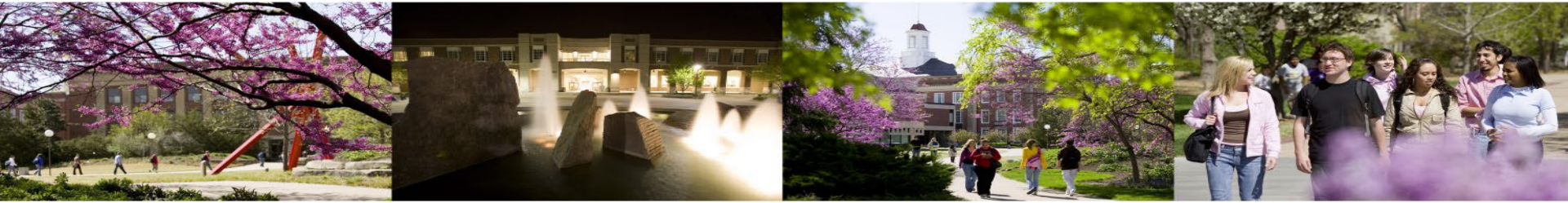
Nanofabrication, Optical Spectroscopy, and Imaging for Fusion and Energy Applications



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University of Pittsburgh | Swanson School of Engineering

INL Idaho National Laboratory

Workshop on Optic Sensor For Energy Applications

March 2-3, 2023, Virtual

University of Nebraska Lincoln

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1. Introduction
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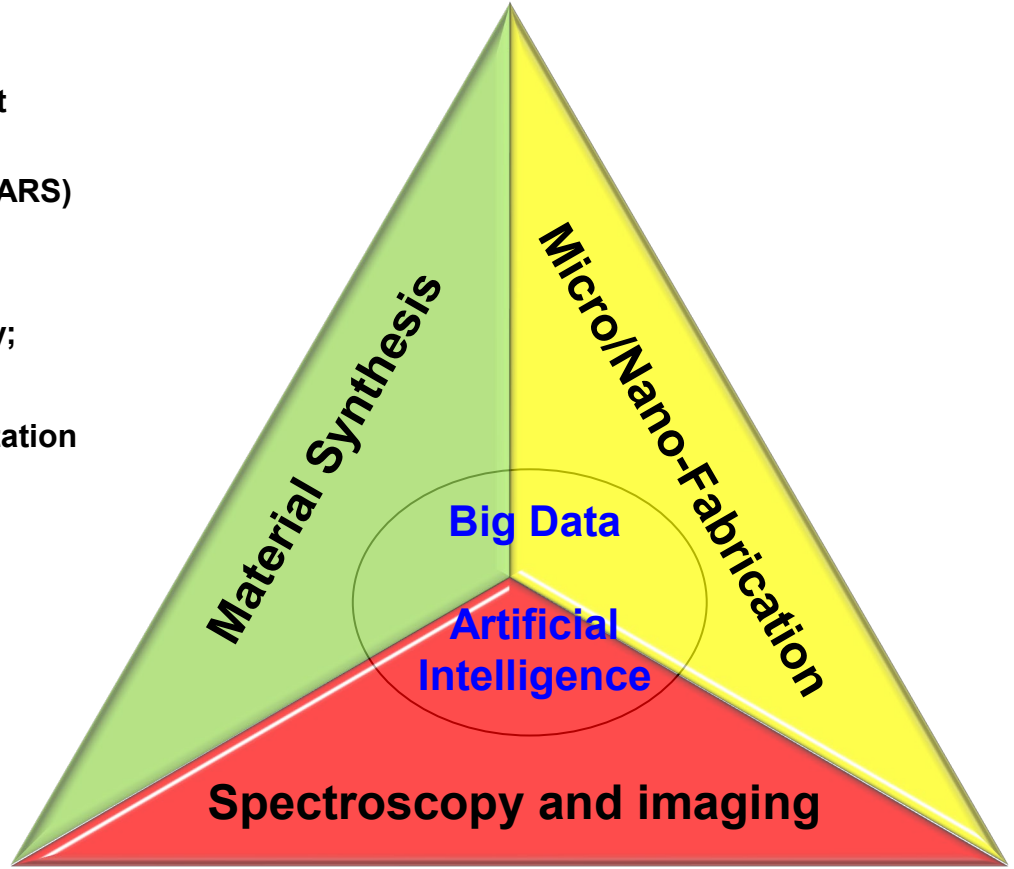
I. Introduction

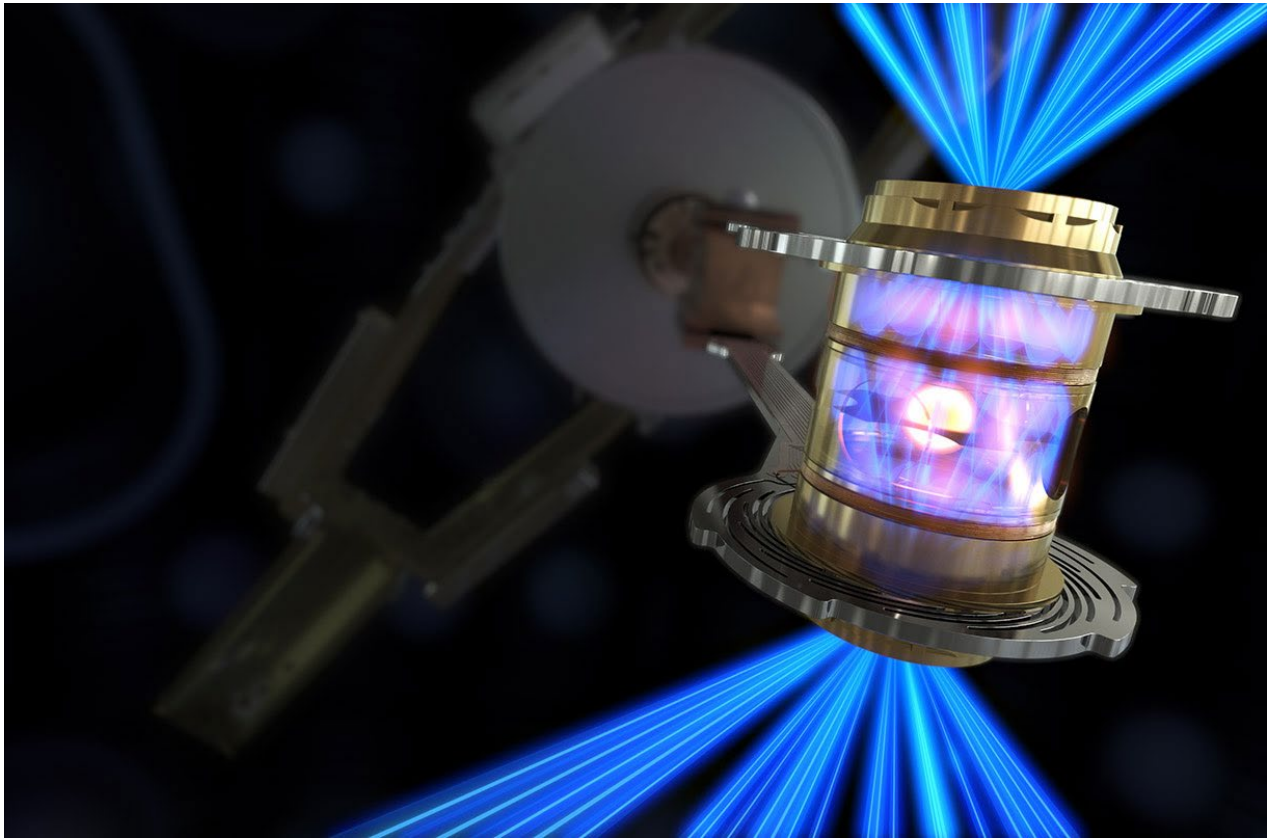
Laser Assisted Nano Engineering (LANE) Laboratory

Established in 2002, LANE is dedicated to the development of laser-based techniques and applications. Research activities include but not limited to:

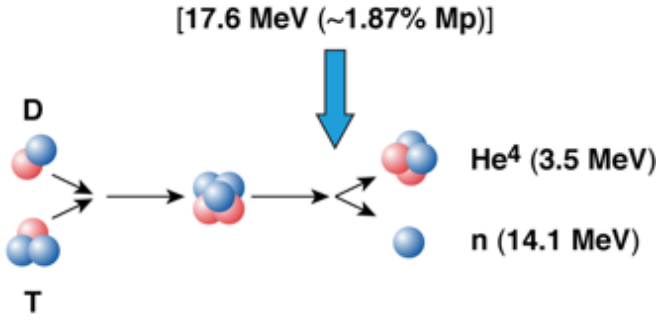
1. **Coherent Anti-Stokes Raman Scattering (CARS) microscopy;**
2. **Laser-induced breakdown spectroscopy;**
3. **Laser-assisted open-air mass spectrometry;**
4. **Nano-Raman spectroscopy and imaging;**
5. **Laser-assisted vibrational / electronic excitation in material synthesis;**
6. **Laser-assisted chemical vapor deposition;**
7. **Pulsed laser deposition;**
8. **3D laser lithography;**
9. **Nanoimprinting;**
10. **Surface cleaning;**
11. **Laser peening; and**
12. **Nanomanufacturing.**

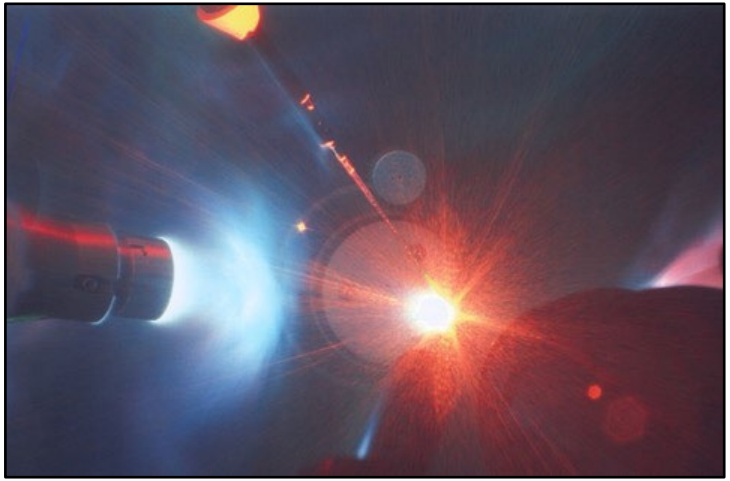


Nuclear fusion – breakthrough and a new start point

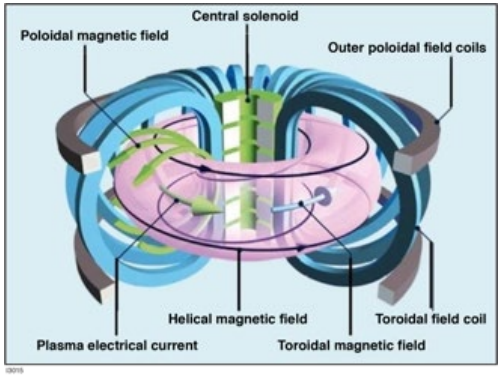


Nuclear fusion



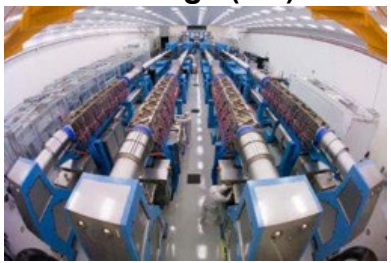


Laser inertial confinement fusion (ICF)

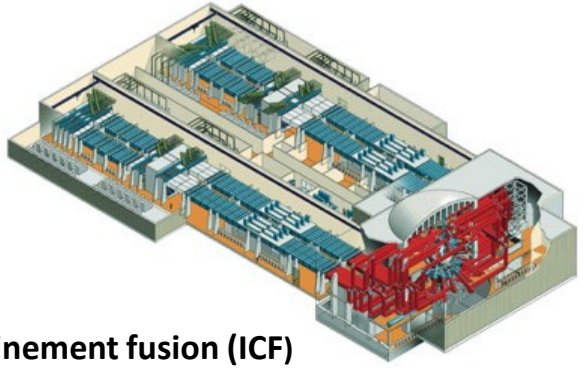


$P\tau^* > 10$ atm-s

Omega (UR)



National Ignition Facility



- **Magnetic fusion (MFE)**
  - Plasma confined by magnetic fields
    - ✓ Pressure is limited by Magnetic field ($P_B \sim B^2$)
    - ✓ Power goes as B^4
  - $n_i \sim 10^{14}$ cm^{-3}
  - $\tau \sim 1$ second

➢ **Pressure ~10 atm**

- **Inertial confinement fusion (ICF)**
  - Plasma confined by inertia
  - $n_i \sim 10^{25}$ cm^{-3}
  - $\tau \sim$ o.1 ns
  - Pressures > 100 Billion atm

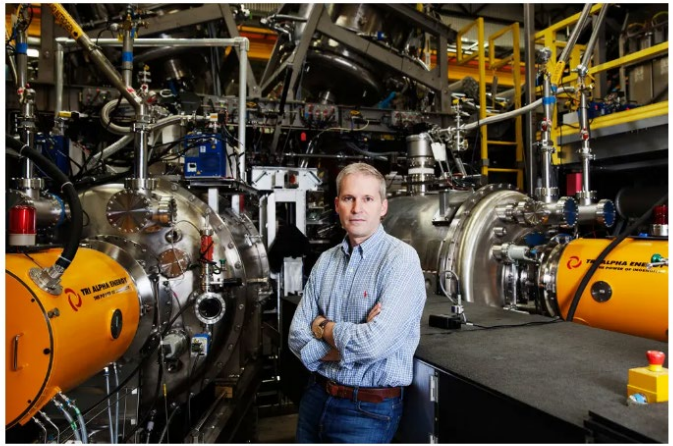
ICF requires "[1]matter at extreme conditions!"

