University of Pittsburgh

High-temperature fiber Bragg grating sensors in microstructured fibers for harsh environment applications

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NETL UCR Annual Meeting
June 7, 2011

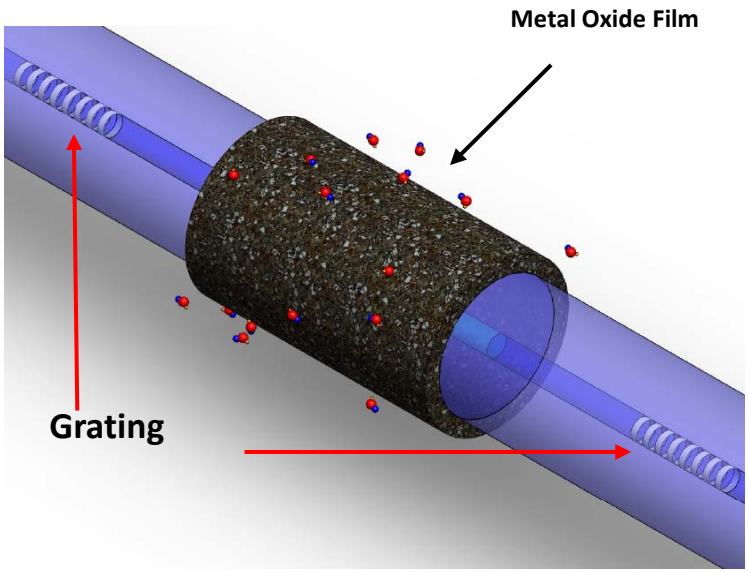
Introduction of Overall Project

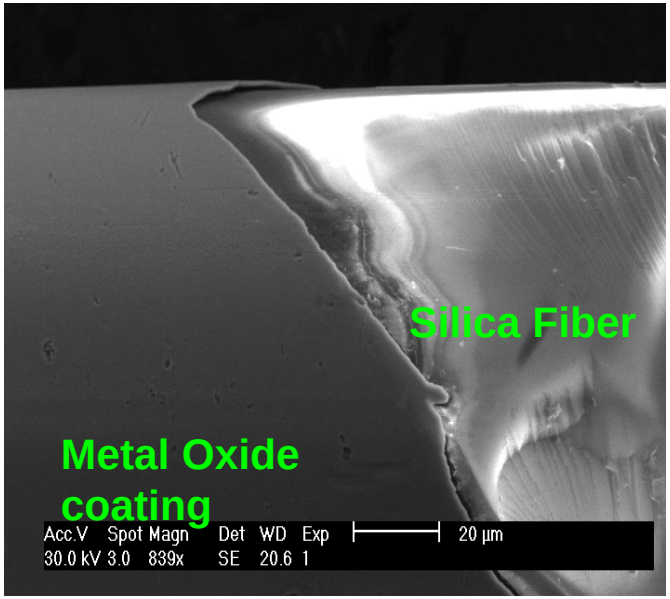
- Attempt Three Chemical Sensing Approaches

- Chemical sensing based on nano-film enabled high-T fiber gratings
- Chemical sensing based on 3D photonic crystal structures
- Chemical sensing based on one-pulse Coherent Anti-Stokes Raman Spectroscopy

- Project Started September 2010

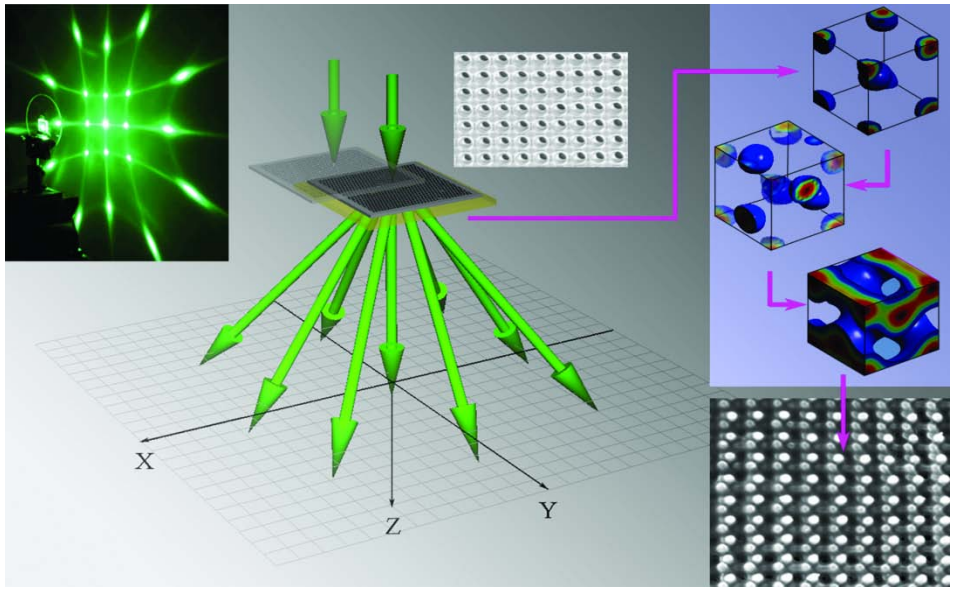
Chemical Sensor Based on Fiber Grating

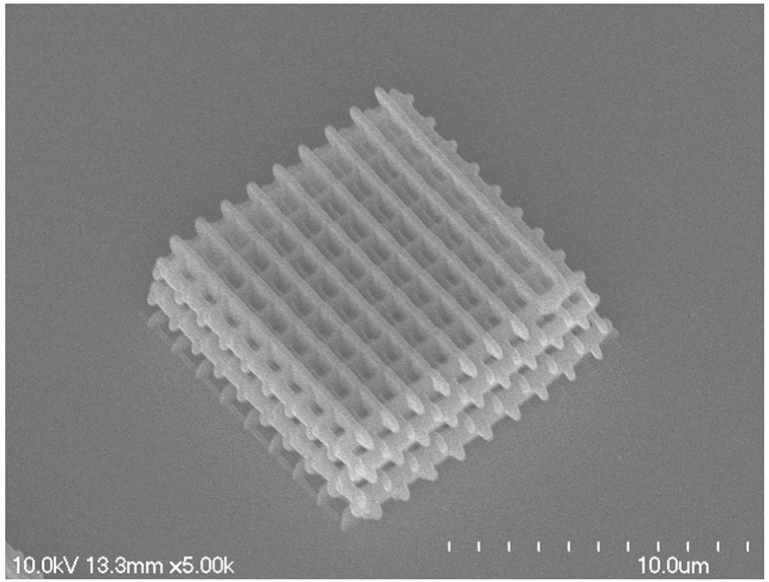




- High-T fiber grating as sensor platform
- Metal oxide over-coating

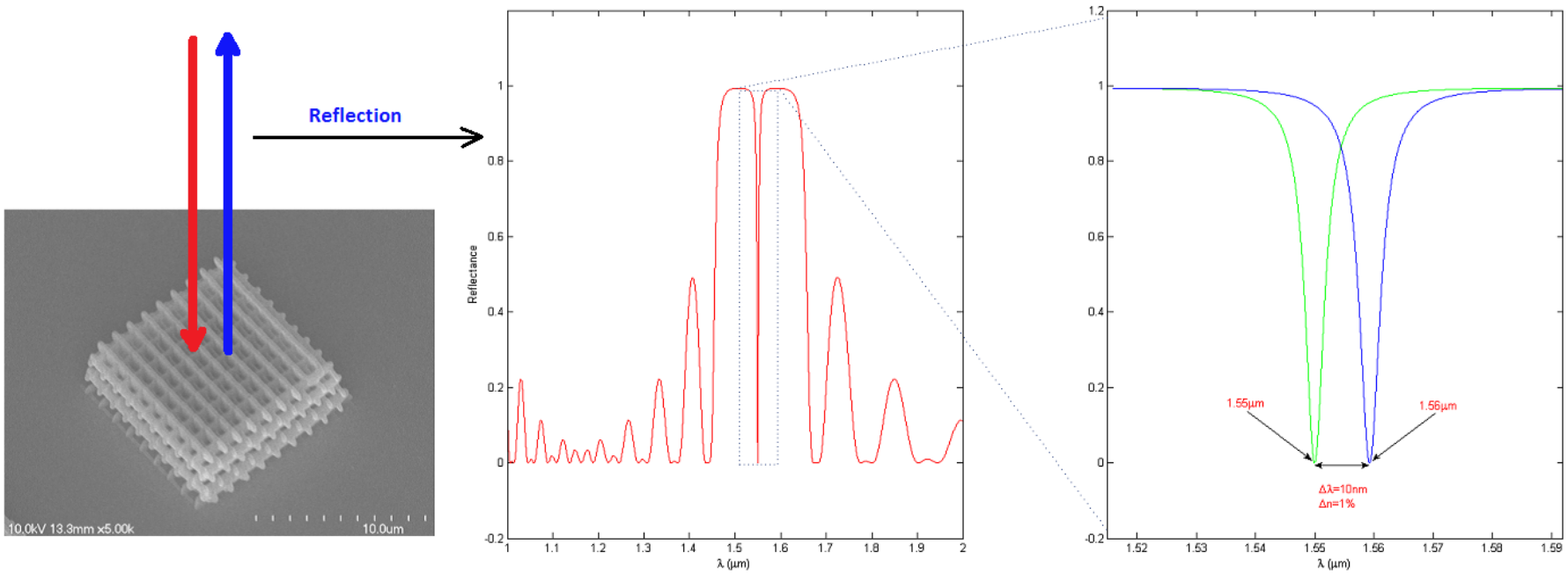
Chemical Sensor Using Photonic Crystal





- Ultrafast laser direct writing and holographic lithography
- 3D Photonic crystal with <u>defects</u> fabricated in SU8
- Metal oxide sol gel infiltration inversion for sensor fabrication

