U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Integrated Stand-Off Optical Sensors for Molten Salt Reactor Monitoring

OVERVIEW

Purpose: This project will develop integrated stand-off optical sensors to perform coolant levels, flow rate, and metal impurity characterization in real time to ensure the safe and efficient operation of Molten Salt Reactors (MSRs). Using a single radiation-harden fused silica rod as the optical port to remotely access reactor cores or flow loops, this project will develop integrated stand-off optical sensors to perform coolant levels, flow rate, and metal impurity characterization in real time to ensure the safe and efficient operation of Molten Salt Reactors.

Objectives:

1 – Optical Frequency Domain Reflectometry (OFDR) Lidar Technology for Coolant Level Monitoring and vapor profile measurements:

2 – Laser Doppler flow velocity sensing based on diode laser self-mixing technology

3 – Laser Induced Breakdown Spectroscopy (LIBS) for metal impurity measurements

IMPACT

Logical Path: Through optical frequency-domain reflectometry and intracavity self-mixing effects, physical parameters of molten salts can be accurately measured in both reactor vessels and flow loops using diode lasers. Using advanced dual-pulse laser-induced breakdown spectroscopy (LIBS), this project will develop a stand-off laser chemical sensor with detection sensitivity better than 10 ppm to measure dissolved metals such as Ni, Cr, and Mn, which are directly connected to molten-salt-induced corrosion of pressure vessels.

Outcomes: This project would produce low-cost laser sensing instruments that can perform highly accurate and real-time measurements of level, flow, and metal impurities for molten salt reactors that were not possible before. The success of this project will provide nuclear industry engineers and national lab scientists with a set of powerful sensor tools to harness real-time data crucial to the safe and efficient operation of molten salt reactors. Through concerted and collaborative R&D efforts with national lab researchers and an industry leader in MSR technology, this project will drastically improve the technology readiness levels of proposed optical sensors and sensor instrumentations to reach TRL5.

DETAILS

Principal Investigator: Kevin P. Chen

Institution: University of Pittsburgh

Collaborators: Kairos Powers LLC, ORNL

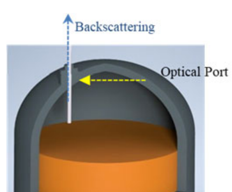
Duration: 3 Years **Total Funding Level**: $1,000,000

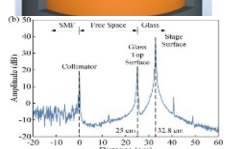
TPOC: Pattrick Calderoni

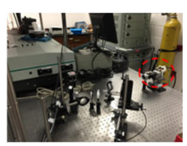
Federal Manager: Daniel Nichols

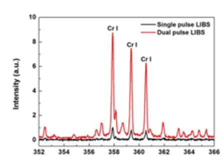
Workscope: (IC-1)

PICSNE Workpackage #:
NU-23-PA-PITT-020101-08









RESULTS

Results:

1. We completed the first milestone and performed a detailed numerical analysis on OFDR LidAR performance amid mode hopping. The results show that liquid-level sensing at the molten salt conditions can be achieved within 1-mm accuracy even with random mode-hopping as long as the mode-hopping does not change the overall wavelength scanning ranges. These results have been submitted to the IEEE Sensor Journal.
2. 2. We have developed a VCSEL control circuit board that can effectively control tunable VCSEL with a scanning rate of 100kHz. The device performance has been validated by continuous scanning operation during a period of two days. 3. We have started to construct a simulated flow loop to perform flow measurements using OFDR LidAR. 4. We visited Kairos Power to discuss potential on-site works.

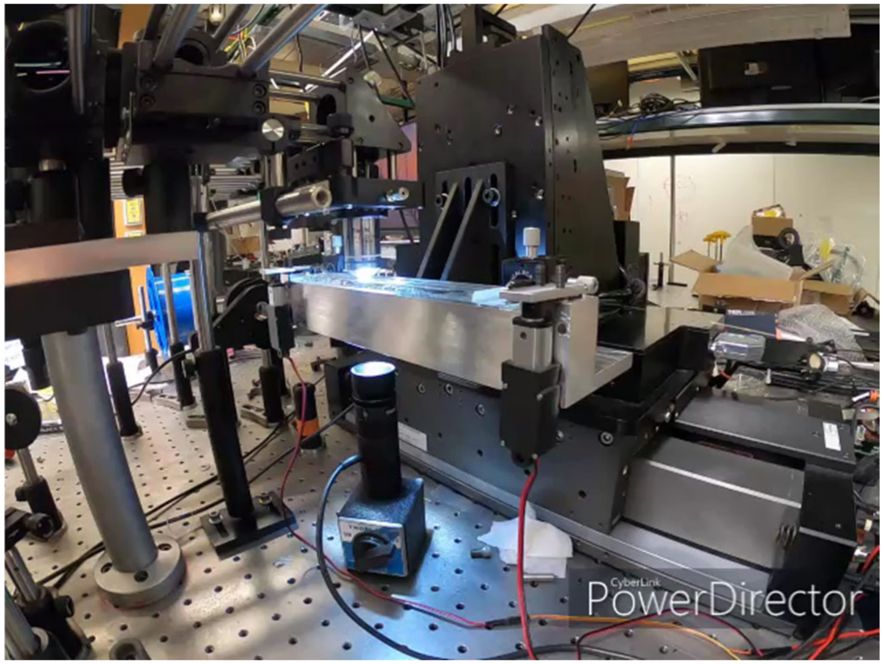
Accomplishments:

1. Qirui Wang, Guangyin Zhang, Kehao Zhao, Jieru Zhao, Shuda Zhong, and Kevin P. Chen, “Real-Time Spatial resolved Smoke Detection with OFDR LiDAR”, to be presented in CLEO 2024.

2. Qirui Wang, Nageswara Lalam, Ruishu Wright, and K. P. Chen, “Analysis of mode hopping impacts on OFDR sensing performance,” Submitted to IEEE Sensor Journal.

Previous NEET Accomplishments

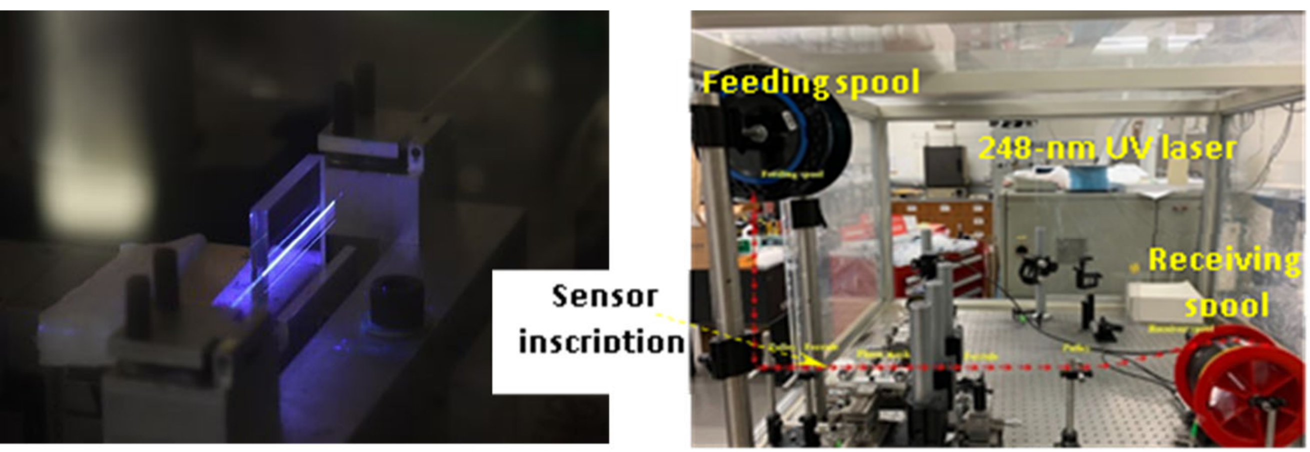
Reel-to-Reel Sensor Fabrication at the University of Pittsburgh



Femtosecond Reel-to-reel fiber writing setup

- 180-fs laser.
- Fabrication of up to 1km of fibers.
- Point-by-point writing: Flexible.
- Through fiber coating fabrication.
- FBG, distributed, IFPI arrays.
- High-T stable distributed sensors.
- Sapphire and silica fibers.
- Develop a process to inscribe fiber sensors in metal-coated fiber and then recoat it.

- Four rounds of MITR test up to 10^22 fast n/cm^2



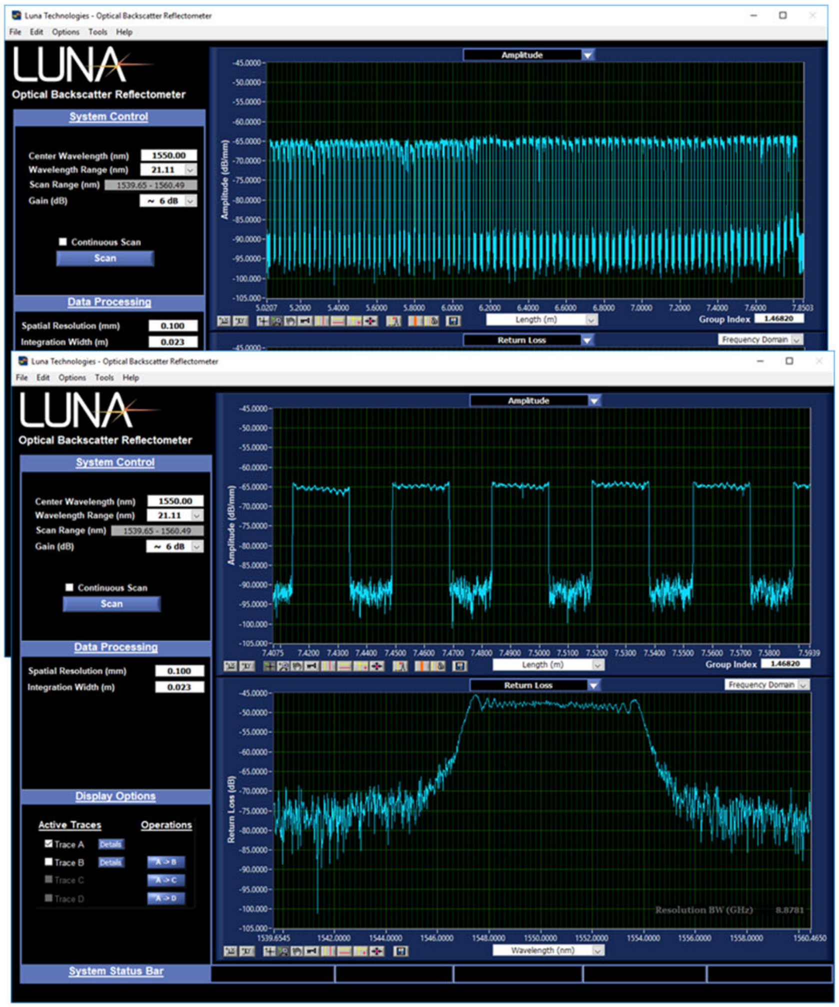
Deep UV Sensing Fiber Fabrication

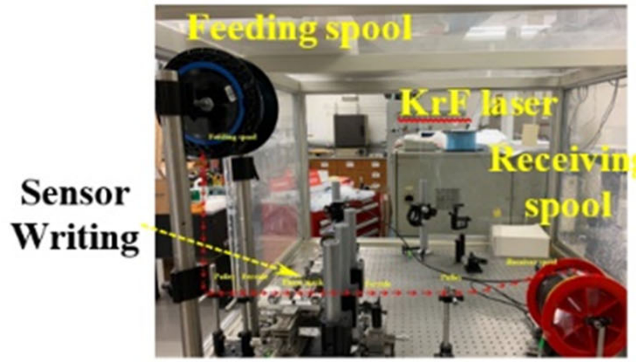
- Standard telecom fiber – through the coating
- One-shot UV phase mask writing
- 10-km continuous sensing fiber
- Draw-tower free
- Sensing fiber cost ~$0.1-$1.0 per meter (competition: $10-30/m)
- Joint pending patent with Corning

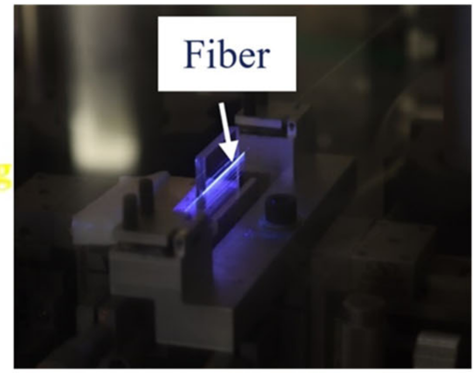
Previous NEET Accomplishments

Reel-to-Reel Sensor Fabrication at the University of Pittsburgh

Industry-leading sensor performance







PITT PATENTED TECHNOLOGY: US PATENT 11,698,483B2 (2023)

EXTRAORDINARY FLEXIBILITY: 4-5 DIFFERENT TYPES OF SENSORS CAN BE INSCRIBED ON THE SAME FIBER

BETTER UNIFORMITY THAN DRAW-TOWER FBG!