Laser inertial confinement fusion (ICF)

The New York Times

Start-Ups Take On Challenge of Nuclear Fusion

Give this article



Michl Binderbauer of Tri Alpha Energy, a fusion start-up. Emily Berl for The New York

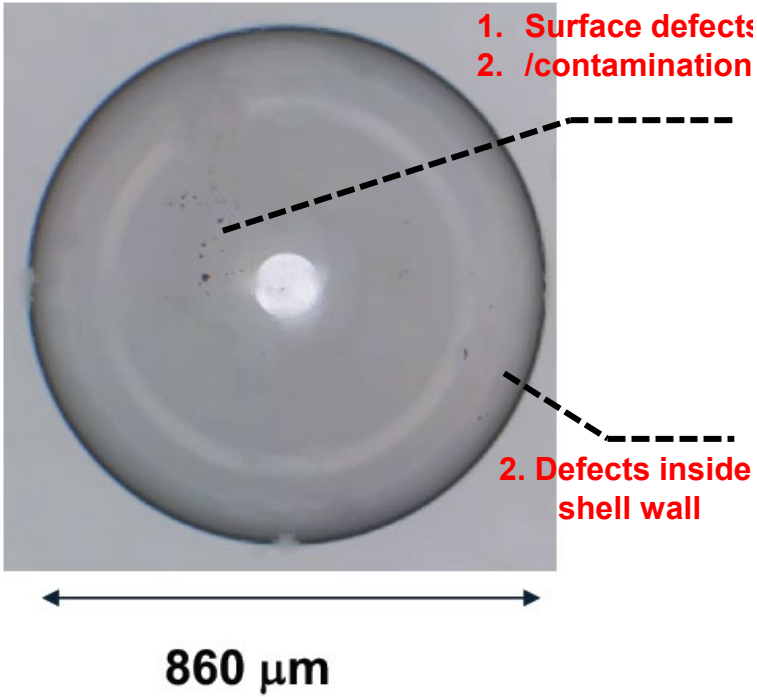
Laser inertial confinement fusion (ICF)

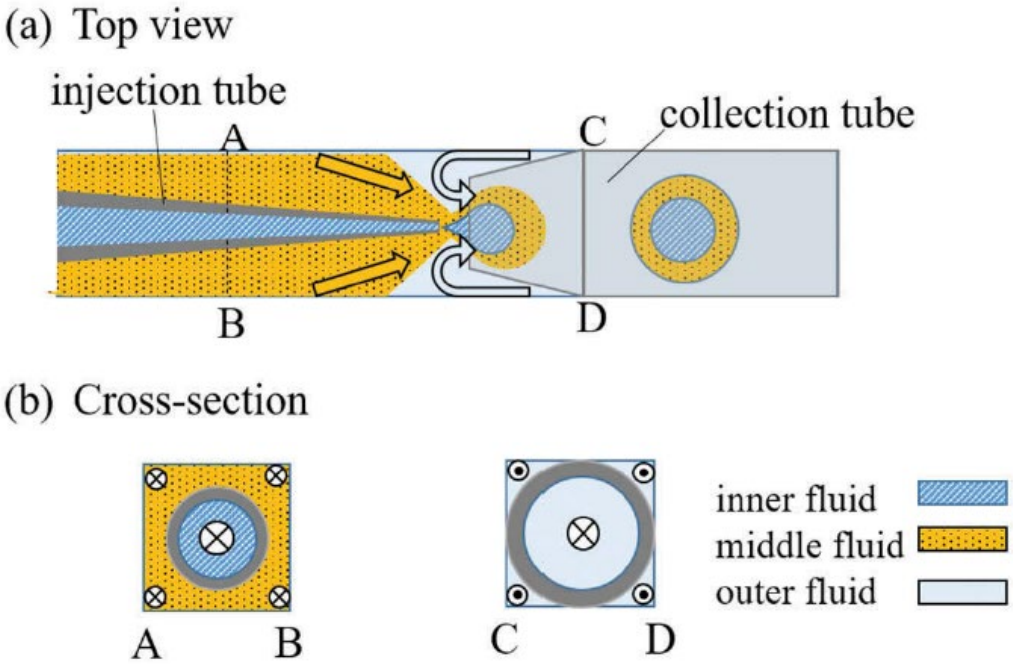
10 years?

II. Target Fabrication Using Two-Photon Polymerization

Fabrication of fuel capsules using emulsions

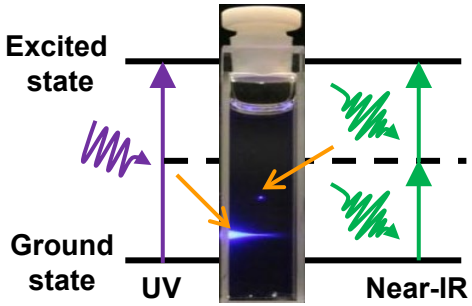
Fuel capsules



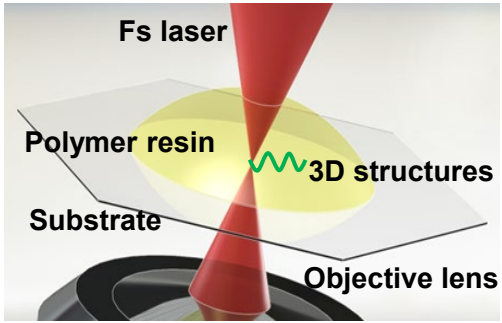


Two-photon Polymerization (TPP) from 2007

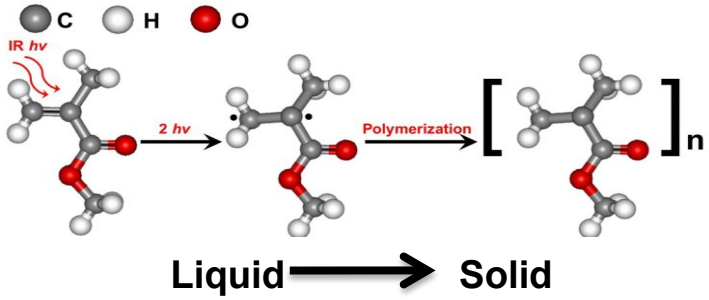
Two-photon absorption

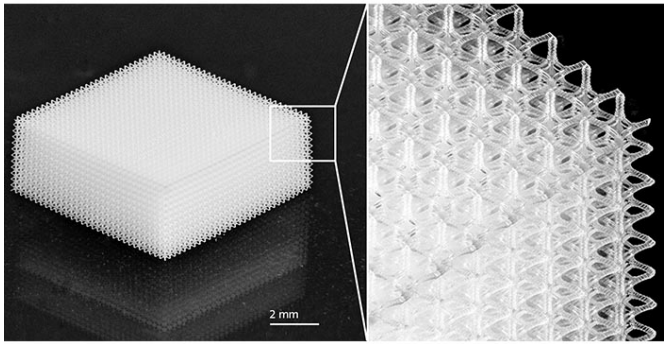


TPP fabrication technique



TPP 3D printing system





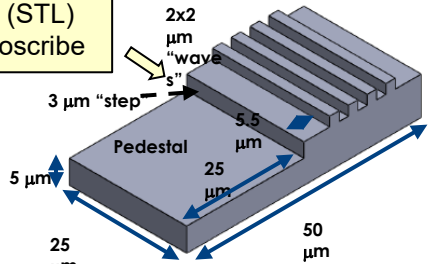
Courtesy of Nanoscribe GmbH

Vendor-defined and DOE-supported projects (2012-2018)

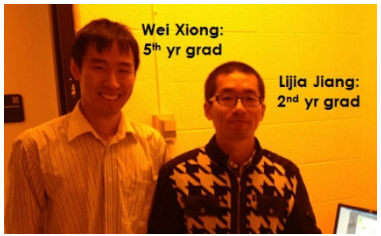
Initial 2PP demos (2012)[+]:

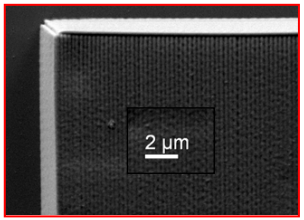
- DOE vendor provided STL files of proto-typical structures
- UNL: Demo 2PP fabrication of structure
- Goal: Achieve precision dimensions

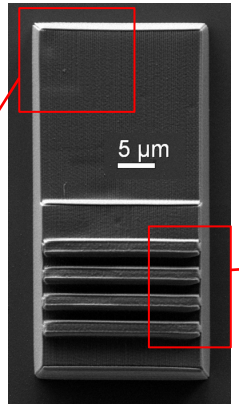
CAD file image (STL) input to the Nanoscribe

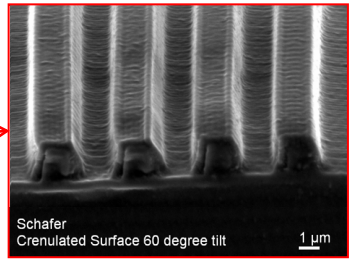


Grad students: Wei Xiong* and Lijia Jiang**









Currently
*Wei Xiong: full Professor at Huazhong University of Sci and Tech
**Lijia Jiang :Senior Research Engineer at Advalue Photonics, Phoenix Az

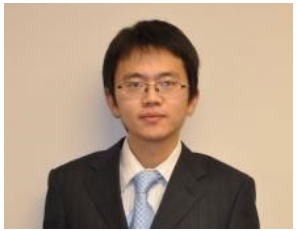
[+]L. J. Jiang et al Fusion Sci. and Tech., v70, p 295-309, (2016)

Vendor-defined and DOE-supported projects (2012-2018)

Zn seeds for DT crystal growth (2014)

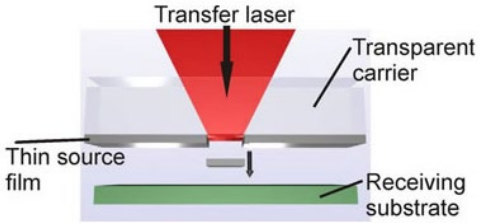
- Demo "LIFT" to deposit ~1um Zn particles
- LIFT= Laser induced Forward Transfer
- Potential seed for Inp DT crystallization

Post doc: Yang Gao*

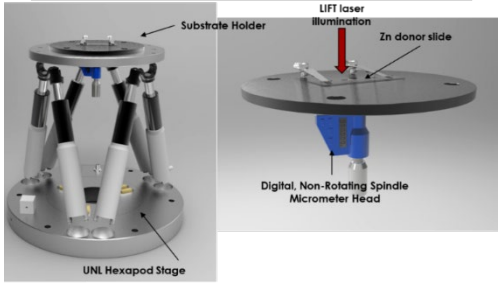


Currently:
*Yang Gao: Professor at East China University of Science and Technology

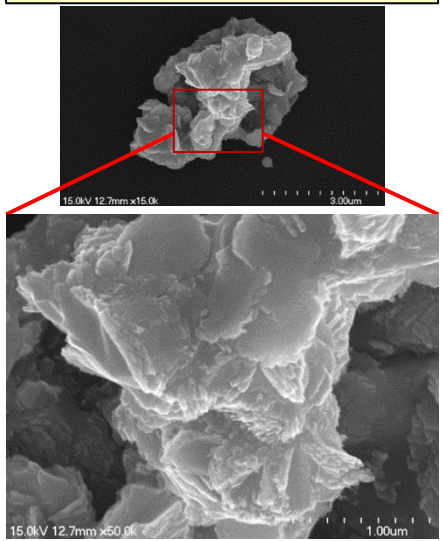
LIFT Schematic



Vendor provided Zn films and film target holder



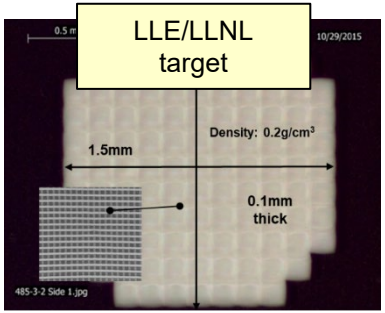
Example of Zn particle deposited using LIFT

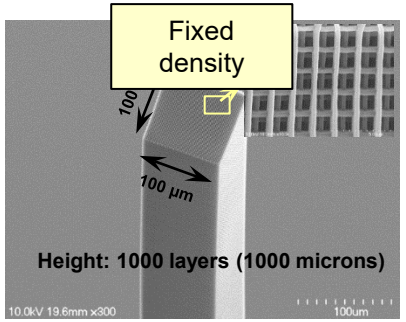


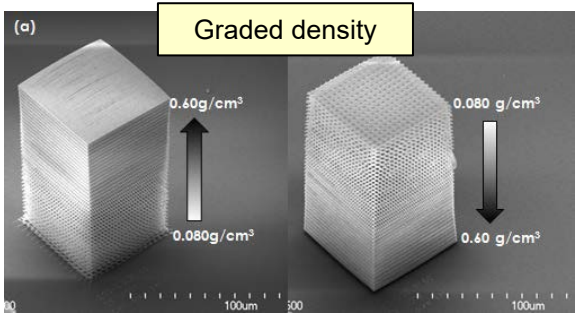
Vendor-defined and DOE-supported projects (2012-2018)

Project objectives

- Demo foams and print “real targets”
- Upgrade Nanoscribe to “GT Professional”
- 100-1000× greater writing speed
- **Fabricate foams with fixed, graded and step-densities**







