

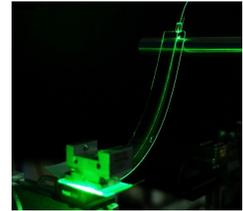
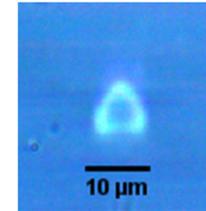
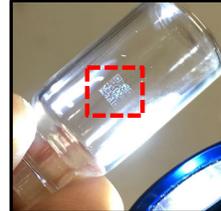
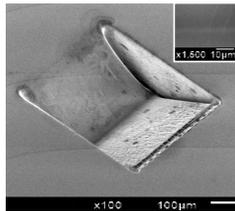
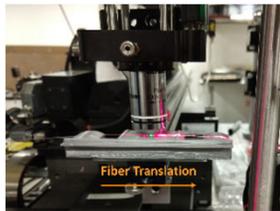
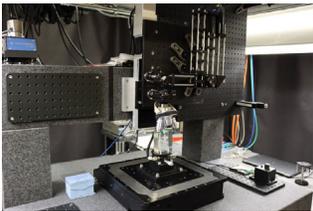


Femtosecond Laser Manufacturing of 3D Photonic Components in Nonlinear Optical Substrates for Electro-Optic Applications

A PA Manufacturing Innovation Project

Presented by:
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Industry Partner: II-VI Inc. and Corning Inc.





Outlines:

- **Motivation**
- Approach
 - Ultrafast laser manufacturing – Controlling laser-matter interaction at –fs time scales and –nm spatial resolution.
- R&D Outcomes
 - High quality lightwave circuits in LiNbO₃ and chalcogenide glass.
 - High quality 3D waveguides in silica glass: Gorilla glass/fused silica.
 - Laser assisted chemical etching: MEMS devices in glass.
 - Fiber Sensors.
- Summary



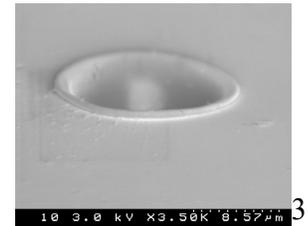
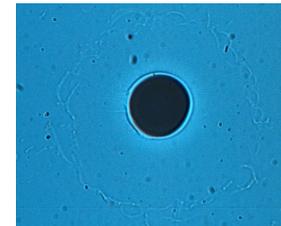
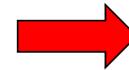
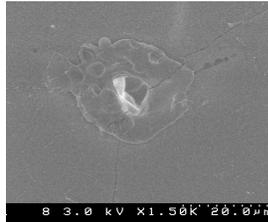
Laser Processing: A key manufacturing technology



<https://www.machinemfg.com/laser-processing-technology/>

Driving the manufacturing of the 21st century

- **Workhorses:** CO2 laser, Excimer Laser, Fiber Laser, YAG laser and femtosecond ultrafast laser.
- **Femtosecond laser processing:**
 - Precision manufacturing
 - Minimal thermal effects
 - Potential for high quality product manufacturing
 - Minimal damage manufacturing
 - Uniquely suitable for micro-electronics/photonics
 - High-value added
 - **“Internal Processing – True 3D Processing”**



Ultrafast Laser Direct Writing: A Versatile 3-D Manufacturing Tool

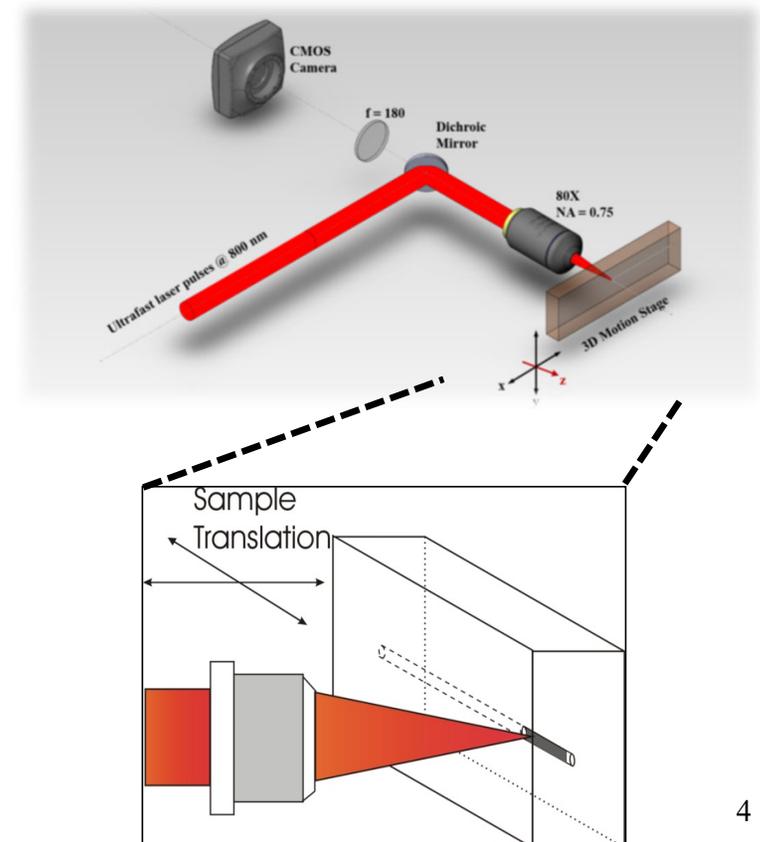
• Mechanism

- Ultrafast laser pulse tightly focused inside the transparent material, the multi-photon process initialized by high intensity pulses; causes energy transfer to the material, leading to a permanent material modification at the focal volume.

• Application of ultrafast laser writing

- Transparent material
- Maskless
- Flexibility (arbitrary complex structure)
- 3-D fabrication
- High quality embedded photonic structures in bulk materials

Ultrafast Laser Writing System

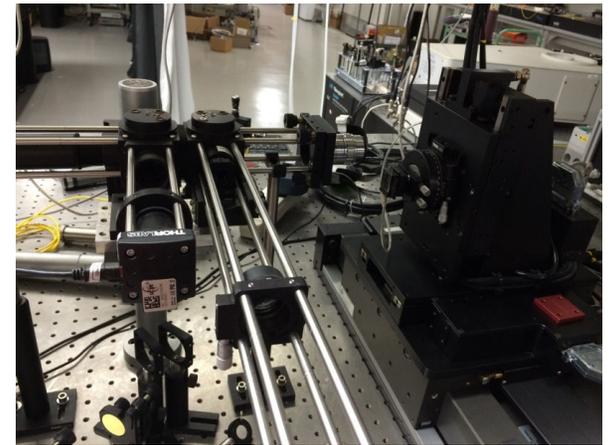
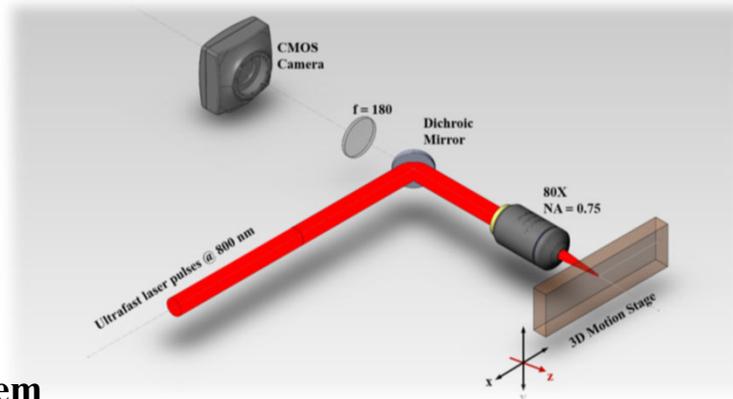




Ultrafast Laser Manufacturing



Ultrafast Laser Writing System



3-Axis Motion Stage

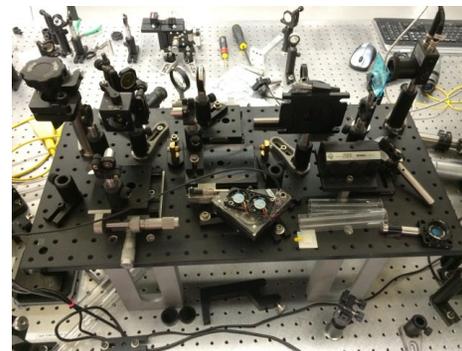
- Computer Control with G codes
- Accuracy: 0.2 μm
- Repeatability: 0.1 μm
- Writing Speed: up to 5 cm/s

Beam Delivery System

- Beam Collimation
- Power Control and Monitoring
- Pulse Width Measurements

Coherent MIRA-RegA Laser System

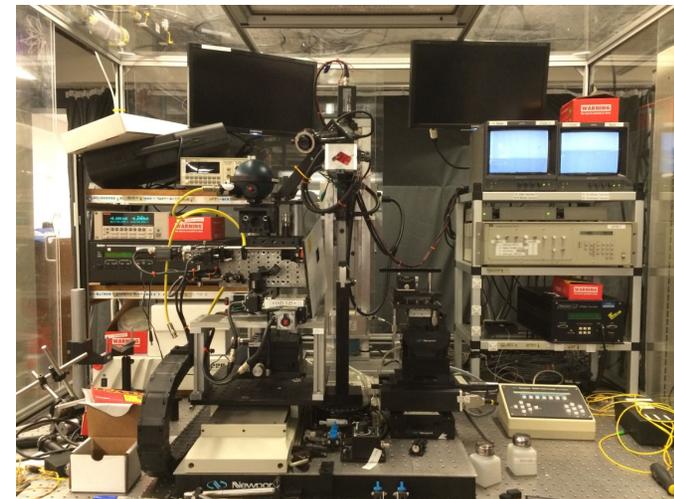
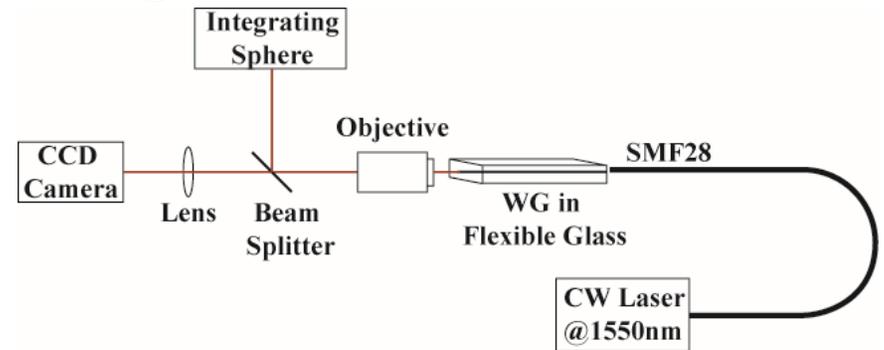
- Ultrafast pulses @ 800nm
- 100-750 kHz repetition rate
- Pulse energy up to 4uJ
- Pulse width from 300fs to 20ps



