CLEMSON UNIVERSITY

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 Project Review meeting, 5/4/2022

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

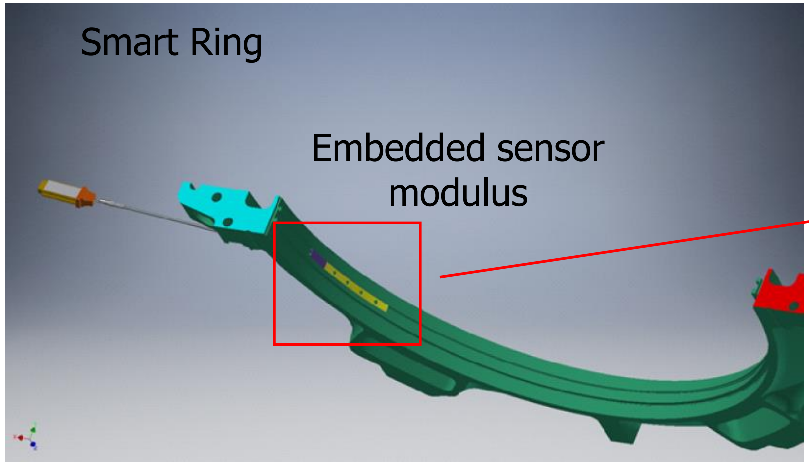
Abdelrhman, Ahmed M., et al. "Condition monitoring of blade in turbomachinery: a review." Advances in Mechanical Engineering, Vol. 6, pp. 210717, 2014.

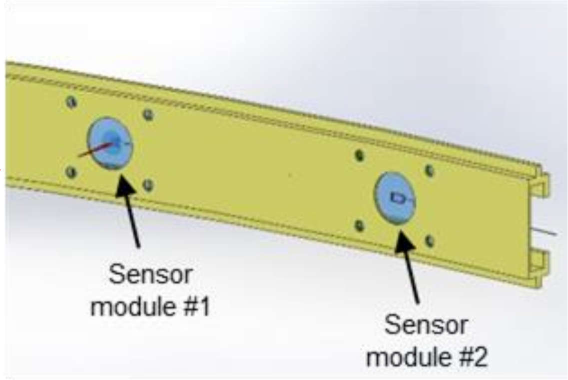
Proposed Solution

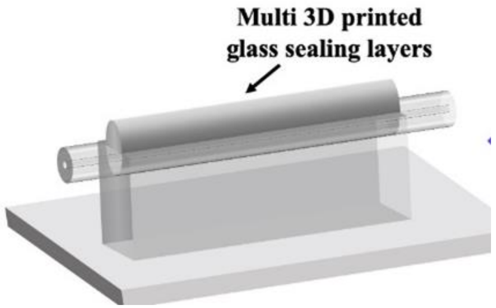
A Smart Ring circumferentially installed inside the turbine casing for in situ monitoring of temperature, pressure and tip-timing

Three types of embedded sensor modules:

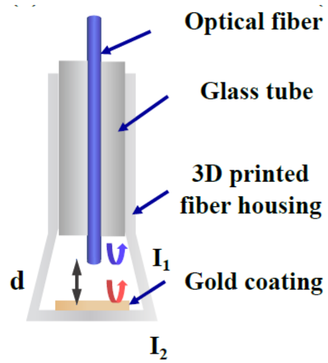
- ❑ **Temperature sensor module**
- ❑ **Pressure sensor module**
- ❑ **Blade tip-timing sensor module**



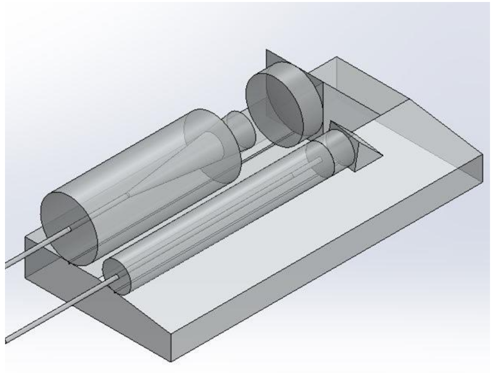




Temperature sensor module



Pressure sensor module



Blade tip-timing sensor module

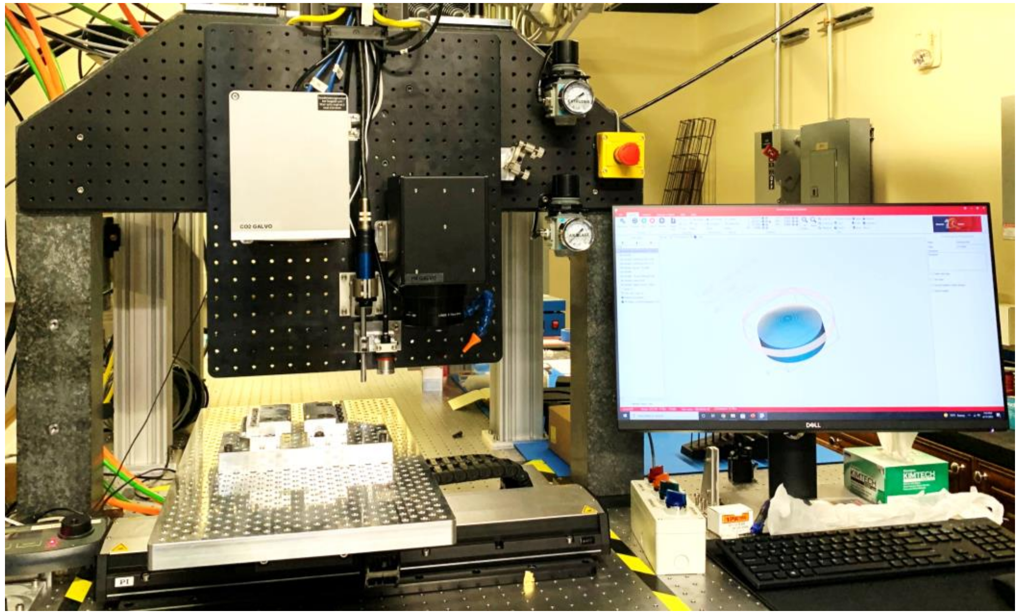
Project Tasks

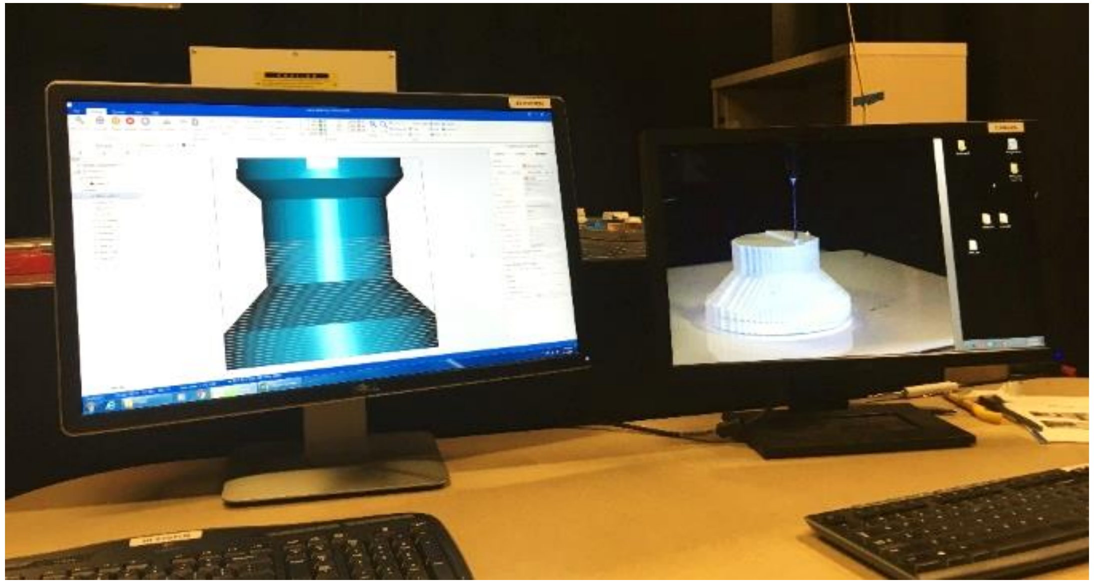
Four Major Tasks

- **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**

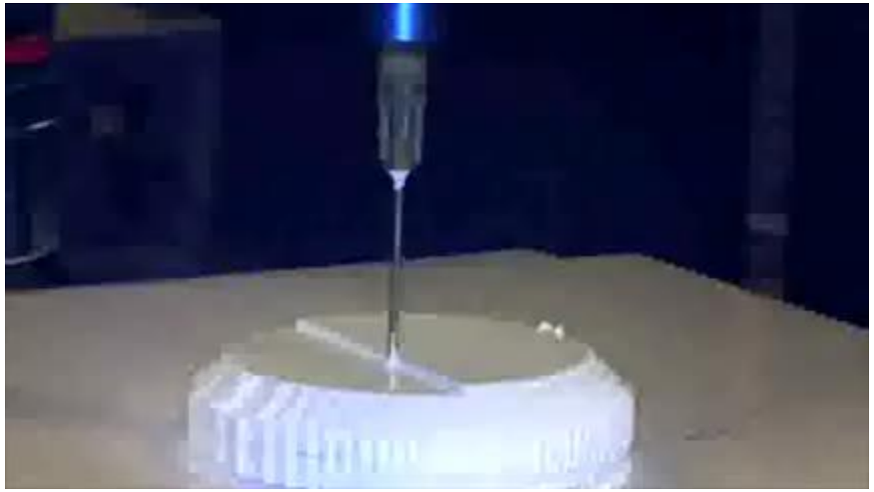
Advanced Manufacturing Capability

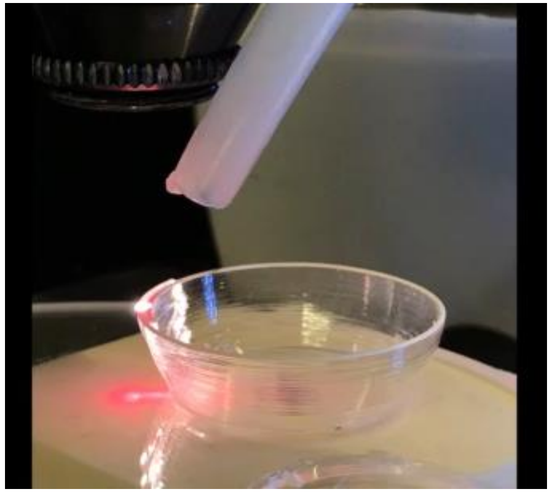
Integrated Additive and Subtractive Manufacturing (IASM)





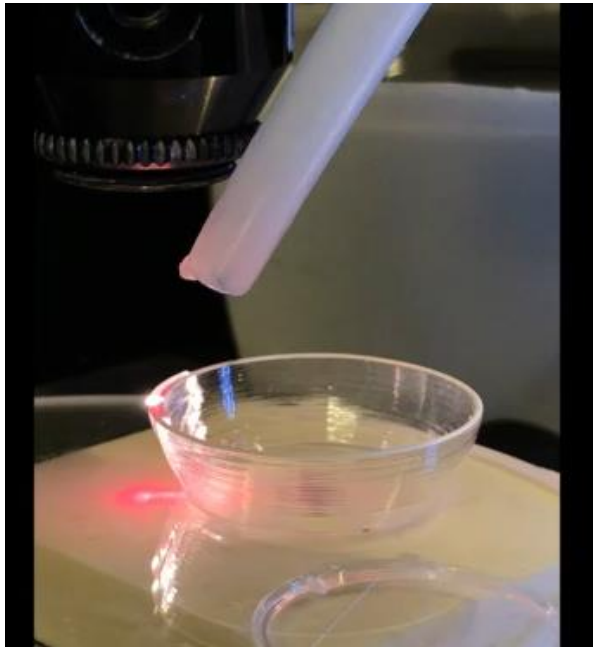
- 3D printing of glass and ceramics
- Laser melting and sintering
- Ultrafast laser micromachining