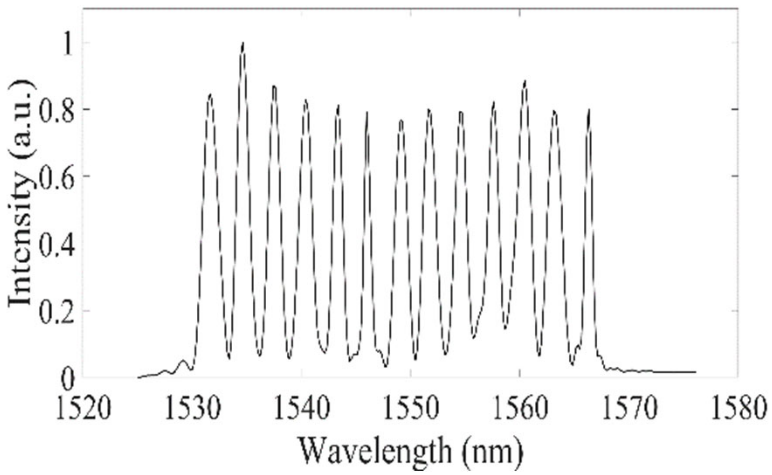
LOW COST: **BASED ON TELECOM FIBERS, NO DRAW-TOWER WRITING, (UP TO 50% COST SAVING).**

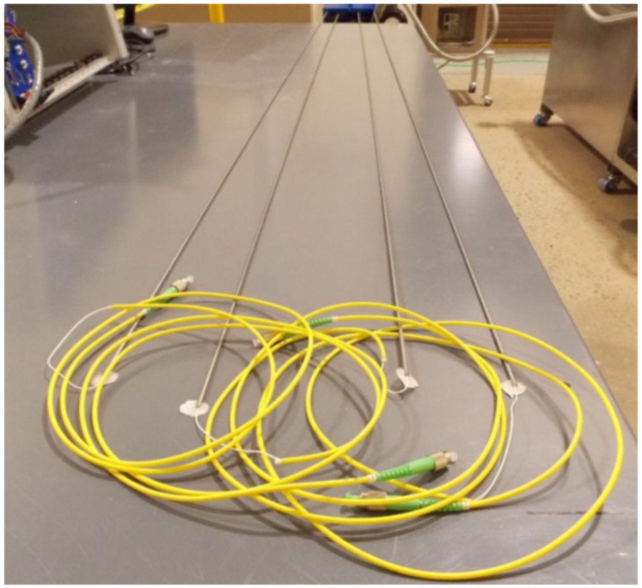
MADE-IN-USA POTENTIAL: 100% AMERICAN SUPPLY CHAIN FROM THE GROUND UP.

WE CAN CONTINUOUSLY FABRICATE 10-KM LONG FBG FIBERS.

FIRST 1-KM LEVEL DEPLOYMENT FOR STRUCTURAL HEALTH MONITORING WILL TAKE PLACE IN DOWNTOWN PITTSBURGH IN 2024.

High-Temperature Stable Multiplexed Fiber Sensors





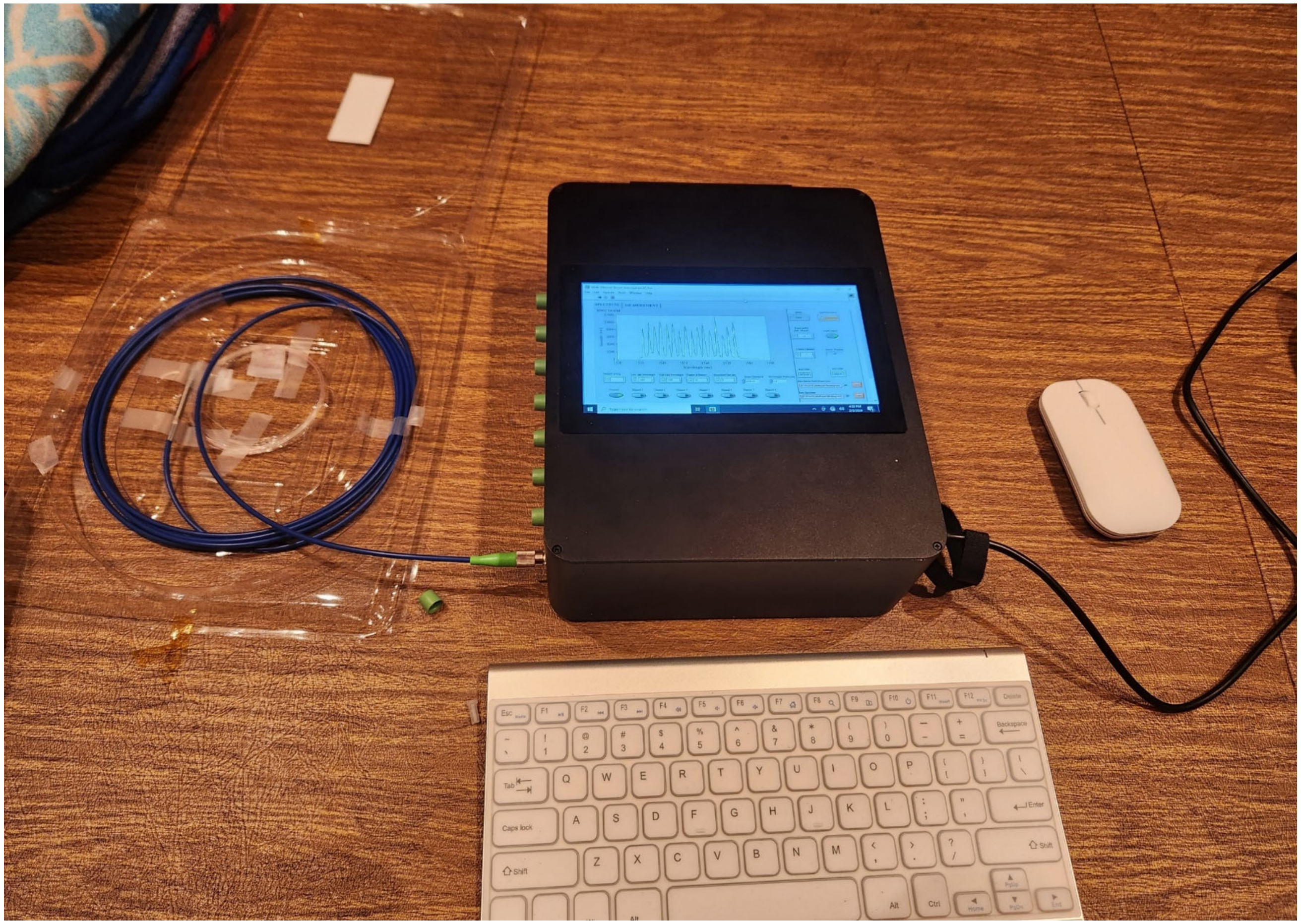
- **Up to 25 high-temperature stable FBG arrays can be fabricated in hydrogen-resistant optical fibers.**
- **Packaged sensors in 316H SS tubing with polymer coating removed.**
- **Each sensor is pre-annealed and calibrated.**
- **Armored cable lead for field deployments.**
- **Hermetic connector rated for 250C.**
- **Packaged fibers can be repeatedly heated with consistent performance.**
- **Optimal operational temperature < 750C and 10^{18} fast-n/cm^2**

High-Temperature FBG Sensor Instruments Made in Pittsburgh

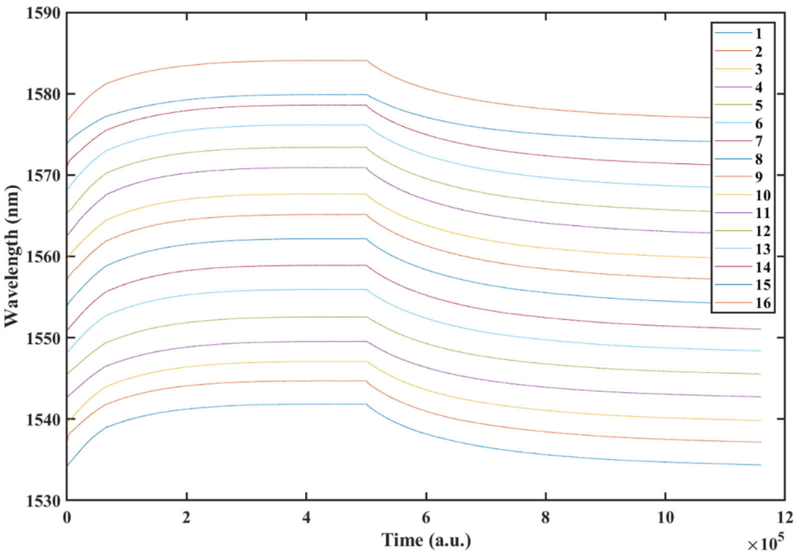
- Fully-integrated instrument (8, 16, 32, 64 channels)
- USB, EIP, wireless data communications.
- 5-kHz sampling rate (over total channel #).
- Fully compatible with Rockwell PLC

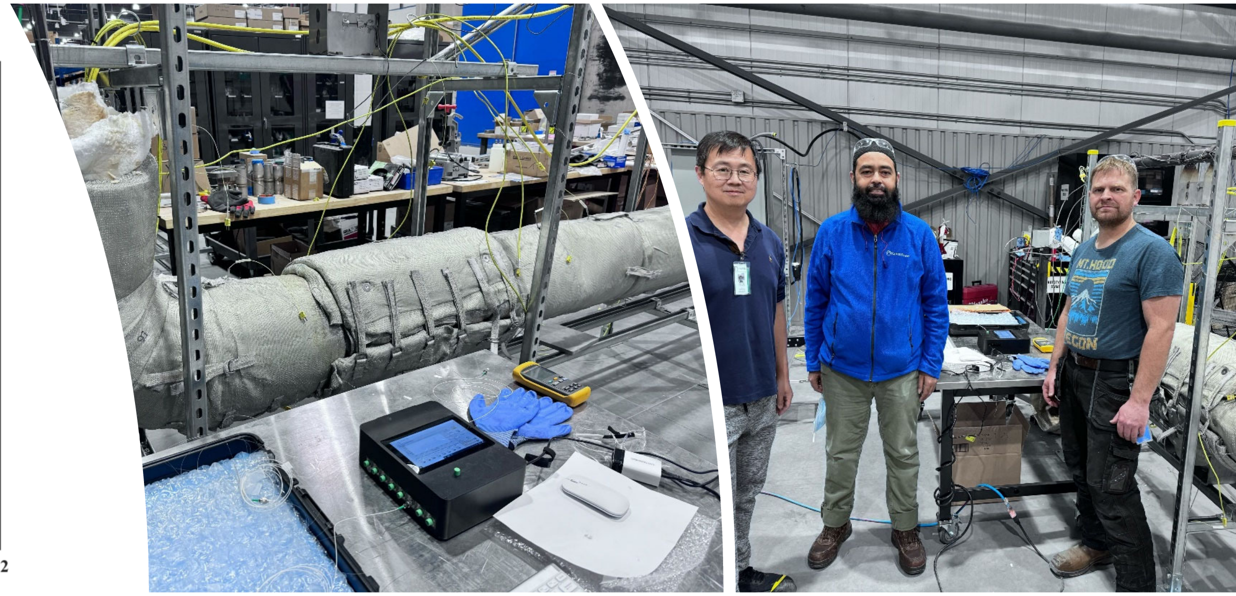
The key is the algorithm!

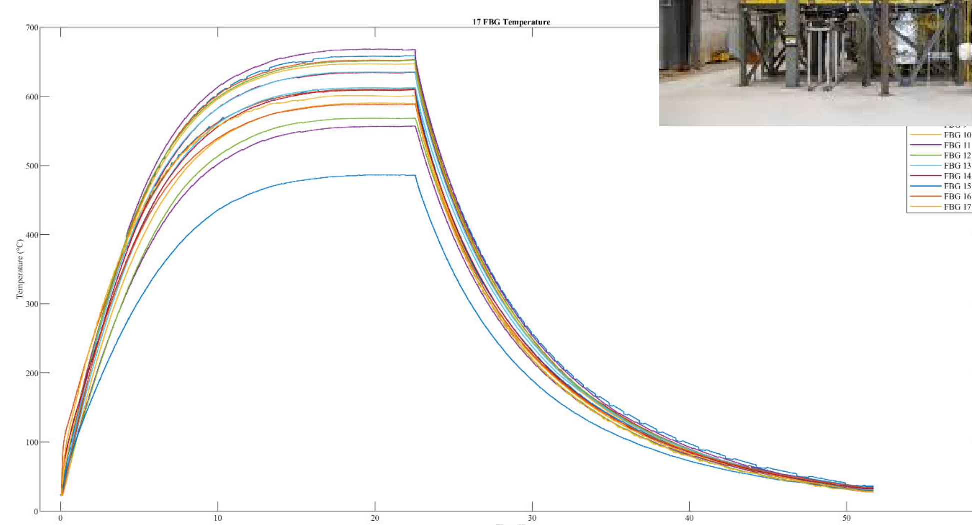
- Three algorithms to ensure accurate sensor demodulation.
- Interrogate both FBG and IFPI arrays.
- Background data screening and validation.
- Can simultaneously interrogate up to 1280 point sensors.
- **The world's first fully calibrated fiber sensors (Guaranteed at up to 650C).**
- Aiming for full calibration at 850C.
- Made in Pittsburgh.



First Field Test: Molten Salt circulation loop







- Completed immune to EM noises
- Radiation harden
- Straightforward calibration.
- Full PLC integrated – Fiber in the Loop

- One-fiber, 25 sensors vs. 50 lead wires – 25 sensors.
- Testing on Kairos ETU2.0 scheduled for 2025

Objectives and Tasks

Task 1 – Optical Frequency Domain Reflectometry (OFDR) Lidar Technology for Coolant Level Monitoring:

- Robust, response time, and reliability
- Radiation resilience, multi-function
- On-site testing and performance evaluation at Kairos ITU1.0 and ORNL TTF

Task 2 – Laser Doppler flow velocity sensing based on diode laser self-mixing technology

- Clean and simple technology
- Insensitive to radiation.
- On-site testing and performance evaluation at Kairos and ORNL.

