Additive Manufacturing of Circumferentially Embedded Optical Sensor Modules for In Situ Monitoring of Coal-Fueled Steam Turbines

DE-FE0031826

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Outline

- **Project Elements/Overview**
- **Introduction and Technical Background**
- **Project Objective**
- **Technical Approaches**
- **Design Specifications**
- **Optical Design and Simulation**
- **Additive Manufacturing Processes**

Project Elements/Overview

- **Awarded under DOE DE-FOA-0002001 - AOI 1 - Advanced Manufacturing of Embedded Sensors**
- **Interdisciplinary team between a university and an industry partner**
  - Clemson University (Lead)
  - GE-Power (Subcontractor)
- **Three-year project started on January 1, 2020**
- **Total project budget: $1,250,000 ($1,000,000 from DOE and $250,000 from the participants as costshare)**

Background

- **Coal fired, steam turbine-based power plants**
  - Represent one of the largest sources of power in the U.S., about 30% of the U.S. power generation in 2016
  - Steam turbines are one of the most critical components in coalfired power plants

- **Steam turbine blade failures**
  - Turbine blades are vulnerable to failures under constant motions and operating under harsh conditions
  - Has been a major cause of unplanned outages of coal-fired power plants
  - Represent the single greatest threat to the reliable operation of the steam turbine-based power plants

New Challenges

- **The increasing contributions of renewable energy sources present new challenges to the operation and maintenance of steam turbine-based power plants**

- **Historically, they have been base-loaded, but today, they have to handle**
  - frequent load changes (e.g., more aggressive coals and biofuels)
  - increased start-ups/shutdowns
  - longer layups for economic reasons

- **These new challenges are exacerbated by the age of these coal plants.**

Steam Turbine Monitoring

- **Current practice to minimize steam turbine failures**
  - Scheduled maintenance (daily, weekly, monthly and annually)
  - Spent millions of dollars, but still cannot completely prevent the unexpected turbine failures and unplanned outages

- **Condition-based monitoring (CBM)**
  - Becomes a necessity
  - Relies on in situ monitoring
  - Currently available sensors and monitoring technologies are insufficient to perform the desired CBM of steam turbines
  - Has long been identified as the “missing and mostly required to fill capability gap” due to the lack of effective monitoring tools

Steam Turbine Monitoring

- **CBM for steam turbine blades**
  - Measure the operating parameters and perform signal analysis
  - Operating parameters: vibration, pressure, temperature, acoustic, strain, and debris
  - Analytical tools: Fourier's analysis, wavelet analysis, machine learning, and artificial intelligence

Table 1: Summary of blade condition monitoring methods.

Blade monitoring methods	Monitoring parameters	Characteristics and applications
Vibration	Blade pass frequency (BPF)	(i) Easy to implement (ii) Suitable for blade rubbing detection (iii) Not sensitive to detect minor faults such as blade geometry alterations
Pressure	Pressure distortion around blades	(i) Suitable for blade deformation and fouling detection (ii) Difficult to deploy under operating conditions
Acoustic	Acoustic signal	(i) Suitable for blade rubbing detection (ii) Sensitive to noise
Debris	Particle in oil and charges	Suitable for blade rubbing and FOD detection
Strain gauge	Displacement	Suitable for blade deformation and blade fatigue detection
Temperature	Temperature	(i) Suitable for blade creep monitoring (ii) Can provide early warning (iii) Embedded temperature sensors are required
Performance	Performance (efficiency, output, fuel consumption, etc.)	(i) Suitable for blade fouling and rotating stall detection (ii) Large number of sensors required (iii) Large number of data and calculation required

Abdelrhman, Ahmed M., et al. "Condition monitoring of blade in turbomachinery: a review." Advances in Mechanical Engineering, Vol. 6, pp. 210717, 2014.

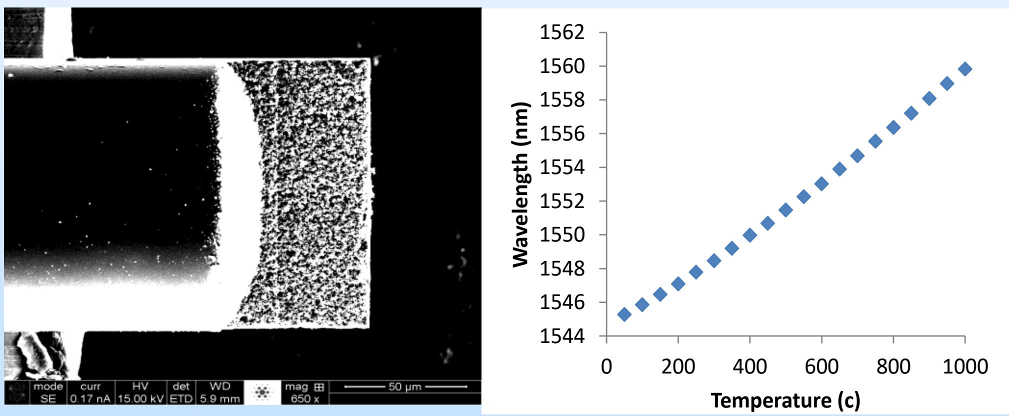
Challenges and Objectives

- **There are very few steam turbines implemented with in situ sensors and CBM, due to**
  - the lack of robust harsh environment sensors
  - the lack of effective methods to package and install the sensors into the steam turbines without degrading their performance

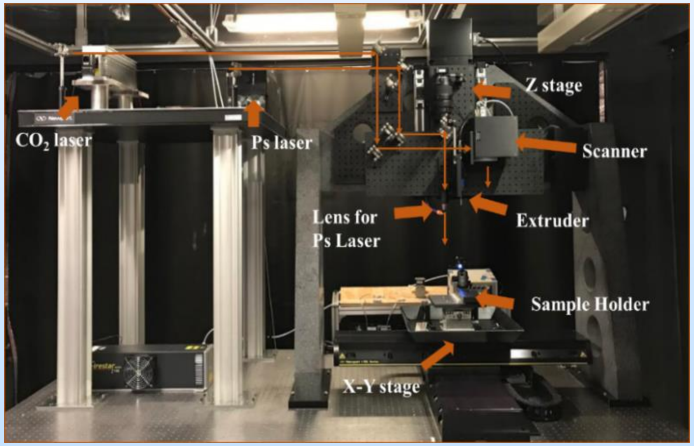
- **Objective**
  - The main objective is to develop, additively manufacture and test the optical sensor modules for in situ monitoring the temperature, pressure and blade tip timing/clearance in turbines

Proposed Solutions

- **Sensor-embedded modules**
  - Sensors capable of operating under extreme conditions
  - Additive manufacturing (AM) to embed sensors



Robust harsh environment sensors



Advanced manufacturing technologies for sensor embedded modules fabrication

Project Tasks

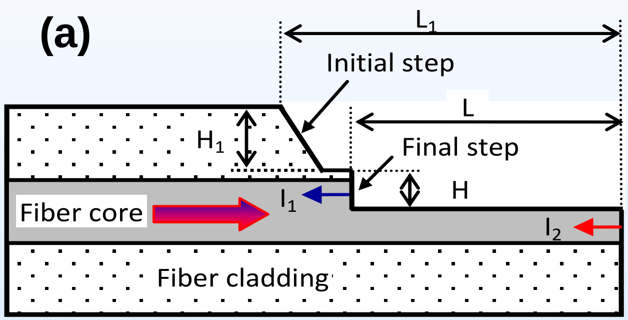
Three types of sensor modules are proposed for in situ monitoring the structural status of stream turbine

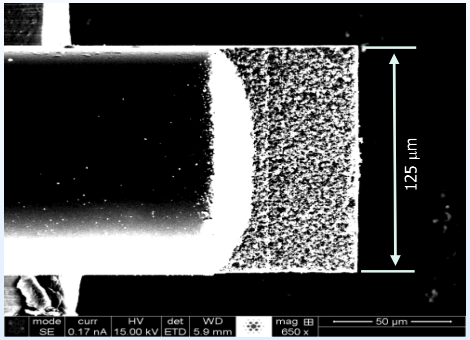
- **Design and simulate** optical temperature, pressure, and blade tip timing/clearance sensor modules
- **Design and develop fabrication processes** to additively manufacture the designed optical sensor modules
- **Test and validate** the optical sensor modules in laboratory simulated environments
- **Test and evaluate** performance of the optical sensor modules in industrial scale test facility

