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

DE-FE0031826

Project Team:

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NETL Sensors and Controls Virtual meeting, 5/19/2021

Project Objective and Background

Objective

To design, additively manufacture, and test the circumferentially installed sensor modules for in-situ monitoring the temperature, pressure and blade tip-timing in turbines.

Background

- **Turbine blade failures**: a major cause of outages of turbomachinery and cost of millions to repair
- **Practice to minimize the turbine blade failures**: **Scheduled maintenance**
  - Millions spent on the parts, labors and more importantly, loss of service
  - Still cannot completely prevent the unexpected turbine failures and unplanned outages

Project Background

Needs Condition-based monitoring (CBM) and Challenges

- Becomes a necessity to handle frequent load changes due to the increasing contributions of renewable energy sources
- Currently available sensors have low survival rate under harsh environment and too expensive to be widely deployed in existing turbines
- Relies on in situ monitoring
- Has long been identified as the "missing and mostly required to fill capability gap" due to the lack of effective monitoring tools

Technology Gaps

- **Gap #1**: the lack of robust harsh environment sensors
- **Gap #2**: the lack of effective methods to package and install the sensors into the turbines without degrading their performance

CBM parameters for turbine blades

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

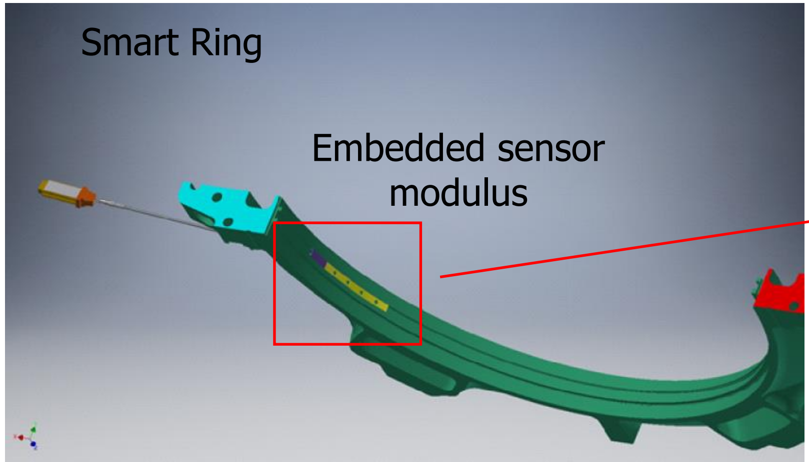
Abdelrhman, Ahmed M., et al. "Condition monitoring of blade in turbomachinery: a review." Advances in Mechanical Engineering, Vol. 6, pp. 210717, 2014.

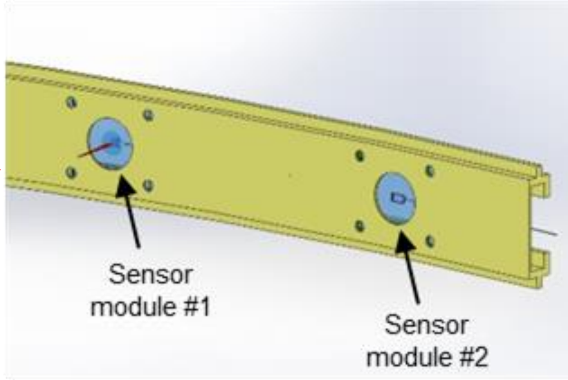
Proposed Solution

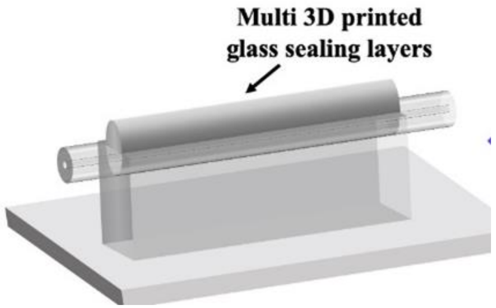
A Smart Ring circumferentially installed inside the turbine casing for in situ monitoring of temperature, pressure and tip-timing

Three types of embedded sensor modules:

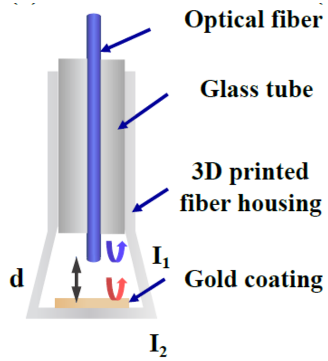
- ❑ **Temperature sensor module**
- ❑ **Pressure sensor module**
- ❑ **Blade tip-timing sensor module**



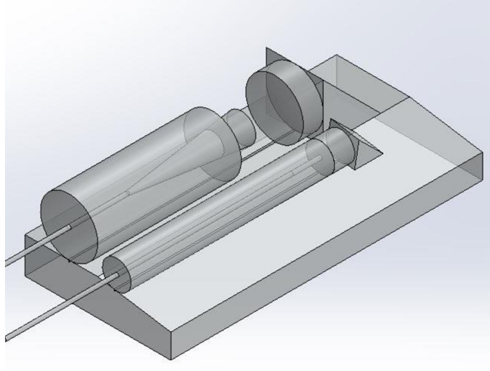




Temperature sensor module



Pressure sensor module



Blade tip-timing sensor module

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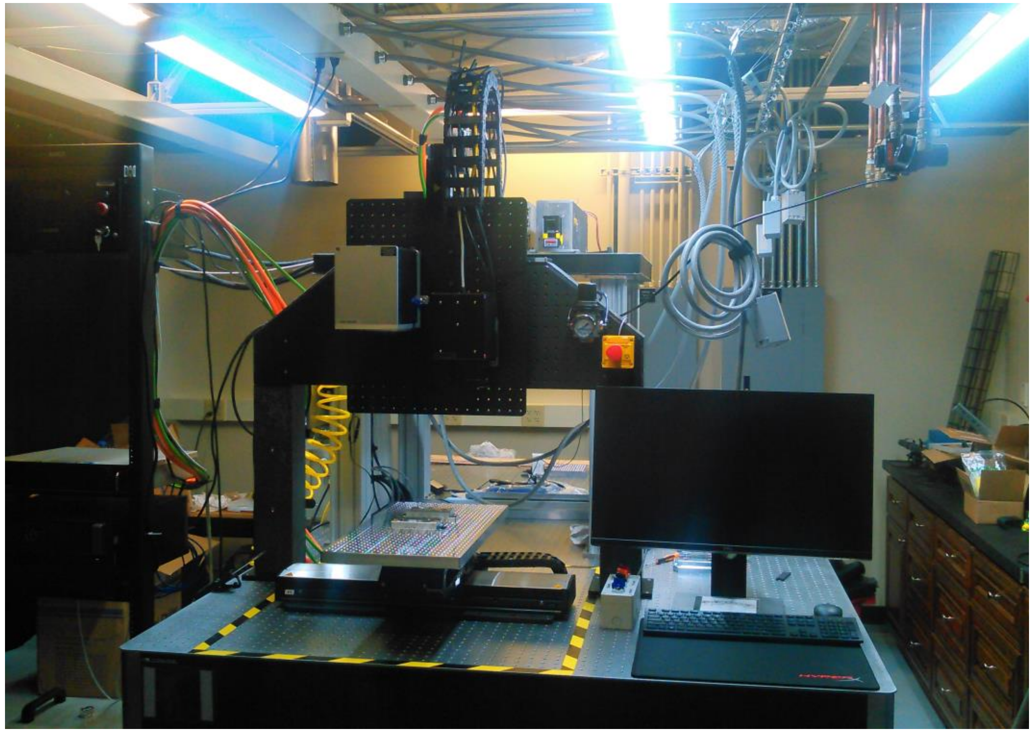
Project Tasks

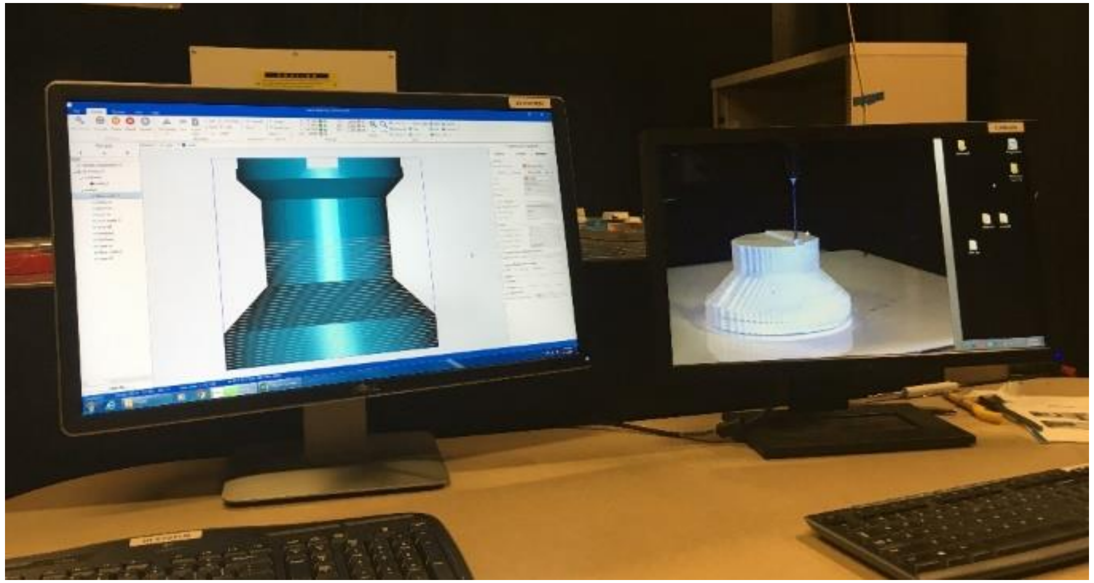
Four Major Tasks

- **Design** optical temperature, pressure, and blade tip timing/clearance sensor modules
- Develop 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 an industrial scale test facility**

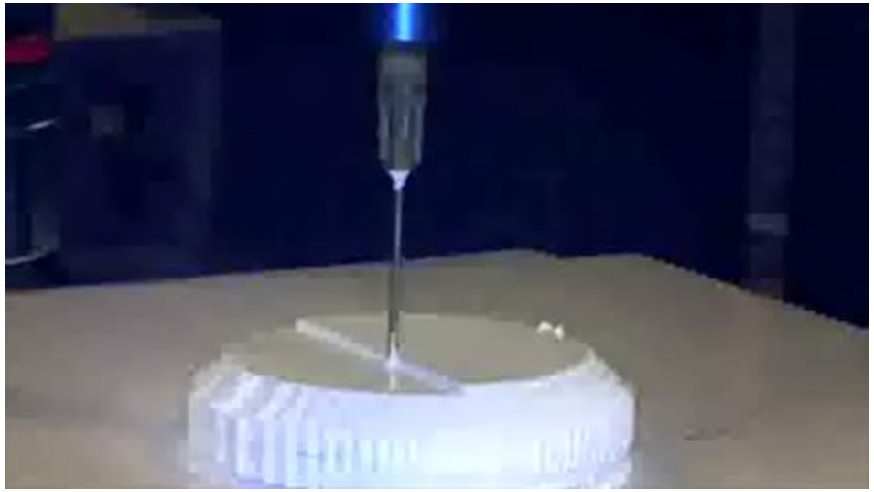
Advanced Manufacturing Capability

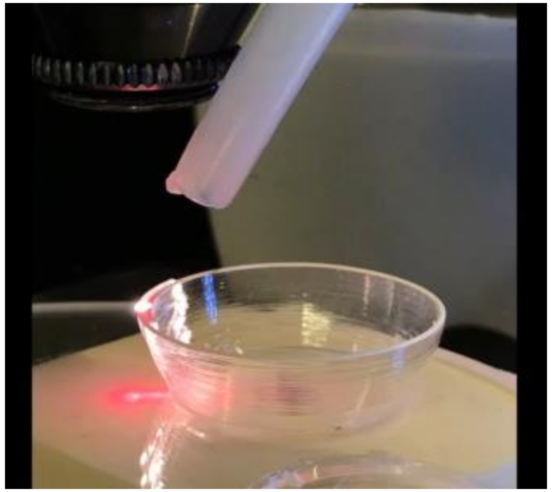
Integrated Additive and Subtractive Manufacturing (IASM)