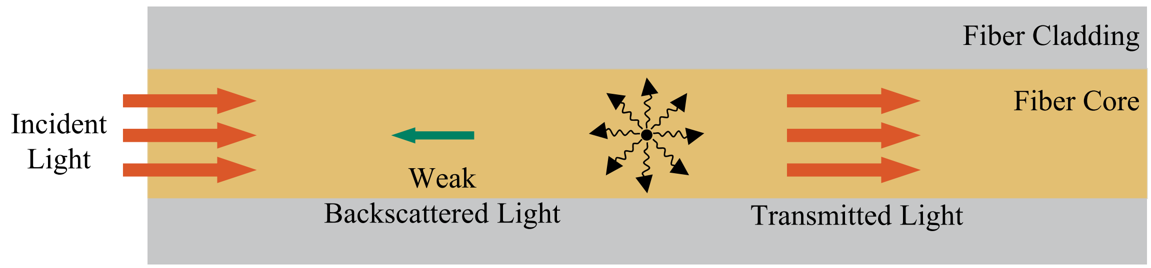
Task 3 – Laser Induced Breakdown Spectroscopy (LIBS) for metal impurity measurements

- Wide applicability: molten salts and other relevant species (e.g., Xe)
- Portable instruments
- Sensitivity improvements

Task 1: OFDR for Molten Salt

OFDR Features

- Weak Rayleigh backscattering
- Use a tunable laser (TL) as light source, wavelength tuning (>20 nm)
- High spatial resolution (20 nm → 40 µm, 80 nm → 10 µm)
- Optical frequency sweeps linearly
- Narrow linewidth (long sensing range)



Ultra weak Rayleigh backscattering in a telecom fiber.

Current Solution: high-performance TL

- Wide tuning range (80-110 nm)
- Narrow linewidth (kHz level)
- High linearity
- **HIGH instrument costs**

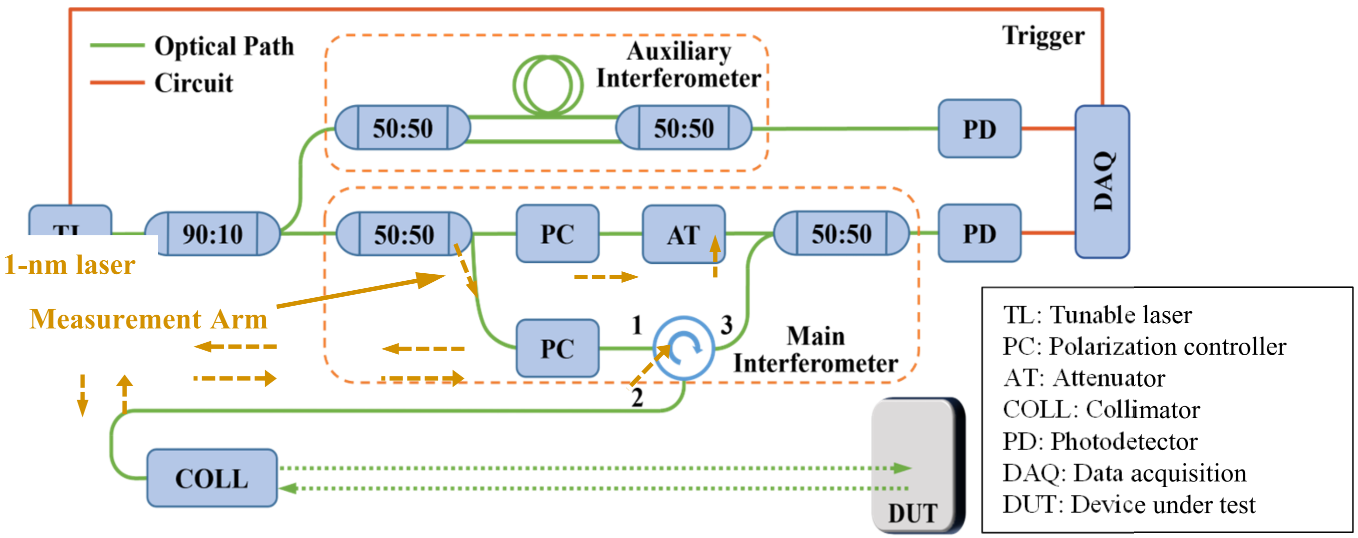
Commercial TLs (80-110 nm) used in OFDR.

A DFB laser (1 nm).

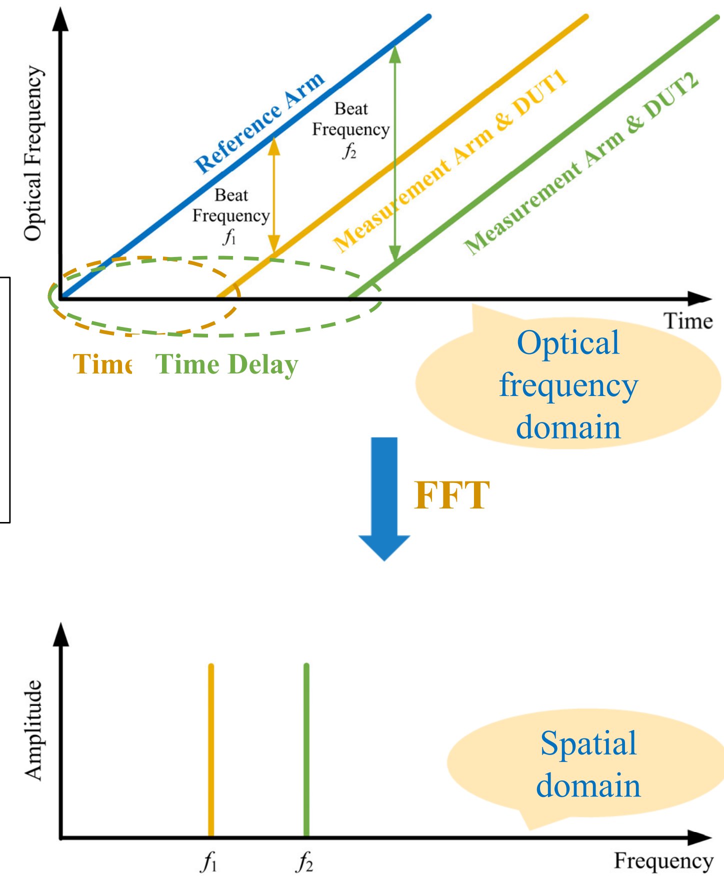
Exploration: OFDR with a low-cost distributed feedback (**DFB**) laser (**1-nm** range, **1-MHz** linewidth)

Applications: free-space LiDAR (**distance**) & in-fiber distributed sensing (**strain**)

Free-Space OFDR LiDAR Distance Sensing – System Overview



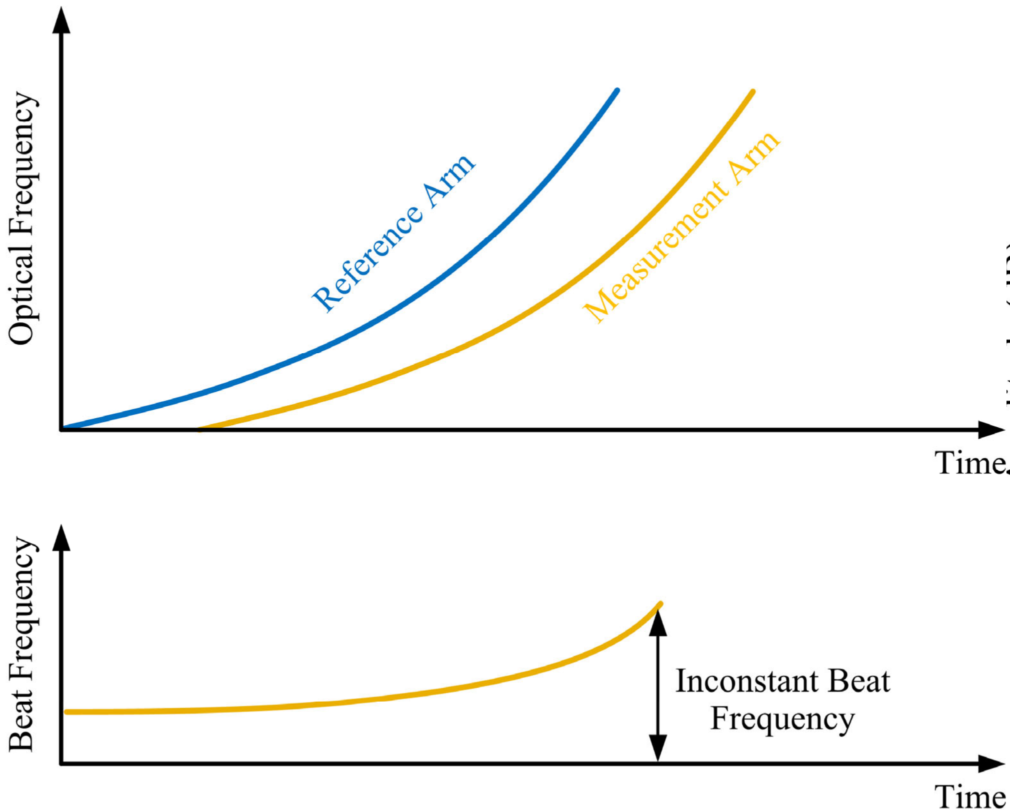
Schematic of a free-space OFDR LiDAR system.



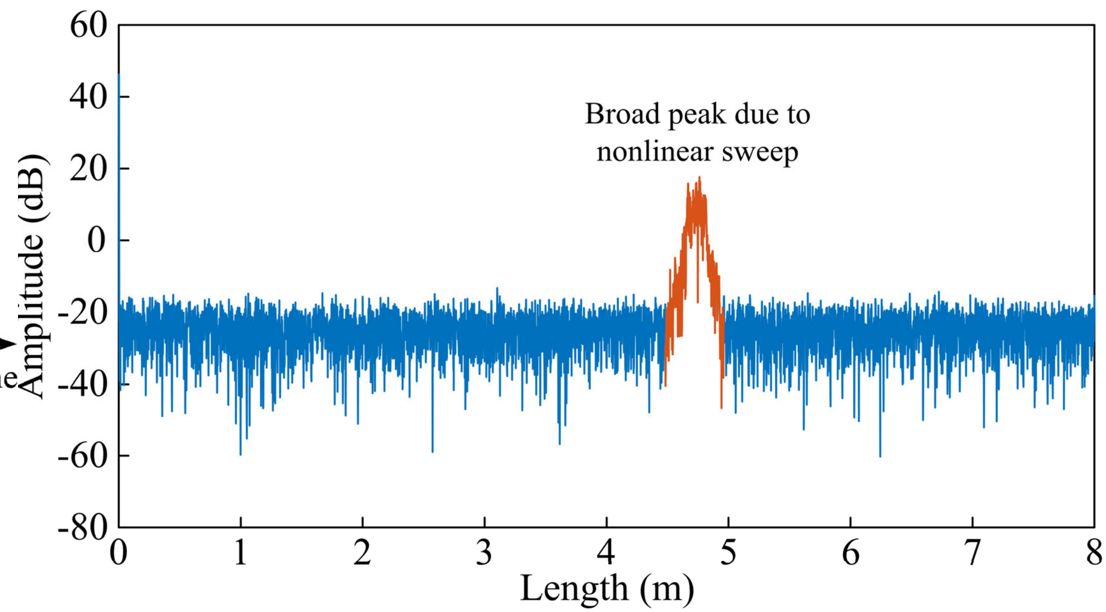
OFDR System

- Auxiliary Interferometer
  - Linearize tuning
- Main Interferometer
  - Real-time sensing
    - **Reference Arm**: Short & fixed path
    - **Measurement Arm**: Long & variable path

Free-Space OFDR LiDAR Distance Sensing – Nonlinear Sweep

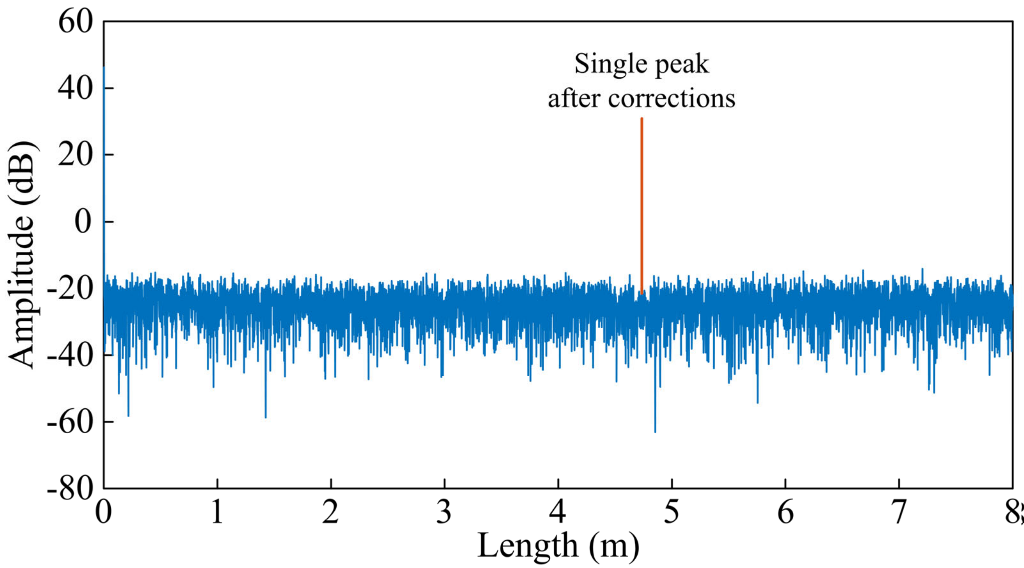


Inconstant beat frequency.



Spatial-domain signal before nonlinearity corrections.

Free-Space OFDR LiDAR Distance Sensing – Nonlinear Sweep



Spatial-domain signal after nonlinearity corrections.