Consistency in our ultrafast writing Process (0.05dB/cm)

Measurement Platform – Waveguide Characteristics

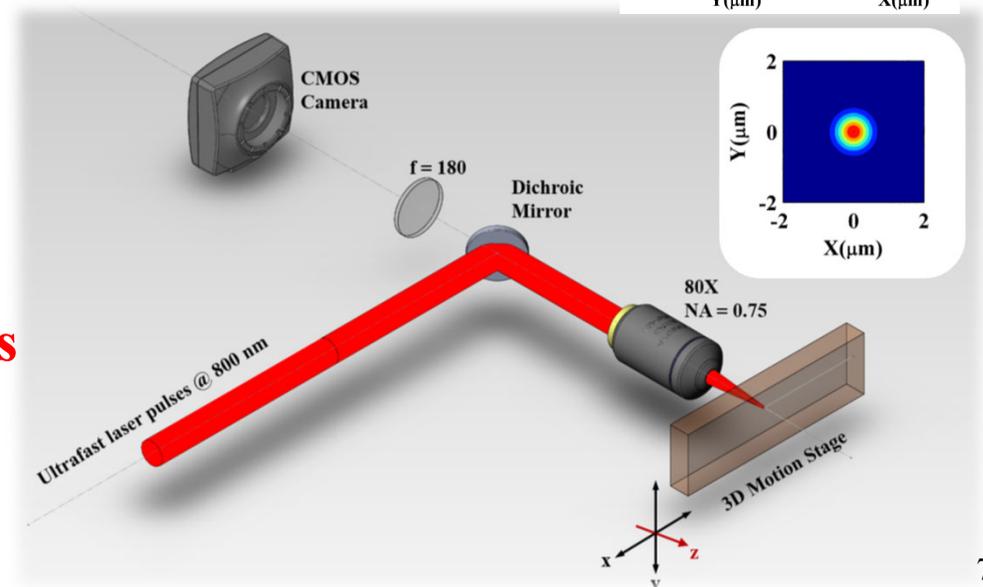
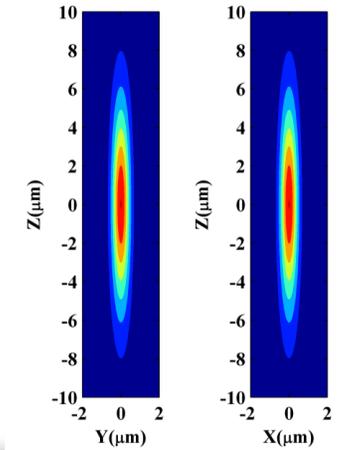
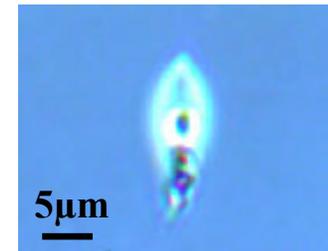
- Optical microscopy
 - Index change profile
 - Characterization of waveguide structure
- Scanning Electron Microscope (SEM)
- Optical backscatter reflectometer (OBR)
 - Propagation loss
- Customized characterization setup
 - Guiding mode profile at 1550 nm
 - Insertion loss



Measurement Platform

Ultrafast Laser – Beam Shaping

- Transverse writing configuration
 - Waveguide cross section
 - Laser beam profile in YZ plane
- Cross section control
 - $Y \sim 2w_0$, $Z \sim 2\pi w_0^2/\lambda$
 - Single mode operation @ 1550nm
 - $Y \sim 10 \mu\text{m}$, $Z > 100 \mu\text{m}$
- Asymmetric waveguide cross section
- **Uncontrollable nonlinear interactions**

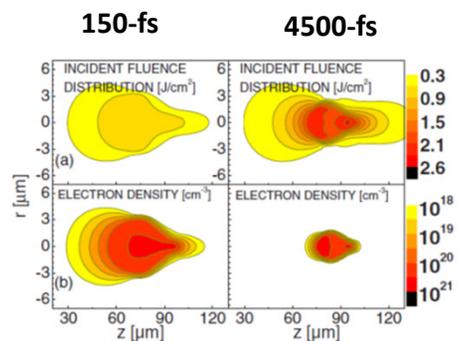
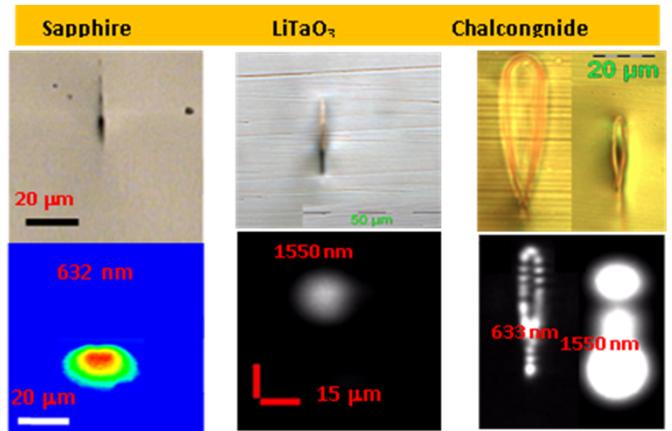
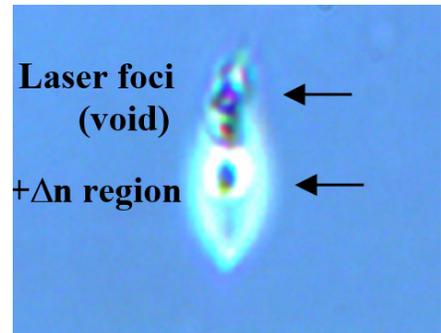




Femtosecond Laser – Matter Interaction: Complex Processes

180 fs results

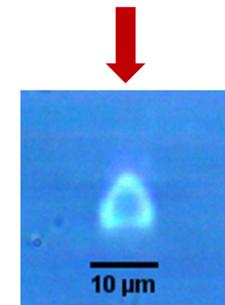
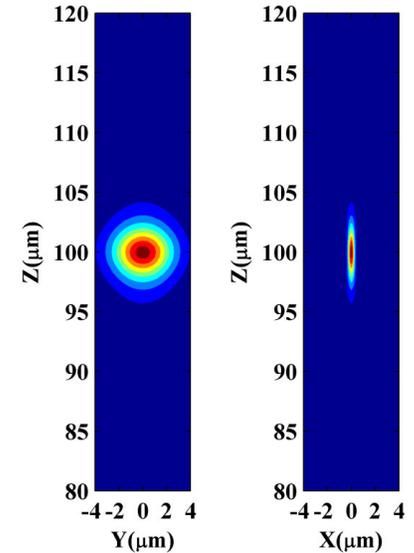
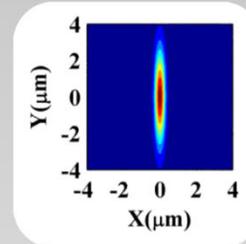
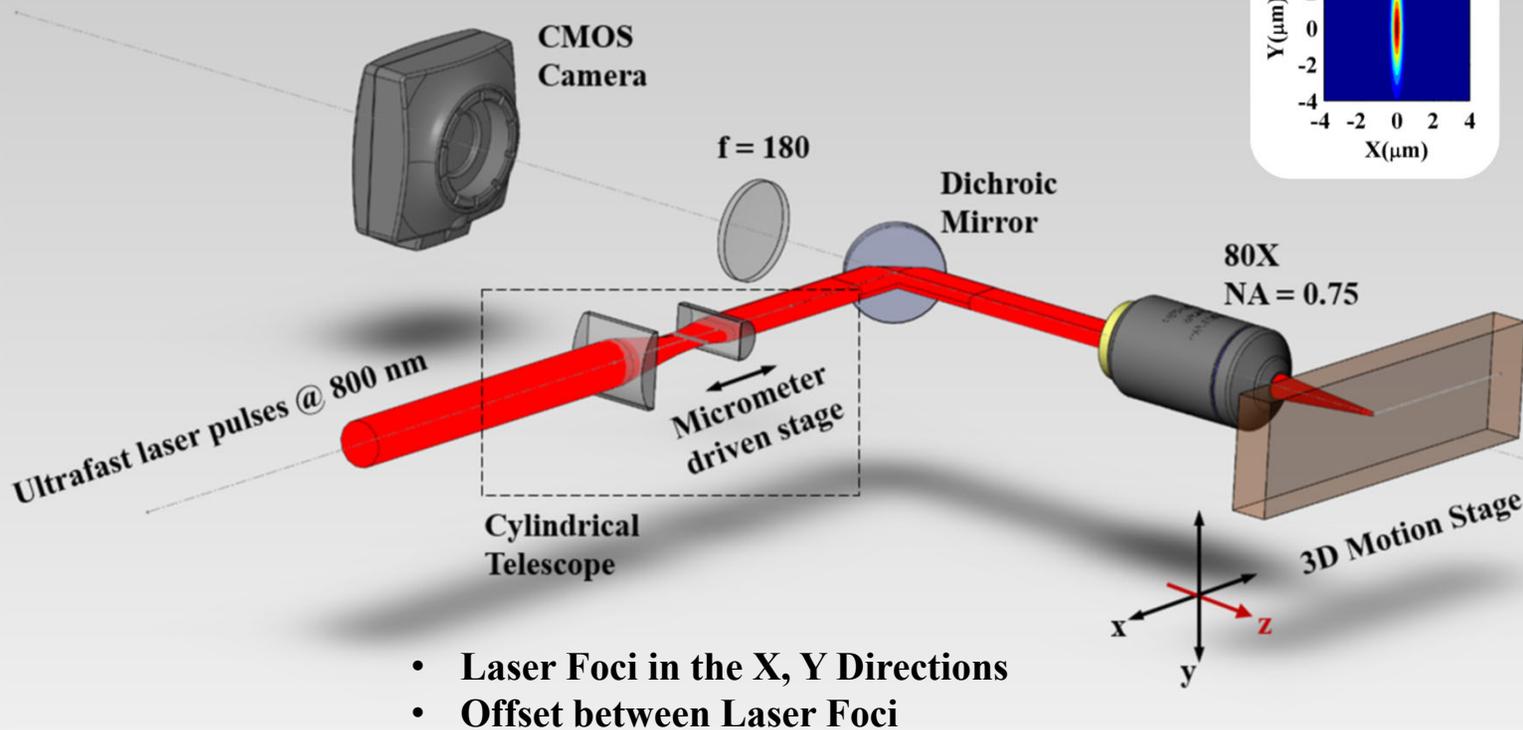
- **Laser-induced Plasma (100 fs to 100 ps)**
 - Form around laser foci ($\sim \text{nm}^3$)
 - Laser focal volume's nonlinear distortion
- **Local thermal relaxation (0.1ns to 10- μs)**
 - Plastified shell (melting)
 - Thermal wave propagation
 - Laser-induced strain
 - Refractive index changes



