time-dependent computer models implemented with advanced parallel algorithms on state-of-the-art supercomputers. Moreover, we are developing an integrated fiber laser system architecture in which intra-system free-space surfaces/interfaces are eliminated to avoid scattering, spurious reflection, uncontrolled heating, and points for optical-thermal- mechanical damage.

Accomplishments: This ARO-JTO funded project focuses on three main areas that collectively aim to increase power scalability in high-power fiber lasers: the design, fabrication, and experimental testing of large mode area Yb-doped fibers, optical fiber components for multi-kW laser systems and anti-resonant hollow-core fibers for high power beam delivery,

This program developed novel large mode area Yb-doped fibers in order to address critical physical limitations of power scaling in single mode fiber lasers, as well as to investigate the nonlinear physics in these complex multi-kW amplifiers. We also explore high power transport in hollow core fibers. The radically hollow core fibers studied here, have the potential for light transport and generation with orders of magnitude improvement compared to conventional single mode fibers. We also demonstrated a new fiber components that allow to control the spatial properties of light - this in turn can be used in high power beam steering and to compensate for beam distortions during propagation through the atmosphere.

Training Opportunities: The graduate students engaged in this project had the opportunity to experience all the steps involved, starting from conceiving an idea, designing a fiber, fabricating and characterizing new fibers and fiber components and to experimentally demonstrating multi-kW laser systems. New experimental setups were developed for testing multi-kW lasers and analyzing the modal content of the high power beams. The students developed software and new numerical models specifically for this task.

Training of students in high energy laser experiments is crucial to the JTO and ARO mission. Graduate students involved in the project participated in all aspects of fiber laser development.

We carried out theoretical and experimental investigations on high power amplifiers. We carried out theoretical and experimental investigations on thermal mode instabilities in multi-kW fiber lasers. The numerical tools developed to model these complex processes can be used to devise novel all- optical techniques through which one can mitigate detrimental nonlinear effects. Students working on this topic have been developing modeling and coding skills that can be transferred to many areas relevant to ARO.

Several of the graduate students that worked on this project are now involved in R&D efforts closely related to HEL. For example Clemence Jollivet, Joshua Bradford and Stefan Gaussman are working for coherent. Clemence is the Sr Sr. Engineering Manager Fiber R&D. Patrick Roumayah now works at Lockheed Martin Corporation.

Results Dissemination: The knowledge acquired during the program has been disseminated by means of presentations, publications, and classroom/laboratory demonstration to graduate students.

Honors and Awards: Corning Outstanding Student Paper Competition - Zahoora Sanjabieznaveh, University of Central Florida, USA (2016)

Axel Schulzgen:
Optical Society of America (OSA) Fellow
International Society for Optics and Photonics (SPIE) Fellow

Martin Richardson:
2017 Fulbright-Tocqueville Distinguished Chair
2015 Fulbright-Tocqueville Professorship (2016)
2015 Fellow, Institute of Physics (IoP), London, U.K
2014 Jefferson Science Fellowship, National Academy of Sciences at t U.S. State Department
2013 SPIE Harold E Edgerton Award

Protocol Activity Status:

Technology Transfer: • Collaboration with AFRL Fiber laser group, Albuquerque NM. Yb and Tm fiber lasers.
• Collaboration with Electro-Optics Center at Penn State University (Technical contact: Dr. Amy Van Newkirk, 2018 AFOSR Young Investigators Award) and Northrop Grumman on HCF fiber high power delivery.

• Collaboration with SAPhotonics developing hollow core optical fibers

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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National Academy Member: N

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Project Contribution:
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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
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National Academy Member: N

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Project Contribution:
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Project Contribution:
National Academy Member: N

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National Academy Member: N

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Project Contribution:
National Academy Member: N

ARTICLES:

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: N **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: Publication Identifier:
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Amplification of nanosecond pulses to megawatt peak power levels in Tm3+-doped photonic crystal fiber rod
Authors:
Keywords: Lasers and laser optics : Lasers, fiber(060.5295) Fiber optics and optical communications : Photonic crystal fibers
Abstract: We report amplification of sub-10–100 ns pulses with repetition rates from 1 to 20 kHz in a rod-type thulium-doped photonic crystal fiber with 80 ?m core diameter. The rod is pumped with a 793 nm laser diode and produces the highest peak power at 1 kHz repetition rate with 6.5 ns pulse duration and more than 7 W average output power. This result exemplifies the potential of this fiber design to scale pulse peak powers and pulse energies to the megawatt and multi-millijoule range in the 2 ?m wavelength regime.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Photonics Technology Letters
Publication Identifier Type: DOI Publication Identifier: 10.1109/LPT.2012.2227308
Volume: 25 Issue: 1 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Strong Bragg Gratings in Highly Photosensitive Photo-Thermo-Refractive-Glass Optical Fiber
Authors:
Keywords: Fiber Bragg grating, optical fiber fabrication, photo thermo refractive glass, photosensitivity.
Abstract: A new type of photosensitive fiber is demonstrated. Long lengths (>100 m) of coreless optical fiber are fabricated from highly photosensitive photo-thermo-refractive glass. A min- imum loss of <2 dB/m is measured. A holographic technique using low power near-UV two-beam interference patterns is applied to record strong and robust Bragg gratings inside the fiber. The gratings show no degradation when heated up to 425 °C for several hours.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Lightwave Technology
Publication Identifier Type: DOI Publication Identifier: 10.1109/JLT.2013.2297337
Volume: 32 Issue: 6 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Detailed Characterization of Optical Fibers by Combining <formula formulatype="inline"><tex Notation="TeX">$\bm S^{\bf 2}$</tex></formula> Imaging With Correlation Filter Mode Analysis
Authors:
Keywords: Fiber characterization, fiber optcis, large mode area fiber
Abstract: Spatially and spectrally resolved imaging (S^2 imaging) and correlation filter technique (CFT) are two very different, widespread fiber mode analysis techniques. Both techniques have been successfully employed to decompose few-modes and multimode beams respectively. In this study, we present a novel experimental tool combining S^2 imaging and CFT mode analyses in a unique system. We demonstrate that both methods are complementary with the ability to fully resolve scalar and vector-valued transverse modal fields. Using results from the combined experiment, mode powers (rho^2) evaluated from CFT analysis and S^2 imaging are directly compared for a wide range of fiber beams (from single- to multi-mode). As a result, we experimentally identify the mode detection limit of each mode analysis and prove that S^2 imaging accuracy range can be considerably increased employing an analytical mode evaluation method. The conclusion contains a table summarizing the expertise of each mode analysis.F
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optical Engineering
Publication Identifier Type: DOI Publication Identifier: 10.1117/1.OE.54.1.011006
Volume: 54 Issue: 1 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Comparative study of light propagation and single-mode operation in large-mode area fibers designed for 2-?m laser applications
Authors:
Keywords: fiber lasers; large-mode area fiber; specialty fiber design; fiber characterization; mode analysis
Abstract: Output performances of fiber-based optical systems, in particular fiber lasers and amplifiers, can be controlled using tailored fiber designs, gain profiles and pump light overlap with the gain medium. Here, the performances of 2 ?m light, propagating in three large-mode area (LMA) fibers, a step-index fiber (SIF), a photonic crystal fiber (PCF) and a leakage channel fiber (LCF), designed to deliver a single-mode (SM) beam at this wavelength, were compared. Using the S2 imaging technique, the transverse mode content has been decomposed and propagation losses, SM purity and mode-field area (MFA) were measured for various input mode overlap and coiling diameters. It was experimentally demonstrated that, coiling the PCF and LCF to 40 cm and 20 cm in diameter respectively resulted in efficient HOM suppression, pure SM beam delivery, moderate (~ 1 dB) coil-induced losses in the fundamental mode and non-distorted, large MFA (~ 1600 ?m2) beam delivery
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: N **Publication Status:** 1-Published
Journal:
Publication Identifier Type: Publication Identifier:
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Highly Photosensitive Fiber Fabricated from Photo-Thermo-Refractive Glass
Authors:
Keywords: Bragg grating
Abstract: With the goal to extend applications of highly photosensitive photo-thermo-refractive (PTR) glass from bulk glass components to the fiber optic platform, we have successfully fabricated single material fibers and step index fibers from PTR type glasses. The fibers were drawn from rod-in-tube preforms which have been prepared using specialty diamond tools for shaping and polishing of the glass materials. We measured attenuations of less than 0.1 dB/cm in our PTR glass fibers. Strong fiber Bragg gratings were inscribed into the novel fibers demonstrating the fibers photosensitivity. High grating strength of up to 20 dB were reached and maintained even at 12 hour exposure to temperatures above 400 °C. Our results open exciting new avenues for the development of holographic PTR glass fiber optic components which may be applied in fiber optic devices that require high temperature stability and high optical power levels.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.39.001212
Volume: 39 Issue: 5 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: High peak-power mid-infrared ZnGeP_2 optical parametric oscillator pumped by a Tm:fiber master oscillator power amplifier system
Authors:
Keywords: (060.5295) Photonic crystal fibers; (190.4970) Parametric oscillators and amplifiers
Abstract: We report on the utilization of a novel Tm:fiber laser source for mid-IR ZnGeP2 (ZGP) optical parametric oscillator (OPO) pumping. The pump laser is built in a master oscillator power-amplifier configuration delivering up to 3.36 W of polarized, diffraction limited output power with 7 ns pulse duration and 4 kHz repetition rate. This corresponds to a peak power of ?121 kW and a pulse energy of ?0.84 mJ. With this source, we generated 27.9 kW of total mid-IR peak power in a doubly resonant oscillator (DRO) configuration. This is, to the best of our knowledge, the highest ever demonstrated mid-IR peak power from a directly Tm:fiber laser pumped ZGP OPO. Moreover, a DRO output with about 284 ?J of total mid-IR pulse energy was demonstrated using 100 ns pump pulses. The wavelength tuning of the idler was extended to 6 ?m with lower output power in another OPO experiment.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.40.000542
Volume: 4.0E+001 Issue: 4.0E+000 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Maximizing power output from continuous-wave single-frequency fiber amplifiers
Authors:
Keywords: (140.3510) Lasers, fiber; (140.3280) Laser amplifiers; (060.2280) Fiber design and fabrication; (190.5890) Scattering, stimulated; (190.3100) Instabilities and chaos.
Abstract: This Letter reports on a method of maximizing the power output from highly saturated cladding-pumped continu- ous-wave single-frequency fiber amplifiers simultaneously, taking into account the stimulated Brillouin scattering and transverse modal instability thresholds. This results in a design figure of merit depending on the fundamental mode overlap with the doping profile, the peak Brillouin gain coefficient, and the peak mode coupling gain coef- ficient. This figure of merit is then numerically analyzed for three candidate fiber designs including standard, seg- mented acoustically tailored, and micro-segmented acoustically tailored photonic-crystal fibers. It is found that each of the latter two fibers should enable a 50% higher output power than standard photonic crystal fiber.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.22.030377
Volume: 2.2E+001 Issue: 2.4E+001 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Mode-resolved gain analysis and lasing in multi-supermode multi-core fiber laser
Authors:
Keywords: (060.3510) Lasers, fiber; (060.4005) Microstructured fibers; (060.2270) Fiber characterization.
Abstract: Multi-core fibers (MCFs) with coupled-cores are attractive large- mode area (LMA) specialty fiber designs that support the propagation of a few transverse modes often called supermodes (SMs). Compared to other LMA fibers, the uniqueness of MCF arises from the higher degrees of design space offered by a multitude of core-array geometries, resulting in extended flexibility to tailor SM properties. To date, the use of MCF as gain media has focused on lasers that operate in only one selected SM, typically the lowest order in-phase SM, which considerably limited the potential of these multi-core structures. Here, we expand the potential of MCF lasers by investigating multi-SM amplification and lasing schemes. Amplifier and laser systems using a 7 coupled-cores Yb-doped MCF as gain medium were successfully designed and assembled. Individual SM could be decomposed using the correlation filter technique mode analysis and the modal amplification factors (?i) were recorded. With access to amplif
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optical Engineering
Publication Identifier Type: DOI Publication Identifier: 10.1117/1.OE.54.7.076104
Volume: 5.4E+001 Issue: 7.0E+000 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Holographically encoded volume phase masks
Authors:
Keywords: holographic optical elements; phase masks; volume gratings; Bragg gratings; laser beam shaping; laser beam combining
Abstract: We present here a method to create spectrally addressable phase masks by encoding phase profiles into volume Bragg gratings, allowing these holographic elements to be used as phase masks at any wavelength capable of satisfying the Bragg condition of the hologram. Moreover, this approach enables the capability to encode and multiplex several phase masks into a single holographic element without cross-talk while maintaining a high dif- fraction efficiency. As examples, we demonstrate fiber mode conversion with near-theoretical conversion efficiency as well as simultaneous mode conversion and beam combining at wavelengths far from the original hologram recording wavelength.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.41.002588
Volume: 41 Issue: 11 First Page #: 2588
Date Submitted: 8/31/16 12:00AM Date Published: 5/1/16 8:00AM
Publication Location:
Article Title: Few-mode erbium-doped fiber amplifier with photonic lantern for pump spatial mode control
Authors: G. Lopez-Galmiche, Z. Sanjabi Eznaveh, J. E. Antonio-Lopez, A. M. Velazquez Benitez, J. Rodriguez As
Keywords: 060.0060) Fiber optics and optical communications; (060.2410) Fibers, erbium; (060.2320) Fiber optics amplifiers and oscillators; (060.4230) Multiplexing
Abstract: We demonstrate a few-mode erbium-doped fiber amplifier employing a mode-selective photonic lantern for controlling the modal content of the pump light. Amplification of six spatial modes in a 5 m long erbium-doped fiber to ?6.2??dBm average power is obtained while maintaining high modal fidelity. Through mode-selective forward pumping of the two degenerate LP21 modes operating at 976 nm, differential modal gains of <1??dB between all modes and signal gains of ?16??dB at 1550 nm are achieved. In addition, low differential modal gain for near-full C-band operation is demonstrated.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.41.003277
Volume: 41 Issue: 14 First Page #: 3277
Date Submitted: 8/31/16 12:00AM Date Published: 7/1/16 4:00AM
Publication Location:
Article Title: Modal analysis of antiresonant hollow core fibers using S^2 imaging
Authors: Amy Van Newkirk, J. E. Antonio-Lopez, James Anderson, Roberto Alvarez-Aguirre, Zeinab Sanjabi Ezn
Keywords: (060.2270) Fiber characterization; (060.2280) Fiber design and fabrication.
Abstract: We analyze the higher-order core mode content in various designs of antiresonant hollow core fibers using spatially and spectrally resolved imaging. Hollow core fibers have great potential for a variety of applications, and understand- ing their mode content is crucial for many of these. Two dif- ferent designs of hollow core fibers are considered, the first with eight nontouching rings and the second with eight touching rings forming a closed boundary core. The mode content of each fiber is measured as a function of length and bending diameter. Low amounts of higher-order modes were found in both hollow core fibers, and mode specific and bending-dependent losses have been determined. This study aids in understanding the core modes of hollow core fibers and possible methods of controlling them.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.41.002157
Volume: 41 Issue: 10 First Page #: 2157
Date Submitted: 8/31/16 12:00AM Date Published: 5/1/16 4:00AM
Publication Location:
Article Title: Mode-selective amplification in a large mode area Yb-doped fiber using a photonic lantern
Authors: S. Wittek, R. Bustos Ramirez, J. Alvarado Zacarias, Z. Sanjabi Eznaveh, J. Bradford, G. Lopez Galmich
Keywords: (060.2320) Fiber optics amplifiers and oscillators; (060.2340) Fiber optics components.
Abstract: We demonstrate selective spatial mode amplification in a few mode, double-clad Yb-doped large mode area (LMA) fiber, utilizing an all-fiber photonic lantern. Amplification to multi-watt output power is achieved while preserving high spatial mode selectivity. We observe gain values of over 12 dB for all modes: LP01 , LP11a , and LP11b, when amplified individually. Additionally, we inves- tigate the simultaneous amplification of LP01 LP11a and LP11a LP11b, and the resultant mode competition. The proposed architecture allows for the reconfigurable excita- tion of spatial modes in the LMA fiber amplifiers, and rep- resents a promising method that could enable dynamic
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.41.002553
Volume: 41 Issue: 11 First Page #: 2553
Date Submitted: 8/31/16 12:00AM Date Published: 5/1/16 8:00AM
Publication Location:
Article Title: Visible supercontinuum generation in a graded index multimode fiber pumped at 1064??nm
Authors: G. Lopez-Galmiche, Z. Sanjabi Eznaveh, M. A. Eftekhar, J. Antonio Lopez, L. G. Wright, F. Wise, D. Chı
Keywords: 190.4370) Nonlinear optics, fibers; (190.4380) Nonlinear optics, four-wave mixing; (190.5650) Raman effect; (190.4410) Nonlinear optics, parametric processes.
Abstract: We observe efficient supercontinuum generation that extends into the visible spectral range by pumping a low differential mode group delay graded index multimode fiber in the normal dispersion regime. For a 28.5 m long fiber, the generated spectrum spans more than two octaves, starting from below 450 nm and extending beyond 2400 nm. The main nonlinear mechanisms contributing to the visible spectrum generation are attributed to multipath four-wave mixing processes and periodic spatio-temporal breathing dynamics. Moreover, by exploiting the highly multimodal nature of this system, we demonstrate versatile generation of visible spectral peaks in shorter fiber spans by altering the launching conditions. A nonlinearly induced mode cleanup was also observed at the pump wavelength. Our results could pave the way for high brightness, high power, and compact, multi-octave continuum sources.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.42.001015
Volume: 42 Issue: 5 First Page #: 1015
Date Submitted: 1/2/19 12:00AM Date Published: 3/1/17 5:00AM
Publication Location:
Article Title: Tailoring frequency generation in uniform and concatenated multimode fibers
Authors: Z. Sanjabi Eznaveh, M. A. Eftekhar, J. E. Antonio Lopez, M. Kolesik, A. Schülzgen, F. W. Wise, D. N. Cl
Keywords: Nonlinear optics, fibers; (190.4410) Nonlinear optics, parametric processes; (190.4380) Nonlinear optics, four-wave mixing; (060.0060) Fiber optics and optical communica- tions.
Abstract: We demonstrate that frequency generation in multimode parabolic-index fibers can be precisely engineered through appropriate fiber design. This is accomplished by exploiting the onset of a geometric parametric instability that arises from resonant spatiotemporal compression. By launching the output of an amplified Q-switched microchip laser delivering 400 ps pulses at 1064 nm, we observe a series of intense frequency sidebands that strongly depend on the fiber core size. The nonlinear frequency generation is analyzed in three fiber samples with 50 ?m, 60 ?m, and 80 ?m core diameters. We further demonstrate that by cas- cading fibers of different core sizes, a desired frequency band can be generated from the frequency lines parametri- cally produced in each section. The observed frequency shifts are in good agreement with analytical predictions and numerical simulations. Our results suggest that core scaling and fiber concatenation can provide a viable avenue in designing optical source
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.42.001974
Volume: 42 Issue: 10 First Page #: 1974
Date Submitted: 1/2/19 12:00AM Date Published: 5/1/17 8:00AM
Publication Location:
Article Title: Reduced-symmetry LMA rod-type fiber for enhanced higher-order mode delocalization
Authors: Z. Sanjabi Eznaveh, J. E. Antonio-Lopez, J. Anderson, A. Schülzgen, R. Amezcua-Correa
Keywords: Fiber design and fabrication; (060.4005) Microstructured fibers; (060.2430) Fibers, single-mode; (060.3510) Lasers, fiber.
Abstract: We present a novel design of a micro-structured large-pitch, large-mode-area (LMA) asymmetric rod-type fiber. By reduc- ing the cladding symmetry through six high-refractive index germanium-doped silica inclusions, the fiber features strong higher-order mode (HOM) delocalization, leading to a po- tentially enhanced preferential gain for the fundamental mode in active fibers. In addition, high resolution spatially and spectrally (S2) resolved mode analysis measurements confirm HOM contributions below 1% and LP1m-like HOM contributions below the detection limit. This pro- posed fiber design enables single-mode operation, with near-diffraction-limited beam quality of M 2 ┌ 1.3 and an effective mode area of 2560 ?m2 at 1064 nm. This design opens new insights into improving the threshold-like onset of modal instabilities in high-power fiber lasers and fiber amplifiers by efficiently suppressing LP11 modes
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.25.009078
Volume: 25 Issue: 8 First Page #: 9078
Date Submitted: 1/2/19 12:00AM Date Published: 4/1/17 12:00PM
Publication Location:
Article Title: Versatile supercontinuum generation in parabolic multimode optical fibers
Authors: M. A. Eftekhar, L. G. Wright, M. S. Mills, M. Kolesik, R. Amezcua Correa, F. W. Wise, D. N. Christodouli
Keywords: Nonlinear optics, fibers; (190.4380) Nonlinear optics, four-wave mixing; (320.6629) Supercontinuum generation
Abstract: We demonstrate that the pump's spatial input profile can provide additional degrees of freedom in tailoring at will the nonlinear dynamics and the ensuing spectral content of supercontinuum generation in highly multimoded optical fibers. Experiments and simulations carried out at 1550 nm indicate that the modal composition of the input beam can substantially alter the soliton fission process as well as the resulting Raman and dispersive wave generation that eventually lead to supercontinuum in such a multimode environment. Given the multitude of conceivable initial conditions, our results suggest that it is possible to pre-engineer the supercontinuum spectral content in a versatile manner.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.25.016701
Volume: 25 Issue: 14 First Page #: 16701
Date Submitted: 1/2/19 12:00AM Date Published: 7/1/17 12:00PM
Publication Location:
Article Title: All-fiber few-mode multicore photonic lantern mode multiplexer
Authors: Z. Sanjabi Eznaveh, J. E. Antonio-Lopez, J. C. Alvarado Zacarias, A. Schülzgen, C. M. Okonkwo, R. Am
Keywords: Multiplexing; (060.2340) Fiber optics components; (060.2330) Fiber optics communications.
Abstract: The emergence of space division multiplexing (SDM) for ultrahigh capacity networks has heralded pioneering Petabit-class optical transmission systems. In parallel to novel SDM fibers, a new class of components to enable scalable, low-loss schemes for unlocking fiber capacity is being developed. In this work, an all-fiber mode selective photonic lantern mode multiplexer designed for launching into few-mode multicore fibers is demonstrated. This device is capable of selectively exciting LP01, LP11a and LP11b modes in a seven-core configuration, resulting in 21 spatial channels, with less than 38 dB core-to-core crosstalk and insertion loss below 0.4 dB. The multicore photonic lantern multiplexer is scalable to larger number of cores and modes per core, and can be easily integrated with emerging ultra-high bandwidth few-mode multicore optical communication systems.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.42.003478
Volume: 42 Issue: 17 First Page #: 3478
Date Submitted: 1/2/19 12:00AM Date Published: 8/1/17 4:00AM
Publication Location:
Article Title: Instant and efficient second-harmonic generation and downconversion in unprepared graded-index multimode fibers
Authors: M. A. Eftekhar, Z. Sanjabi-Eznaveh, J. E. Antonio-Lopez, F. W. Wise, D. N. Christodoulides, R. Amezcu
Keywords: Nonlinear optics, fibers; (190.2620) Harmonic generation and mixing; (190.4223) Nonlinear wave mixing; (190.4380) Nonlinear optics, four-wave mixing.
Abstract: We show that germanium-doped graded-index multimode silica fibers can exhibit relatively high conversion efficien- cies (?6.5%) for second-harmonic generation when excited at 1064 nm. This frequency-doubling behavior is also found to be accompanied by an effective downconversion. As op- posed to previous experiments carried out in single- and few-mode fibers where hours of preparation were required, in our system, these ?┌2┌ related processes occur almost in- stantaneously. The efficiencies observed in our experiments are, to the best of our knowledge, among the highest ever reported in unprepared fibers
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.42.004179
Volume: 42 Issue: 20 First Page #: 4179
Date Submitted: 1/2/19 12:00AM Date Published: 10/1/17 4:00AM
Publication Location:
Article Title: Nonlinear pulse compression to 43??W GW-class few-cycle pulses at 2???m wavelength
Authors: M. Gebhardt, C. Gaida, T. Heuermann, F. Stutzki, C. Jauregui, J. Antonio-Lopez, A. Schulzgen, R. Ame
Keywords: Ultrafast optics; (320.5520) Pulse compression; (140.3070) Infrared and far-infrared lasers.
Abstract: High-average power laser sources delivering intense few-cycle pulses in wavelength regions beyond the near infrared are promising tools for driving the next generation of high-flux strong-field experiments. In this work, we report on nonlinear pulse compression to 34.4 ?J-, 2.1-cycle pulses with 1.4 GW peak power at a central wavelength of 1.82 ?m and an average power of 43 W. This performance level was enabled by the combination of a high-repetition-rate ultrafast thulium- doped fiber laser system and a gas-filled antiresonant hollow- core fiber.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Scientific Reports
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41598-018-27072-2
Volume: 8 Issue: 1 First Page #:
Date Submitted: 1/2/19 12:00AM Date Published: 6/1/18 4:00AM
Publication Location:
Article Title: Scaling photonic lanterns for space-division multiplexing
Authors: Amado M. Velázquez-Benítez, J. Enrique Antonio-López, Juan C. Alvarado-Zacarías, Nicolas K. Fontair
Keywords: mode multiplexer, photonic lantern, mode control
Abstract: We present a new technique allowing the fabrication of large modal count photonic lanterns for space-division multiplexing applications. We demonstrate mode-selective photonic lanterns supporting 10 and 15 spatial channels by using graded-index fibres and microstructured templates. These templates are a versatile approach to position the graded-index fibres in the required geometry for efficient mode sampling and conversion. Thus, providing an effective scalable method for large number of spatial modes in a repeatable manner. Further, we demonstrate the efficiency and functionality of our photonic lanterns for optical communications. Our results show low insertion and mode dependent losses, as well as enhanced mode selectivity when spliced to few mode transmission fibres. These photonic lantern mode multiplexers are an enabling technology for future ultra-high capacity optical transmission systems.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: APL Photonics
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.5044659
Volume: 4 Issue: 2 First Page #: 022803
Date Submitted: 1/16/21 12:00AM Date Published: 2/1/19 3:00PM
Publication Location:
Article Title: A systematic analysis of parametric instabilities in nonlinear parabolic multimode fibers
Authors: H. E. Lopez-Aviles, F. O. Wu, Z. Sanjabi Eznaveh, M. A. Eftekhar, F. Wise, R. Amezcua Correa, D. N. C
Keywords: fiber optics, nonlinear optics
Abstract: We provide a systematic analysis of geometric parametric instabilities in nonlinear graded-index multimode fibers. Our approach implicitly accounts for self-focusing effects and considers dispersion processes to all orders. It is shown that the resulting para- metric problem takes the form of a Hill's equation that can be systematically addressed using a Floquet approach. The theory developed indicates that the unstable spectral domains associated with such geometric parametric instabilities can be signifi- cantly altered as the power levels injected in a parabolic multimode fiber increase. These predictions are in excellent agreement with experimental data gathered from graded-index multimode structures.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Lightwave Technology
Publication Identifier Type: DOI Publication Identifier: 10.1109/JLT.2020.2969012
Volume: 38 Issue: 7 First Page #: 1953
Date Submitted: 1/16/21 12:00AM Date Published: 4/1/20 4:00AM
Publication Location:
Article Title: S2 Measurements Showing Suppression of Higher Order Modes in Confined Rare Earth Doped Large Core Fibers
Authors: Stefan Gausmann, Jose E. Antonio-Lopez, James Anderson, Steffen Wittek, Sanjabi Eznaveh Eznaveh
Keywords: Doped fiber amplifiers, fiber lasers, optical fibers.
Abstract: We present a detailed investigation on higher order mode suppression due to differential gain in large mode area step index fiber amplifiers with confined Yb doping using spatially and spectrally resolved imaging (S2). A novel active fiber with Yb doping confined to the central 30% of the core area is fabricated and its performance is directly compared to a fiber with a conventional homogeneously doped core with almost identical parameters. At high pump rates, S2 and beam pointing stability measurements clearly demonstrate fundamental mode operation of the confined doping few mode fiber, even under imperfect launching conditions and environmental perturbations. In addition, we discuss the mode content as a function of gain in co-pumped fiber amplifiers with and without confined rare earth core doping using a power propagation model for fibers with similar parameters to those used in our exper- iments. Our simulation results as well as amplification experiments indicate the great poten
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Photonics Technology Letters
Publication Identifier Type: DOI Publication Identifier: 10.1109/LPT.2019.2908953
Volume: 31 Issue: 10 First Page #: 795
Date Submitted: 1/16/21 12:00AM Date Published: 5/1/19 4:00AM
Publication Location:
Article Title: Extreme UV Light Generation Through Dispersive Wave Trapping in a Tapered Gas-Filled Hollow Fiber
Authors: Md. Selim Habib, Christos Markos, J. E. Antonio-Lopez, Rodrigo Amezcua-Correa
Keywords: Hollow-core anti-resonant fiber, ultrafast non- linear dynamics, pulse compression, gas-filled fiber taper
Abstract: In this letter, we demonstrate how the soliton– plasma interaction initiates trapping of the generated dispersive waves (DWs) in an experimentally feasible tapered He-filled hollow-core anti-resonant fiber (HC-ARF). We show that the taper gradient strongly influences the pulse trapping dynam- ics and thus determines the intensity and blueshift of the trapped DW. This process leads to an efficient DW generation down to 100 nm with a 3.4-octave supercontinuum spanning 100–1150 nm (2.73 PHz) by tapering a 36-?m core HC-ARF to 18 ?m under 19-bar He, pumped at 800 nm with 6-?J pulse energy. The proposed fiber taper structure could be an alternative route to generate light in the extreme ultra-violet (EUV) spectral range using moderate gas pressure and relatively low pulse energy.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Journal of Selected Topics in Quantum Electronics
Publication Identifier Type: DOI Publication Identifier: 10.1109/JSTQE.2017.2775964
Volume: 24 Issue: 3 First Page #: 1
Date Submitted: 1/16/21 12:00AM Date Published: 5/1/18 4:00AM
Publication Location:
Article Title: High Average Power Thulium-Doped Silica Fiber Lasers: Review of Systems and Concepts
Authors: Alex Sincore, Joshua D. Bradford, Justin Cook, Lawrence Shah, Martin C. Richardson
Keywords: 2 ?m, cross-relaxation, energy transfer processes, high power fiber lasers, in-band pumping, resonant pumping, tan- dem pumping, thulium-doped fiber lasers.
Abstract: Thulium-doped fiber lasers (TDFLs) have had the second highest growth in average output power next to ytterbium- doped fiber lasers. This has been enabled by access to high power, high brightness ?790-nm pump diodes in conjunction with the cross-relaxation process that improves laser efficiency. While numerous high power TDFLs have been recently demonstrated, a 1-kW result from 2010 remains the highest output power system reported to date. This paper reviews these systems and the con- cepts behind high power TDFLs. The spectroscopic properties of Tm3+ -doped silica are first detailed, revealing complex processes and large variations among published measurements. Notable multi-100 W TDFLs are then summarized, with outputs ranging from 1908 to 2130 nm. Another route for power scaling is to in- band pump with another TDFL to enable >90% efficiencies. Both 790- and 1900-nm pumped TDFL architectures are theoretically modeled based on currently available systems. Hindered by high background
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Lightwave Technology
Publication Identifier Type: DOI Publication Identifier: 10.1109/JLT.2020.2971943
Volume: 38 Issue: 7 First Page #: 1959
Date Submitted: 1/16/21 12:00AM Date Published: 4/1/20 4:00AM
Publication Location:
Article Title: Design of Negative Curvature Hollow Core Fiber Based on Reinforcement Learning
Authors: Xiaowen Hu, Axel Schulzgen
Keywords: Negative curvature hollow core fiber, optical fiber design, reinforcement learning.
Abstract: in negative curvature hollow core fibers (NCHCFs), light guidance is based on the capillary structure in the cladding. To achieve desirable fiber propagation properties, various designs of the capillary structure have been proposed in literature. However, the design process so far depends more or less on experience. In this article, we propose a reinforcement learning (RL) based method of systematically optimizing the capillary structure to achieve low average confinement loss (CL) for a given operating wavelength range and core radius. We use a recurrent neural network (RNN) to interactively study the properties of different capillary structures. The wavelength averaged CLs of the resulting designs are more than one order of magnitude lower than the lowest average CL of prior designs in literature. The same approach can be applied to search for optimum capillary structures in terms of other fiber propagation properties such as bending loss (BL), higher order modes extinction ratio (HO
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Physics: Conference Series
Publication Identifier Type: DOI Publication Identifier: 10.1088/1742-6596/1003/1/012120
Volume: 1003 Issue: First Page #: 012120
Date Submitted: 1/16/21 12:00AM Date Published: 5/1/18 4:00AM
Publication Location:
Article Title: Influence of Temperature on Nanosecond Pulse Amplification in Thulium Doped Fiber Lasers
Authors: Ali Abdulfattah, Stefan Gausmann, Alex Sincore, Joshua Bradford, Nathan Bodnar, Justin Cook, Lawrer
Keywords: 2um laser, thulium fiber
Abstract: in negative curvature hollow core fibers (NCHCFs), light guidance is based on the capillary structure in the cladding. To achieve desirable fiber propagation properties, various designs of the capillary structure have been proposed in literature. However, the design process so far depends more or less on experience. In this article, we propose a reinforcement learning (RL) based method of systematically optimizing the capillary structure to achieve low average confinement loss (CL) for a given operating wavelength range and core radius. We use a recurrent neural network (RNN) to interactively study the properties of different capillary structures. The wavelength averaged CLs of the resulting designs are more than one order of magnitude lower than the lowest average CL of prior designs in literature. The same approach can be applied to search for optimum capillary structures in terms of other fiber propagation properties such as bending loss (BL), higher order modes extinction ratio (HO