Grad Students: Lijia Jiang** and Ying Liu***

[+]*L. J. Jiang et al Fusion Sci. and Tech., v70, p 295-309, (2016)*

Currently:

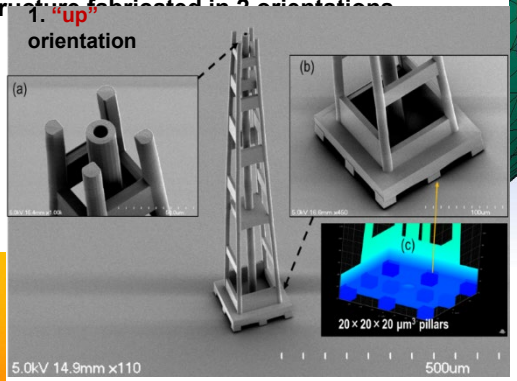
****Dr. Lijia Jiang :Senior Research Engineer at Advalue Photonics, Phoenix Az**

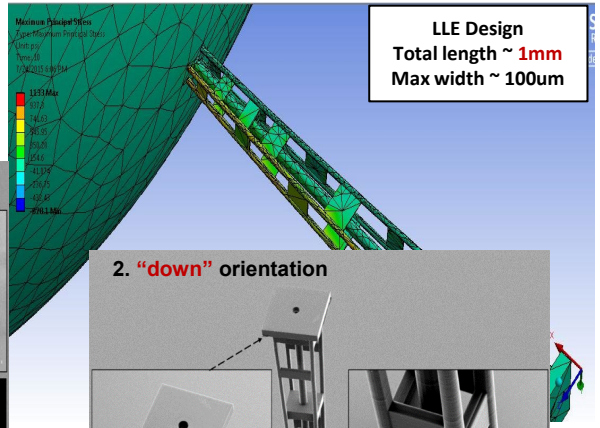
***** Dr. Ying Liu : Senior Research Scientist, Corning Inc., Corning NY**

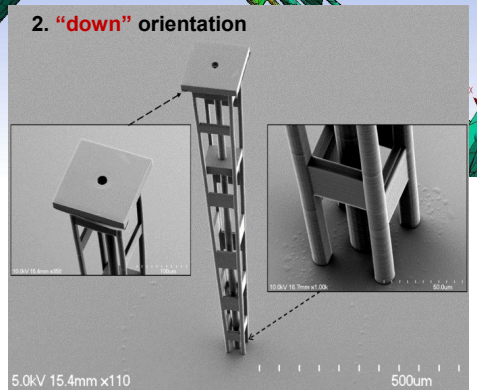
Vendor-defined and DOE-supported projects (2012-2018)

Project objectives and results

- 2PP fabrication of LLE-designed fill tube support
- CAD drawing provided by LLE; 2PP at UNL
- Support structure fabricated in 2 orientations







Grad student

Currently: Dr. Lijia Jiang :Senior Research Engineer at Advalue Photonics, Phoenix Az

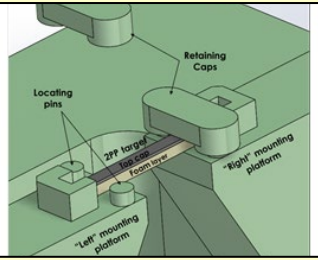
Vendor-defined and DOE-supported projects (2012-2018)

+

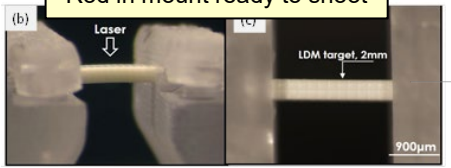
Project objectives and results

- Design, print and field 2PP foam rods at NRL+
- 12 targets provided to NRL and shot on NIKE Laser

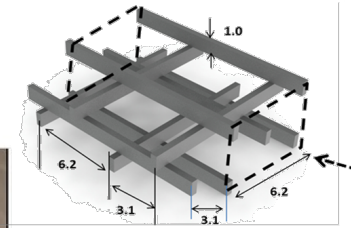
Schematic: Rod target assembly

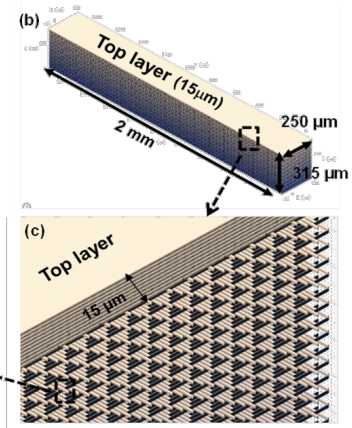


Rod in mount ready to shoot



Rod/foam design and structure





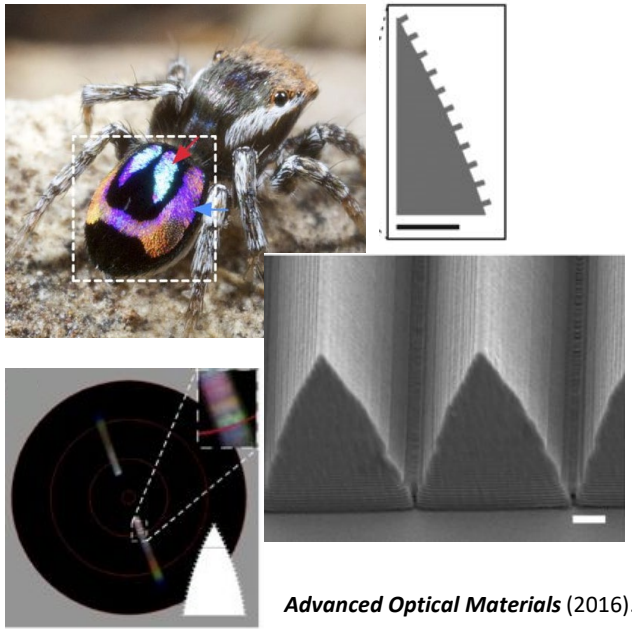
Grad student Ying Liu

Dr. Ying Liu : Senior Research Scientist, Corning Inc., Corning NY

+*O. Stein, Y. Liu, et al Fusion Sci. and Tech. (2018)*

TPP 3D micro-/nanofabrication in LANE

- Rainbow peacock spiders inspire miniature super-iridescent optics



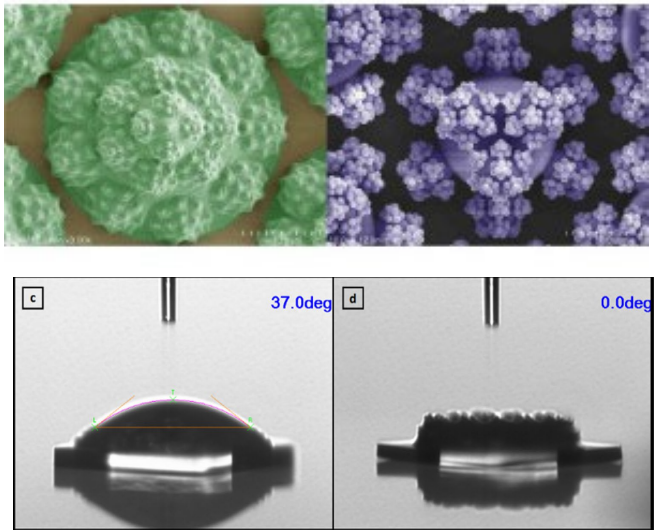
Advanced Optical Materials (2016).

Nature communications (2017).

- Wetting characteristics of 3D fractal surfaces

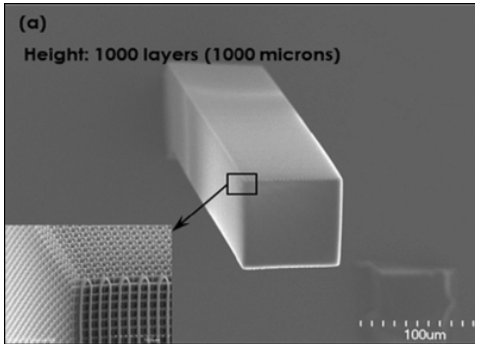
Romanesco broccoli fractal surface

Sphereflake fractal surface

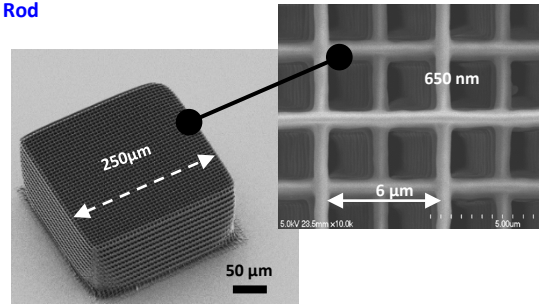


Applied Surface Science 392 (2017)

Targets Already Achieved at UNL for NRL:

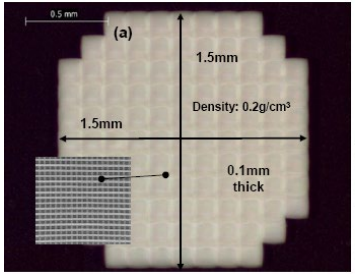


Foam Rod

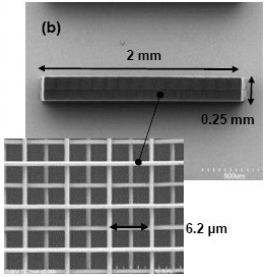


Targets Already Achieved at UNL for LLE:

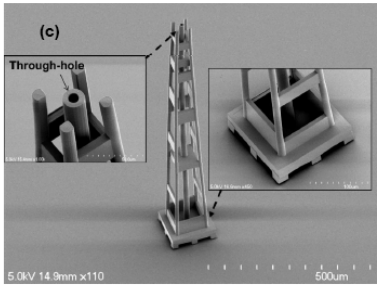
Foam Plate

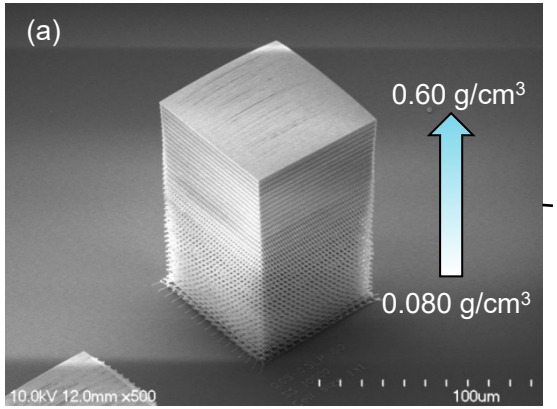


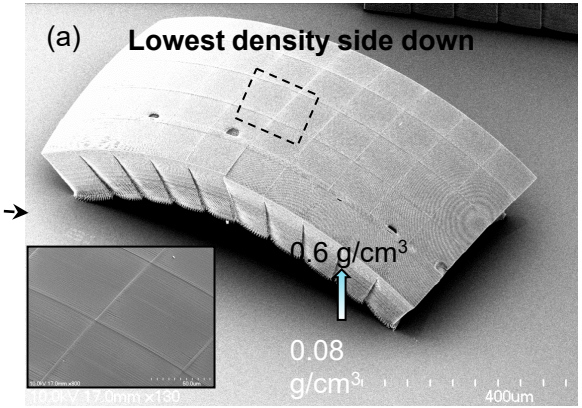
Foam Rod



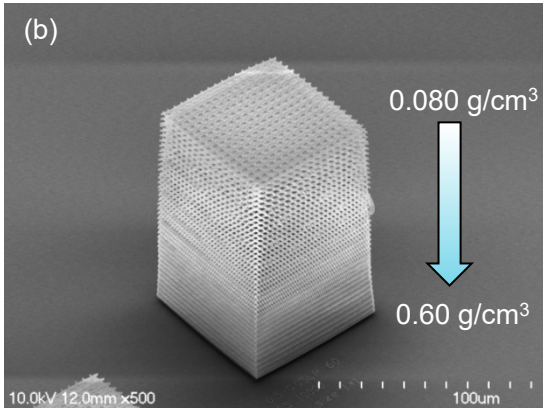
Low mass/High stiffness Target Support

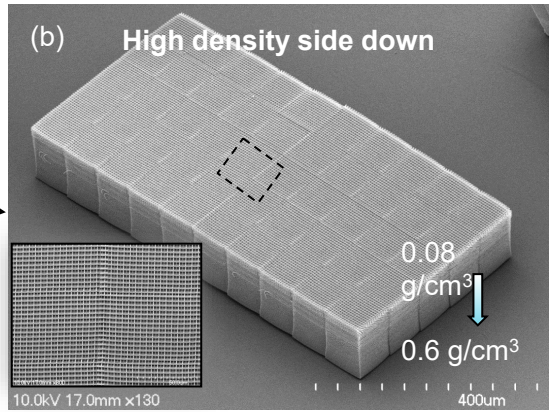






Bending

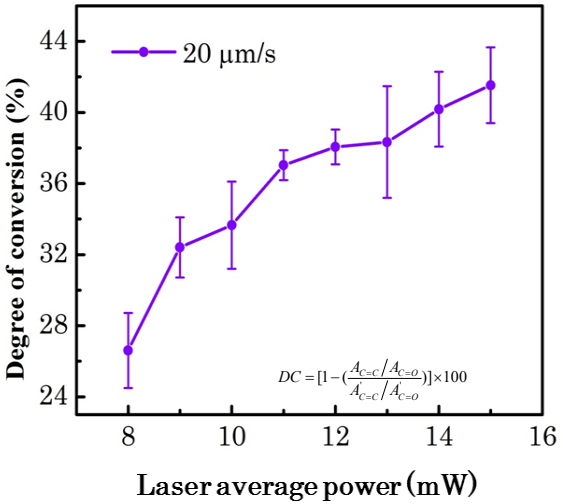


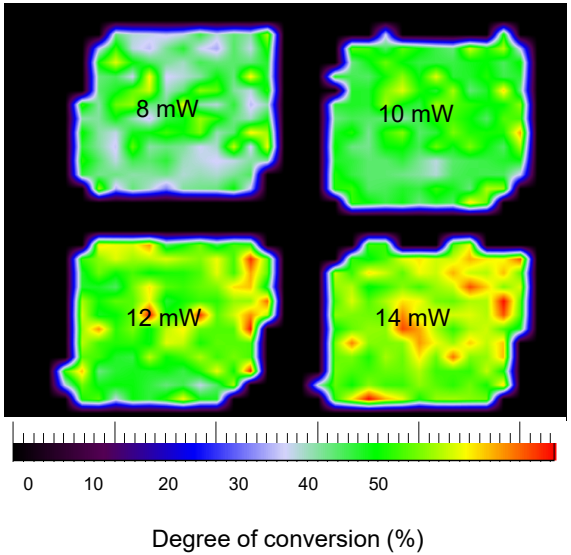


Better adhesion

1. Stitching
2. Scanning Complexity
3. Deformation/strength
4. Speed

Degree of conversion in TPP





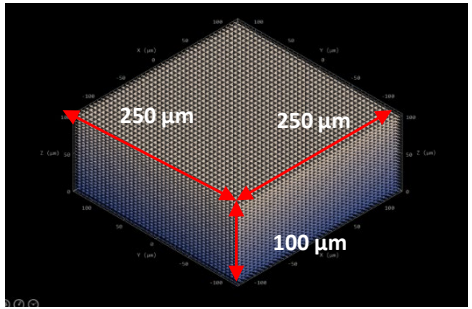
Jiang L.J., et al., Opt. Letts., 2014

Modification of foam block to reduce deformation

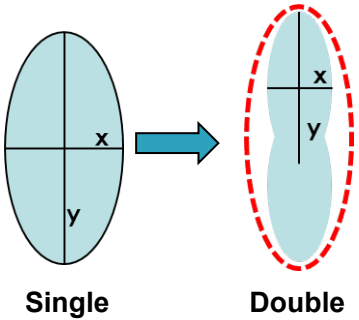
- Methods to reduce foam block deformation
  - Mesoscale matched photoresist with high mechanical stability

IPS	Resolution	Shrinkage
Index-matched medium-resolution resist for smooth surfaces and fast structuring of large 3D parts	Medium	Low

  - Enlarged TPP fabrication units



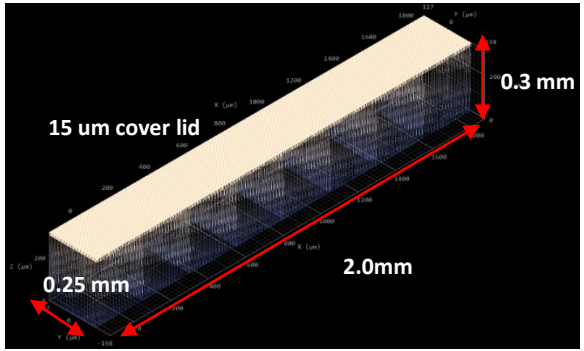
  - Double-line scan mode

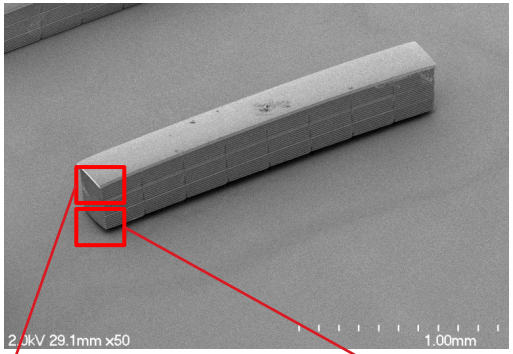


Modification of foam block to reduce deformation

- Foam block fabricated with modified design

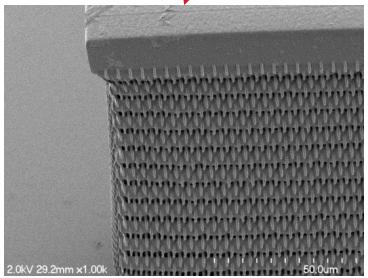
Foam design

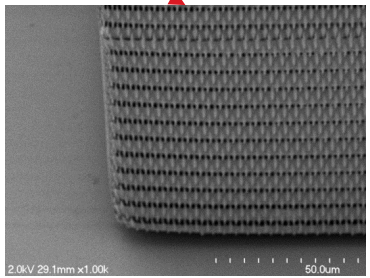




Writing time: ~1 hr.

Arch-shape deformation was largely reduced

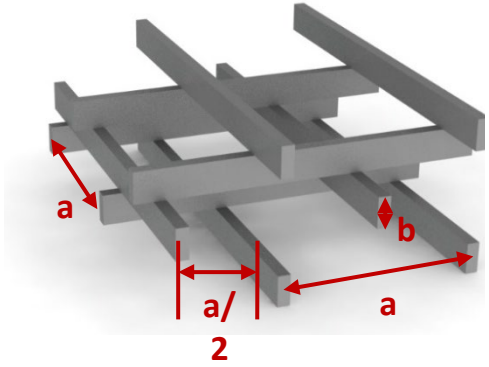




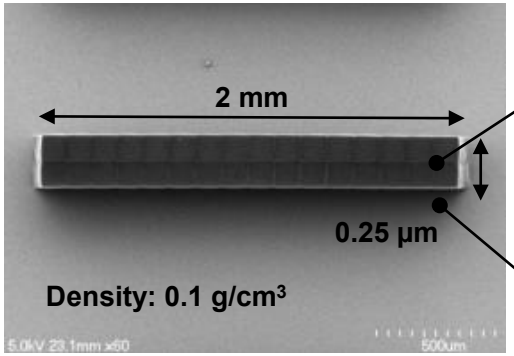
Foam rods fabricated and shot at Naval Research Lab

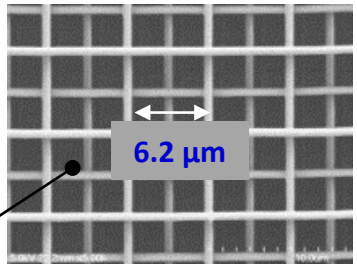
NRL foam rods target design

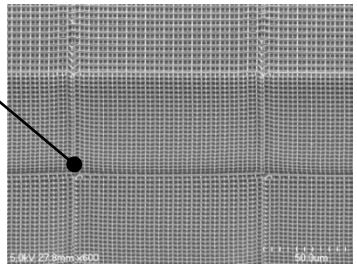
Log-pile foam structural sub-unit (cell)



Foam rod

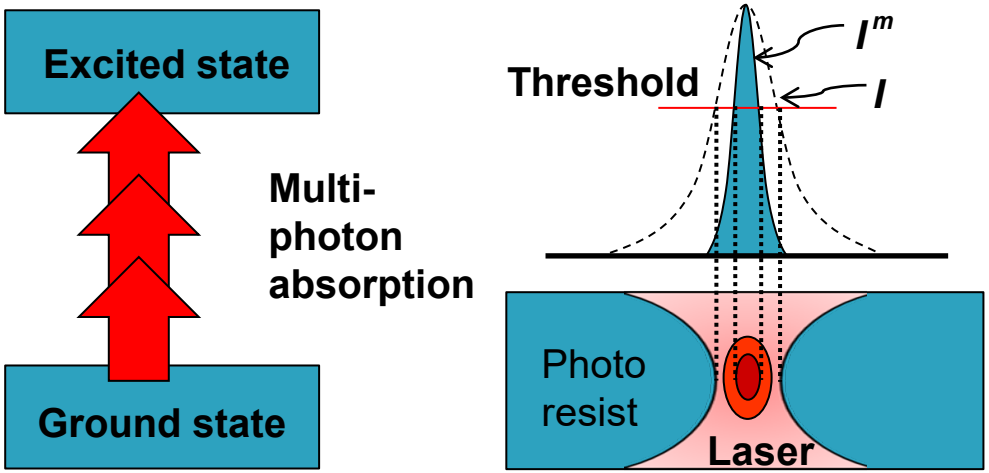






96 sub-blocks (0.125 × 0.125 × 0.1 mm^3)

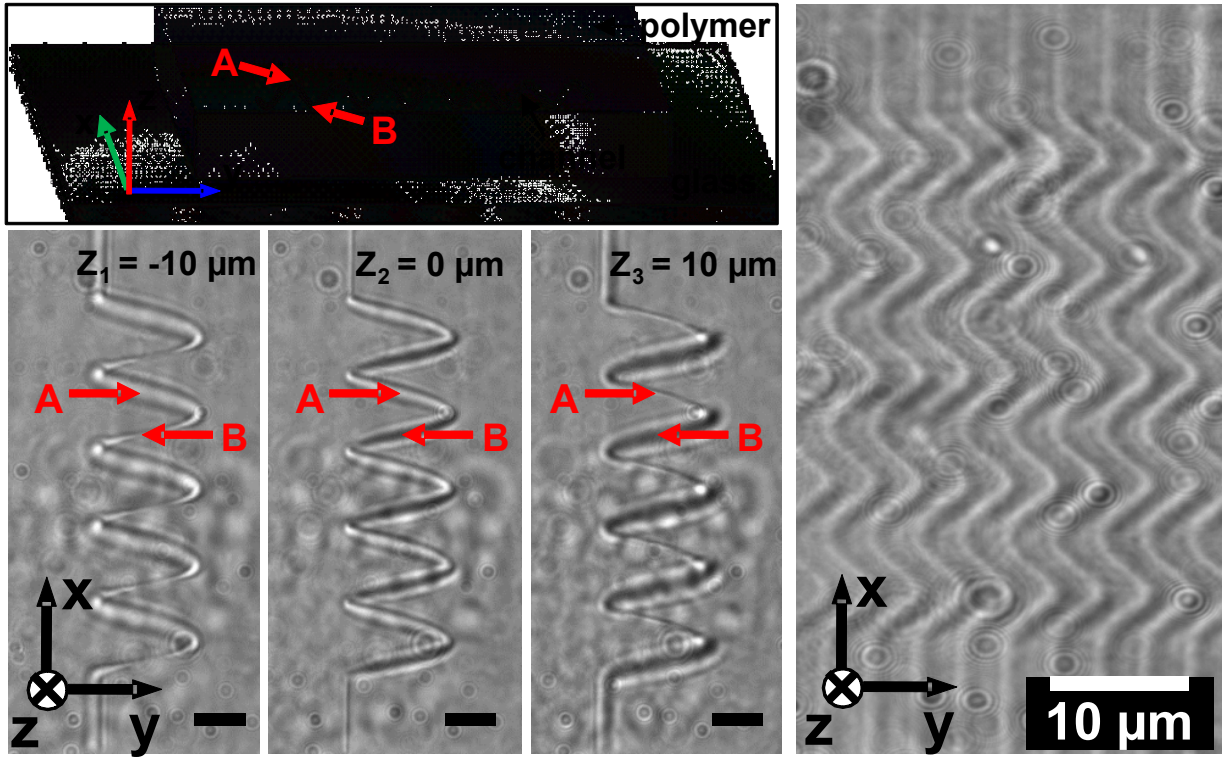
Material: Acrylate IP-Dip/IP-S photoresin



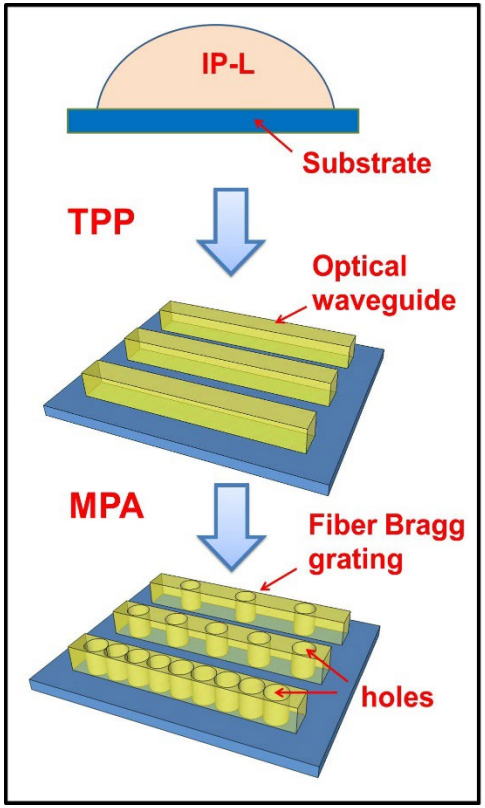
Schematics of multi-photon absorption.

