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Micro-Structured Sapphire Fiber Sensors for Harsh Environment Applications

Dr. Hai Xiao
Samuel Lewis Bell Distinguished Professor
Department of Electrical and Computer Engineering
Center for Optical Materials Science and Engineering Technologies (COMSET)
Clemson University
Tel: 864-656-5912
Email: haix@clemson.edu
http://people.clemson.edu/~haix/

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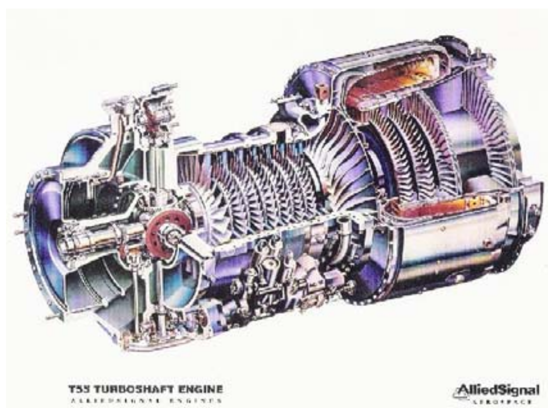
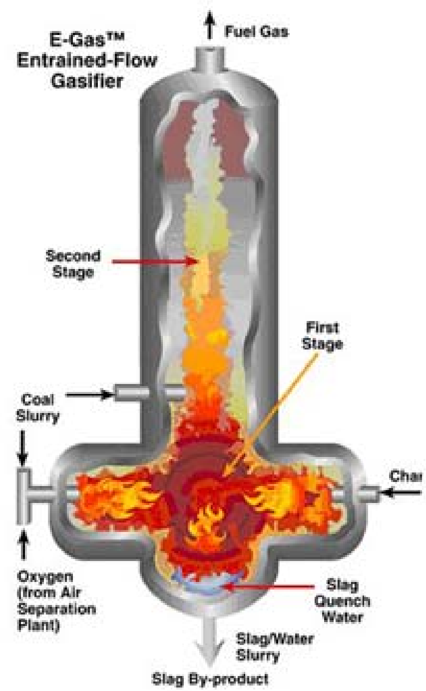
Outline

- Introduction
- Objectives
- Assembly-free, micromachined sensors
- The novel OCMI concept and results
- Summary

Introduction

- **Demands:** Advanced energy systems (e.g., clean coal) will rely heavily on sensors and instrumentation for
  - Advanced process control/optimization
  - Key components monitoring, protection, maintenance scheduling, lifecycle management
  - Increased efficiency, reduced emission and lowered cost





Sensor Requirements

Temperature	**Up to 1600°C**
Pressure	**Up to 1000 psi**
Atmosphere	**Highly erosive and/or corrosive**
Loading	**Large strain/stress**

- Survive and operate in the high-T, high-P and corrosive/erosive harsh environments for a long period of time
  - Dependable performance
  - Robustness
  - Long term stability
  - Easy installation and maintenance
  - Acceptable cost
- Sensors and monitoring technologies (commercial and research) capable of operating in harsh conditions are extremely limited

Project Overview

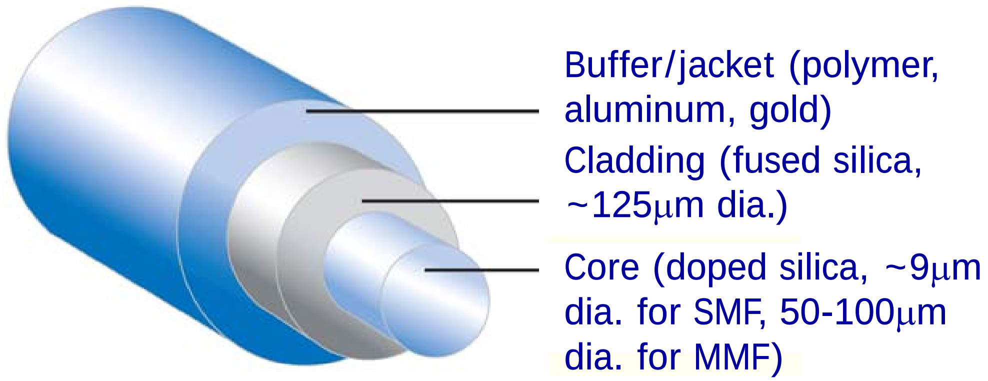
- Main objective:
  - Development and demonstration of sensors for measurements of high temperature (up to 1600^{o}C), strain, and pressure.
- Awarded under the Cross-cutting Advanced Research Program:
  - DE-FE0001127
  - Program managers: Susan Maley and Barbara Carney
- Interdisciplinary team:
  - Missouri S&T (lead), Clemson University, University of Cincinnati, and Ameren Corp. (consultant)
  - Project started on Oct. 1, 2009
- Success criteria:
  - Demonstrate capability in simulated laboratory environments.

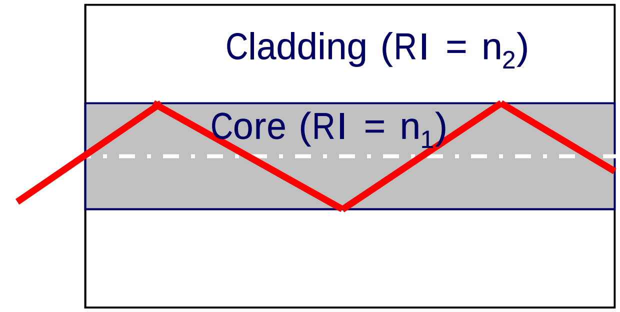
Approaches

- **Dependable Performance:** Micro-structured sapphire fiber interferometers
- **Robustness:** Assembly-free, one-step fs laser micromachining of the sensor directly on a sapphire fiber
- **Long-term stability:** Novel sapphire fiber cladding technology
- **Distributed measurement:** Multiplexed sensors
- **Demonstration:** Tests and performance evaluations in simulated high temperature laboratory conditions

Optical Fiber Sensor

- **Optical fiber:** A light pipe made of doped fused silica





Total internal reflection when $n_1 > n_2$

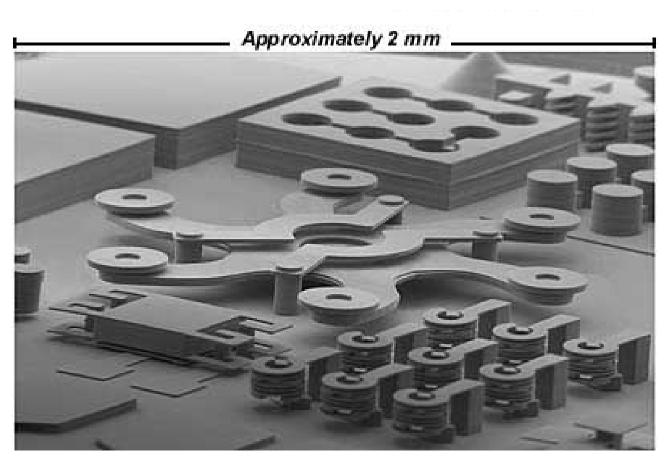
- **Fiber sensors:** proven advantages for applications in hostile environments
  - Small size/lightweight
  - Immunity to electromagnetic interference (EMI)
  - Resistance to chemical corrosion
  - High temperature capability
  - High sensitivity
  - remote operation
  - Multiplexing and distributed sensing

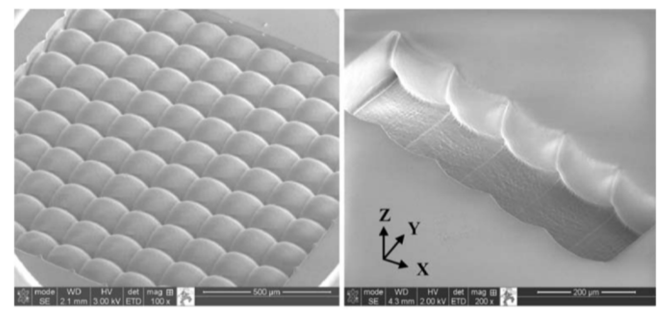
Single Crystal Sapphire Fiber

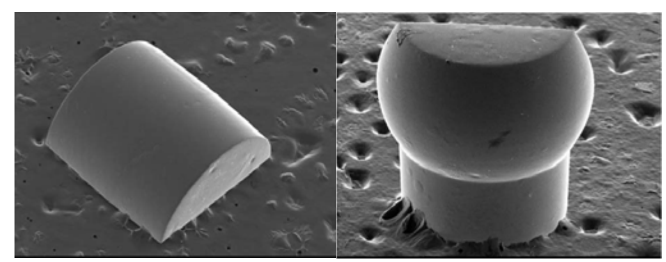
- Limitations of Fused Silica Fibers
  - Operation temperatures are limited under 800°C
  - Long term stability is a concern
- Single crystal sapphire fibers
  - Very high melting temperature (2053°C)
  - Large transmission window (200 – 5000 nm)
  - Fabrication method: Laser-Heated Pedestal Growth (LHPG, lower loss) or Edge-Defined Film-Fed Growth (EFG)
  - Good candidate for high temperature sensing
- The issues
  - High loss
  - Poor waveguide (no cladding, highly multimode, contamination)
  - Difficult in connection (NA mismatch, diameter mismatch, cannot fusion splice)

Assembly-Free Sensors

- Micromachining methods
  - Photolithography and etching (e.g., MEMS)
  - Micromachining (e.g., Laser, focused ion-beam)
- Advantages
  - Dependable performance (guaranteed by design)
  - Improved Robustness (No CTE mismatch)
  - Enhanced functionality (3D structures)
  - Low cost and fast prototyping
- Assembly-free micromachining
  - A promising approach to fabricate robust sensors for harsh environment applications





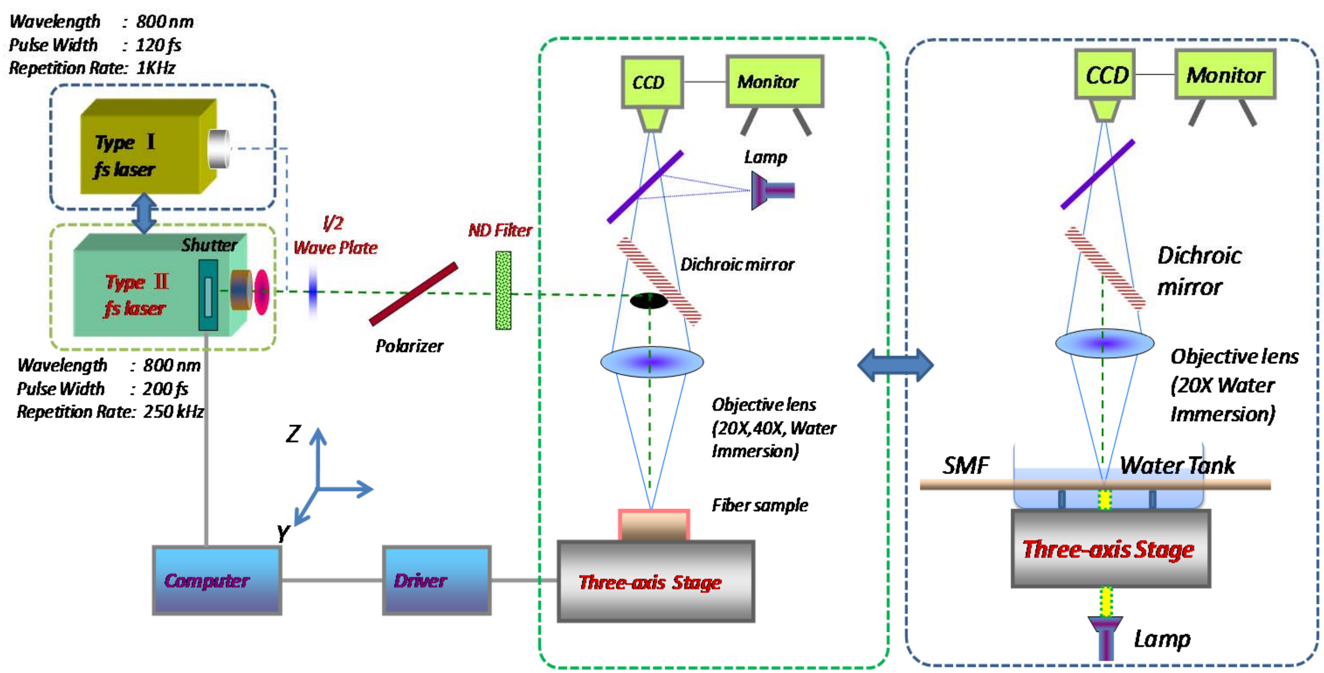


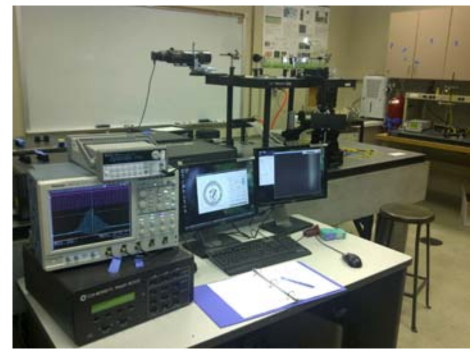
Micro-Assembly based Sensors

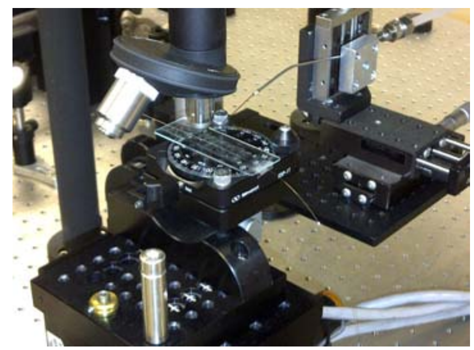
- **Micro Assembly:** The conventional way to fabricate silica fiber sensors
- **Disadvantages**: Complicated process, time consuming, non guaranteed performance, minimum robustness(CTE difference, strength of the bonding), high cost
- Fusion based assembly cannot used to join two crystal materials such as sapphire fibers
- Micro-assembly is not a valid solution for high temperature harsh environment applications