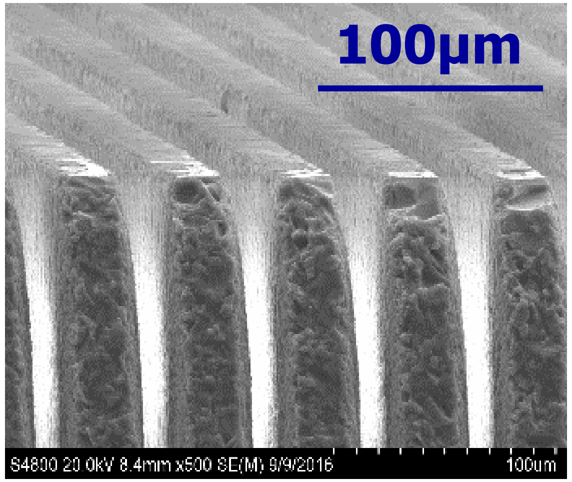
- 3D printing of glass and ceramics
- Laser melting and sintering
- Ultrafast laser micromachining

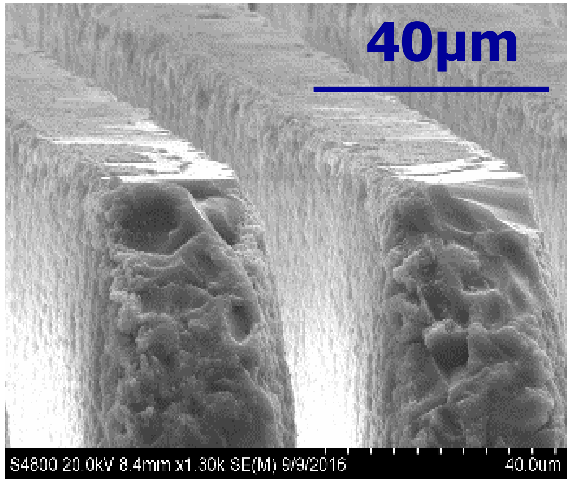


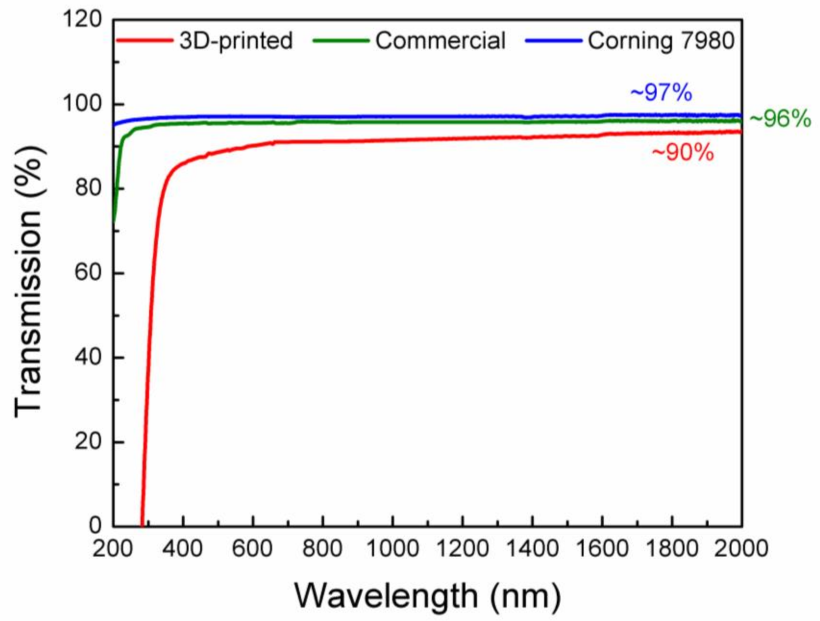


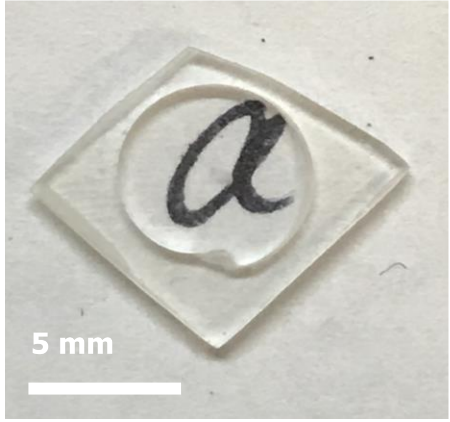
3D printing of Glass

Print Fused Silica Glass with Embedded Structures



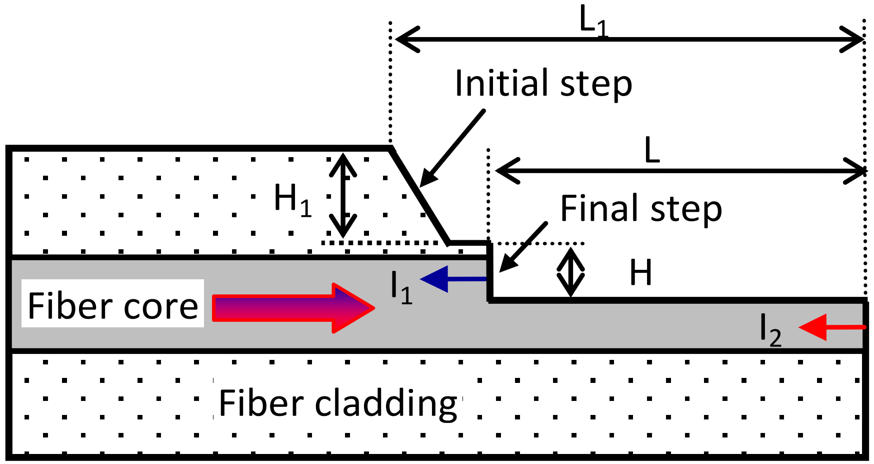


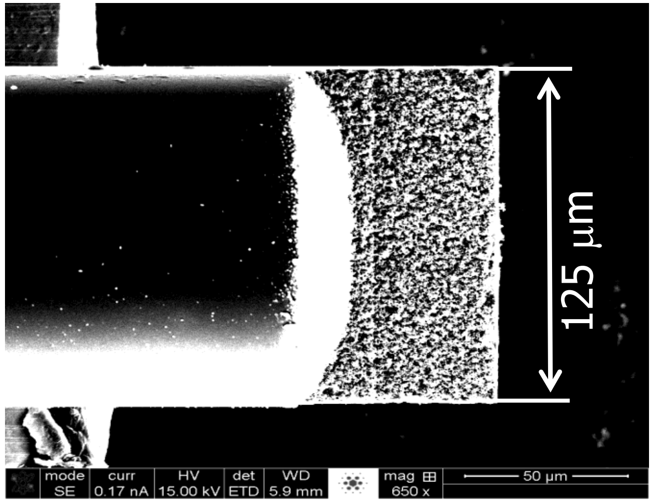


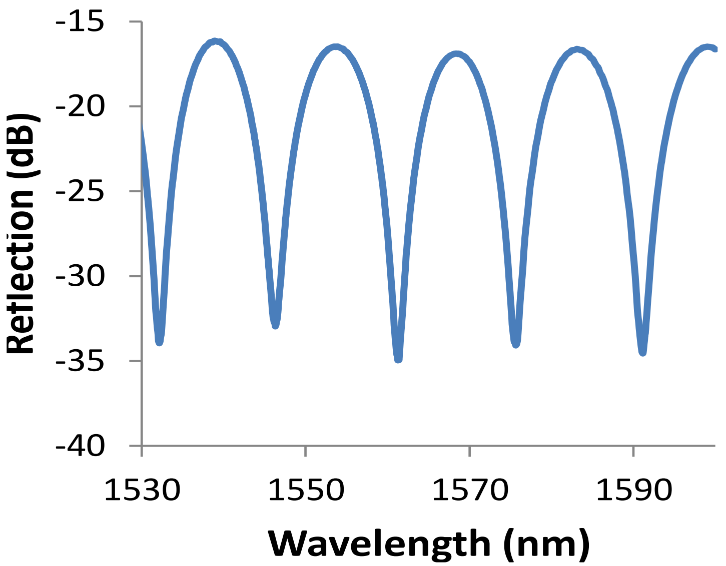


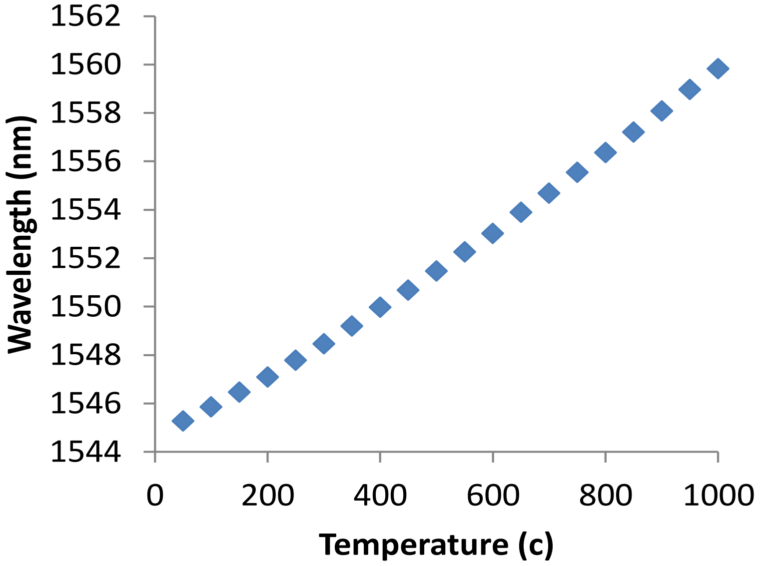
Temperature Sensor

Femtosecond Laser Micromachined Michelson Interferometers



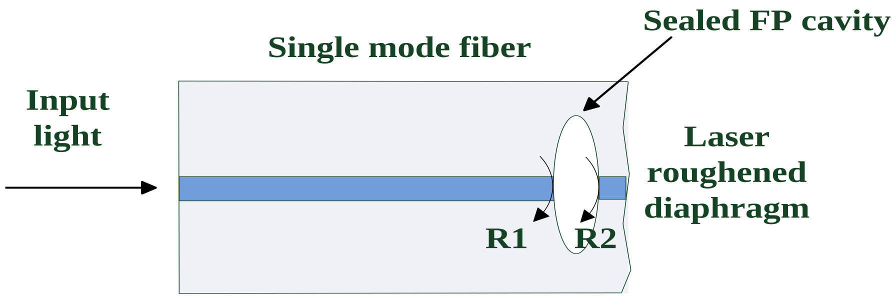


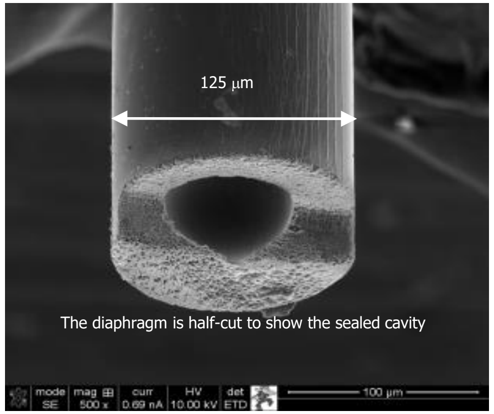