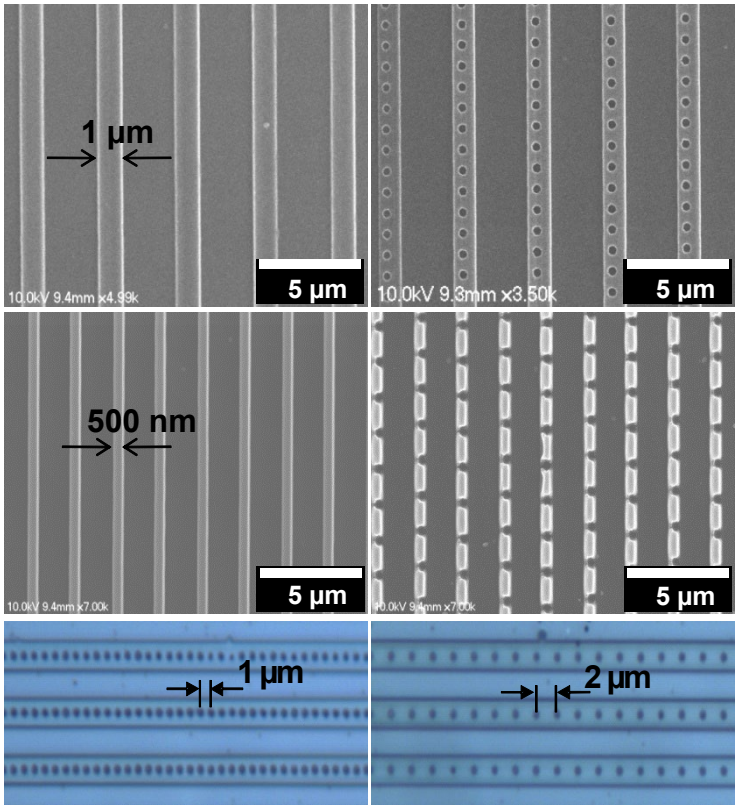
Light: Sci. & Appl. (Nature Group), 1, e6; doi:10.1038/lsa.2012.6 (2012)

“TPP + MPA” Fabrication: Microfluidic Channels



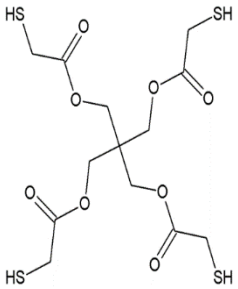
W. Xiong, *et al. Light Sci. Appl. (Nature Publishing Group)*, 1, e6 (2012).


IP-L
Substrate
TPP
Optical waveguide
MPA
Fiber Bragg grating
holes

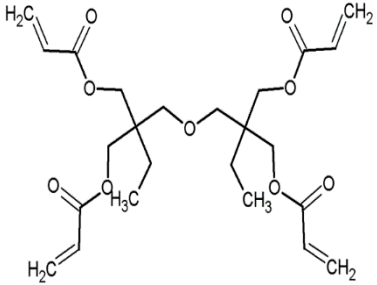

1 µm
5 µm
10.0kV 9.4mm x4.99k
10.0kV 9.3mm x3.50k
5 µm
500 nm
5 µm
5 µm
1 µm
2 µm

TPP 3D microfabrication using thiol-acrylate

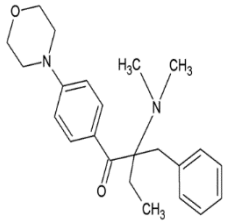
(b)



Thiol:
PETMP

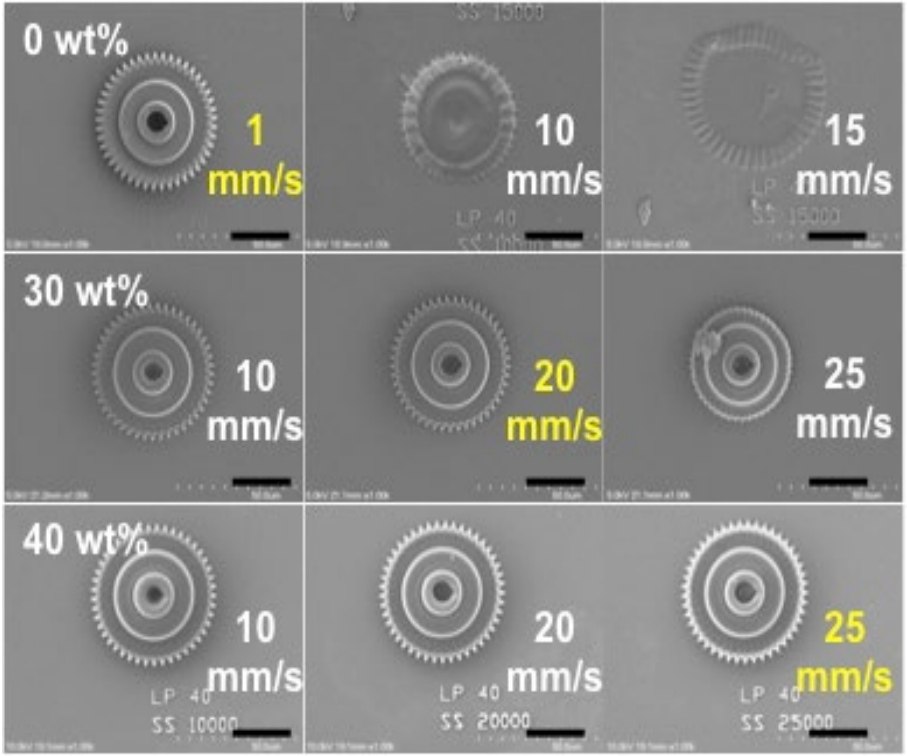


Acrylate: Di
TMPTTA



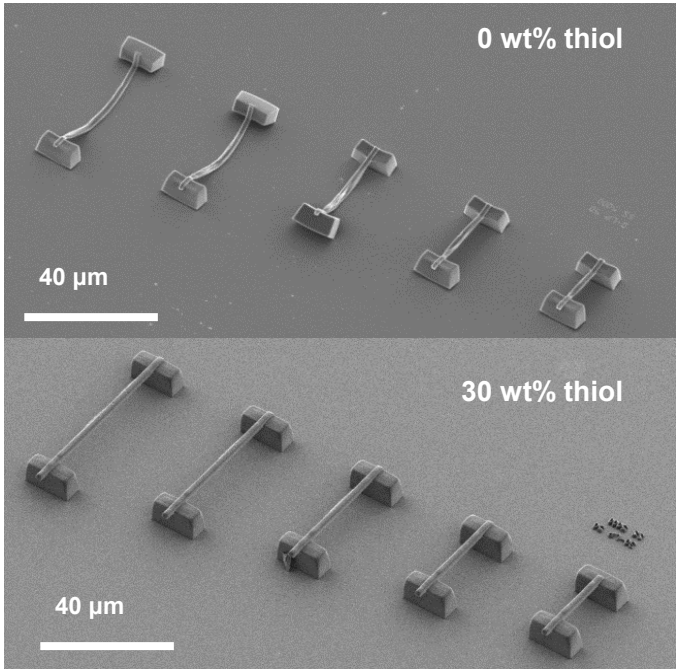
Photoinitiator: BDMP

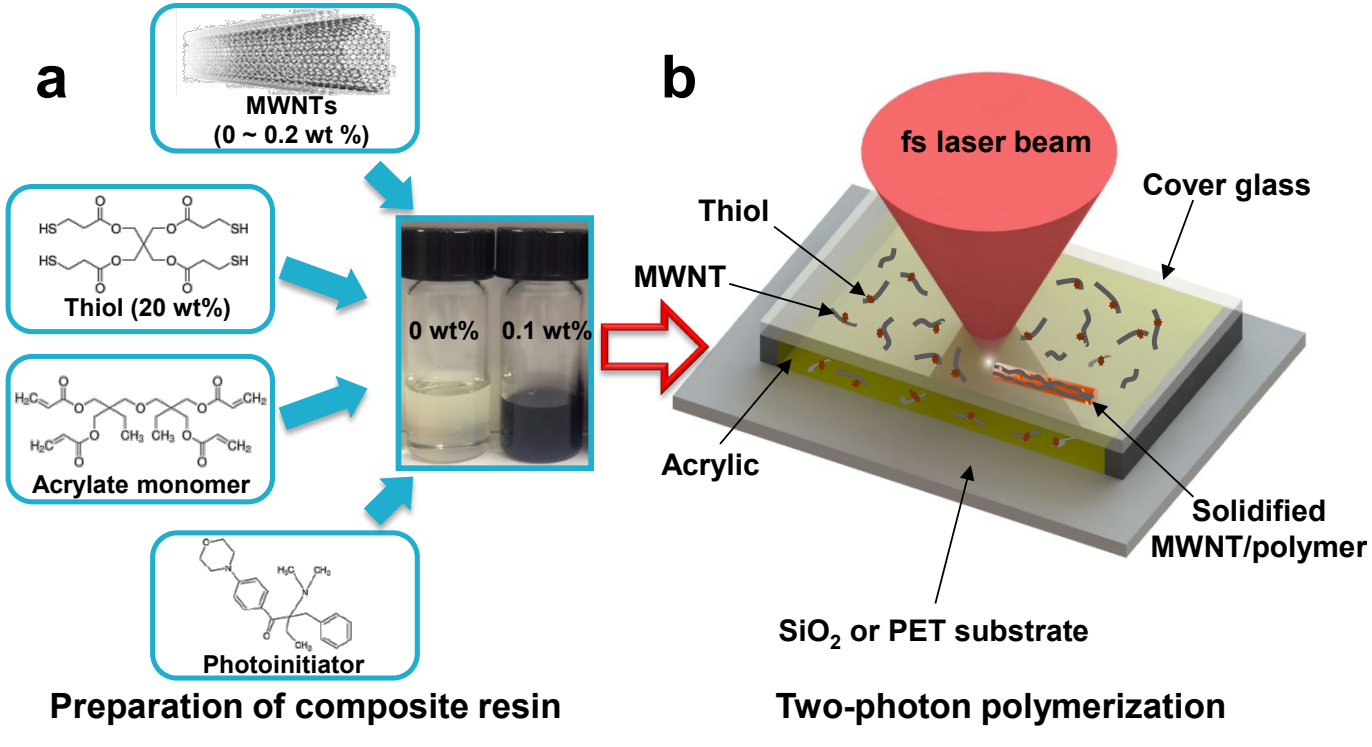
The dependence of critical speed on the concentration of the ink



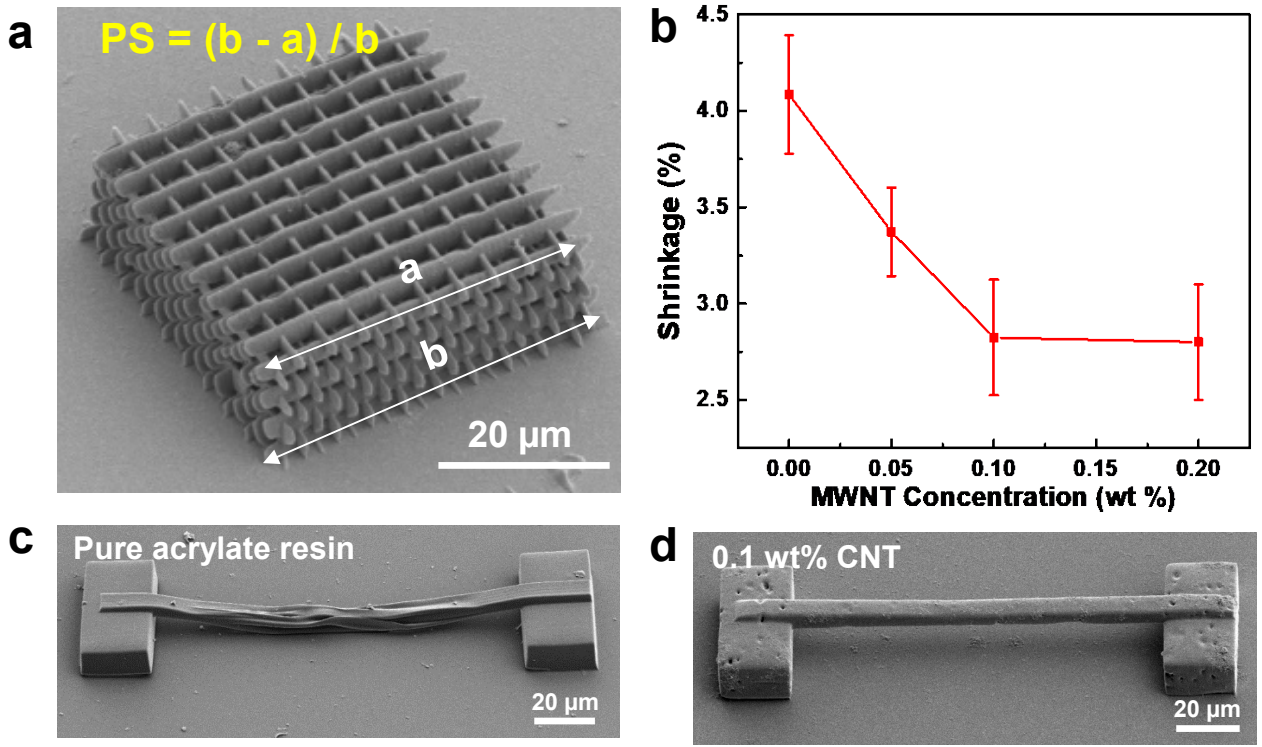
Thiol-acrylate reduces shrinkage and improves strength