Chemical Sensor Using Photonic Crystal



- Ultrafast laser direct writing and holographic lithography
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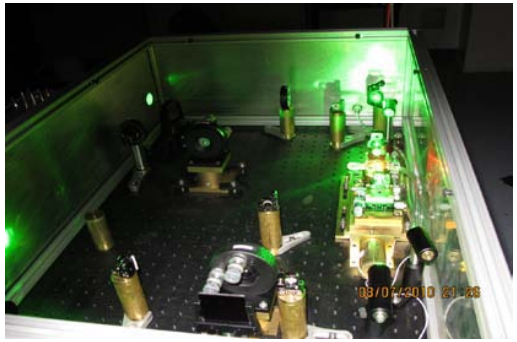
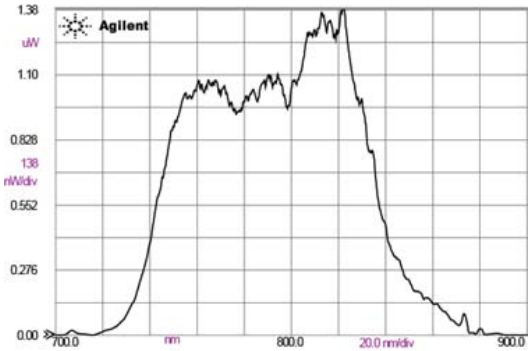
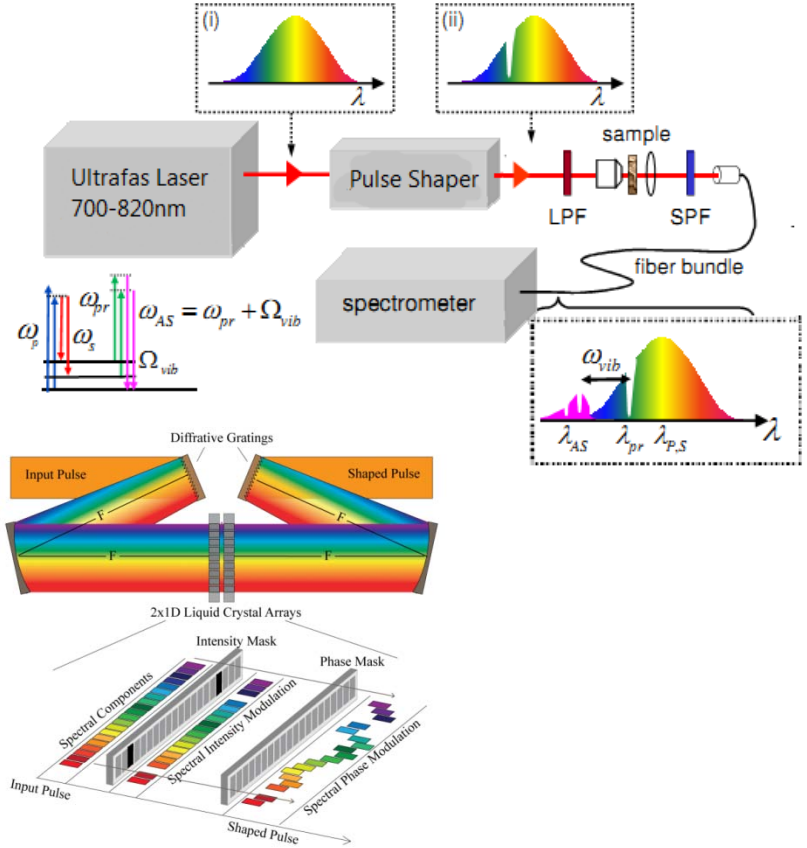
- Metal oxide sol gel infiltration inversion for sensor fabrication

Chemical Sensor Using CARS



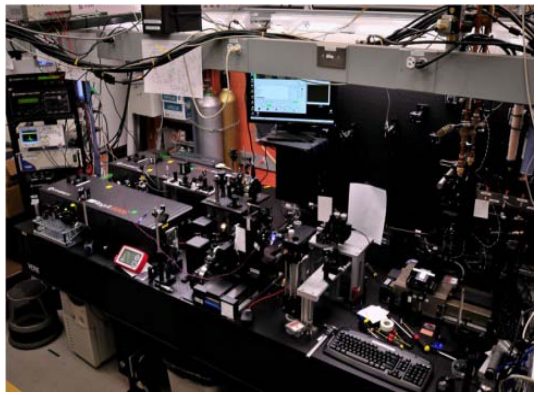


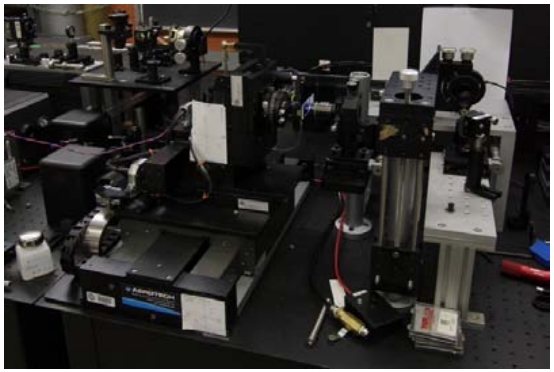


- Construction of 7-fs ultrafast laser with over 100 nm FWHM spectral width (> 2000cm-1)
- Spatial light modulator for pulse shaping (spectral shaping)
- Multiple Raman traces can be interrogated with a single broadband source

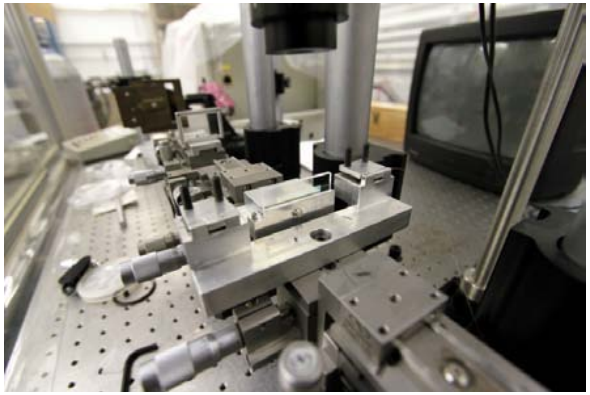
The group

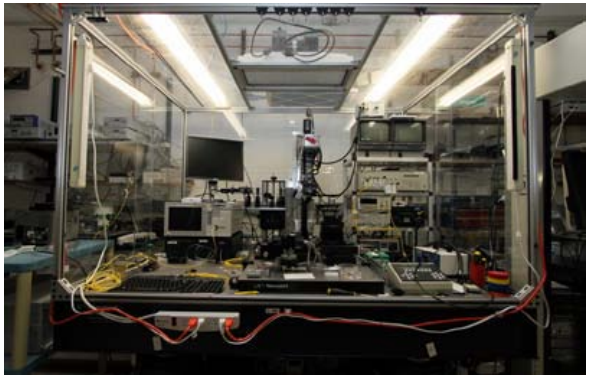
Ultrafast Laser Fabrications





UV Laser Grating Fabrications





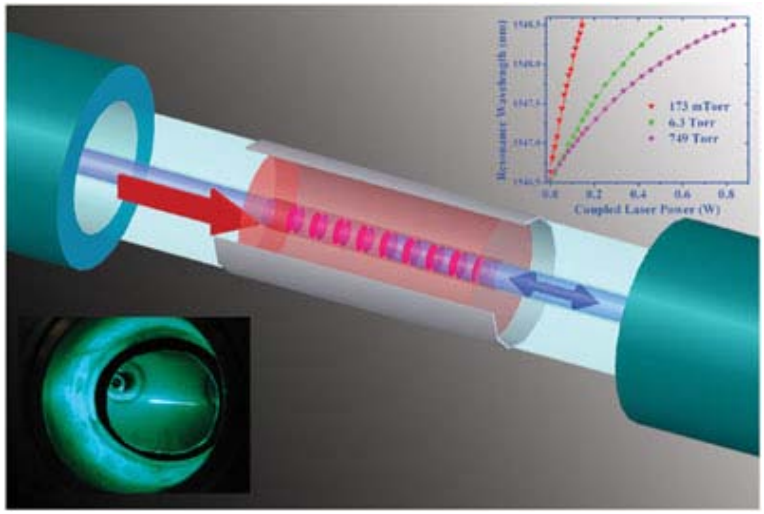
- 9 Graduate student researchers and 1 Postdoc
- Ultrafast lasers and UV lasers for Sensor fabrication