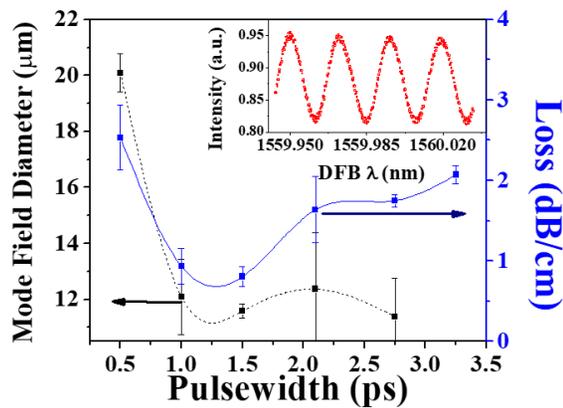
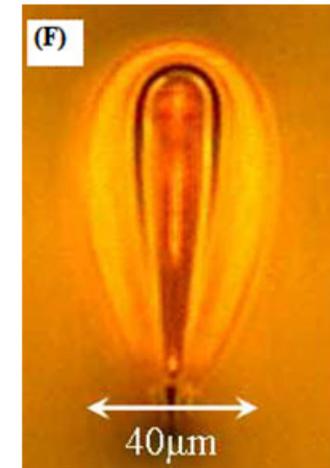
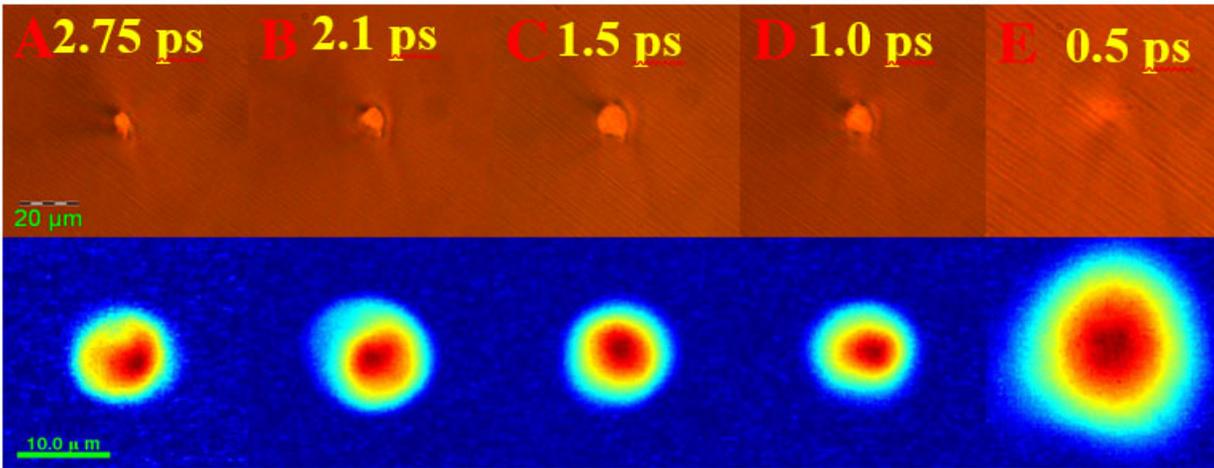
- Nonlinear distortion become significant at extreme laser intensity.
- Distortion of laser focal volume (size and shape).
- Laser energy transfer into electron plasma depends on laser intensity
 - **Size and shape of focal volumes**
 - **Pulse duration**

Ultrafast Laser – Beam Shaping

Performance of beam shaping

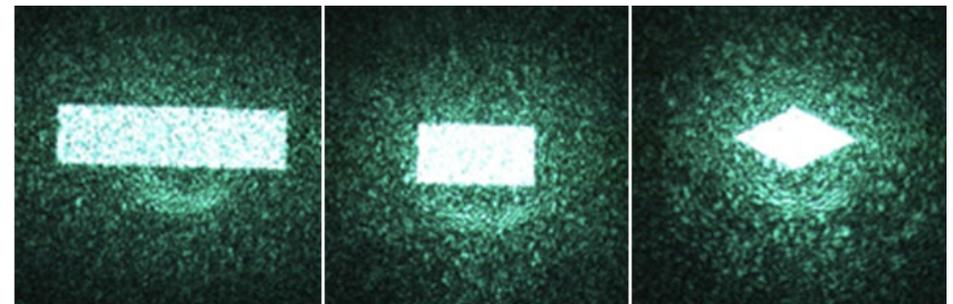
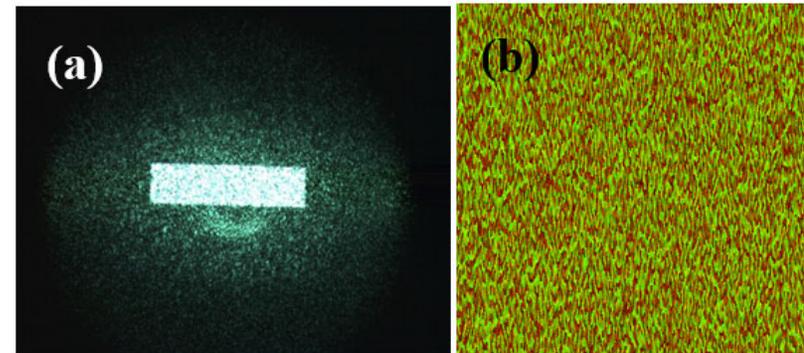
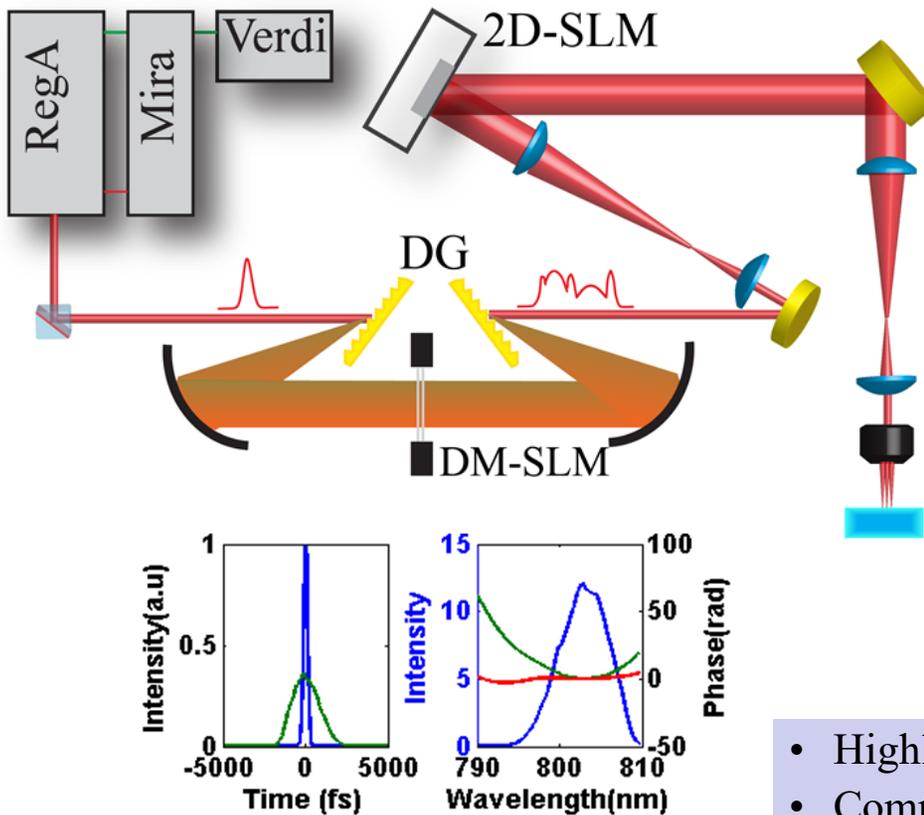


Ultrafast Laser – Beam Shaping and Pulse Shaping



- Control of focal volume and size by introducing optical aberration
- Moderating nonlinear pre-focal plasma formation via pulse shaping from 150-fs to ps
- Additional beam shaping can further improve effects