Stiffness





Adv Mater DOI: 10.1002/adma.201505516, 2016

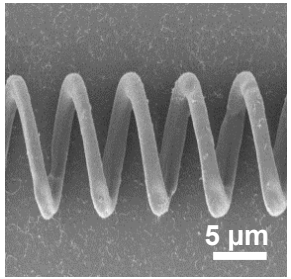


Adv Mater DOI: 10.1002/adma.201505516, 2016

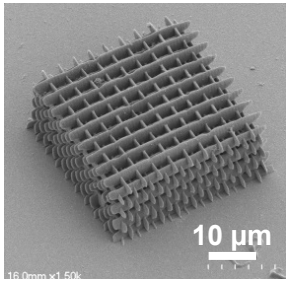
TPP fabrication of 3D

Flexible substrate

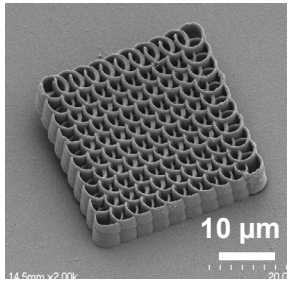
Microcoil



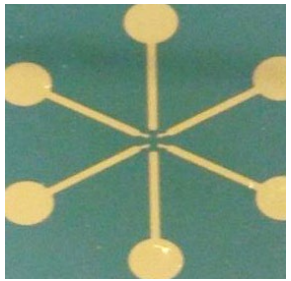
Woodpile



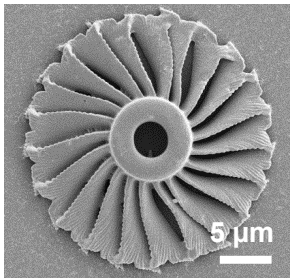
Spiral photonic crystal



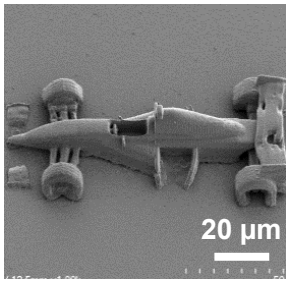
SiO_2/Si substrate



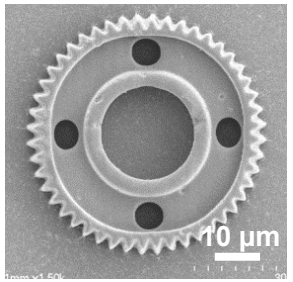
Micro inlet fan



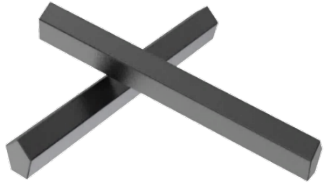
Microcar



Microgear



Conductive AgNW-polymer

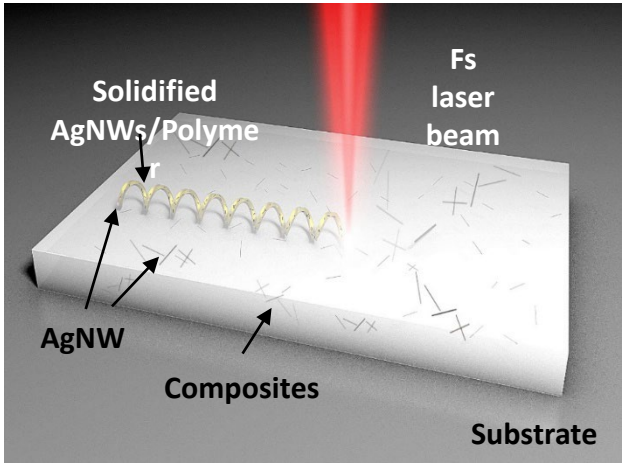


One dimensional Silver nanowires(AgNWs)

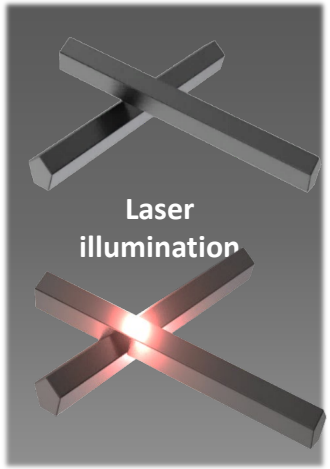
Ideal conductive material (6.3 × 10^7 S/m);

Higher aspect ratio; Joining capability.

TPP of AgNWs/polymer

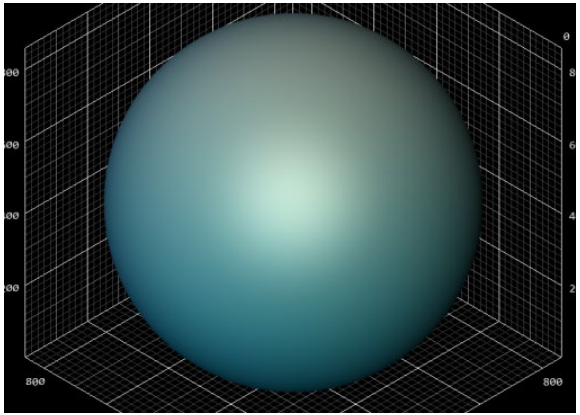


Nanojoining of AgNW junctions



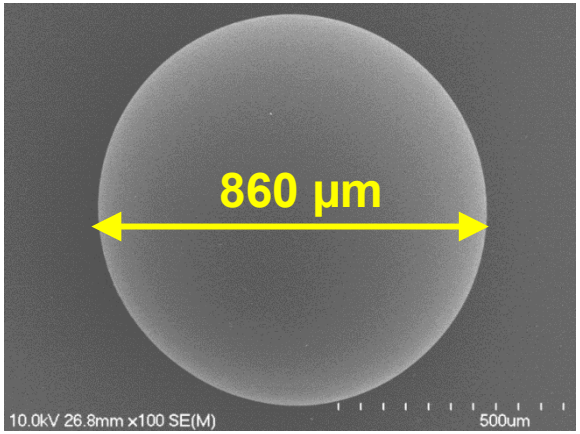
Shell targets fabricated

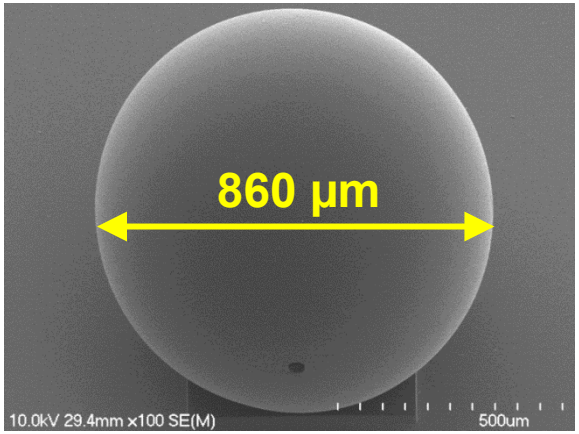
Design



Photo

Top-view SEM





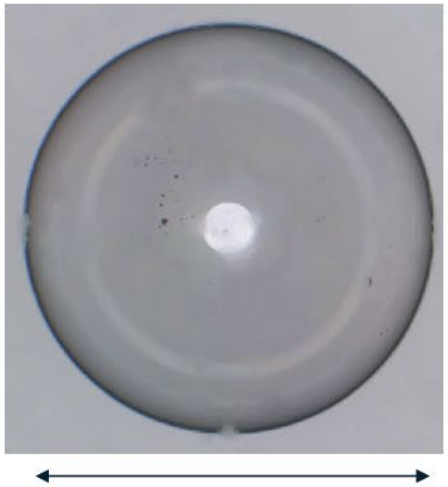
Tilt-view SEM

III. Farget Verification Using Coherent Anti-Stokes Raman Spectroscopic (CARS) Imaging

Belcan

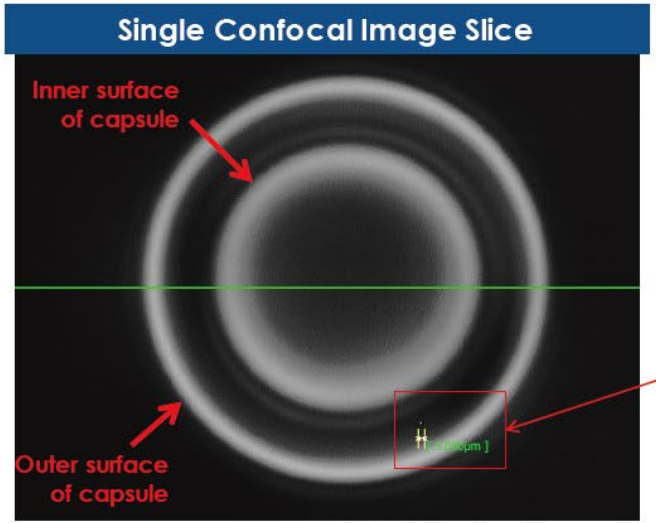
Microscopic surface particles and wall inclusions must be characterized and limited

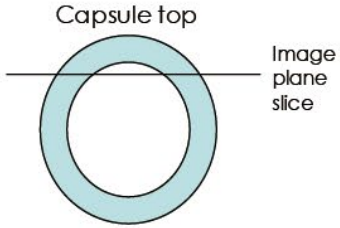
Particle contaminants

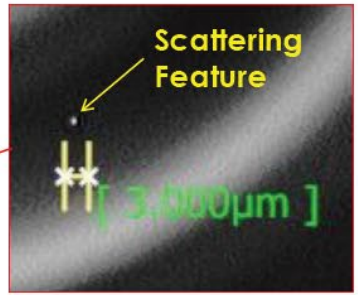


860 μm

Wall inclusions

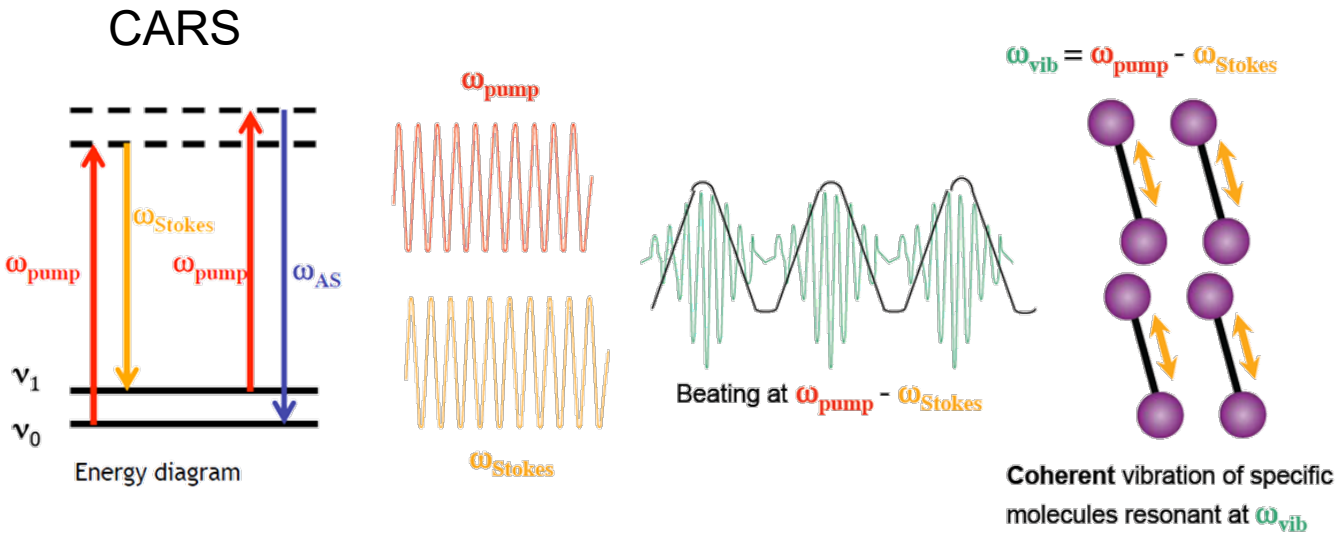






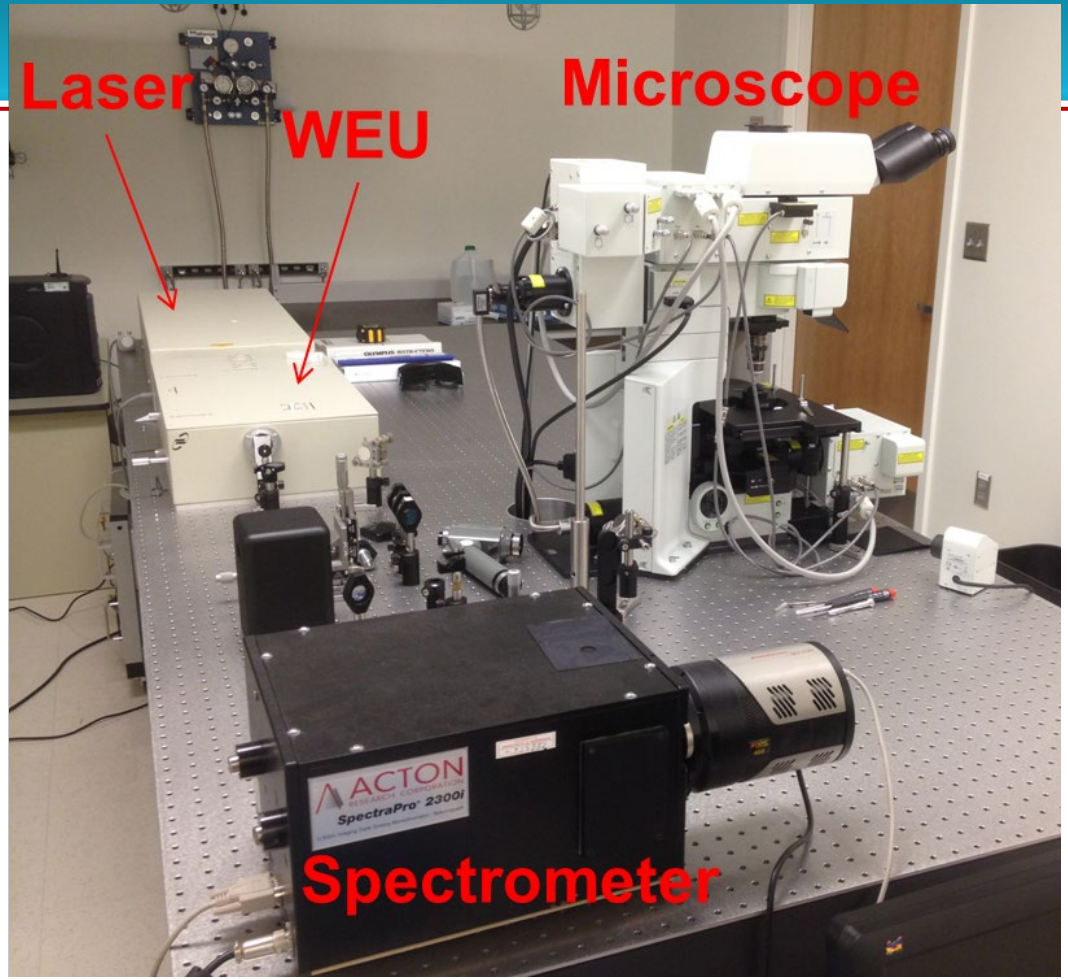
Characterize inclusions down to 100 nm sizes