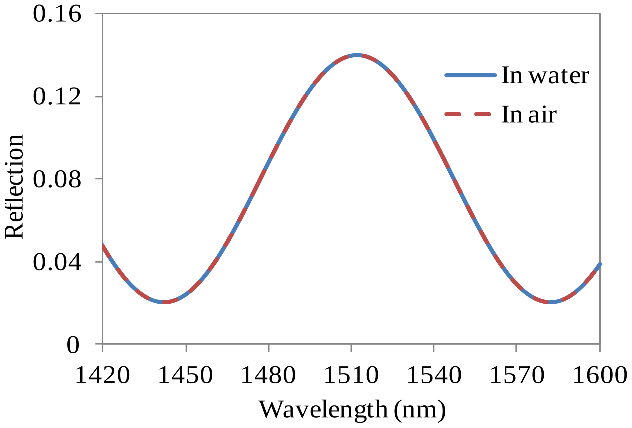


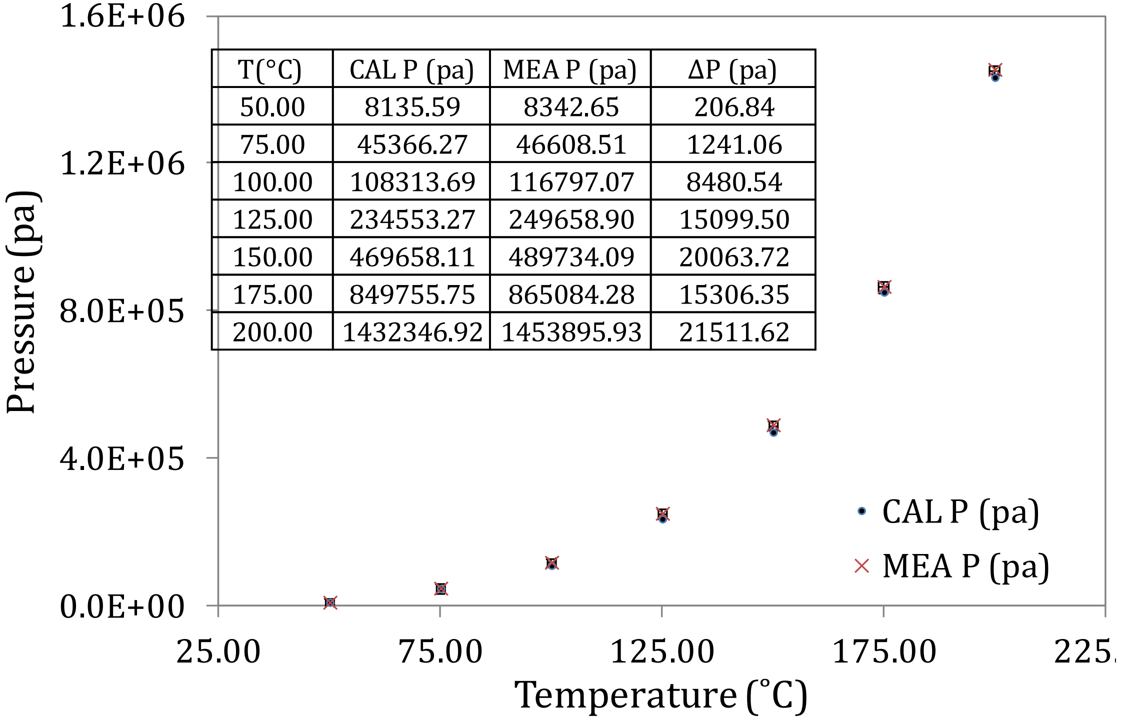
Pressure Sensor

Femtosecond Laser Micromachined Fabry Perot Interferometer





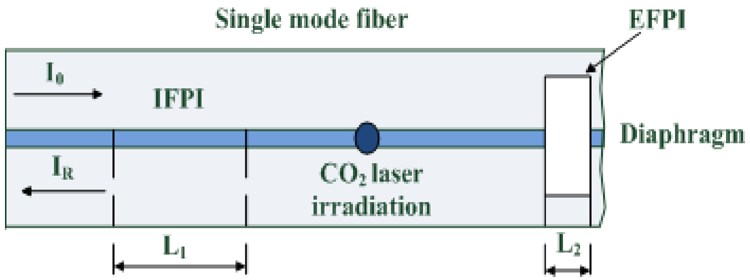




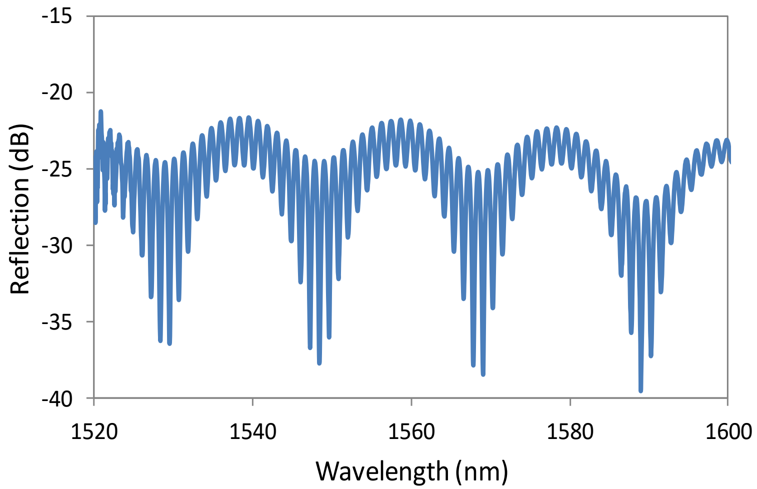
T(°C)	CAL P (pa)	MEA P (pa)	ΔP (pa)
50.00	8135.59	8342.65	206.84
75.00	45366.27	46608.51	1241.06
100.00	108313.69	116797.07	8480.54
125.00	234553.27	249658.90	15099.50
150.00	469658.11	489734.09	20063.72
175.00	849755.75	865084.28	15306.35
200.00	1432346.92	1453895.93	21511.62

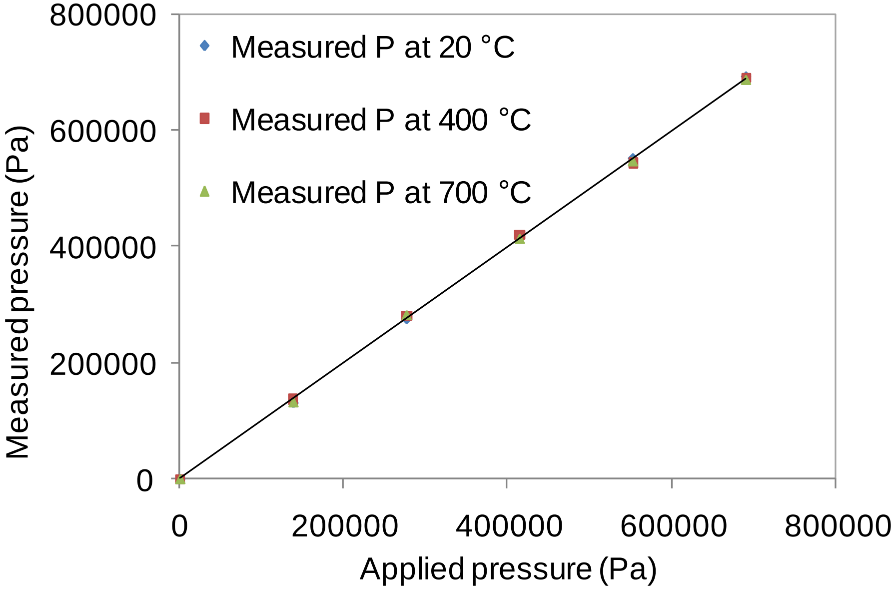
Simultaneous T and P Measurement

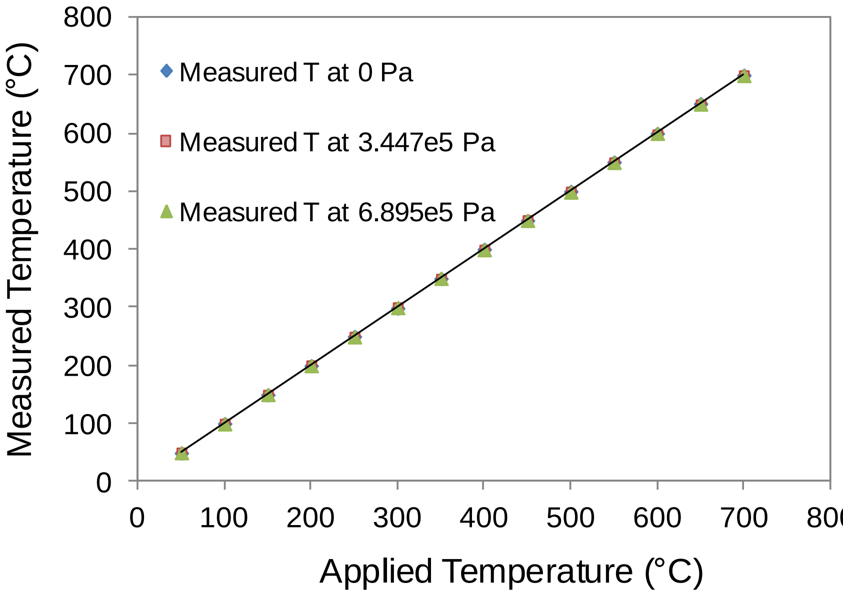
Cascaded Intrinsic and Extrinsic Fabry-Perot Interferometers