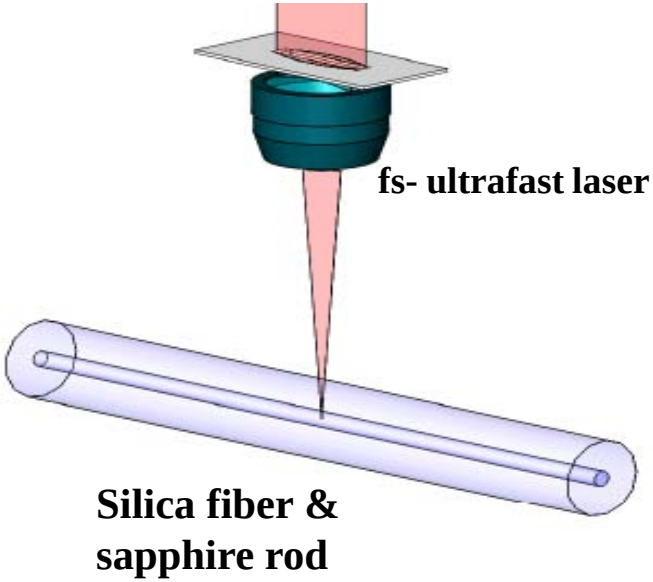
Objective

- Turn a $20 commercially off-the-shelf fiber grating sensors into high-temperature sensors

- Expanding high-T grating into air-hole microstructured fibers

Fiber Gratings as High-T Sensors



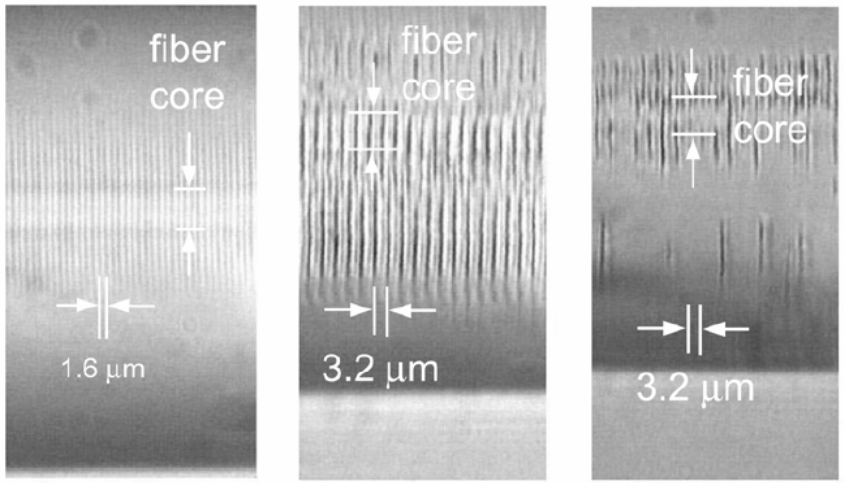


Fabrication of high-temperature stable fiber Bragg gratings

- FBG in nitrogen-doped fibers
- **Ultrafast laser fabrication**
- Chemical regenerative process

C. W. Smelser, et al., *Opt. Express*, **13**, 14, 5377 (2005)

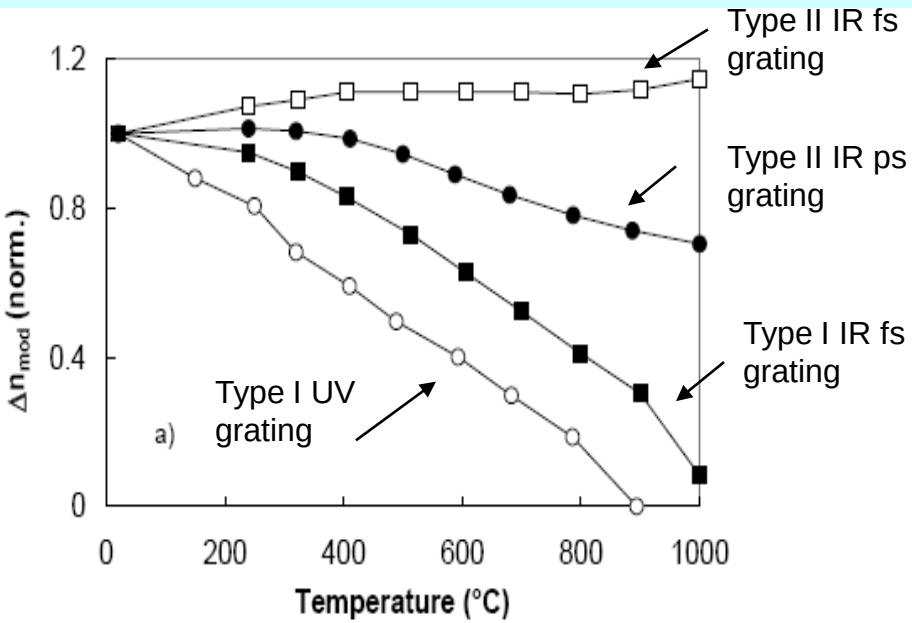
fs-Laser Fabrication of Fiber Gratings as High-T Sensors



Type I IR
125 fs grating

Type II IR
125 fs grating

Type II IR
1.6 ps grating

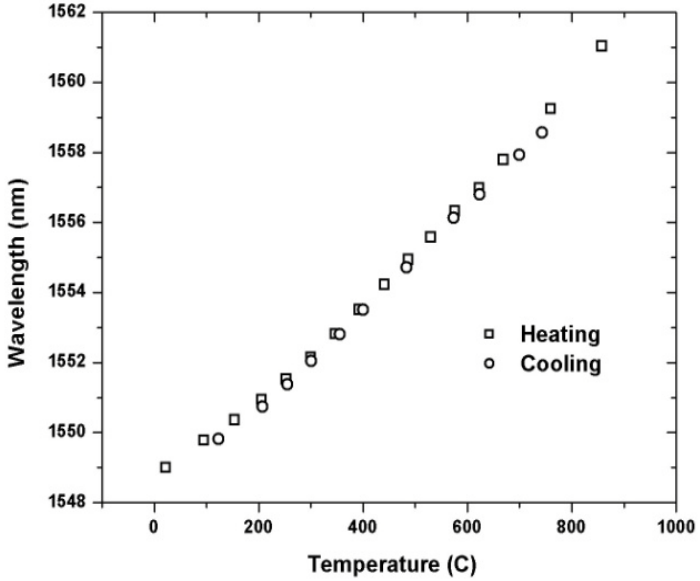


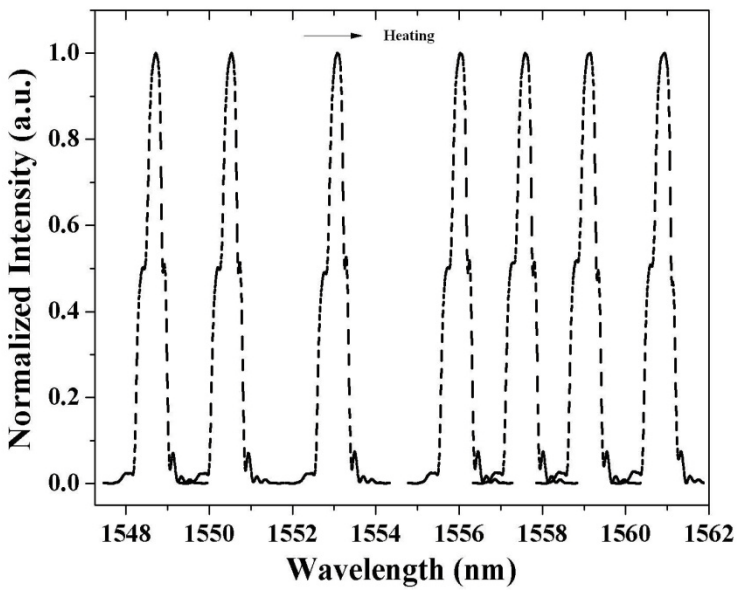
- Type II gratings fabricated with a femtosecond ultrafast laser.
- Writing wavelength 800 nm
- Type II IR gratings are stable at temperature in excess of 1000°C
- Universally applicable fabrication

- **Poor spectral quality (in comparison to Type I grating)**
- **Expensive**

C. W. Smelser, et al., *Opt. Express*, **13**, 14, 5377 (2005)

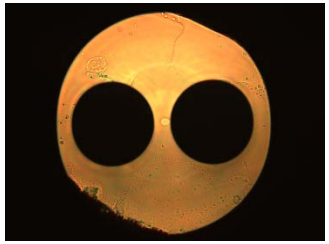
Type II ultrafast laser induced FBG's temperature response