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Applied Optics
Publication Identifier Type: DOI Publication Identifier: 10.1364/AO.58.0000D7
Volume: 58 Issue: 13 First Page #:
Date Submitted: 1/16/21 12:00AM Date Published: 3/1/19 5:00AM
Publication Location:
Article Title: Multioctave supercontinuum from visible to mid-infrared and bend effects on ultrafast nonlinear dynamics in gas-filled hollow-core fiber
Authors: Md Selim Habib, Christos Markos, J. E. Antonio-Lopez, Rodrigo Amezcua-Correa
Keywords: hollow core fiber, nonlinear fiber optics
Abstract: Broadband supercontinuum generation is numerically investigated in a Xe-filled nested hollow-core antiresonant (HC-AR) fiber pumped at 3 ?m with pulses of 100 fs duration and 15 ?J energy. For a 25 cm long fiber, under 7 bar pressure, the supercontinuum spectrum spans multiple octaves from 400 nm to 5000 nm. Furthermore, the influence of bending on ultrafast nonlinear pulse propagation dynamics is investigated for two types of HC-AR fibers (nested and non-nested capillaries). Our results predict similar nonlinear dynamics for both fiber types and a significant reduction of the spectral broadening under tight bending conditions.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Lightwave Technology
Publication Identifier Type: DOI Publication Identifier: 10.1109/JLT.2017.2729508
Volume: 35 Issue: 18 First Page #: 4000
Date Submitted: 1/16/21 12:00AM Date Published: 9/1/17 4:00AM
Publication Location:
Article Title: SBS Threshold Dependence on Pulse Duration in a 2053 nm Single-Mode Fiber Amplifier
Authors: Alex Sincore, Nathan Bodnar, Joshua Bradford, Ali Abdulfattah, Lawrence Shah, Martin C. Richardson
Keywords: 2 ?m, fiber laser, nanosecond pulsed fiber laser, narrow linewidth, nonlinear optics, stimulated Brillouin scattering, thulium-doped fiber amplifier.
Abstract: Stimulated Brillouin scattering (SBS) is the first non- linear effect that limits power scaling of narrow linewidth fiber lasers. Nonlinearities typically have a reduced impact when op- erating at longer wavelengths. However, the SBS gain is consid- ered wavelength independent. To investigate this further, a pulsed 2053 nm source with MHz-linewidth is amplified to >100 W peak powers in single-mode, thulium-doped fiber. The SBS thresholds were measured while varying the pulse duration. Analyzing the SBS threshold measurements suggests that the peak Brillouin gain coefficient is ?12.2 pm/W with a spontaneous Brillouin bandwidth of ?17.5 MHz in the passive single-mode fiber at 2053 nm. While the peak Brillouin gain coefficient is comparable to those reported at shorter wavelengths, the spontaneous Brillouin bandwidth is significantly narrower. This indicates that long wavelength sources can inhibit the onset of SBS more readily than short wavelength sources.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.26.024357
Volume: 26 Issue: 19 First Page #: 24357
Date Submitted: 1/16/21 12:00AM Date Published: 9/1/18 4:00AM
Publication Location:
Article Title: Multi-stage generation of extreme ultraviolet dispersive waves by tapering gas-filled hollow-core anti-resonant fibers
Authors: Md. Selim Habib, Christos Markos, J. Enrique Antonio-Lopez, Rodrigo Amezcua Correa, Ole Bang, Mor
Keywords: Photonic crystal fibers; (060.5530) Pulse propagation and temporal solitons; (190.7110) Ultrafast nonlinear optics; (190.7220) Upconversion.
Abstract: In this work, we numerically investigate an experimentally feasible design of a tapered Ne-filled hollow-core anti-resonant fiber and we report multi-stage generation of dispersive waves (DWs) in the range 90-120 nm, well into the extreme ultraviolet (UV) region. The simulations assume a 800 nm pump pulse with 30 fs 10 ?J pulse energy, launched into a 9 bar Ne-filled fiber with a 34 ?m initial core diameter that is then tapered to a 10 ?m core diameter. The simulations were performed using a new model that provides a realistic description of both loss and dispersion of the resonant and anti-resonant spectral bands of the fiber, and also importantly includes the material loss of silica in the UV. We show that by first generating solitons that emit DWs in the far-UV region in the pre-taper section, optimization of the following taper structure can allow re-collision with the solitons and further up-conversion of the far-UV DWs to the extreme-UV with energies up to 190 nJ in the 90-120 n
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.26.030042
Volume: 26 Issue: 23 First Page #: 30042
Date Submitted: 1/16/21 12:00AM Date Published: 10/1/18 4:00AM
Publication Location:
Article Title: Photonic lantern broadband orbital angular momentum mode multiplexer
Authors: Zeinab Sanjabi Eznaveh, Juan Carlos Alvarado Zacarias, Jose Enrique Antonio Lopez, Kai Shi, Giovanı
Keywords: photonic lantern, orbital angular momentum
Abstract: Optical vortex beams that carry orbital angular momentum (OAM), also known as OAM modes, have attracted considerable interest in recent years as they can comprise an additional degree of freedom for a variety of advanced classical and quantum optical applications. While canonical methods of OAM mode generation are effective, a method that can simultaneously generate and multiplex OAM modes with low loss and over broad spectral range is still in great demand. Here, via novel design of an optical fiber device referred to as a photonic lantern, where the radial mode index (“m”) is neglected, for the first time we demonstrate the simultaneous generation and multiplexing of OAM modes with low loss and over the broadest spectral range to date (550 nm). We further confirm the potential of this approach to preserve the quality of studied OAM modes by fusion splicing the end-facet of the fabricated device to a delivery ring-core fiber (RCF).
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.26.032777
Volume: 26 Issue: 25 First Page #: 32777
Date Submitted: 1/16/21 12:00AM Date Published: 11/1/18 4:00AM
Publication Location:
Article Title: Transverse mode-switchable fiber laser based on a photonic lantern
Authors: Ning Wang, J. C. Alvarado Zacarias, J. Enrique Antonio-Lopez, Z. Sanjabi Eznaveh, Cedric Gonnet, Pie
Keywords: photonic lantern, few mode laser
Abstract: We propose and experimentally demonstrate an intra-cavity transverse mode- switchable fiber laser based on a mode-selective photonic lantern and a few-mode Er-doped fiber amplifier. The six lowest-order LP modes can lase independently and are switchable by changing the input port of the photonic lantern. We measured the slope efficiency, mode intensity profile, and optical spectrum of each lasing mode. In addition, we demonstrate donut-shaped LP11 and LP21 modes using incoherent superposition and simultaneous lasing of the two degenerate modes.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.27.000225
Volume: 27 Issue: 1 First Page #: 225
Date Submitted: 1/16/21 12:00AM Date Published: 1/1/19 5:00AM
Publication Location:
Article Title: Achromatic complex holograms for laser mode conversion
Authors: Ivan Divliansky, Evan R. Hale, Marc Segall, Leonid B. Glebov
Keywords: phase masks, mode conversion
Abstract: While conventional complex phase masks are chromatic, we present an achromatic holographic phase mask capable of performing optical beam transformations in a spectral range exceeding 1000 nm. The system consists of a holographic phase mask fabricated by encoding the desired phase profiles into volume Bragg gratings, inserted in between two surface gratings. This device automatically adjusts each spectral component diffracted by the surface grating to the Bragg angle of the volume Bragg grating and equalizes phase incursion for all diffracted wavelengths. Transverse mode conversion is demonstrated and compared with theory for multiple narrow line laser sources operating from 488 to 1550 nm and for a broadband femtosecond source.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.27.003824
Volume: 27 Issue: 4 First Page #: 3824
Date Submitted: 1/16/21 12:00AM Date Published: 2/1/19 5:00AM
Publication Location:
Article Title: Single-mode, low loss hollow-core anti-resonant fiber designs
Authors: Md. Selim Habib, J. E. Antonio-Lopez, Christos Markos, Axel Schülzgen, Rodrigo Amezcua-Corre
Keywords: hollow core fiber
Abstract: In this paper, we numerically investigate various hollow-core anti-resonant (HC- AR) fibers towards low propagation and bend loss with effectively single-mode operation in the telecommunications window. We demonstrate how the propagation loss and higher-order mode modal contents are strongly influenced by the geometrical structure and the number of the anti-resonant cladding tubes. We found that 5-tube nested HC-AR fiber has a wider anti- resonant band, lower loss, and larger higher-order mode extinction ratio than designs with 6 or more anti-resonant tubes. A loss ratio between the higher-order modes and fundamental mode, as high as 12,000, is obtained in a 5-tube nested HC-AR fiber. To the best of our knowledge, this is the largest higher-order mode extinction ratio demonstrated in a hollow- core fiber at 1.55 ?m. In addition, we propose a modified 5-tube nested HC-AR fiber, with propagation loss below 1 dB/km from 1330 to 1660 nm. This fiber also has a small bend loss of ~15 dB/km f
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.27.035962
Volume: 27 Issue: 24 First Page #: 35962
Date Submitted: 1/16/21 12:00AM Date Published: 11/1/19 4:00AM
Publication Location:
Article Title: Low-crosstalk few-mode EDFAs using retro-reflection for single-mode fiber trunk lines and networks
Authors: Ning Wang, Inwoong Kim, Olga Vassilieva, Tadashi Ikeuchi, He Wen, J. E. Antonio-Lopez, J. C. Alvarac
Keywords: few mode fiber amplifier, photonic lanterns
Abstract: Few-mode EDFAs with low channel crosstalk can replace multiple parallel single- mode EDFAs in single-mode fiber trunk lines and networks. Here we proposed a low-crosstalk few-mode EDFA by exploiting the unitary property of the coupling matrix of a symmetric photonic lantern. We experimentally demonstrated a 3-channel few-mode EDFA using retro-reflection of a 3-mode symmetric photonic lantern. The small signal gain for all three channels are measured to be larger than 25 dB over the entire C-band and the crosstalks are below ?10 dB.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1364/OL.43.000423
Volume: 43 Issue: 3 First Page #: 423
Date Submitted: 1/16/21 12:00AM Date Published: 1/1/18 5:00AM
Publication Location:
Article Title: Single-frequency blue laser fiber amplifier
Authors: Masoud Mollaee, Xiushan Zhu, Jie Zong, Kort Wiersma, Arturo Chavez-Pirson, Mehmetcan Akbulut, Yu
Keywords: Fiber optics amplifiers and oscillators; (140.3510) Lasers, fiber; (140.3280) Laser amplifiers; (140.3613) Lasers, upconversion; (140.7300) Visible lasers.
Abstract: An all-fiber amplifier for a single-frequency blue laser was demonstrated for the first time, to the best of our knowl- edge. Over 150 mW continuous-wave single-transverse- mode blue laser output was obtained with a 10 m 1000 ppm thulium-doped fluoride fiber pumped by a 1125 nm fiber laser at a power of 2 W. The output power was limited due to the onset of the competitive lasing at 783 nm. Photodarkening and photo-curing of the thulium-doped
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Light; Science & Applications
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41377-018-0099-5
Volume: 7 Issue: 1 First Page #:
Date Submitted: 1/16/21 12:00AM Date Published: 11/1/18 4:00AM
Publication Location:
Article Title: Watt-scale super-octave mid-infrared intrapulse difference frequency generation
Authors: Christian Gaida, Martin Gebhardt, Tobias Heuermann, Fabian Stutzki, Cesar Jauregui, Jose Antonio-Lo
Keywords: fiber laser, mid-infrared, hollow core fiber
Abstract: the development of high-power, broadband sources of coherent mid-infrared radiation is currently the subject of intense research that is driven by a substantial number of existing and continuously emerging applications in medical diagnostics, spectroscopy, microscopy, and fundamental science. One of the major, long-standing challenges in improving the performance of these applications has been the construction of compact, broadband mid-infrared radiation sources, which unify the properties of high brightness and spatial and temporal coherence. Due to the lack of such radiation sources, several emerging applications can be addressed only with infrared (IR)-beamlines in large- scale synchrotron facilities, which are limited regarding user access and only partially fulfill these properties. Here, we present a table-top, broadband, coherent mid-infrared light source that provides brightness at an unprecedented level that supersedes that of synchrotrons in the wavelength range between 3.7
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Communications
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41467-019-09687-9
Volume: 10 Issue: 1 First Page #:
Date Submitted: 1/16/21 12:00AM Date Published: 4/1/19 4:00AM
Publication Location:
Article Title: Accelerated nonlinear interactions in graded-index multimode fibers
Authors: M. A. Eftekhar, Z. Sanjabi-Eznaveh, H. E. Lopez-Aviles, S. Benis, J. E. Antonio-Lopez, M. Kolesik, F. W
Keywords: multimode optical fibers, nonlinear fiber optics
Abstract: Multimode optical fibers have recently reemerged as a viable platform for addressing a number of long-standing issues associated with information bandwidth requirements and power-handling capabilities. As shown in recent studies, the complex nature of such heavily multimoded systems can be effectively exploited to observe altogether novel physical effects arising from spatiotemporal and intermodal linear and nonlinear processes. Here, we study for the first time, accelerated nonlinear intermodal interactions in core-diameter decreasing multimode fibers. We demonstrate that in the anomalous dispersion region, this spatio- temporal acceleration can lead to relatively blue-shifted multimode solitons and blue-drifting dispersive wave combs, while in the normal domain, to a notably flat and uniform super- continuum, extending over 2.5 octaves. Our results pave the way towards a deeper under- standing of the physics and complexity of nonlinear, heavily multimoded optical systems, and could
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 06-Oct-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Scientific Reports
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41598-019-39302-2
Volume: 9 Issue: 1 First Page #:
Date Submitted: 1/17/21 12:00AM Date Published: 3/1/19 5:00AM
Publication Location:
Article Title: Deep-UV to Mid-IR Supercontinuum Generation driven by Mid-IR Ultrashort Pulses in a Gas-filled Hollow-core Fiber
Authors: Abubakar I. Adamu, Md. Selim Habib, Christian R. Petersen, J. Enrique Antonio Lopez, Binbin Zhou, Ax
Keywords: hollow core fiber, nonlinear fiber optics
Abstract: supercontinuum (sC) generation based on ultrashort pulse compression constitutes one of the most promising technologies towards ultra-wide bandwidth, high-brightness, and spatially coherent light sources for applications such as spectroscopy and microscopy. Here, multi-octave SC generation in a gas-filled hollow-core antiresonant fiber (HC-ARF) is reported spanning from 200 nm in the deep ultraviolet (DUV) to 4000 nm in the mid-infrared (mid-IR) having an output energy of 5 ?J. This was obtained by pumping at the center wavelength of the first anti-resonant transmission window (2460 nm) with ~100 fs pulses and an injected pulse energy of ~8 ?J. the mechanism behind the extreme spectral broadening relies upon intense soliton-plasma nonlinear dynamics which leads to efficient soliton self-compression and phase-matched dispersive wave (DW) emission in the DUV region. The strongest DW is observed at 275 nm which corresponds to the calculated phase-matching wavelength of the pump. Furthermo
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Scientific Reports
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41598-020-61847-w
Volume: 10 Issue: 1 First Page #:
Date Submitted: 1/17/21 12:00AM Date Published: 3/1/20 5:00AM
Publication Location:
Article Title: Noise and spectral stability of deep-UV gas-filled fiber-based supercontinuum sources driven by ultrafast mid-IR pulses
Authors: Abubakar I. Adamu, Md. Selim Habib, Callum R. Smith, J. Enrique Antonio Lopez, Peter Uhd Jepsen, R
Keywords: hollow core fiber, nonlinear fiber optics, frequency generation
Abstract: Deep-UV (DUV) supercontinuum (SC) sources based on gas-filled hollow-core fibers constitute perhaps the most viable solution towards ultrafast, compact, and tunable lasers in the UV spectral region, which can even also extend into the mid-infrared (iR). noise and spectral stability of such broadband sources are key parameters that define their true potential and suitability towards real-world applications. In order to investigate the spectral stability and noise levels in these fiber-based DUV sources, we generate an SC spectrum that extends from 180 nm (through phase-matched dispersive waves - DWs) to 4 ?m by pumping an argon-filled hollow-core anti-resonant fiber at a mid-IR wavelength of 2.45 ?m. We characterize the long-term stability of the source over several days and the pulse-to-pulse relative intensity noise (RIN) of the DW at 275 nm. The results indicate no sign of spectral degradation over 110 hours, but the RIN of the DW pulses at 275 nm is found to be as high as 33.3%. Num
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.422537
Volume: 29 Issue: 8 First Page #: 12516
Date Submitted: 5/19/21 12:00AM Date Published: 4/1/21 4:00AM
Publication Location:
Article Title: Enhanced birefringence in conventional and hybrid anti-resonant hollow-core fibers
Authors: Md. Selim Habib, Abubakar I. Adamu, Christos Markos, Rodrigo Amezcua-Correa
Keywords: HCF, anti resonant fiber
Abstract: A hollow-core anti-resonant fiber (HC-ARF) design based on hybrid silica/silicon cladding is proposed for single-polarization, single-mode and high birefringence. We show that by adding silicon layers in a semi-nested HC-ARF, one of the polarization states can be strongly suppressed while simultaneously maintaining low propagation loss for other polarization states, single-mode and high birefiringence. The optimized HC-ARF design exhibits propagation loss, high birefringence, and polarization-extinction ratio of 0.05 dB/m, 0.5 × 10?4, >300 respectively for y-polarization while the loss of x-polarization is >5 dB/m at 1064 nm. The fiber also has low bend-loss and thus can be coiled to a small bend radii of 5 cm having ?0.06 dB/m bend loss.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Communications Physics
Publication Identifier Type: DOI Publication Identifier: 10.1038/s42005-021-00640-1
Volume: 4 Issue: 1 First Page #:
Date Submitted: 6/21/21 12:00AM Date Published: 5/31/21 10:00PM
Publication Location:
Article Title: General theory and observation of Cherenkov radiation induced by multimode solitons
Authors: M. A. Eftekhar, H. Lopez-Aviles, F. W. Wise, R. Amezcua-Correa, D. N. Christodoulides
Keywords: Multimode fiber, nonlinear optics
Abstract: Advancements in computational capabilities along with the possibility of accessing high power levels have stimulated a reconsideration of multimode fibers. Multimode fibers are nowadays intensely pursued in terms of addressing longstanding issues related to informa- tion bandwidth and implementing new classes of high-power laser sources. In addition, the multifaceted nature of this platform, arising from the complexity associated with hundreds and thousands of interacting modes, has provided a fertile ground for observing novel phy- sical effects. However, this same complexity has introduced a formidable challenge in understanding these newly emerging physical phenomena. Here, we provide a comprehen- sive theory capable of explaining the distinct Cherenkov radiation lines produced during multimode soliton fission events taking place in nonlinear multimode optical fibers. Our analysis reveals that this broadband dispersive wave emission is a direct byproduct of the nonlinear merging of
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: Science and Innovations
Date Received: Conference Date: 09-Jun-2013 Date Published:
Conference Location:
Paper Title: Amplification of ns-pulses beyond 1 MW-peak power in Tm3+-doped photonic crysral fiber rod
Authors:
Acknowledged Federal Support:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Workshop on Specialty Optical Fibers and their Applications
Date Received: Conference Date: Date Published:
Conference Location: Sigtuna
Paper Title: Photo-Thermo-Refractive Glass Fibers
Authors:
Acknowledged Federal Support:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Defense + Security
Date Received: Conference Date: 11-Mar-2014 Date Published:
Conference Location: Baltimore, Maryland, USA
Paper Title: Thulium fiber laser and application development
Authors:
Acknowledged Federal Support:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Photonics West 2014
Date Received: Conference Date: 11-Mar-2014 Date Published:
Conference Location:
Paper Title: Photonic crystal fiber pump combiner for high-peak power all-fiber thulium lasers
Authors:
Acknowledged Federal Support:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Photonics West 2014
Date Received: Conference Date: 11-Mar-2014 Date Published:
Conference Location:
Paper Title: Numerical analysis of modal instability onset in fiber amplifiers
Authors:
Acknowledged Federal Support:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Mid-Infrared Coherent Sources
Date Received: Conference Date: 27-Oct-2013 Date Published:
Conference Location: Paris
Paper Title: Nanosecond Tm:fiber MOPA System for High Peak Power Mid-IR Generation in a ZGP OPO
Authors:
Acknowledged Federal Support:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Advanced Solid State Lasers
Date Received: Conference Date: 27-Oct-2013 Date Published:
Conference Location: Paris
Paper Title: Integrated All-fiber Thulium-doped PCF Pump Combiner
Authors:
Acknowledged Federal Support:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE LASE
Date Received: Conference Date: Date Published:
Conference Location: San Francisco, California, United States
Paper Title: Bi-directional pump configuration for increasing thermal modal instabilities threshold in high power fiber amplifiers
Authors:
Acknowledged Federal Support:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Optical Fiber Communication Conference
Date Received: 31-Aug-2016 Conference Date: 21-Mar-2016 Date Published:
Conference Location: Anaheim, California
Paper Title: All-Fiber Mode Multiplexers
Authors: Rodrigo Amezcua Correa
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE OPTO
Date Received: 31-Aug-2016 Conference Date: 01-Feb-2016 Date Published:
Conference Location: San Francisco, California, United States
Paper Title: Gain-controlled erbium-doped fiber amplifier using mode-selective photonic lantern
Authors: G. Lopez-Galmiche ; Z. Sanjabi Eznaveh ; J. E. Antonio-Lopez ; A. M. Velazquez-Benitez ; J. Rodriguez
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: Science and Innovations
Date Received: 31-Aug-2016 Conference Date: 13-Jun-2016 Date Published:
Conference Location: San Jose, California
Paper Title: High-power mode-selective amplification in large mode area ytterbium-doped fiber using photonic lanterns
Authors: S. Wittek, R. Bustos Ramirez, J. Alvarado Zacarias, Z. Sanjabi Eznaveh, G. Lopez Galmiche, J. Bradfor
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Specialty Optical Fibers
Date Received: 31-Aug-2016 Conference Date: 18-Jul-2016 Date Published:
Conference Location: Vancouver
Paper Title: Higher Order Modes in Anti-Resonant Hollow Core Fibers
Authors: Amy Van Newkirk, J. E. Antonio-Lopez, James Anderson, Roberto Alvarez-Aguirre, Rodrigo Amezcua-
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Optical Fiber Communication Conference
Date Received: 31-Aug-2016 Conference Date: 22-Mar-2016 Date Published:
Conference Location: Anaheim, California
Paper Title: Multi-mode Optical Fiber Amplifier supporting over 10 Spatial Modes
Authors: Nicolas K. Fontaine, Bin Huang, Zeinab Sanjabi Eznaveh, Haoshuo Chen, Jin Cang, Burcu Ercan, Ama
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Optical Fiber Communication Conference
Date Received: 31-Aug-2016 Conference Date: 22-Mar-2016 Date Published:
Conference Location: Anaheim, California
Paper Title: Few Mode Multicore Photonic Lantern Multiplexer
Authors: Z. Sanjabi Eznaveh, J.E. Antonio Lopez, G. Lopez Galmiche, J. Rodriguez Asomoza, D. Van Ras, P. Sil
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Optical Fiber Communication Conference
Date Received: 02-Jan-2019 Conference Date: 19-Mar-2017 Date Published:
Conference Location: Los Angeles, California
Paper Title: Tailoring nonlinear frequency generation in graded-index multimode fibers
Authors: M.A. Eftekhar, Z. Sanjabi Eznaveh, J. E. Antonio Lopez, M. Kolesik, A. Schülzgen, F. W. Wise, D. N. Ch
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Optical Fiber Communication Conference
Date Received: 02-Jan-2019 Conference Date: 19-Mar-2017 Date Published:
Conference Location: Los Angeles, California
Paper Title: Annular Core Photonic Lantern OAM Mode Multiplexer
Authors: Z. Sanjabi Eznaveh, J. C. Alvarado Zacarias, J. E. Antonio Lopez, Y. Jung, K. Shi, B. C. Thomsen, D. J.
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: Science and Innovations
Date Received: 02-Jan-2019 Conference Date: 14-May-2017 Date Published:
Conference Location: San Jose, California
Paper Title: Broadband supercontinuum generation in tapered multimode graded-index optical fibers
Authors: M. A. Eftekhar, Z. Sanjabi-Eznaveh, J. E. Antonio-Lopez, J. C. Alvarado Zacarias, A. Schülzgen, M. Kol
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: QELS_Fundamental Science
Date Received: 02-Jan-2019 Conference Date: 14-May-2017 Date Published:
Conference Location: San Jose, California
Paper Title: Modulational Instability in Normally Dispersive Tapered Multimode Fibers
Authors: Helena Lopez Aviles, Mohammad Amin Eftekhar, Z. Sanjabi Eznaveh, R. Amezcua Correa, Demetrios N
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Advanced Solid State Lasers
Date Received: 02-Jan-2019 Conference Date: 01-Oct-2017 Date Published:
Conference Location: Nagoya, Aichi
Paper Title: High average power nonlinear self-compression to few-cycle pulses at 2 ?m wavelength in antiresonant hollow-core fiber
Authors: artin Gebhardt, Christian Gaida, Fabian Stutzki, Cesar Jauregui, Jose Antonio-Lopez, Axel Schulzgen, F
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Optical Fiber Communication Conference
Date Received: 02-Jan-2019 Conference Date: 11-Mar-2018 Date Published:
Conference Location: San Diego, California
Paper Title: Blue-Enhanced Supercontinuum Generation in a Graded-Index Fluorine-Doped Multimode Fiber
Authors: Z. Sanjabi Eznaveh, M.A. Eftekhar, J.E. Antonio Lopez, M. Kolesik, H. Lopez Aviles, F. W. Wise, D. N. C
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: QELS_Fundamental Science
Date Received: 02-Jan-2019 Conference Date: 13-May-2018 Date Published:
Conference Location: San Jose, California
Paper Title: Analysis of Parametric Instabilities in Parabolic Multimode Fibers under High Intensity Conditions
Authors: Helena Lopez Aviles, Fan Wu, Z. Sanjabi Eznaveh, Mohammad Amin Eftekhar, Frank W. Wise, R. Ame
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: QELS_Fundamental Science
Date Received: 02-Jan-2019 Conference Date: 13-May-2018 Date Published:
Conference Location: San Jose, California
Paper Title: Accelerating nonlinear interactions in tapered multimode fibers
Authors: M. A. Eftekhar, Z. Sanjabi-Eznaveh, J. E. Antonio-Lopez, H. E Lopez Aviles, S. Benis, M. Kolesik, A. Sc
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: Applications and Technology
Date Received: 02-Jan-2019 Conference Date: 13-May-2018 Date Published:
Conference Location: San Jose, California
Paper Title: Visible to Mid-infrared Supercontinuum Generation Using a Gas-filled Hollow-core Fiber
Authors: Md. Selim Habib, Christos Markos, A. Isa Adamu, J. E. Antonio-Lopez, and Rodrigo Amezcua-Correa
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Bragg Gratings, Photosensitivity and Poling in Glass Waveguides and Materials
Date Received: 02-Jan-2019 Conference Date: 02-Jul-2018 Date Published:
Conference Location: Zurich
Paper Title: Supercontinuum generation from deep-UV to mid-IR in a noble gas-filled fiber pumped with ultrashort mid-IR pulses
Authors: Abubakar I. Adamu, Md. Selim Habib, Christian R. Petersen, Binbin Zhou, Axel Schülzgen, J. Enrique A
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Optical Fiber Communication Conference
Date Received: 02-Jan-2019 Conference Date: 11-Mar-2018 Date Published:
Conference Location: San Diego, California
Paper Title: Mode Selective Photonic Lantern with Graded Index Core
Authors: Juan Carlos Alvarado-Zacarias, Nicolas K. Fontaine, Jose Enrique Antonio-Lopez, Zeinab Sanjabi Ezna
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Frontiers in Biological Detection: From Nanosensors to Systems XI
Date Received: 16-Jan-2021 Conference Date: 02-Feb-2019 Date Published:
Conference Location: San Francisco, United States
Paper Title: Towards an all-fiber system for detection and monitoring of ammonia
Authors: Abubakar I. Adamu, Manoj K. Dasa, Md. Selim Habib, Rodrigo Amezcua-Correa, Ole Bang, Christos Ma
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2016 IEEE Photonics Conference
Date Received: 16-Jan-2021 Conference Date: 02-Oct-2016 Date Published:
Conference Location: Waikoloa, HI, USA
Paper Title: Antiresonant hollow core fiber with seven nested capillaries
Authors: Jose E. Antonio-Lopez, Selim Habib, Amy Van Newkirk,1 Gisela Lopez-Galmiche,1 Zeinab S. Eznaveh,
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 International Conference on Optical MEMS and Nanophotonics
Date Received: 16-Jan-2021 Conference Date: 13-Aug-2017 Date Published:
Conference Location: Santa Fe, NM, USA
Paper Title: Mode-group mixing device via complex phase masks printed on fiber tip
Authors: Miri Blau, Moriya Rosenfeld, Juan Carlos Alvarado Zacarias, Rodrigo Amezcua Correa, Dan M. Marom
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO; QELS_Fundamental Science
Date Received: 17-Jan-2021 Conference Date: 01-May-2017 Date Published:
Conference Location: San Jose, California
Paper Title: Topological Aharonov-Bohm Suppression of Optical Tunneling in Twisted Nonlinear Multicore Fibers
Authors: M. Parto, H. Lopez, M. Khajavikhan, R. Amezcua-Correa, D. N. Christodoulides
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Optical Fiber Communication Conference
Date Received: 17-Jan-2021 Conference Date: 03-Mar-2019 Date Published:
Conference Location: San Diego, California
Paper Title: Single mode, Low-loss 5-tube Nested Hollow-core Anti-resonant Fiber
Authors: Md. Selim Habib1,, Enrique Antonio-Lopez1, Christos Markos2, Axel Schulzgen1, Rodrigo Amezcua-Co
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Optical Fiber Communication Conference
Date Received: 17-Jan-2021 Conference Date: 03-Mar-2019 Date Published:
Conference Location: San Diego, California
Paper Title: Low-Loss 19 core Fan-in Fan-out Device Using Reduced-Cladding Graded Index Fibers
Authors: Juan Carlos Alvarado-Zacarias(1), J. Enrique Antonio-Lopez(1), Md. Selim Hal
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO; Science and Innovations
Date Received: Conference Date: 05-May-2019 Date Published:
Conference Location: San Jose, California
Paper Title: Gain dependent mode analysis of large mode area fiber with confined Ytterbium doping
Authors: Stefan Gausmann, Jose Enrique Antonio Lopez1, James Anderson1, Steffen Wittek1, Rodrigo Amezcua
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO; QELS Fundamental Science
Date Received: Conference Date: 05-May-2018 Date Published:
Conference Location: San Jose, California
Paper Title: Observation of Aharonov-Bohm Suppression of Optical Tunneling in Twisted Multicore Fibers
Authors: M. Parto, H. Lopez-Aviles, J. E. Antonio-Lopez, J. C. Alvarado Zacarias, M. Khajavikhan, R. Amezcua- (
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO; Applications and Technology
Date Received: 17-Jan-2021 Conference Date: 05-May-2019 Date Published:
Conference Location: San Jose, California
Paper Title: Parabolic Pulse Generation in Totally Passive Tapered Multimode Fibers
Authors: H. E. Lopez Aviles1, M. Buttolph2, F. W. Wise2, R. Amezcua Correa1, D. N. Christodoulides1
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: University of Central Florida
Date Received: 21-Sep-2022 Completion Date: 2/17/18 6:06PM
Title: HIGH POWER FIBER LASERS AND FIBER DEVICES
Authors: ZEINAB, SANJABIEZNAVEH
Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation
Institution: University of Central Florida
Date Received: Completion Date: 12/10/20 5:00AM
Title: DEVELOPMENT OF HIGH-POWER SINGLE-MODE YB-DOPED FIBER AMPLIFIERS AND BEAM ANALYSIS
Authors: STEFFEN, WITTEK
Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation
Institution: University of Central Florida
Date Received: 03-Oct-2022 Completion Date: 11/30/22 6:31PM
Title: SPECIALTY OPTICAL FIBERS AND THEIR APPLICATION IN FIBER LASER SYSTEMS
Authors: STEFAN GAUSMANN
Acknowledged Federal Support: **N**