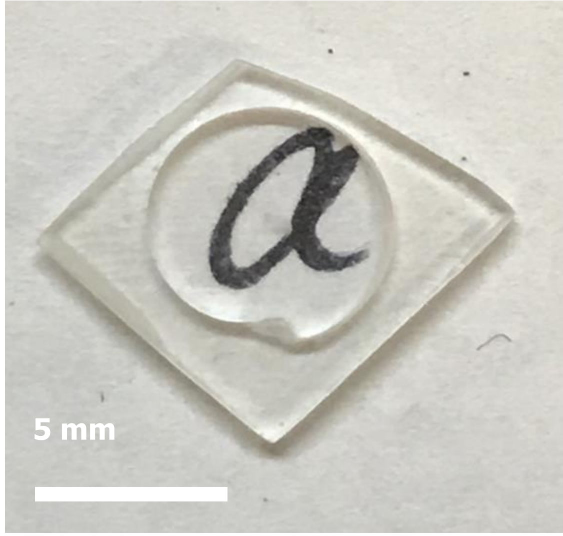


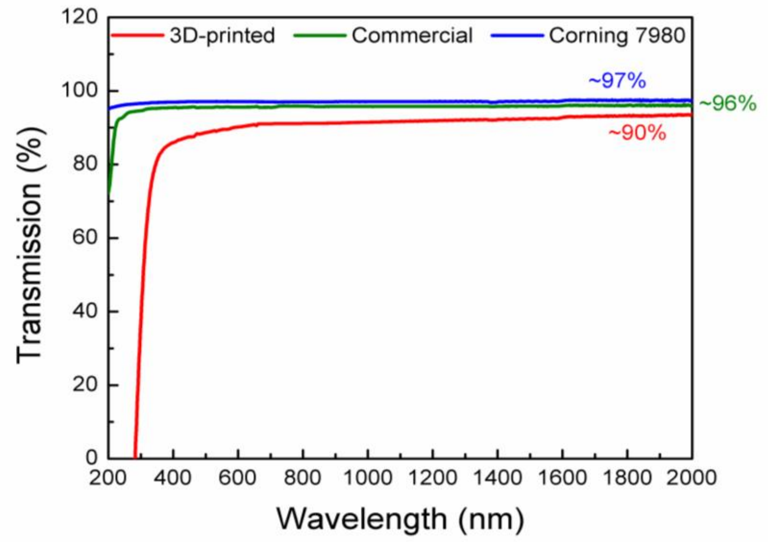


3D printing of Glass

3D print fused silica glass with excellent optical quality

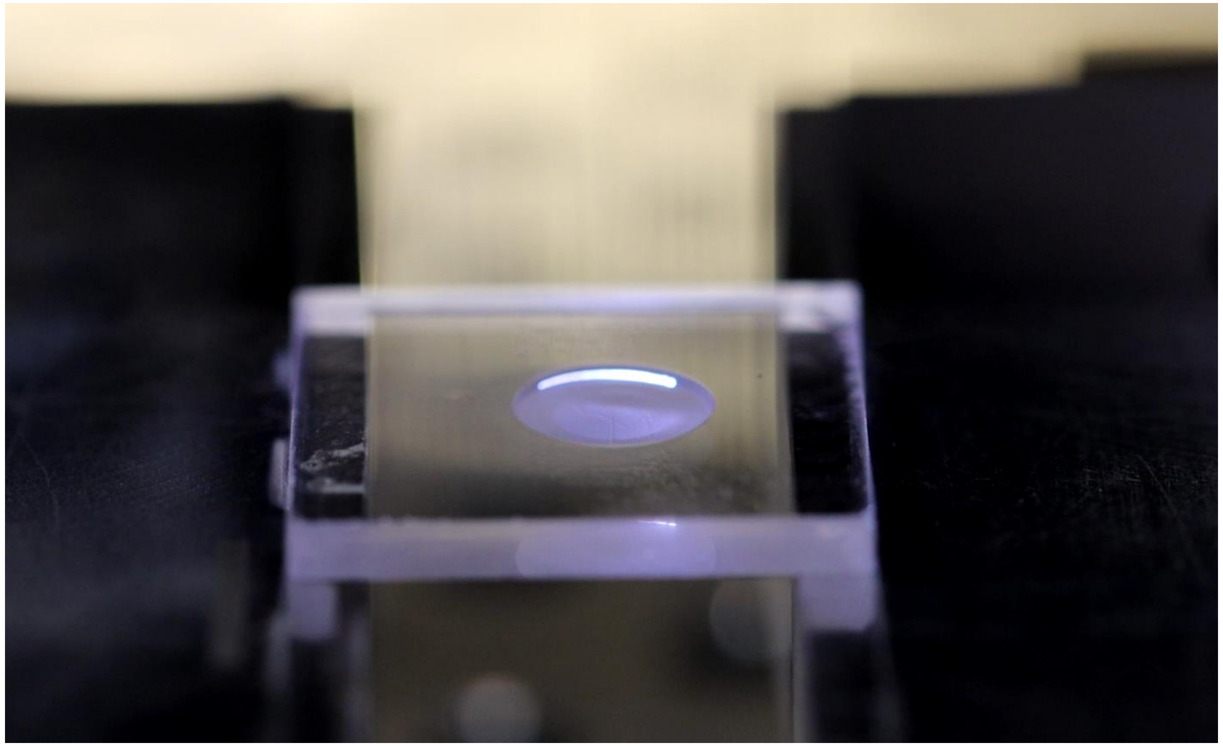


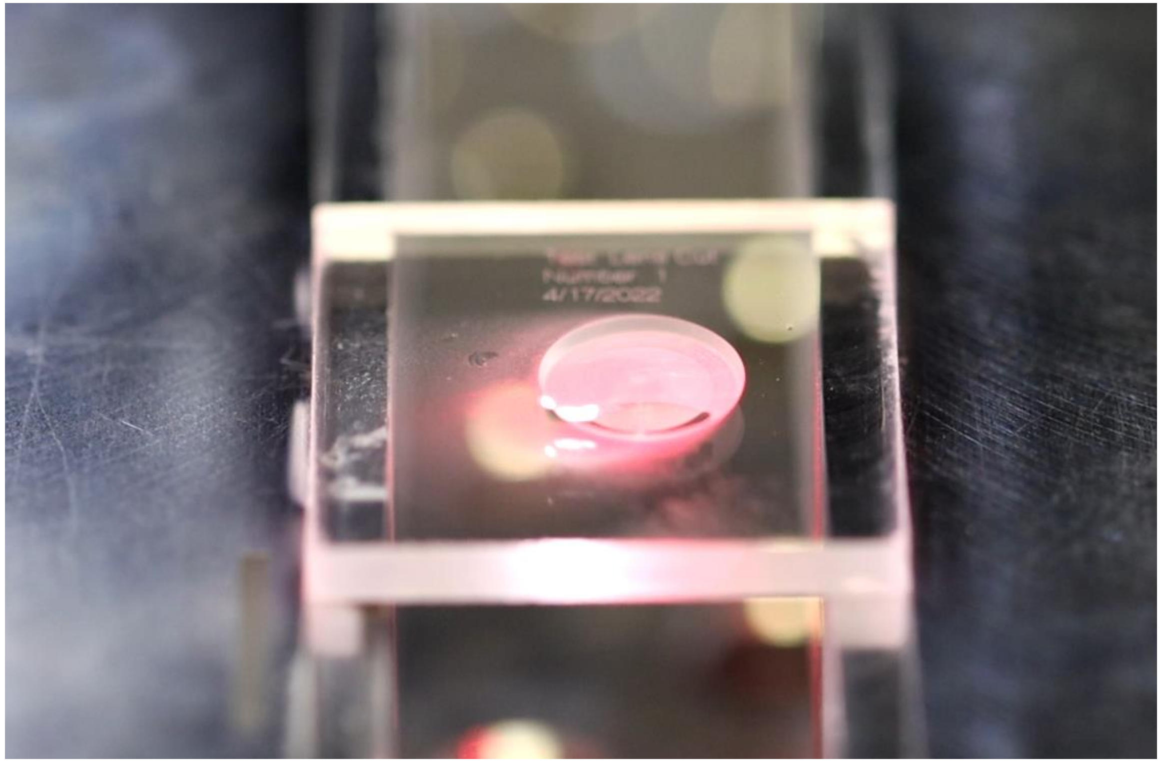




Laser cutting and resurfacing

- Use picosecond laser to cut the shape of an optical component (e.g., a lens)