Coherent anti-Stokes Raman spectroscopy (CARS)

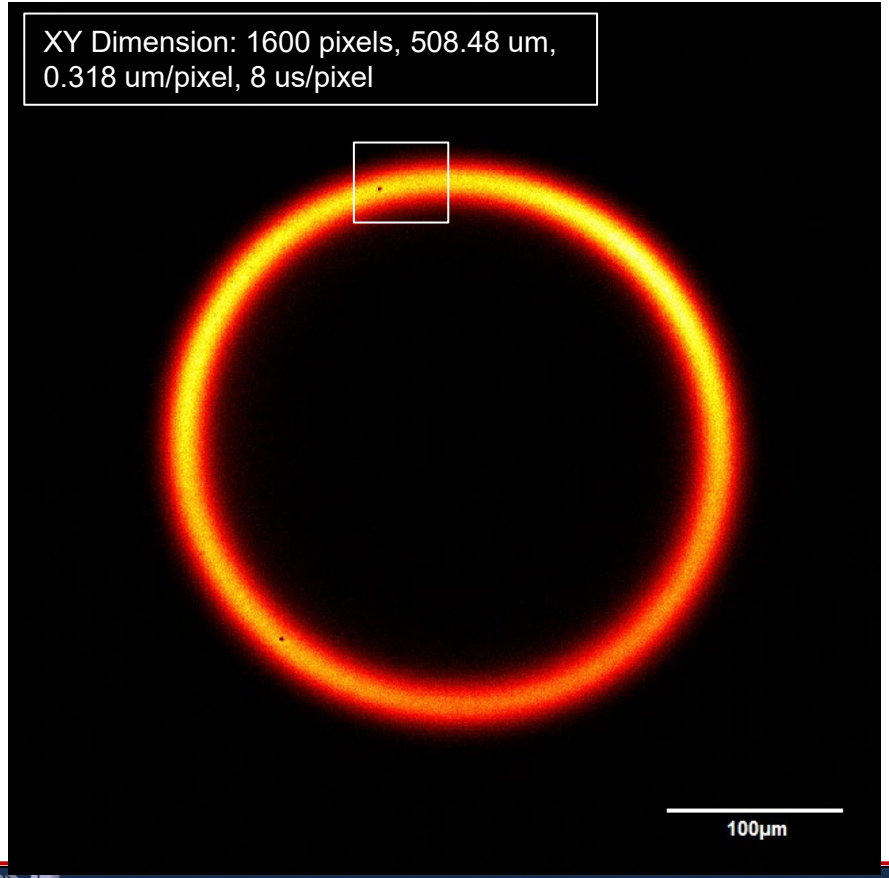


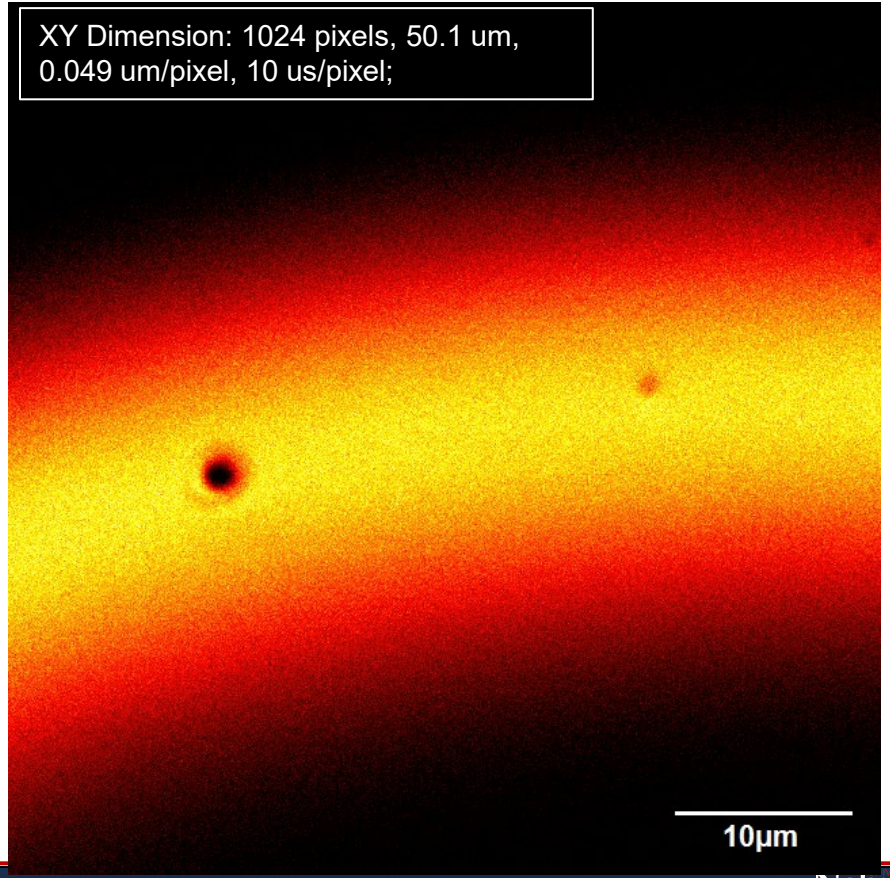
$$\omega as = 2\omega p - \omega s$$

J. Chan, Selected Topics in Biophotonics (EAD289)


Laser
WEU
Microscope
ACTON
SpectraPro 2300i
Spectrometer

A typical slice of a polystyrene shell



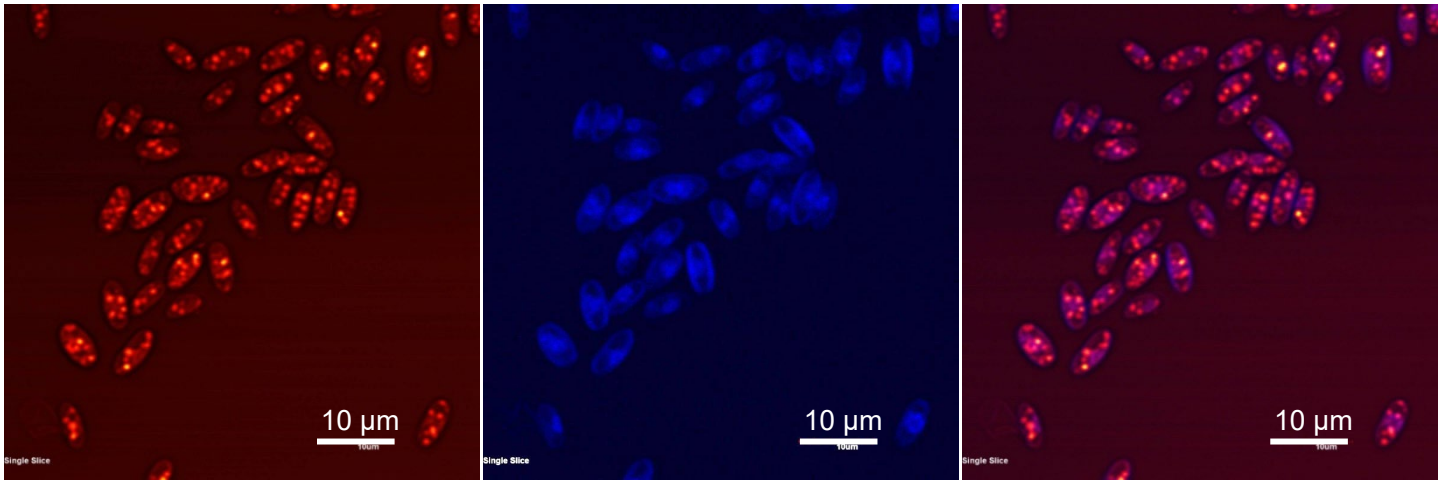


IV. Spectroscopy, mass spectrometry, and imaging for energy applications

CARS movie of algae (5D imaging)

CARS microscopy imaging

(a) (b) (c)



CARS

(650 nm filter 2800-3000 cm^{-1})

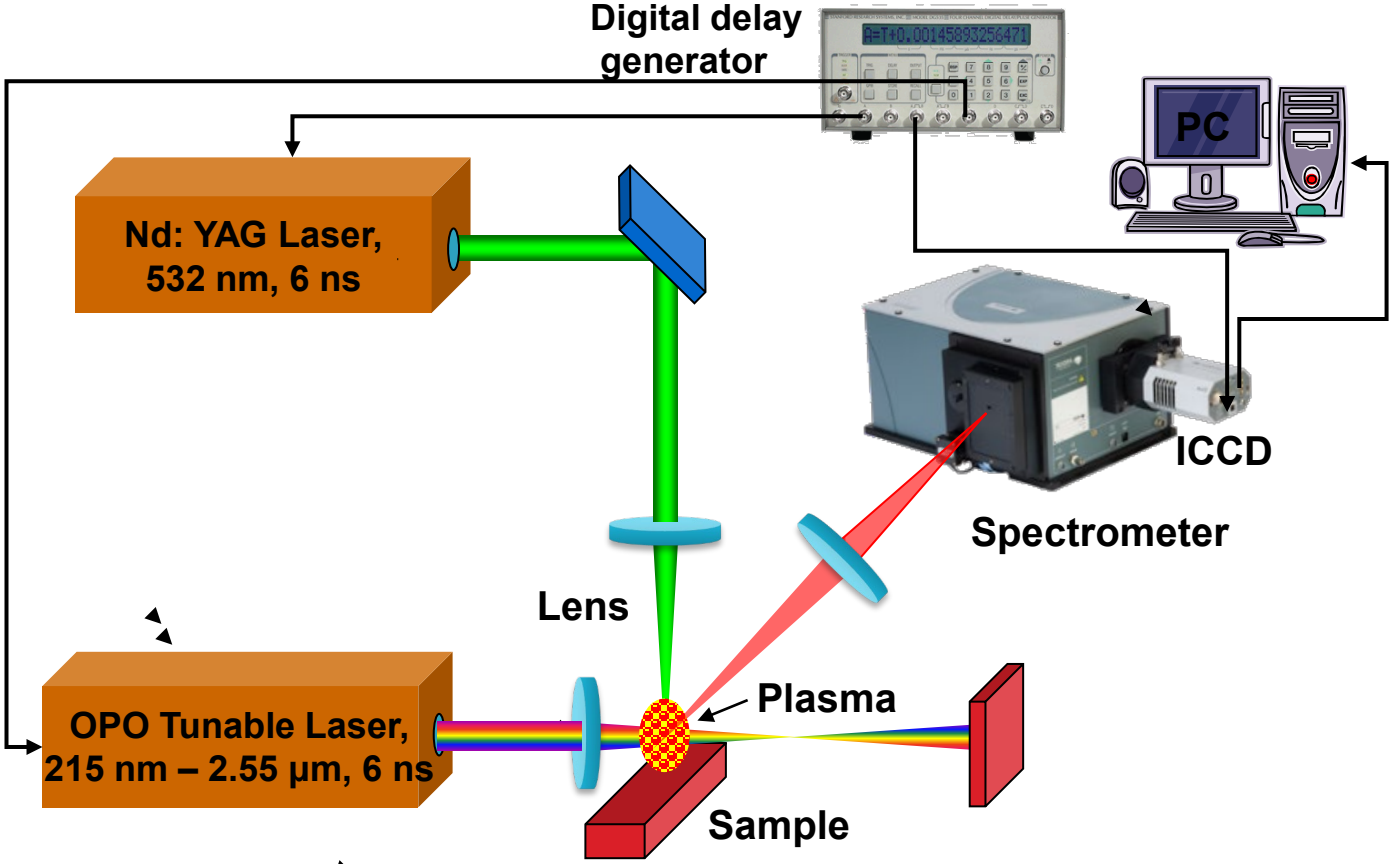
Autofluorescence

(450 nm filter)

Composite image of (a) and (b)

- **Autofluorescence parts of algae cells locate differently to tryglycerides**
- **The autofluorescence signals are supposed to be chlorophyll (green part of the cell)**