RPPR Final Report
as of 06-Oct-2022

PATENTS:

Intellectual Property Type: Patent Date Received: **21-Sep-2022**
Patent Title: ACTIVETRANSVERSEMODEINSTABILITY MITIGATION FOR HIGH POWER FIBER AMPLIFIERSAPPARTUS,METHODS,AND APPLICATIONS
Patent Abstract:
Patent Number: US202/0158405A1
Patent Country: USA
Application Date: 19-Nov-2020 Application Status: 3
Date Issued: 19-May-2022

Intellectual Property Type: Patent Date Received: **21-Sep-2022**
Patent Title: ACTIVETRANSVERSEMODEINSTABILITY MITIGATION FOR HIGH POWER FIBER AMPLIFIERSAPPARTUS,METHODS,AND APPLICATIONS
Patent Abstract:
Patent Number: US202/0158405A1
Patent Country: USA
Application Date: 19-Nov-2020 Application Status: 3
Date Issued: 19-May-2022

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Rodrigo Amezcua
Signature Date: 10/3/22 2:49PM

Fiber Laser Light Engines

A New Platform to Collectively Address Power-Limiting Constraints

Final Report

Rodrigo Amezcua Correa, Martin Richardson, and Axel Schülzgen
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University of Central Florida

Program Manager:
Dr. Michael Gerhold, ARO

Focus of Program

Mode instability (MI) limits output power of single mode fiber lasers

Objectives

1. Numerical and experimental investigations of MI in the kW regime
   - New fiber schemes for robust single mode operation
   - Effective fiber concepts for overcoming mode instability
2. Advanced Fiber Fabrication
   - Large pitch PCF rod type fibers for mode area scaling
   - Control of dopant concentration and refractive index profile in Yb-doped fibers
3. All-fiber integration
   - Passive fiber components for advanced laser systems
4. New fiber-based light sources

Program Overview

Fiber design, fabrication and characterization

Passive fiber components development

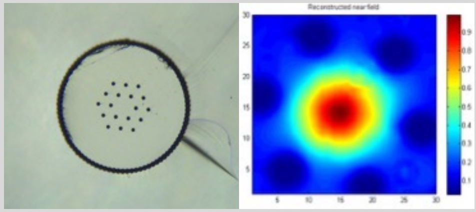
Demonstrate effective fiber concepts for overcoming mode instability in high power amplifiers

Multi-kW fiber laser development and characterization

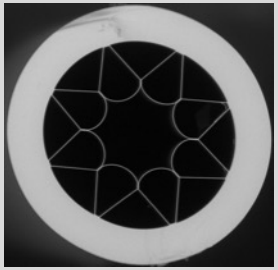
New passive fibers

High fidelity mode instability modeling

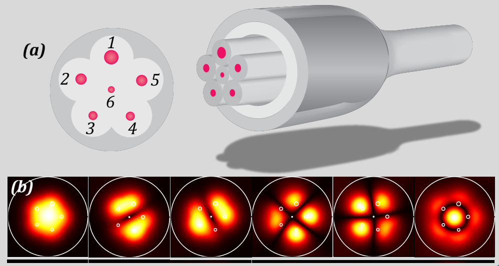
LMA Fiber Development



Extreme Power Transport



Mode Control



Summary of Accomplishments

We have satisfied the broad objectives of the original MRI proposal

Strong Educational Program – 10 students graduated

Strong Publication Record – >20 journal papers and >30 conference presentations, including invited talks and post-deadline presentations, 2 patent disclosures

Fiber Development

- Precise fiber fabrication – active, passive and hollow core fibers
- Fabrication of Yb-doped PCFs
- Fabrication of low NA Yb-doped LMA fibers
- Short lead time from design to production

High Power Single Mode Yb-fiber Laser Development

- Current 700 W

Numerical Studies of Fiber Amplifiers

- Numerical tools for time-dependent modal instability simulation

Laser Component Development

- Large diameter end cap splicing, photonic lantern mode converters, pump combiners, multicore fiber multiplexers

Facilities Development

- New MCVD lathe system installation be completed in December 2018 January 2019

Technology Transition to DoD strategic collaborators

- SA Photonics - DARPA sponsored program
- Electro-Optics Center (EOC) at The Pennsylvania State University

Specialized Workforce

Corning outstanding student paper competition, OFC

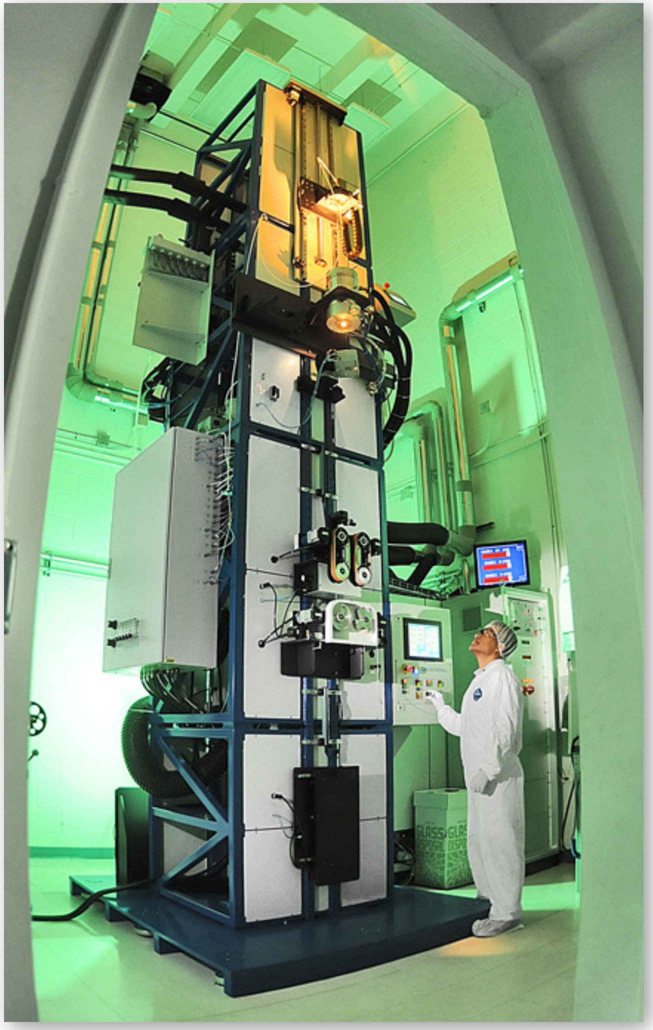
1st place OFC 2016 and 2nd place in 2017

PRISM award for the flat-top fiber technology

Student involvement in all aspects of fiber laser development from fiber design and fabrication to kW-laser testing

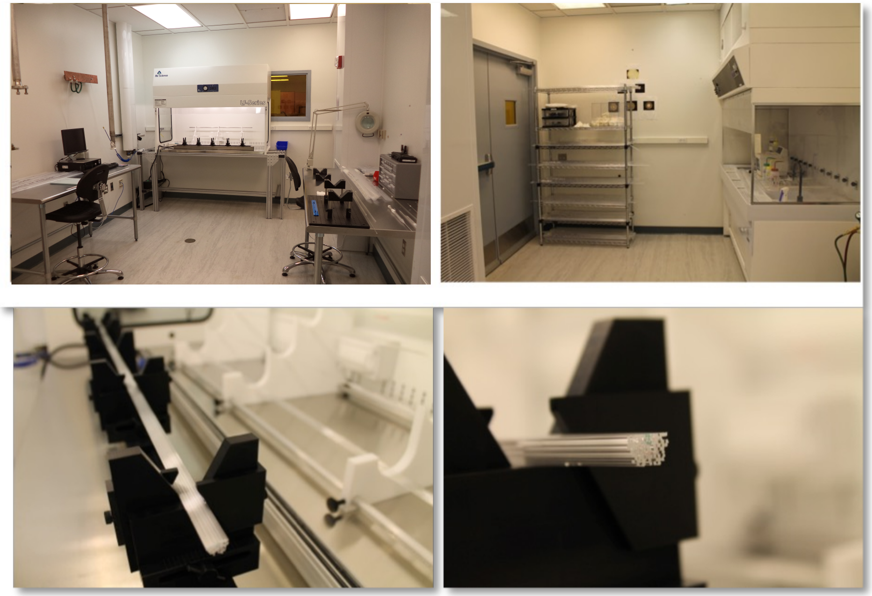
Optical Fiber Fabrication Facilities

Draw Tower for Microstructured Optical Fiber Fabrication



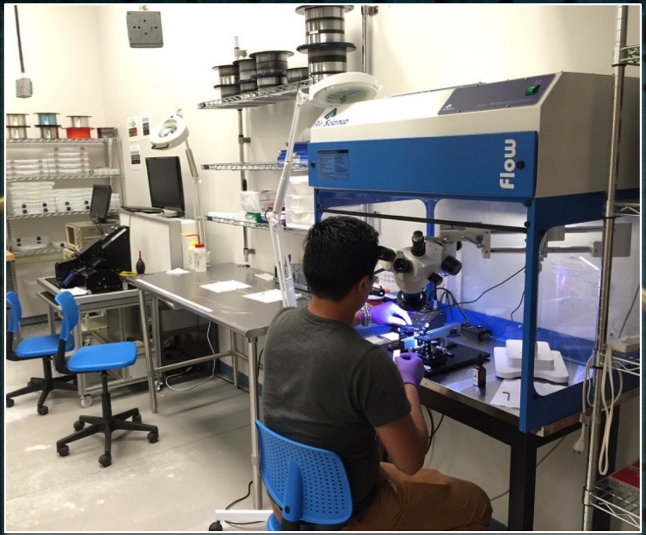
MCVD Preform Fabrication System

Microstructured Optical Fiber Fabrication Cleanroom



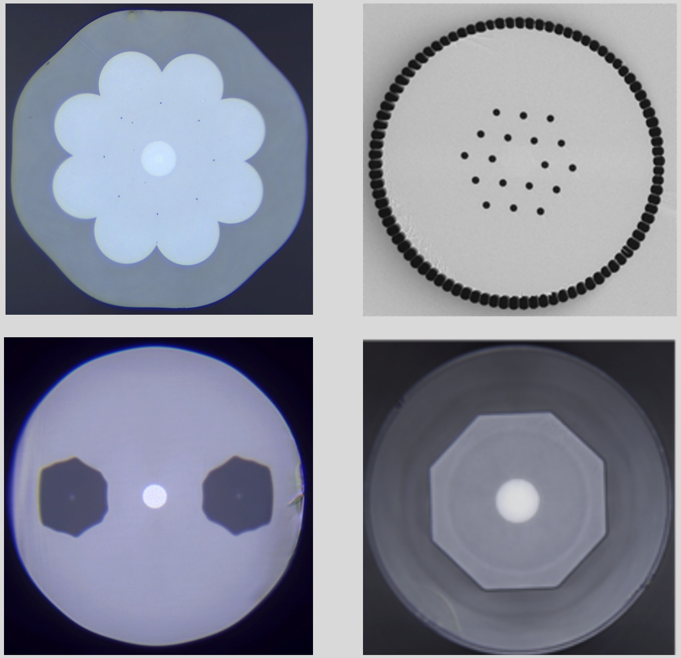
Optical Fiber Devices & Fiber Characterization