IFPI made by fs laser micromachining

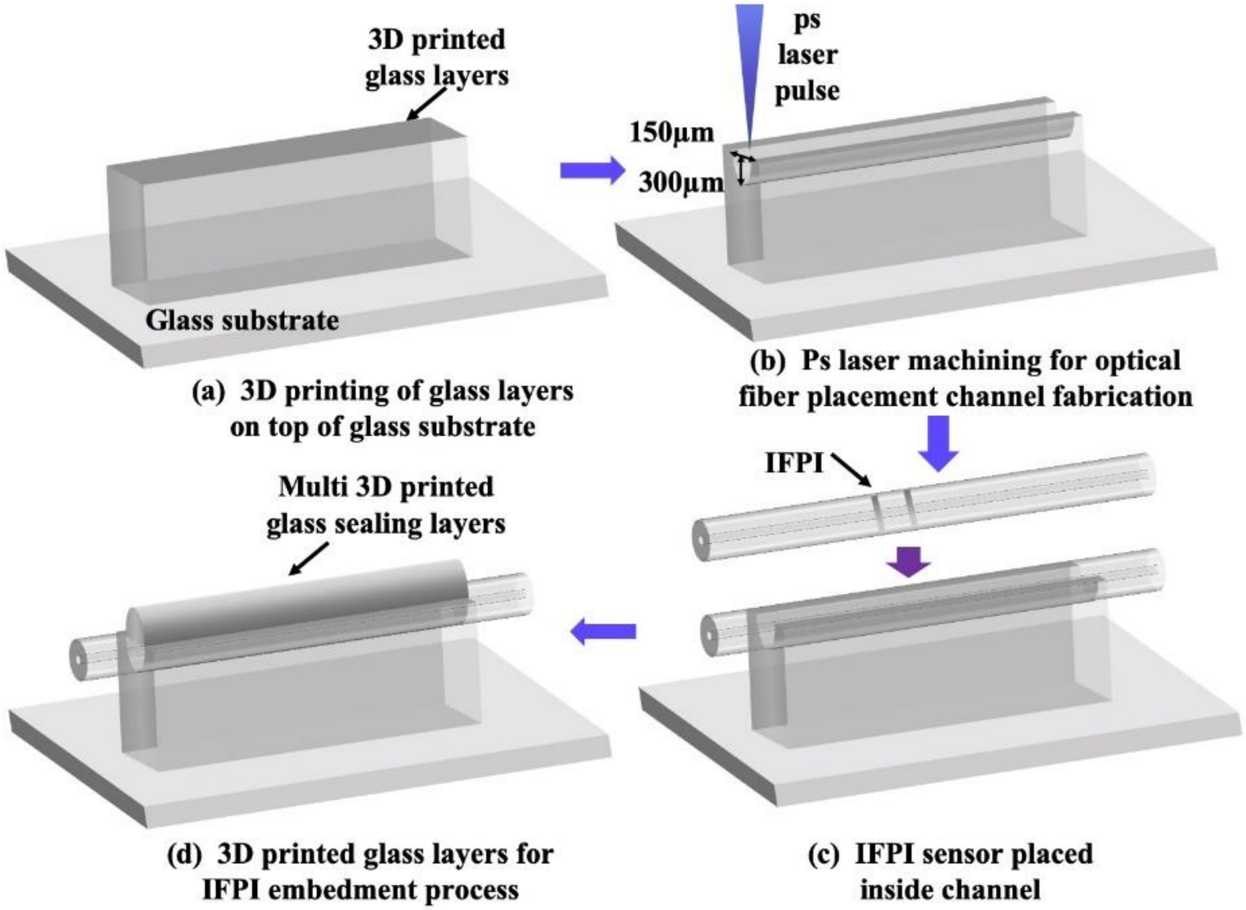




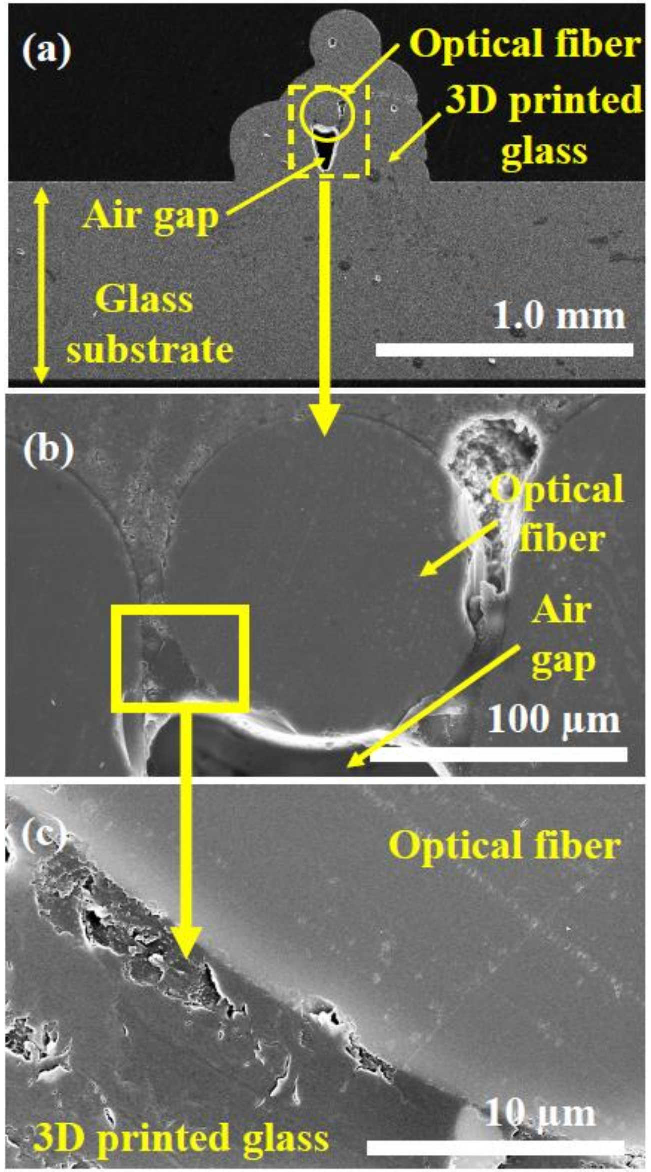


Embed the sensor in a 3D printed glass housing

- ❑ **Protect the fiber sensor**
- ❑ **Easy to handle and install**

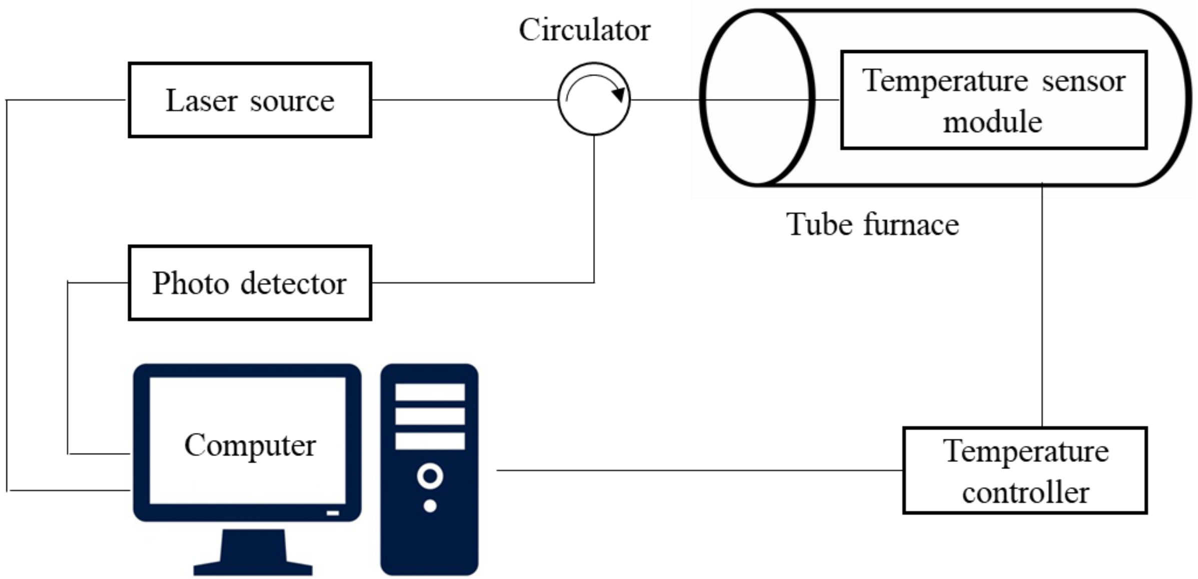


(a) 3D printing of glass layers on top of glass substrate
(b) Ps laser machining for optical fiber placement channel fabrication
(c) IFPI sensor placed inside channel
(d) 3D printed glass layers for IFPI embedment process