Experimental Setup for LIBS-LIF



Appl. Opt., 2008, 47(11), 1810

Uranium Detection

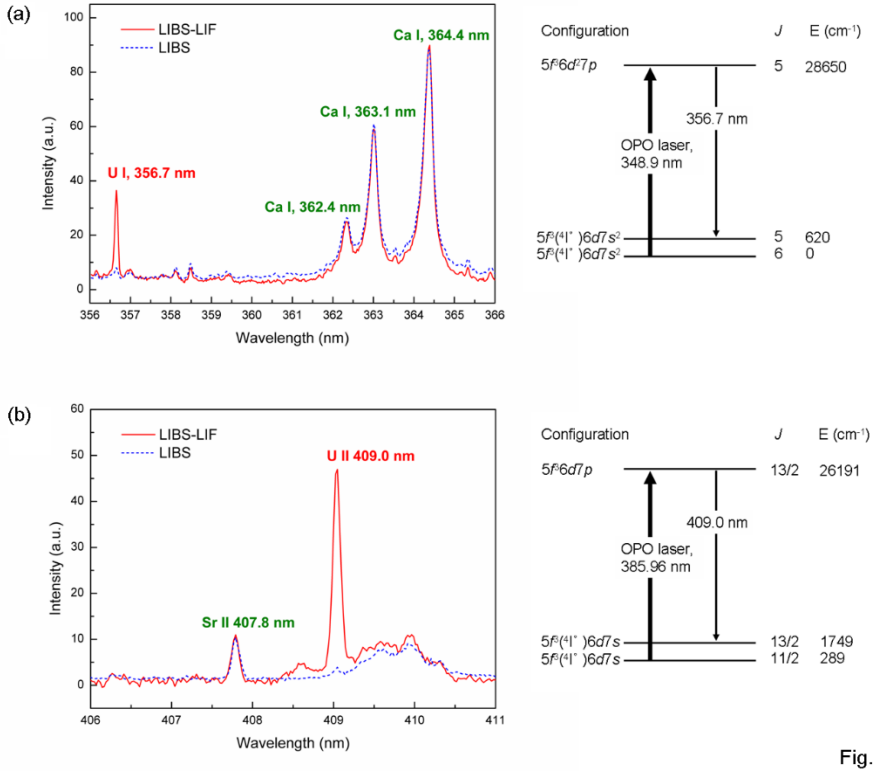


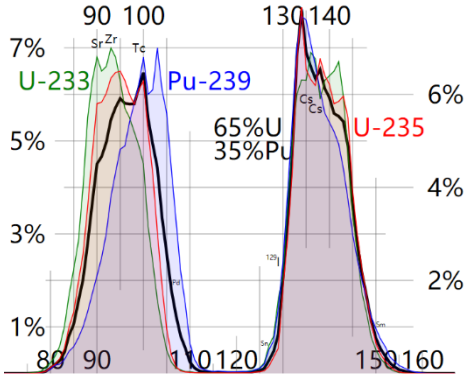
Fig. 3

Appl. Opt., 2008, 47(11), 1810

Open air mass spectroscopy—nuclear accidents, Construction materials

Nuclear explosion

Elemental and isotopic composition of the debris



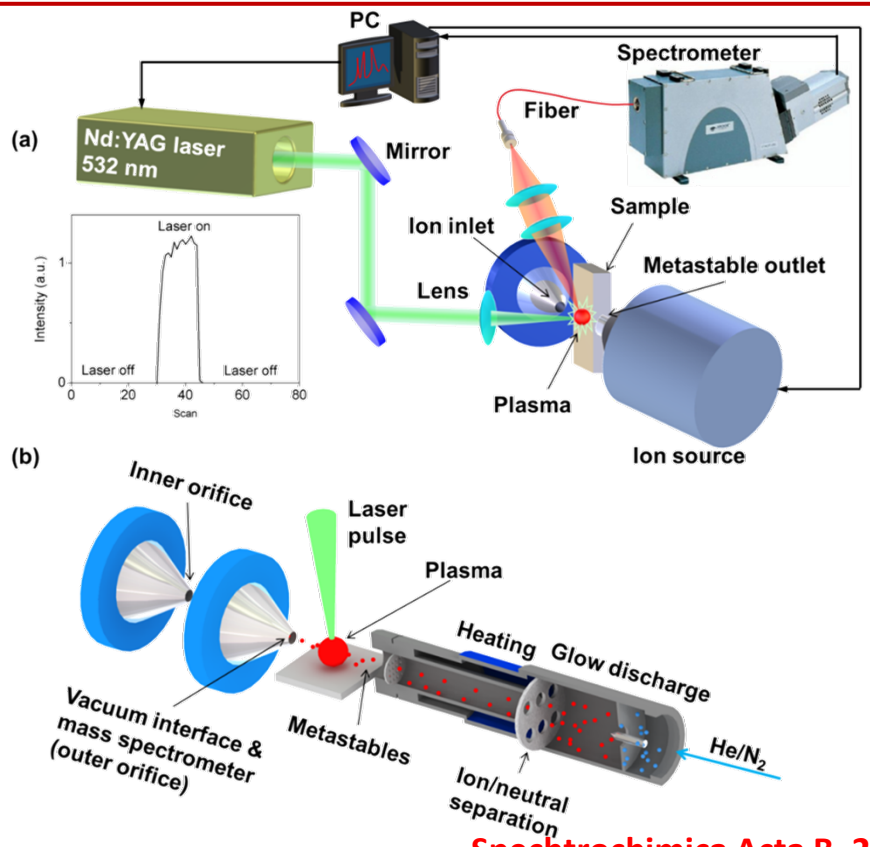
Pu/U ratio

$^{239}Pu/^{240}Pu$ ratio

Pu in debris: 400 ppb

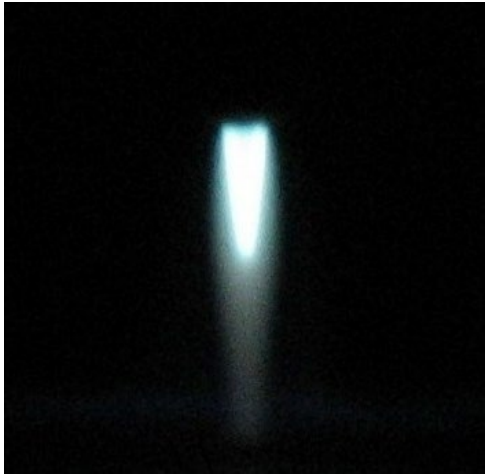
Origin: nuclear weapon

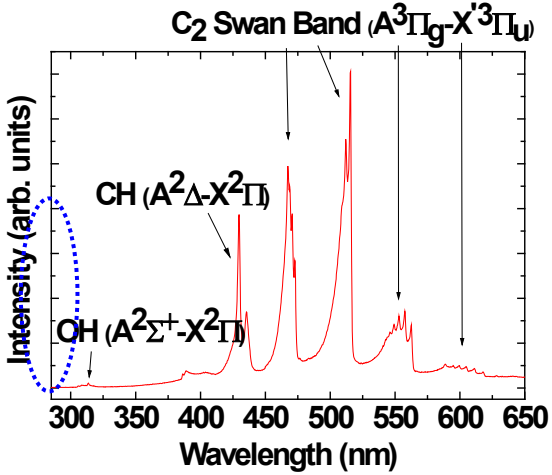
Open-air mass spectrometry - Isotope resolved



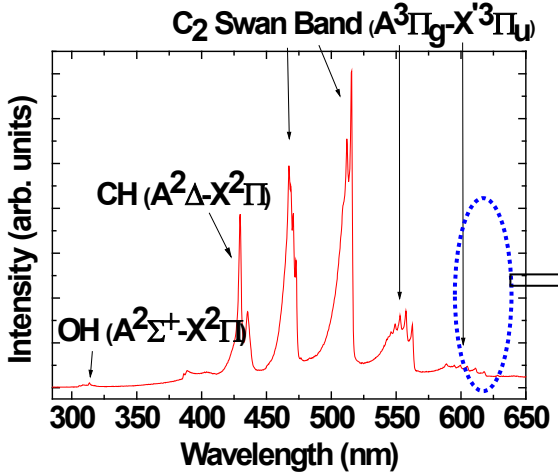
Spechtrochimica Acta B, 2012, 67, 64

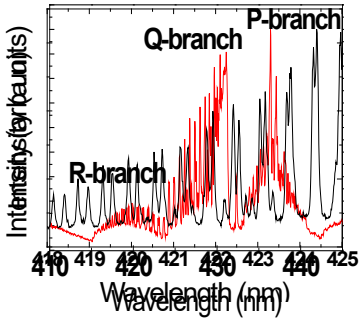
Temperature distribution for combustion





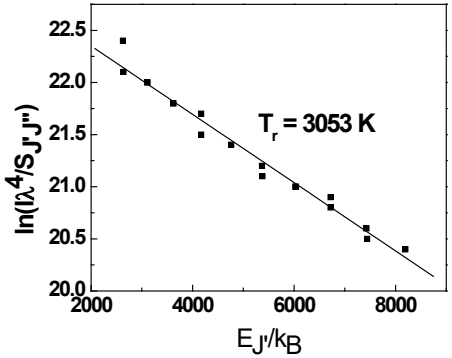
Temperature distribution for combustion



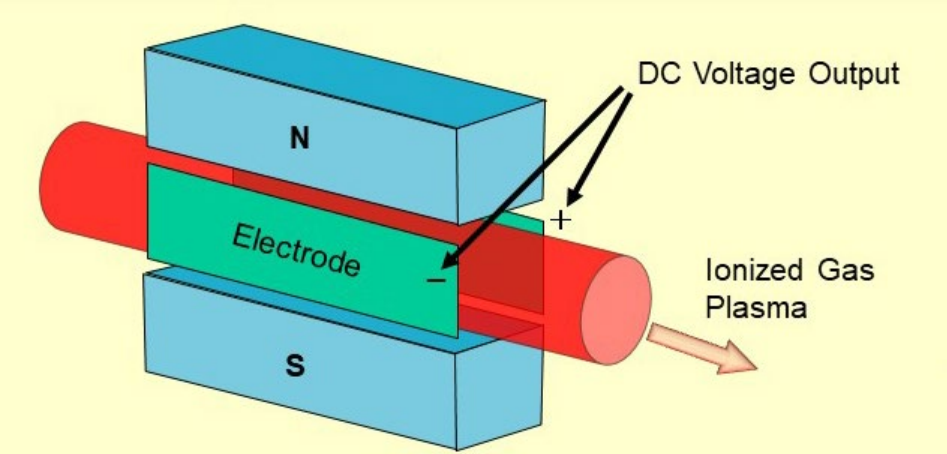


$$I = CS_{J'J''}\lambda^{-4}\exp(-\frac{E_{J'}}{k_B T_r})$$

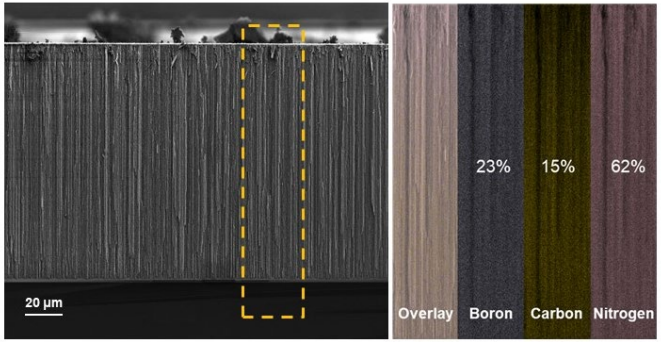
$$\ln(I\lambda^4 / S_{J'J''}) = -\frac{1}{T_r} * \frac{E_{J'}}{k_B} + \ln C$$



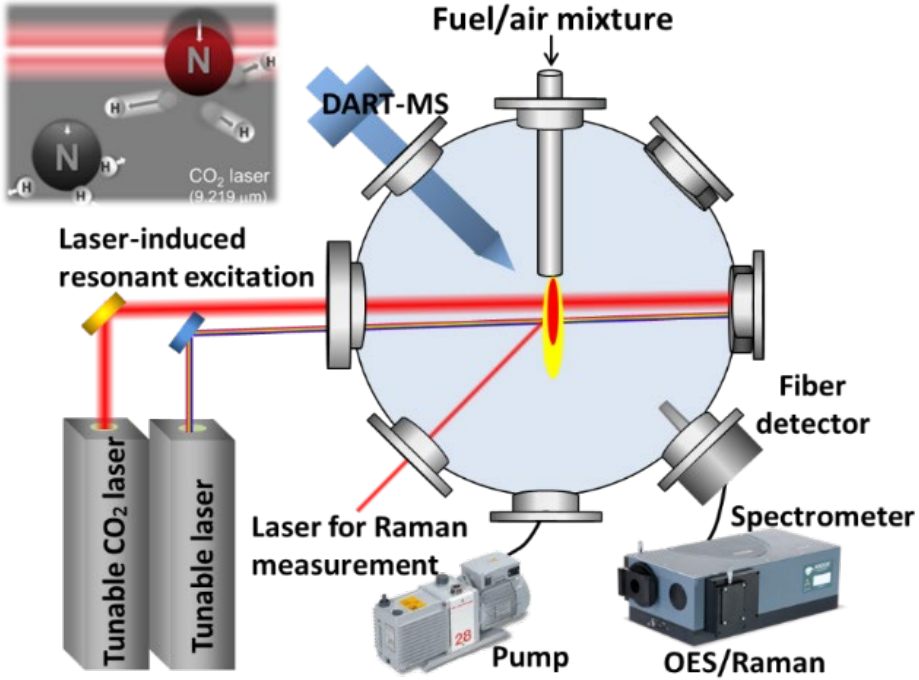
Magnetohydrodynamics (MHD) power systems

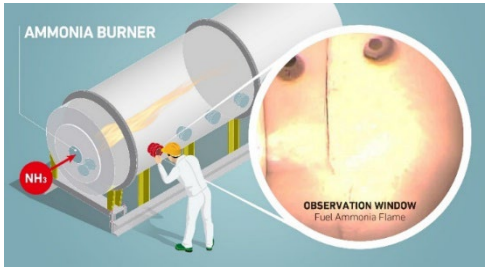


Infiltration of BN into VACNT arrays (EDS mapping)



Carbon-neutral combustion ($NH_3 + O_2$)





V. Conclusions

Summary

1. **Target Fabrication**
2. **Target Verification**
3. **Spectroscopy, mass spectrometry, and imaging for energy applications**