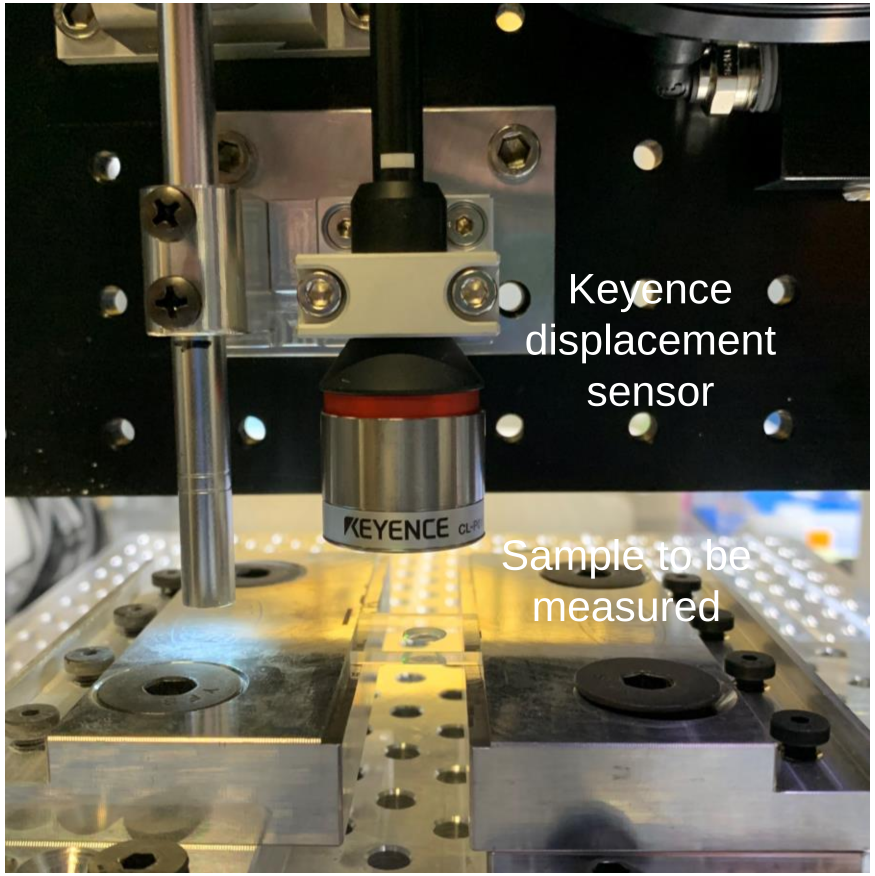


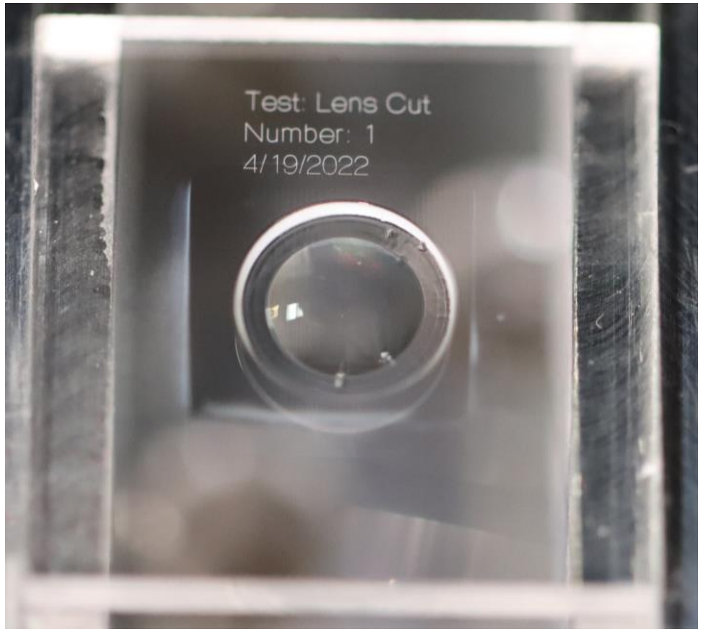


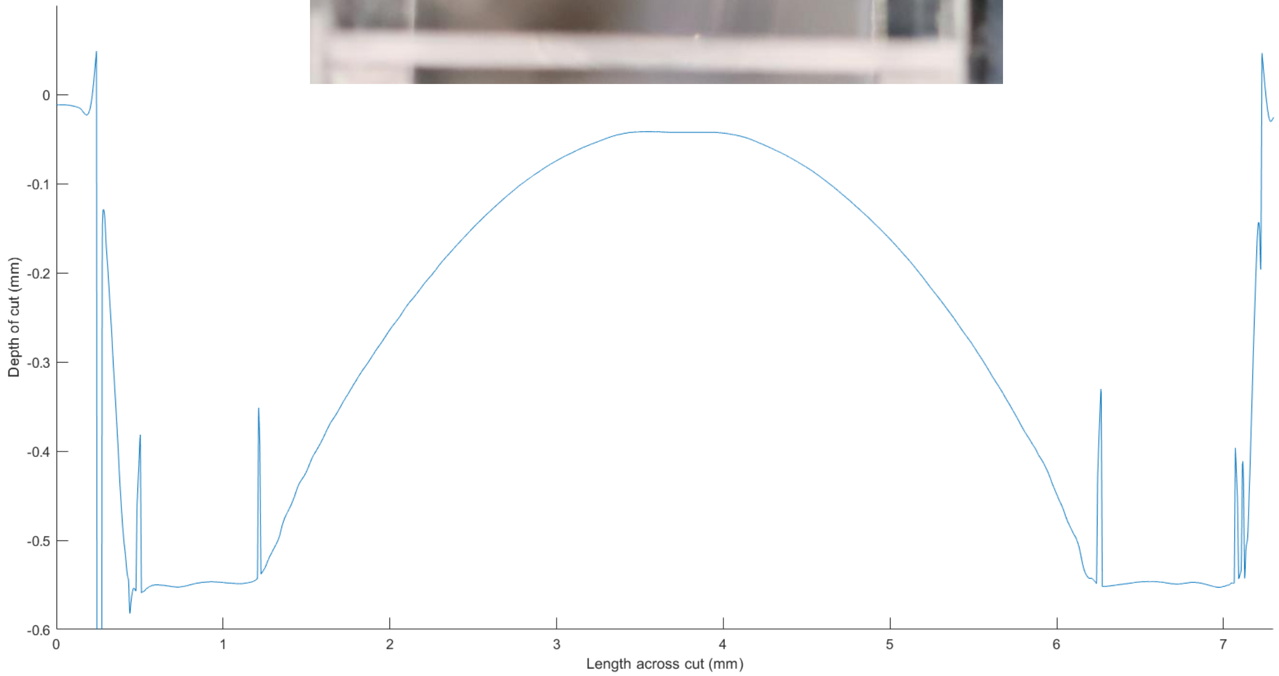
Keyence Sensor

Confocal displacement sensor:

- ❑ Range: ± 1.3 mm
- ❑ Resolution: 0.25 µm
- ❑ Spot size: 25 µm

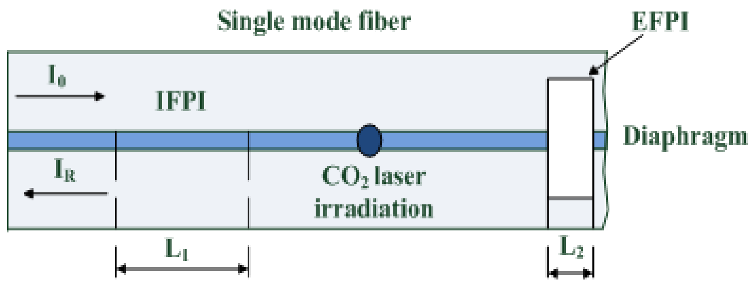


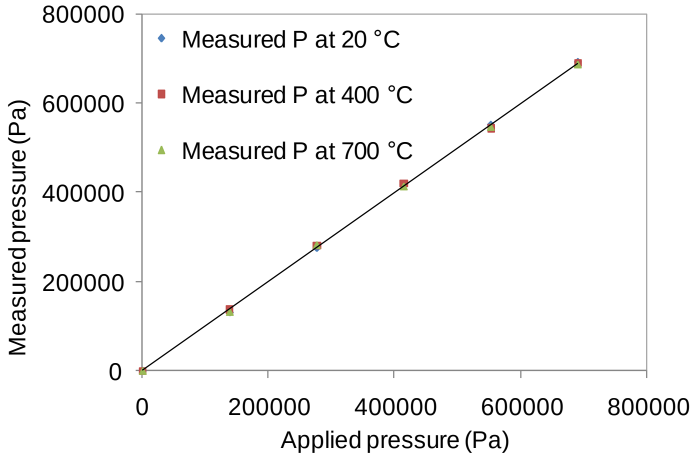


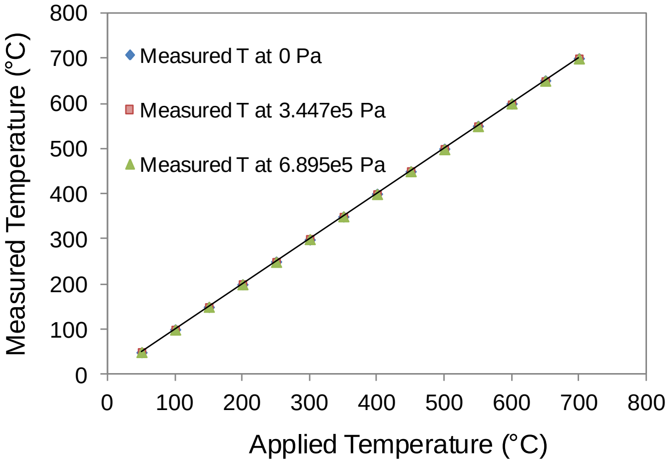


Embedded T & P Sensor

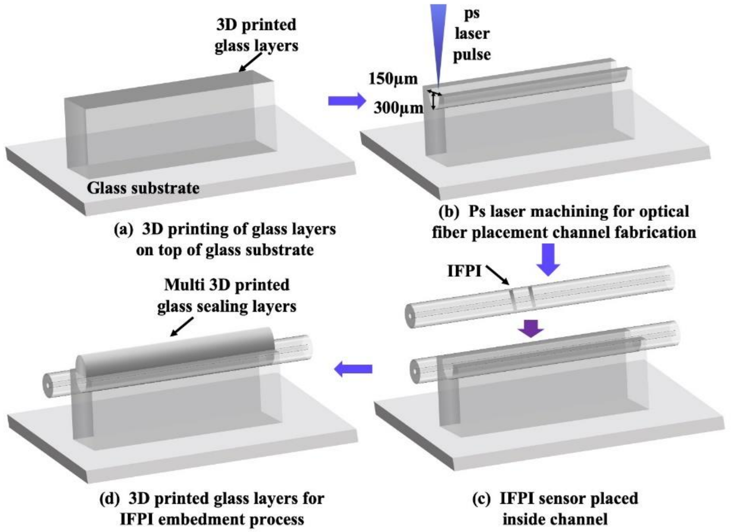
Cascaded Intrinsic and Extrinsic Fabry-Perot Interferometers