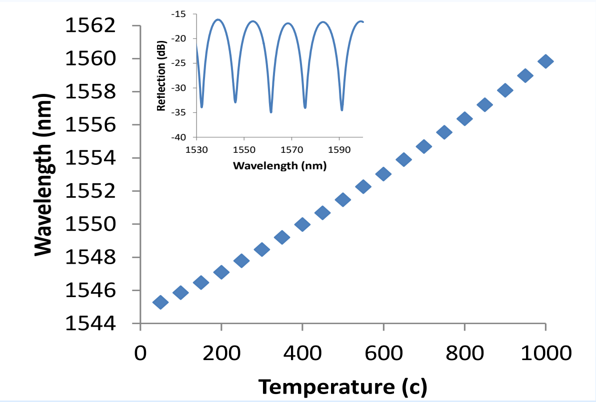
Optical Fiber Temperature and Pressure Sensors

- **Fs laser micromachined optical fiber temperature and pressure sensors**

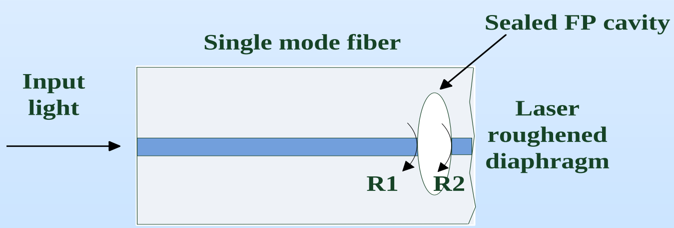
(a)

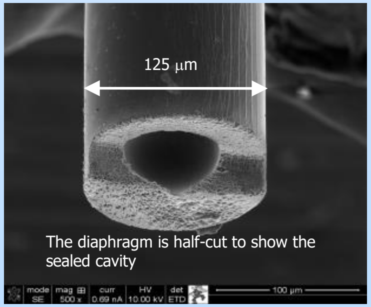


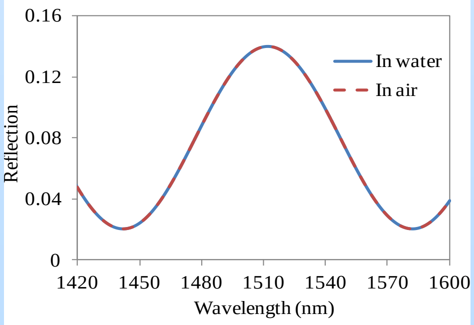


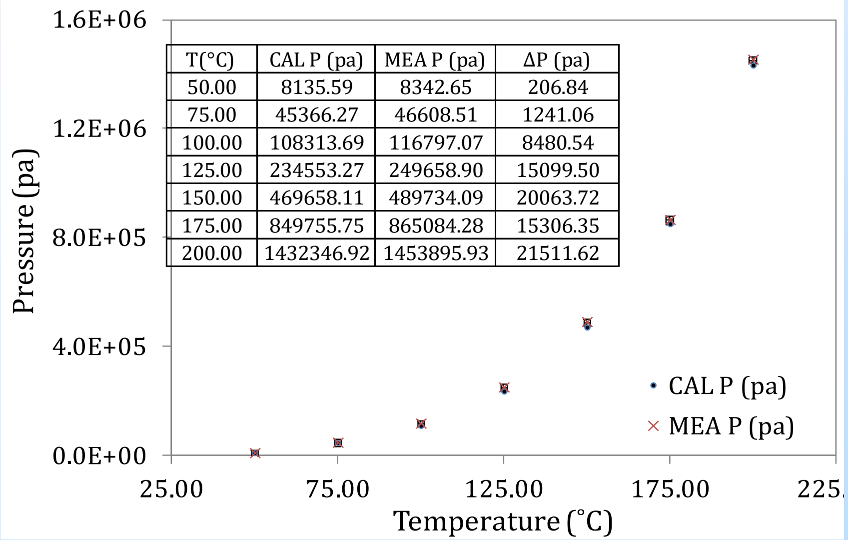


(b)





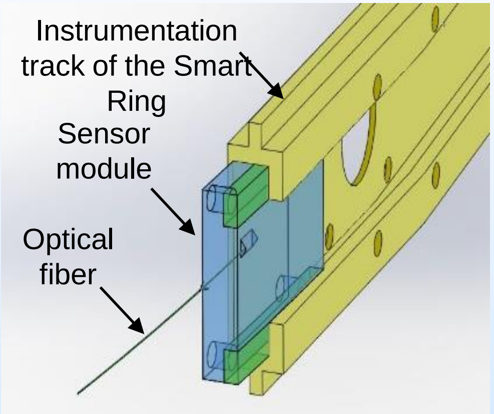


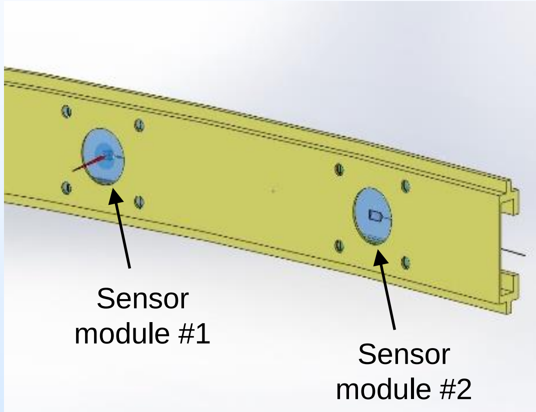


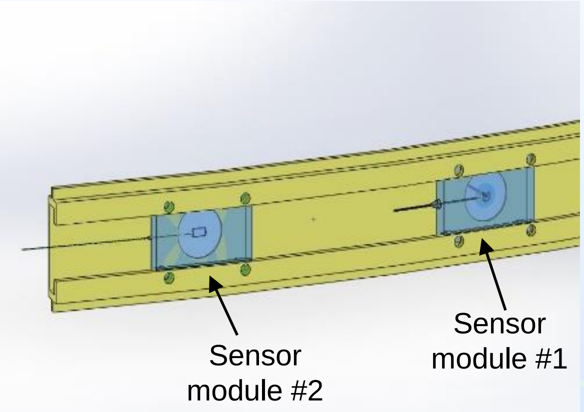
T(°C)	CAL P (pa)	MEA P (pa)	ΔP (pa)
50.00	8135.59	8342.65	206.84
75.00	45366.27	46608.51	1241.06
100.00	108313.69	116797.07	8480.54
125.00	234553.27	249658.90	15099.50
150.00	469658.11	489734.09	20063.72
175.00	849755.75	865084.28	15306.35
200.00	1432346.92	1453895.93	21511.62