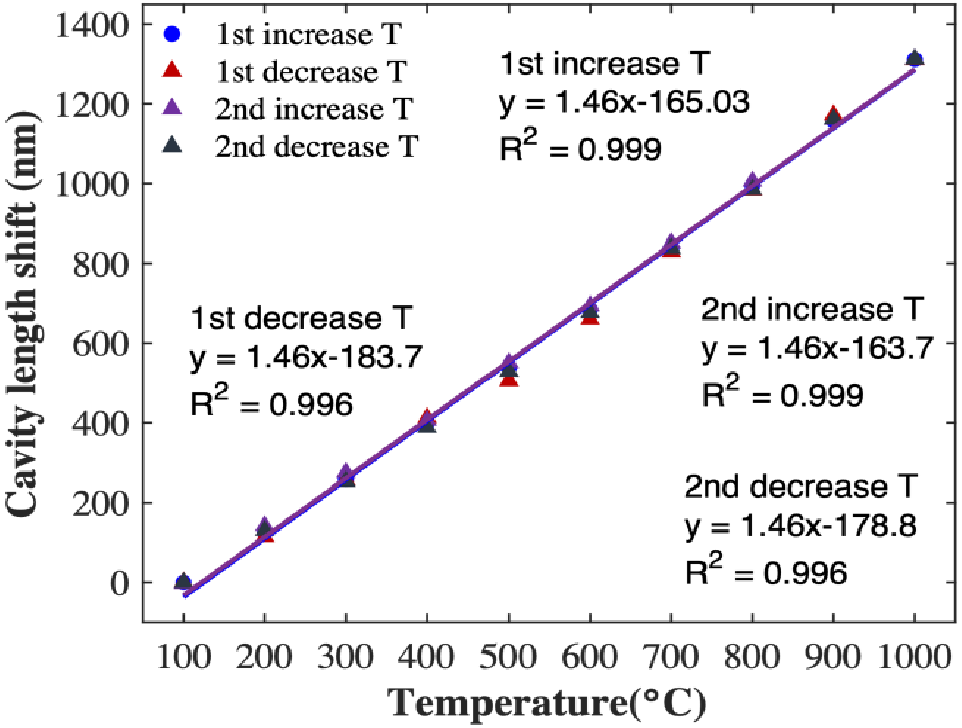


Temperature sensor

Packaged Temperature Sensor in-lab Testing



Schematic of the in-lab test setup

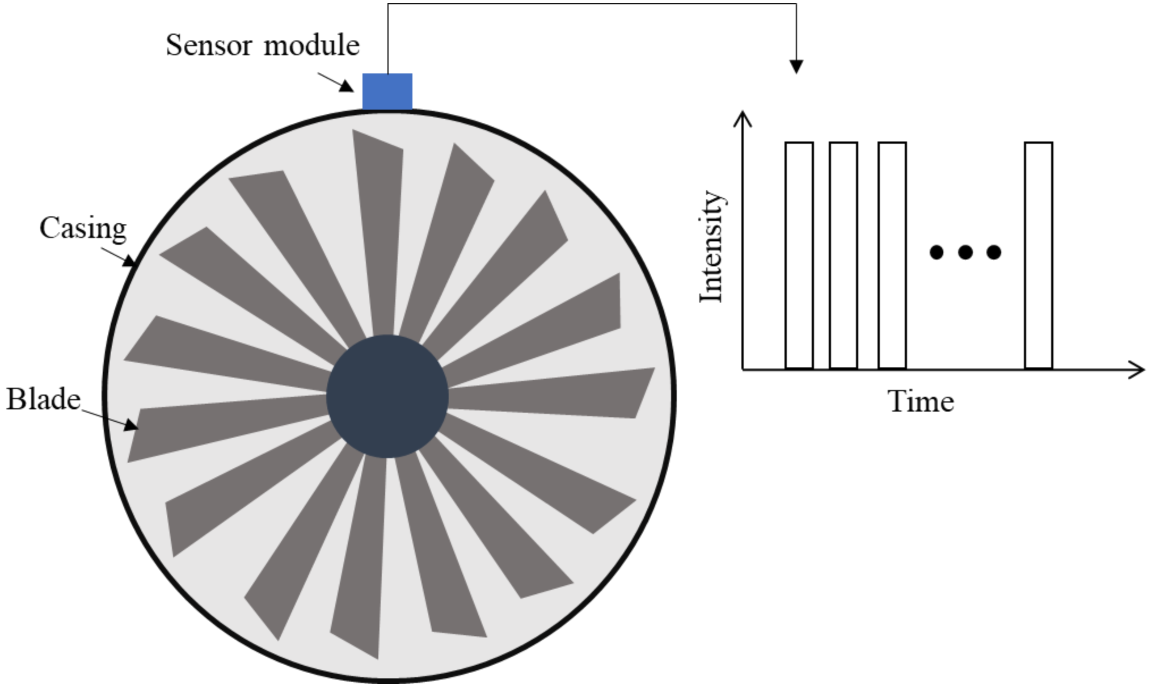


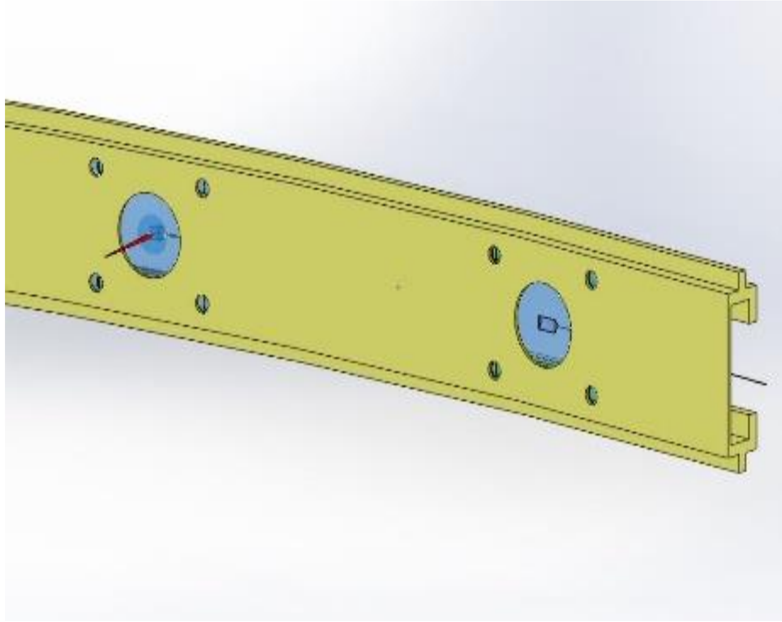
Test results

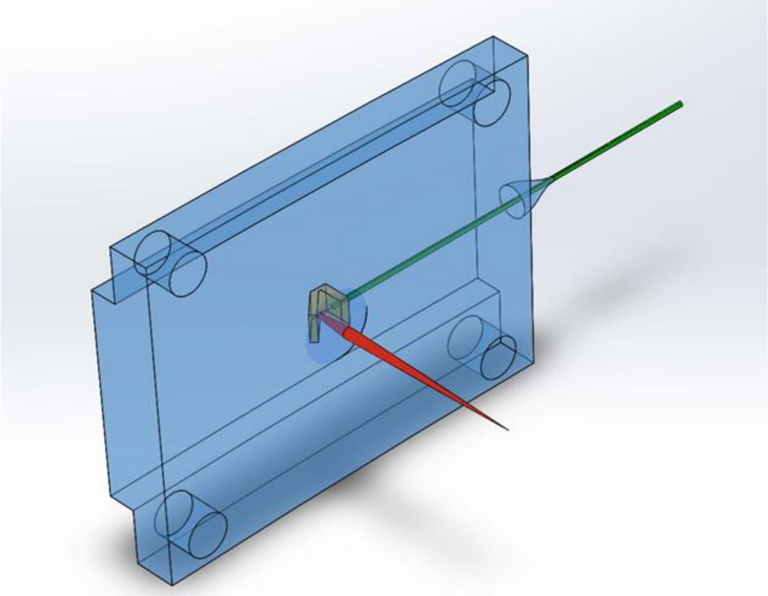
Blade tip-timing

Blade Tip-Timing Sensing Requirements

- High time resolution (~ns)
- High signal-to-noise ratio
- Circumferentially positioned
- Low profile







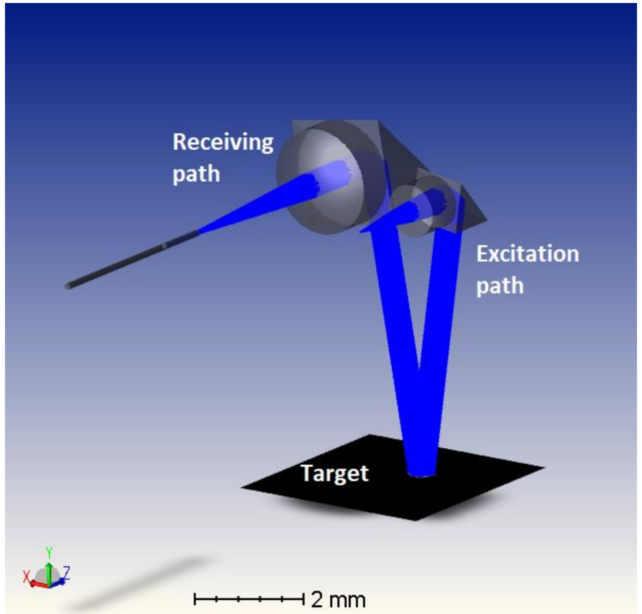
Simulation with raytracing software

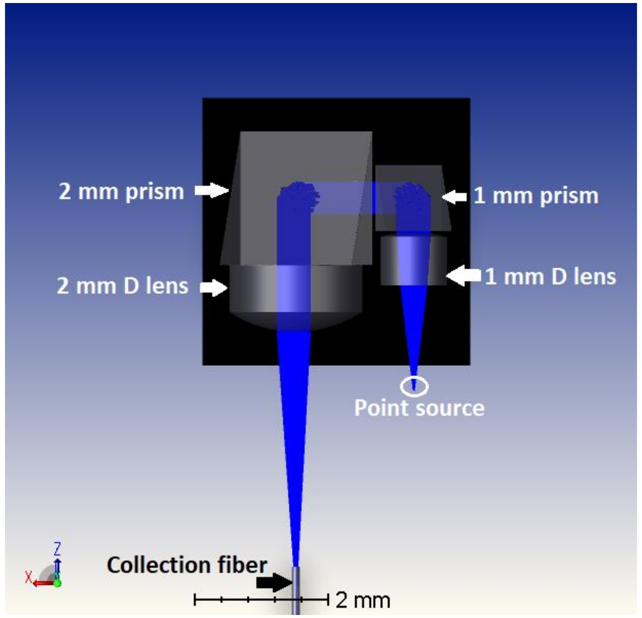
Optical design is simulated and optimized in Zemax OpticStudio:

- ❑ Sizes of the optical components.
- ❑ Separation between the excitation and receiving path.

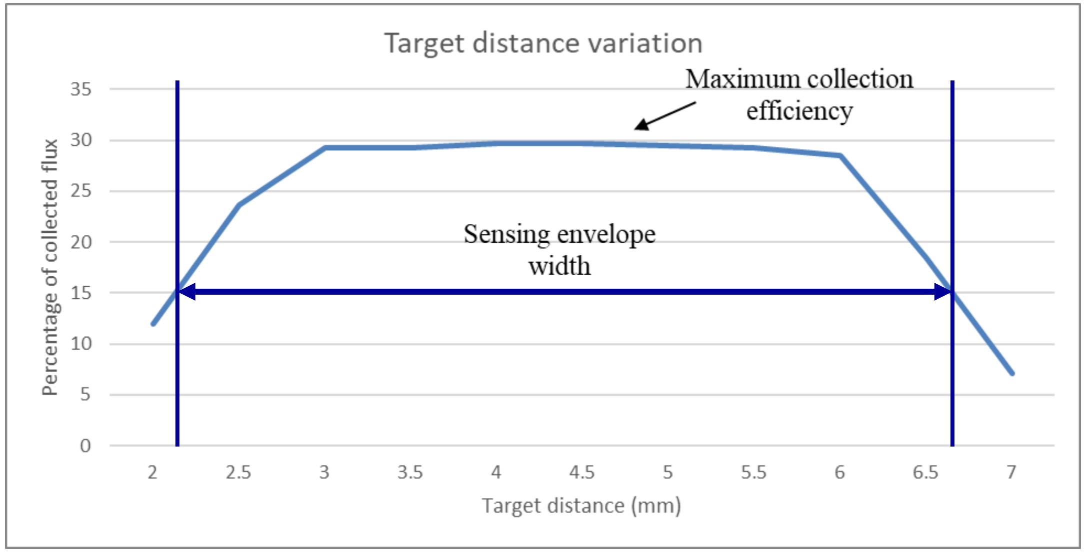
Evaluate the optical design

- ❑ Maximum collection efficiency.
- ❑ Sensing envelope.





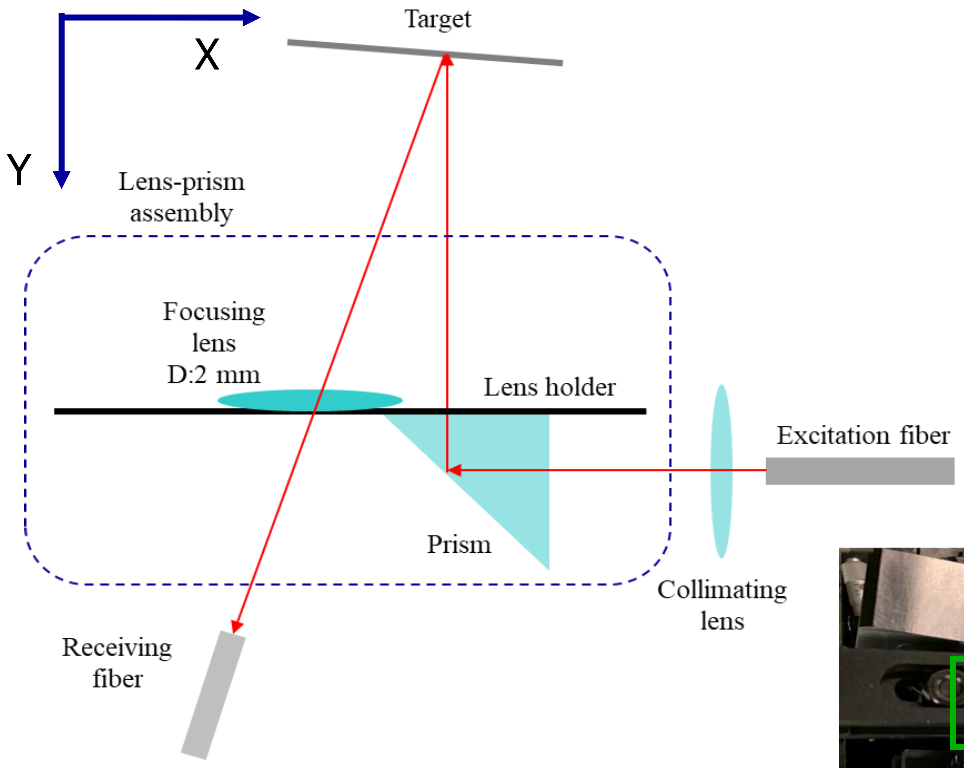
Isometric and top view of the blade tip-timing sensor design

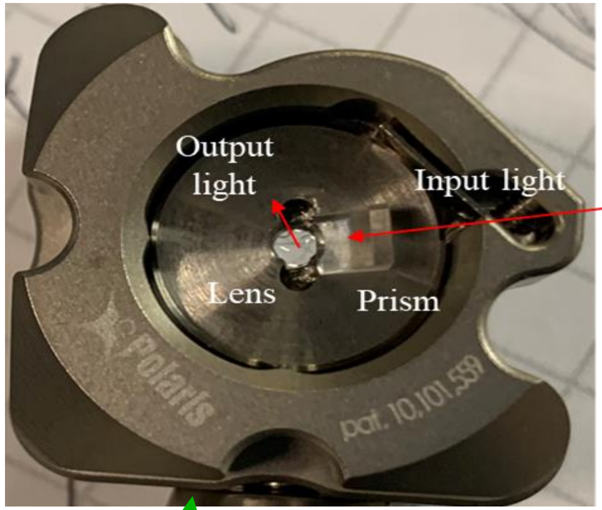


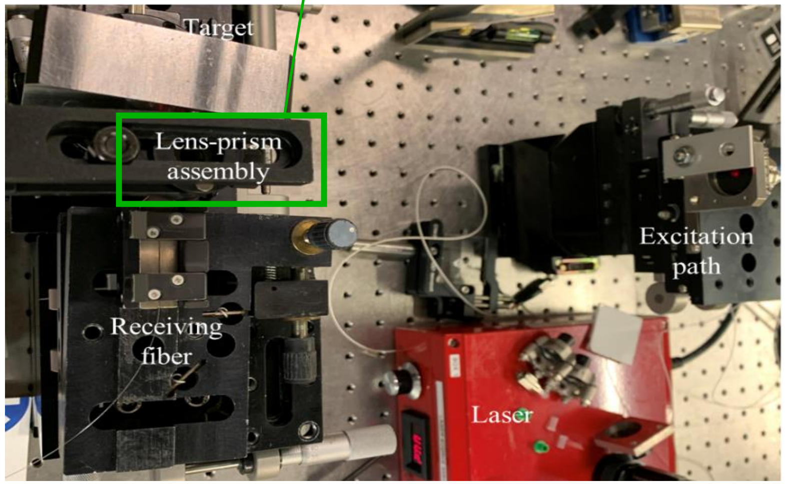
Collection efficiency and sensing envelope