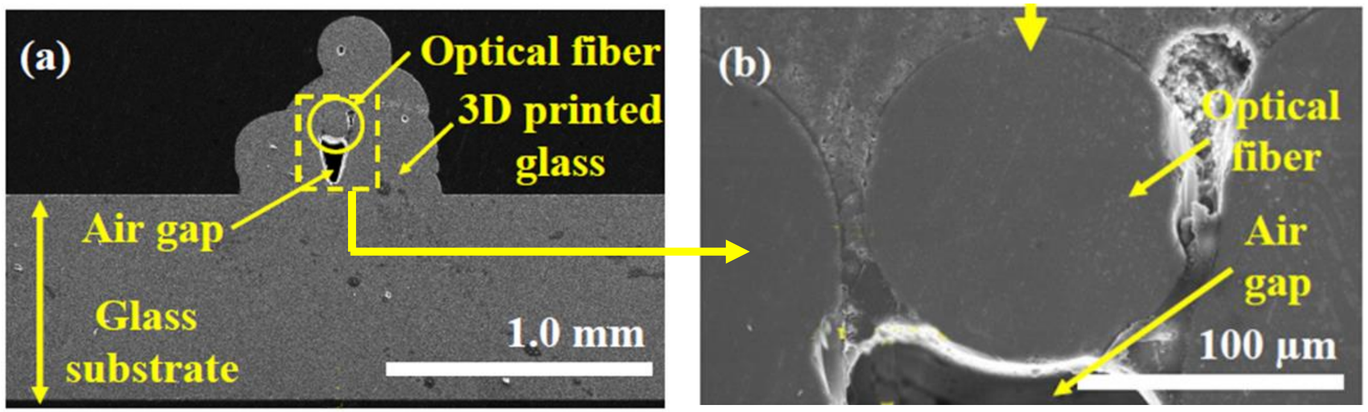






Embed the sensor in a 3D printed glass housing

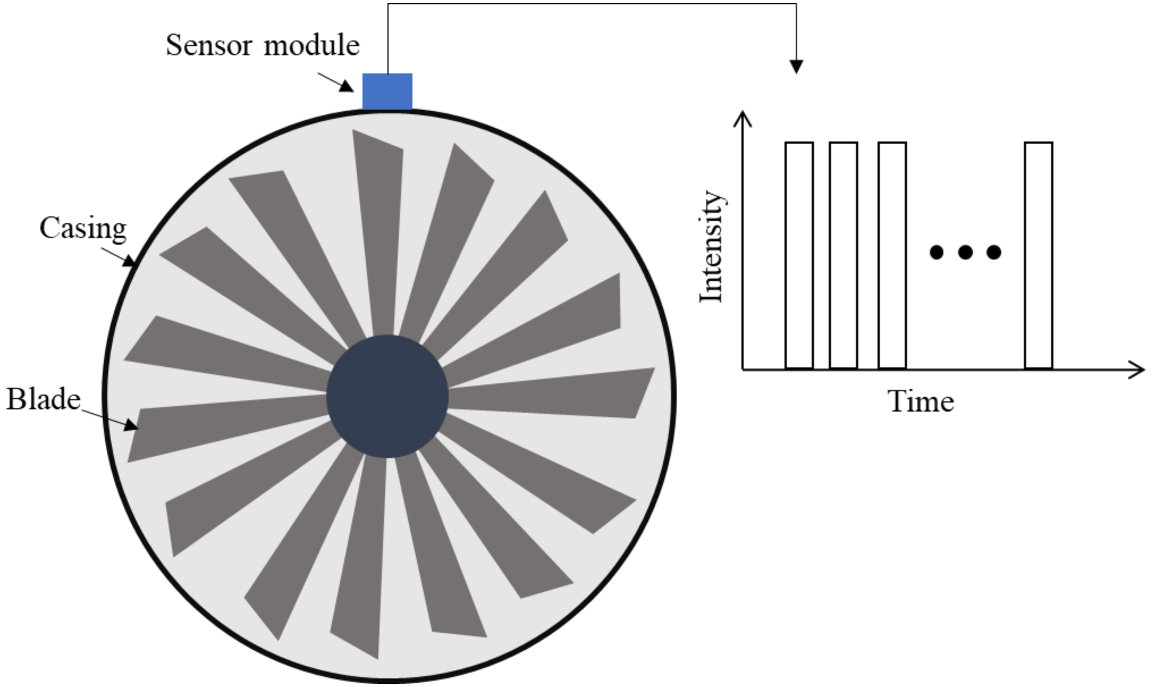


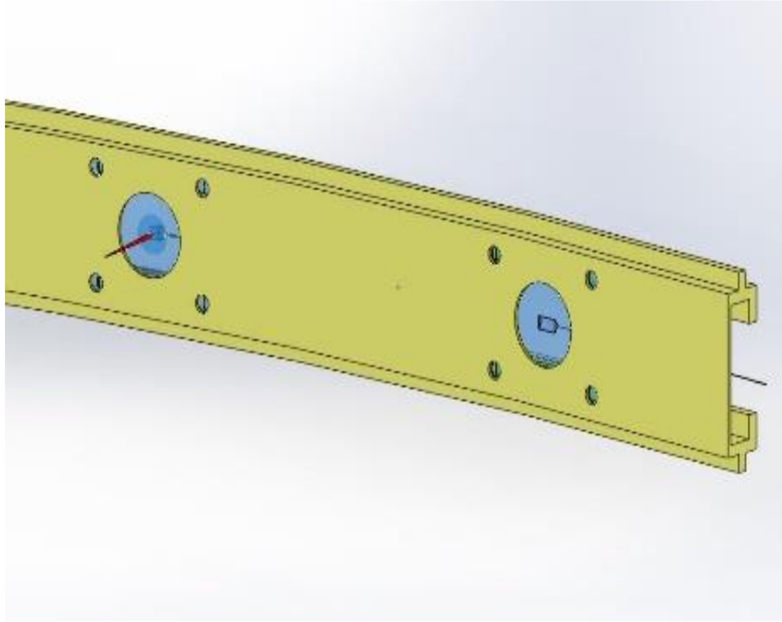


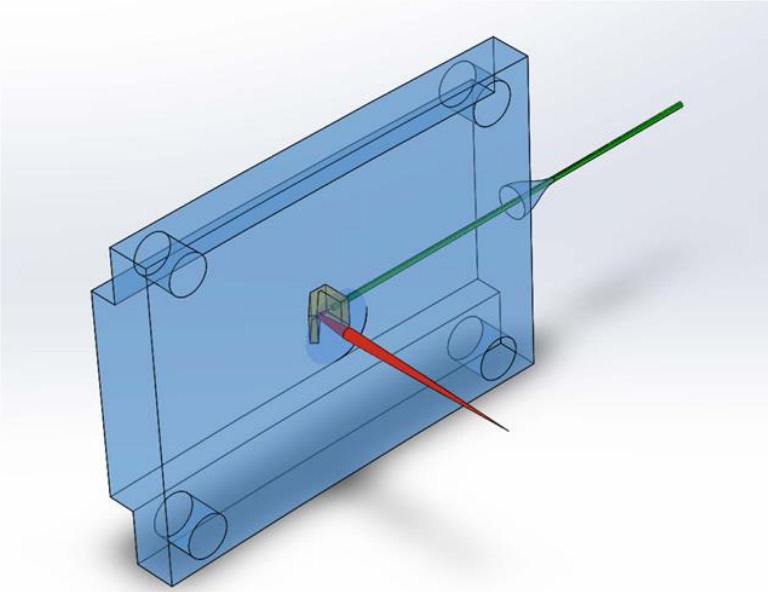
Blade tip-timing sensor

Blade Tip-Timing Sensing Requirements

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

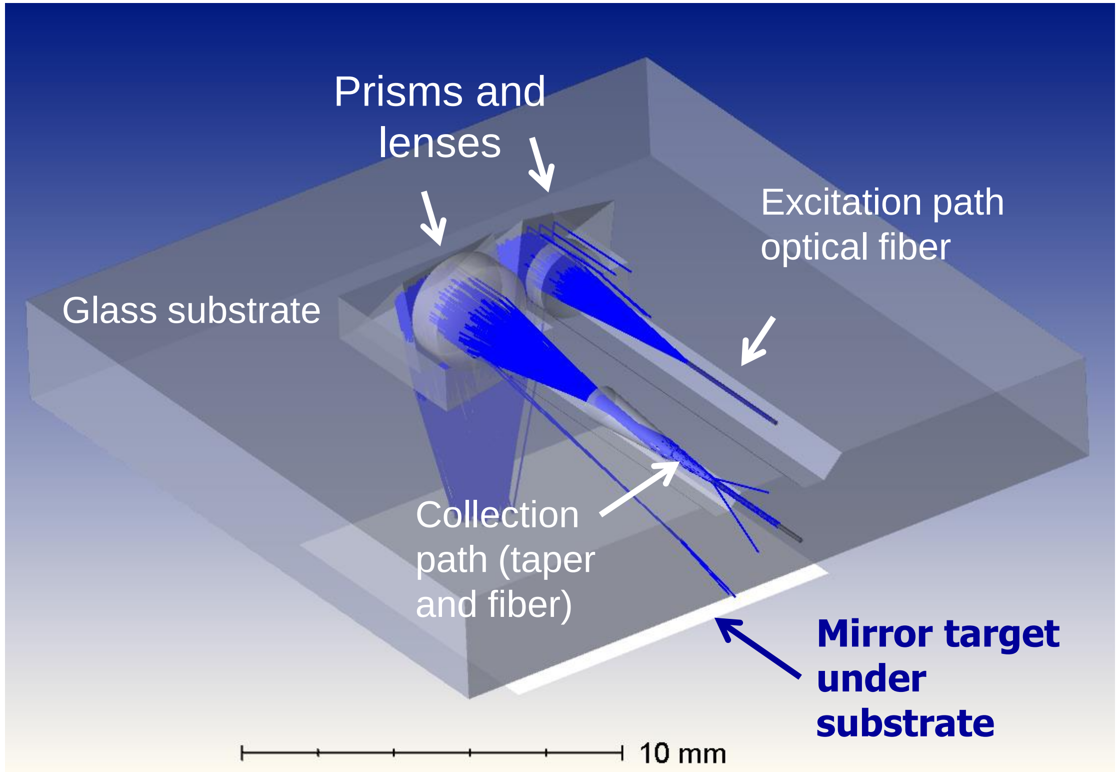




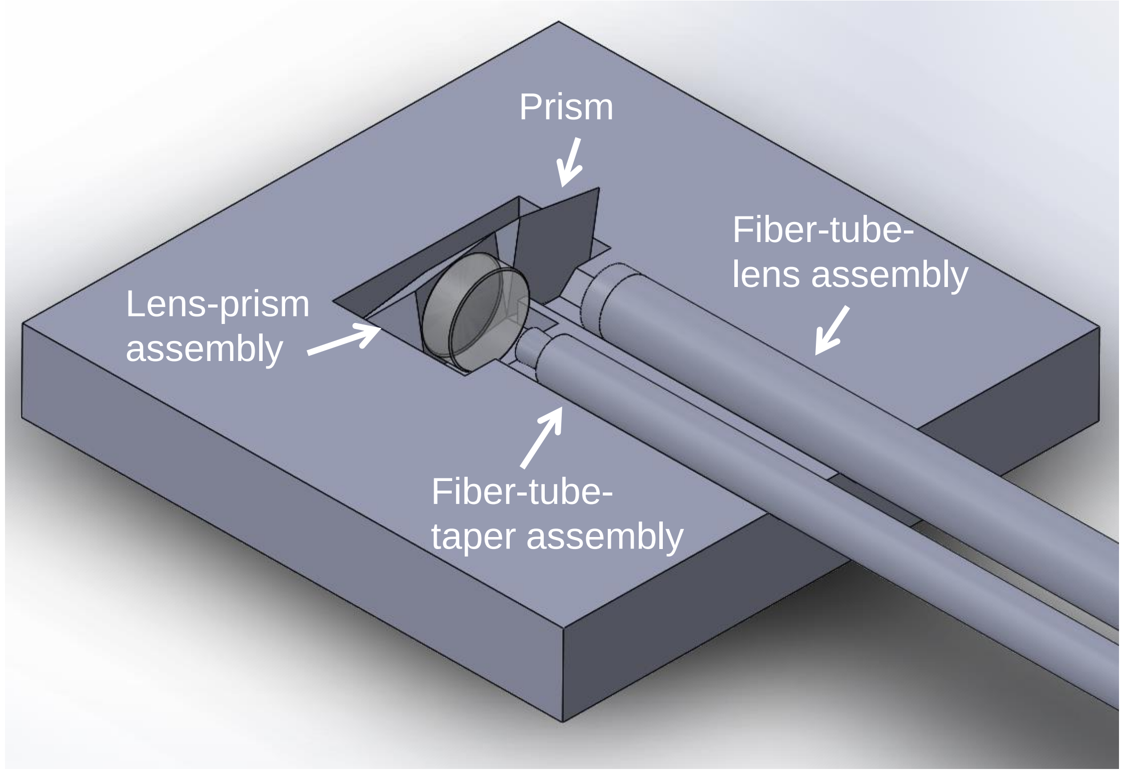


Blade tip-timing sensor

Sensor design in raytracing software (Zemax)



Zemax simulation

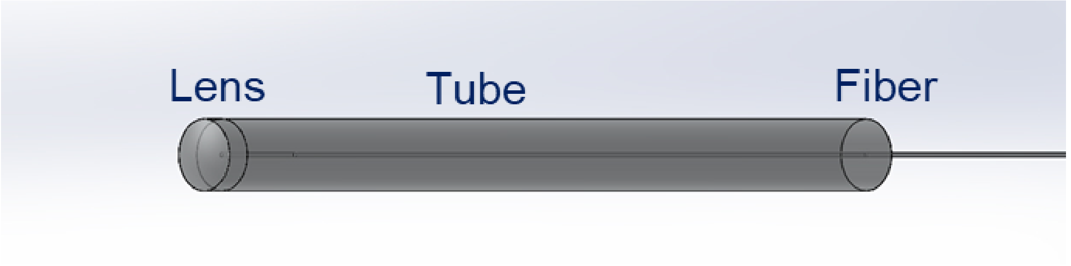


CAD model

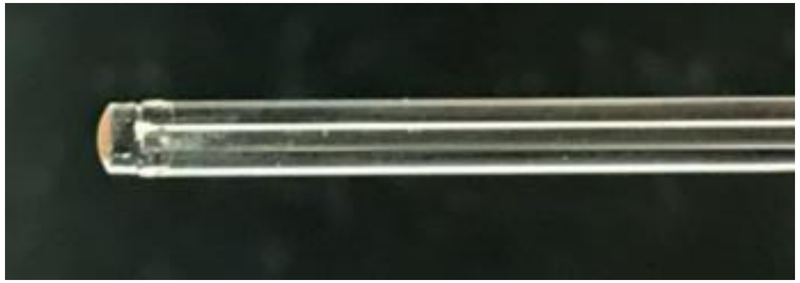
Fabrication of the Module

Fiber-tube-lens assembly:

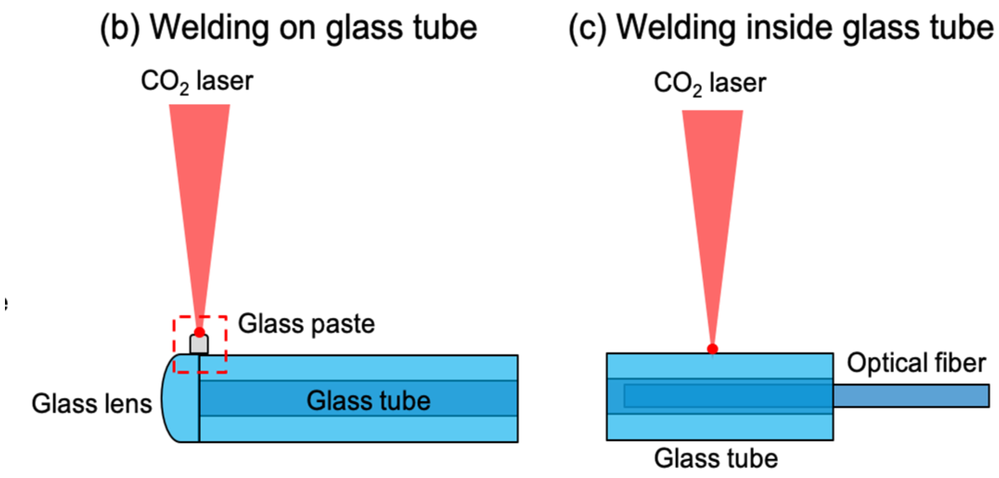
- A lens (D: 2mm) is welded on a tube (OD:2mm, IN:0.2mm) using a CO_2 laser.
- A fiber (D: 125 µm) is inserted into the tube and welded.