Fs Laser Micromachining

- Femtosecond (fs) laser micromachining:
  - High accuracy (sub-micron)
  - One-step, fast ablation or material modification
  - Works for a diverse variety of materials including metal, silica, polymer, sapphire, etc.
  - 3D capability, inside the material (underneath the surface)







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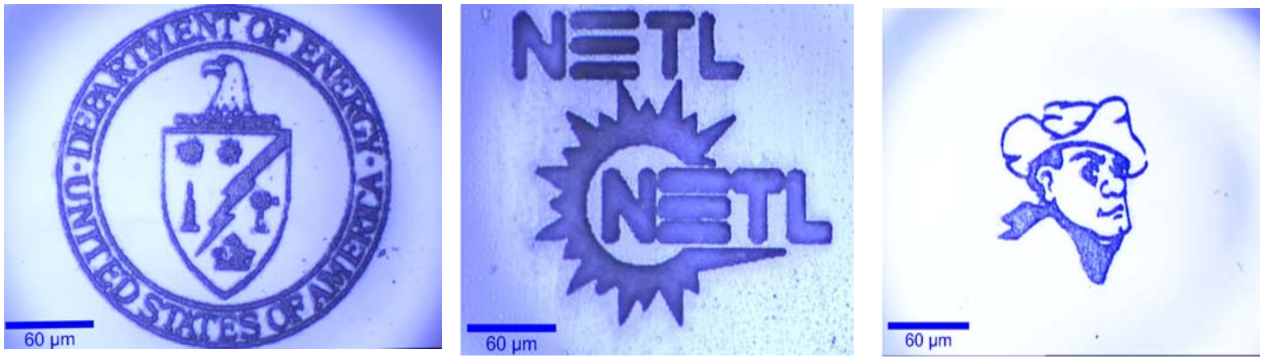
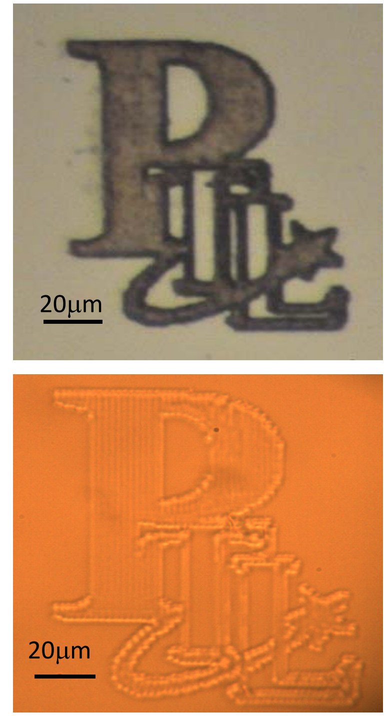
Micro-machined Patterns



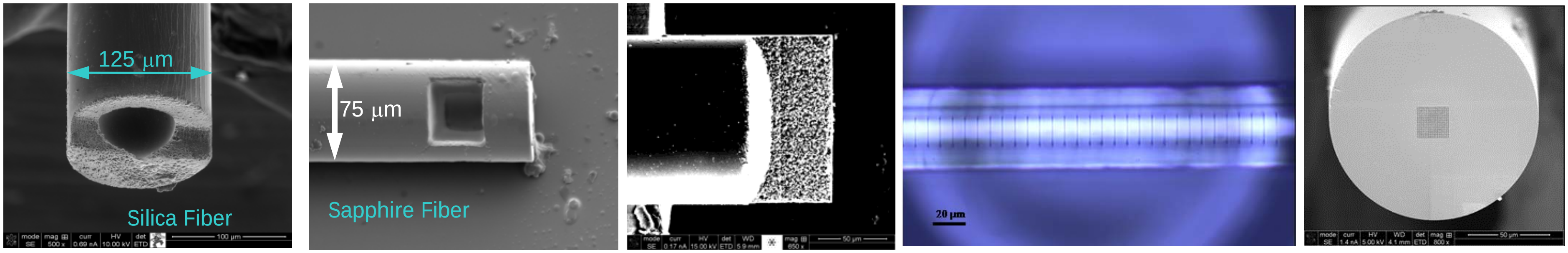


Enabling a new paradigm of fabricating micro sensors and devices

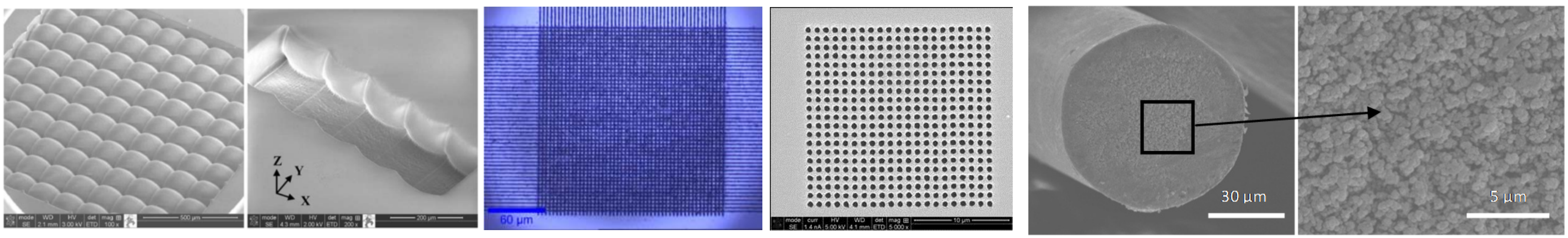
fs laser micromachining

Assembly-Free Micro Devices

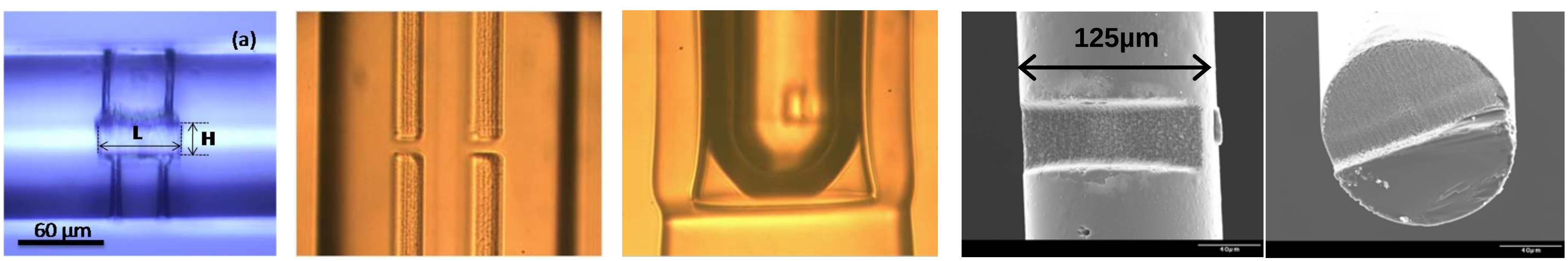
✓ **Assembly-free fiber optic sensors**



✓ **Photonic micro/nanostructures**

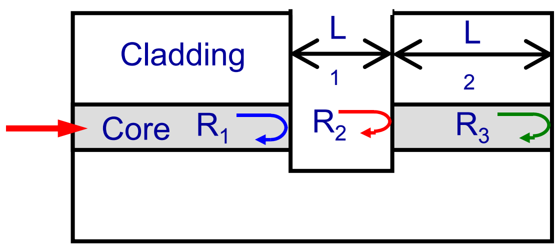


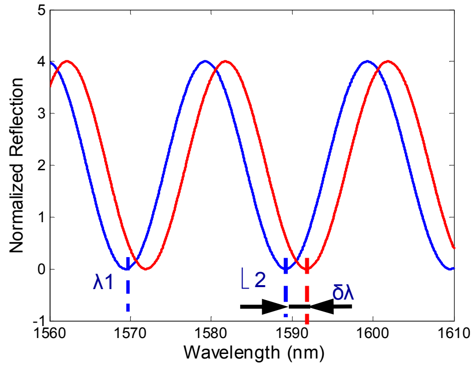
✓ **Microfluidics and optofluidics**

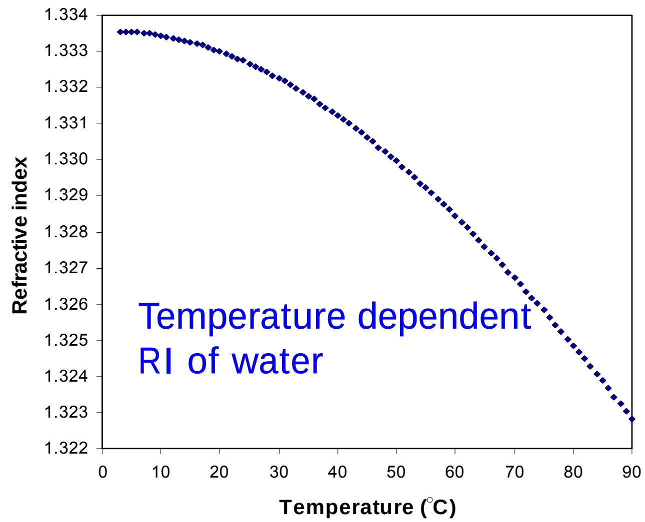


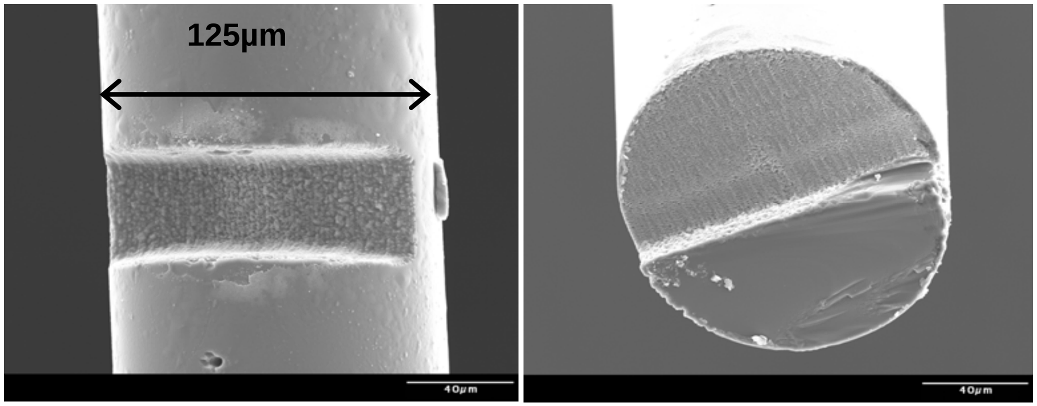
Assembly-Free Inline FPI

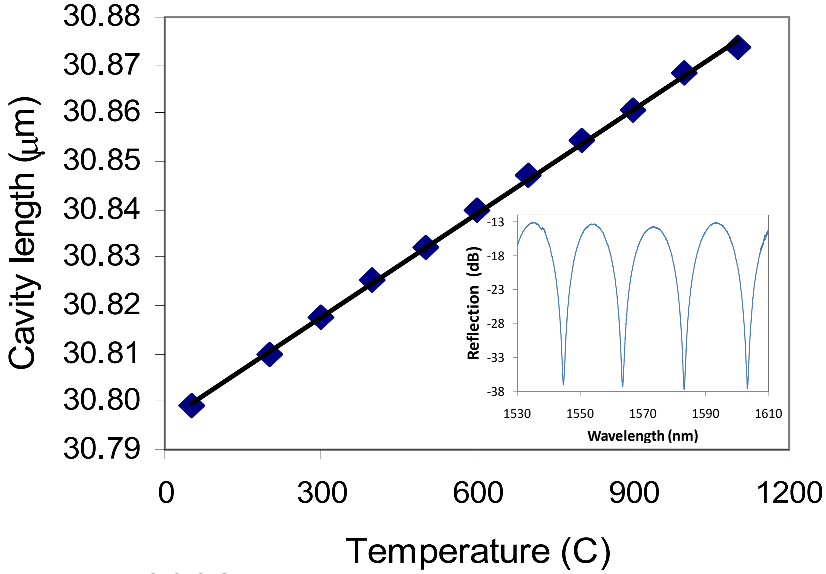
- Inline FPI fabricated by fs laser micromachining
  - High-T capability (1100^{o}C)
  - Negligible T-cross sensitivity
  - Bending measurement
  - RI measurement through the open cavity