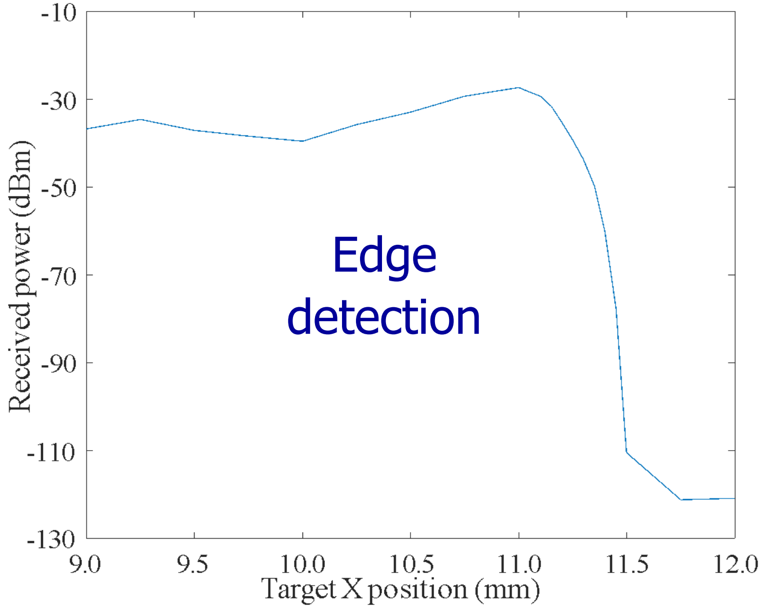
Blade tip-timing

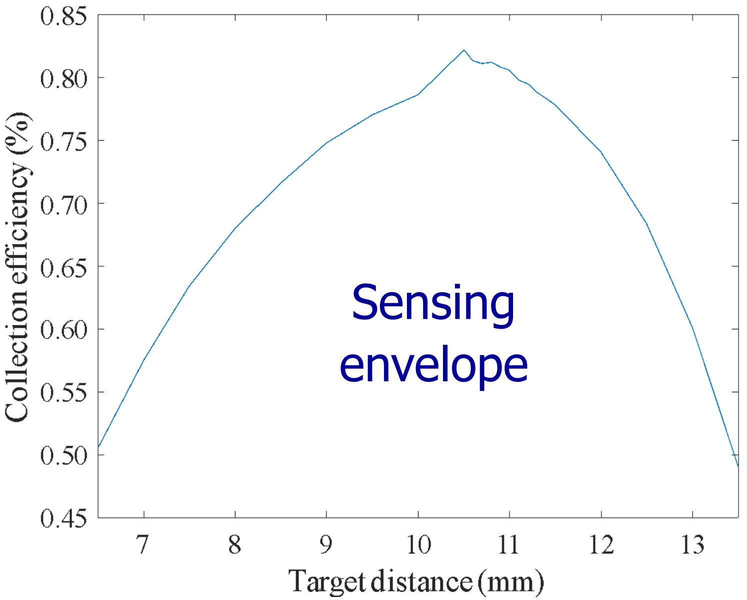
Validating the optical design with in-lab testing