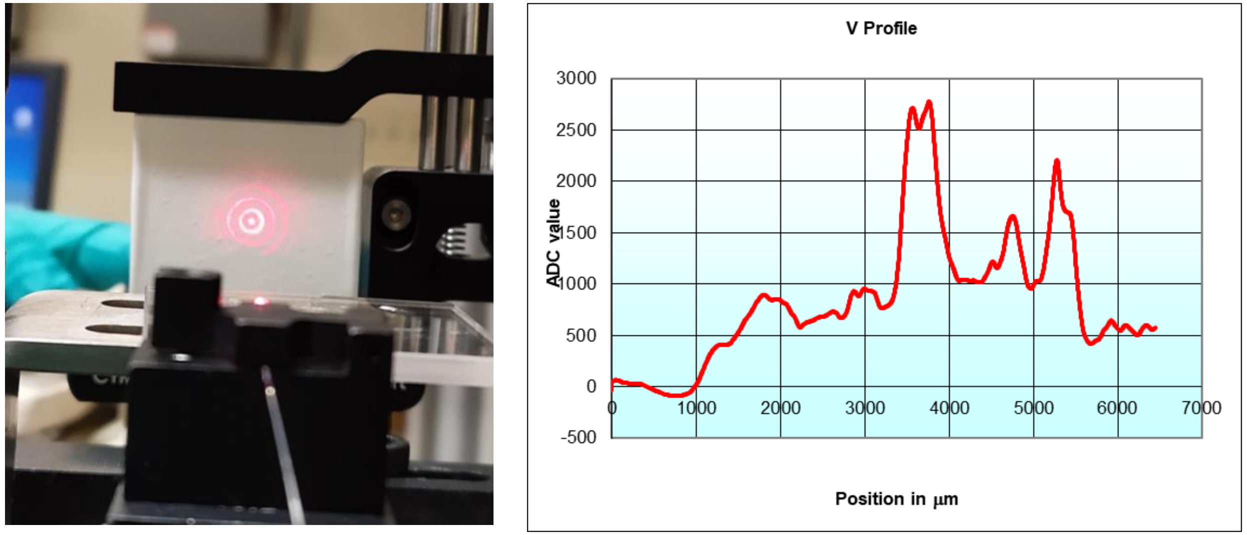
CAD model of lens-tube-fiber assembly



Welded lens-tube-fiber assembly



Laser welding procedures

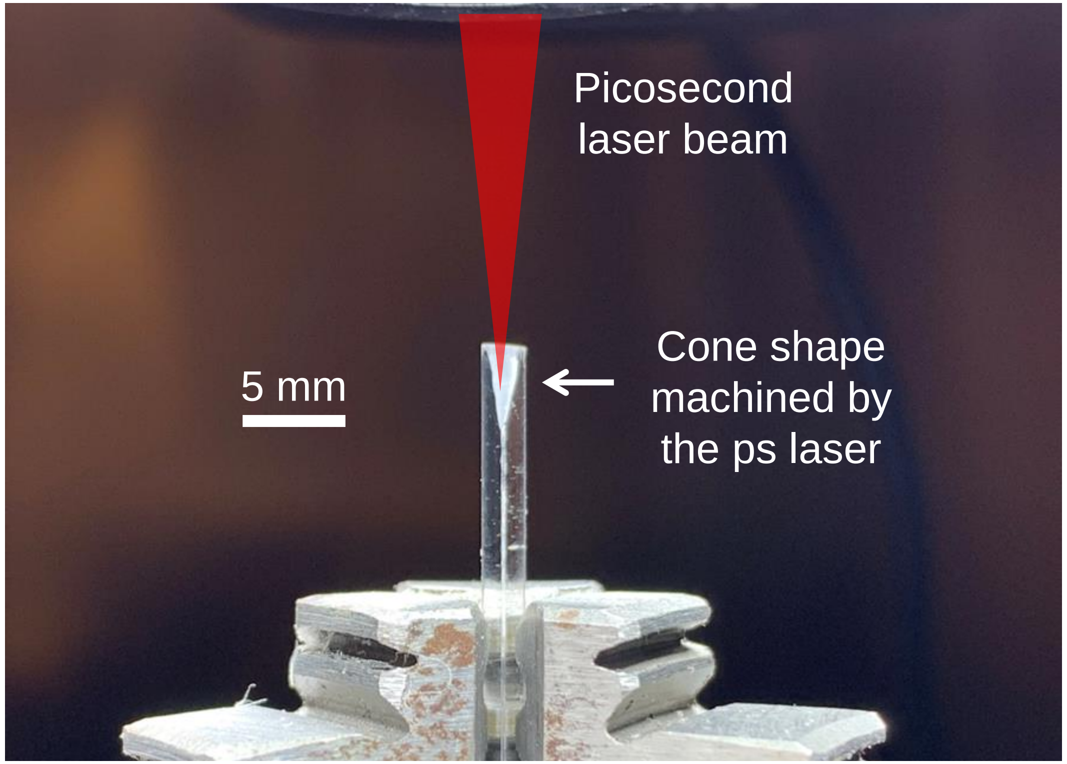


Output beam profile

Blade tip-timing sensor

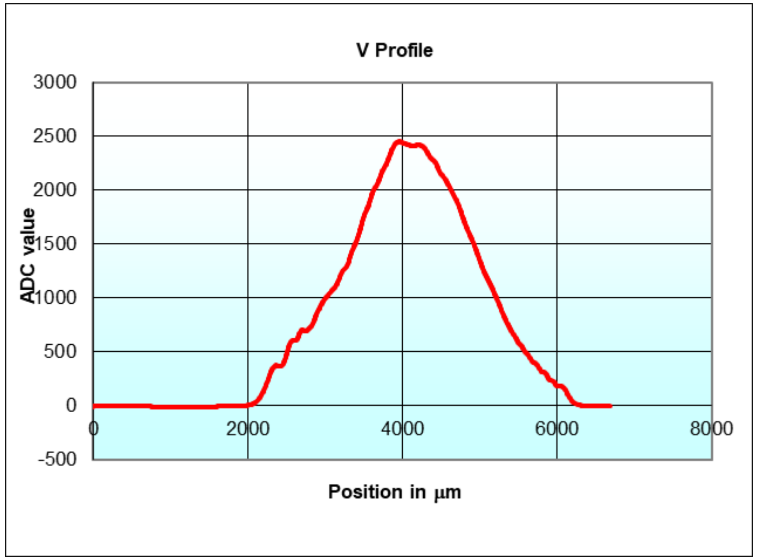
Fiber-tube-lens assembly:

- A cone-shaped opening is cut using a picosecond laser on one end of the tube to preserve the output beam's shape.



Ps laser cutting procedure

Fabricated lens-tube assembly

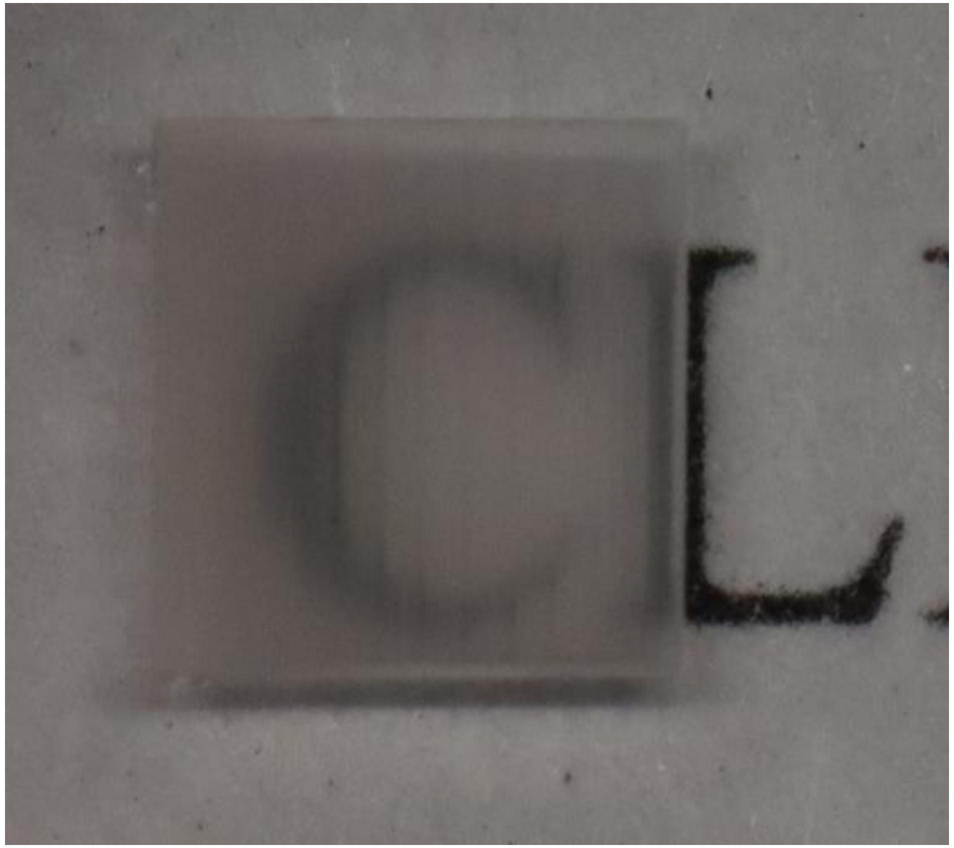


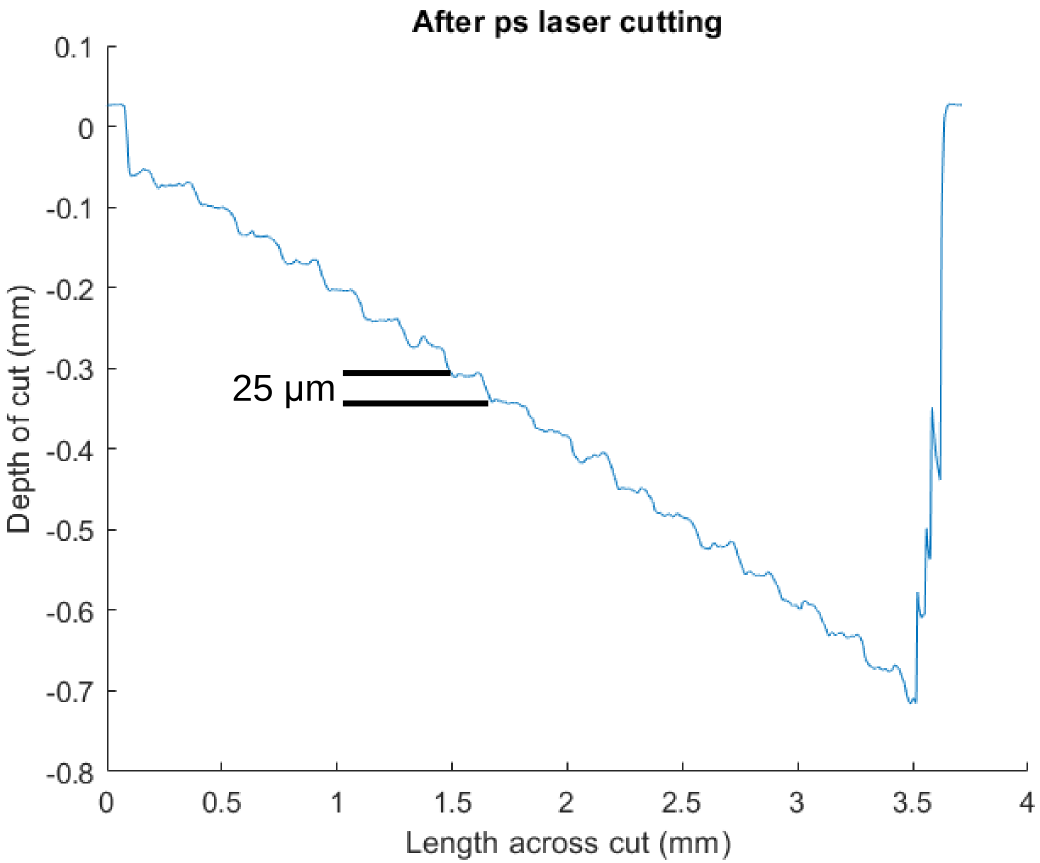
Output beam profile

Blade tip-timing sensor

9-degree tilted slant:

- The slant is cut by the picosecond laser layer by laser.
- One cutting layer is 25 μm.