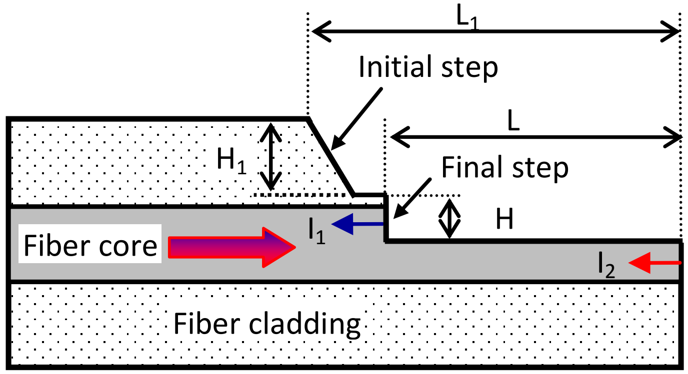


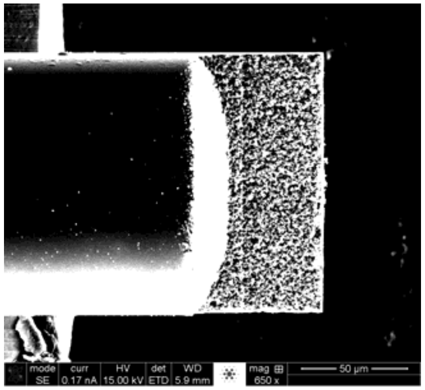


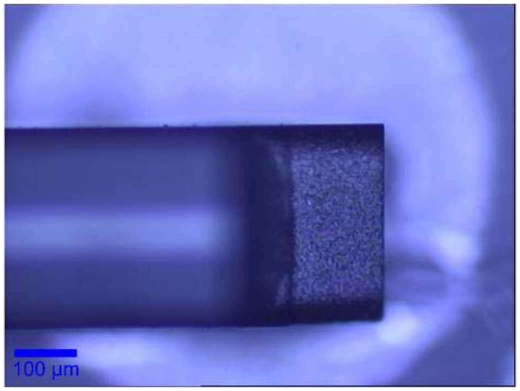
T. Wei et al. Optics Letters, 2008; T. Wei et al. Optics Express, 2008.

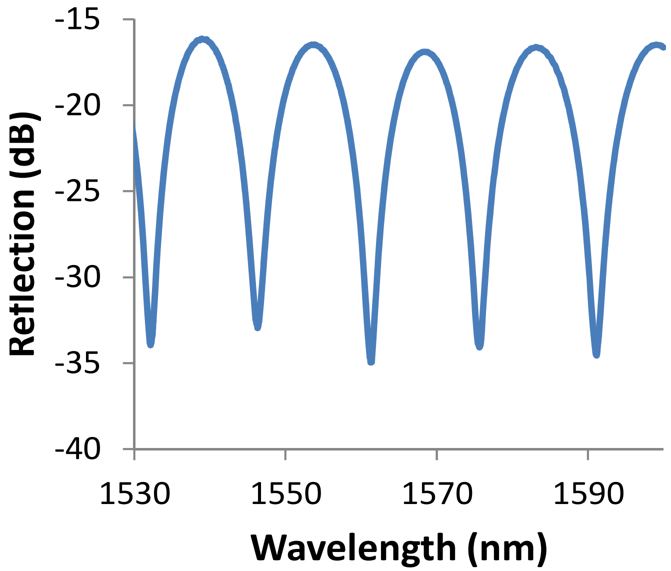
Inline Michelson Interferometer

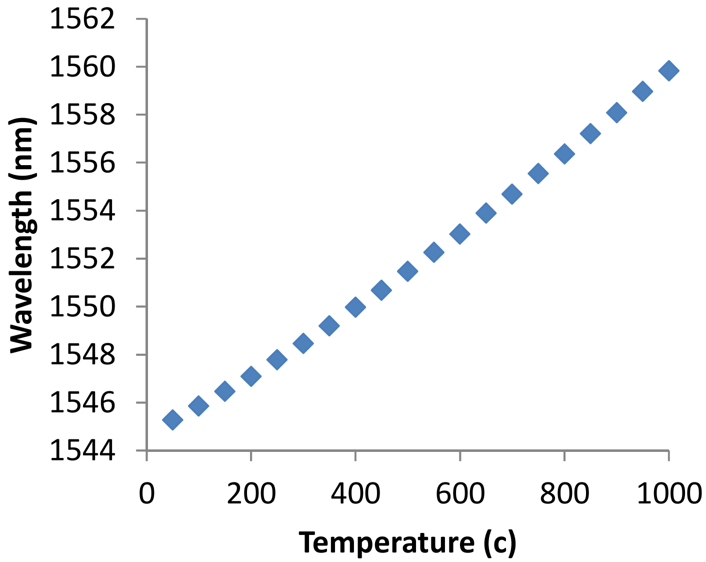
- Michelson Interferometer made by splitting a fiber tip







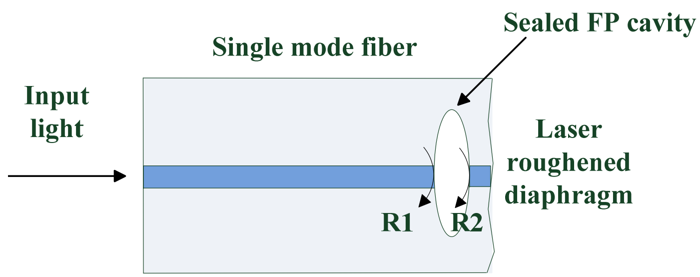


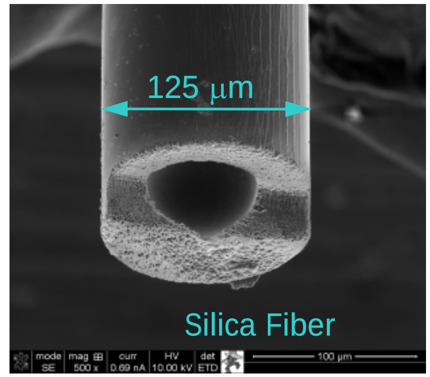


L. Yuan et al. Optics Letters, 2012.

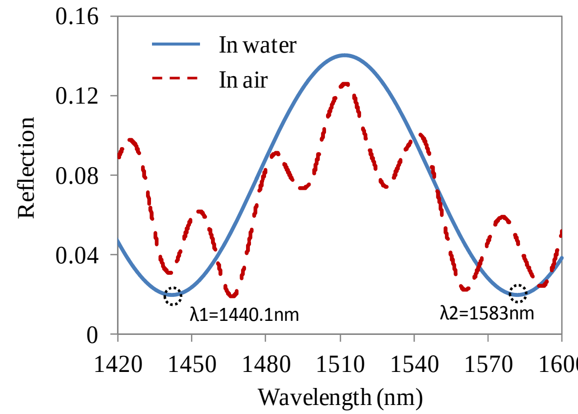
Pressure sensor at high-T

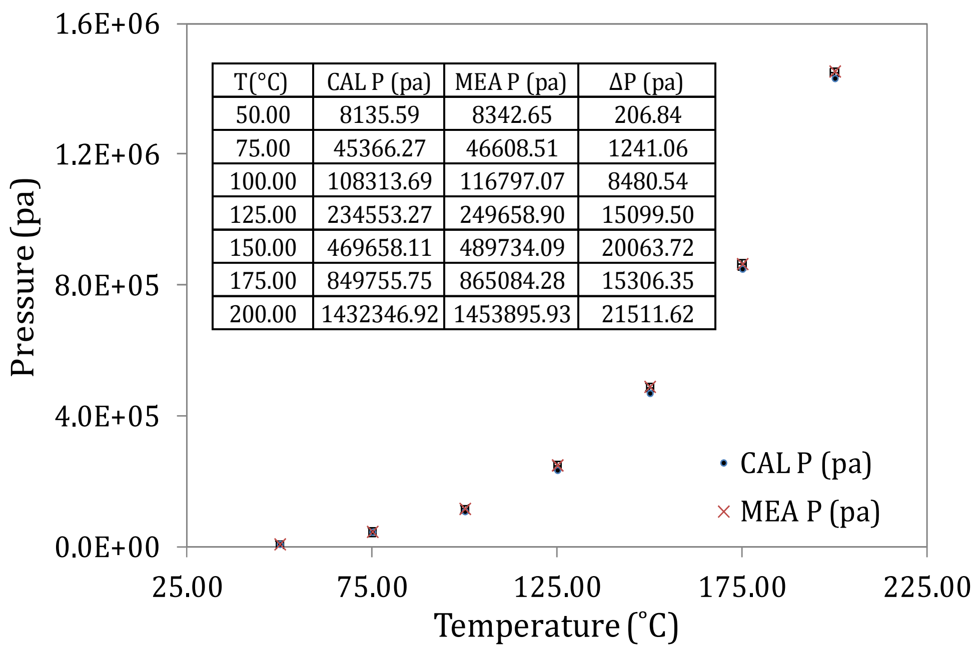
- Pressure measurement with minimum temperature cross-coupling