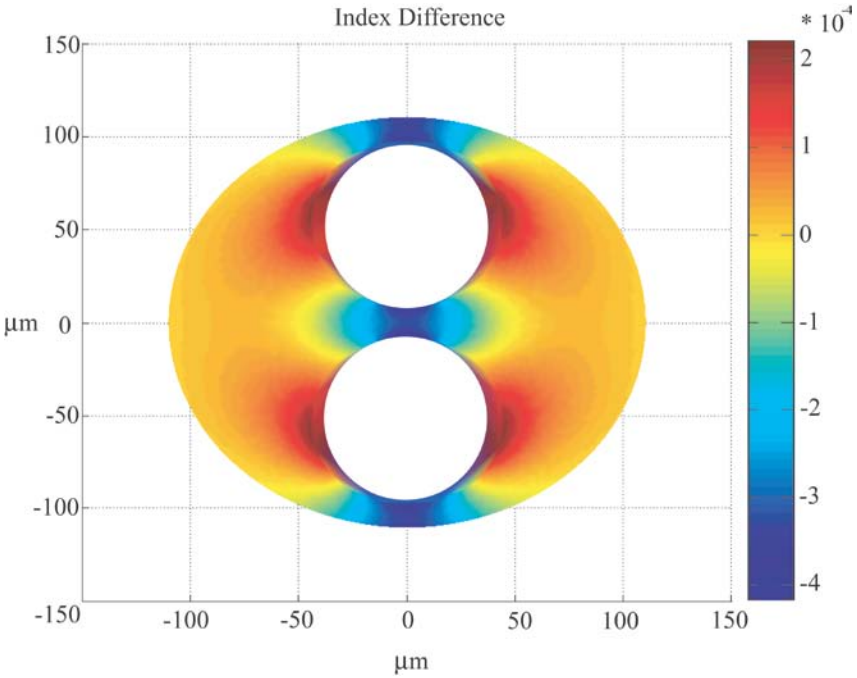


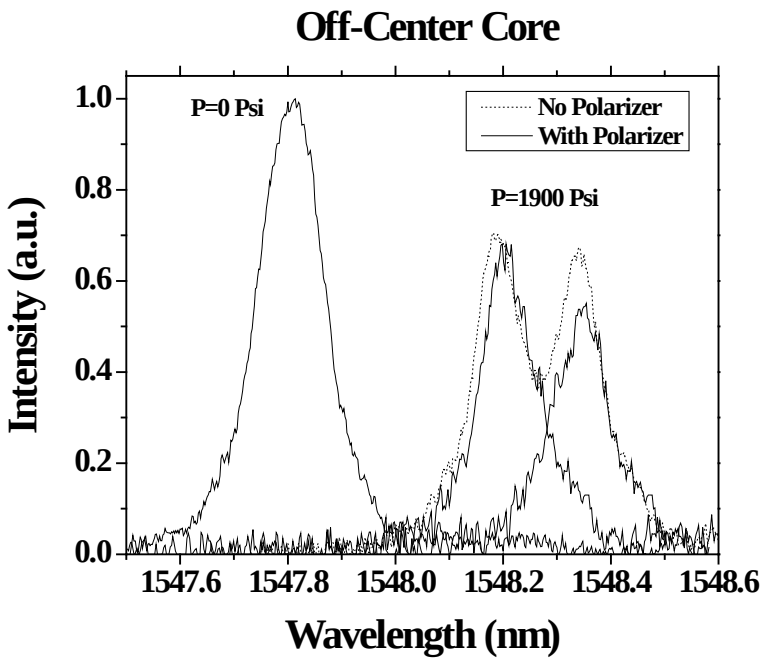
Type II FBG reflection spectra peaks at 23, 198, 383, 570, 666, 760, and 858 ºC (left), the FBG response at 23, 198, 383, 570, 666, 760, and 858 ºC (right).

- **Type II FBG inscribed by a kHz Ti: Sapphire ultrafast laser**
- **Thermal cycle from 20C to 858C**
- **No thermal degradation**
- **No hysteresis**



FBG Birefringence Response to Pressure: Simulation

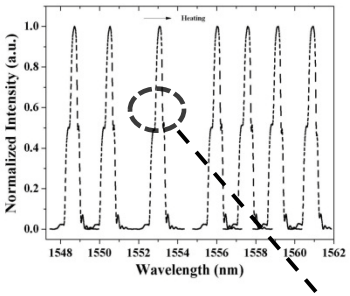


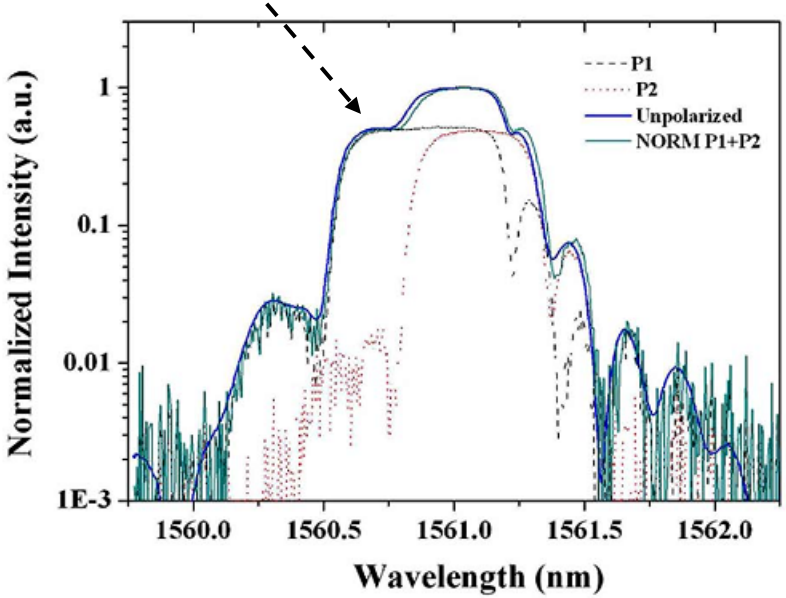


Simulation shows that birefringence can also be induced by pressure.

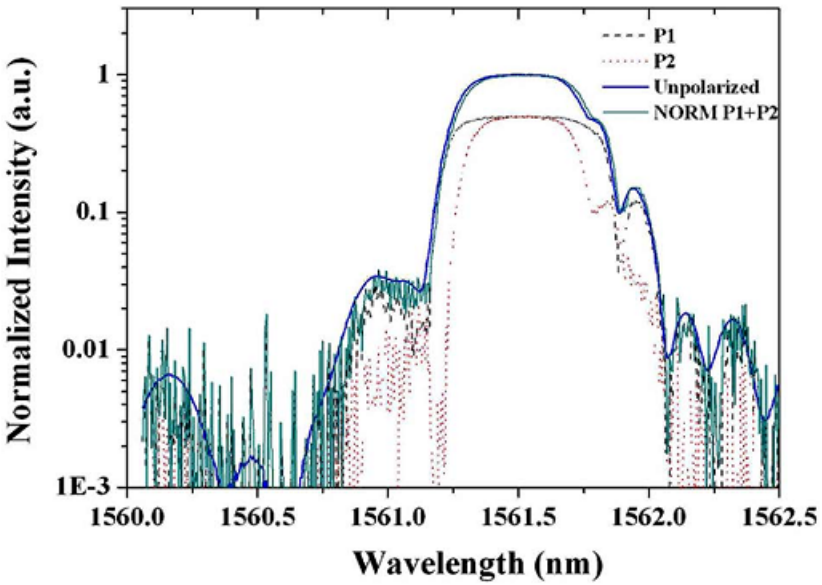
C. Jewart, etc. *OFS.* 2008

Ultrafast laser written FBG





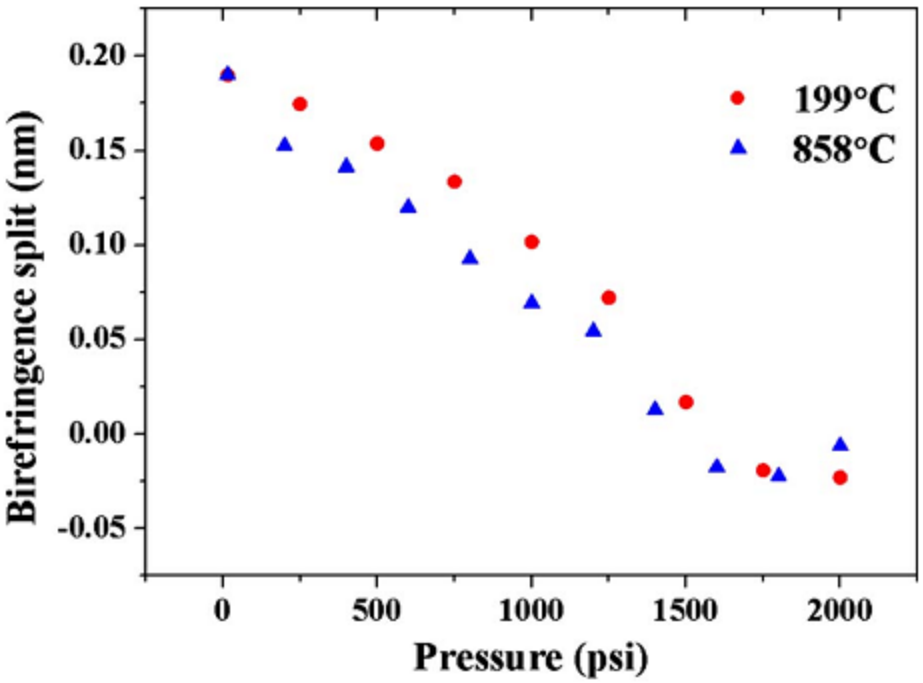
Peak splitting under 15-psi at 858°C.