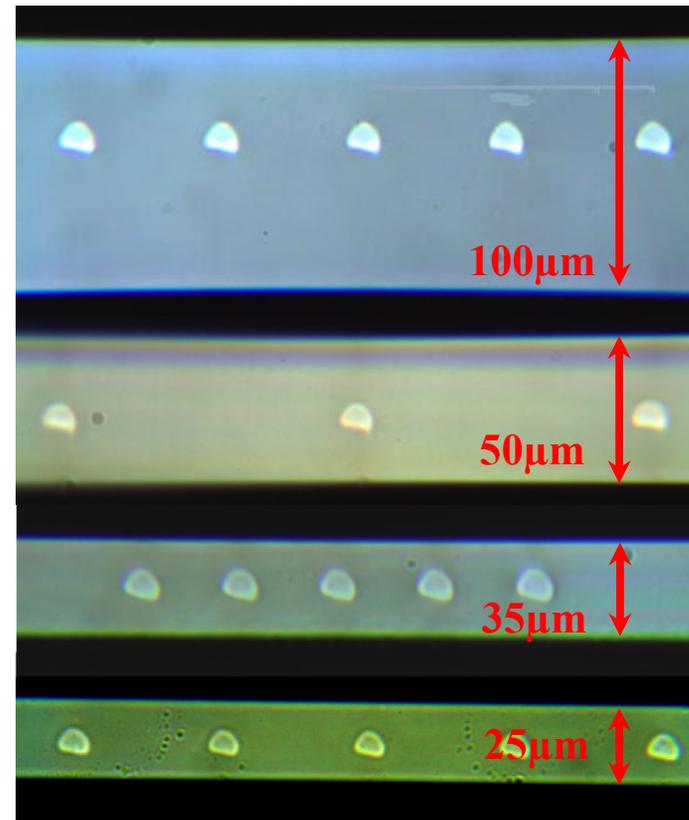
A flexible beam shaping tool: Spatial Light Modulator



- Highly flexible beam shaping tool
- Computer generated hologram to adjust focal volume on the fly

Waveguides in Flexible Glass

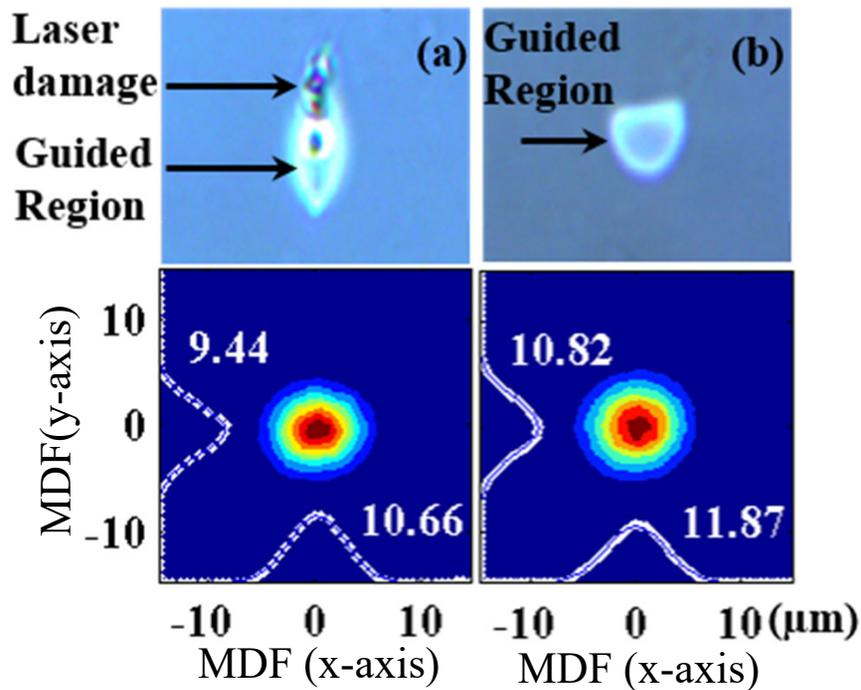
- Glass substrates
 - Thickness: 100, 50, 35, 25 μm
 - WG Depth: 35, 30, 20, 15 μm
- Optimized experimental parameters for writing waveguides in glass:
 - Pulse Width = 300 fs
 - Pulse Energy = 1000 nJ
 - Writing Speed = 10 mm/s



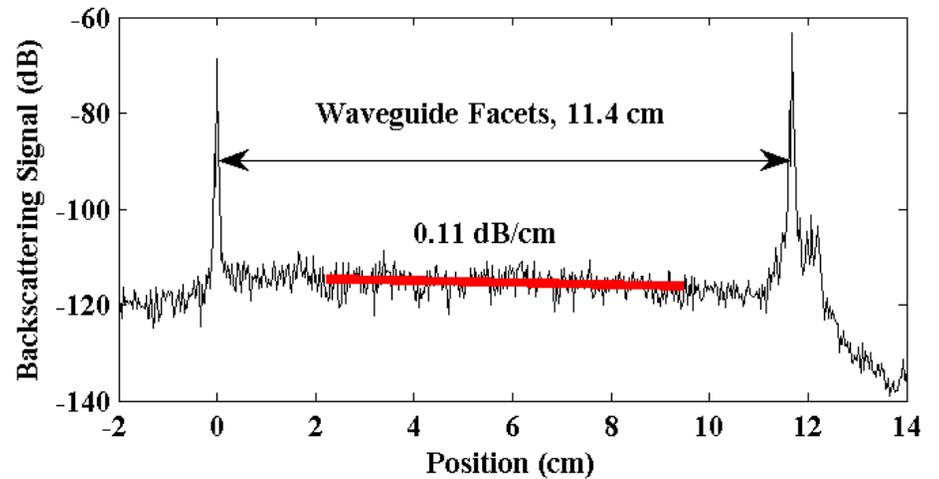
Cross section view of waveguides in glass samples

Waveguides in Flexible Glass

Mode Profile without(a) and with(b) beam shaping



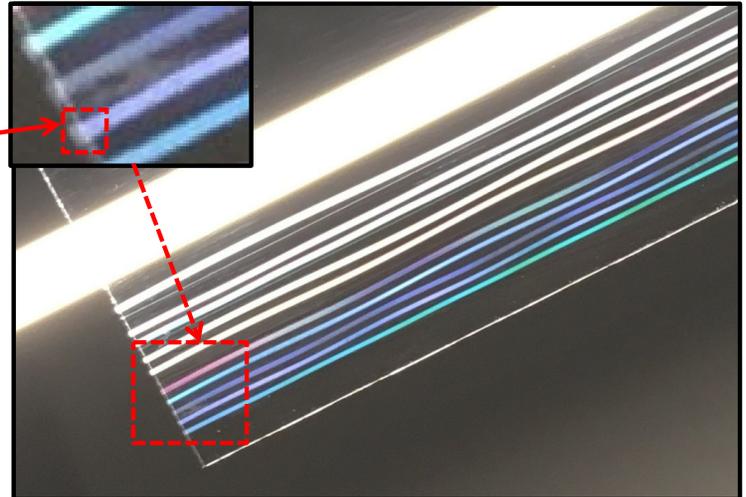
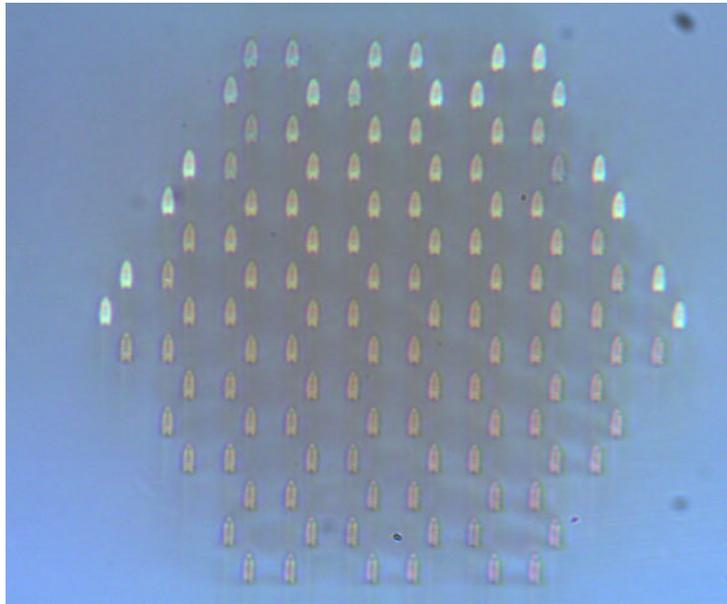
Propagation loss measurement by OFDR



- **Low Propagation Loss** in glass waveguides
 - Embedded WG loss: 0.11dB/cm
 - Polymer WG loss: 0.5dB/cm