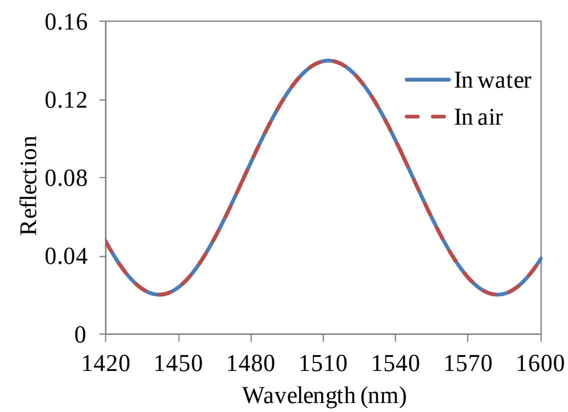
Before laser roughening





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

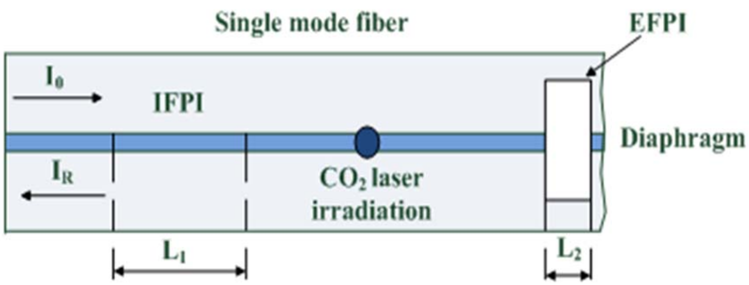
After laser roughening

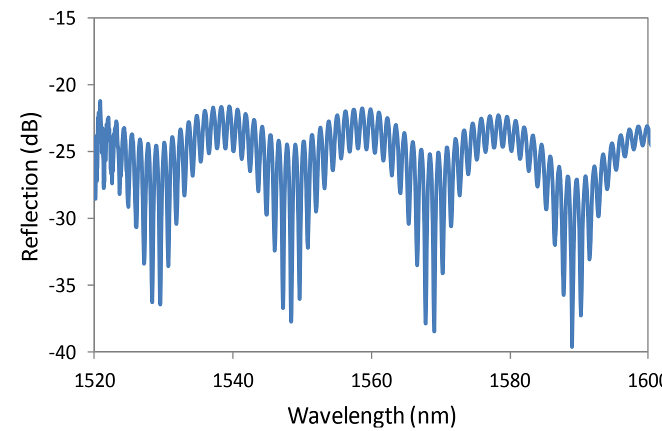


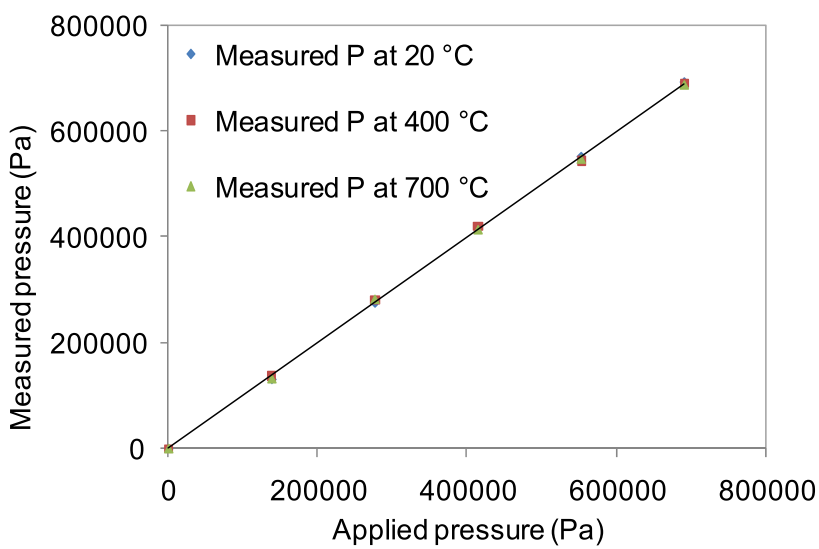
Y. Zhang et al., Optics Letters, 2013

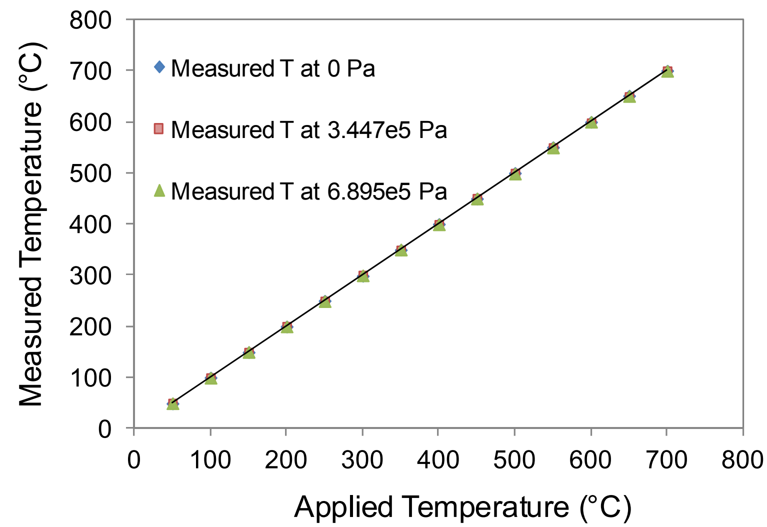
Simultaneous Measurements

- Multiplexed IFPI and EFPI for simultaneous measurements of high pressure and high temperature





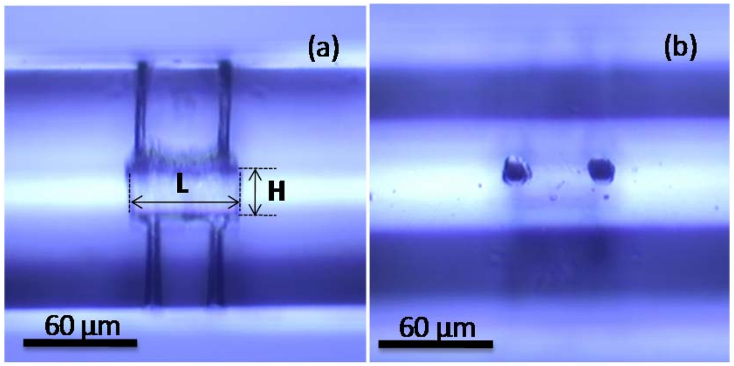


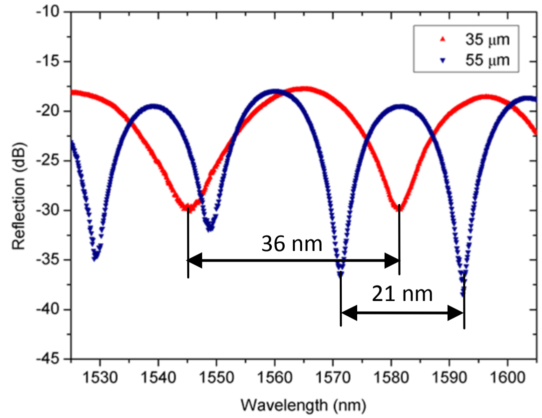


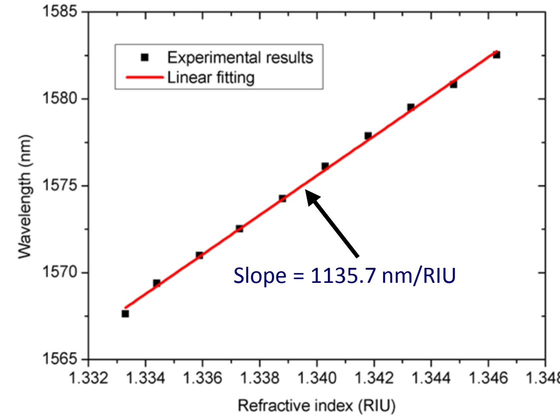
***Y. Zhang et al., Optical Engineering*, 2014**

Optofluidics, Waveplates and SERS

- All-in-fiber inline opto-fluidic sensor

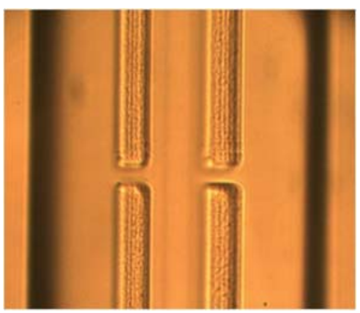


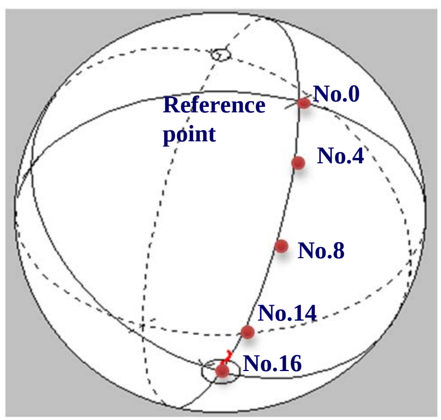


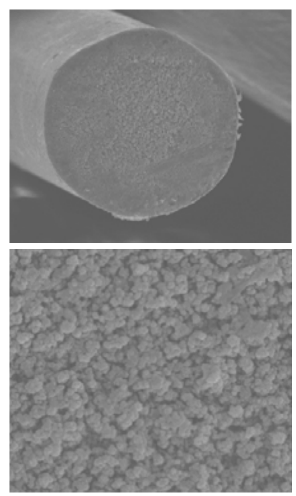


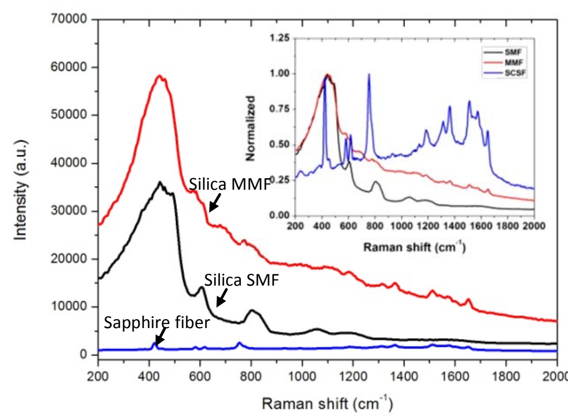
L. Yuan *et al. Optics Letters*, 2014.

- Fiber inline waveplates and sapphire fiber SERS probes





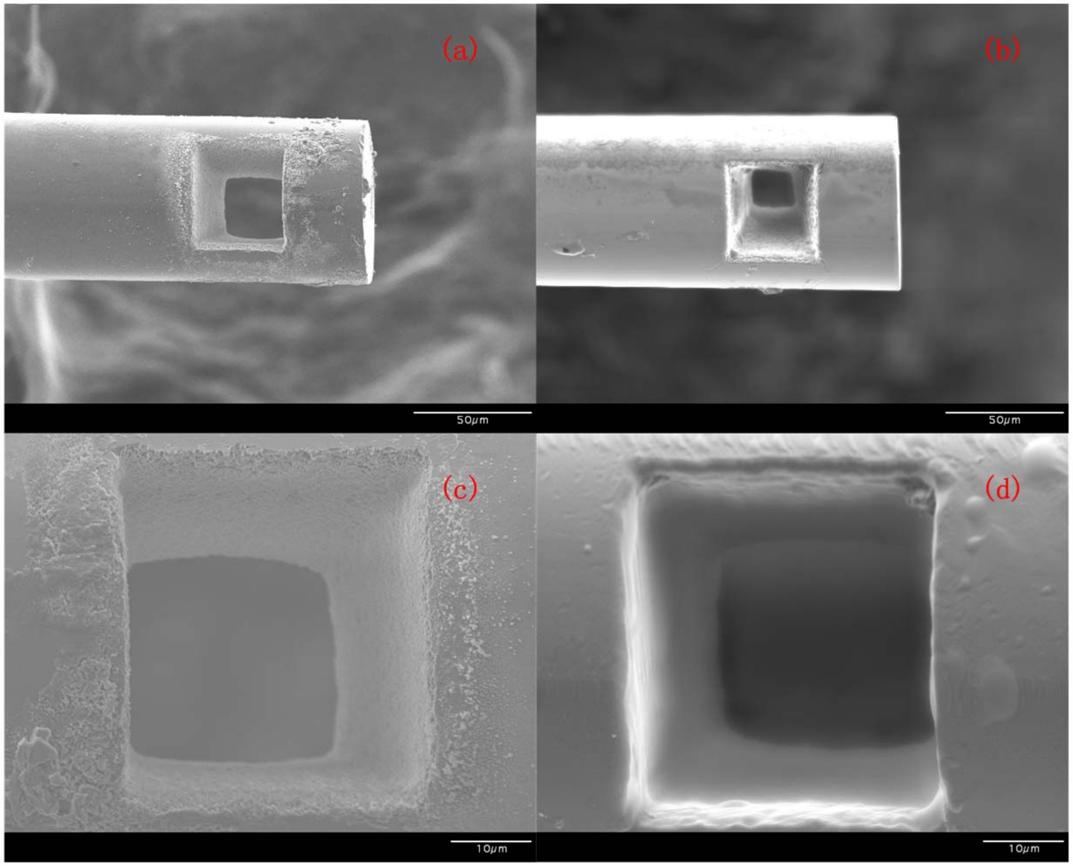




L. Yuan et al. IEEE Photonics Technology Letters, 2014.

Sapphire EFPI

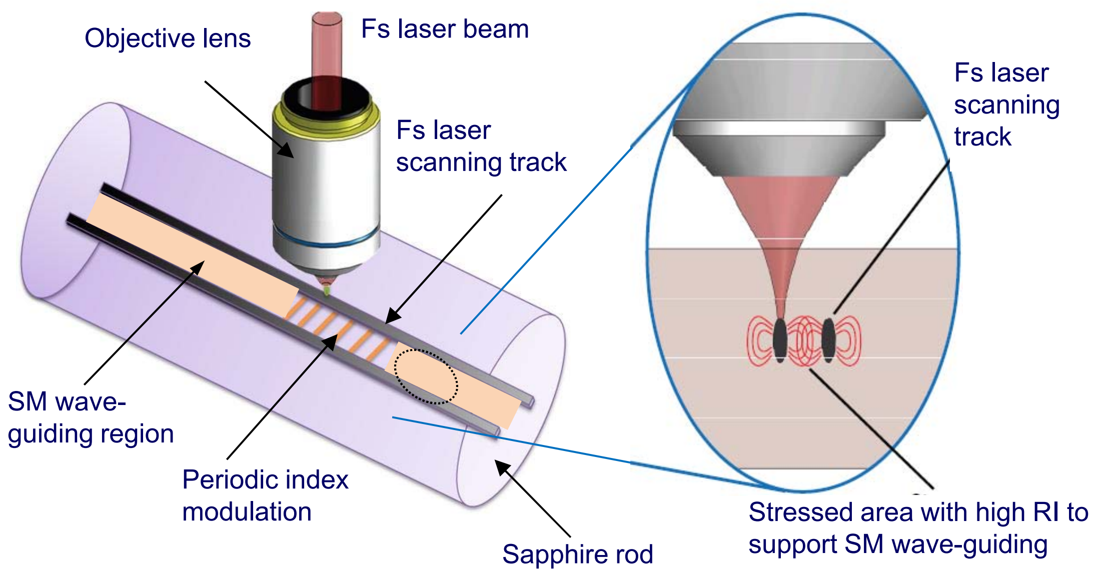
- Sapphire fiber Fabry-Perot Interferometer fabricated by fs laser micromachining