Optical Temperature, Pressure, and Blade Tip Timing/clearance Sensor Modules

- **Preliminary designs of the sensor modules**



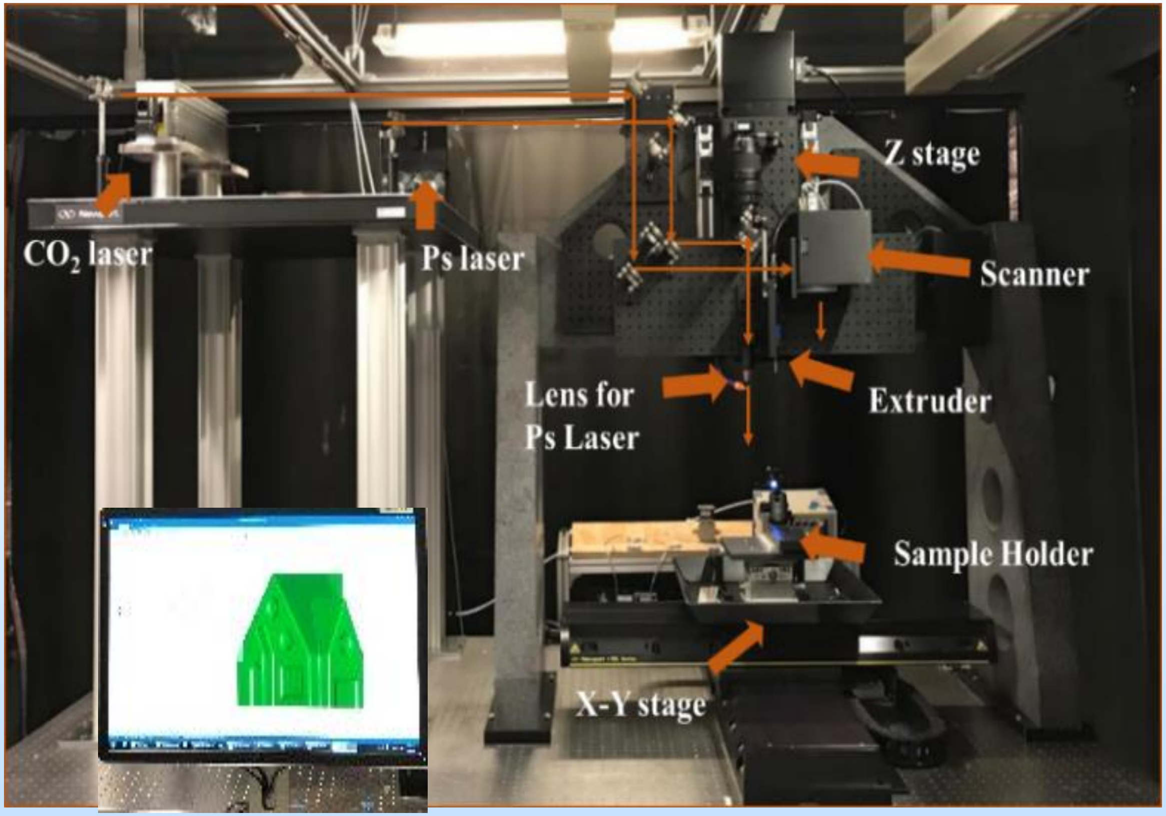




- **Sensor modules integrated with the GE's Smart Ring**
- **Integrated additive and subtractive manufacturing (IASM) process to fabricate the modules and embed the sensors during fabrication**

Additive Manufacturing of The Sensor Modules

- **The IASM system at Clemson**



- 3D printing of ceramic and glass materials
- Laser sintering
- Laser micromachining
- Fully automatic control
- Rapid prototyping

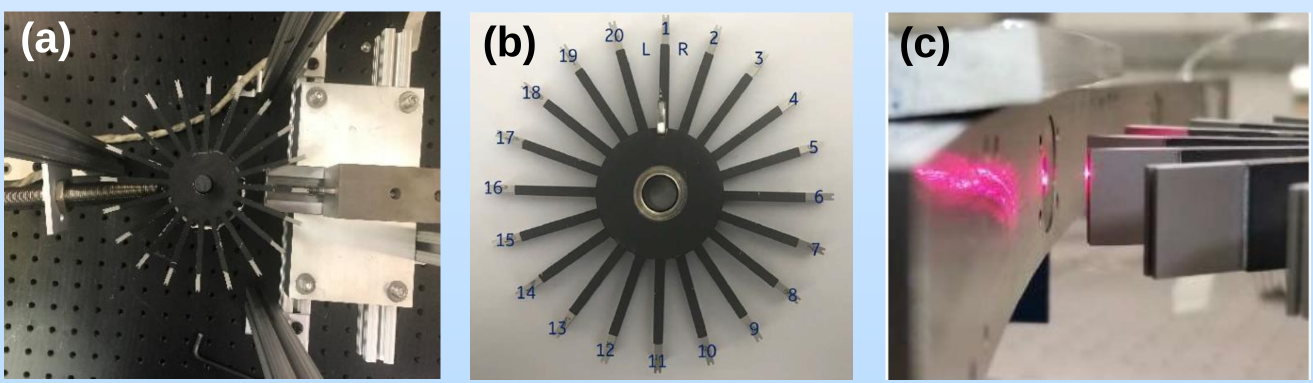
Picture and function blocks of the integrated additive and subtractive manufacturing (IASM) system available at Clemson for fabrication of the proposed sensor modules. This platform integrates a number of advanced manufacturing tools into a single system, including freeze form extrusion, inkjet printing, laser sintering, laser micromachining and an interactive interface to import from CAD models.

Laboratory-based Tests

- **Test and validate the temperature and pressure sensor modules**
  - Temperature up to 1,100ºC, pressure up to 2,000 psi
  - Elevated temperature up to 180°C, elevated humidity up to 90%

- Survivability/repeatability
- Sensitivity
- Response time
- Temperature cycling effect
- Temperature cross sensitivity
- Long-term (~400 hours) drift

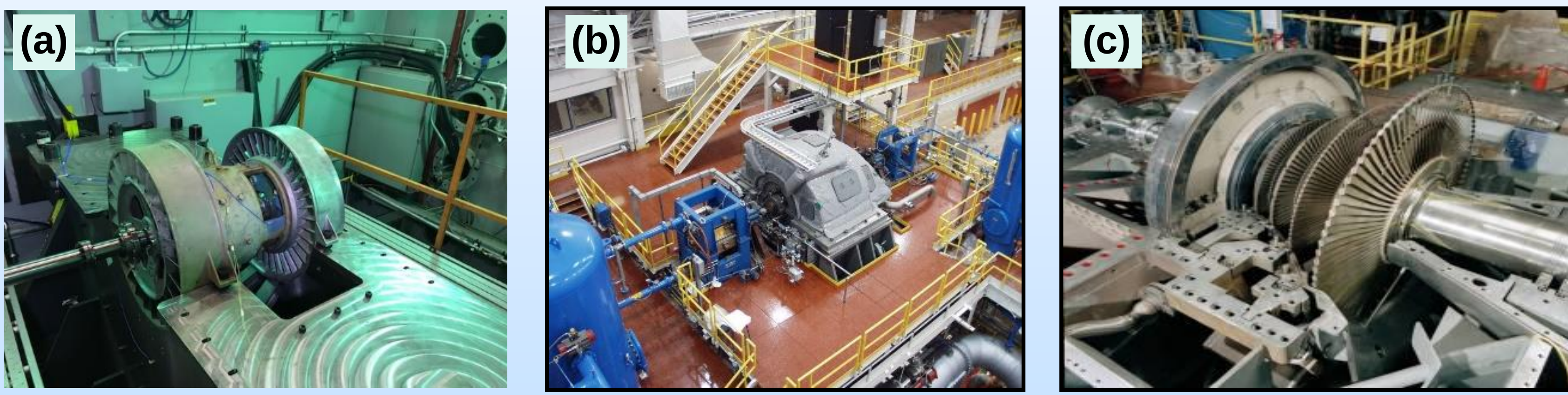
- **Test and validate the blade tip timing/clearance modules**



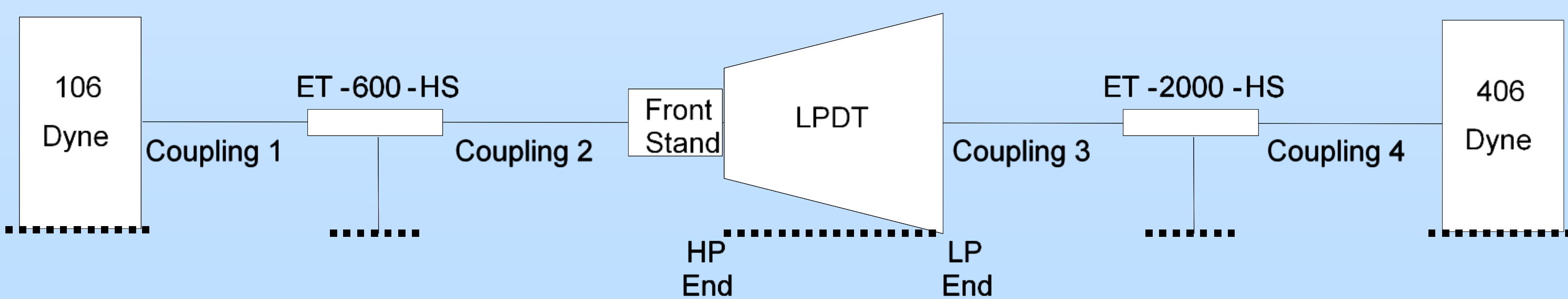
- Tip timing resolution
- Tip clearance measurement range and resolution
- Capability of the module for blade vibration analysis
- Temperature and humidity effects on the measurements
- Tolerance to misalignment