Peak splitting under 2000-psi at 858°C.

C. Jewart, etc. *Optics Lett.* 2010

Pros & Cons with Ultrafast laser written FBG compared with UV inscribed type-I grating



Pros:

- **No photosensitization, no annealing.**
- **High temperature stable.**
- **Structures in Sapphire up to 1600C**

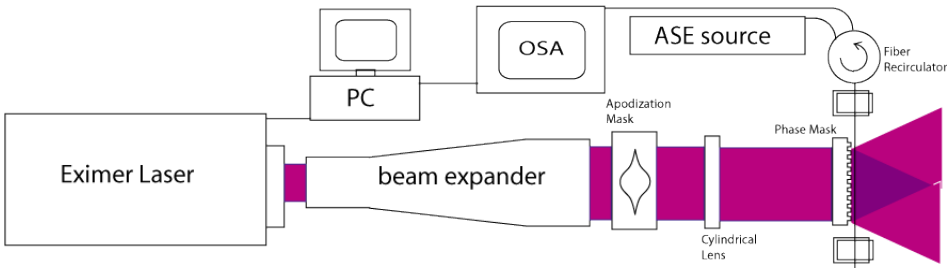
Cons:

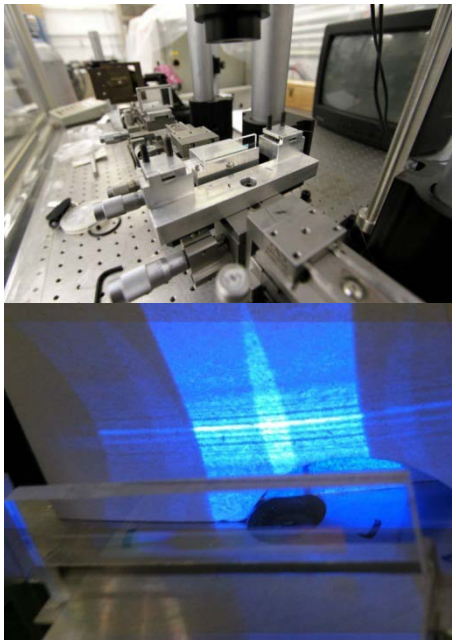
- **More complex setup.**
- **Expensive**
- **Poor quality**
  - **Large line-width**
  - **Large intrinsic birefringence.**

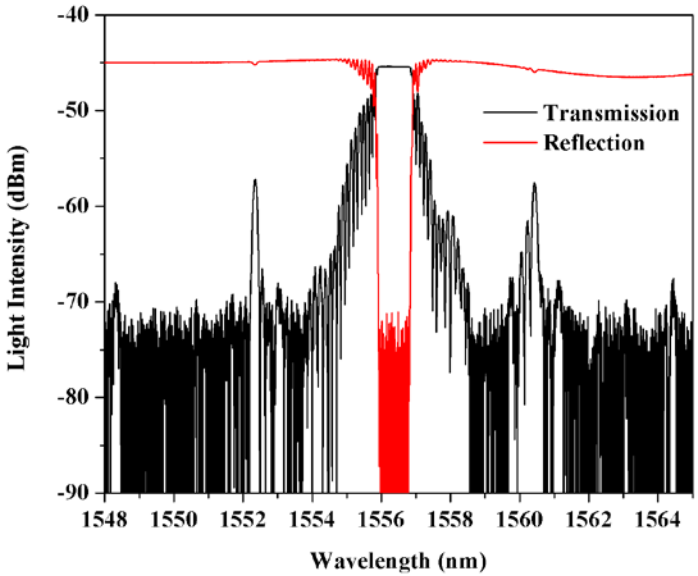
So we need a <u>Better</u> fabrication technique

Chemically Regenerative Process

- **Step I: Type I FBG fabrication (or purchase at $20/piece)**
- **Step II: Hydrogen loading**