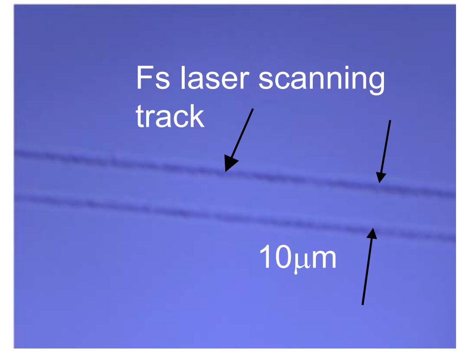


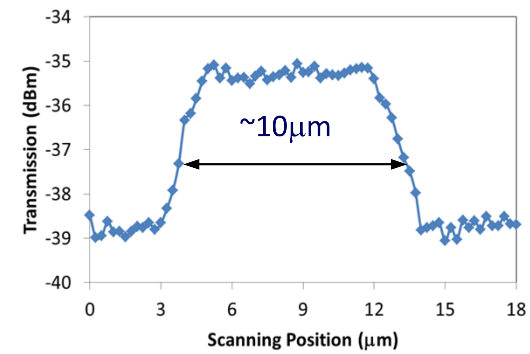
Before heating

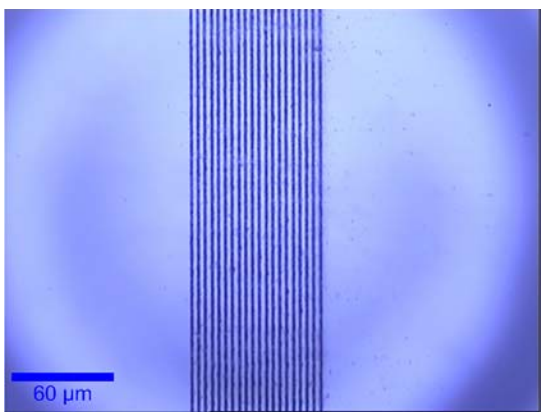
After heating at 1600ºC for 3 days

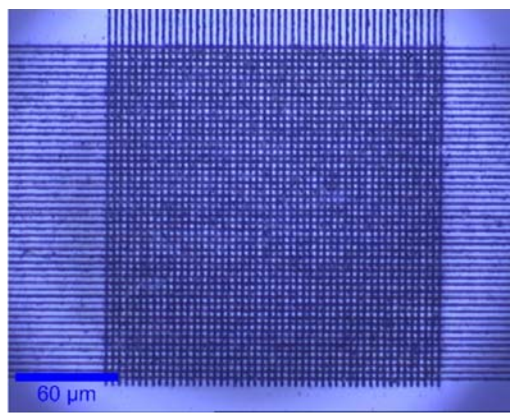
Sapphire waveguides and gratings

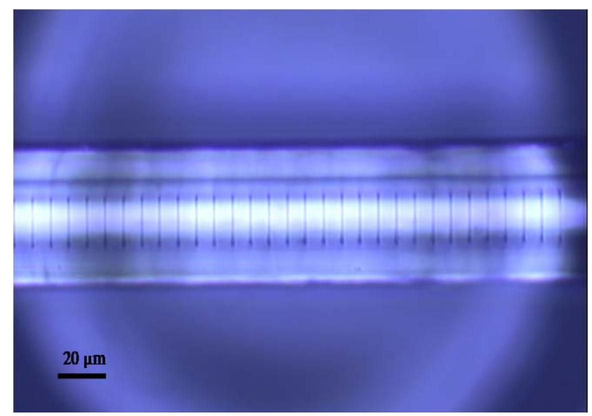




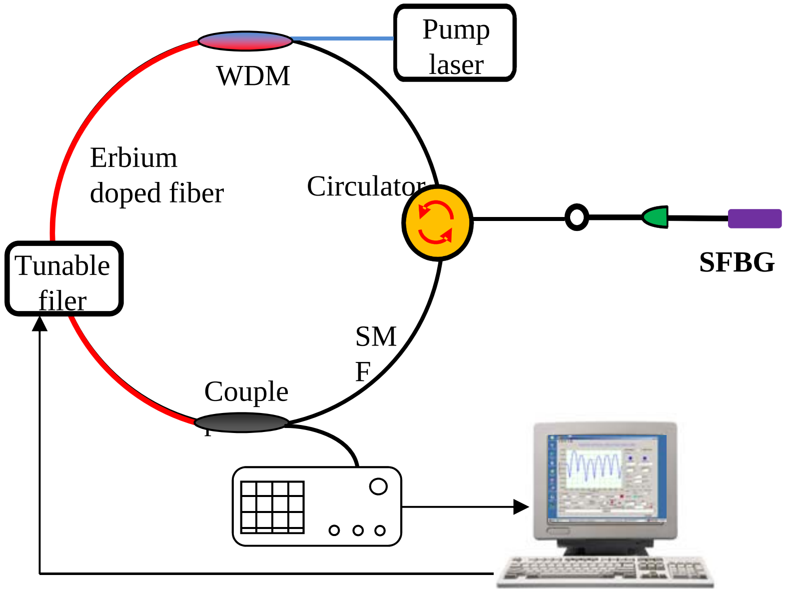


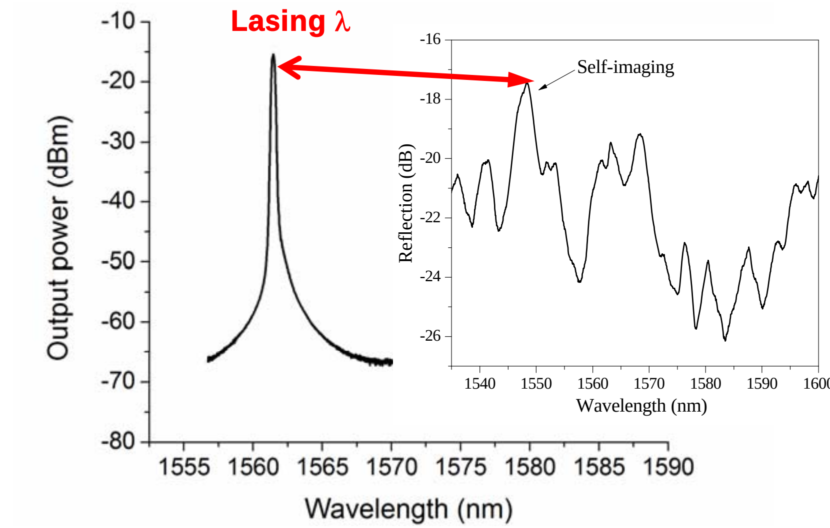


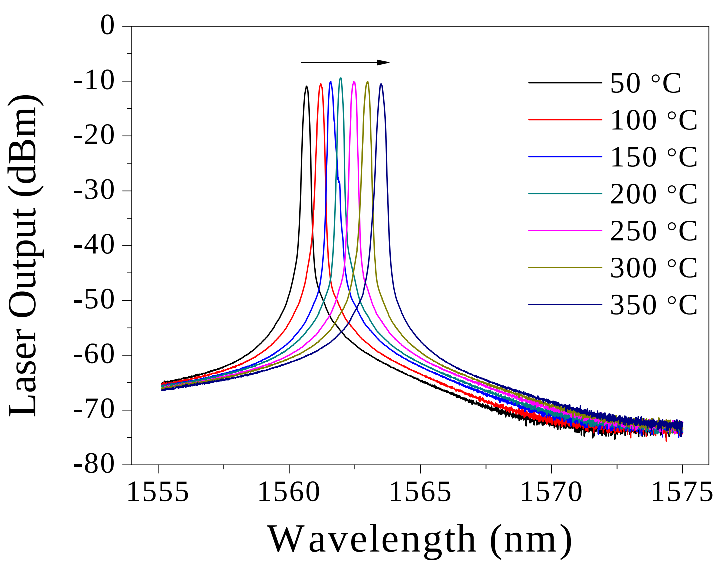


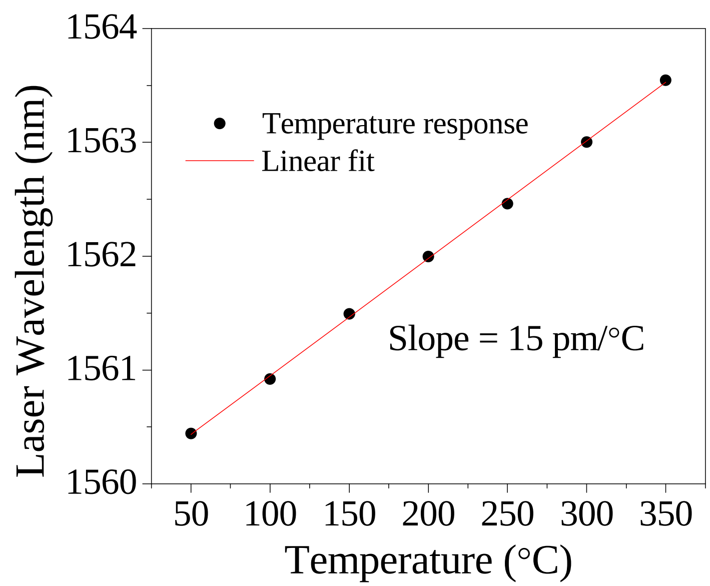


Ring laser based interrogation





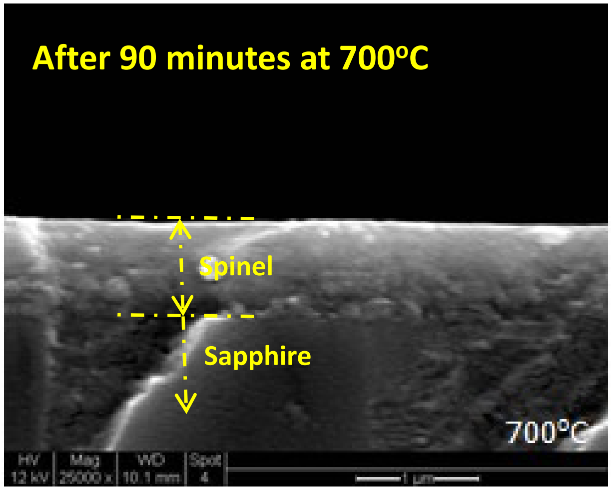


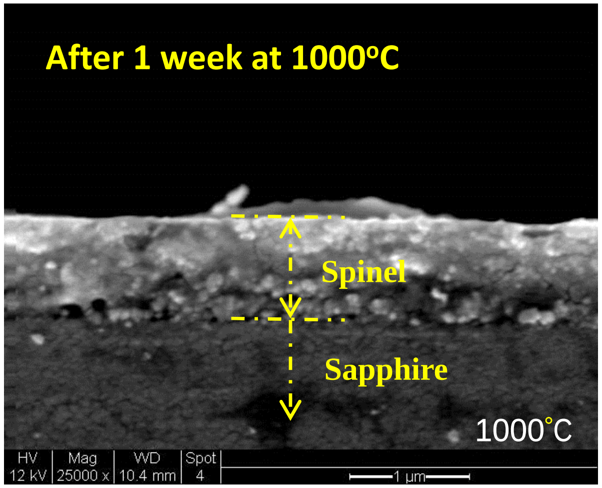


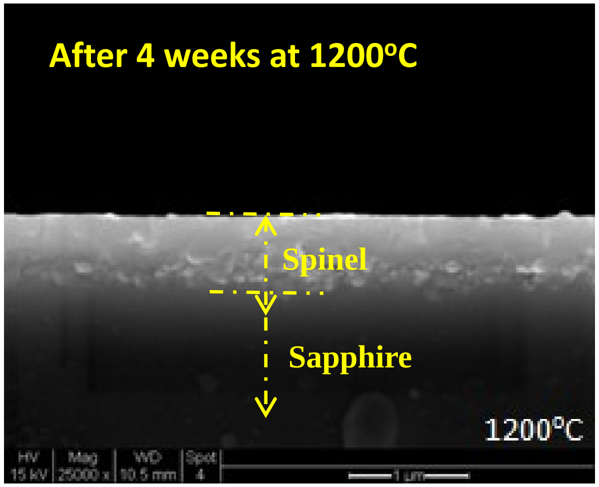
X. Lan et al., Sensors and Actuators B-Chemical, 2013

