Development of High Sensitivity Engineered Optical Fiber for Distributed Acoustic Sensing

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LLNL-PRES-771698

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Objectives

- Long-term: Combine LBNL's DAS expertise with LLNL's optical fiber expertise to enable:
  - Rapid imaging of CO_2/pressure plumes
  - Higher-resolution characterization of faults and fracture networks
  - Improved detection of fluid flows
  - Detection and diagnosis of imminent wellbore integrity problem
- Near-term: Demonstrate 10× improvement in DAS sensitivity

Ground floor of LLNL's 3-story draw tower

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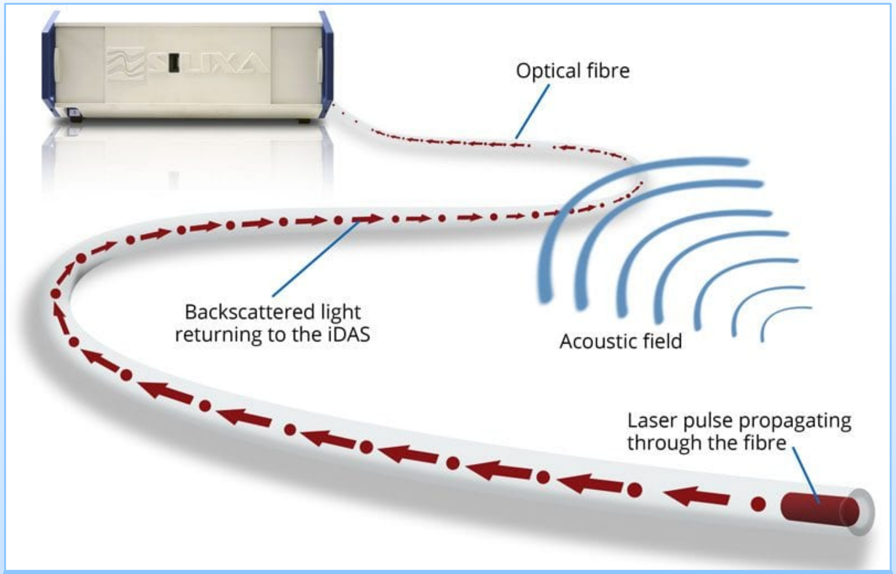
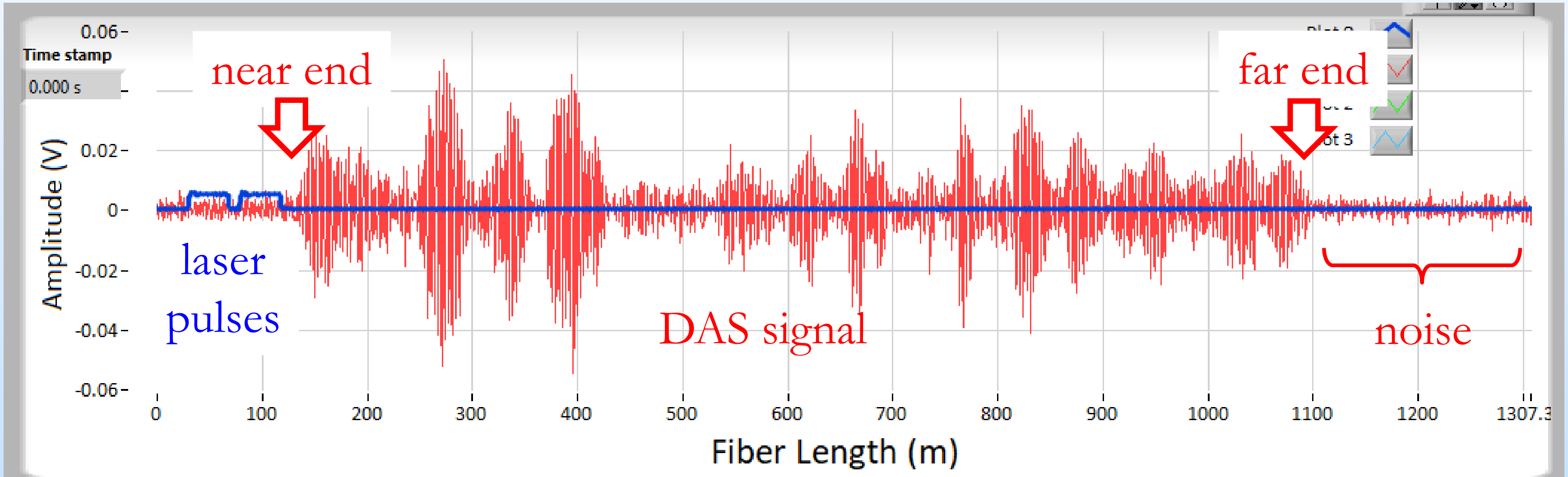
Distributed acoustic sensors