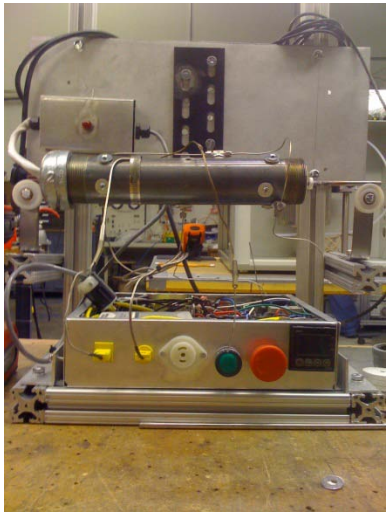


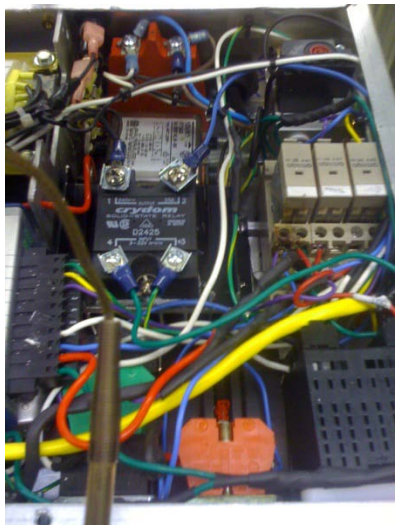


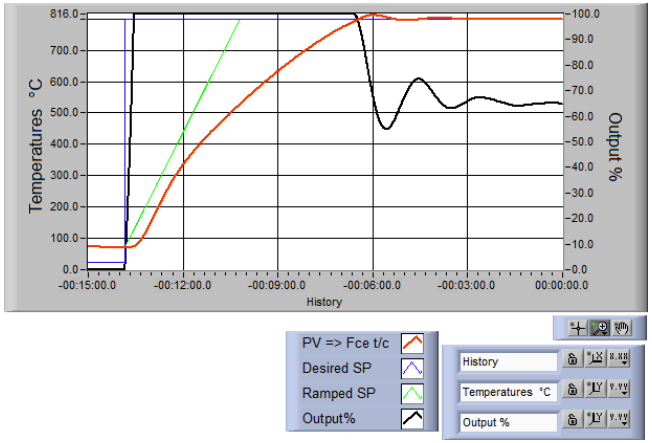


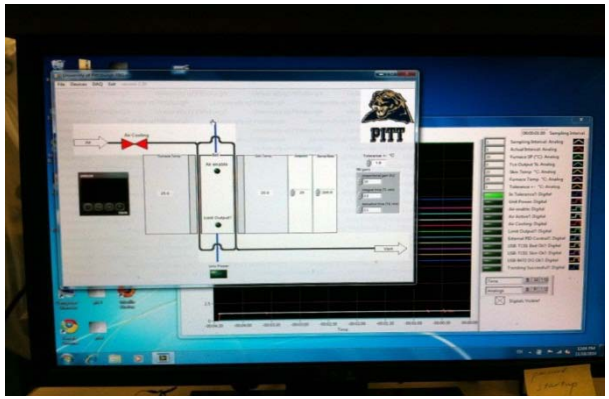
High-T Fiber sensor from Type I grating

- **Step III: Chemical Regeneration (<u>Rapid</u> Heating)**





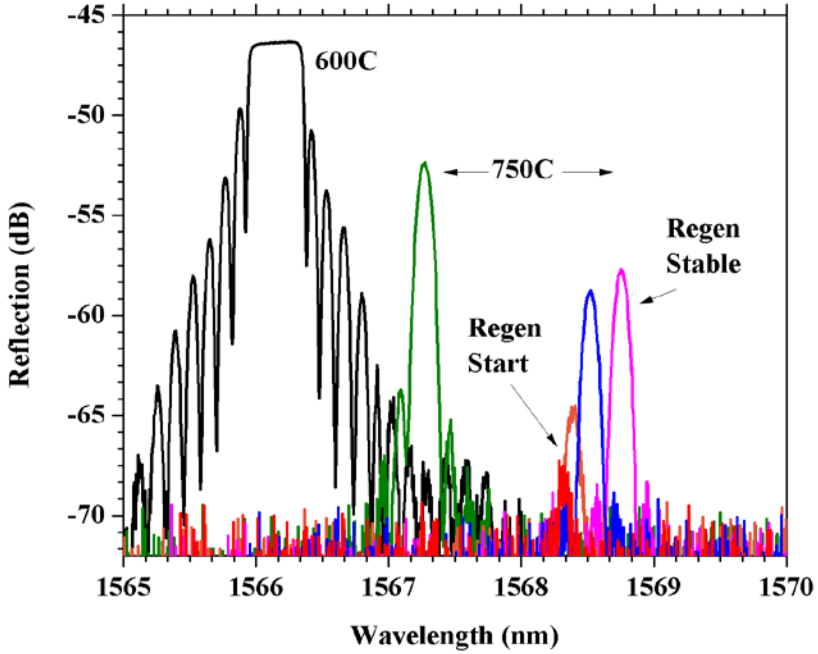


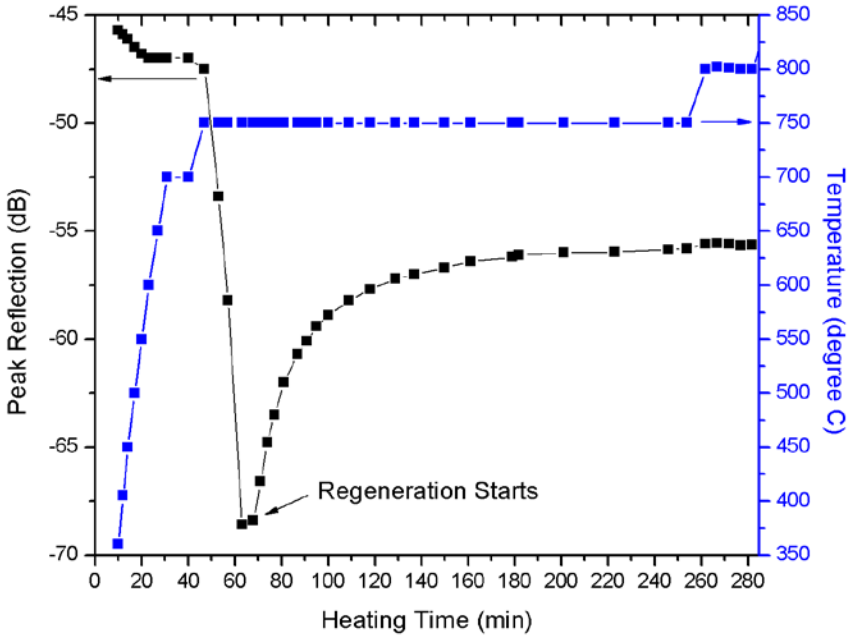


- **Custom-developed miniaturized furnace**
- **Pulse width modulation control scheme**
- **Rapid heating: 20C-800C in <u>9 minutes</u>**

Regenerated Type I Fiber Bragg-Grating:

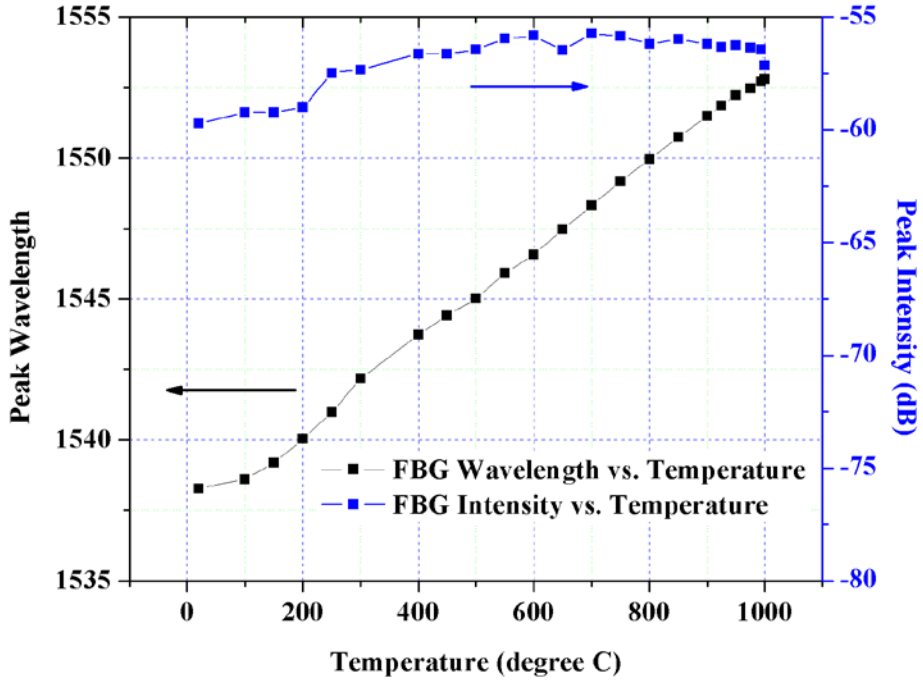
Regeneration process in Corning SMF-28 fiber

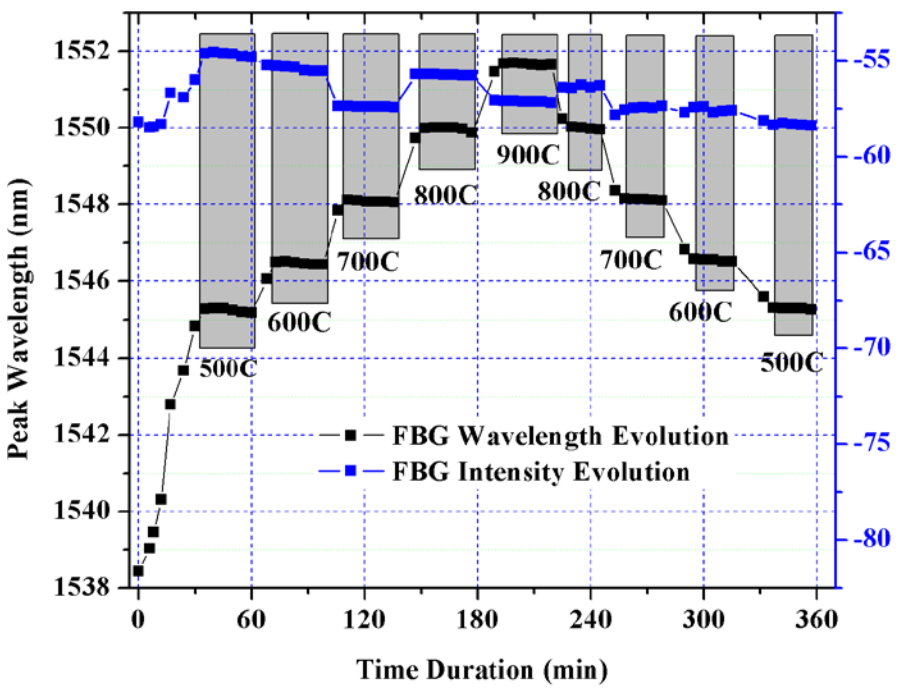




- Saturated FBG writing (Flat-top spectra).
- Grating regeneration at high temperature and peak wavelength red-shift.

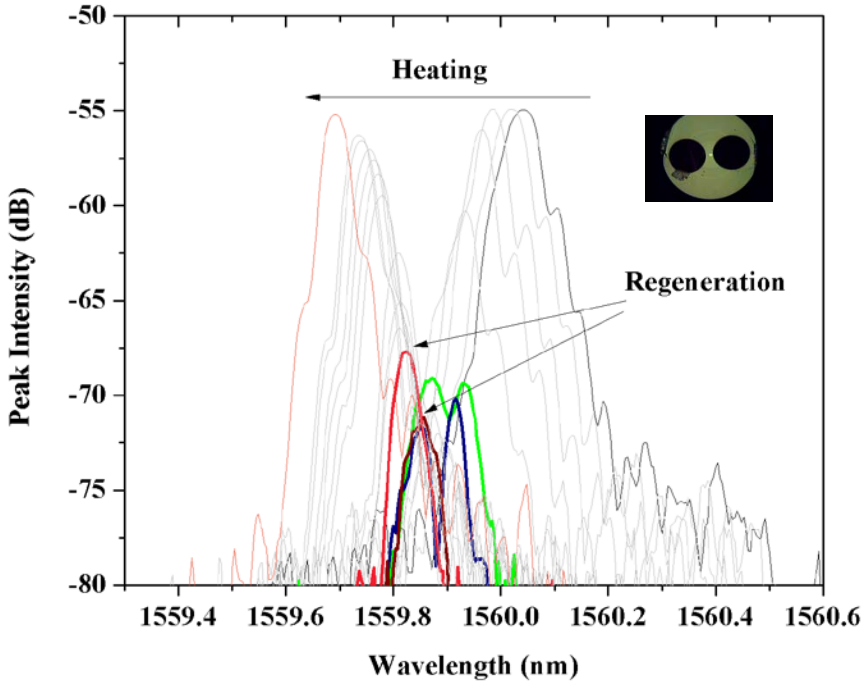
Regenerated Type I Fiber Bragg-Grating: High temperature test with Corning SMF-28 Fiber

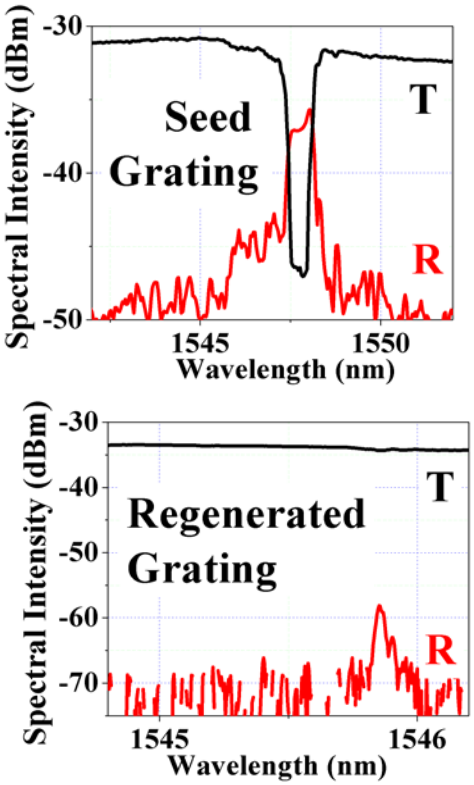




FBG stable up to 1000 degree C. (>1200 degree C reported)