Clad the sapphire fiber

- Spinel $MgAl_2O_4$ Cladding For Sapphire Fiber stable up to 1200°C





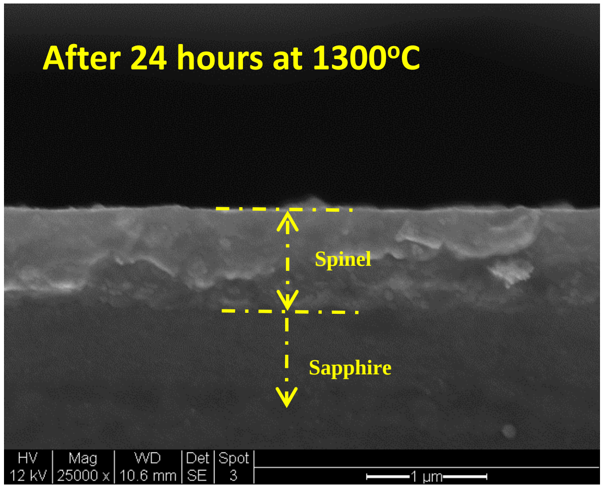


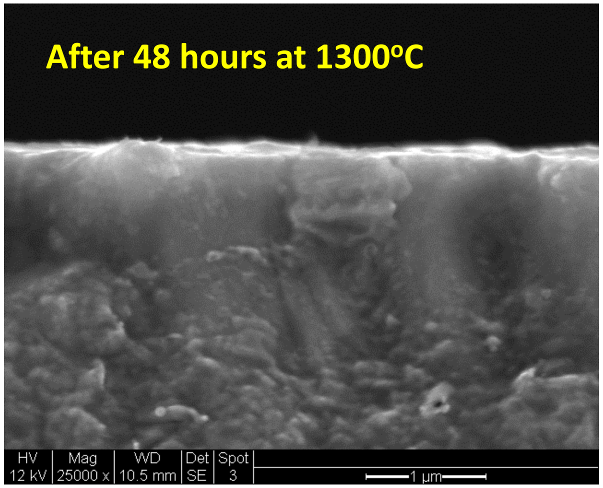
UNIVERSITY OF Cincinnati

Prof. Junhang Dong

dongj@ucmail.uc.edu

(513) 556-3992

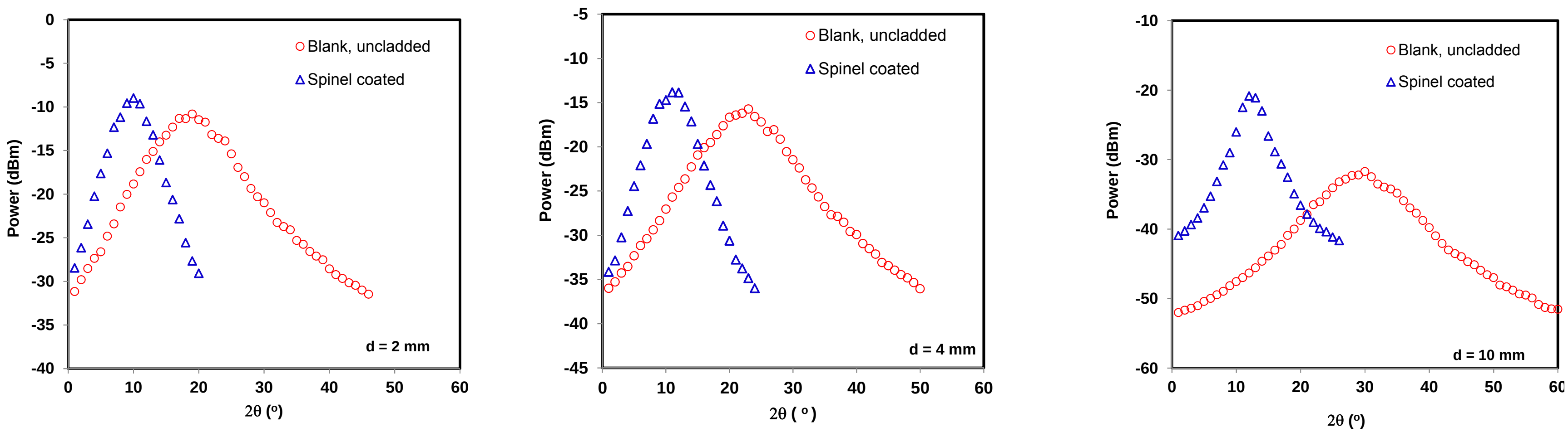




***H. Jiang et al., Thin Solid Films*, 2013**

Refractive index and NA

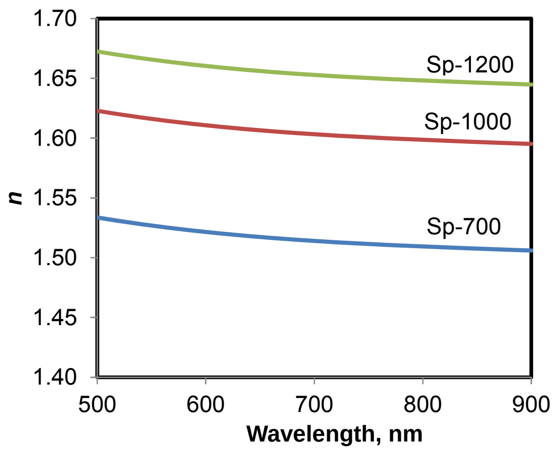
- Dramatically reduced numerical aperture (NA)
- Reduced optical transmission loss



Prof. Junhang Dong

dongj@ucmail.uc.edu

(513) 556-3992



Refractive indices of the spinel films on sapphire wafers Sp-700 (700ºC, 1.5 h), Sp-1000 (1000ºC, 168 h), and Sp-1200 (1200ºC, 168 h)

Table Results of NA measurements at output power of 1% of the maximum power for the uncoated and spinel-coated sapphire fibers

	2θ (NA=Sinθ)		
Distance, mm	2	4	10
Uncoated	41º (0.350)	48º (0.407)	58º (0.485)
Spinel-coated	22º (0.191)	23.5º (0.204)	23.5º (0.204)

H. Jiang et al., Thin Solid Films, 2013

Pure Optics

- Sensors based on pure optics
  - Advantages
    - Very small size (microns)
    - High accuracy/resolution
    - Low loss in transmission
    - Immunity to Electromagnetic interference
  - Disadvantages
    - Need very high fabrication precision (1/20 wavelength or ~50nm surface quality)
    - Waveguide dependent (difficult to fabricate sensors on highly multimode waveguide, e.g., sapphire fibers)

- Fabrication of pure optical sapphire sensors (e.g., FBG and interferometer) is extremely difficult

  → have to look into other technologies

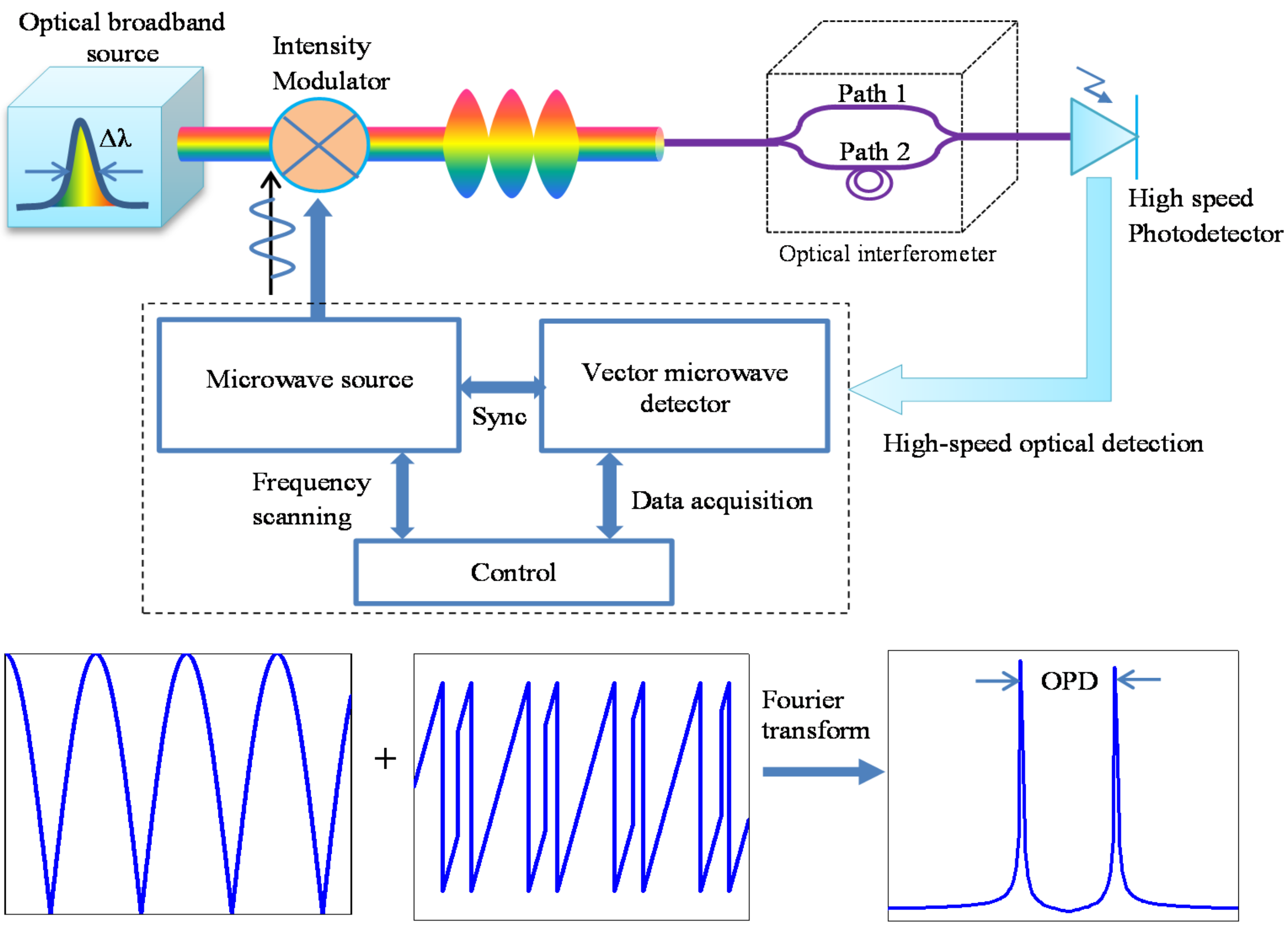
The Breakthroughs

- Microwave inspired by Optics (e.g., coaxial cable sensors)
  - We demonstrated that optical fiber devices (FBG, resonator, interferometer, etc.) can be implemented in microwave domain using a coaxial cable

- How about "Microwave on Optics"?
  - Use light as the carrier
  - Use a microwave signal to modulate the optical carrier (now the microwave becomes the envelop)
  - Send the microwave-modulated signal through the optical waveguide
  - Receive the signal and strip off the optics to obtain the microwave information only
  - The demodulated microwave signals can now be used for sensing

Concept of OCMI

- Optical carrier based microwave interferometer (OCMI)