Comprehensive fiber laboratories

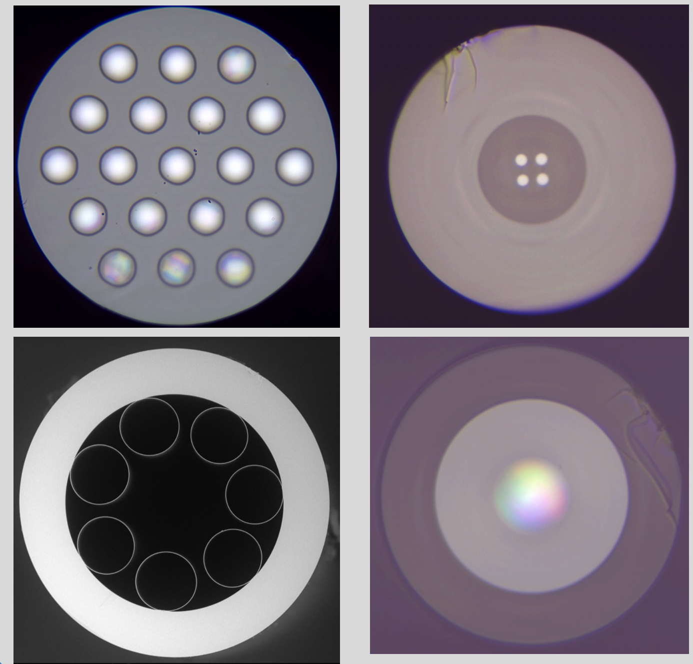


Advanced Fiber Fabrication

Active Fibers for High Power Lasers



Advanced Passive Fibers

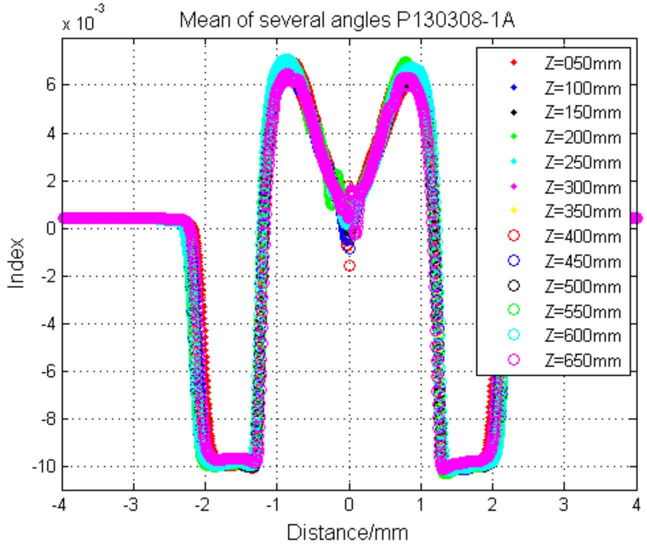


- Accurate PCF fabrication
- Low NA LMA Fibers
- Pump cladding-shaping
- High NA F-doped pump claddings
- Large pitch photonic crystal fiber
- PM Fibers
- Repeatable and fast fabrication process

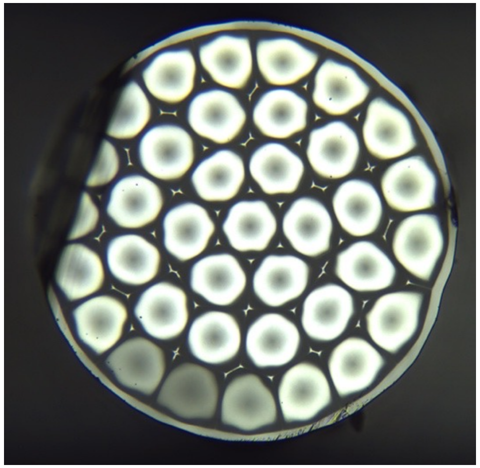
- New fabrication processes for hollow-core fibers for kW class laser delivery
- Antiresonant hollow-core fibers for guidance from 1000 nm to 3000 nm

Homogeneously Doped Yb Core Material

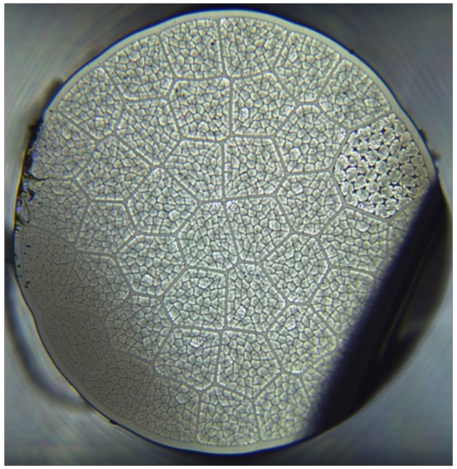
Initial Yb-doped rod



1st stacking stage



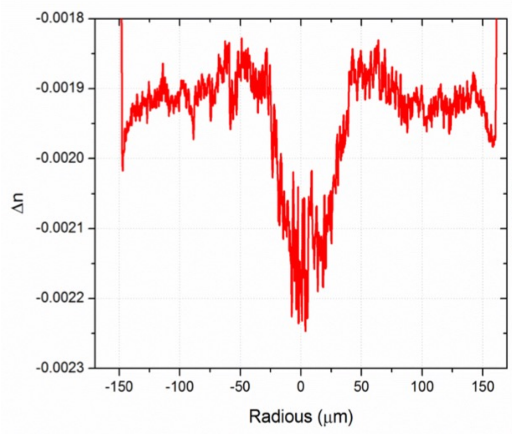
Intermediate step
rod with ~46656 Yb-doped struts

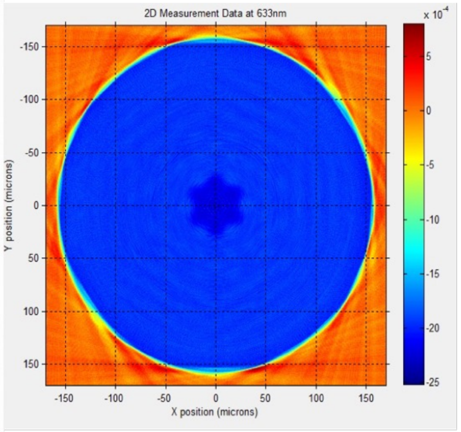


Advantages of Yb homogenization process

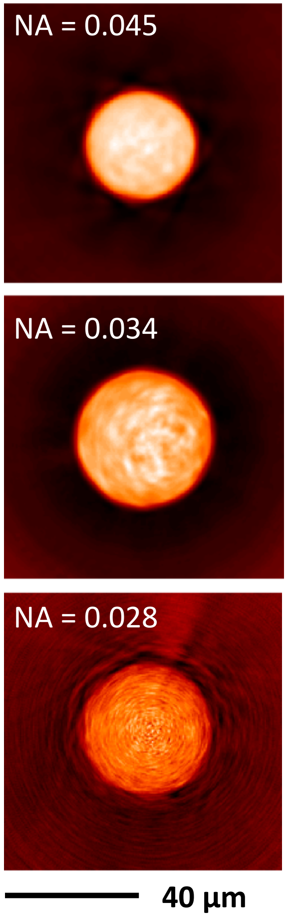
- Precise control of active material distribution, NA control beyond what it is possible with MCVD
- Core composed of ~100,000 s of Yb doped filaments with ~200 nm diameter in a F-doped background
- Refractive index homogeneity better than $2x10^{-4}$

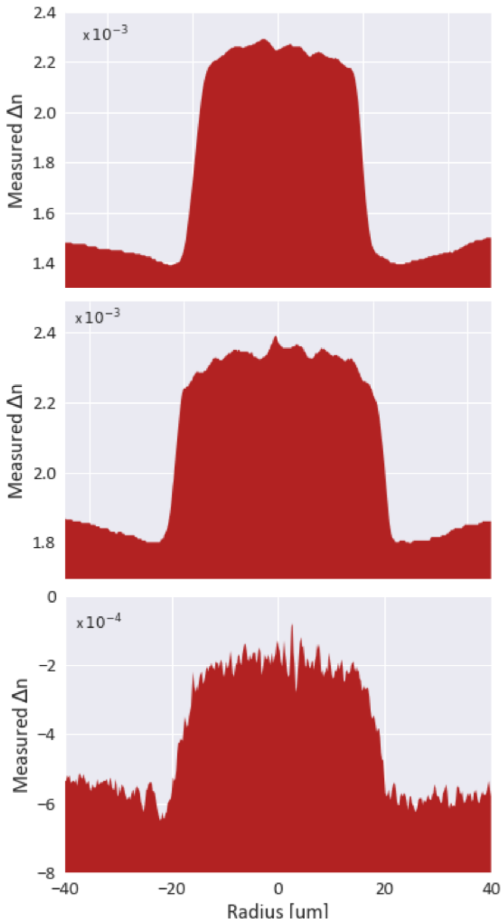
Refractive index profiles of final ~60 um core fiber.
Core consists of ~ 300,000 Yb-doped nano-filaments





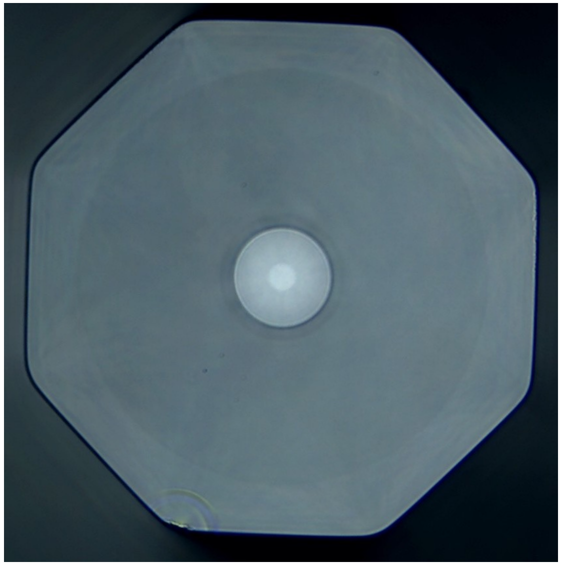
Low NA Yb-doped Step Index Fiber





Low NA Yb-doped step index fibers

- 22 μm core/430 μm cladding few mode fiber
  - Octagonal pump cladding
  - 0.46 polymer coating

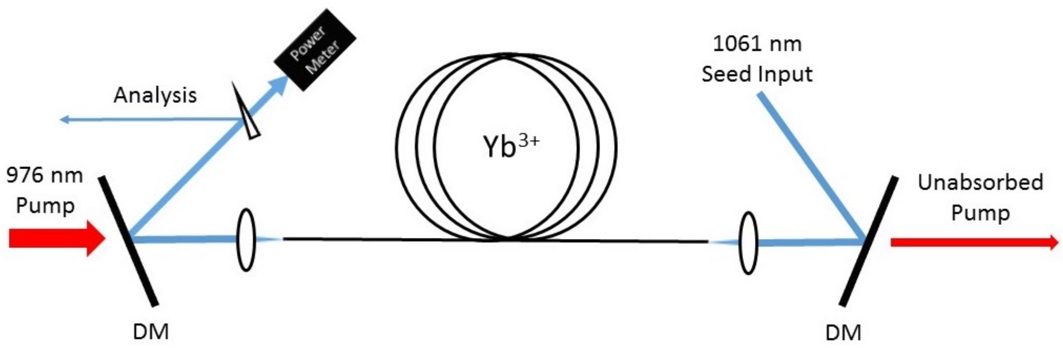


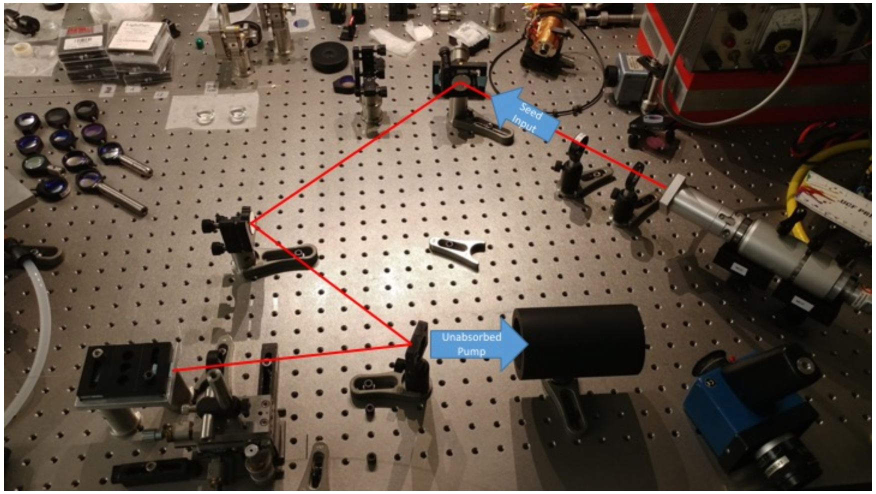
Multi-kW Fiber Laser Facility

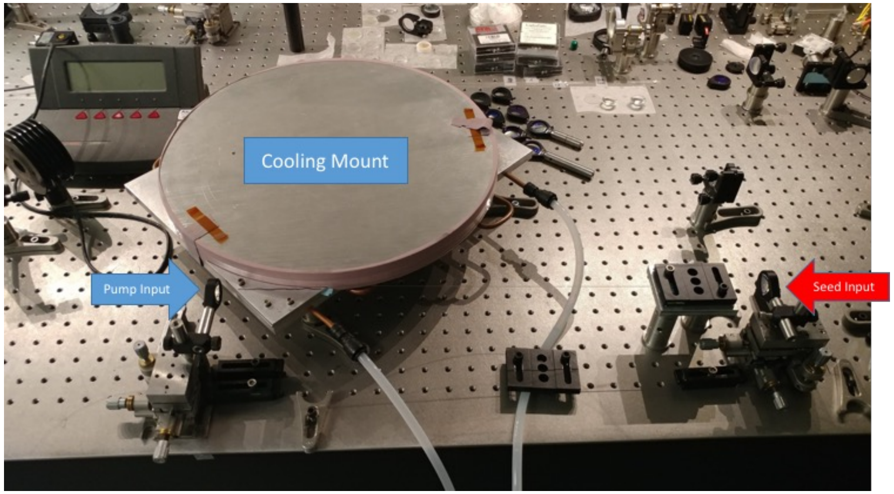
Capabilities:

- 3 kW OE 30020 pumps
- 150W seed laser

Amplifier Layout



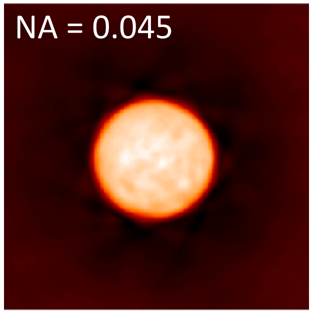


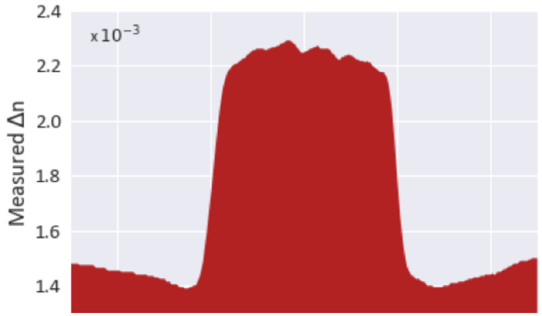


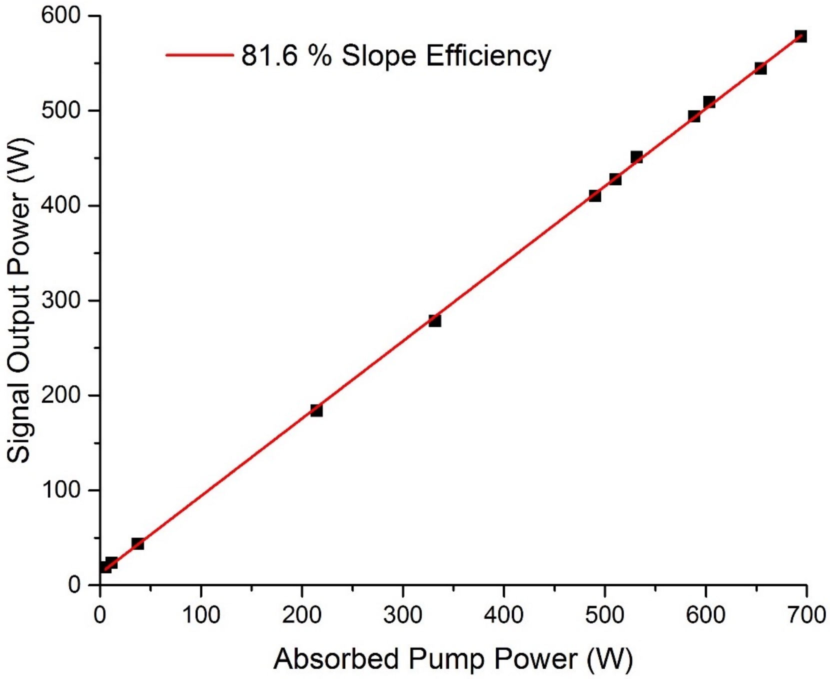
Low NA Yb-doped Fiber Amplifier Performance

Low NA air-clad step index fiber

- $22\mu m$ core/$420\mu m$ cladding
  - ~7 m long amplifier
  - 680 W output signal power

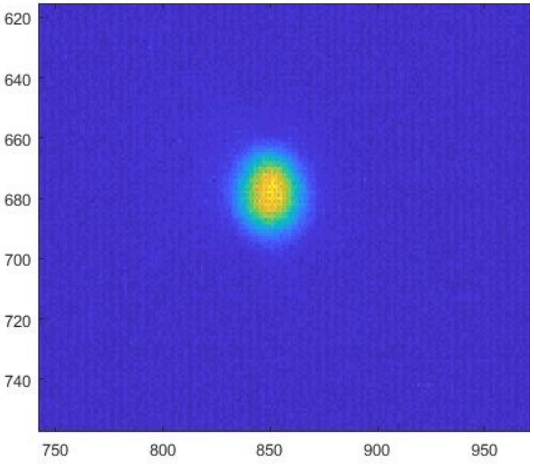






20 W Input Seed
578 W Output
≈ 900 W Launched Pump
≈ 680 W Absorbed Pump

400 W beam profile



Confined Doping Low NA Yb-doped Fiber

- **Semi-analytical approach of TMI power threshold**

The paraxial wave equation under the slowly-varying envelope approximation,

$$\frac{\partial Es}{\partial z} + \frac{1}{v_g}\frac{\partial Es}{\partial t} - \frac{i}{2\beta s}\{\nabla_T^2 + [n_0^2 k_0^2 - \beta s^2]\}Es = \frac{i}{2\beta s}\omega_0^2 \mu_0 P_{NL}$$ where:

$P_{NL}=\varepsilon_0 \Delta\varepsilon_{NL} Es,\ \ \Delta\varepsilon_{NL} \approx 2n_0 \Delta n_{NL},\ \ \Delta n_{NL} = \frac{dn}{dT}\Delta T$

$\rho_0 C_0 \frac{d\Delta T}{dt} - \mathrm{K}_0 \nabla_T^2(\Delta T) = Q_T$ ΔT is given by the heat equation:

$Q_T = q_D \frac{dIs}{dz} + \alpha_s Is$ heat power density

$q_D = \left(\frac{\lambda_s}{\lambda_p}\right) - 1$ quantum defect

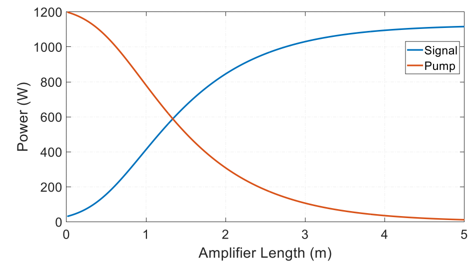
$\rho_0, C_0, \mathrm{K}_0$ are constants

$$P_{TMI}^{thr} = \frac{\mathrm{K}_0 U_e^2 (U_e^2 - U_s^2)}{4\pi n_{eff}\left(\frac{\partial n}{\partial t}\right)\acute{\alpha} s}\left(\frac{\lambda_s}{D_0}\right)^2$$ in the case of high power and high saturation

where $\acute{\alpha} s \cong \alpha_s + 0.5 q_D g_s$, λs is the signal wavelength and D_0 is the core diameter, Uε and Us are the transverse wavenumbers of the perturbation and fundamental mode (FM).