Industrial-scale Tests

- **Test and evaluate in industrial scale test facility**
  - Small-scale industry turbine testing rig at GE's Greenville Turbine Testing Laboratory (GTTL) in Greenville, SC
  - GE's Low-Pressure Development Turbine (LPDT) testing rig in Schenectady Technology Laboratory (STL) in Schenectady, NY



(d)



Design Specifications of The Sensor Modules

Measurement requirements of the sensor modules in turbines

Parameter	Value	Units
Max temperature	1200 or 650	^{o}F or ^{o}C
Max pressure	300	psi
Blade rotor speed	3,600	RPM
Number of sensor modules	6 – 8	----
Distance from the sensor output to the blade tip	1.5	mm

Material properties of fused silica glass

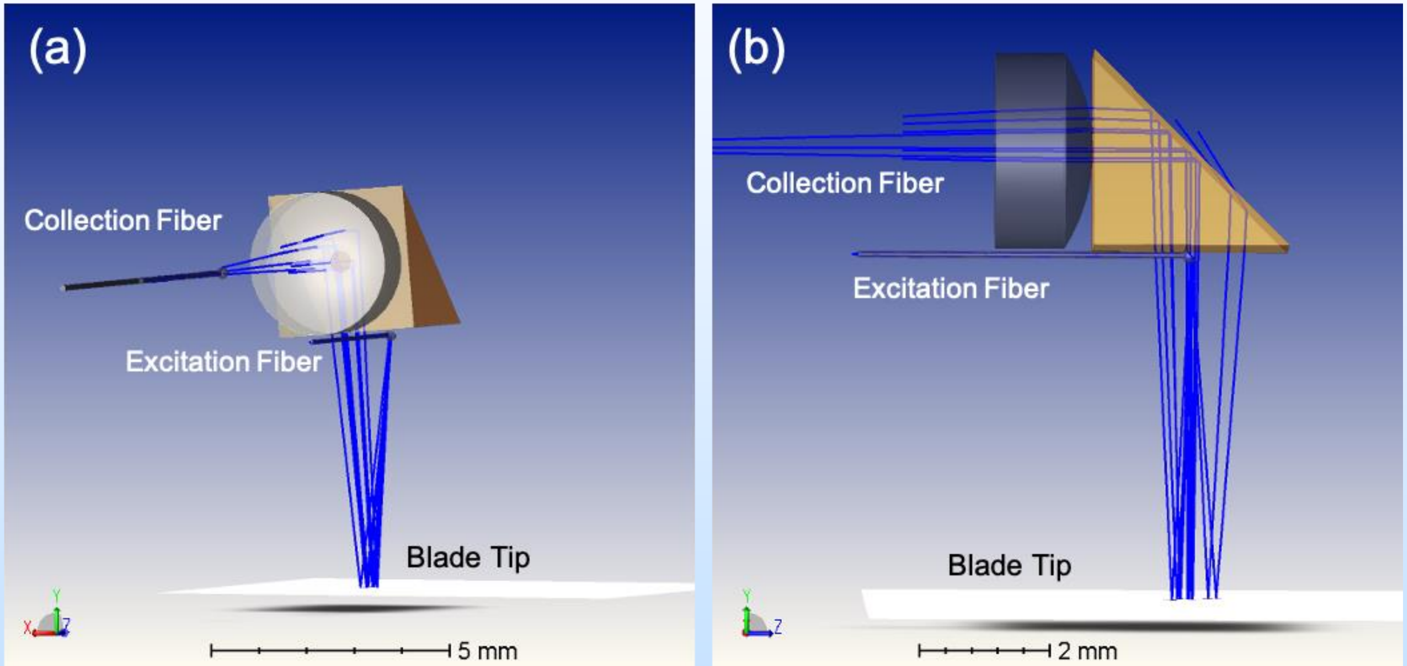
Material properties	Value	Units
Max use temperature	2012 or 1100	^{o}F or ^{o}C
Compressive strength	1.6×10^{5}	psi
Coefficient of thermal expansion (CTE)	0.55×10^{-6}	$^{o}C^{-1}$
Optical transparency	> 90% (200 - 2000 nm)	----

Test parameters for sensor modules performance evaluation

Sensor types	Temperature	Pressure	Blade tip timing/clearance
Test results	• Survivability/repeatability • Measurement sensitivity • Response time • Temperature cycling effects • Long-term drift	• Survivability/repeatability • Measurement sensitivity • Response time • Temperature cycling effects • Temperature cross sensitivity • Long-term drift	• Tip timing resolution • Vibration analysis • Temperature and humidity effects on the measurements • Tolerance to misalignment

Tip-timing Modules - Angled Ball Lensed Fiber

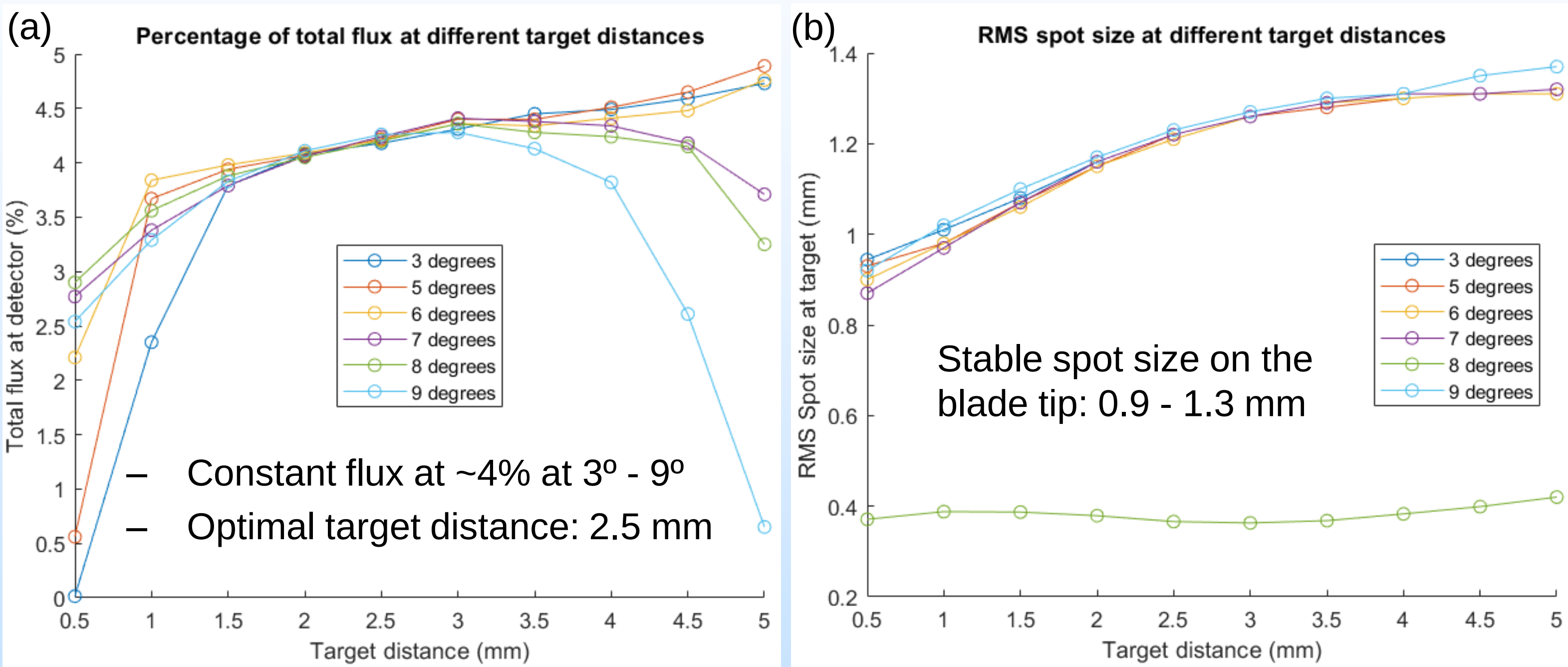
Design schematic



(a) Schematic of the optical design using ball lensed fibers with a 5º tilted angle; (b) Side view of (a).