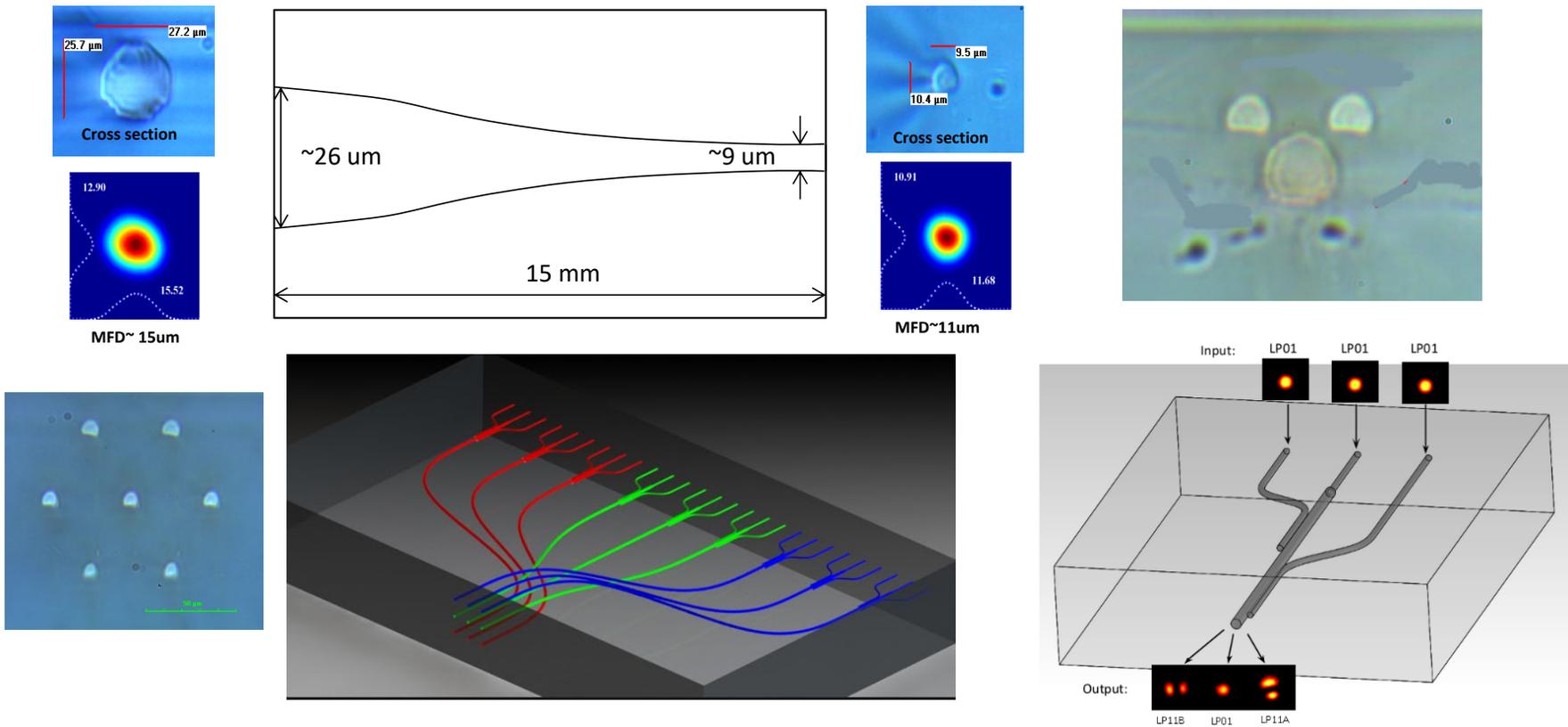


The scale of our fabricated 3-D waveguide arrays





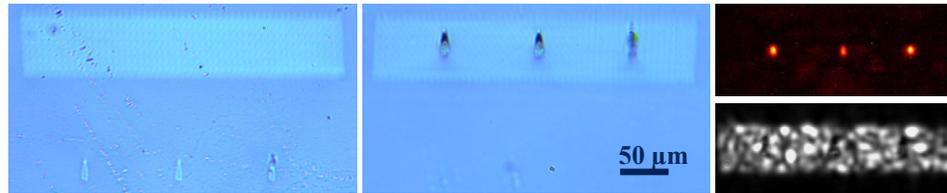
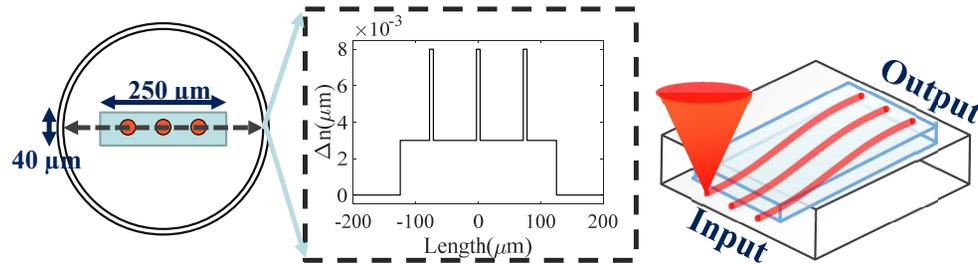
3-D Waveguide Circuits for Multi-Core Few Mode Fibers



Optical Interconnect

Hmm... shall I get rid of these two pages?

- Optical fibers with novel geometry are designed in optical communication to maximize bandwidth and minimize loss
- A multicore fiber with a Er-doped extra cladding layer (NEC Inc) needs an all-photonic devices to couple/decouple the pump and real signals to the fiber from separate devices



- Waveguides written separately for the pump light and signal light with different refractive indices
- Signal propagation and pump light transmission verified at 1550 nm and 980 nm separately

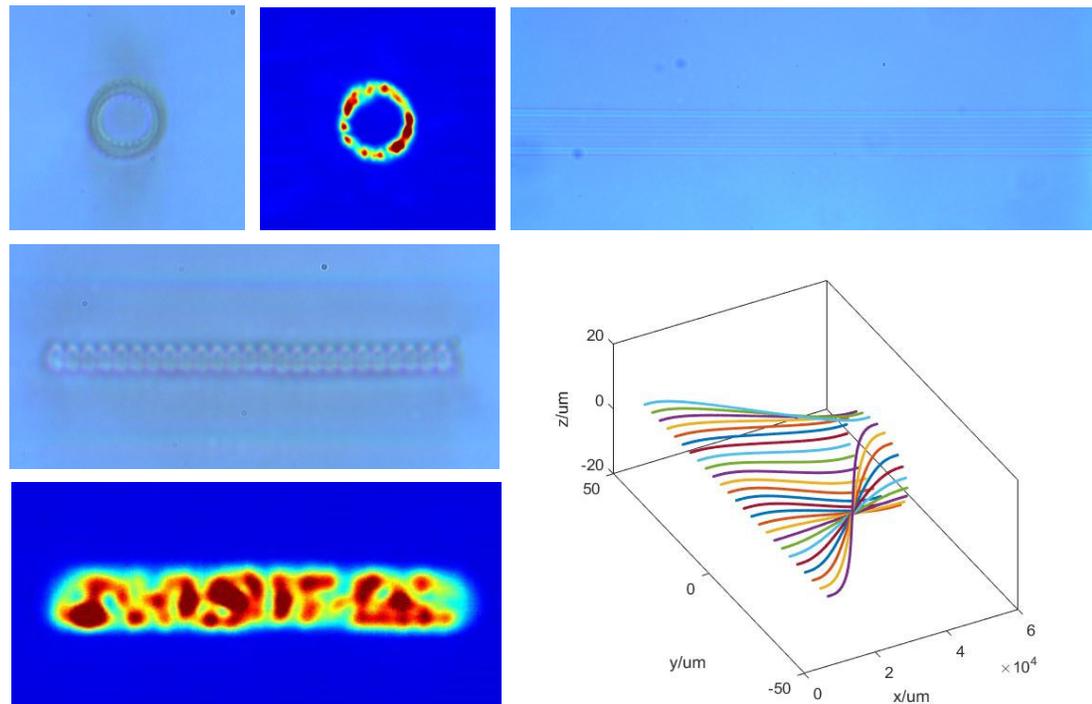
Part II
Bulk Platform



Optical Interconnect

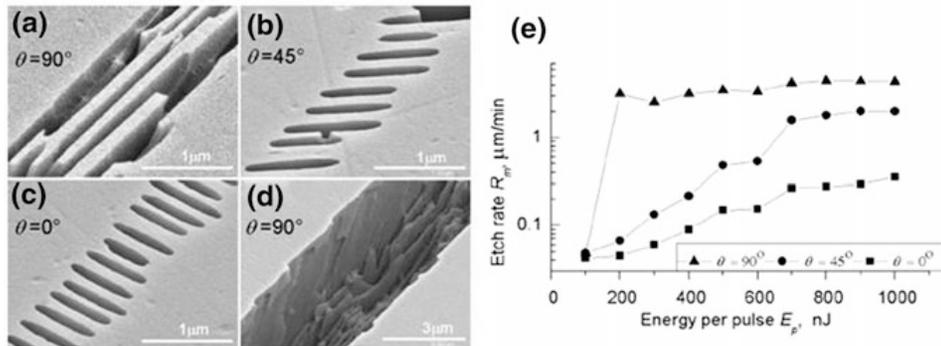
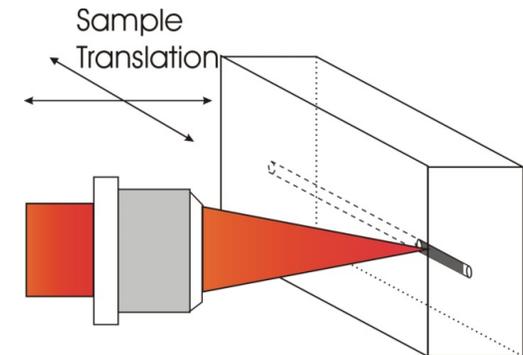
- Telecommunication fiber with ring-shaped Er-doped layer (NEC Inc.) requires an all-photonic device to couple light from the bar-shaped laser diode pump
- Geometry of the waveguide was designed to match the coupling of the optical fiber

Part II
Bulk Platform

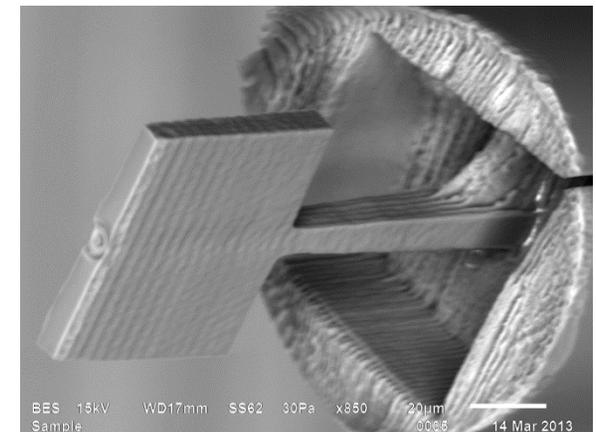


Ultrafast Laser Micromachining in Fused Silica Glass: introduction

- Formation of periodic nanograting-like structures.
- Etch rate and selectivity strongly depend on the polarization of the writing pulses (selectivity up to two orders of magnitude)
 - Flexibility, arbitrary complex structure; True -3D fabrication
 - Embedded micro structures in bulk materials