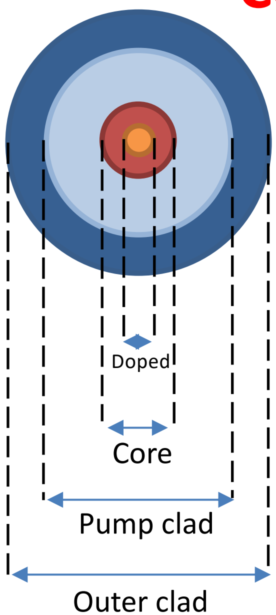
Confined Doping Low NA Yb-doped Fiber

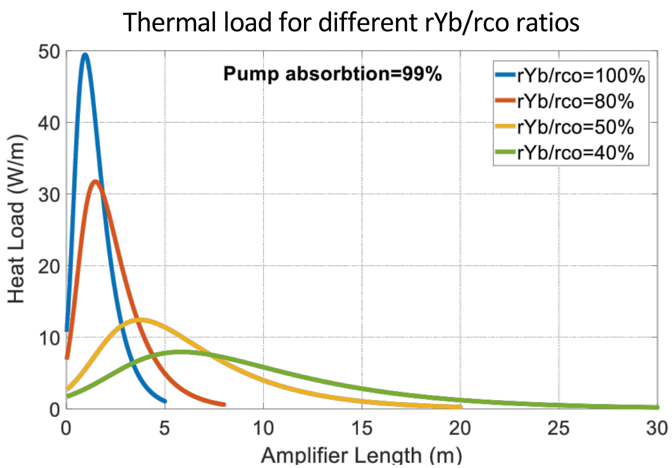
Fiber Parameters
Input Pump= 1200W
Input Signal=30W
Pump Absorption=99%
Core Diameter= 30µm
λs=1064nm, λp=976nm
Yb=3.25e25 m-3
NA=0.076



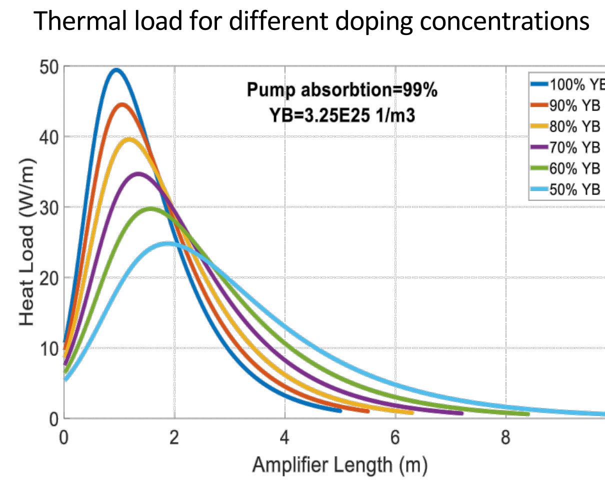
TMI threshold=3.28 kW

Confined Doping





Reduced Yb-Doping Concentration

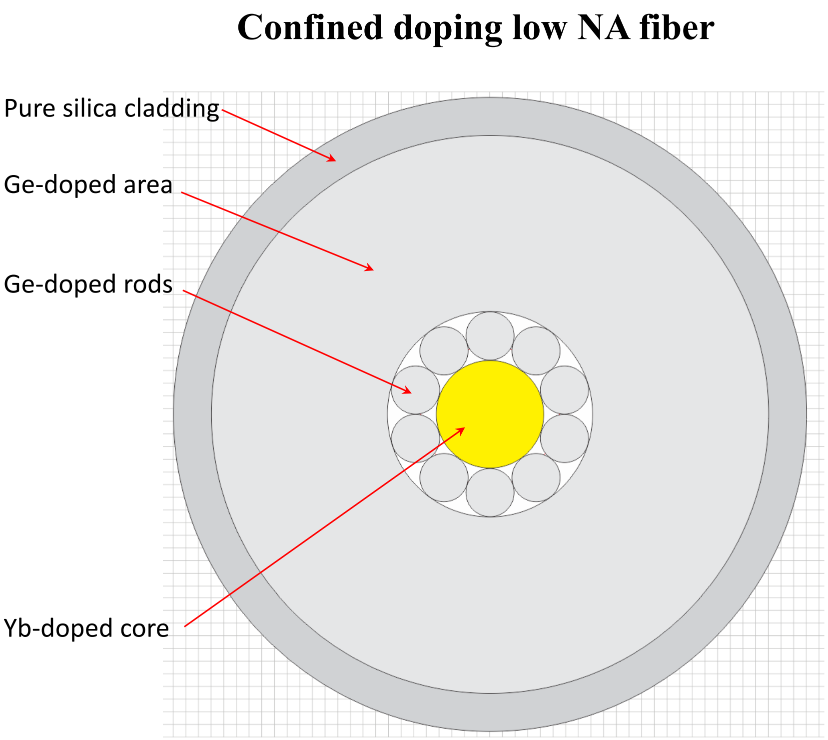


Thermal load=50 W/m → TMI threshold=3.28KW

Thermal load=30 W/m → TMI threshold=5 KW

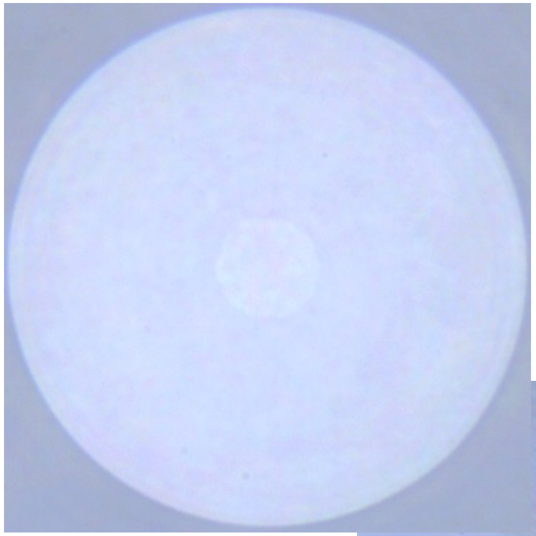
→ **TMI threshold ~ 1/ Thermal load**

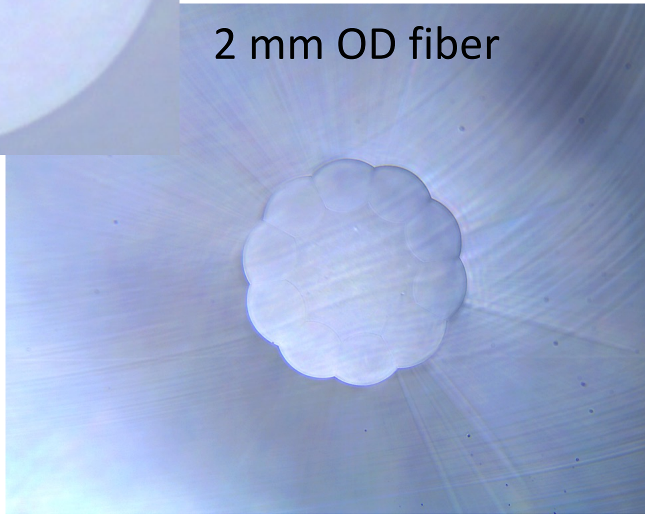
Confined Doping Low NA Yb-doped Fiber



25μm core/420μm cladding

- Yb-doping core 60% core diameter





Multi-channel Yb-Fiber Amplifier

Multicore fiber to circumvent mode instability

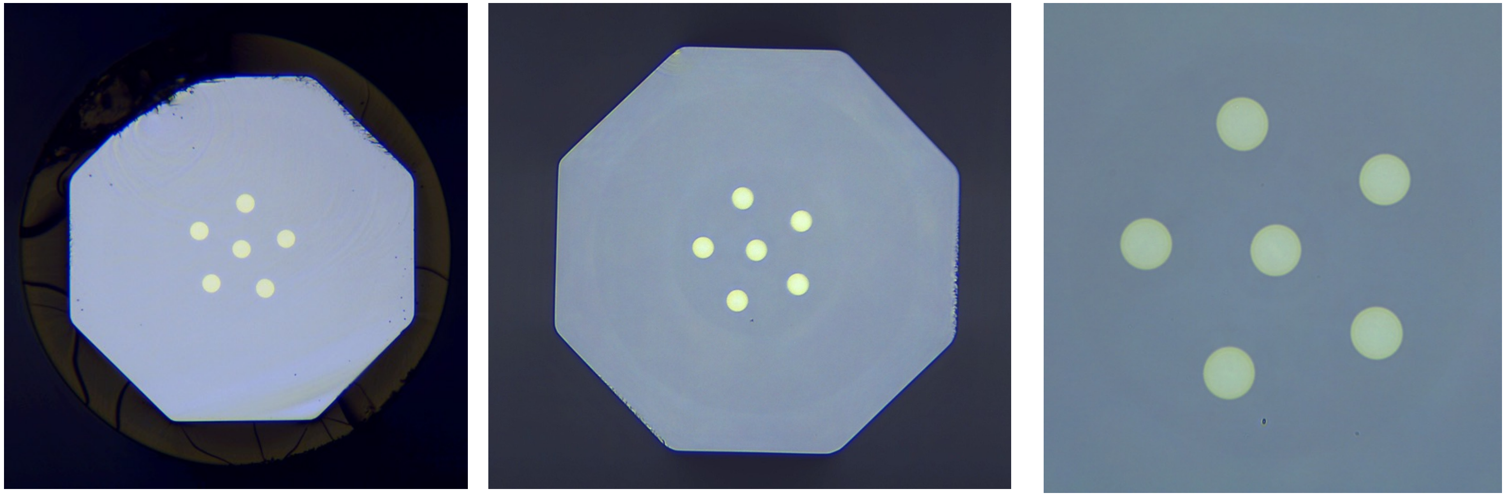
- Requires coherent beam combining
  - Single fiber mode instability threshold scales with number of cores
  - Uncoupled cores
  - Fiber based pump signal combiner

6 core Yb-doped fiber

22μm core/420μm cladding

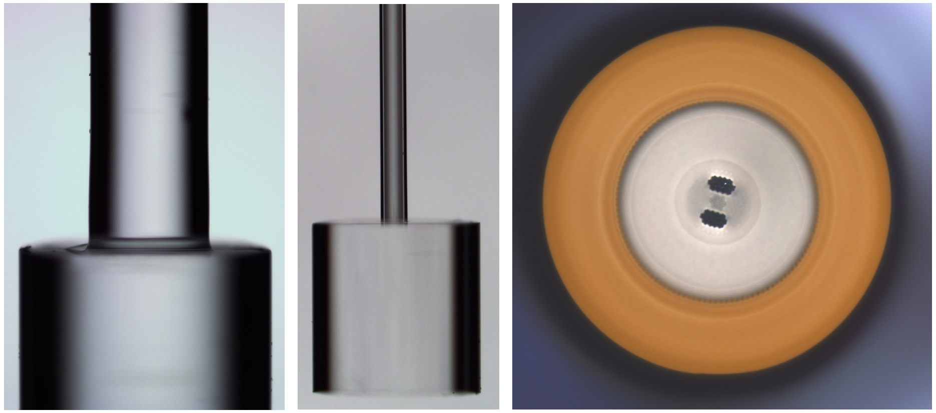
70 μm core to core distance

NA ~ 0.06

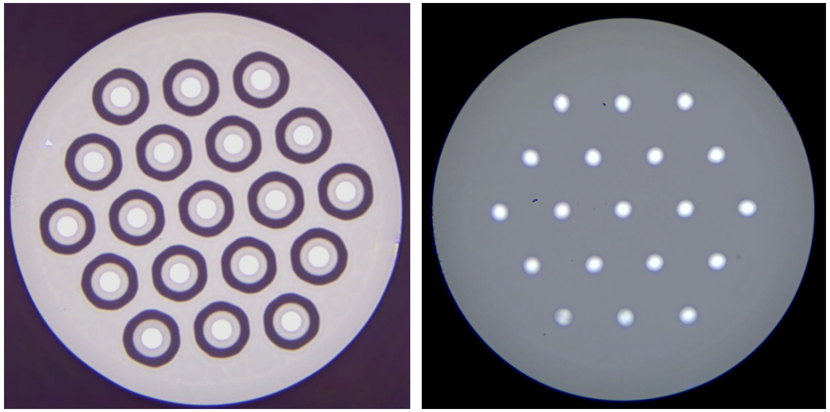


Passive High Power Fiber Laser Components

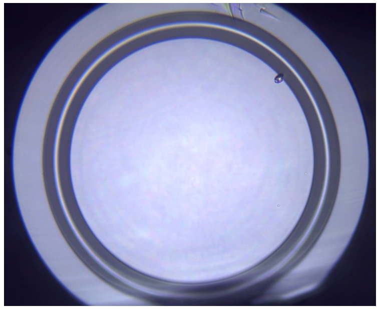
End cap Splicing

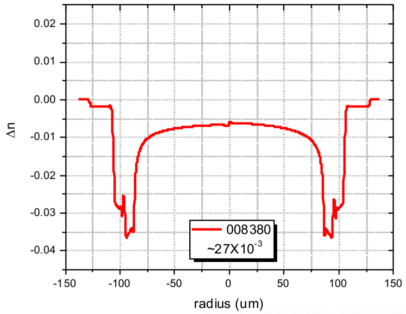


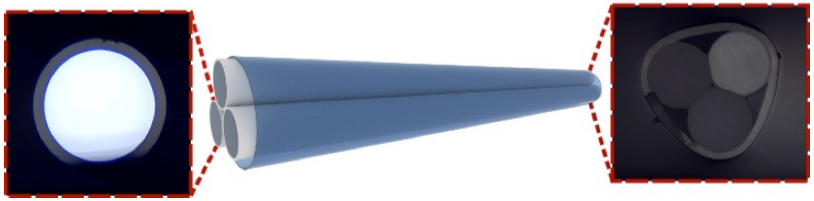
Multicore Fiber Fan-In Devices



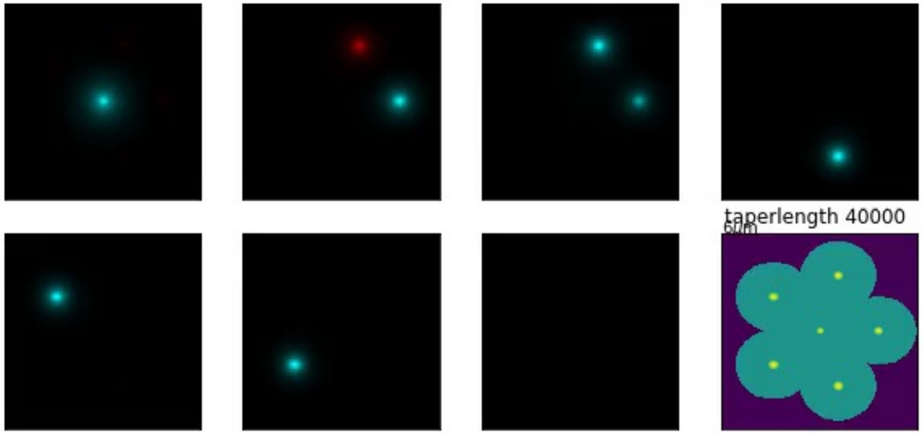
Pump Combiners and High NA Capillaries







Photonic Lantern Mode Converters



Photonic Lanterns

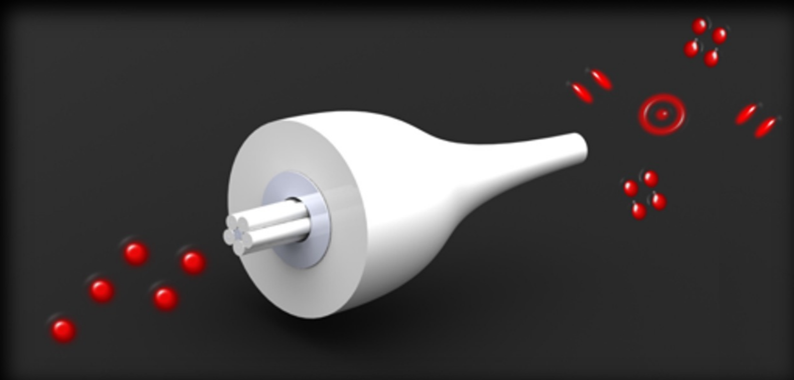
The photonic lantern is a versatile and powerful concept, allowing the transformation of an optical multimode system into a single-mode one and vice versa

Potential high power applications include:

- Modal control in high power amplifiers
- All-fiber beam combining
- Beam shaping and steering (all-fiber spatial light modulator)

Single Mode Fibers

» N fibers
» Low refractive index glass capillary



Multimode Fiber

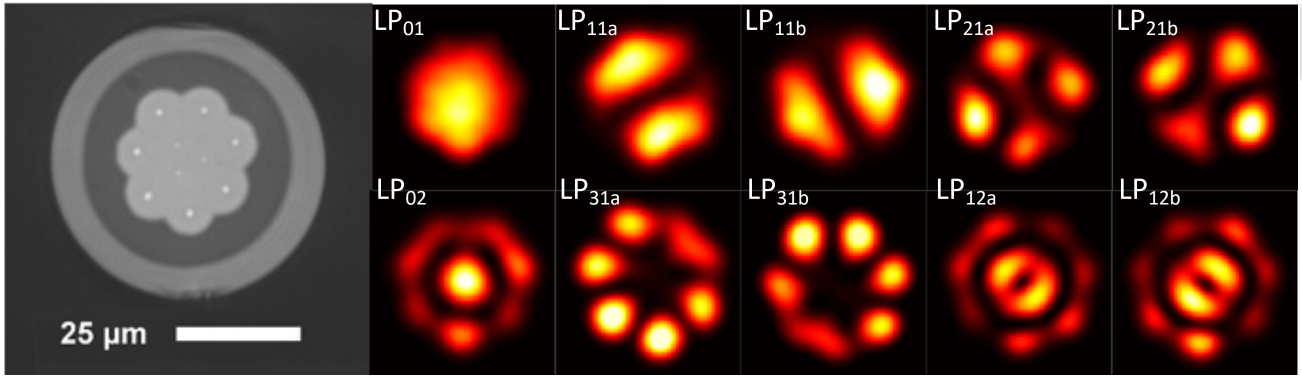
» N modes
» F-doped capillary becomes cladding

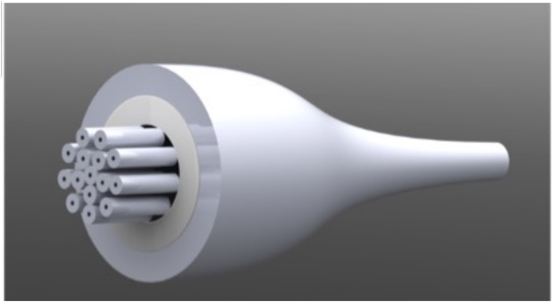
» **Same degrees of freedom N fibers = N modes**
» **Adiabatic transition**
» **Scalable to large number of modes**
» **All-fiber monolithic integration**

Leon-Saval et al, Opt.Exp. 18, 8430 (2010)

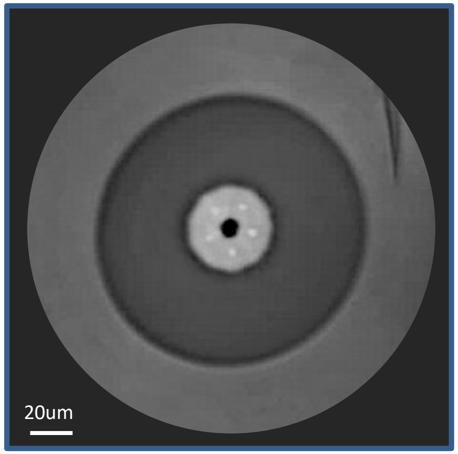
Photonic Lantern for High Power Applications