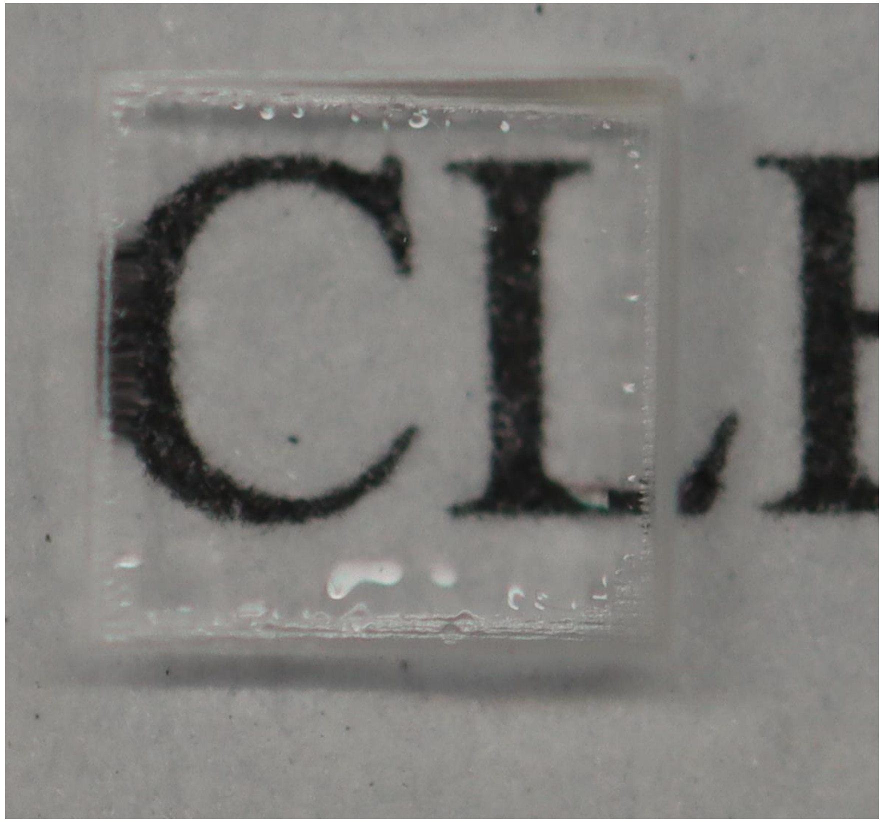


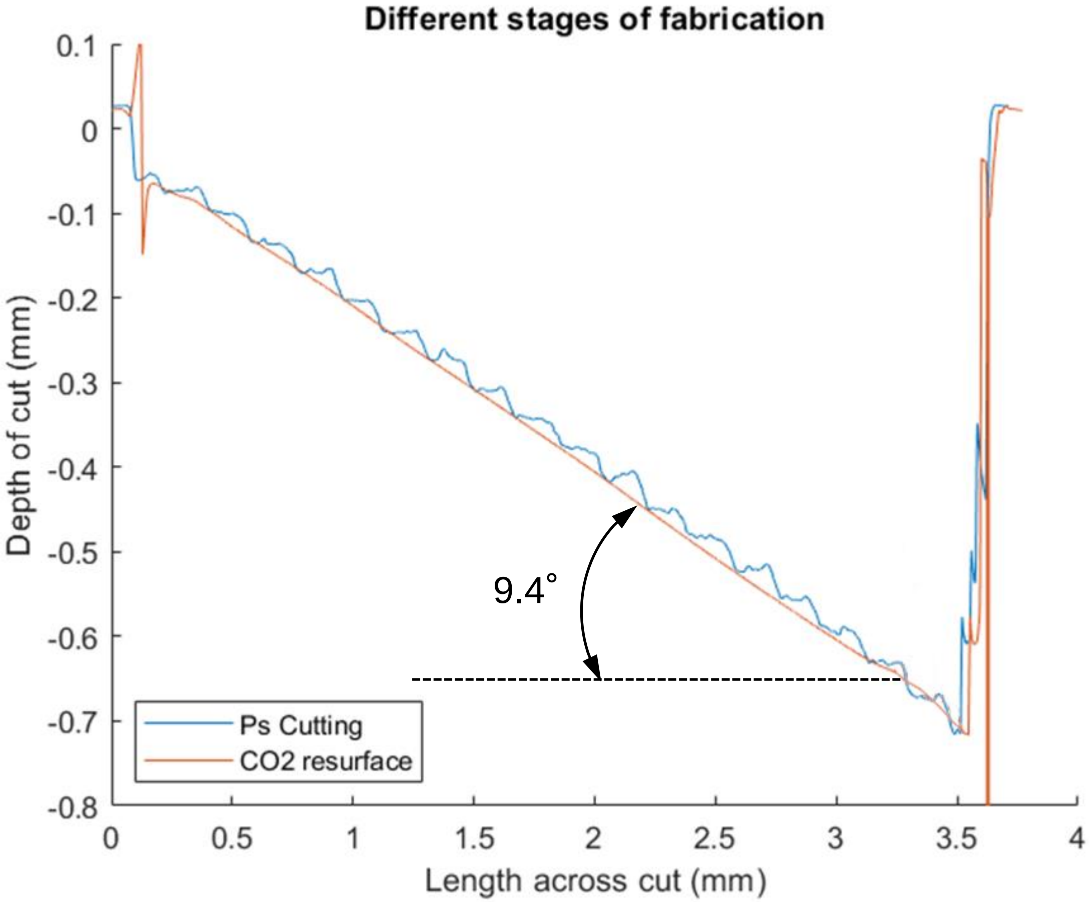


Blade tip-timing sensor

9-degree tilted slant:

- CO2 resurfacing reduces the surface roughness and makes it transparent.

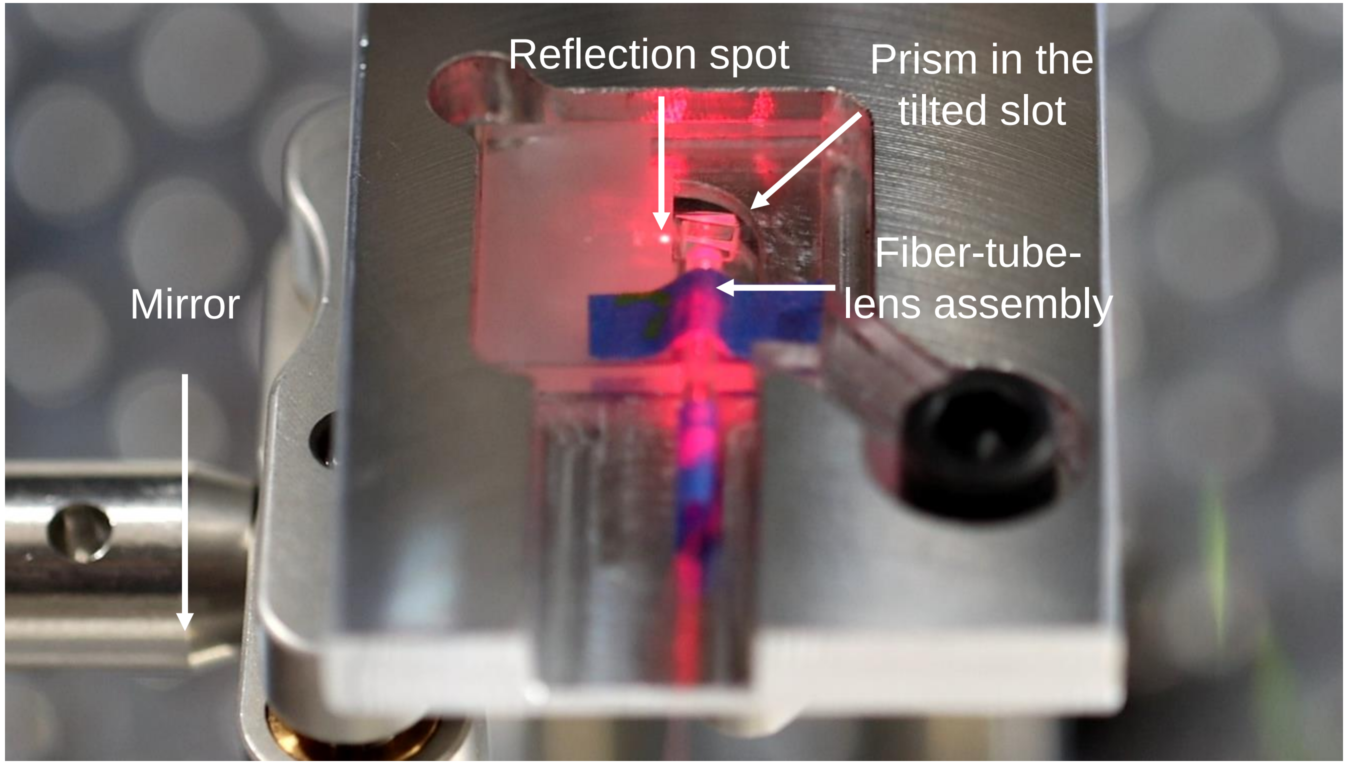


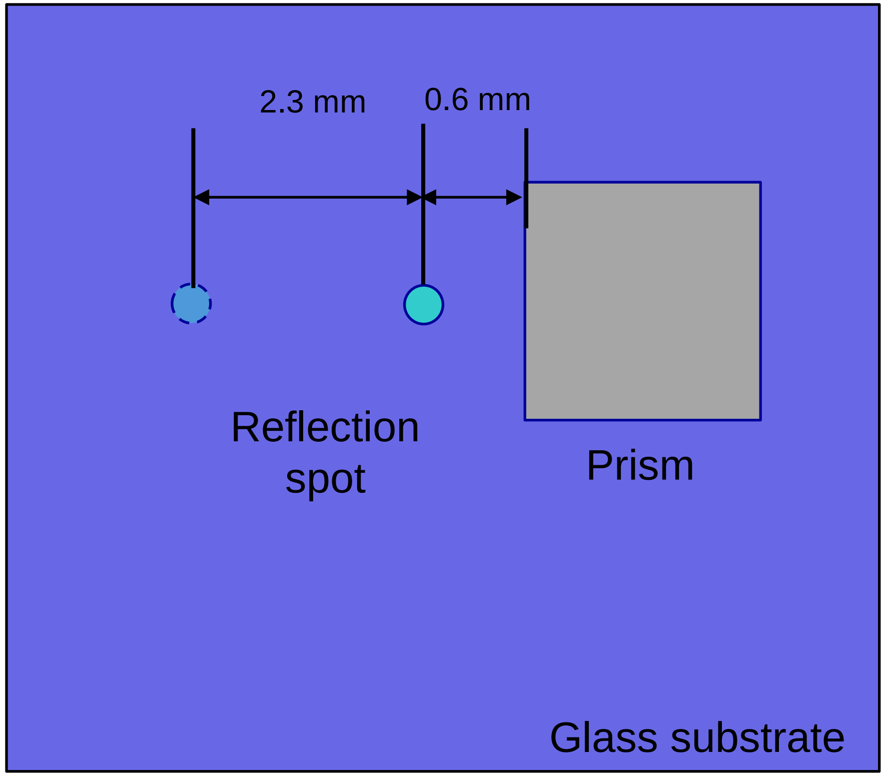


Blade tip-timing sensor

Excitation path:

- Fiber, tube and lens are fused together.
- Implement a fixture to align the component in-situ during fabrication.

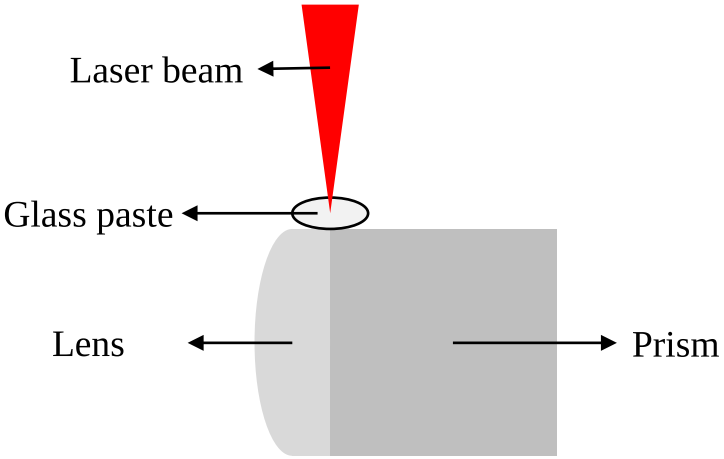




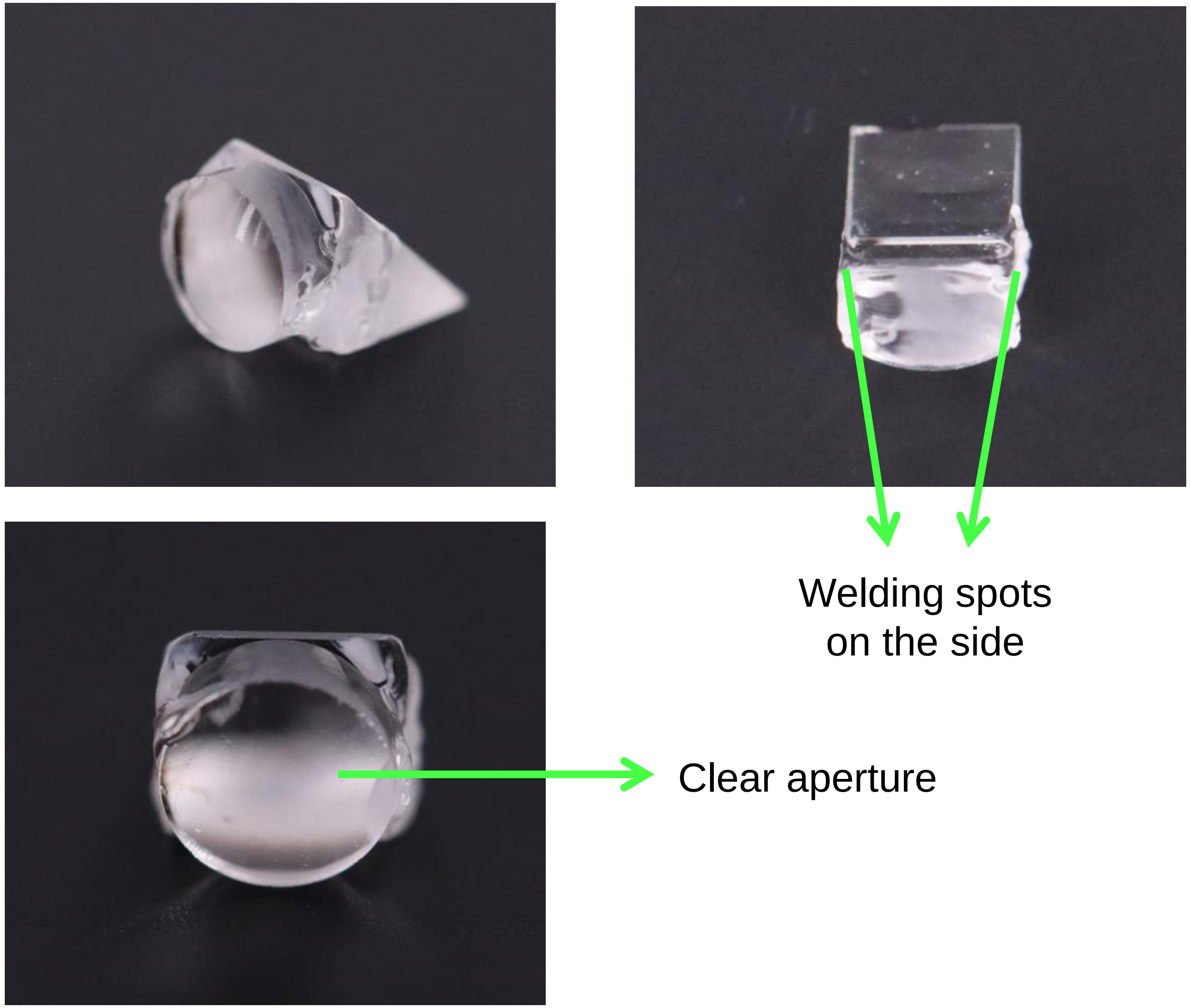
Blade tip-timing sensor

Lens-prism assembly:

- A 3 mm lens and a 3 mm prism are welded together using a CO_2 laser.