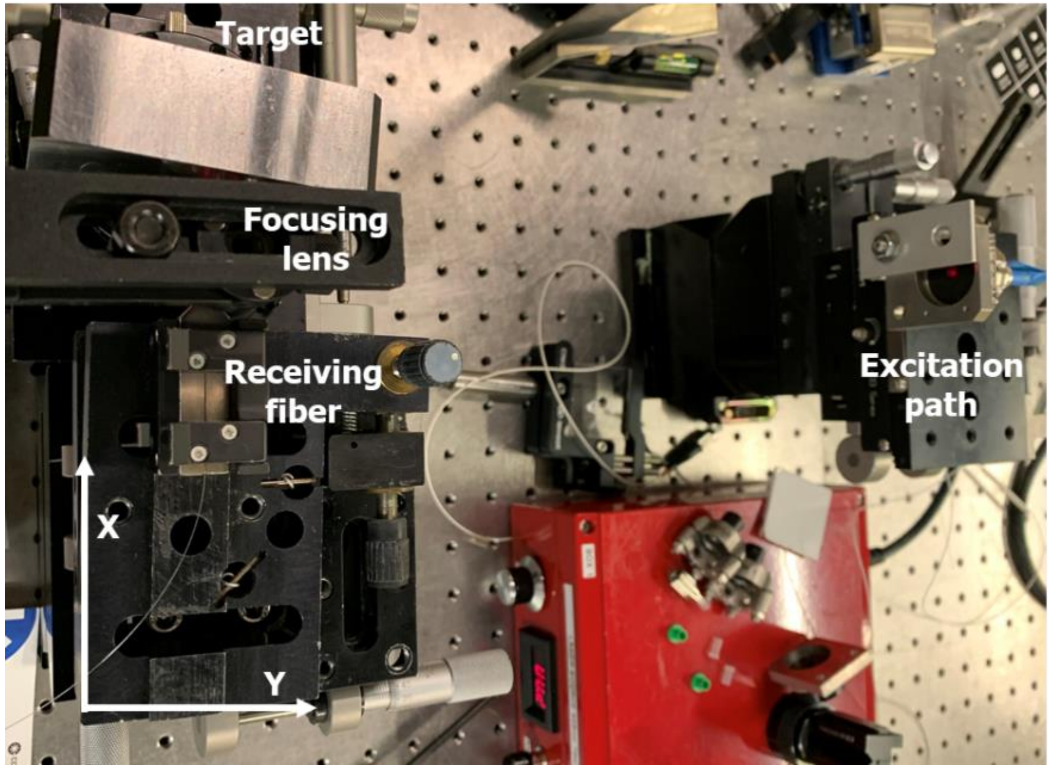


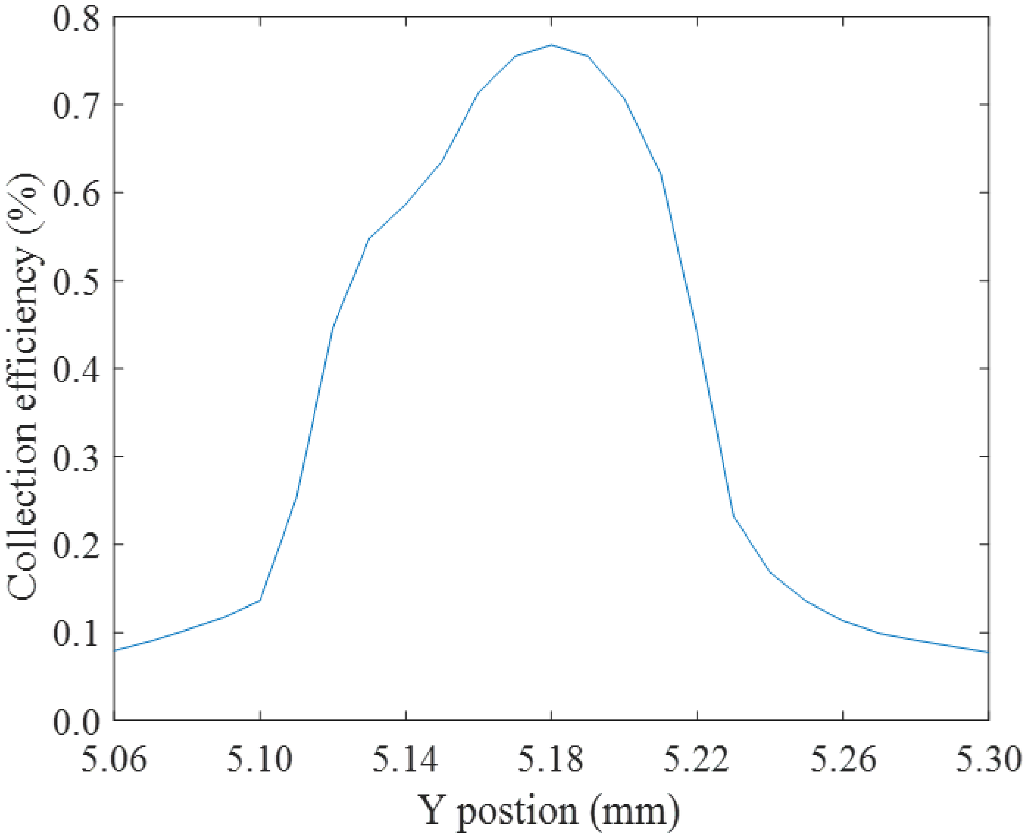


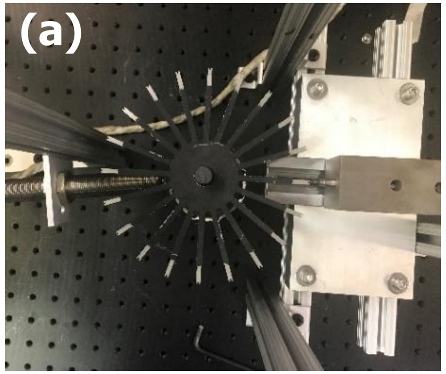


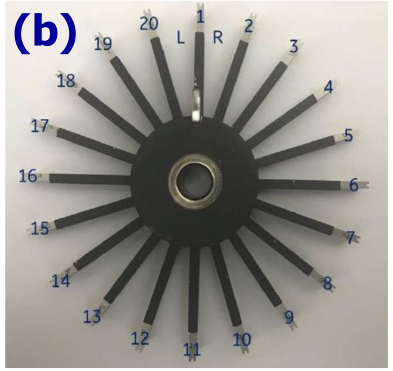
Blade tip-timing

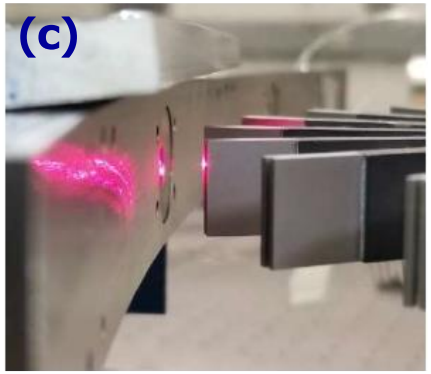
Alignment tolerance





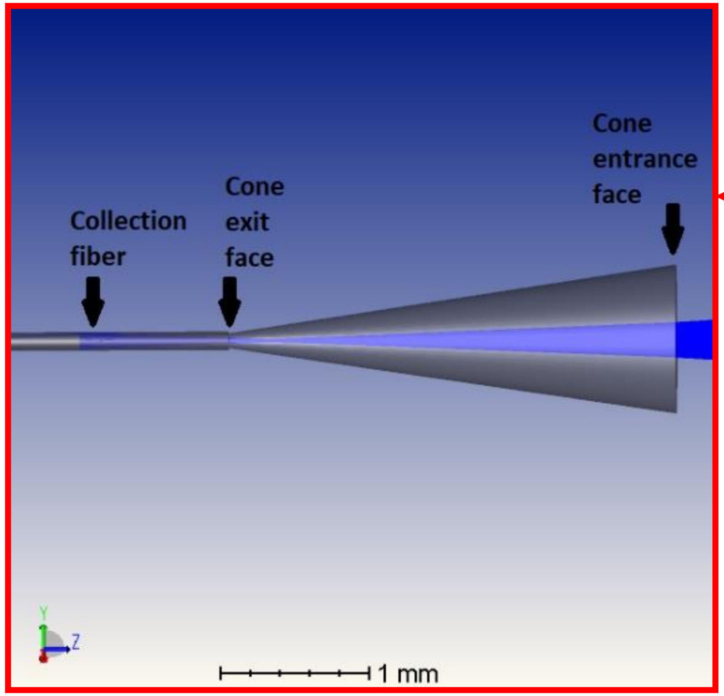




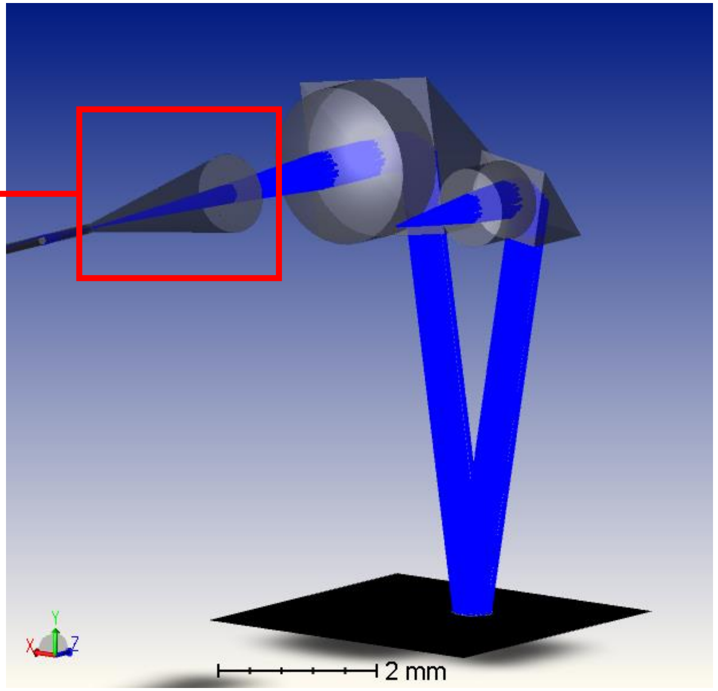


Collection efficiency vs. Y position of the receiving fiber

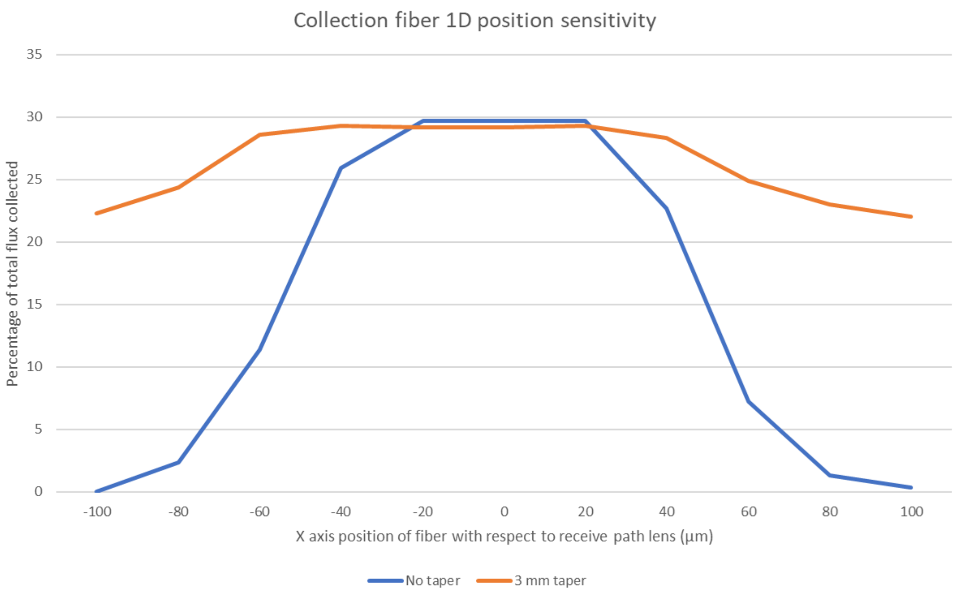
Tapered optical waveguide to help the collection



Tapered optical waveguide



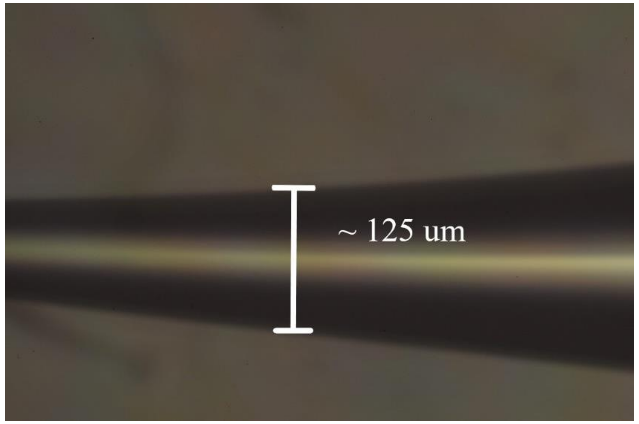
Improved optical design



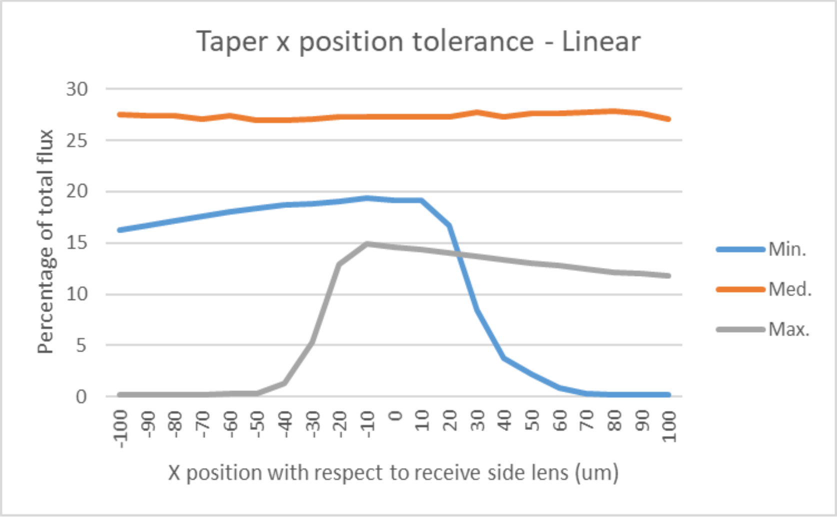
Improved alignment tolerance

Blade tip-timing

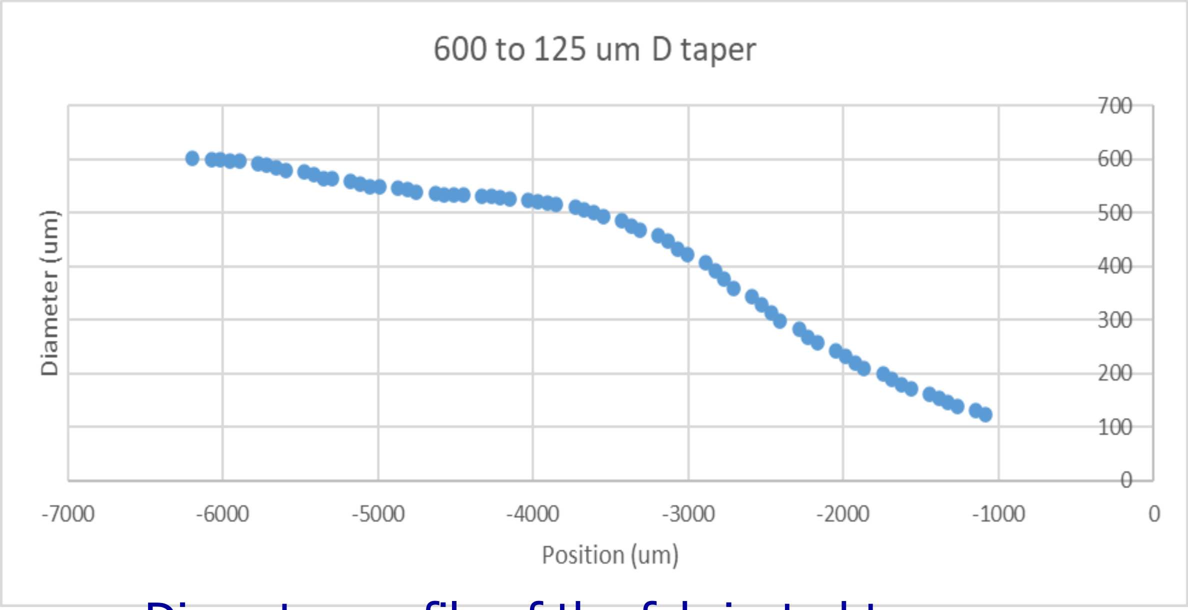
Fabricate the tapered optical waveguide



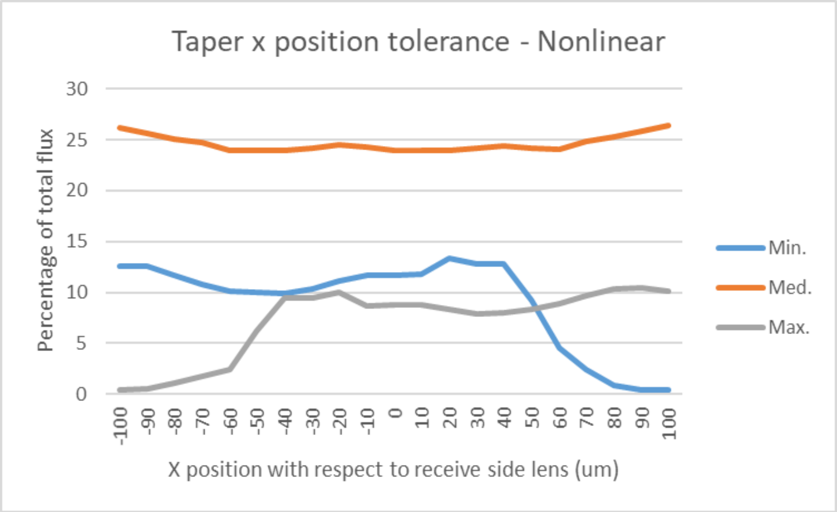
Microscopic image of a tapered



Performance of an ideal taper



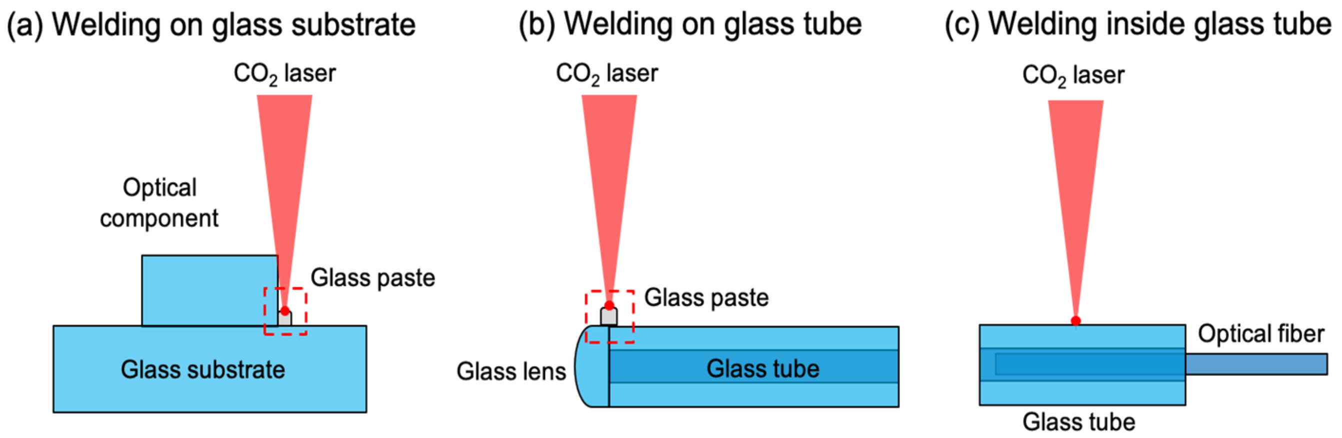
Diameter profile of the fabricated taper