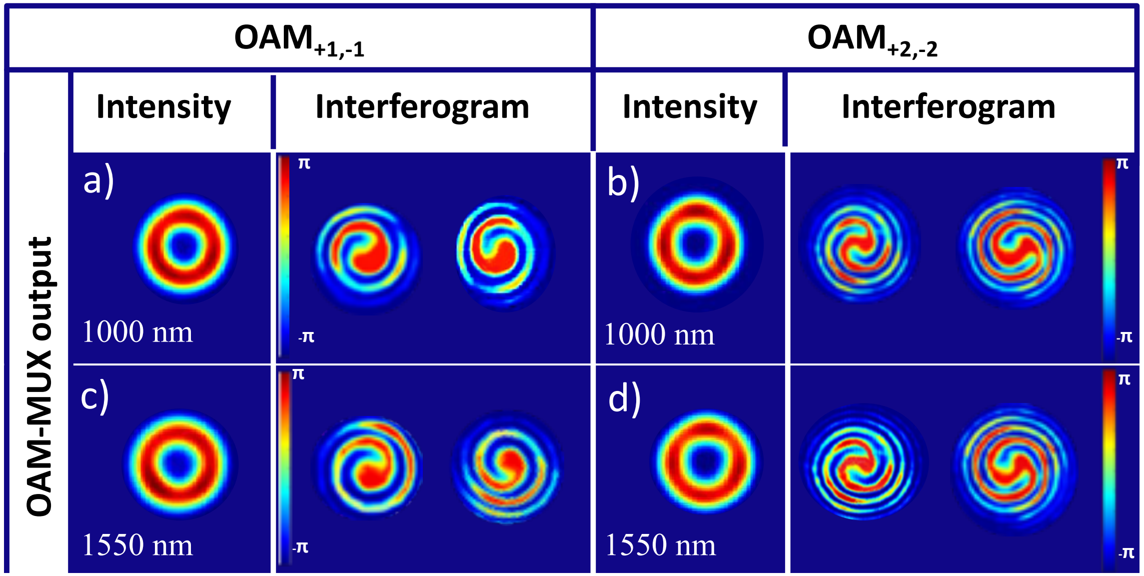
Towards larger number of modes and high power operation



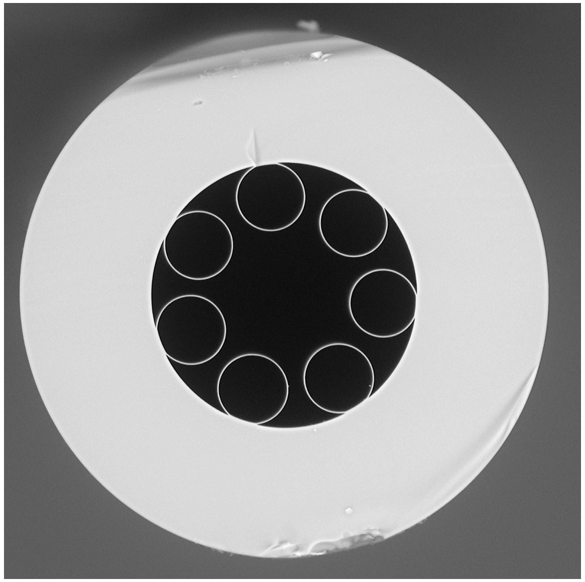


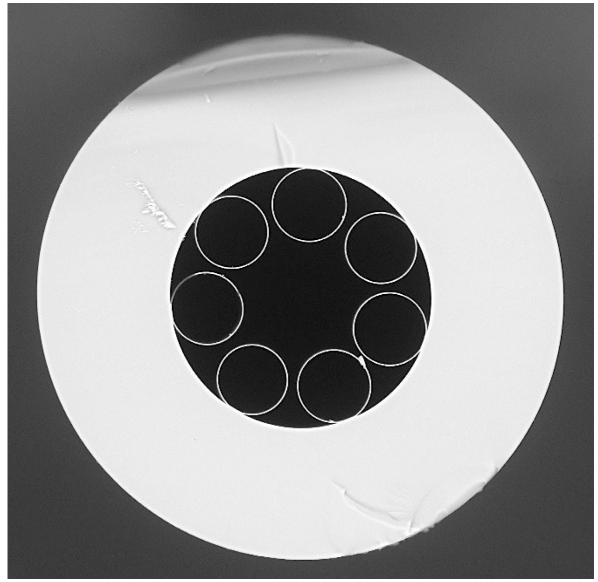
15 Mode photonic lantern

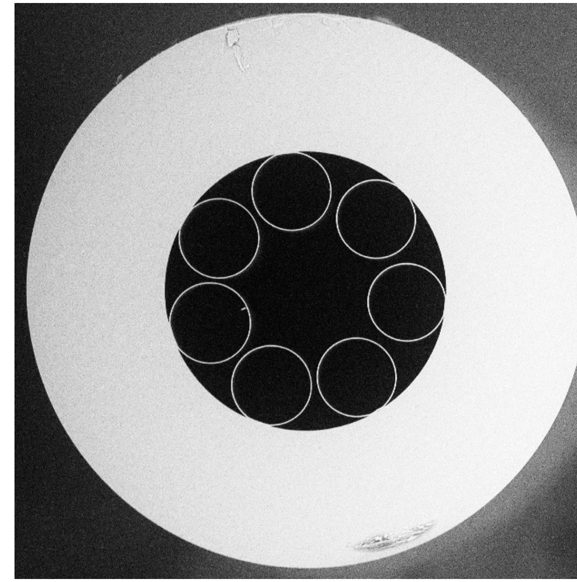




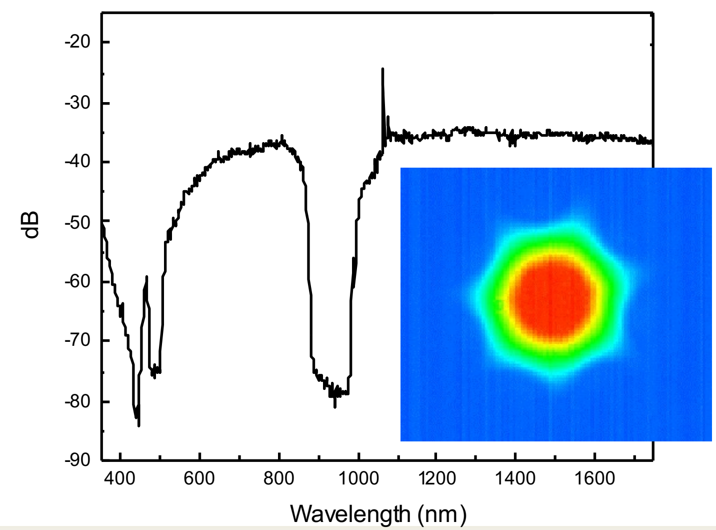
ANTIRESONANT HOLOW-CORE FIBER FABRICATION







- Broadband transmission
- Ultra thin core wall thickness ~420 nm operation in first antiresonant window
- Low loss < 100 dB/km
- High power handling
- Quasi single mode operation for >1 m fiber length
- Touching and non-touching core boundary negative curvature fibers



Light Generation in Hollow-core Fibers

Pulse propagation modeling

The optical pulse propagation was numerically calculated using a **unidirectional pulse propagation equation**

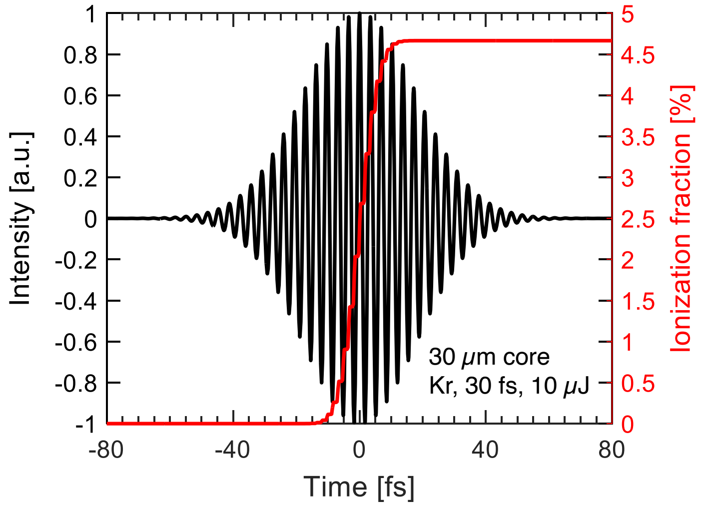
$$\frac{\partial E}{\partial z} = i\left(\beta(\omega) - \frac{\omega}{v_g}\right)E(z,\omega) - \frac{\alpha(\omega)}{2}E(z,\omega) + \frac{i\omega^2}{2c^2\epsilon_0\beta(\omega)}\mathcal{F}\left[\underbrace{P_{Kerr}(z,t)}_{\text{Kerr nonlinearity}} + \underbrace{P_{ion}}_{\text{Ionization}}\right]$$

$$\frac{\partial P_{ion}}{\partial t} = \frac{I_p}{E(z,t)}\frac{\partial N_e}{\partial t} + \frac{e^2}{m_e}\int_{-\infty}^{t'} N_e(z,t')E(z,t')dt'$$

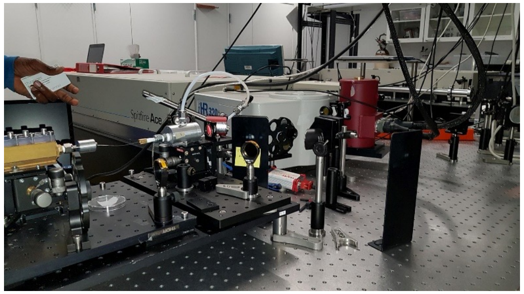
β(ω) = propagation constant
α(ω) = attenuation
c = velocity of light in vacuum
ϵ_0 = permittivity
v_g = pump group velocity
Ne = free electron density

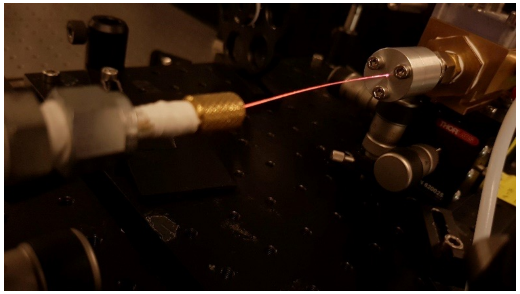
Inside HC-AR fibers:

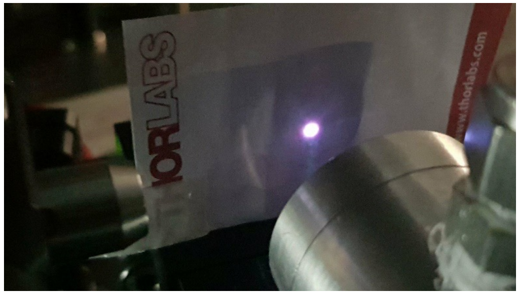
- Peak intensity can reach >100 TW/cm^2
- **Free electron density ~**10^{17}cm^{-3}
- Sufficient to ionize the gas and form a plasma
- Free electron density was calculated using ADK model

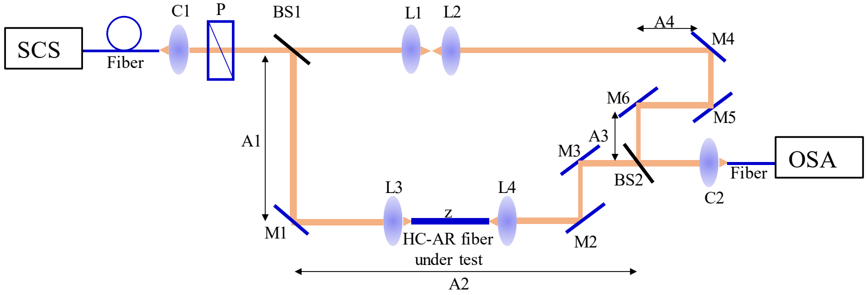


UV to mid-IR Supercontinuum Generation

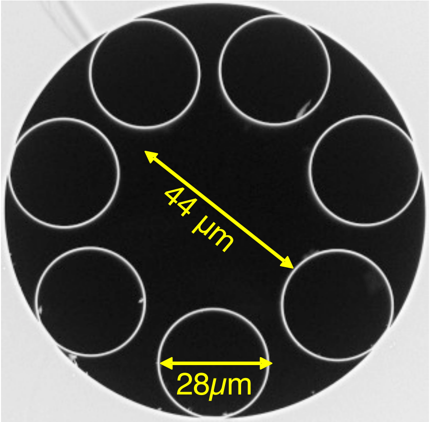








Supercontinuum covering 250 nm- 4000 nm



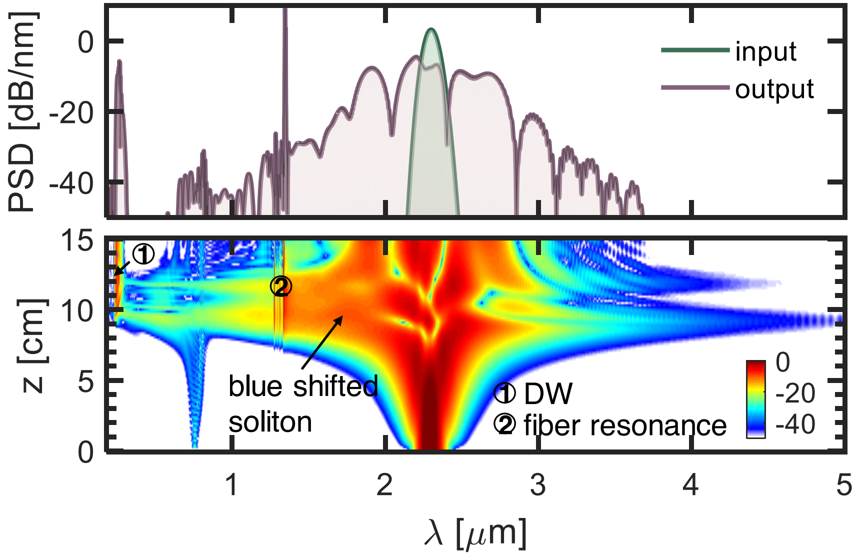
44 μm core diameter

28 bar Ar

100 fs, 6.5 μJ

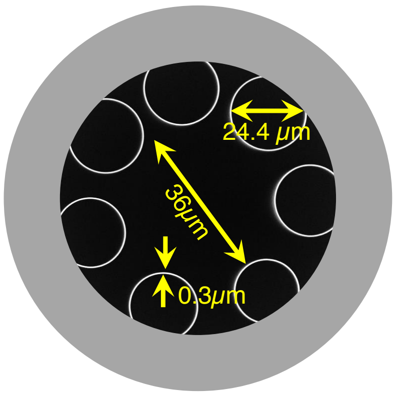
Pump wavelength: 2300nm

DW: dispersive wave

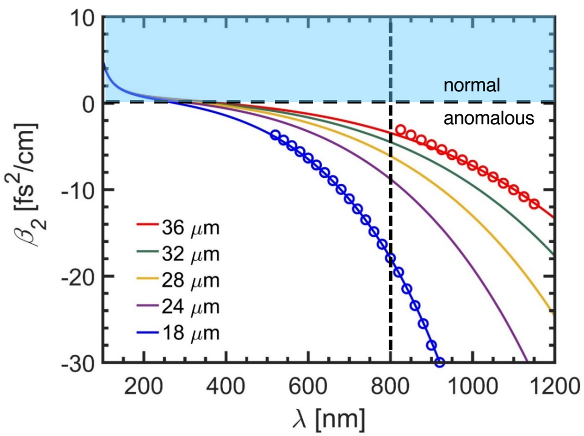


VUV Generation in Tapered AR-HCF

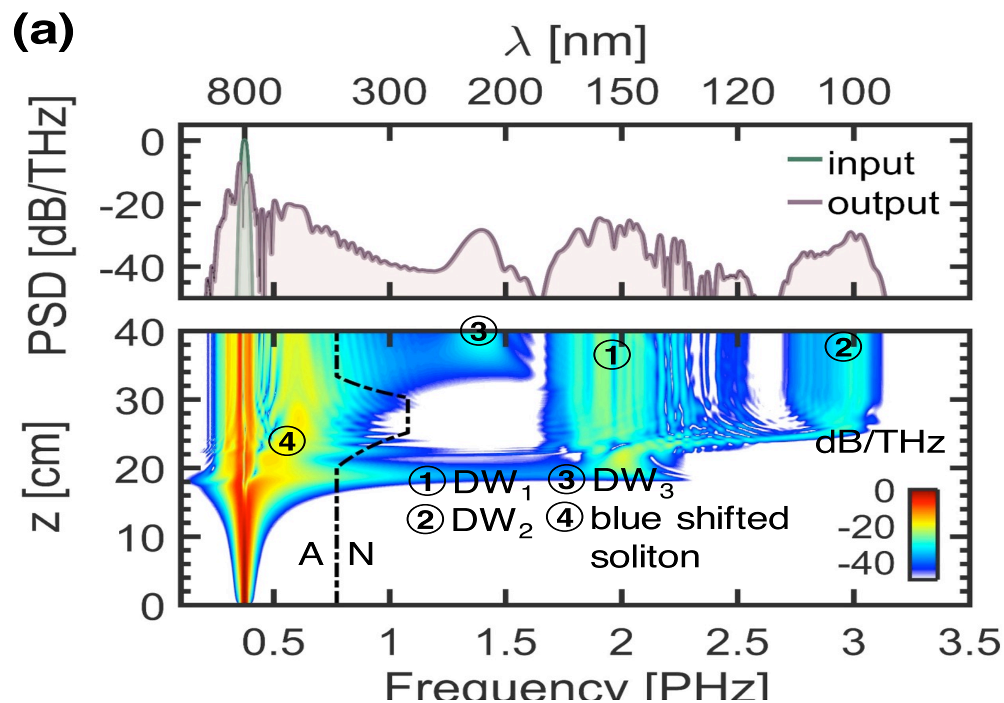
Tapered hollow-core fiber



GVD of tapered hollow-core fiber



VUV generation spectrum covering 100 to 900 nm



Fiber and pulse parameter:

43.7 μm core diameter
1.2 bar Xe, 100 fs, 20 μJ, 3000 nm
$n_2 = 8\times10^{-23}$ m^2/w

Nonlinear Compression in AR-HCF

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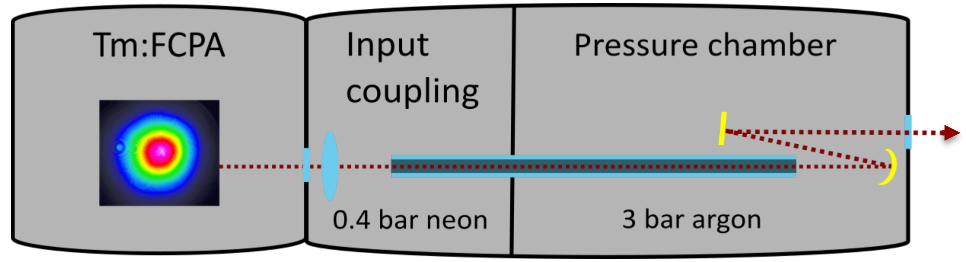
Experimental setup