Tip-timing Modules - Angled Ball Lensed Fiber

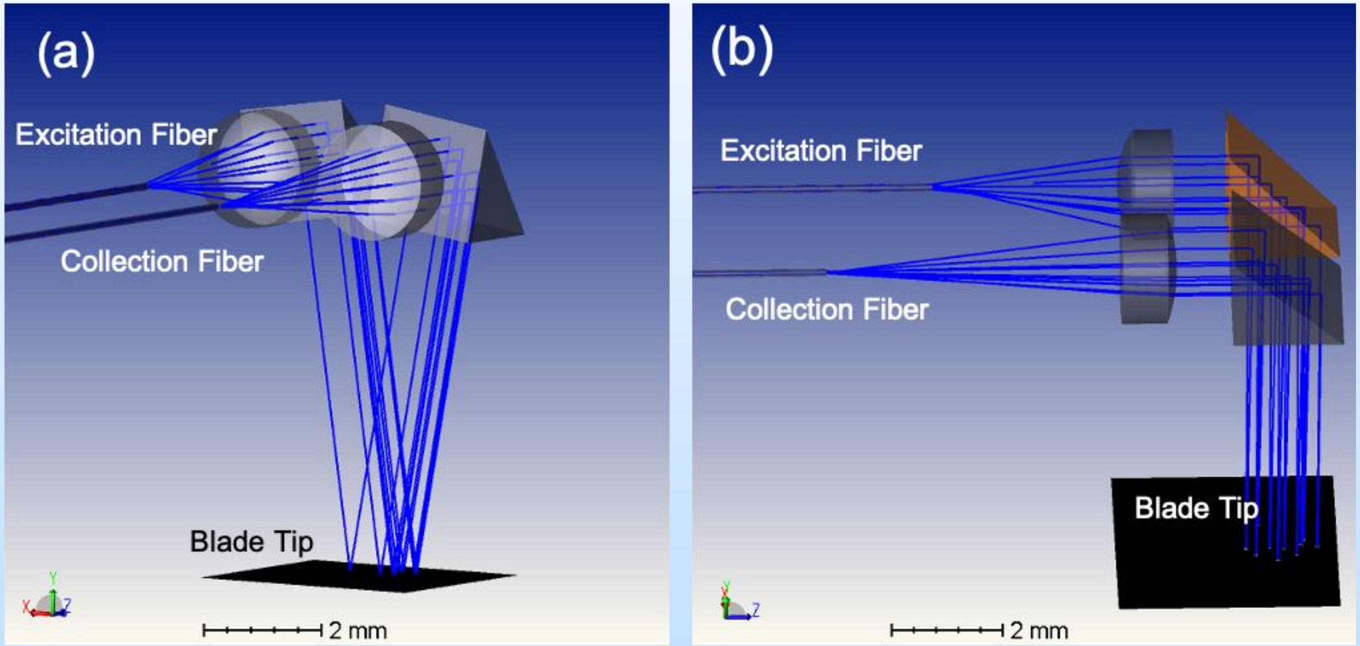
- **Optimize the angle, distance and lens**



(a) Percentage of receiving optical flux and (b) Excitation spot size on blade tips at different tilted angles of ball lensed fibers and target distance.

Tip-timing Modules – Lens Prism Assembly

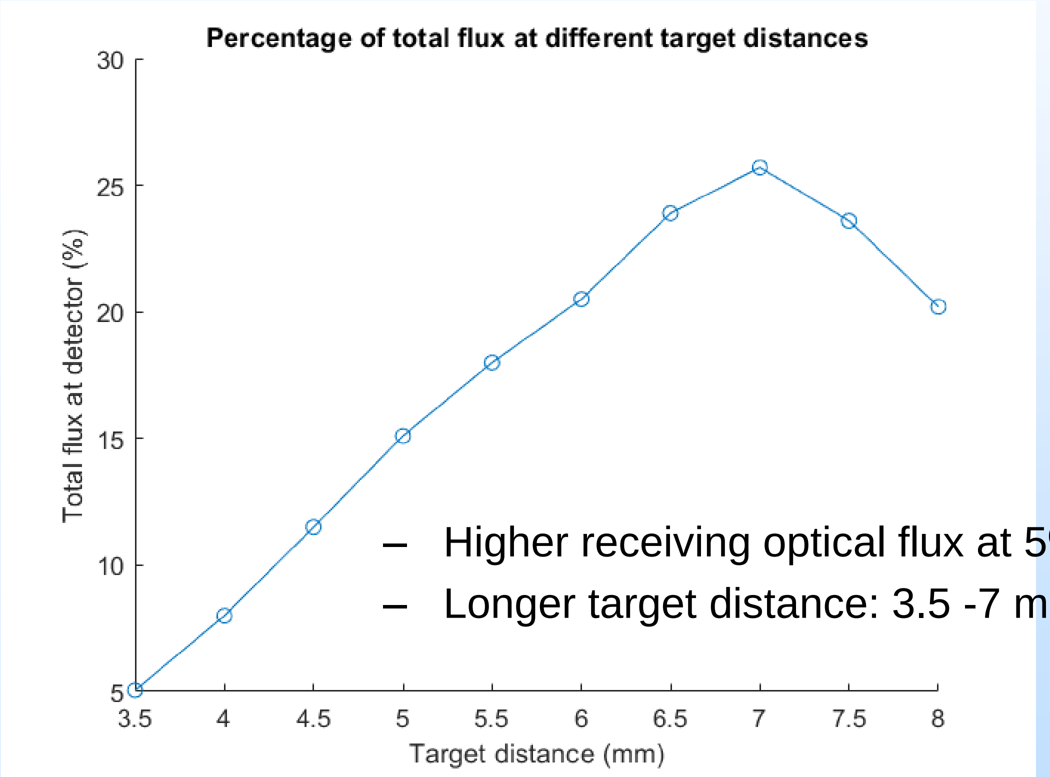
Design schematic



(a) Schematic of the optical design using two lens-prism assemblies with a 9º tilted angle;
(b) Side view of (a).