Spatial Resolution Δz

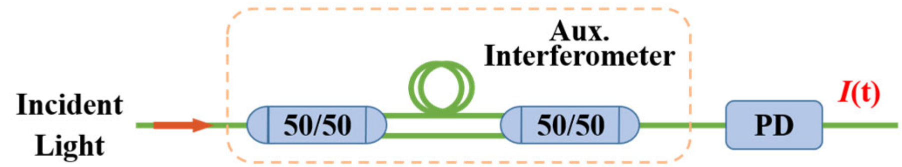
$$\Delta z = \frac{c}{2n\Delta\nu} = 1.2\ \text{mm}$$

c: Speed of light in a vacuum

n: Refractive index (1 in free space)

$\Delta\nu$: Frequency tuning range

(1 nm → 125 GHz)



Schematic of an auxiliary interferometer.

$$I(t) = I_0 \cos\left[2\pi\tau_A \nu(t)\right]$$

I_0: Amplitude τ_A: Time delay

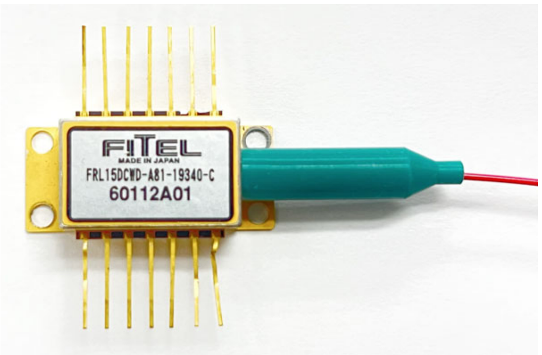
$\nu(t)$: Instantaneous frequency of TL

$$\Phi(t) = 2\pi\tau_A\nu(t) = \arctan\frac{H\left[I(t)\right]}{I(t)}$$

Hilbert Transform

$$\nu(t) = \frac{1}{2\pi\tau_A}\Phi(t)$$

Free-Space OFDR LiDAR Distance Sensing – Experiments

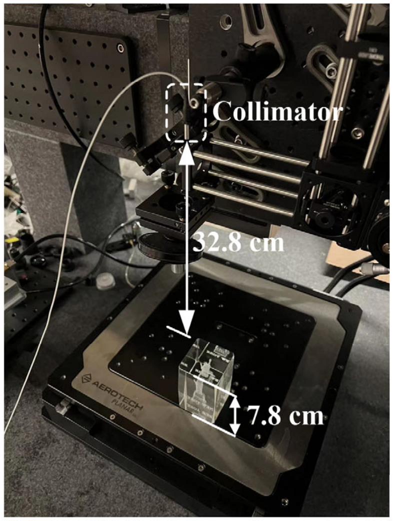


Current Modulation

Range: 1549-1550 nm (125 GHz)

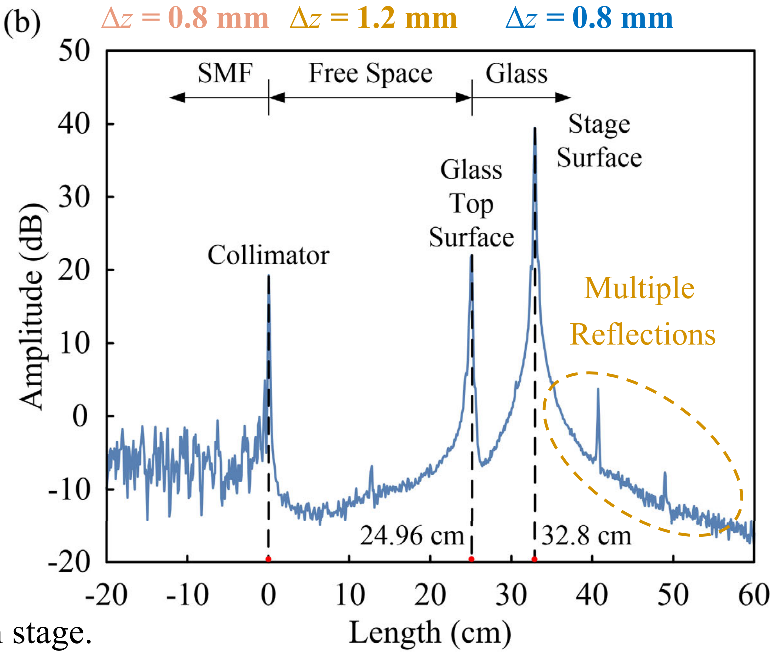
Sweep Rate: 100 nm/s

(a)



Collimator & glass cuboid on a motion stage.

(b)

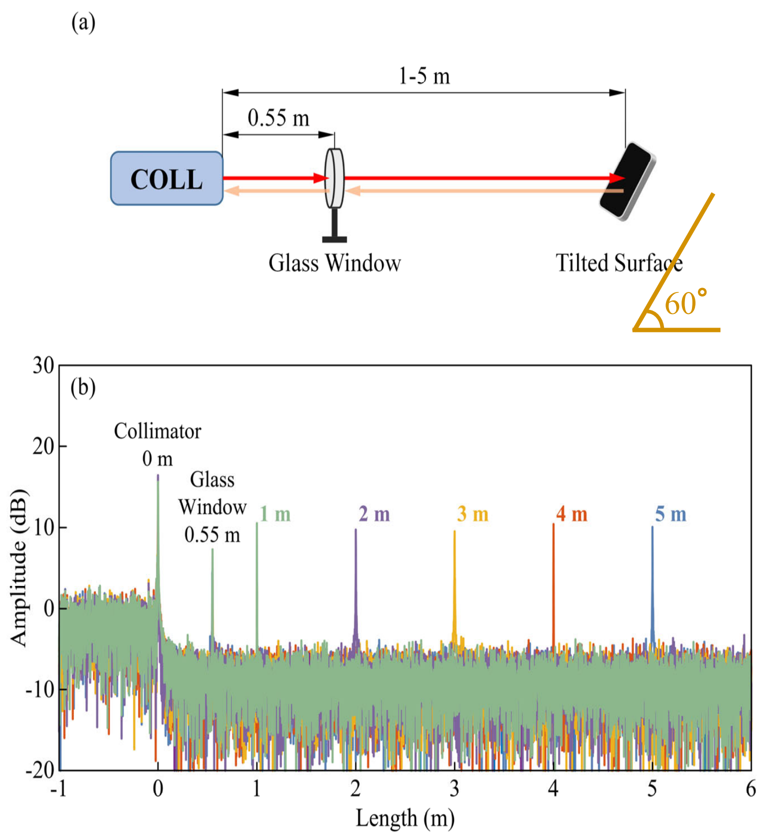


Spatial Resolution Δz

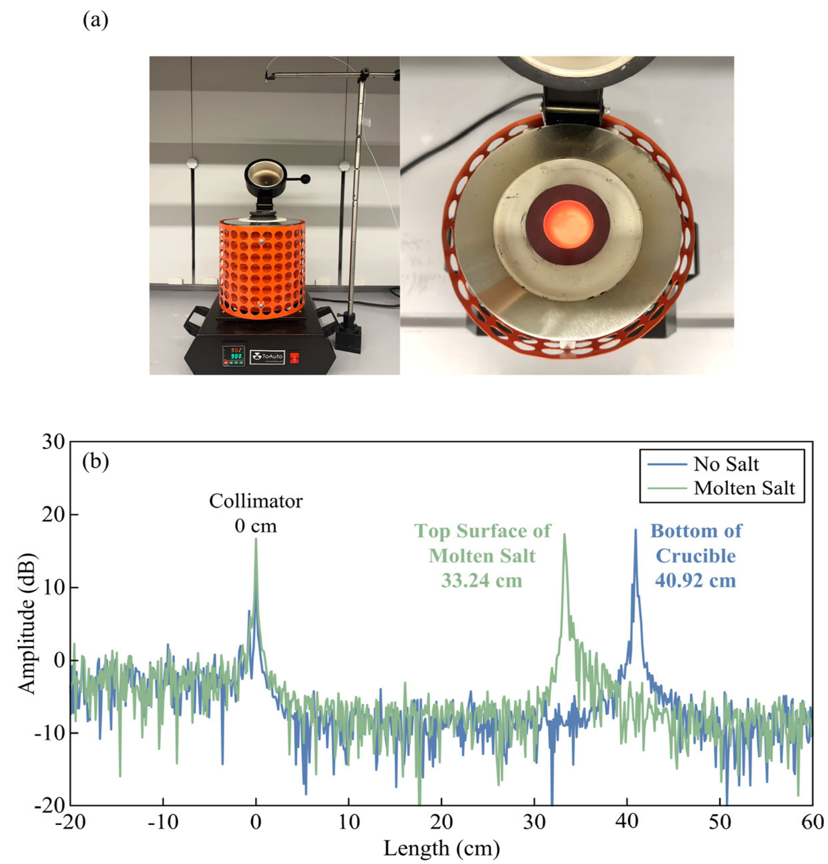
Free Space: 1.2 mm (refractive index $n = 1$)

SMF/**Glass**: 0.8 mm (refractive index $n = 1.5$)

Free-Space OFDR LiDAR Distance Sensing – Nonlinear Sweep

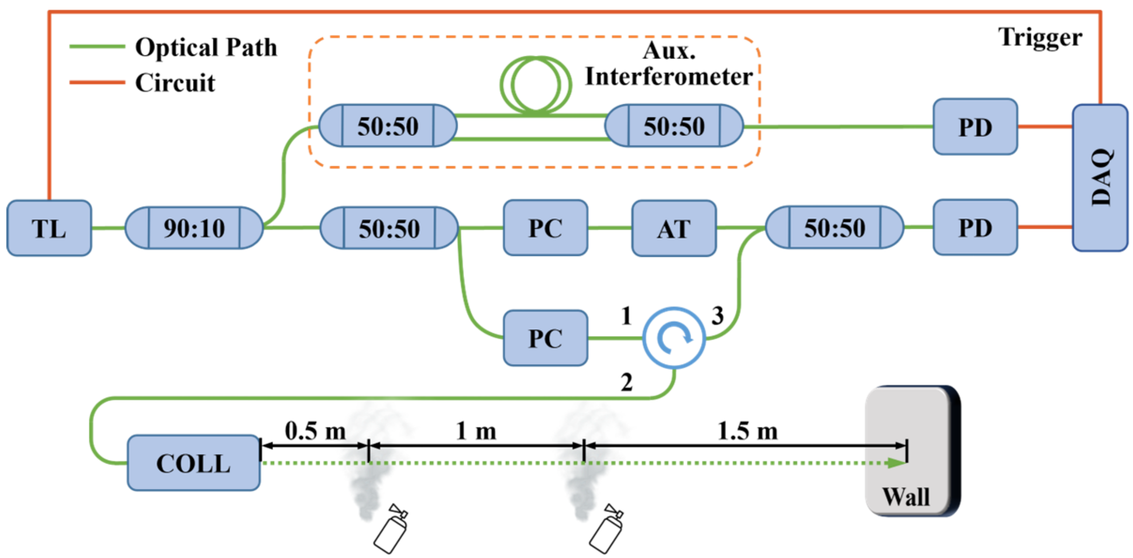


Distance sensing with a tilted surface (60-degree angle).

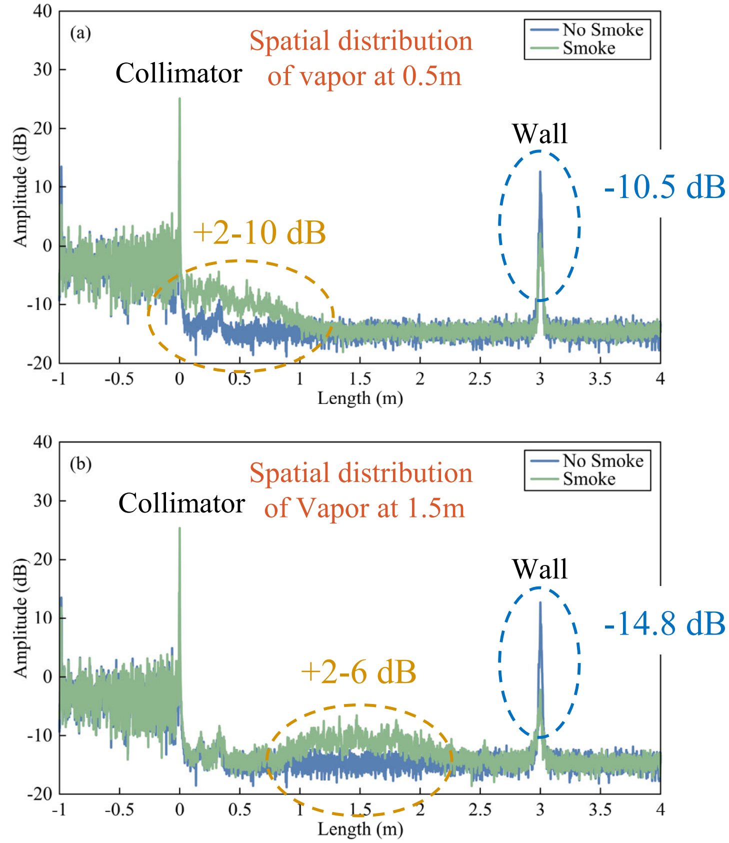


Molten salt level sensing at 900°C.

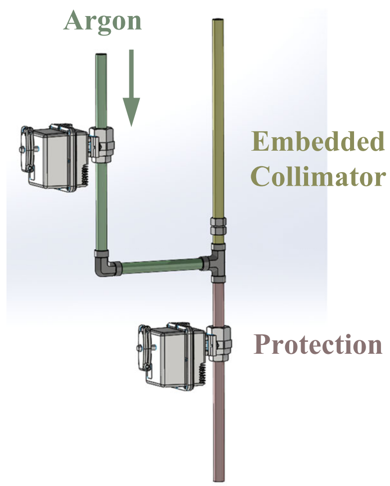
Free-Space OFDR LiDAR Distance Sensing – Vapor and Level Sensing

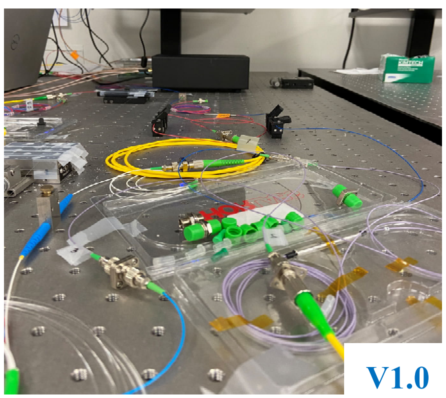


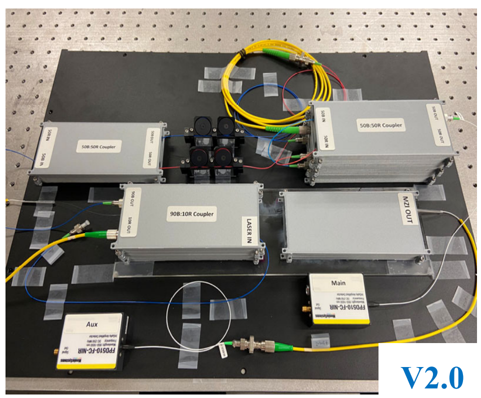
The OFDR LiDAR setup for airborne particle detection.