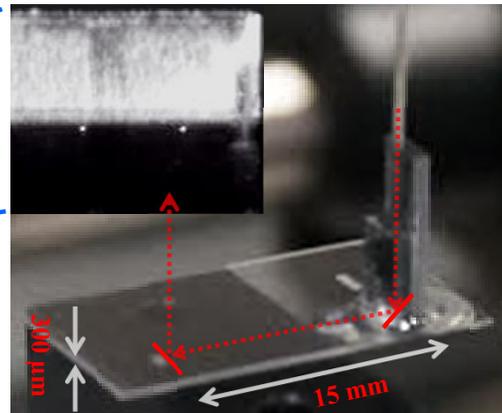
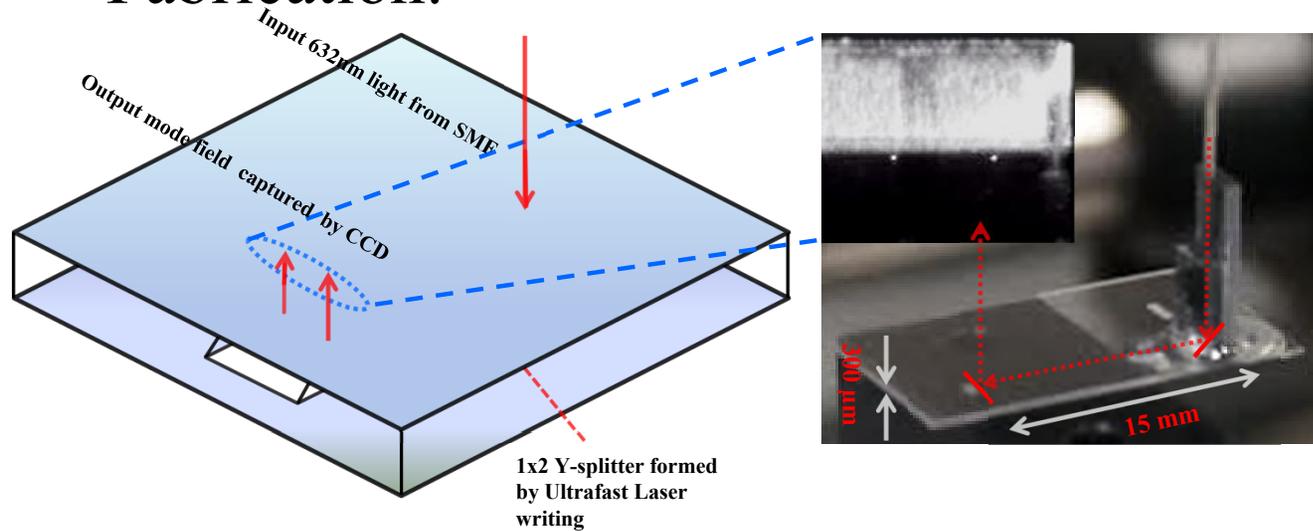
Hnatovsky et al, 2005



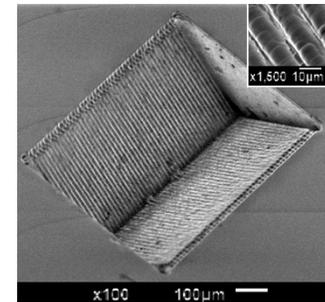
Our 3-D printed MEMS on Fiber

Project 2 – Vertical Coupling Micromirror

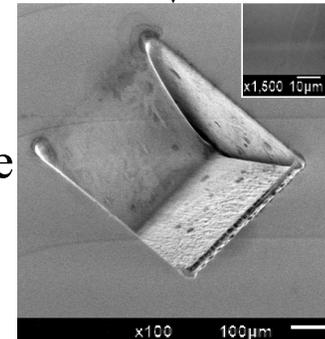
- Fabrication:



SEM Photo



↓ Laser reflow

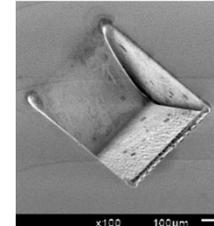
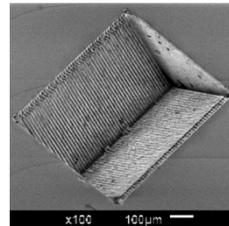
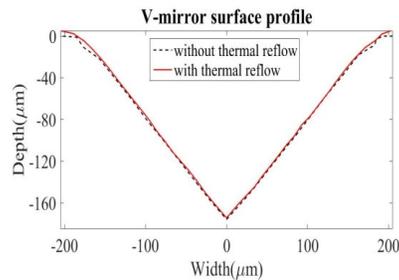


- Laser assisted etching/laser micromachining to form V-shaped volume
- Laser written waveguides to form 1x2 beam splitter.
- Improved surface quality by CO₂ laser reflow

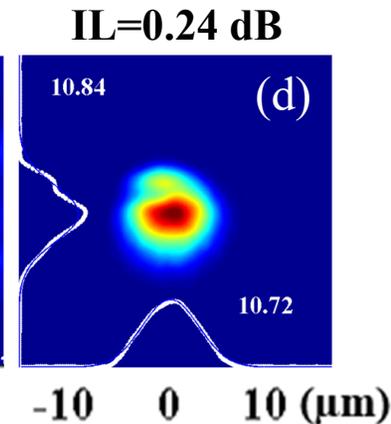
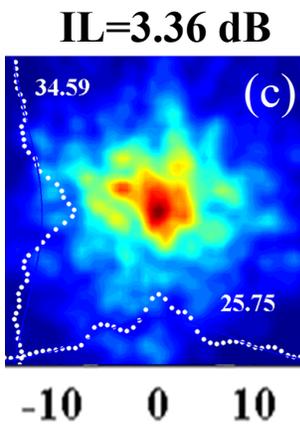
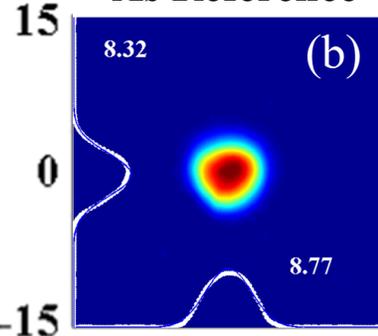
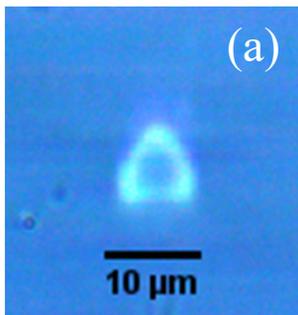
Project 2 – Vertical Coupling Micromirror

- Micromirror Performance Characterization

Slope profile before
and after laser reflow



Cross section



(a) Cross Section View of WG (b) Mode profile without mirror;
Mode profile propagating after the mirror without (c) and with (d) laser reflow

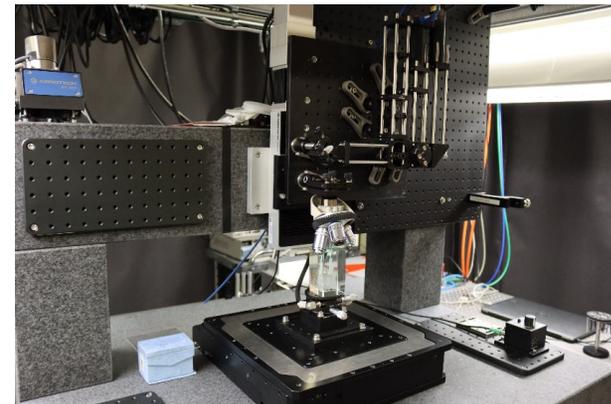
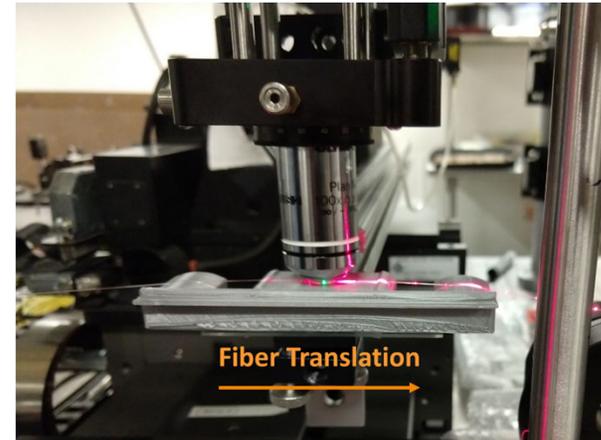
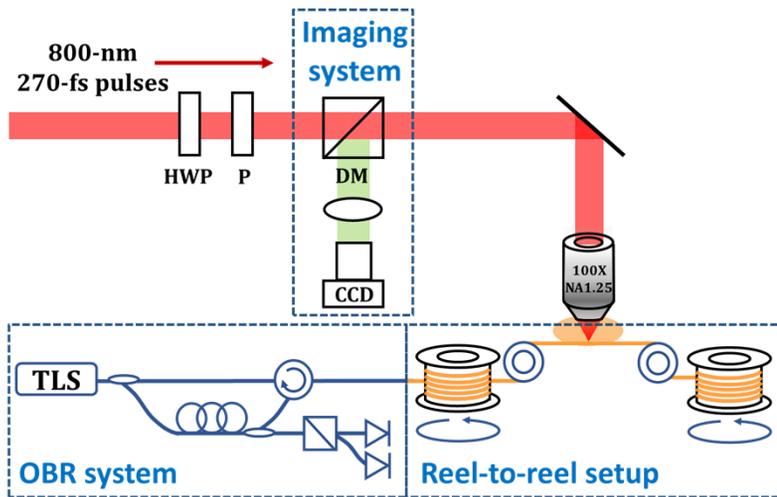