Tip-timing Modules – Lens Prism Assembly

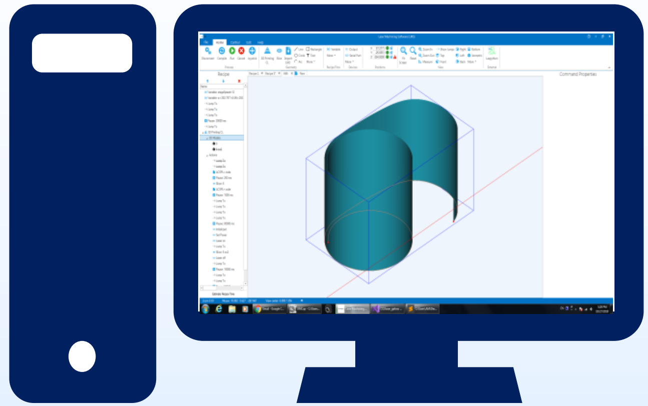
Receiving optical flux at different target distance

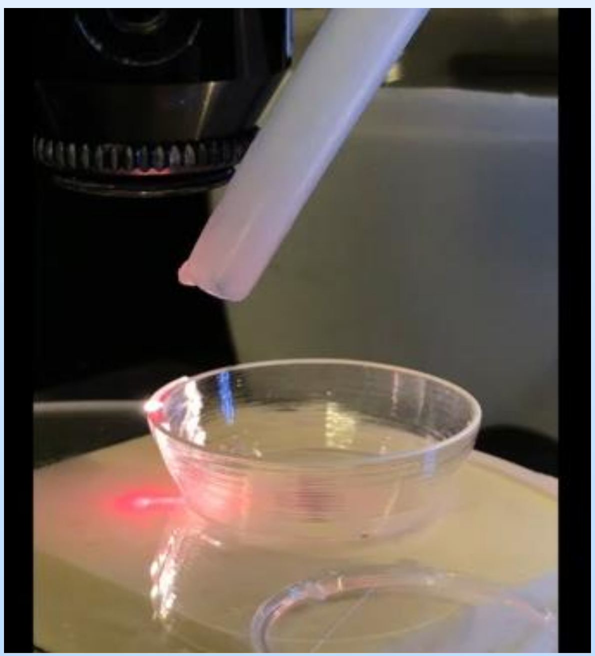


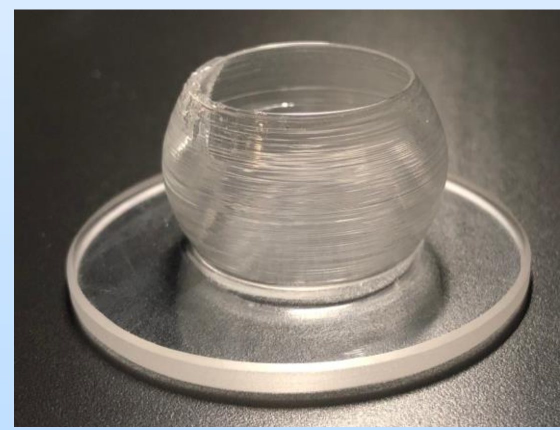
- Higher receiving optical flux at 5% - 25%
- Longer target distance: 3.5 -7 mm

Percentage of receiving optical flux of the two lens-prism assemblies at different target distance.

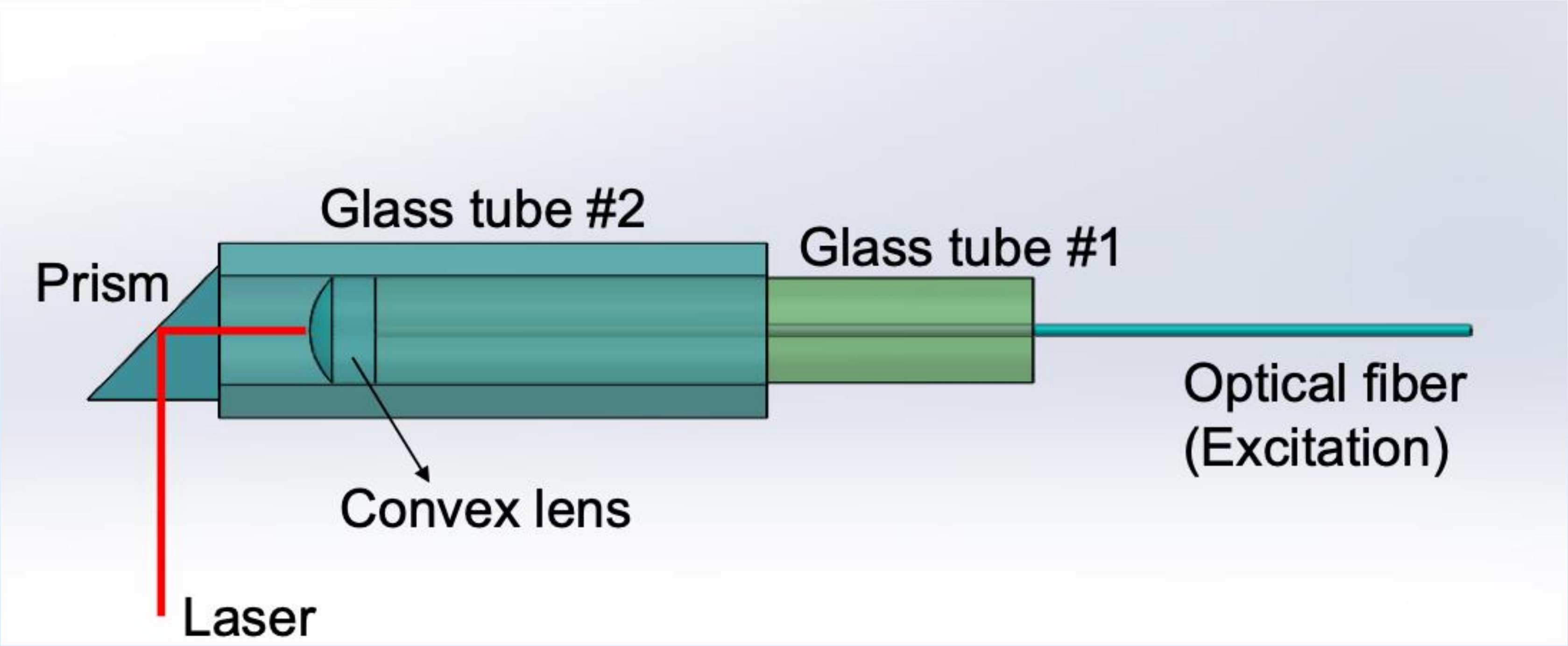
3D printing glass







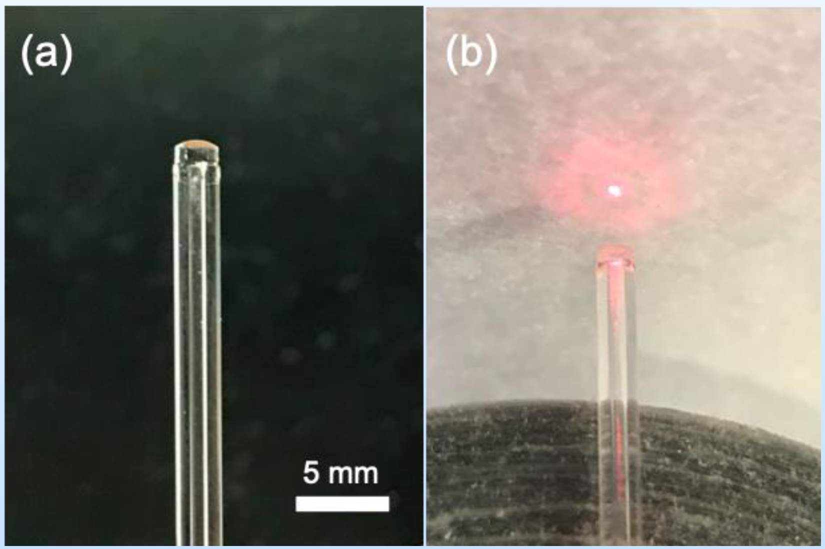
Prototypes



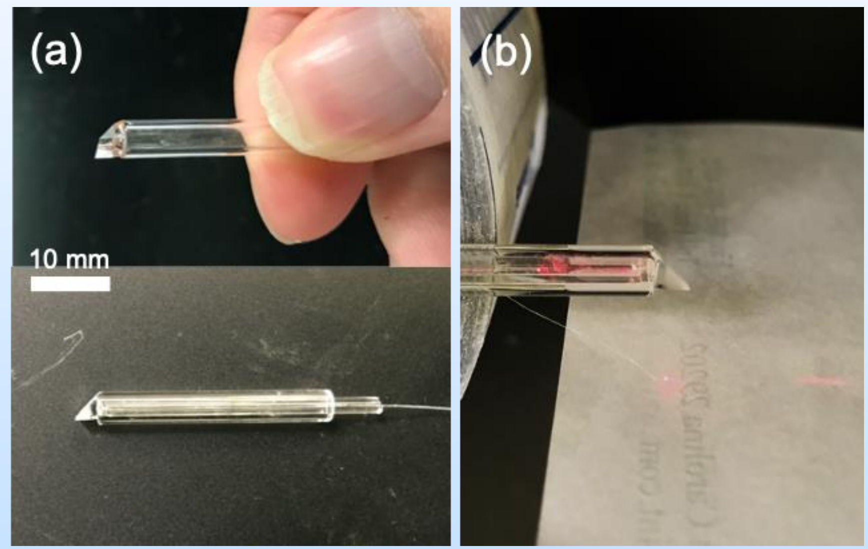
Glass tube #2
Glass tube #1
Prism
Optical fiber
(Excitation)
Convex lens
Laser