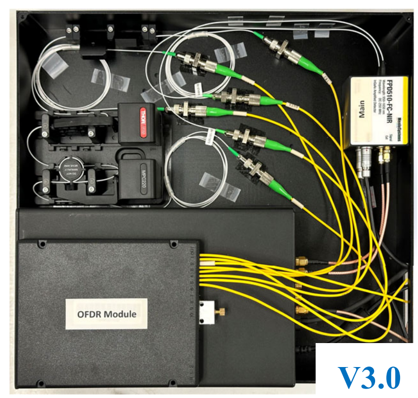


Free-Space OFDR LiDAR Distance Sensing – Instrumentation and Insertion

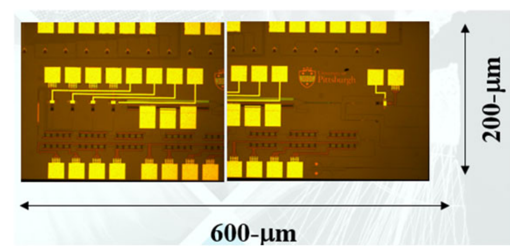



V1.0


V2.0



V3.0



Update

Complete the first milestone – Task 1

- Milestone 1 - Numerical studies of DFB laser diode mode-hopping impacts on LIDAR Performance.
- Published one journal paper and one conference paper.
- Look ahead to experiment for molten salts here at Pitt (coating effect and potential laser removing scheme) then move to Kairo power (level sensing) and ORNL

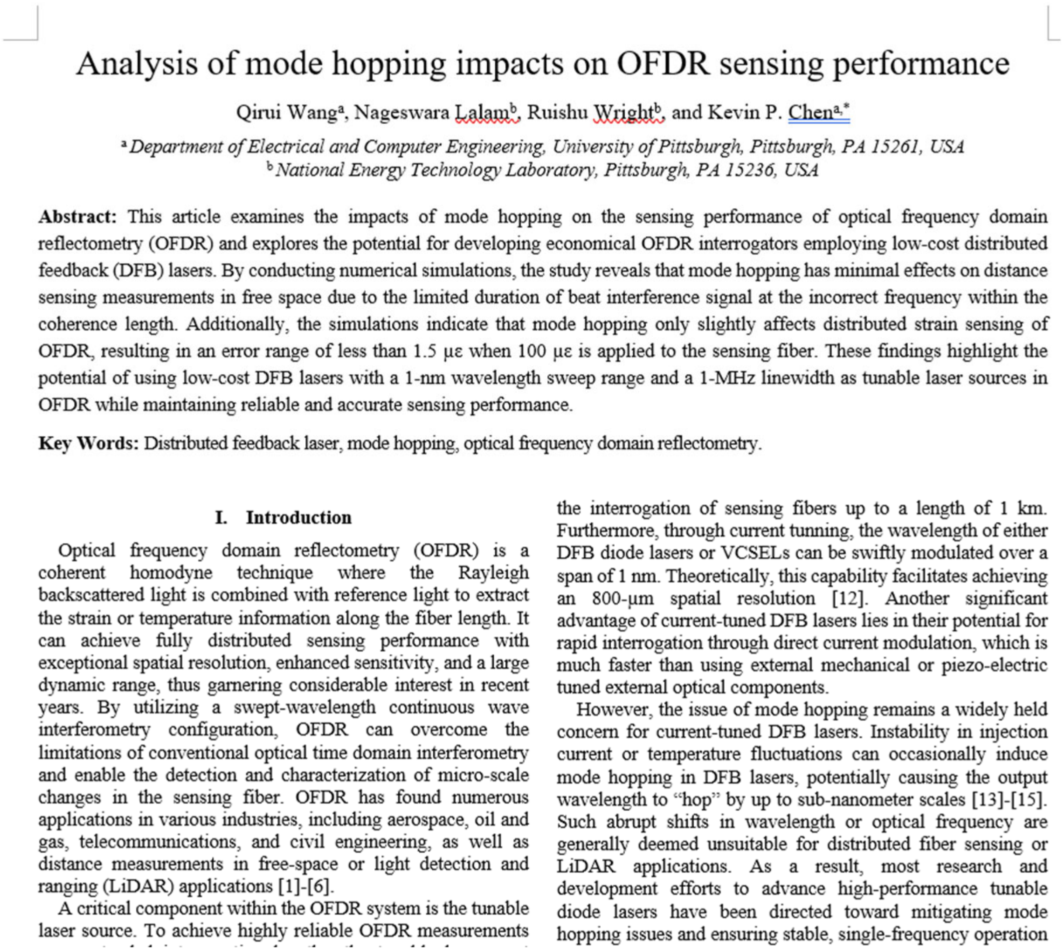
Planning for field works.

- Visited Kairos Power in February to schedule a field test later this year.
- Visited ORNL on Nov 15 to perform field work and discuss further experiments.
- To visit Kairos for experiments.

Instrumentation Design.

- Complete validation of VCSEL control circuits.
- All functions fully tested

Mode-hopping Impact on OFDR Lidar



Analysis of mode hopping impacts on OFDR sensing performance

Qirui Wang[a], Nageswara Lalam[b], Ruishu Wright[b], and Kevin P. Chen[a,*]

[a] *Department of Electrical and Computer Engineering, University of Pittsburgh, Pittsburgh, PA 15261, USA*
[b] *National Energy Technology Laboratory, Pittsburgh, PA 15236, USA*

Abstract: This article examines the impacts of mode hopping on the sensing performance of optical frequency domain reflectometry (OFDR) and explores the potential for developing economical OFDR interrogators employing low-cost distributed feedback (DFB) lasers. By conducting numerical simulations, the study reveals that mode hopping has minimal effects on distance sensing measurements in free space due to the limited duration of beat interference signal at the incorrect frequency within the coherence length. Additionally, the simulations indicate that mode hopping only slightly affects distributed strain sensing of OFDR, resulting in an error range of less than 1.5 με when 100 με is applied to the sensing fiber. These findings highlight the potential of using low-cost DFB lasers with a 1-nm wavelength sweep range and a 1-MHz linewidth as tunable laser sources in OFDR while maintaining reliable and accurate sensing performance.

Key Words: Distributed feedback laser, mode hopping, optical frequency domain reflectometry.

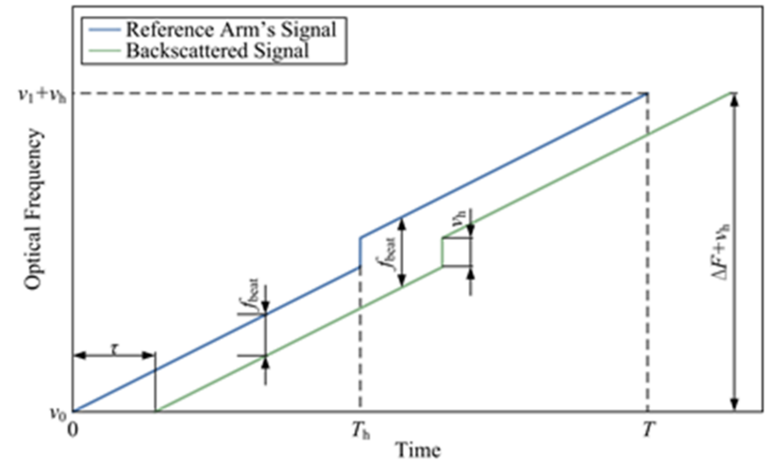
I. Introduction

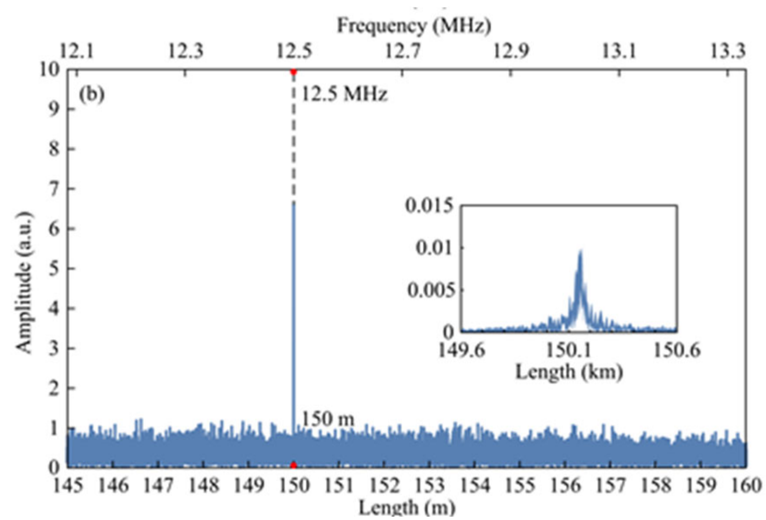
Optical frequency domain reflectometry (OFDR) is a coherent homodyne technique where the Rayleigh backscattered light is combined with reference light to extract the strain or temperature information along the fiber length. It can achieve fully distributed sensing performance with exceptional spatial resolution, enhanced sensitivity, and a large dynamic range, thus garnering considerable interest in recent years. By utilizing a swept-wavelength continuous wave interferometry configuration, OFDR can overcome the limitations of conventional optical time domain interferometry and enable the detection and characterization of micro-scale changes in the sensing fiber. OFDR has found numerous applications in various industries, including aerospace, oil and gas, telecommunications, and civil engineering, as well as distance measurements in free-space or light detection and ranging (LiDAR) applications [1]-[6].

A critical component within the OFDR system is the tunable laser source. To achieve highly reliable OFDR measurements

the interrogation of sensing fibers up to a length of 1 km. Furthermore, through current tunning, the wavelength of either DFB diode lasers or VCSELs can be swiftly modulated over a span of 1 nm. Theoretically, this capability facilitates achieving an 800-μm spatial resolution [12]. Another significant advantage of current-tuned DFB lasers lies in their potential for rapid interrogation through direct current modulation, which is much faster than using external mechanical or piezo-electric tuned external optical components.

However, the issue of mode hopping remains a widely held concern for current-tuned DFB lasers. Instability in injection current or temperature fluctuations can occasionally induce mode hopping in DFB lasers, potentially causing the output wavelength to "hop" by up to sub-nanometer scales [13]-[15]. Such abrupt shifts in wavelength or optical frequency are generally deemed unsuitable for distributed fiber sensing or LiDAR applications. As a result, most research and development efforts to advance high-performance tunable diode lasers have been directed toward mitigating mode hopping issues and ensuring stable, single-frequency operation

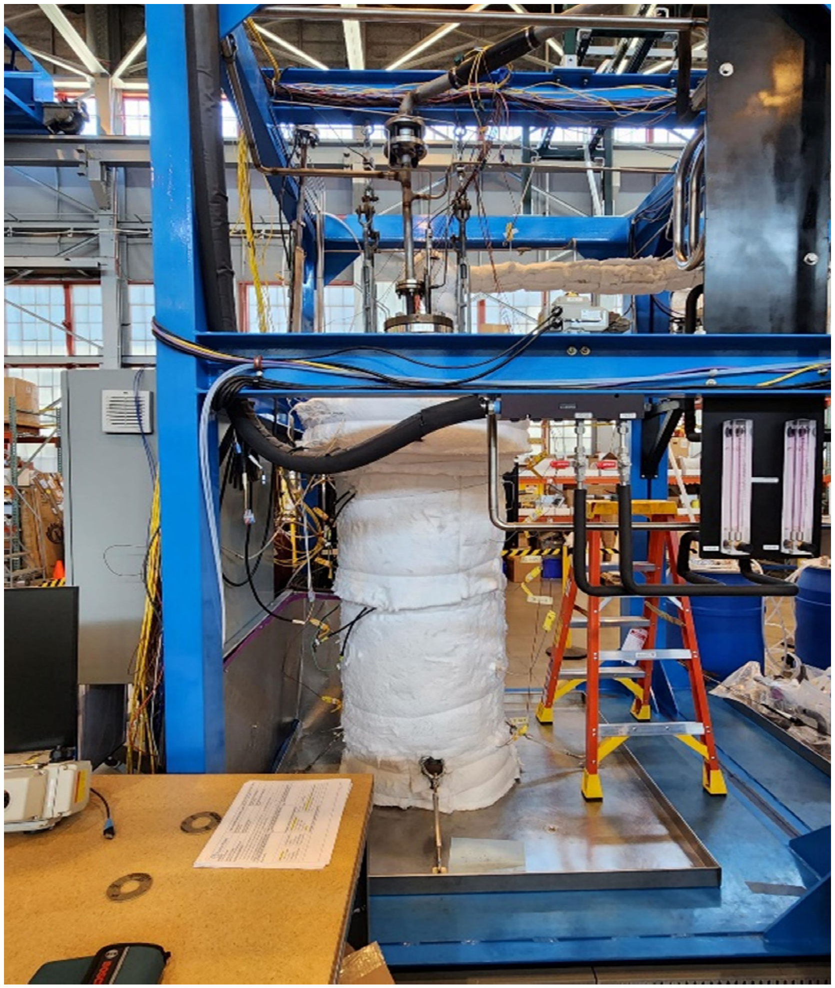




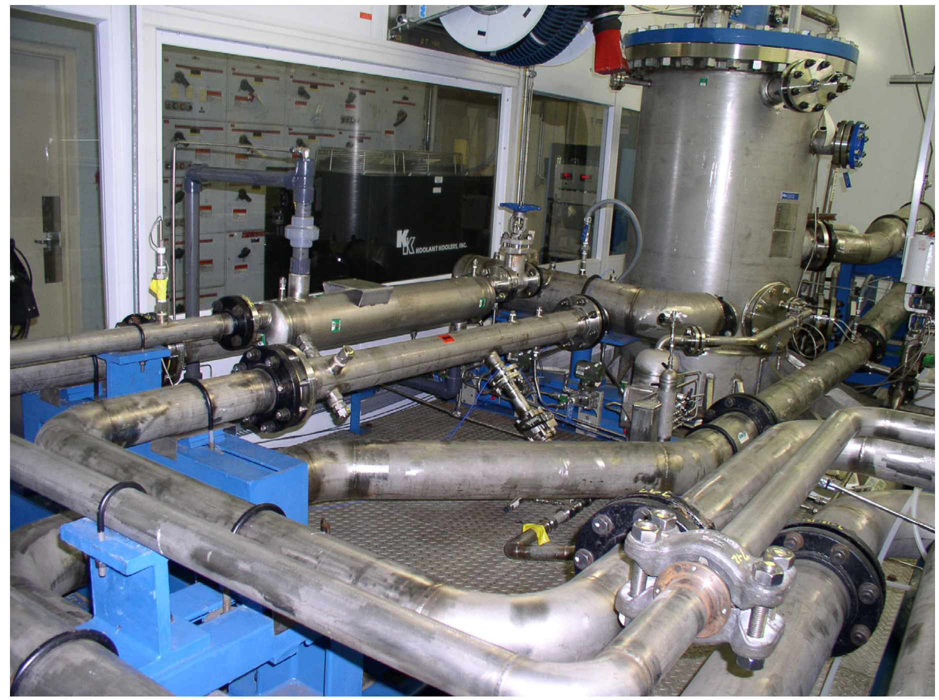
- Pittsburgh Super Computer Simulation.
- Mode-hopping will incur less than 1-mm error (10-meter sensing length) for distance measurements, if the overall wavelength tuning range stays the same.