PA

pennsylvania
DEPARTMENT OF COMMUNITY
& ECONOMIC DEVELOPMENT

Developing World-Class Manufacturing Technology in Pennsylvania

Fiber Sensor Fabrication

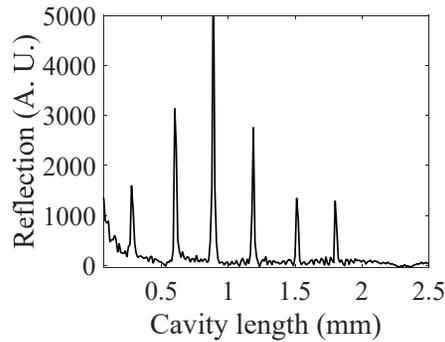
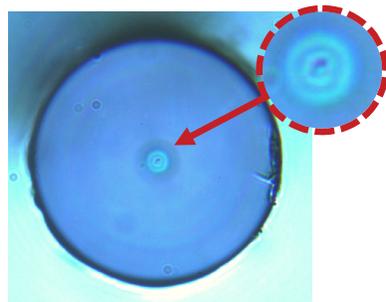
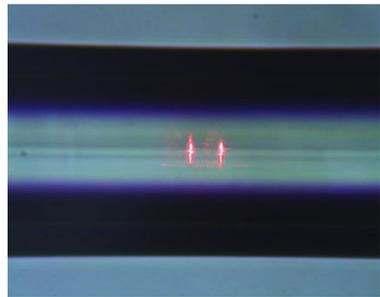
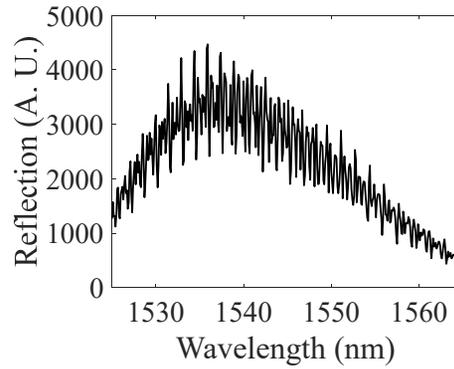
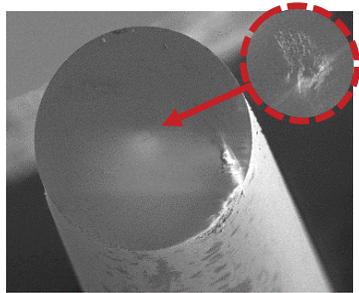
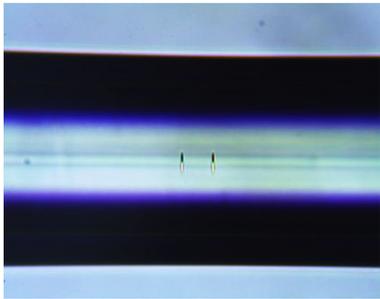


Reel-to-reel oil-immersion fiber writing setup

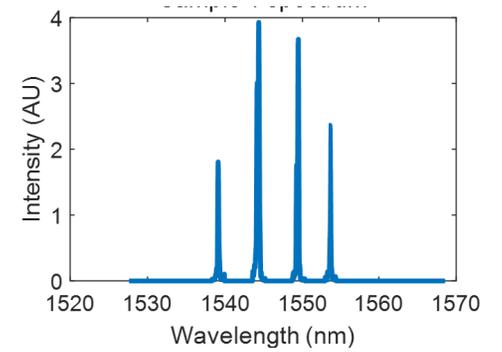
- Fast and continuous fabrication over >tens meters
- -fs (190fs – 5 ps), 800-nm, 532-nm, 355 nm outputs
- Sensors fabrication over 20 m continuously
- Applied to wide array of rad-hard fibers
- Real-time monitoring
- New laser system comes online



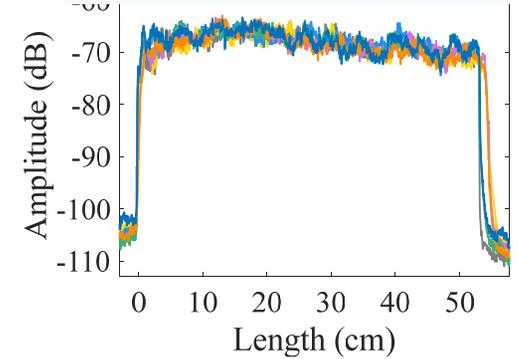
Fs-laser inscription of Type-II Nanograting and IFPI Sensor Array



FBG Sensor String

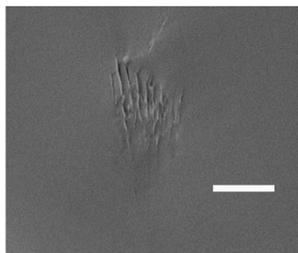


Laser Enhanced Rayleigh Scattering Profile

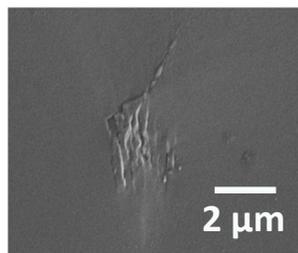




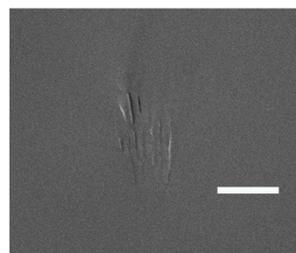
Optimization of Laser Processing to Ensure High-T Stability and Low-Loss



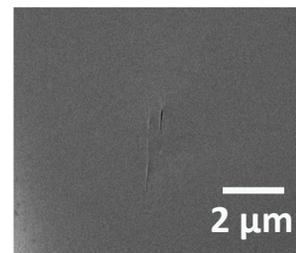
160-nJ



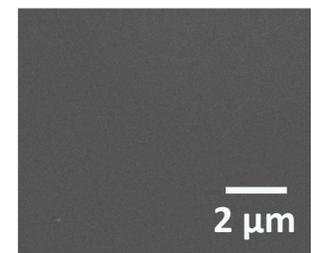
140-nJ



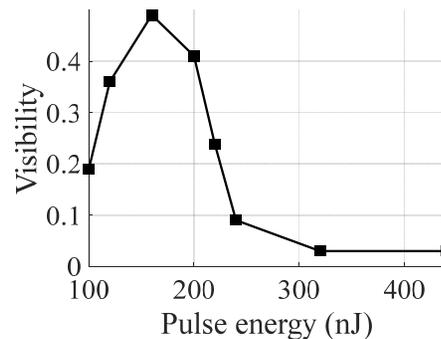
120-nJ



100-nJ



80-nJ

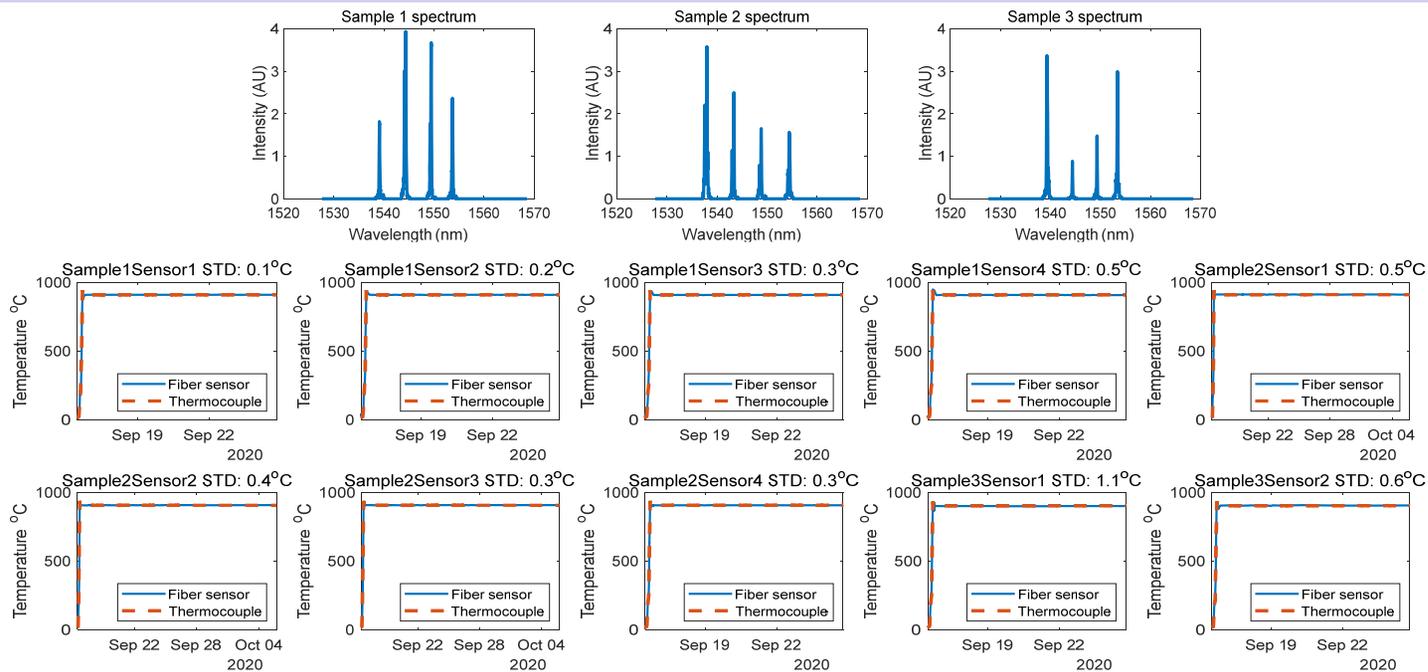


- Nanograting formation threshold at 100 nJ pulse energy
- With the increase of pulse energy, size of nanograting increases
- High visibility of 0.49 at optimized pulse energy of 160 nJ
- Low insertion loss of 0.0024 dB per sensor