(a) Amplitude spectrum $2A^2M\cos\left[\Omega\frac{L_{O1}-L_{O2}}{2c}\right]$

(b) Phase spectrum $\Omega\left(\frac{2W+L_{O1}+L_{O2}}{2c}\right)$

(c) Propagation delay

J. Huang et al., Optics Express, submitted

SMF Mach-Zehnder OCMI

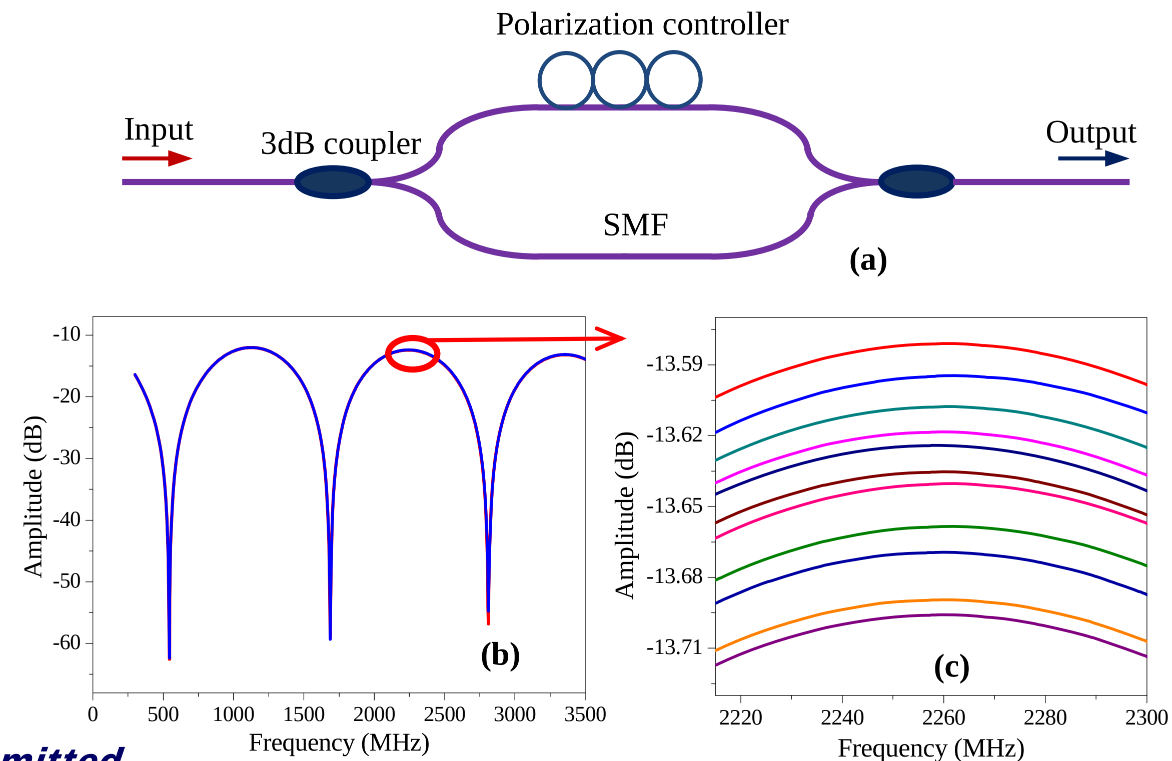
Microwave term

$$|E|^2 = |E_1+E_2|^2 = 2A^2 + 2A^2 M\cos\left[\Omega\frac{L_{O1}-L_{O2}}{2c}\right]\cos\left[\Omega\left(t+\frac{2W+L_{O1}+L_{O2}}{2c}\right)\right]$$

$$+2A^2\sqrt{\left\{1+M\cos\left[\Omega\left(t+\frac{W+L_{O1}}{c}\right)\right]\right\}\left\{1+M\cos\left[\Omega\left(t+\frac{W+L_{O2}}{c}\right)\right]\right\}}\cdot\int_{\omega_{min}}^{\omega_{max}}\cos\left(\omega\frac{L_{O1}-L_{O2}}{c}\right)d\omega$$

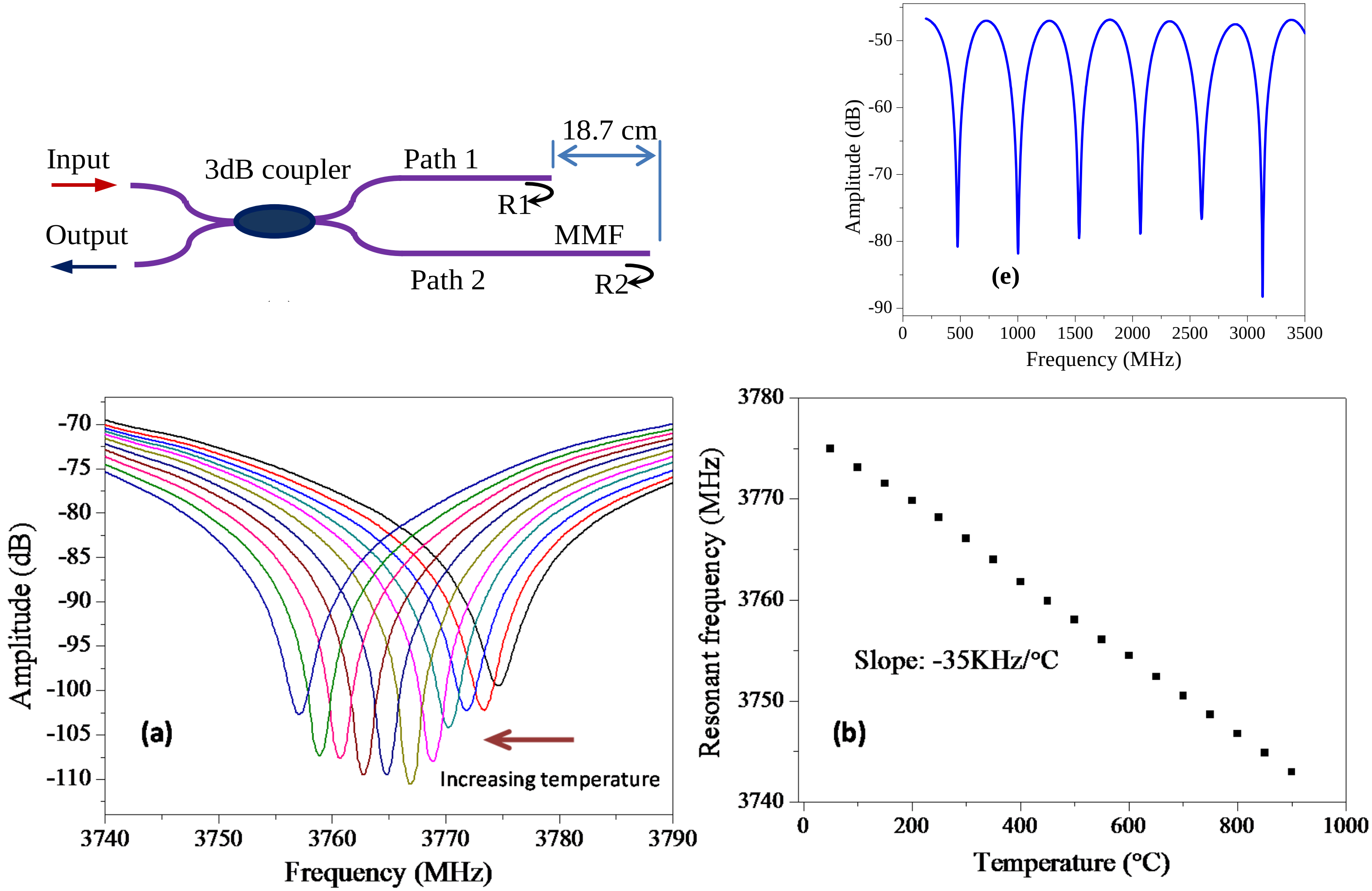
Optical term

Polarization insensitive (no more polarization fading)



J. Huang et al., Optics Express, submitted

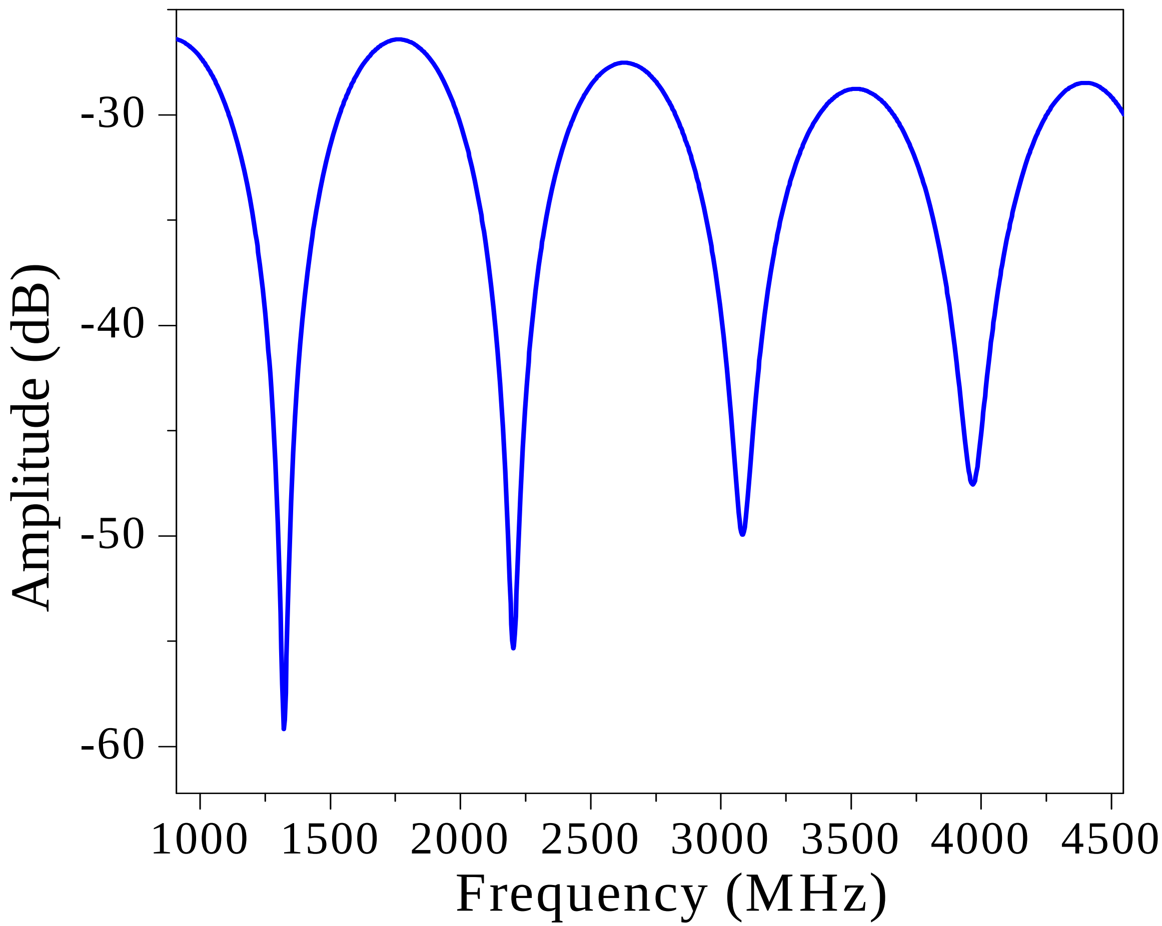
MMF Michelson OCMI



Insensitive to multimodal influences (can be implemented using highly multimode fibers)

J. Huang et al., Optics Express, submitted

Sapphire fiber Michelson OCMI



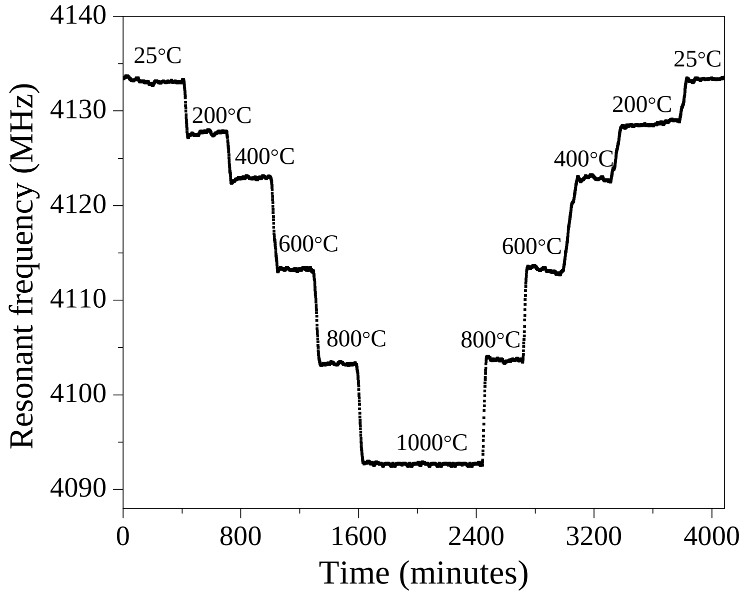
Excellent signal quality using highly multimode sapphire fibers (uncladded, 125μm diameter)