Sensor Test at Kairos and ORNL

Kairos Salt Facility



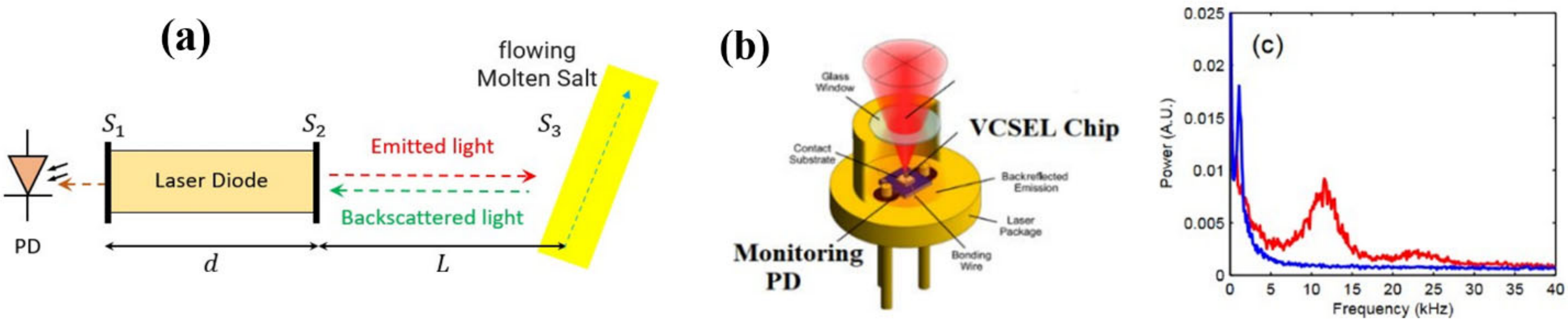
TTF Liquid Metal Facility



Task 2: Laser Doppler flow velocity sensing with laser self-mixing technology

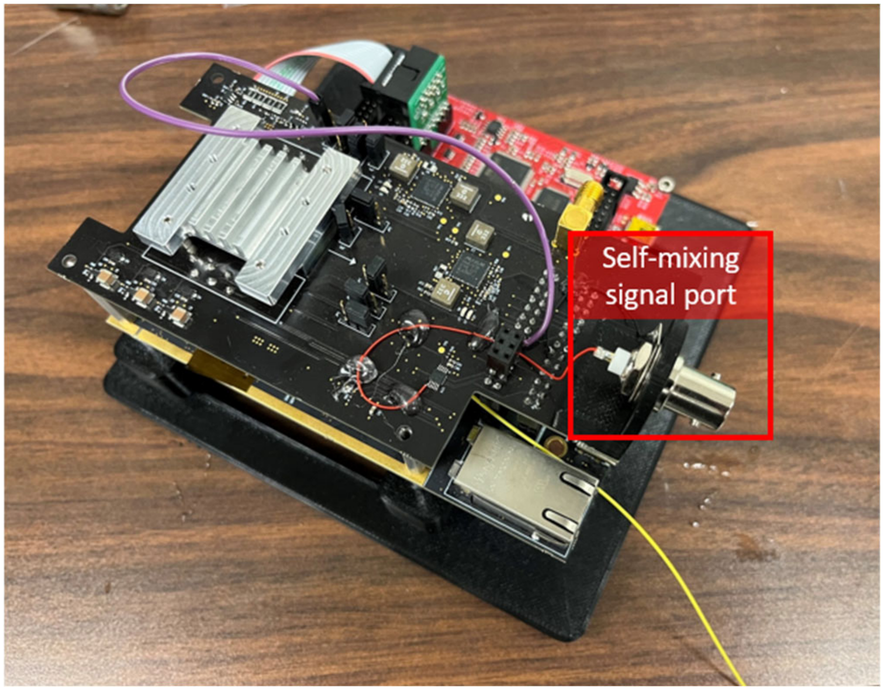
$$E(t) = A_0 r_2 \exp\left\{ j\left[\omega\left(t - \frac{2nd}{c} \right) + \phi_0 \right] \right\} + A_0 (1-r_2)^2 r_3 \exp\left\{ j\left[\omega\left(t - \frac{2nd + L + vt}{c} \right) + \phi_0 \right] \right\}$$

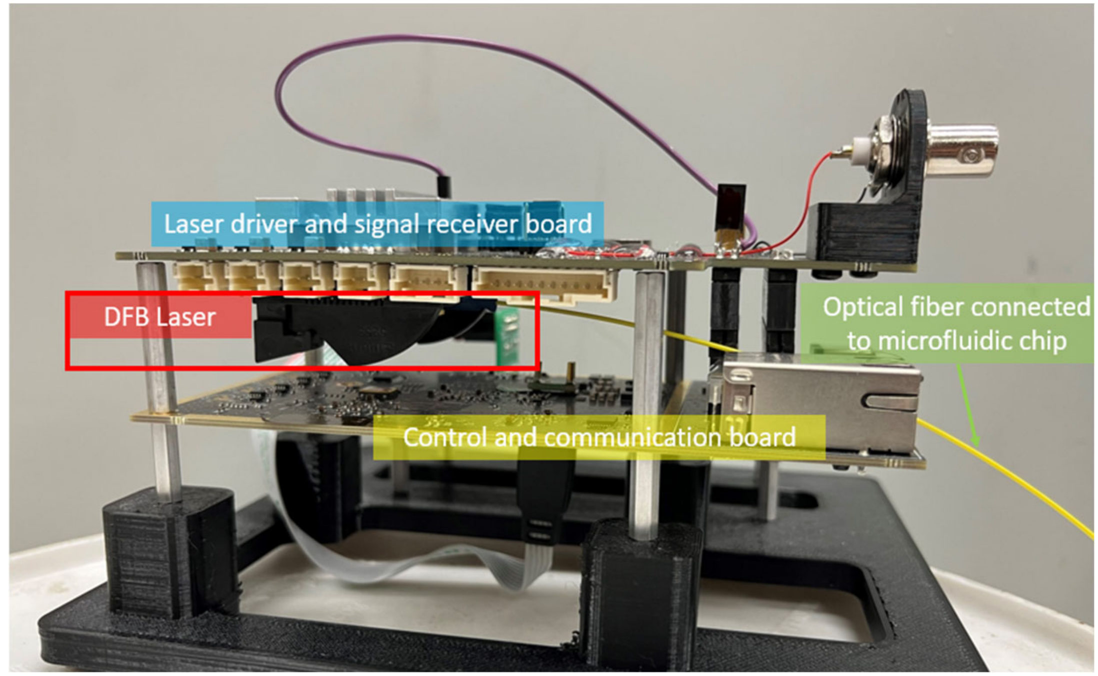
$$I(t) = I_0 + 2A_0^2 (1-r_2)^2 r_2 r_3 \exp\left(-j\frac{2\omega vt}{c} \right)$$



- **Simple to implements.**
- **Very low ADC rate (10 cm/s up to 10 m/s).**
- **Extremely low instrumentation cost**
- **Radiation-harden fiber lead can mitigate radiation-induced damage**

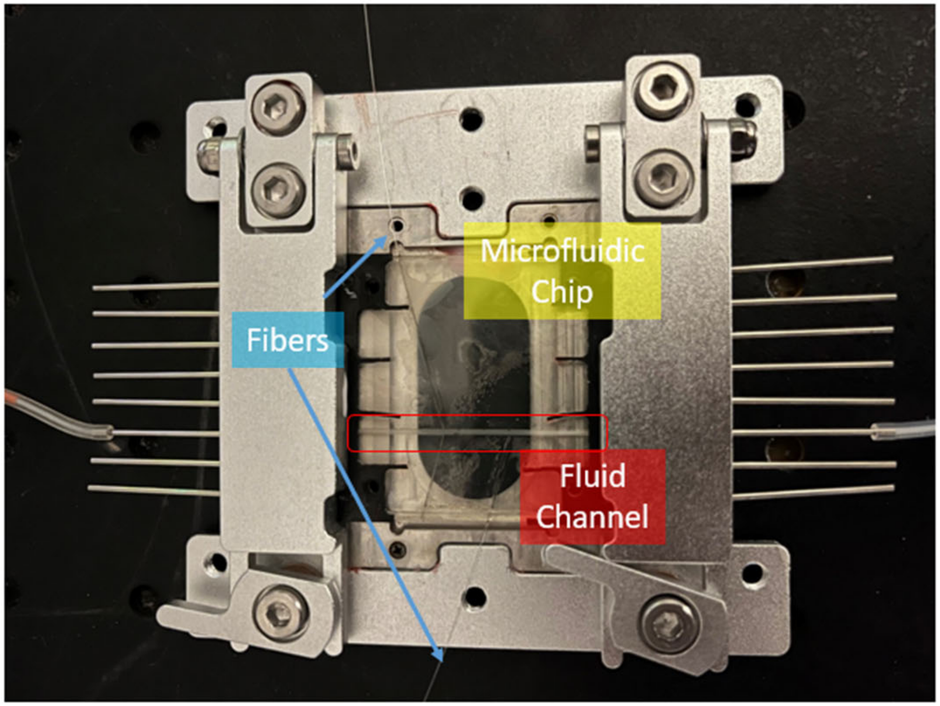
Task 2: Laser Doppler flow velocity sensing with laser self-mixing technology





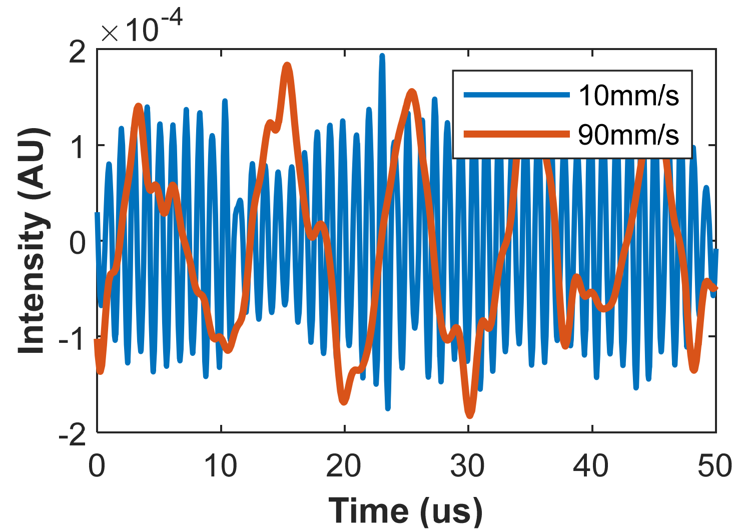
- Simple to implement.
- Very low ADC rate (1 mm/s up to 10 m/s).
- Extremely low instrumentation cost
- Radiation-harden fiber lead can mitigate radiation-induced damage

Task 2: Laser Doppler flow velocity sensing with laser self-mixing technology



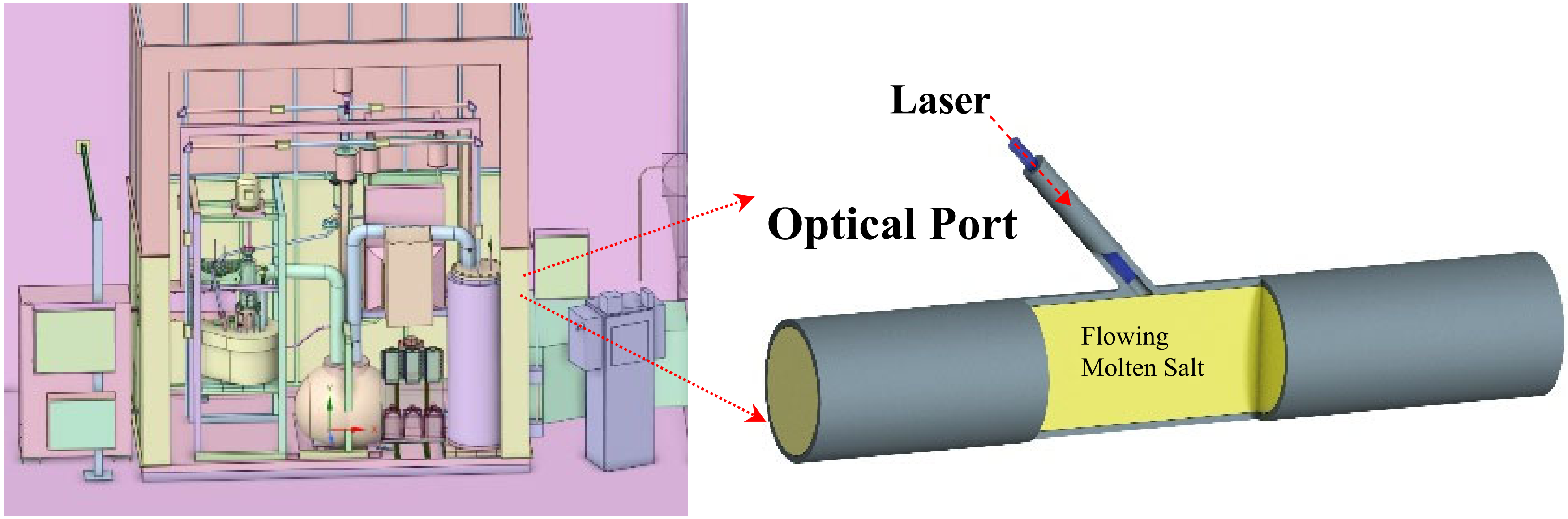
Fluid outlet

Fluid inlet



- Simple to implement.
- Very low ADC rate (1 cm/s up to 1 m/s).
- Extremely low instrumentation cost
- Radiation-harden fiber lead can mitigate radiation-induced damage