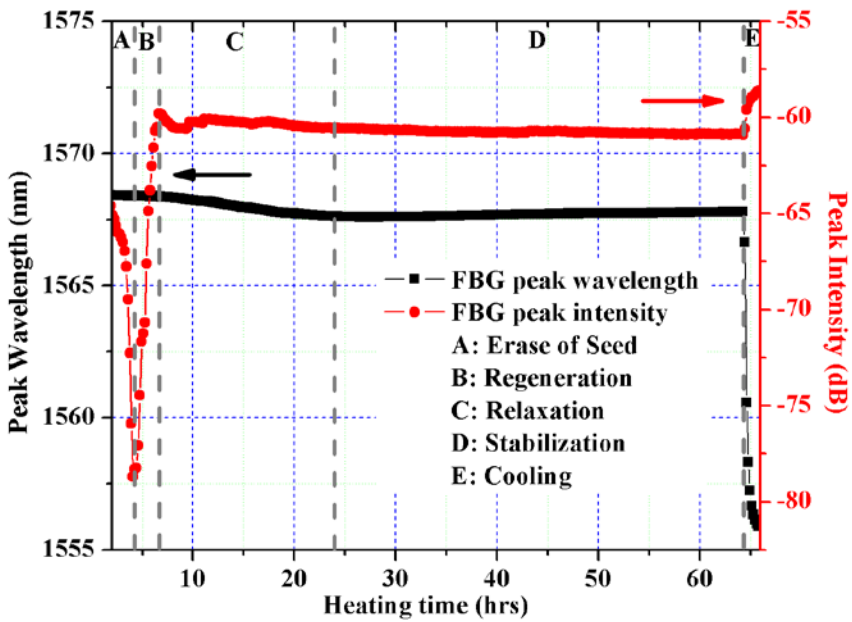
Regenerated Grating in Air-hole Microstructured Fiber: Regeneration process at 800C

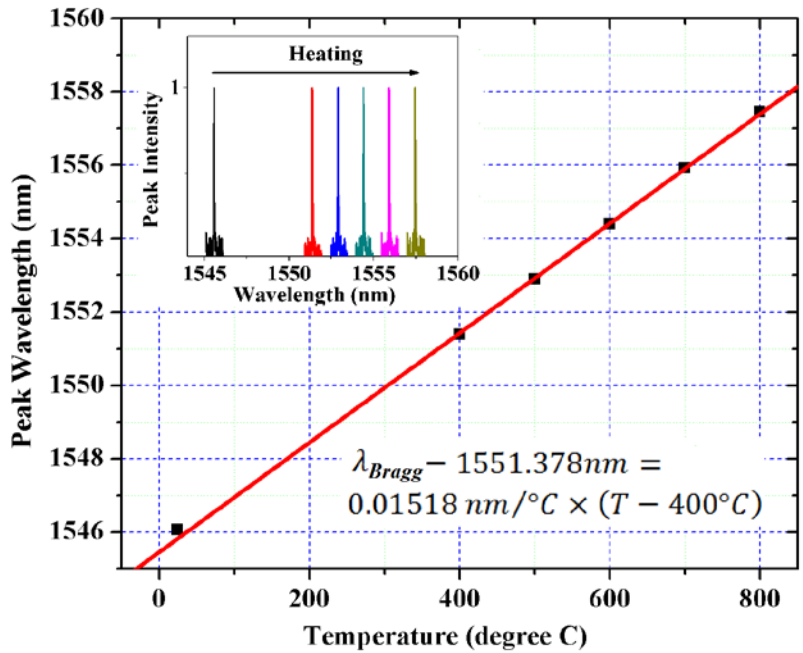




Contrary to the grating regeneration in Corning SMF-28 fiber, blue shift is observed in twin-hole fiber grating regeneration. The reflection R~97.5% for seed grating and ~2.3% for regenerated grating

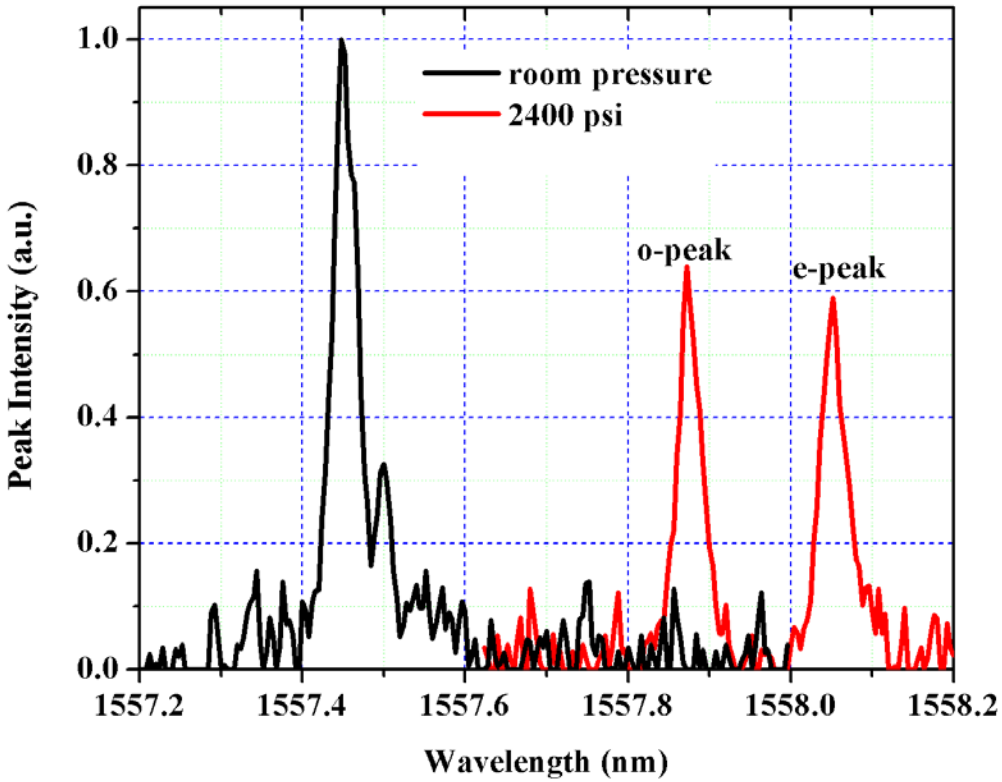
Regenerated Grating in Twin-hole Fiber: Temperature response and long-time tests





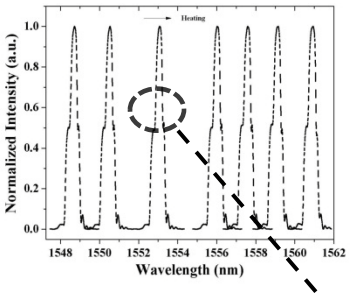
Left: 65hrs of FBG regeneration and stabilization cycle.
Right: Annealing Stable and linear high temperature operation.

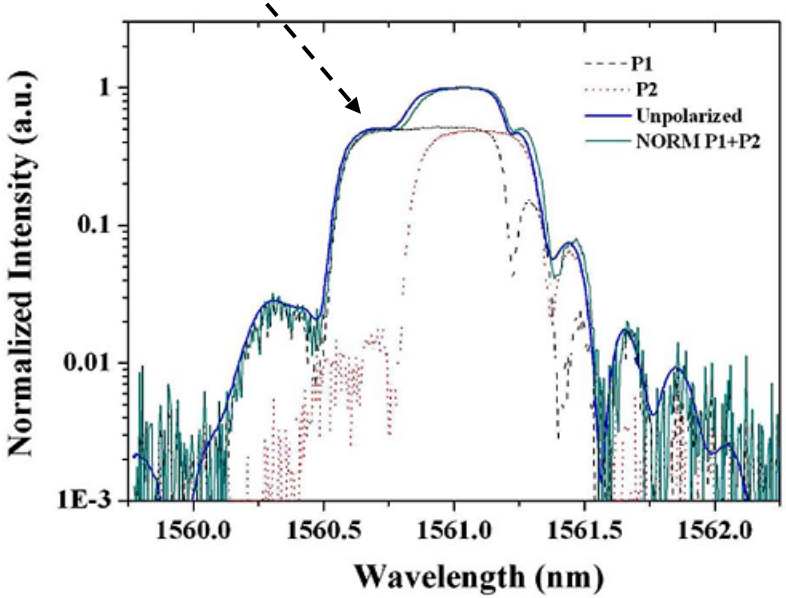
Regenerated Grating in Twin-hole Fiber: the pressure induced peak splitting at 800C