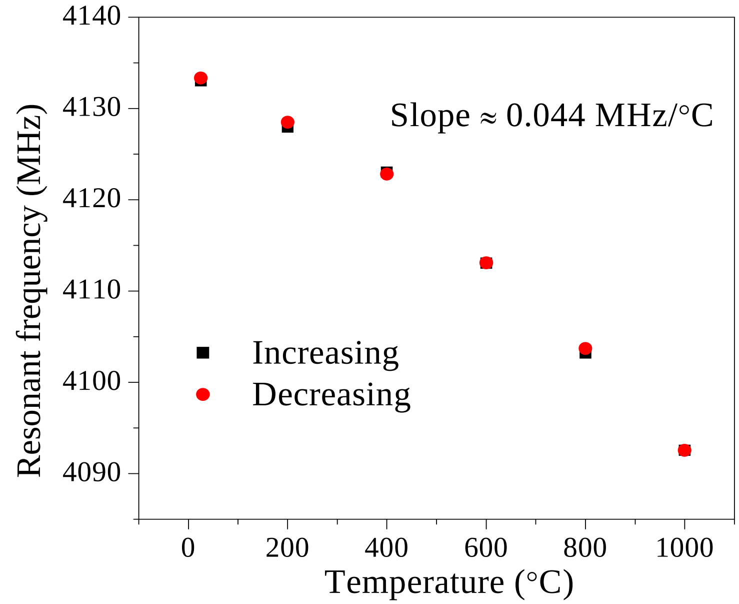
J. Huang et al., Optics Letters, submitted

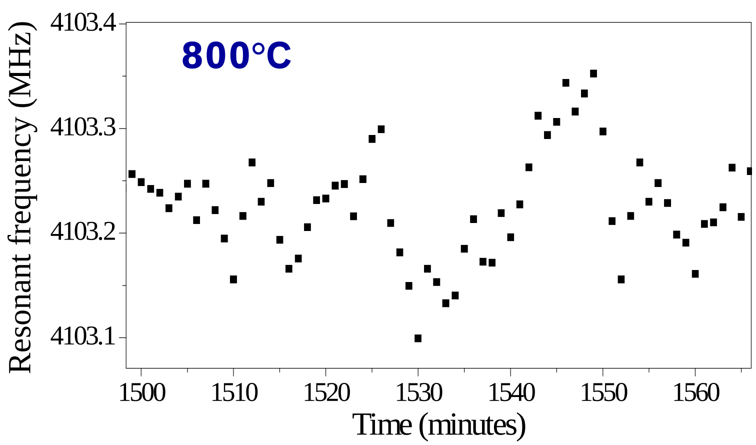
Sapphire fiber T-sensing

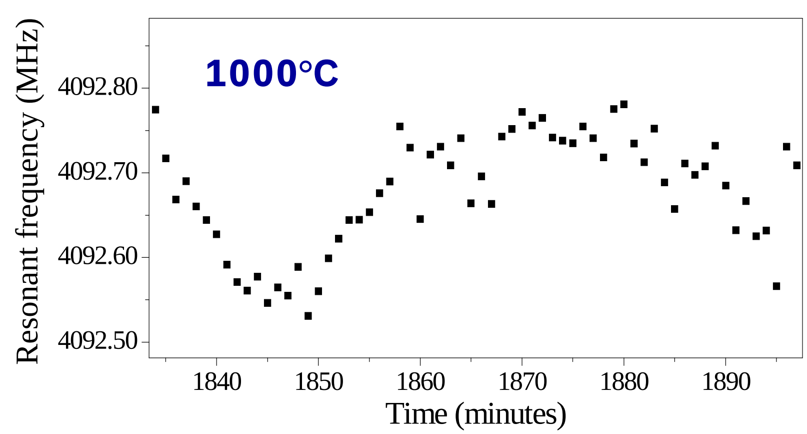
Sapphire fiber high-T sensor

- Excellent measurement resolution and stability







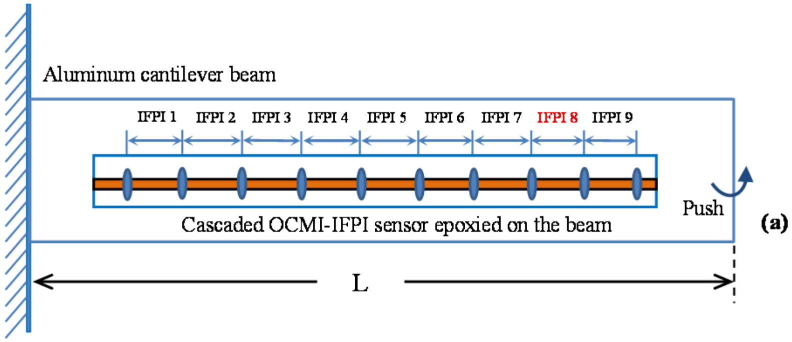


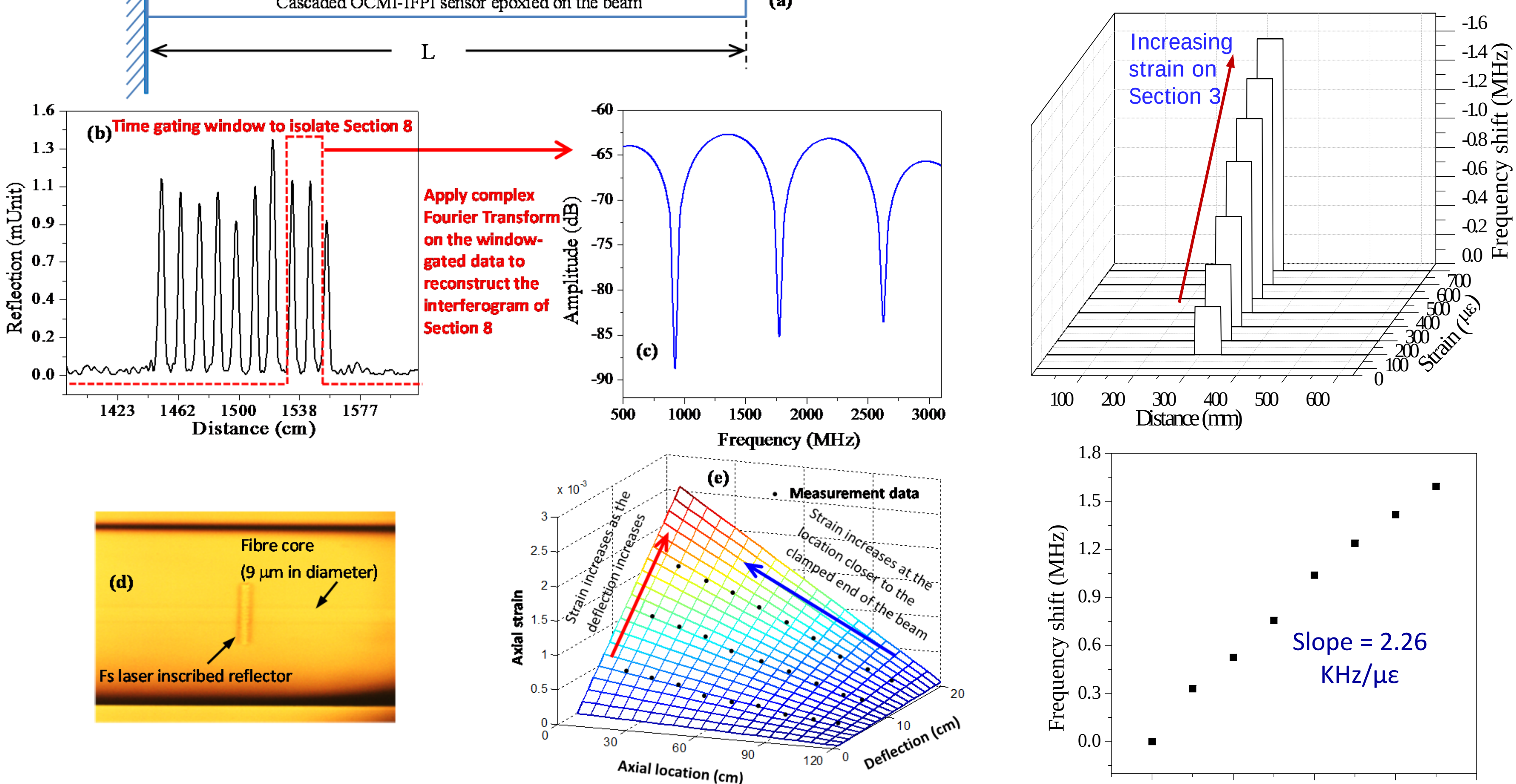
J. Huang et al., Optics Letters, submitted

Distributed Strain Sensing (Video)

Fabry-Perot OCMIs

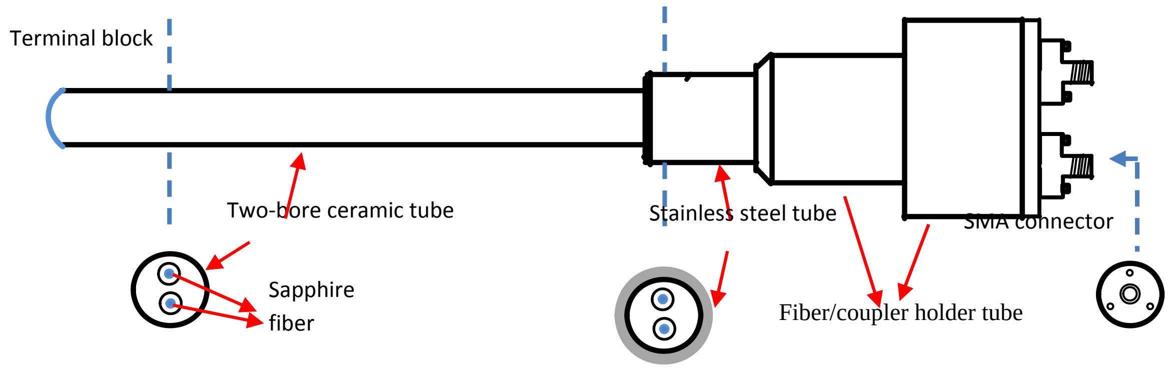
Spatially-continuous distributed sensing with spatial resolution of 1 cm)

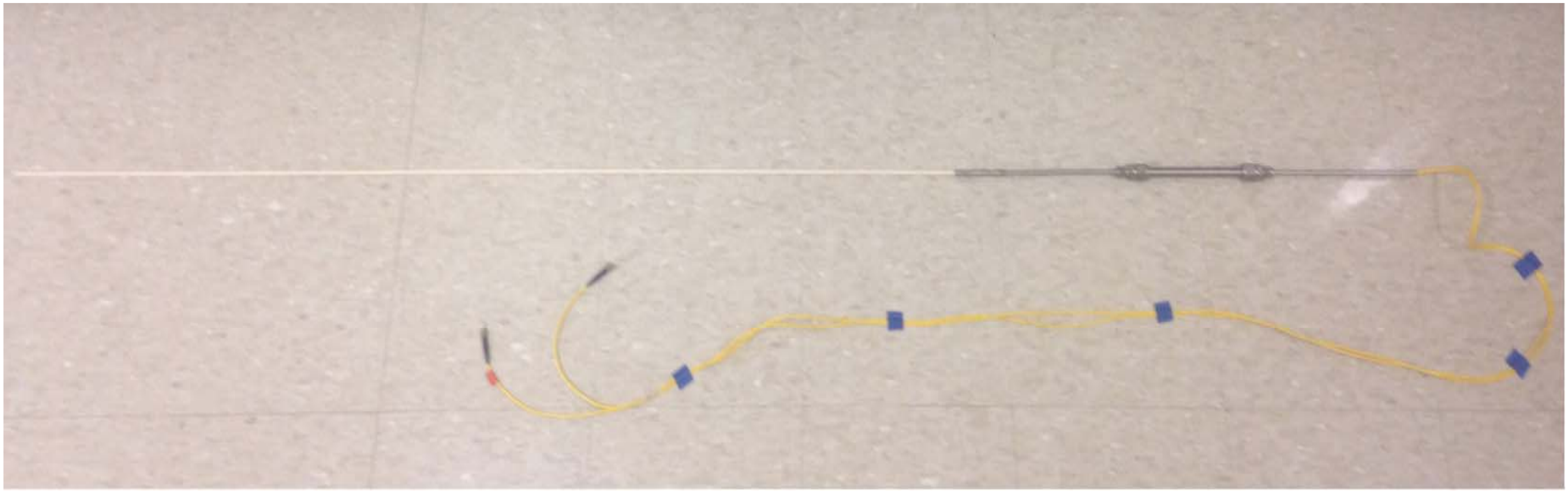




J. Huang et al., Optics Express, submitted

Sapphire sensor packaging





Summary

- Challenging problems solved by the novel OCMI concept
  - Excellent SNR, high resolution
  - Insensitive to polarization variations
  - Low dependence on multimodal influences
  - Relieved requirement on fabrication (very easy to fabricate the sensors including the previously very difficult, if not impossible, sapphire fiber sensors
  - Truly distributed sensing capability with spatial continuity and cm spatial resolution

- Assembly-free OCMI sensors for harsh environments
  - Dependable Performance
  - Robustness
  - Long-term stability