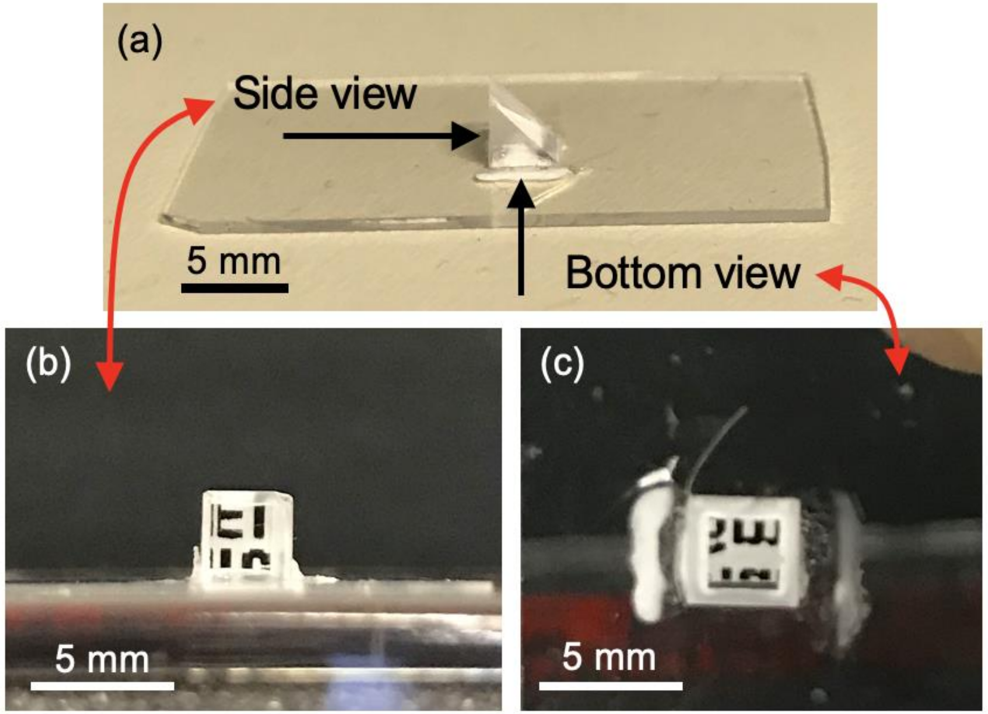
Performance of the fabricated taper

Fabrication of the Module

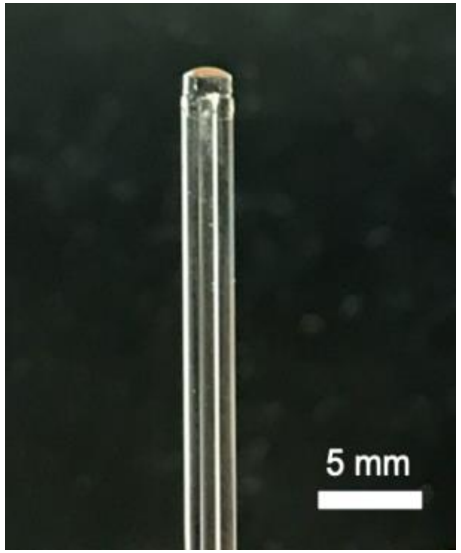
Laser micro-welding



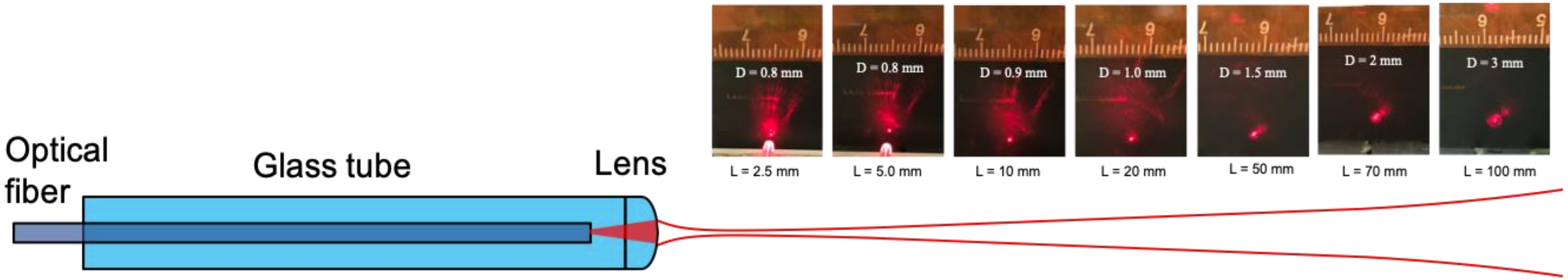
Laser welding procedures



Welded prism

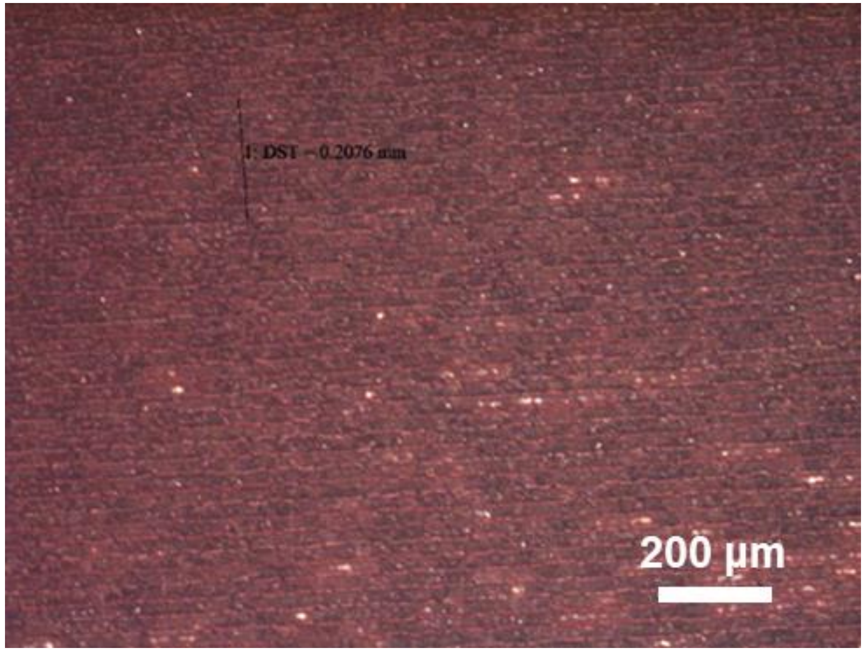


Welded lens-tube-fiber assembly

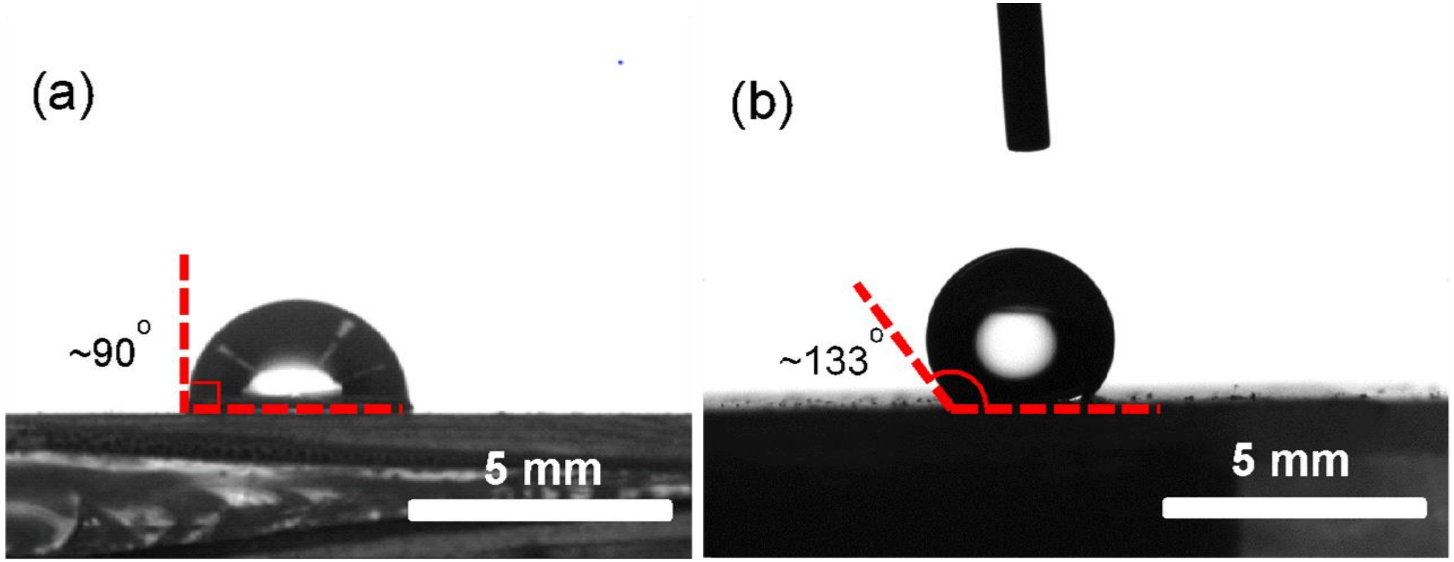


Collimation of the lens-tube-fiber assembly

Superhydrophobic Coating



ceramic-coated glass surface after ps laser micromachining



Water drop on (a) the coating surface before ps laser scanning; (b) the coating surface after ps laser scanning.

Project Status

Budget Period I (01/2020-12/2021)

Scope of Work in Budget Period I

- ❑ Optical designs of the sensor module (**Completed**)
- ❑ Temperature sensor prototypes are fabricated and confirmed by laboratory tests (**Completed**)
- ❑ Pressure sensors prototypes are fabricated and confirmed by laboratory tests (**06/30/2021, on schedule to complete**)
- ❑ Tip timing sensor module prototypes are fabricated, assembled and tested under laboratory conditions (12/31/2021).

Progresses of the project

- ❑ The technical progress of the project is on track.
- ❑ All the milestones have been met.

Plan

Fabrication & Testing of Sensor Modules

Remaining BP1 (12/31/2021):

- Continue to fabricate and package tressure and tip-timing sensor prototypes
- Test the sensor modules in lab.

BP2 (1/1/2022 – 12/31/2022):

- Fabricate and package temperature, pressure and tip-timing sensor modules.
- Install and test the sensor modules using a test Rig

Thank you!

Acknowledgment and Disclaimer

Acknowledgment: This material is based upon work supported by the Department of Energy Award Number DE-FE0031826.