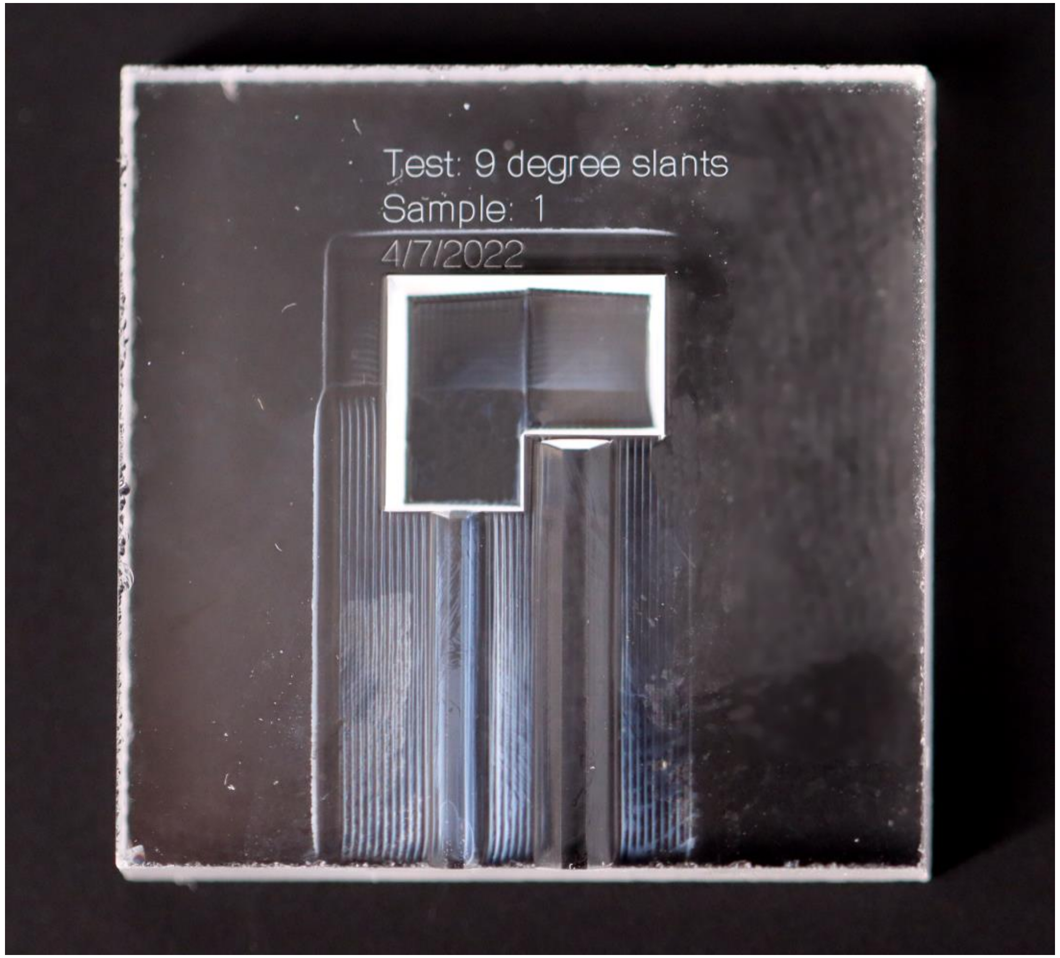
Laser welding procedures

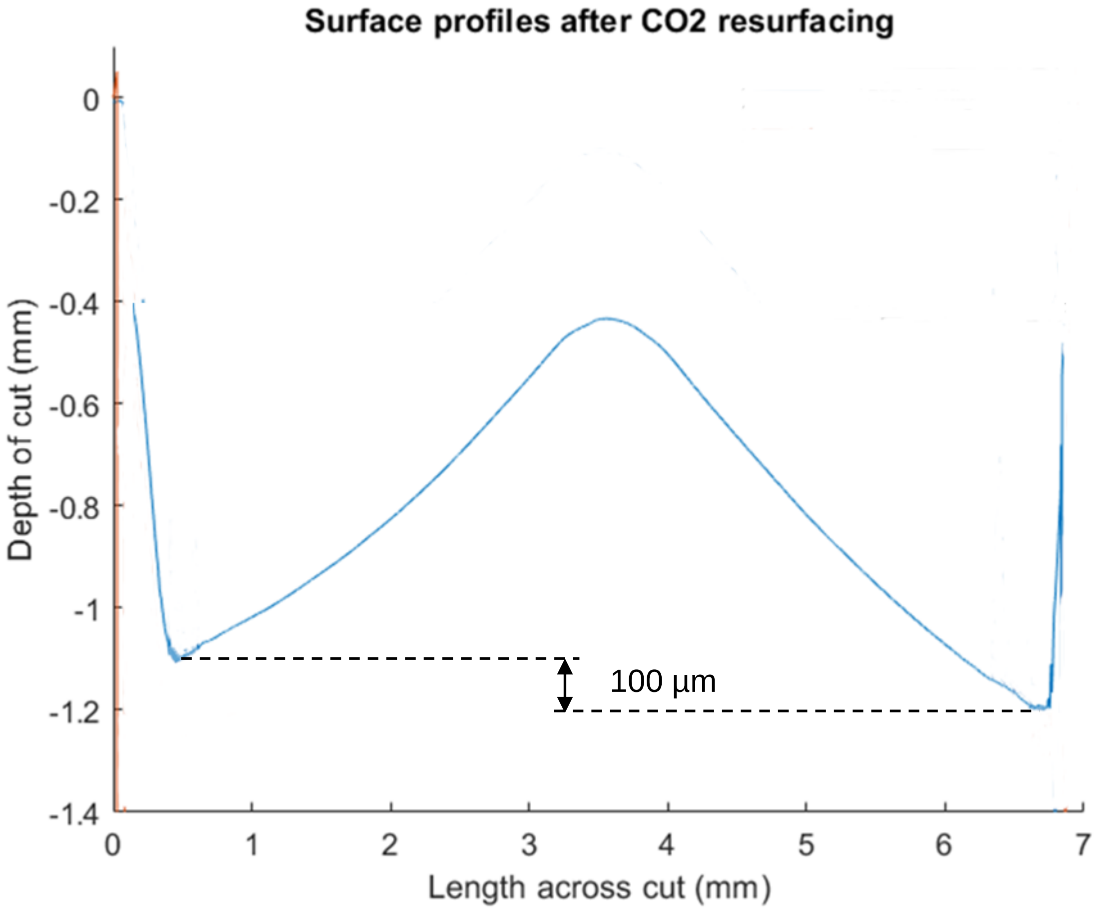


Blade tip-timing sensor

Fabricate both slots in one step:

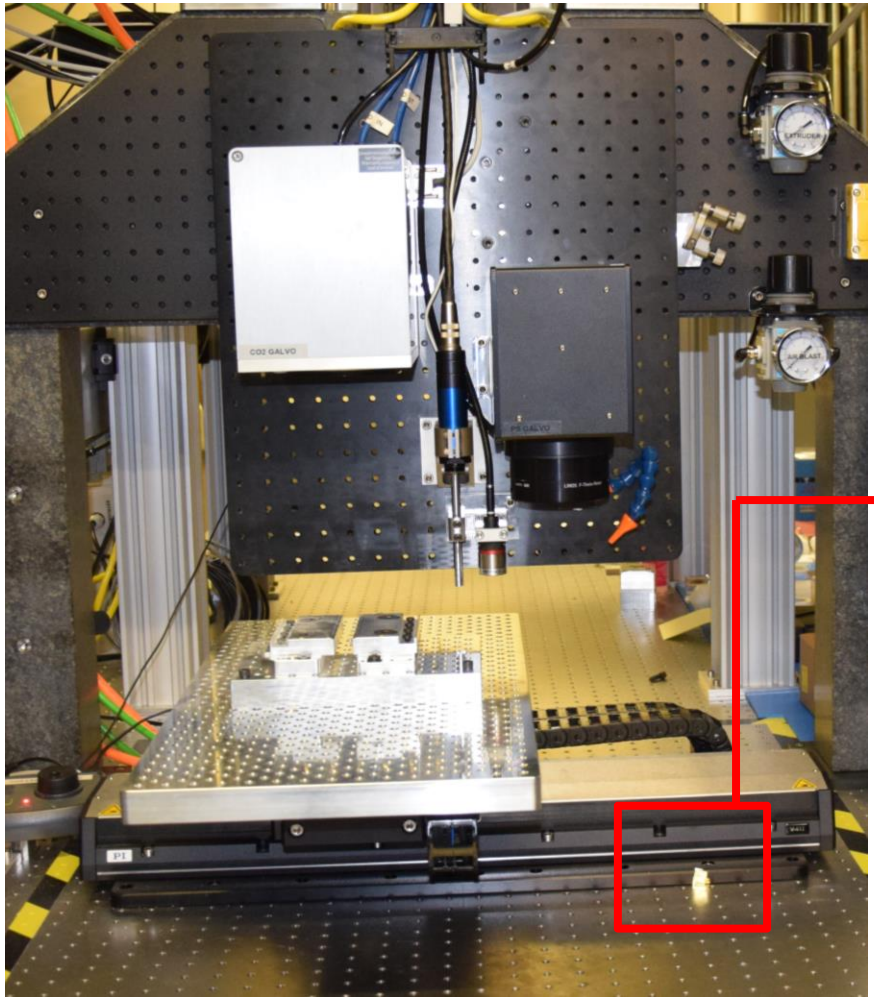
- ❑ Two tilted slots are cut and resurfaced.
- ❑ Collection efficiency is low because the tilting angle of the slots are not symmetric.