Making the Prototypes

AM and laser welding process to assemble the fiber, lens and prism



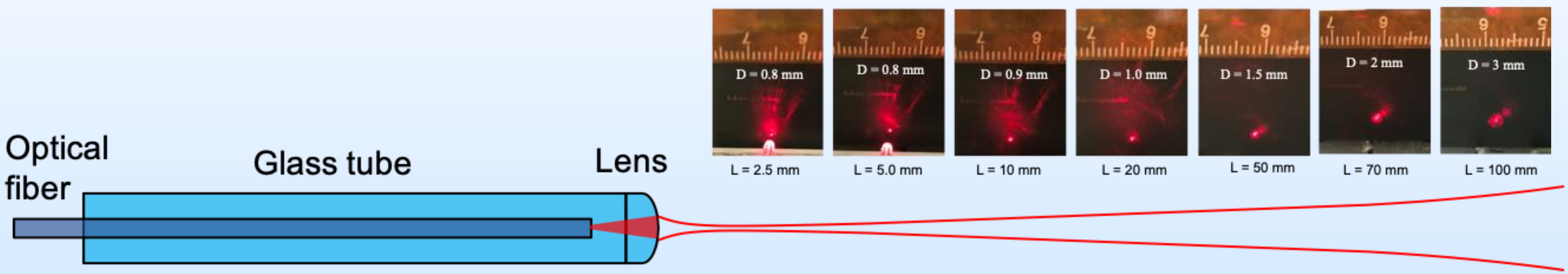
(a) A plano-convex lens fused on one end of a glass tube with an optical fiber inserted into the tube; (b) A red laser light pumped into the optical fiber and focused by the lens.



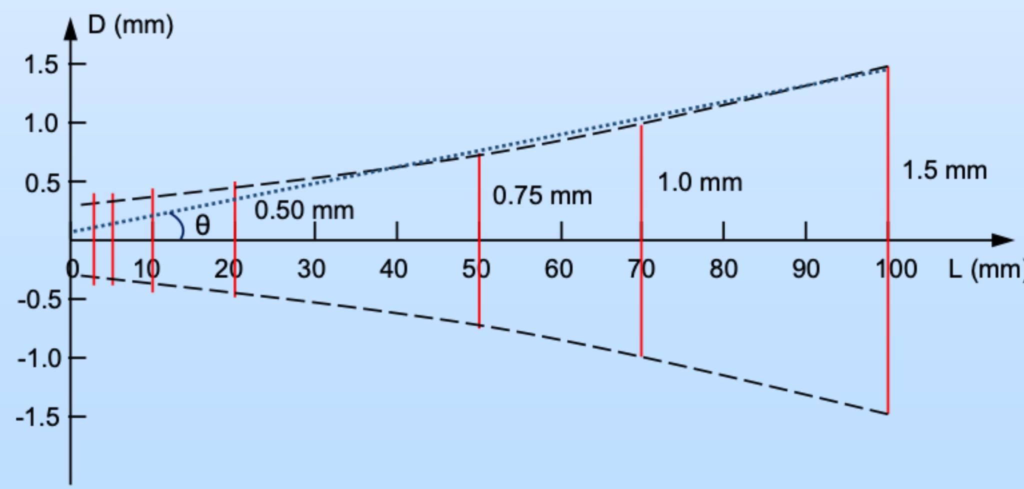
(a) A prism fused on one end of the glass tube with the lens-tube assembly inserted (b) A red laser light pumped into the optical fiber, focused by the lens, and bended by the prism.