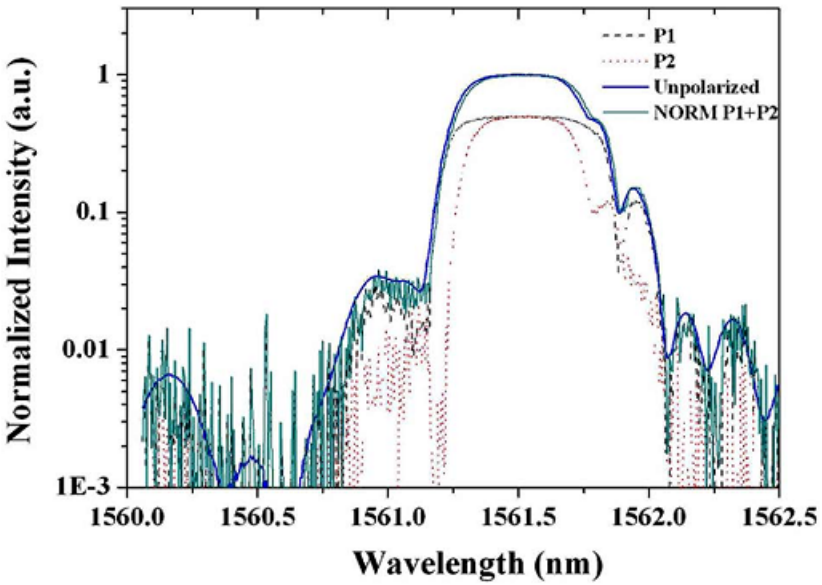
Black: The regenerated FBG has minimum intrinsic birefringence and only 35-pm FWHM linewidth. Red: The two polarization eigenmodes are separated by 180-pm under 2400-psi pressure

Ultrafast laser written FBG





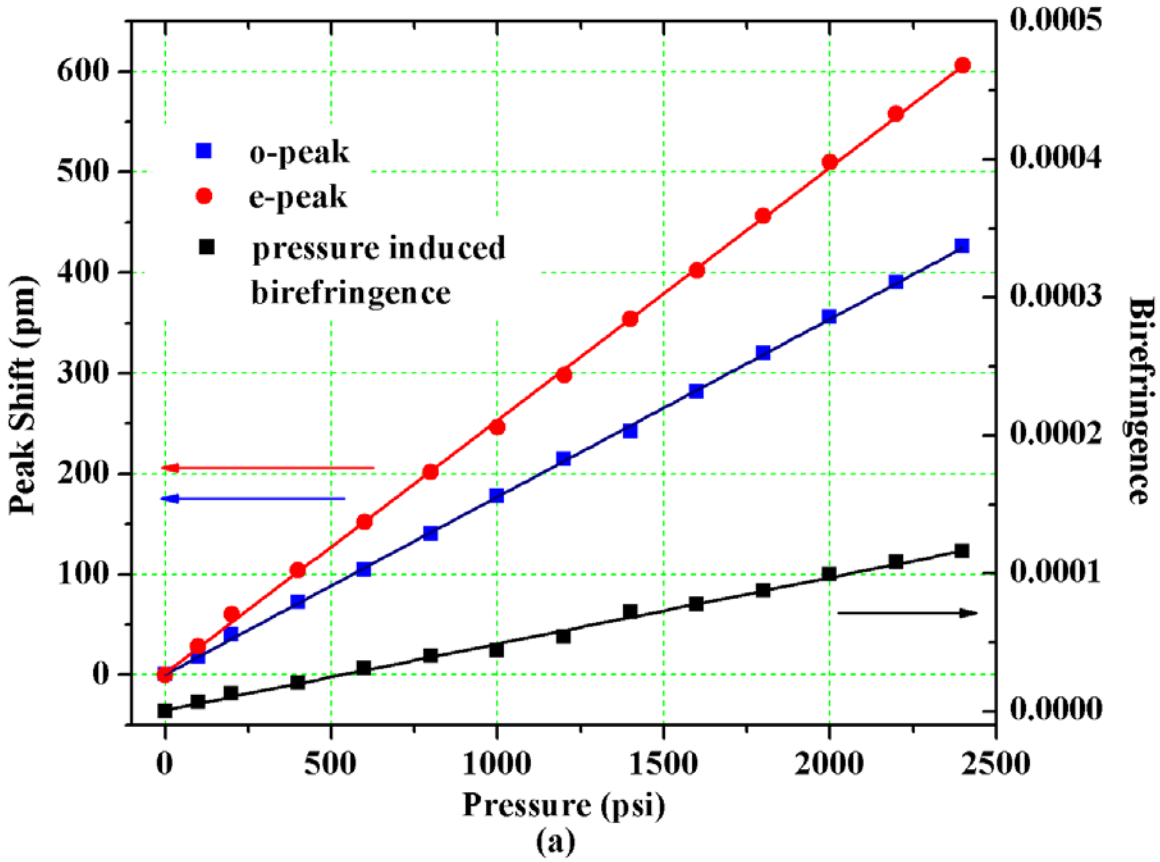
Peak splitting under 15-psi at 858°C.



Peak splitting under 2000-psi at 858°C.

C. Jewart, etc. *Optics Lett.* 2010

Regenerated Grating in Twin-hole Fiber: Pressure induced peak splitting at 800C



Linear pressure response from 15-2400 psi at 800C.

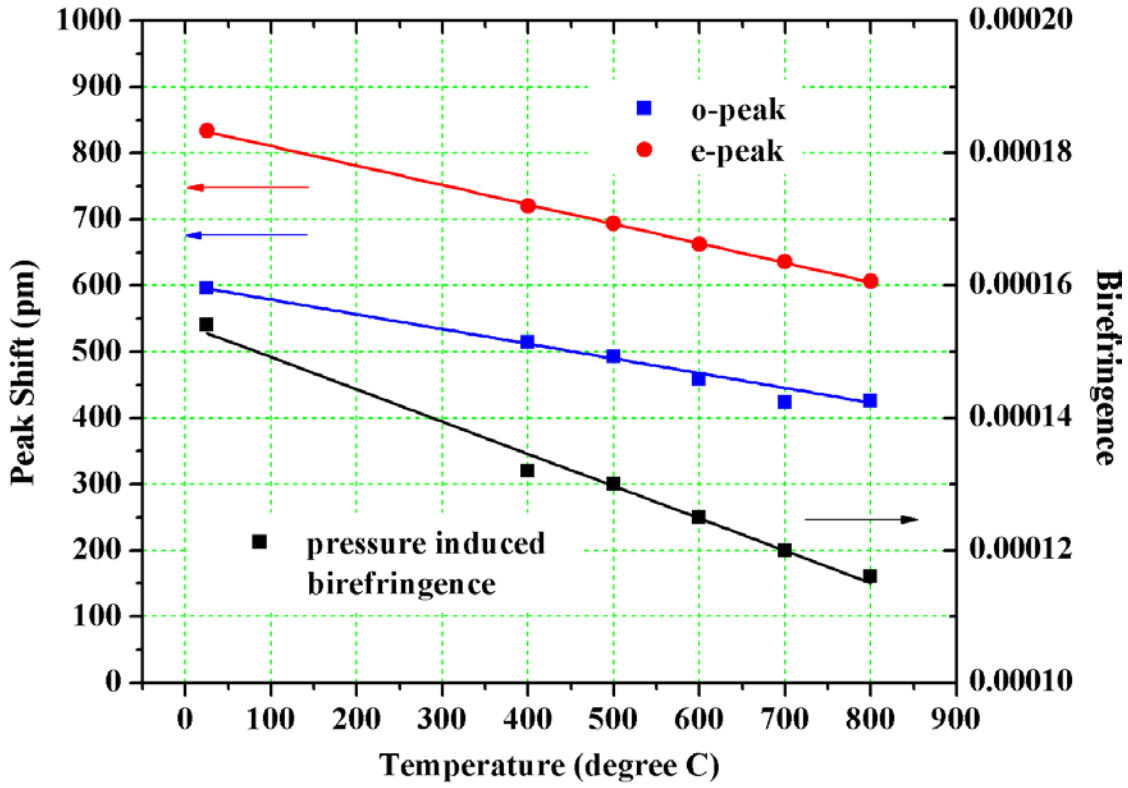
Regenerated Grating in Twin-hole Fiber: the sensor response matrix

$$\begin{pmatrix} \Delta\lambda_o \\ \Delta\lambda_e \end{pmatrix} = 1.518\times10^{-2}\, nm/^\circ C\, \Delta T$$

$$+\begin{pmatrix} 2.521\times10^{-4}\, nm/psi - 9.185\times10^{-8}\, nm/^\circ C/psi\Delta s \\ 3.526\times10^{-4}\, nm/psi - 1.232\times10^{-7}\, nm/^\circ C/psi\Delta s \end{pmatrix}\Delta P$$

$$\Delta\lambda_{o,e} = (\lambda - 1551.378)nm, \Delta T = (T - 400)^\circ C, \Delta P = (P - 0)\, psi$$

Regenerated Grating in Twin-hole Fiber: the pressure induced peak splitting at diff



(b)

Pressure induced birefringence is temperature dependent at 2400 psi.

Summary and Accomplishment

- **First Demonstration of Chemical Regenerative Process in Air-hole Microstructured fiber.**
- **Turn a low-cost commercially off-shelf FBG into high-T sensor with exceptional performance**
- **Simultaneous Measurement of *T* and *P* at high temperatures**
- **Working with an industry partner for commercialization**
  - **Lakeshore Cryotronics Inc.**

Future work

- **LPG and Tilted FBG fabrication**
- **Coating functional metal oxide materials (on-going)**