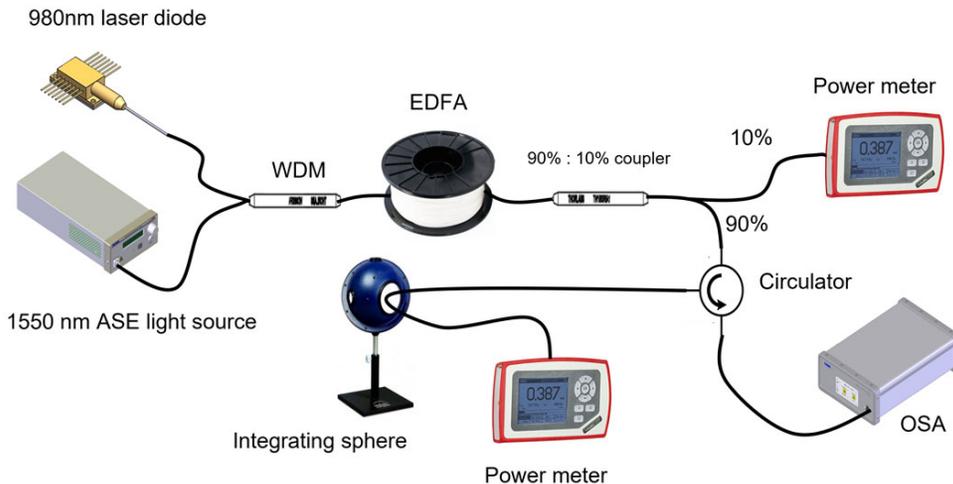
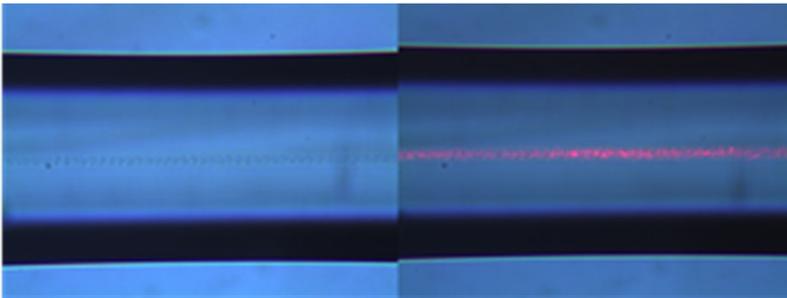
Improving TRL for Reactor Deployments

- **Comprehensive FBG sensor array high-T testing (900°C-1000°C)**
- **Interrogation electronics and algorithm used for demodulation**
- **Average STD <0.6°C over 10 days spans at 900°C (comparing with TC)**
- **Further increase sensor counts (200) and testing duration (2 months) in 2021-2022.**





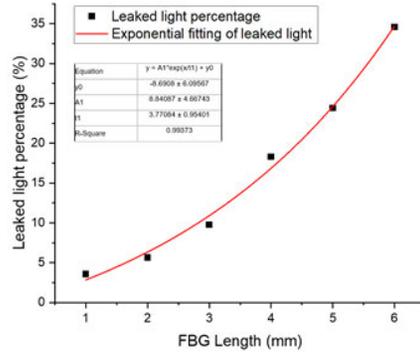
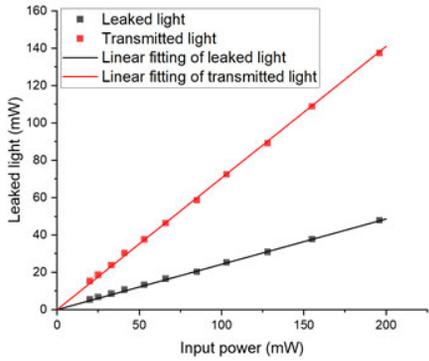
Multiplexable Active Fibers Power by In-Fiber Light



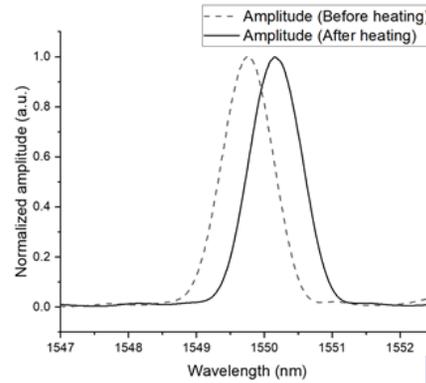
- The scattering loss depends on laser processing parameters...
- Can we use light scattered out from fiber sensor devices?
- Yes--
- If we can convert the scattered optical power into heat... then we can measure more parameter!
 - When the power light is turned down... fiber sensors perform passive measurements (strain/temperature)
 - When the power light is turned up... fiber sensors perform active measurements (level, flow, etc!)
- Truly Multiplexable (multiple sensors inscribed in a single fiber)
- US Provisional Patent funded by this project



Multiplexable Active Fibers Power by In-Fiber Light

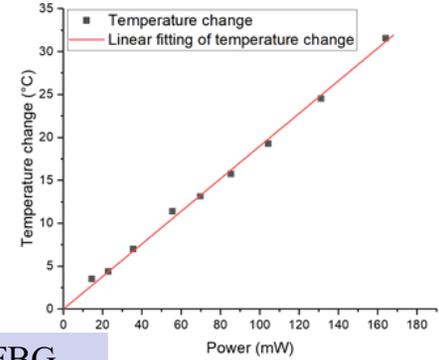


(a)

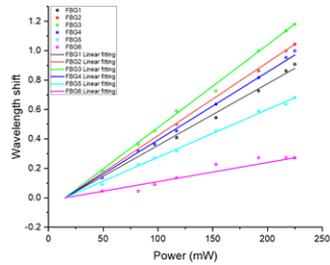
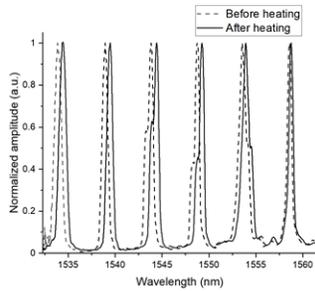


1-mm FBG

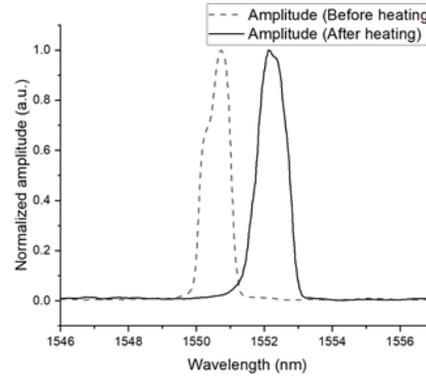
(b)



$$\Delta\lambda_B = 2\left(\Lambda \frac{\partial n_{eff}}{\partial T} + n_{eff} \frac{\partial \Lambda}{\partial T}\right)\Delta T = \lambda_{B0}(\alpha_n + \alpha_\Lambda)\Delta T$$

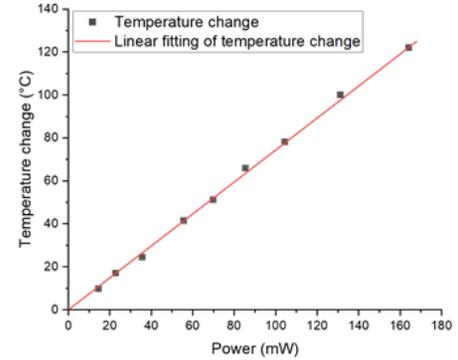


(c)



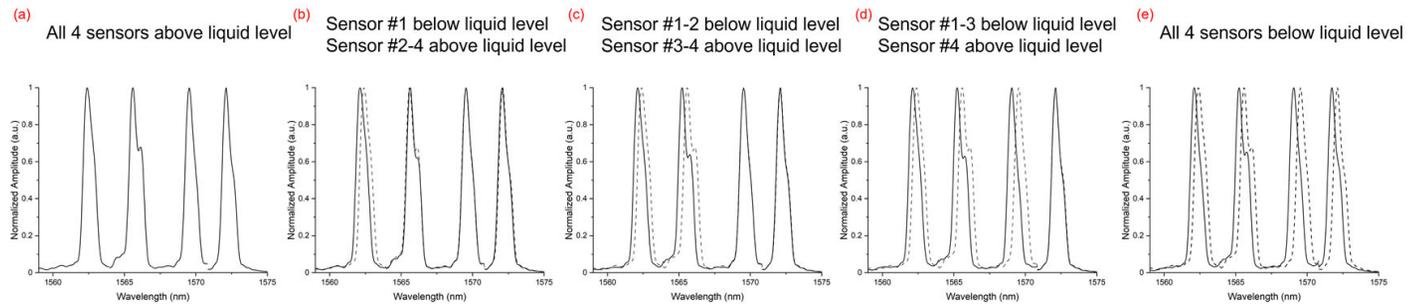
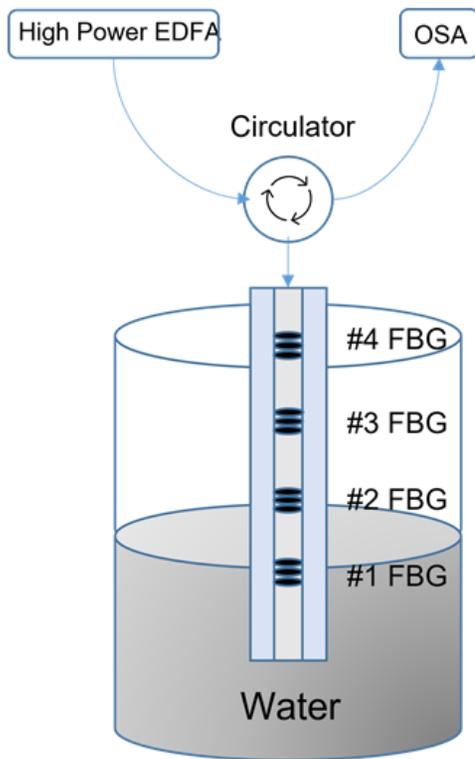
6-mm FBG

(d)





Multiplexable Active Fibers Power by In-Fiber Light



- **First ever multiplexable active fiber sensors**
- **Functional for a wide temperature ranges (cryogenic to 800C)**
- **Multi-functional: (passive: temperature/strain. Active: flow, liquid)**
- **Maximum sensor counts: 20 on one fibers**
- **Suitable for harsh environment applications**
- **Energy application identified.**



Summary and Outcomes

- **Two journal papers under reviews**
- **Three referred conference papers**
- **A US provisional patent filed (to be converted)**
- **Establish an important and unique 3D laser processing capability in Pennsylvania**
- **Laser systems available for industry and academic collaborations**
- **Strong industry collaboration established: II-VI, Westinghouse Electric Company, Corning**
– **We welcome more!**
- **We will continue our laser manufacturing efforts toward for basic research and toward Technology-to-Market Transition**

Thank you!

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