Task 2: Laser Doppler flow velocity sensing with laser self-mixing technology



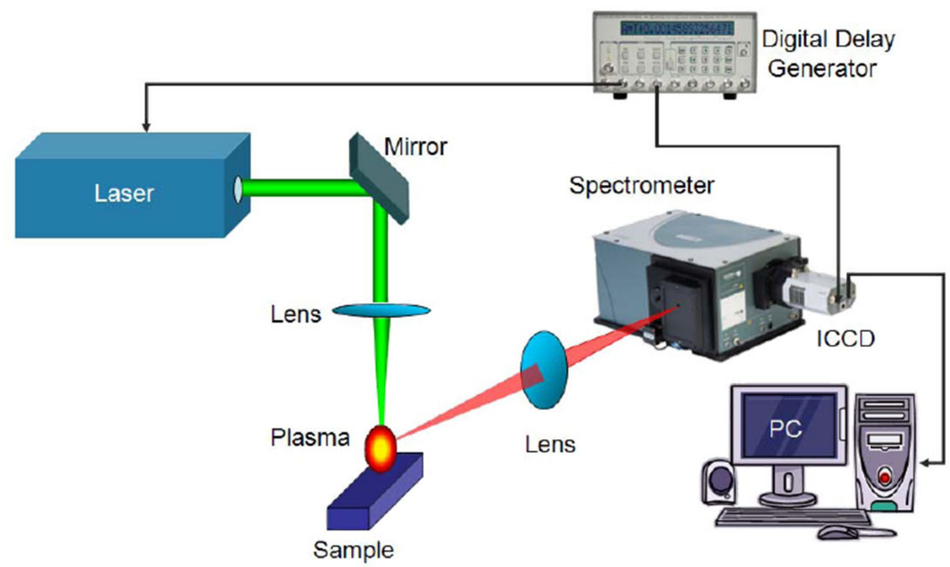
- ORNL flow loop and Kairos ITU testing facility.
- Simple to implements.
- Very low ADC rate (10 cm/s up to 10 m/s).
- Extremely low instrumentation cost
- Radiation-harden fiber lead can mitigate radiation-induced damage

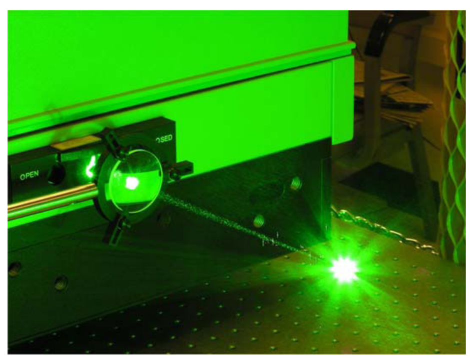
Task 3: LIBS for metal impurity Sensing

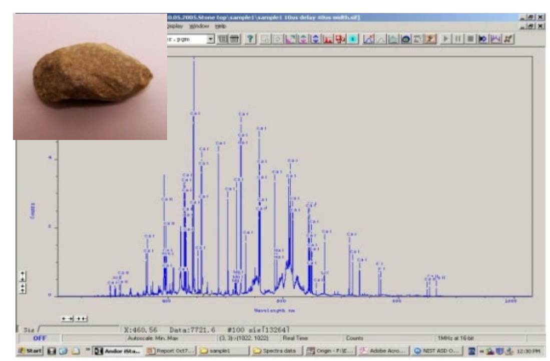
Nuclear Energy University Program
U.S. Department of Energy

LIBS applicable fields

Schematic diagram of a typical LIBS system

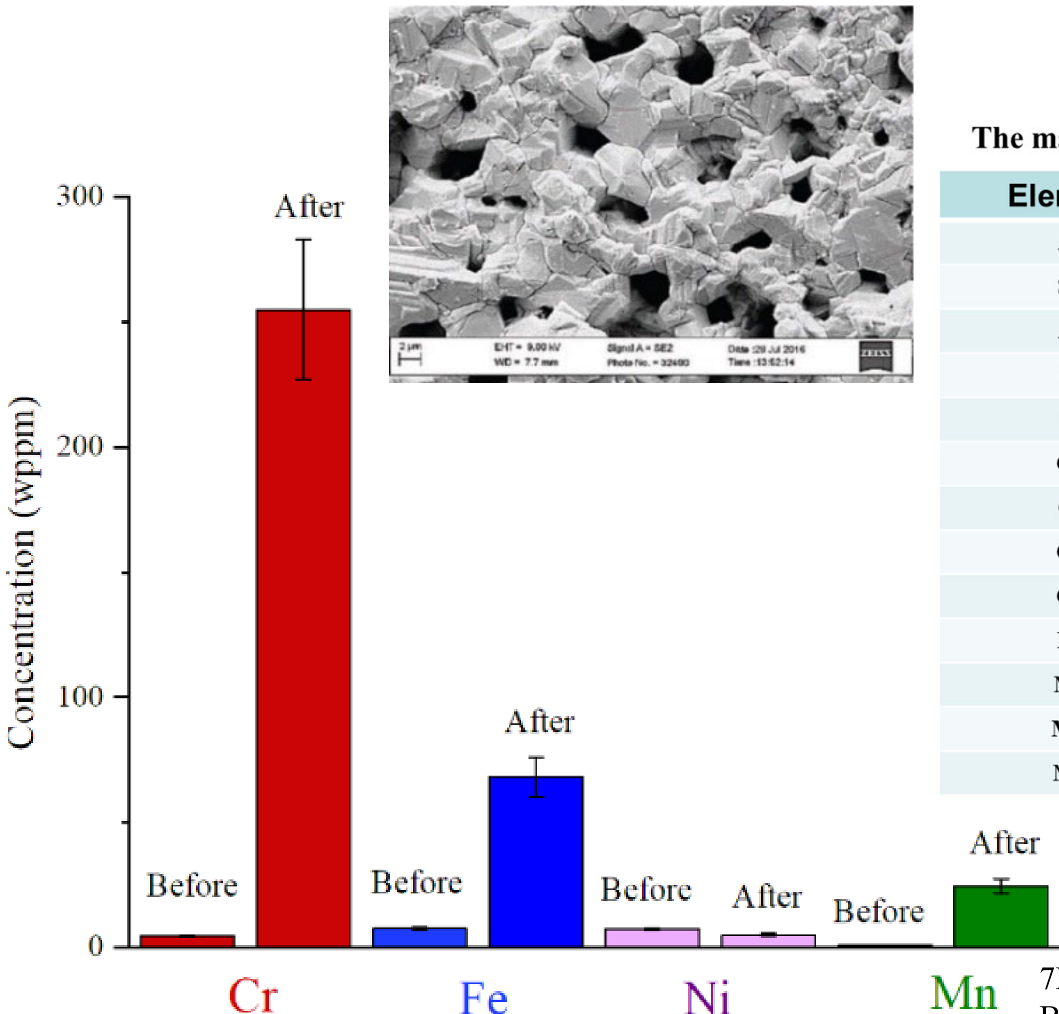






Task 3: LIBS for metal impurity Sensing

- Explore the limit of LIBS through laser-plasma interaction engineering.
- Portable LIBS instrumentation development for on-site testing.



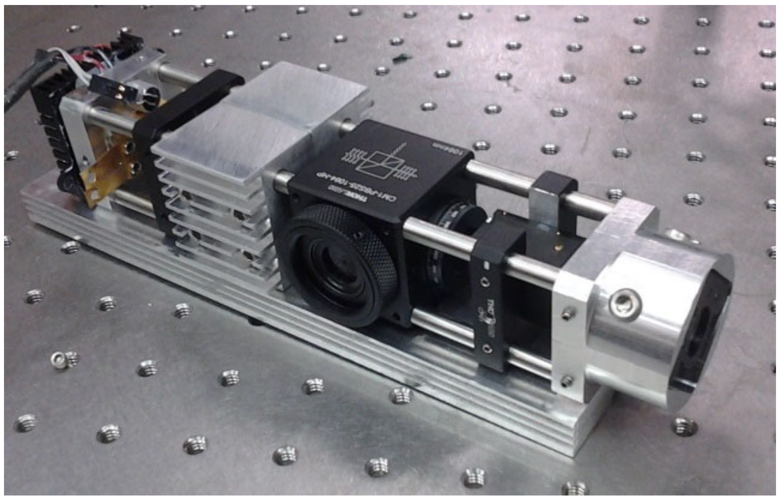
The main composition of the NIST 1262B sample is Fe(95.3 wt.%)

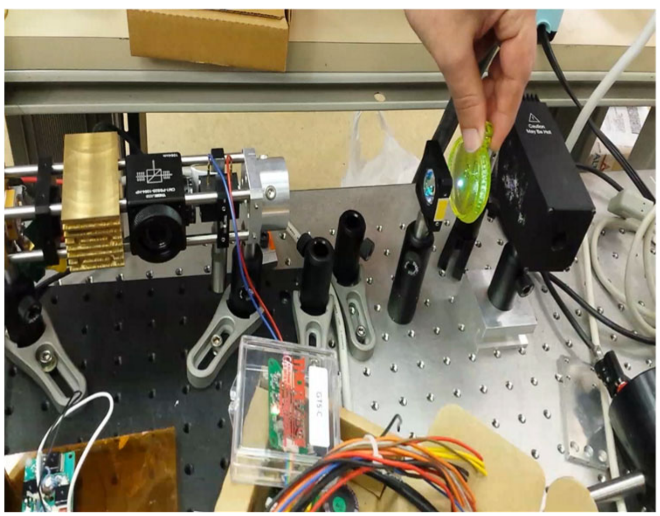
Element	Wt.%	Element	Wt.%
Al	0.0810	Nd	0.0006
Sb	0.0120	Ni	0.5900
Ar	0.0960	Nb	0.3000
B	0.0025	P	0.0440
C	0.1600	Si	0.4000
Ce	0.0019	Ag	0.0011
Cr	0.3000	S	0.0370
Co	0.3000	Ta	0.2000
Cu	0.5100	Sn	0.0160
Pb	0.0004	Ti	0.1000
Mg	0.0006	W	0.2000
Mn	**1.0500**	V	0.0410
Mo	0.0700	Zr	0.2200

7Pint, Bruce, et al. Corrosion of 316H Stainless Steel in Flowing FLiBe (LiF-BeF2). No. ORNL/SPR-2022/2492. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 2022.

Task 3: LIBS for metal impurity Sensing

- Explore the limit of LIBS through laser-plasma interaction engineering.
- Portable LIBS instrumentation development for on-site testing.



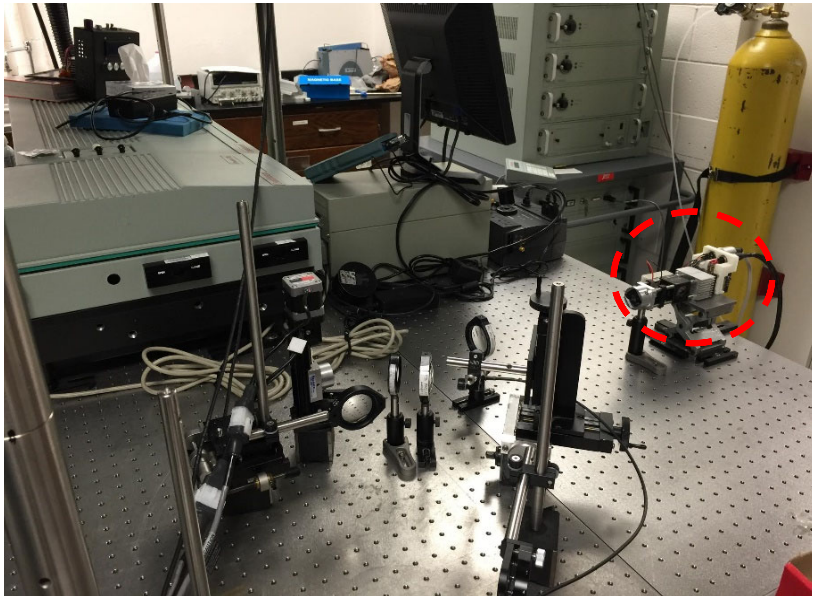


Controller Box

- Complete instrumentation
- Laser controlled via
  - USB port (PC)
  - Bluetooth (Android/Apple cellular phone)
  - Stand-alone (via internal single-chip computer)