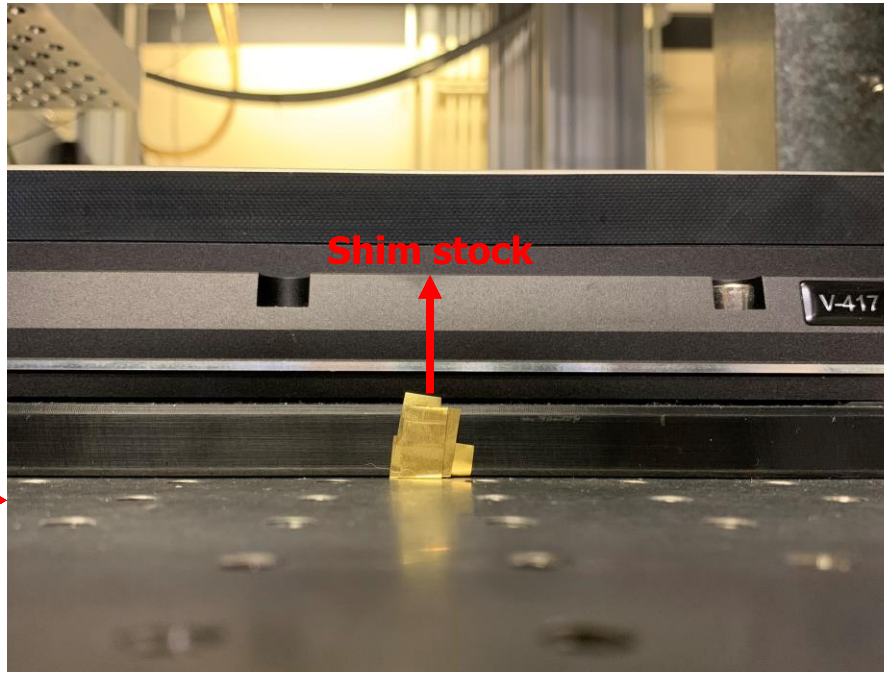




Blade tip-timing sensor

Stage alignment:





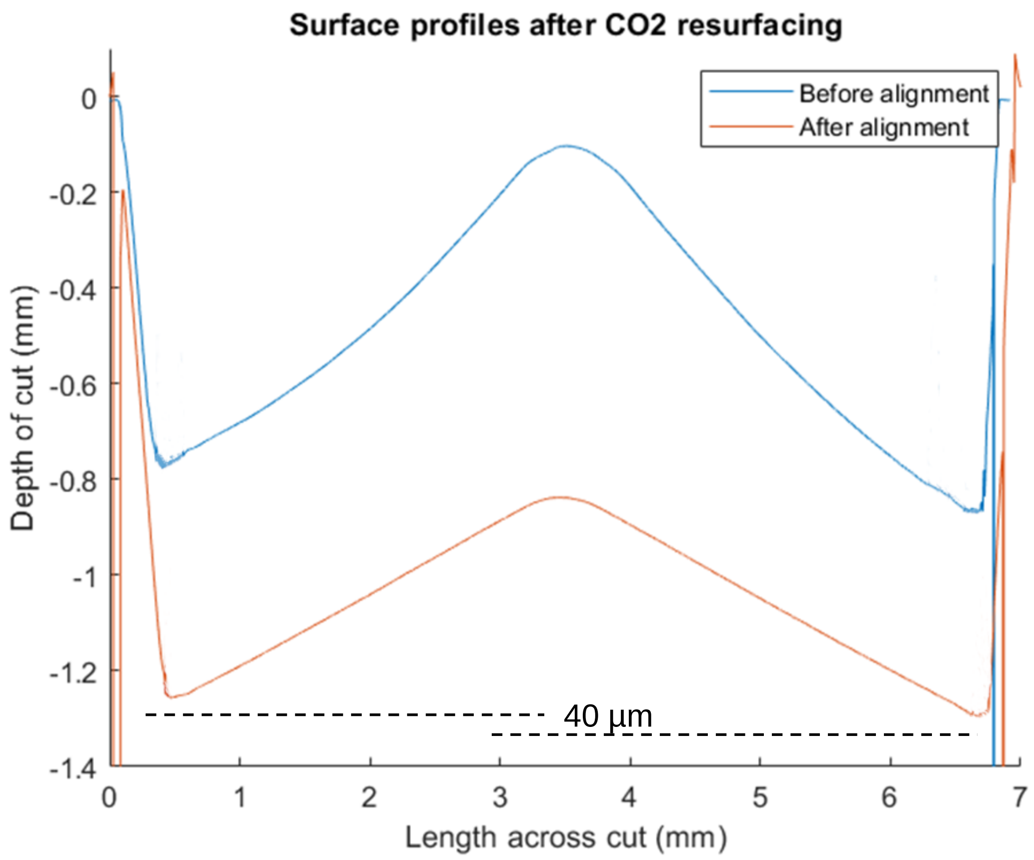
After alignment, tilt w.r.t the picosecond laser cutting plane:

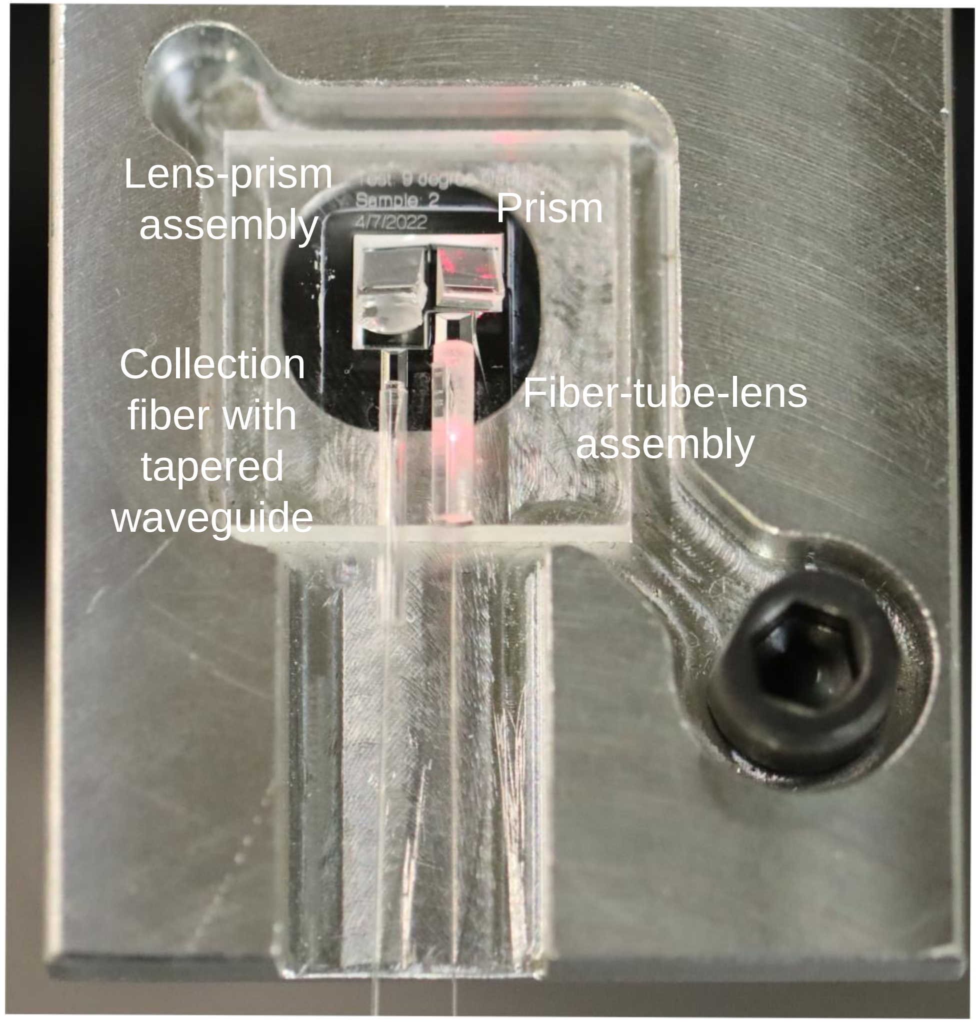
- 40 µm per 10 mm in X direction.
- 16 µm per 10 mm in Y direction.

Blade tip-timing sensor

Improved substrate fabrication:

- After alignment, the slots are symmetric.
- The sensor prototype is assembled and tested.
- Reception is improved by 20 dB.

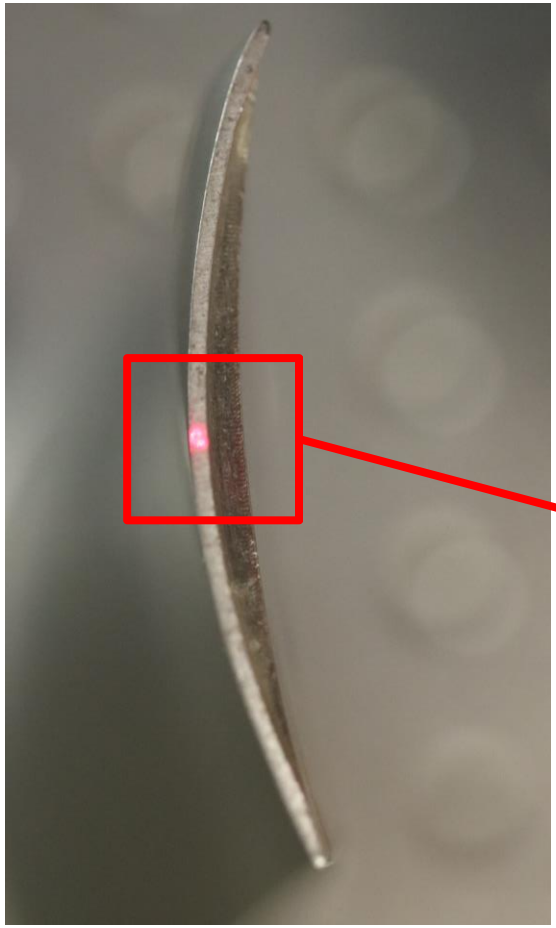


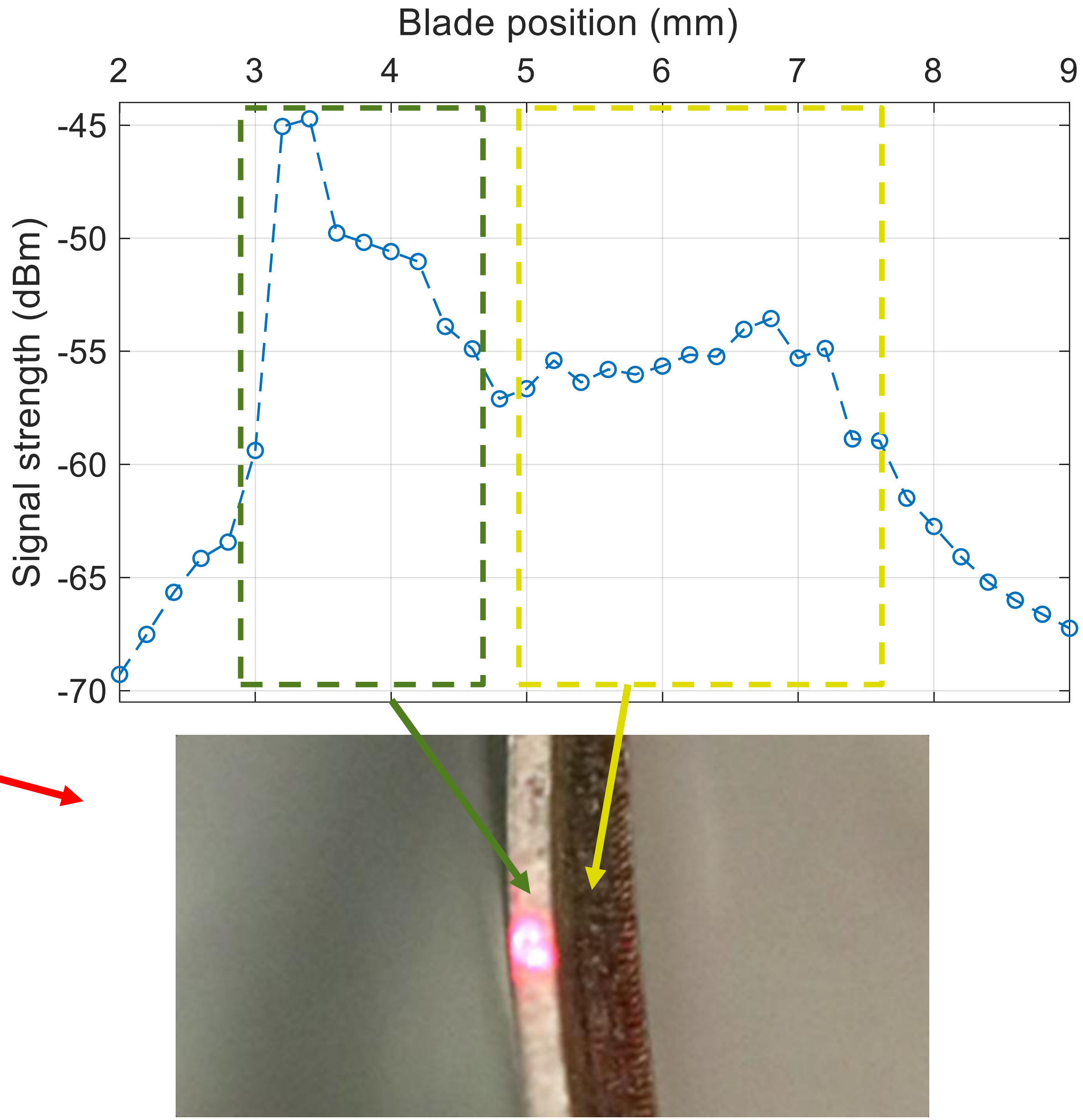


Blade tip-timing Sensor

Prototype test with a blade model:

- Peak received power is -44.6 dBm, with 10 dBm input power.
- Signal-to-noise ratio is about 20 dB.





Project Status

Budget Period I (01/2020-09/2022)

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 (**Completed**)
- ❑ Tip timing sensor module prototypes are fabricated, assembled and tested under laboratory conditions (**09/30/2022, on schedule to complete**).

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 (09/30/2022):

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

BP2 (10/01/2022 – 09/30/2023):

- ❑ 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.