Test the Prototype

Beam divergence measurement of the optical assembly

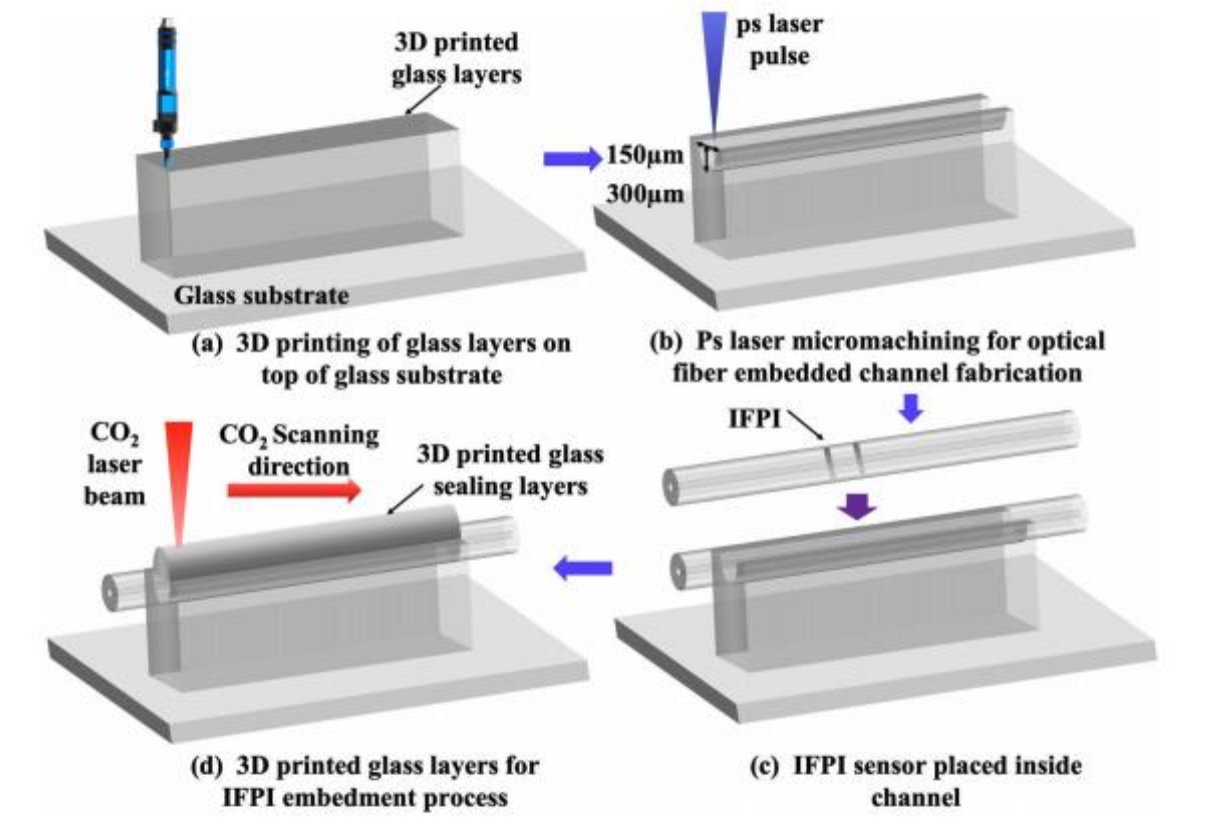


- Focal length: 2 - 6 mm
- Calculated 2θ ≈ 1.72º = 0.03 rad



AM Sensor-Embedded Glass Module

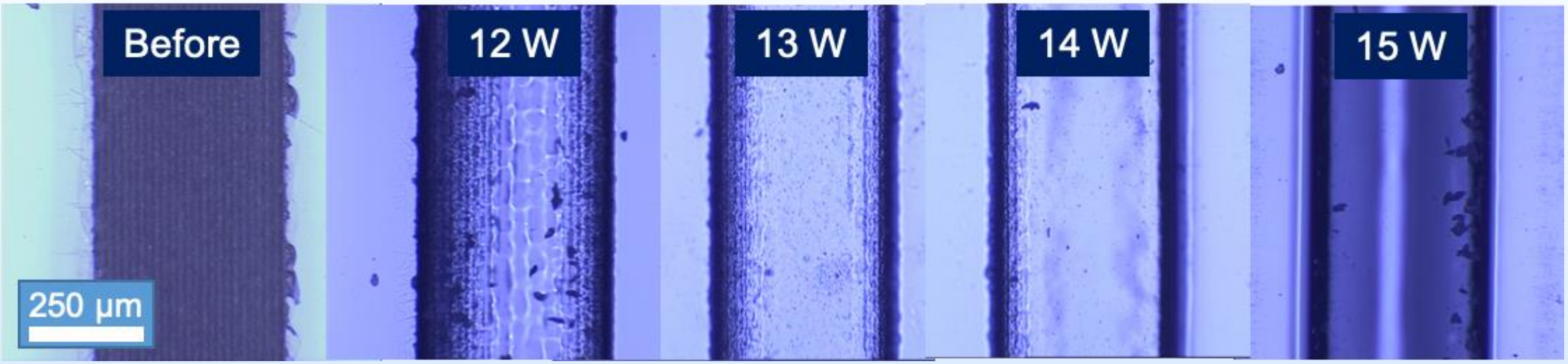
AM of fused silica glass temperature sensor module



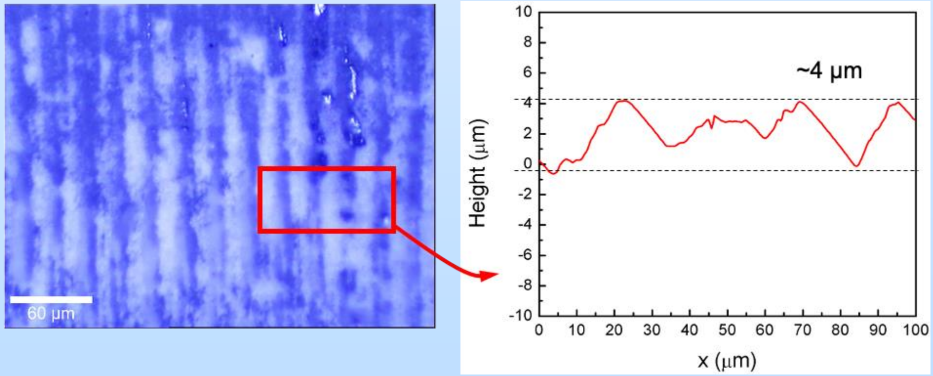
Schematic of the designed fabrication process of the temperature sensor modules

Fabrication Processes Development

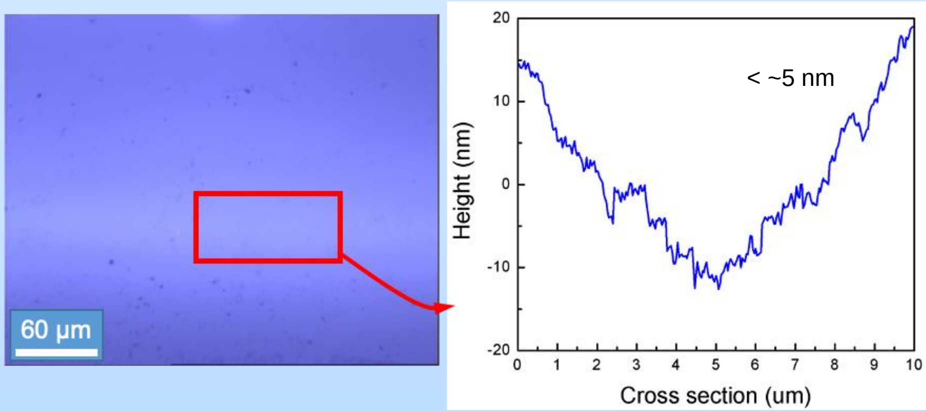
Additive Manufacturing of Fused Silica Glasses



Before resurfacing: Rough



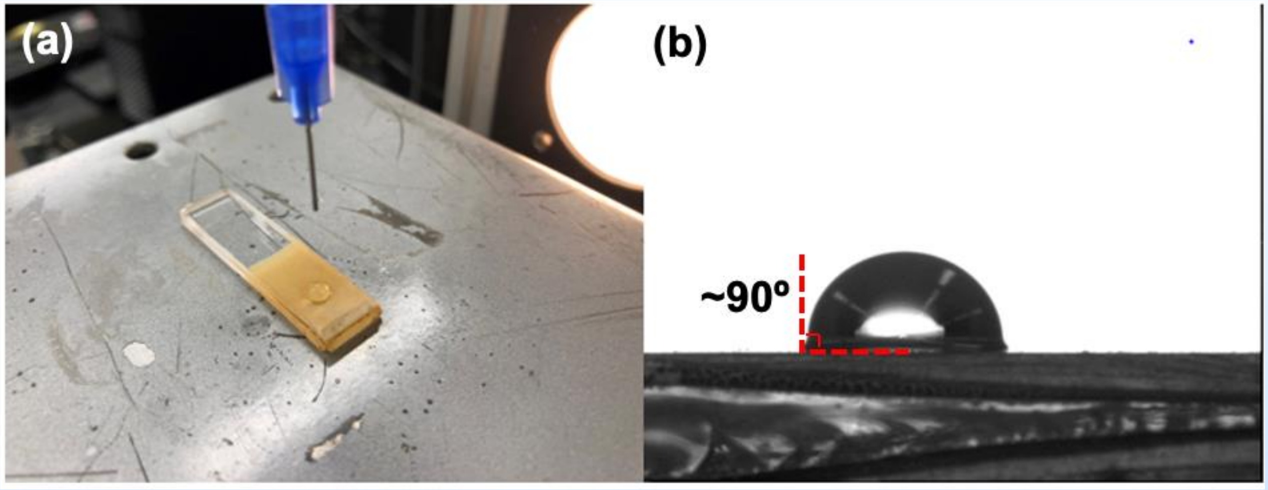
After resurfacing: Smooth



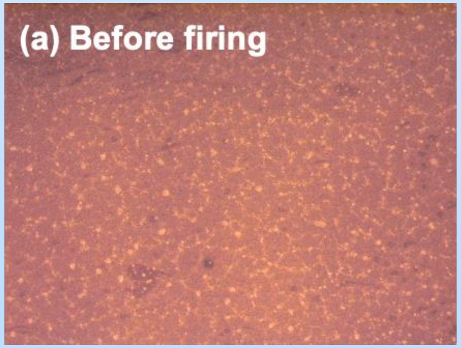
Fabrication Processes Development

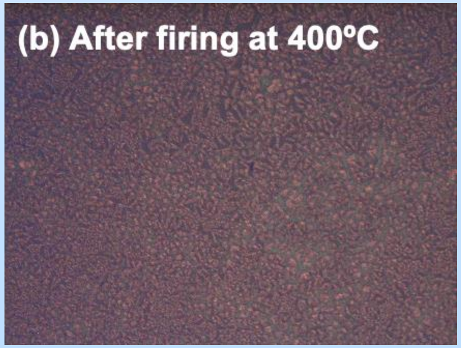
- **Superhydrophobic coatings for optical sensor modules to minimize condensation effect**

Hydrophobic CeO_2 ceramic coating on glass surface with 90º contact angle

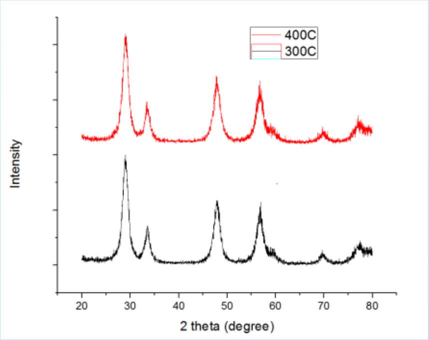


Crack-free coating after firing





Crystallization of CeO_2 coating



Thank You!

Questions?