Task 3: LIBS for metal impurity Sensing

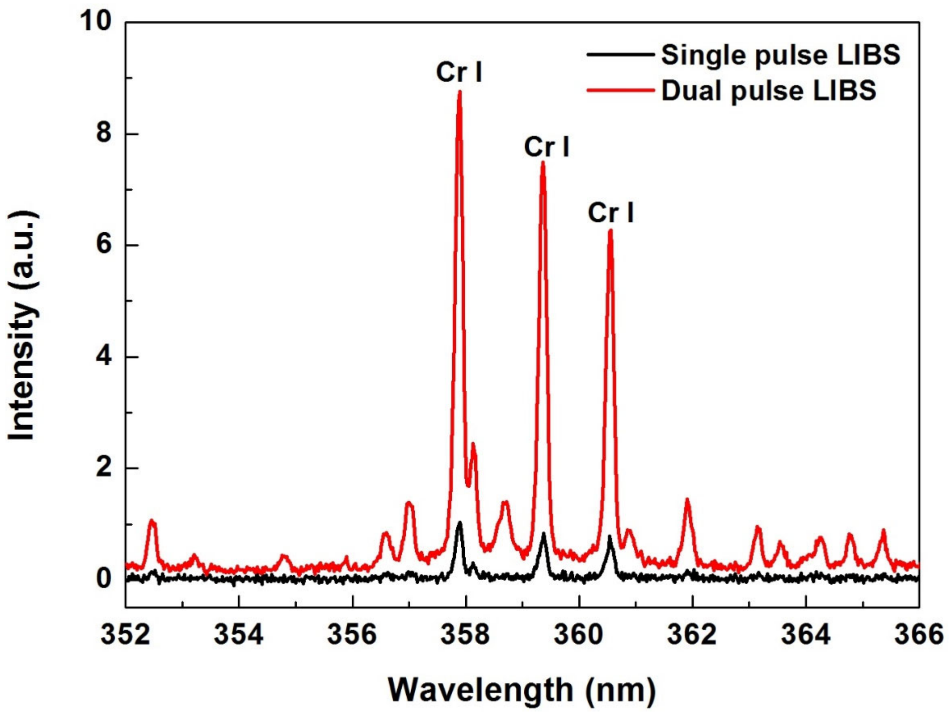
- **Explore the limit of LIBS through laser-plasma interaction engineering.**
- **Portable LIBS instrumentation development for on-site testing.**



Miniaturized laser can be external triggered

<6-ns time jittering

20-mJ output pulse energy

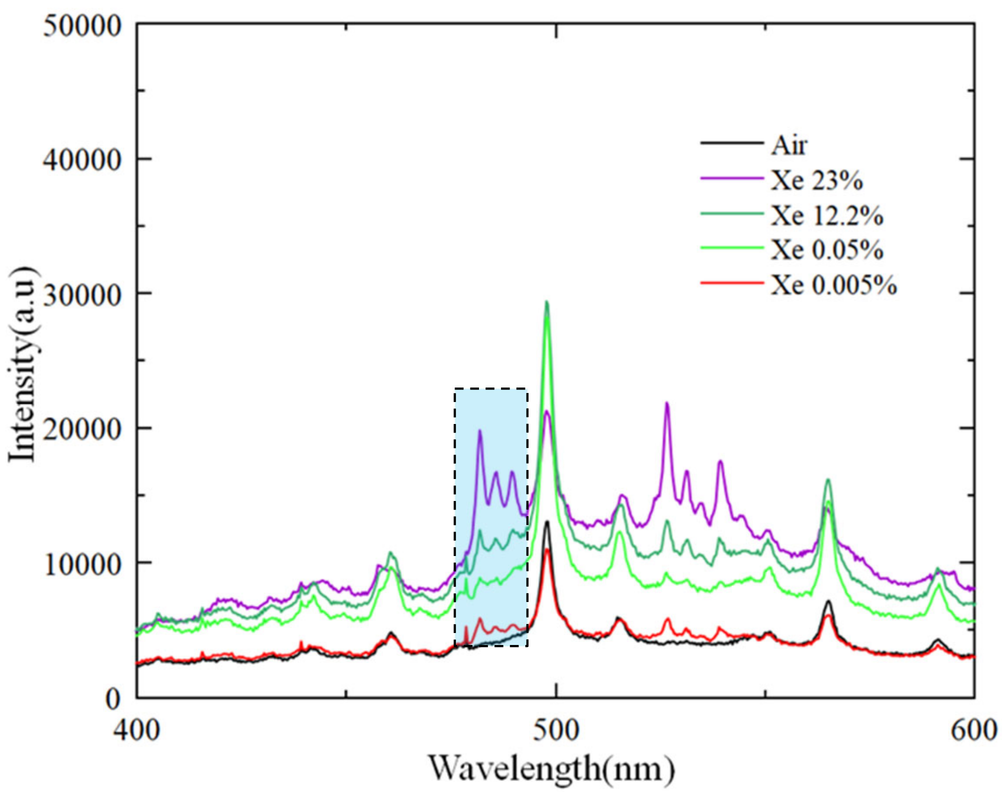


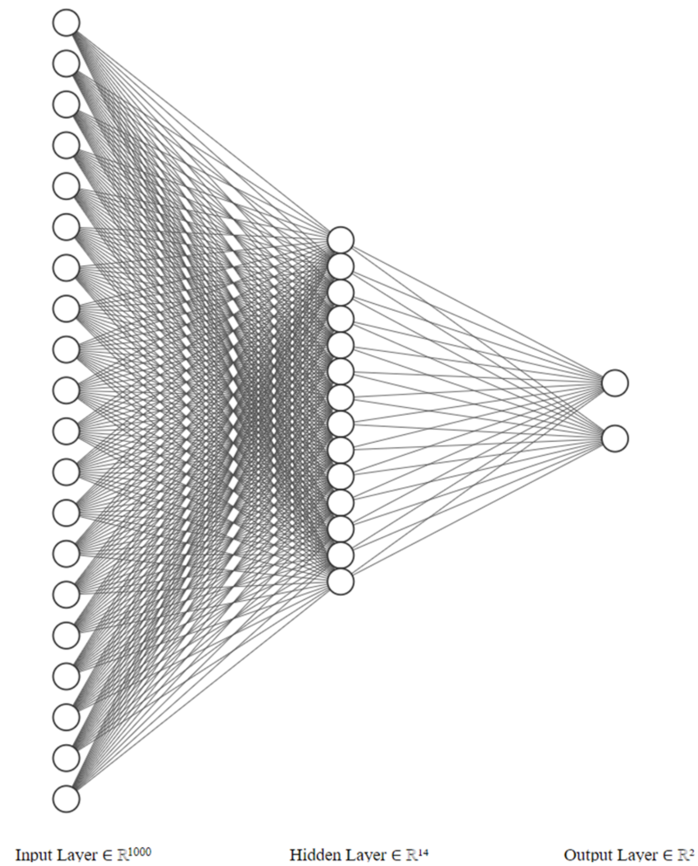
Gate delay: 1 μs

Gate width: 10 μs

Accumulation: 30

Laser Induced Breakdown Spectroscopy (LIBS)

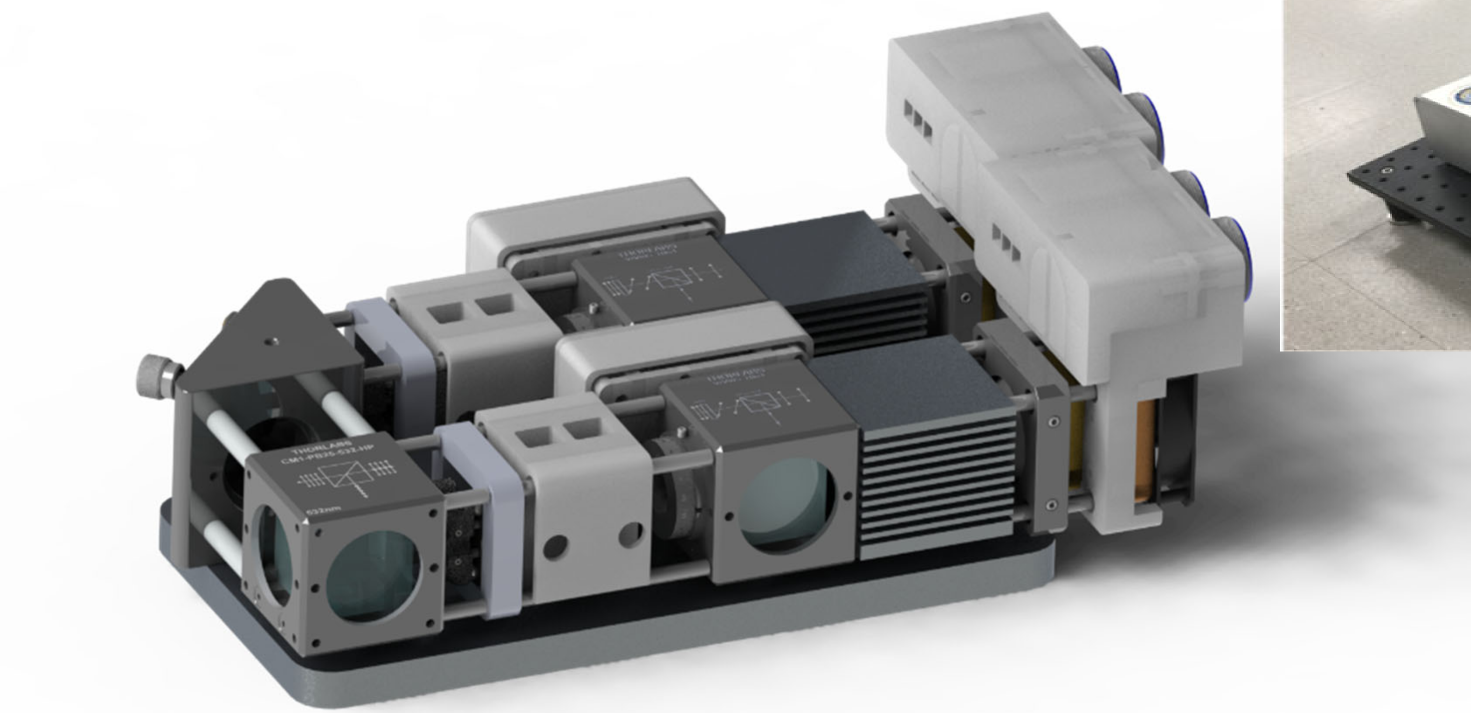


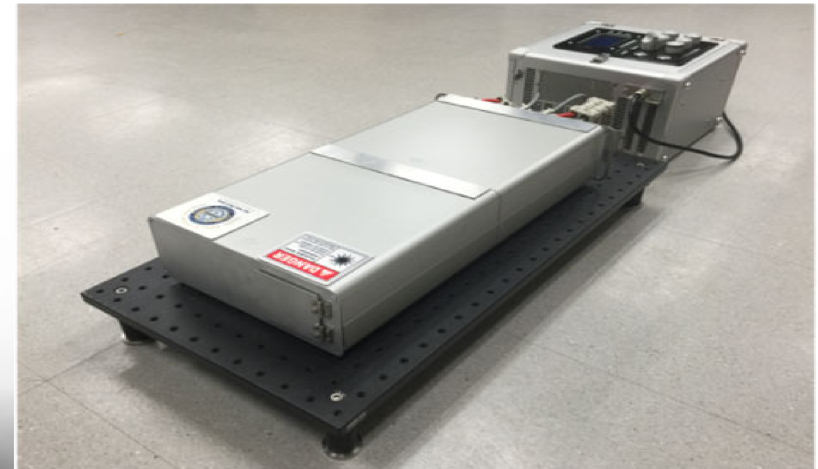


- 50-ppm detection Xe in air using a single-pulse LIBS.
- Expected to reach sub-ppm with dual-pulse scheme.
- Developing a machine-learning algorithm to determine the existence of elements, which can be further refined to quantify the elements.

Task 3: LIBS for metal impurity Sensing

- **Miniaturized Dual Pulse Laser**
- **Improve to 100 mJ – level**
- **Samples provided by ORNL and Kairos**





Publications and Results

Q. Wang, N. Lalam, K. Zhao, S. Zhong, G. Zhang, R. Wright, K. P. Chen, "**Simulation Analysis of Mode Hopping Impacts on OFDR Sensing Performance**," Photonics, vol. 11, no. 6, p. 580, June 2024.

Y. Li, K. Zhao, J. Zhao, Q. Wang, S. Zhong, M. Lalam, R. Wright, P. Zhou, K. P. Chen, **FiberFlex: Real-time FPGA-based Intelligent & Distributed Fiber Sensor System**, ACM Trans. on Reconfigurable Technology and Systems. https://doi.org/10.1145/3690389 (2024)

Y. Li, J. Zhao, G. Ma. Shuda Zhong, M. Buric, M. Li, K. P. Chen, "**Low-cost Multi-point Raman Fiber-optic Temperature Sensors Enabled by CCD Cameras,**" IEEE J. Lightwaves Technol. , doi: 10.1109/JLT.2024.3443749 (2024).

Z. Fan, S. Zhong, K. Zhao, Q. Wang, &. Li, G. Zhang, J. Sharma, and K. Chen, "**A Hermetic Package Technique for Multi-Functional Fiber Sensors through Pressure Boundary of Energy Systems Based on Glass Sealants**," Photonics, vol. 11, No. 9, 2024.

Schedule

	Year 1			Year 2			Year 3		
	4	8	12	16	20	24	28	32	36
Task 1.0: OFDR Lidar sensors for coolant level sensing									
1.1 – Lab sensor R&D, modeling of mode-hopping effects	■	■	■	■	■				
1.2 – hardware and software developments			■	■	■				
1.3 – Working with ORNL and Kairos for LSTL/ITU testing				■	■	■			
Task 2.0: Development of Laser Doppler flow velocity sensing based on diode laser self-mixing technology.									
2.1: Laboratory studies, testing and function validation	■	■	■	■					
2.2: Design sensor hardware and software.			■	■	■	■	■		
2.3: Working with ORNL and Kairos for LSTL/ITU testing			■	■	■	■	■		
Task 3.0: Laser Induced Breakdown Spectroscopy Sensor for molten salt impurity detections									
3.1: Laboratories studies of single- and dual-pulse LIBS to determine detection limit.			■	■	■				
3.3: LIBS sensor testing and validations at LSTL or ITU for field validation and potential capability demonstration using ETU1.0						■	■	■	■
Final Reports									■

Q&A

- Thank you!
- Question?

Kevin P. Chen

pec9@pitt.edu or pchenc@gmail.com

Tel. 724-612-8935