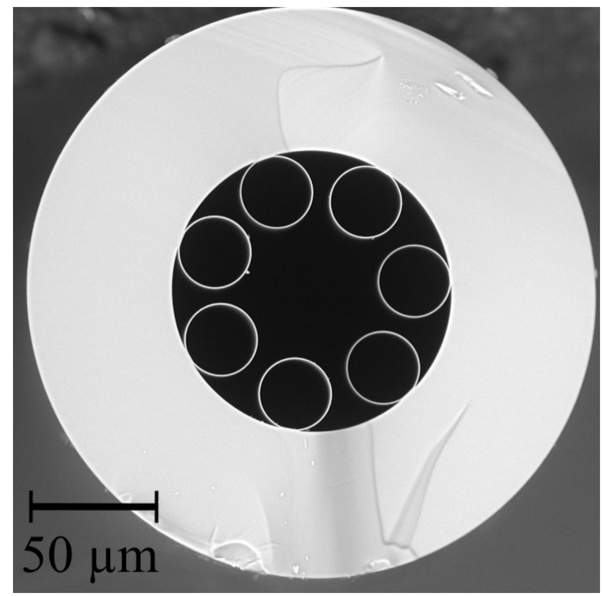


- Input:
  - ✓ 110 fs, 41 µJ pulses at 1.25 MHz (51 W)

- Coupling: 0.4 bar neon
  - ✓ Mitigating thermal blooming
  - ✓ Sufficient heat conductivity[2]

$$n^2(\lambda,p,T) = n_{gas}^2(\lambda,p,T) - \frac{2.405}{4\pi^2 a^2}\lambda^2$$

- Antiresonant hollow-core fiber
  - ✓ 42 cm length, 53 µm core diameter
  - ✓ Weak anomalous dispersion
  - ✓ >90% transmission
  - ✓ 3 bar argon



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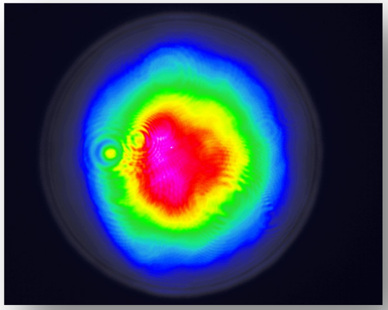
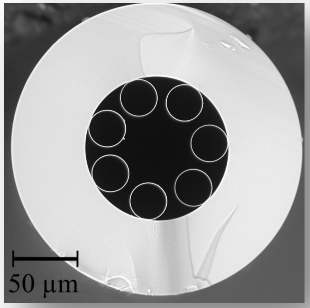
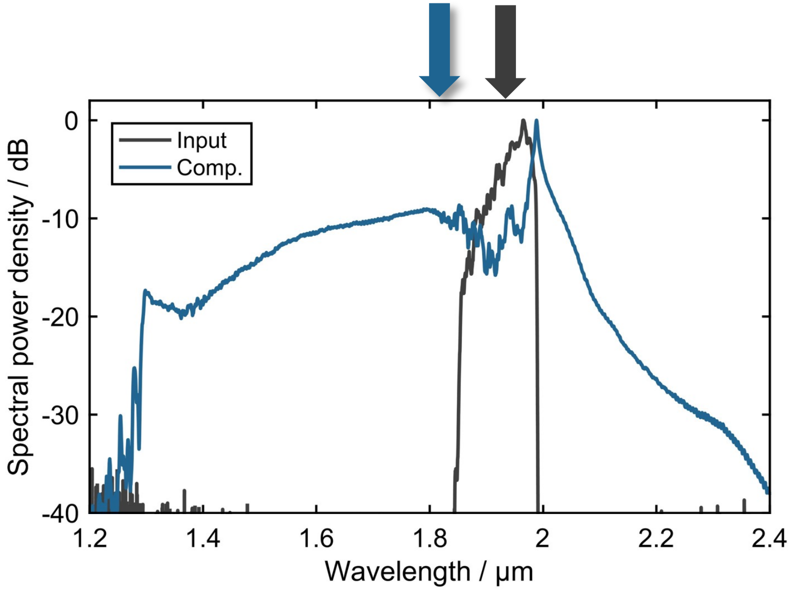
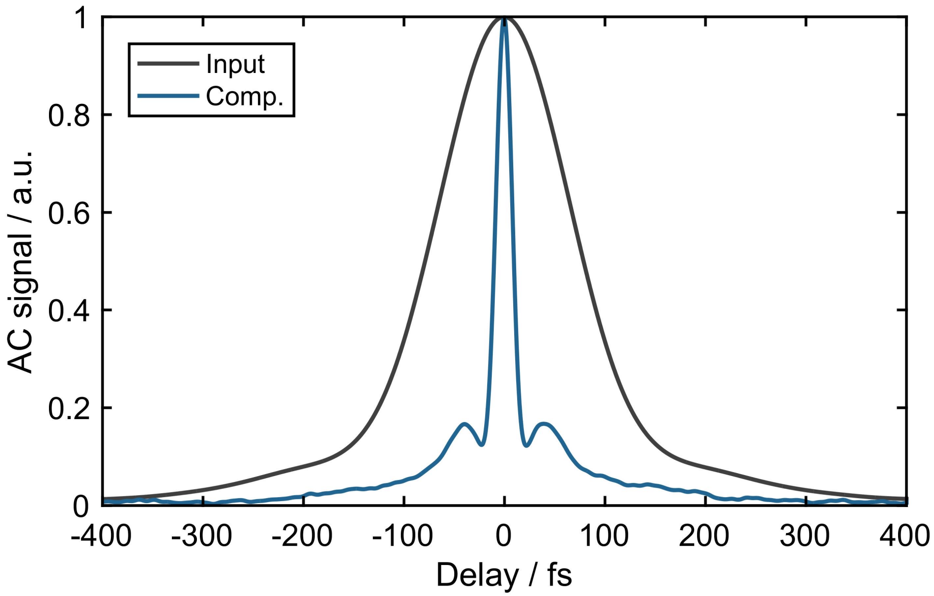
Experimental results

- 43 W compressed average power
- 34.4 μJ pulse energy









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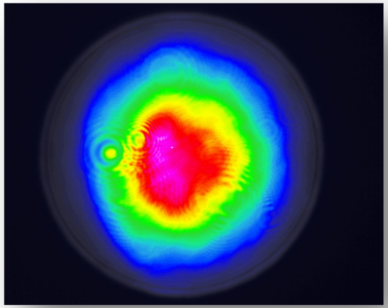
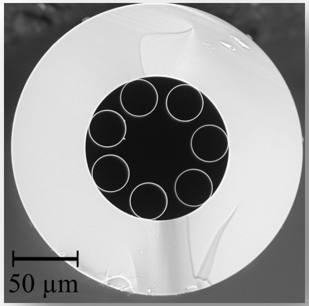
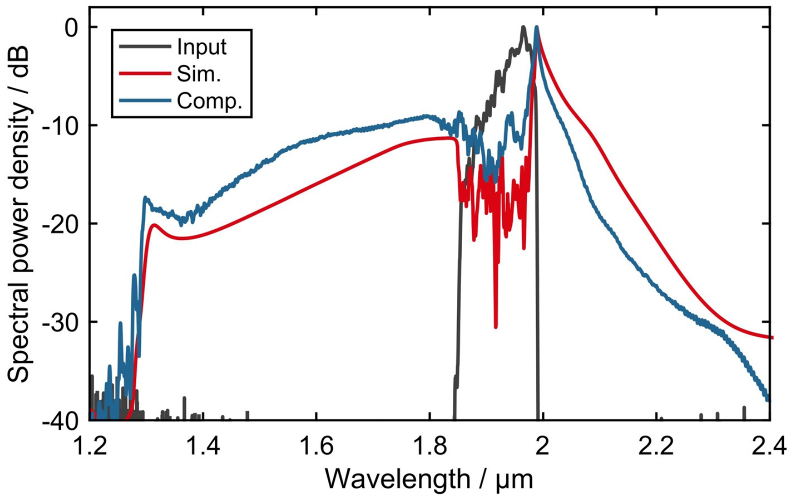
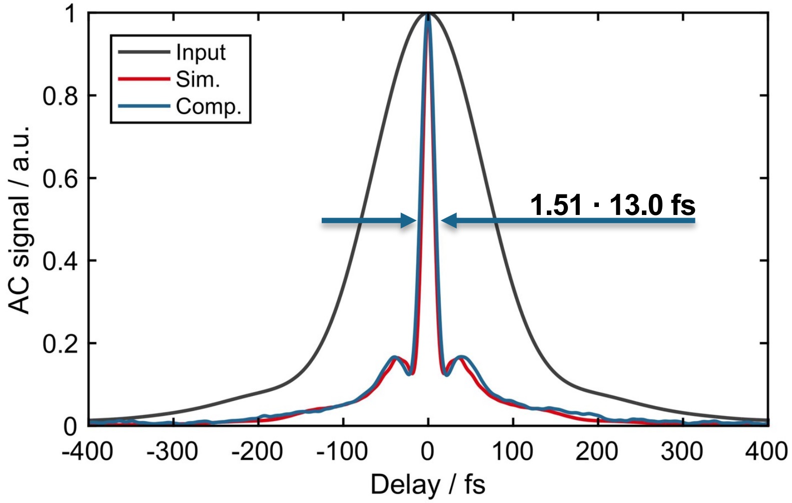
Experimental results

- Split-step Fourier method
- Capillary model for dispersion
- Ionization rates using ADK-model









Nonlinear Compression in AR-HCF

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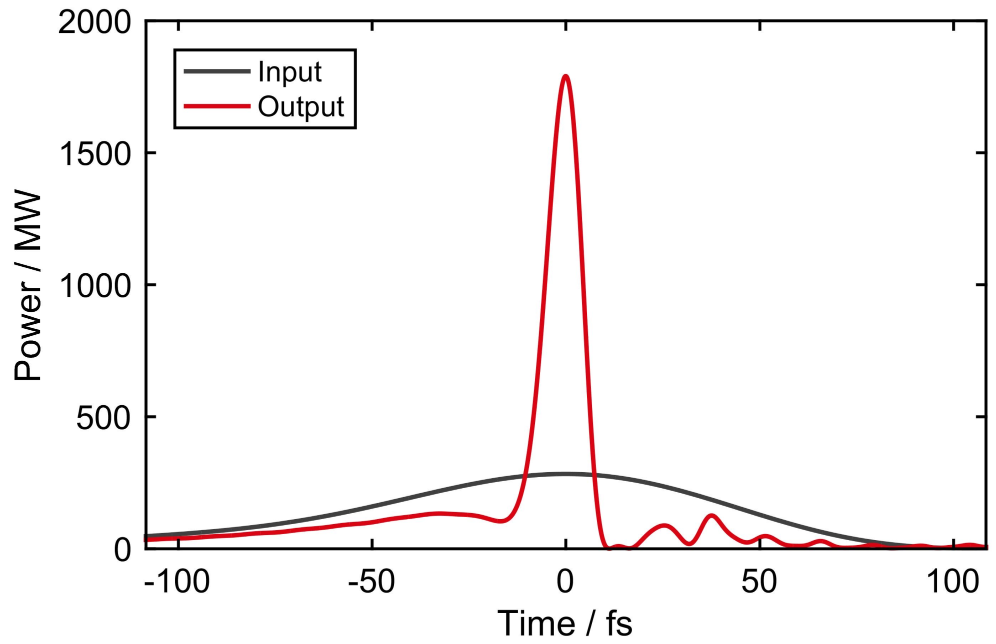
Retrieved pulse parameters

- 13 fs pulse duration
- 2.1 optical cycles
- >1 GW peak power
- **43 W average power**



✓ Highest average power few-cycle source at around 2 µm

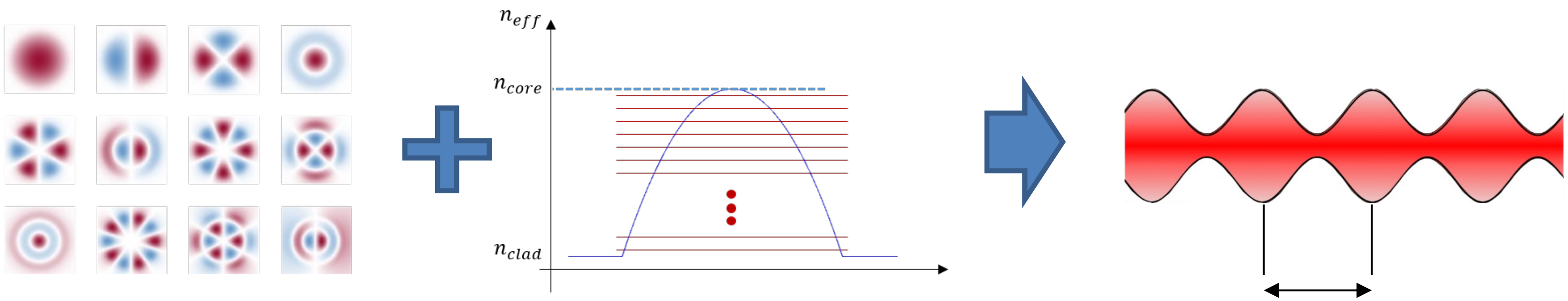
✓ Single pulse compression stage

➢ **Pulse energy scaling**

100 W-class few-cycle laser at around 2 µm wavelength with mJ-level pulse energies

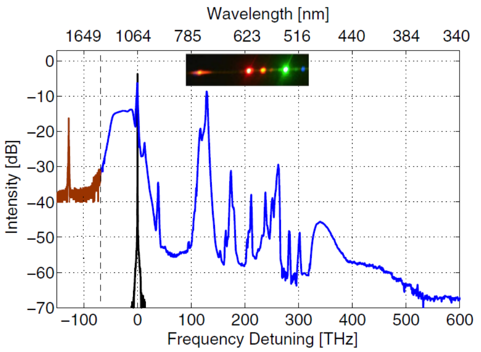
New Light Sources Using GI-MMF

Sideband generation in GI-MMF fibers

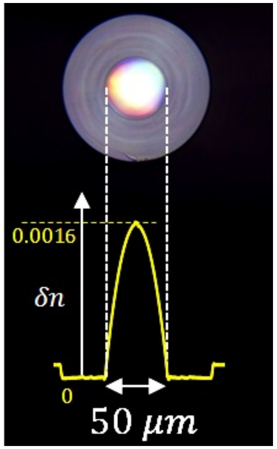


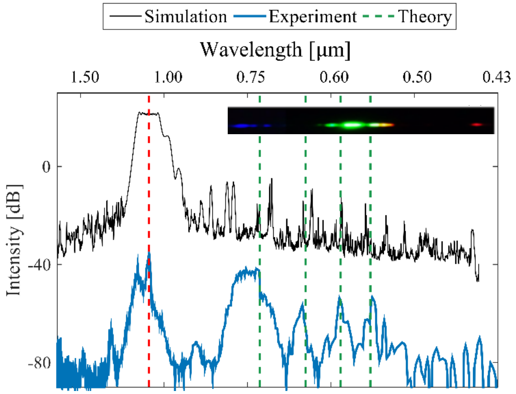
$$\xi = \frac{\pi a}{\sqrt{2\Delta}}$$

$$f_{SB}^{m} = f_0 \pm \sqrt{m} f_{SB} \quad , \quad f_{SB} = \sqrt{\frac{1}{\xi |k_0''| 2\pi}}$$



Krupa et al, Phys. Rev. Lett. 116, 183901 (2016)



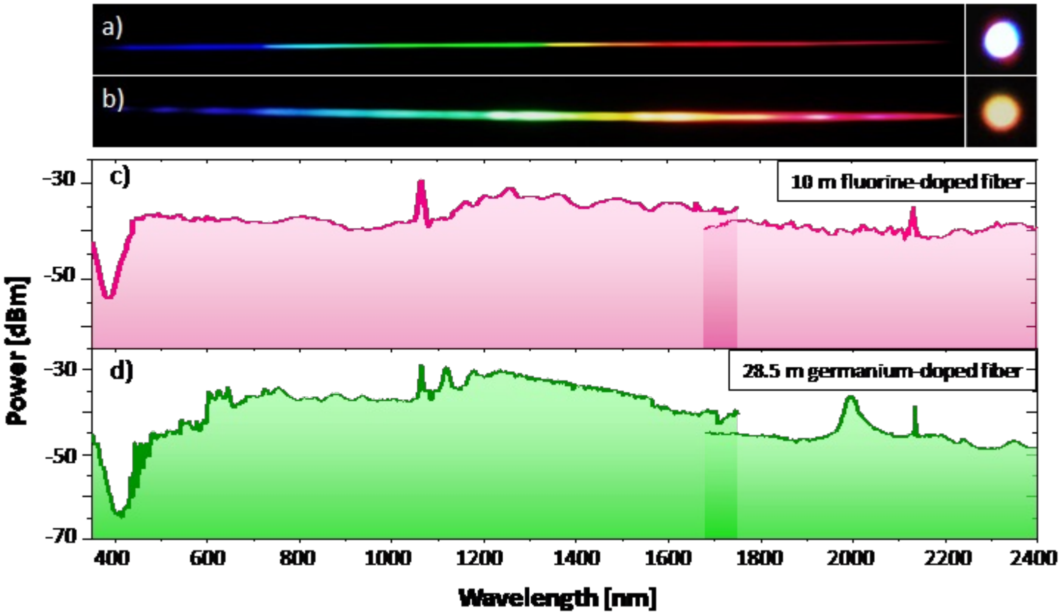


G. Lopez-Galmiche et al, Opt. Lett. **41**, 2553 (2016)

[1] Stefano Longhi, Opt. Lett. **28**, 2363-2365 (2003)

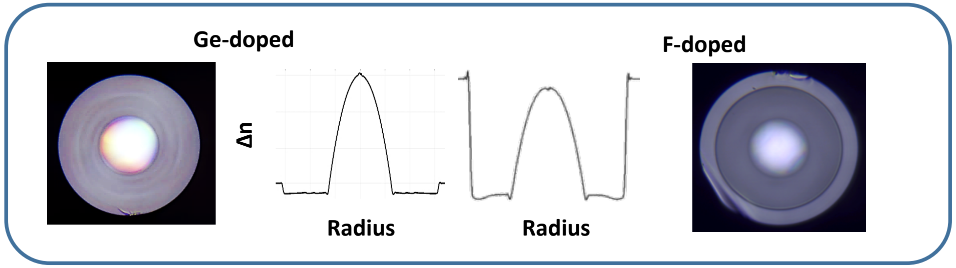
Supercontinuum Generation in GI-MMF

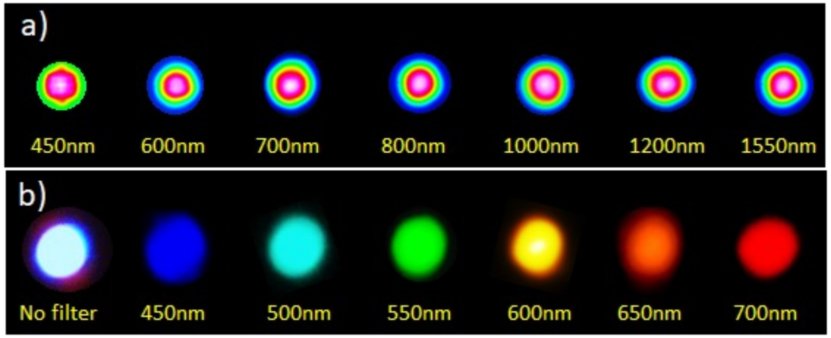
Supercontinuum generation in two types of GI-MMFs



Pump in normal dispersion region and far from the zero dispersion wavelength

- Remarkable spectral broadening: from ~450 nm to 2400 nm
- Rather uniform spectrum
- Visible spectrum comparable to that generated in small core PCF
- Good beam quality





Future Work

Short to long term plans

Design and Fabrication on Novel Fibers and Active Materials

- In house fabrication of Yb-doped and Tm-doped preforms using new MCVD lathe

High power testing of Yb-doped LP-PCF

- Experimental MI studies at multi-kW powers

Advance Mode High Power Amplifier Simulation Tools

- Use experimental feedback to improve predictable capabilities

New High Power Fiber Amplifier Schemes

- Modal control in kW amplifiers using photonic lanterns
- Coherent beam combining using multicore fiber amplifier