- All optical fibers backscatter a portion of the light they carry
  - Scattering occurs throughout the fiber's length
- DAS interferes the backscattered light with a reference beam to monitor changes in strain along the fiber's length
  - The fiber is the sensor



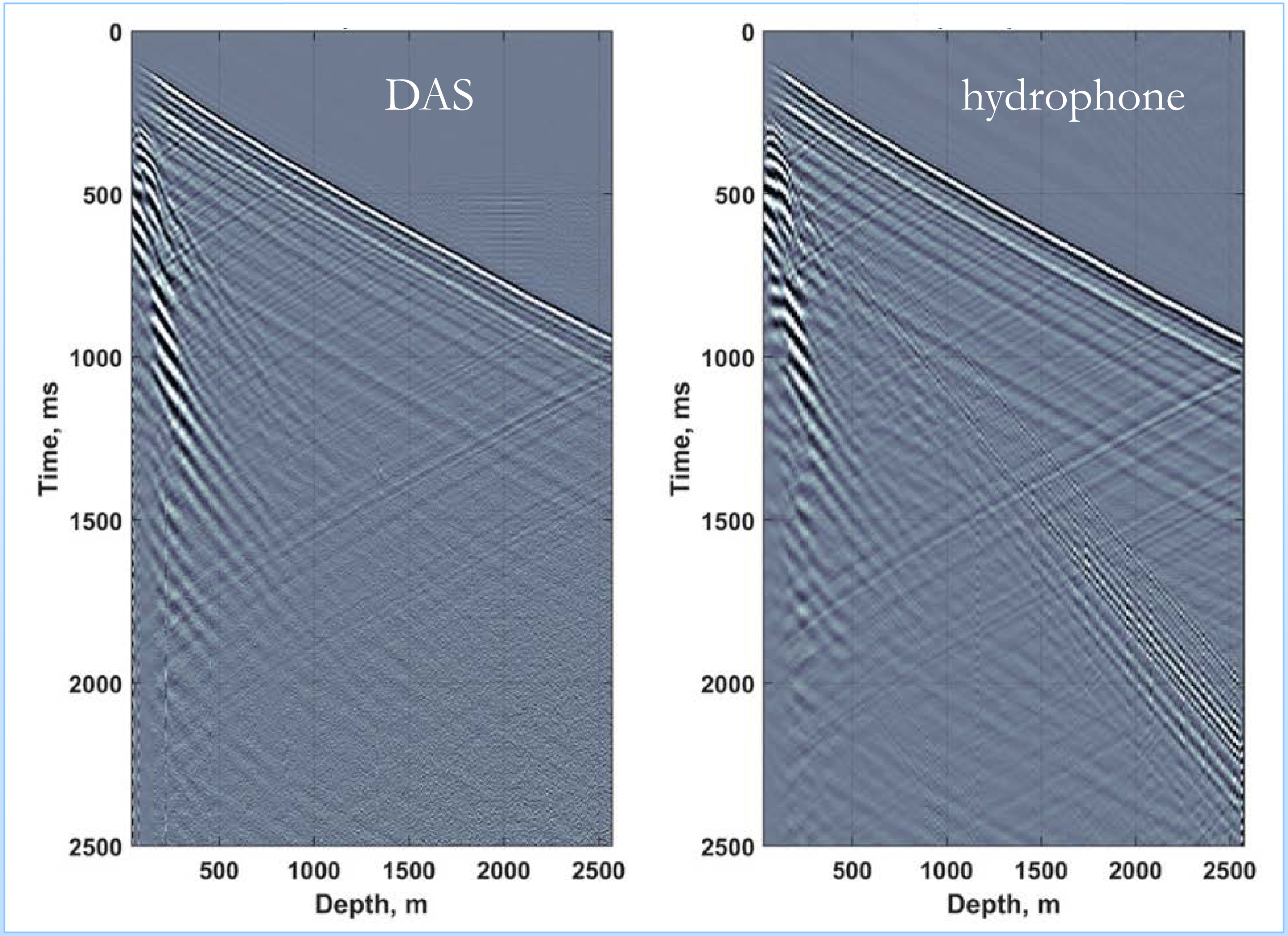
DAS senses strain changes caused by acoustic fields

DAS is already viable and valuable, but its signal-to-noise ratio tends to be low



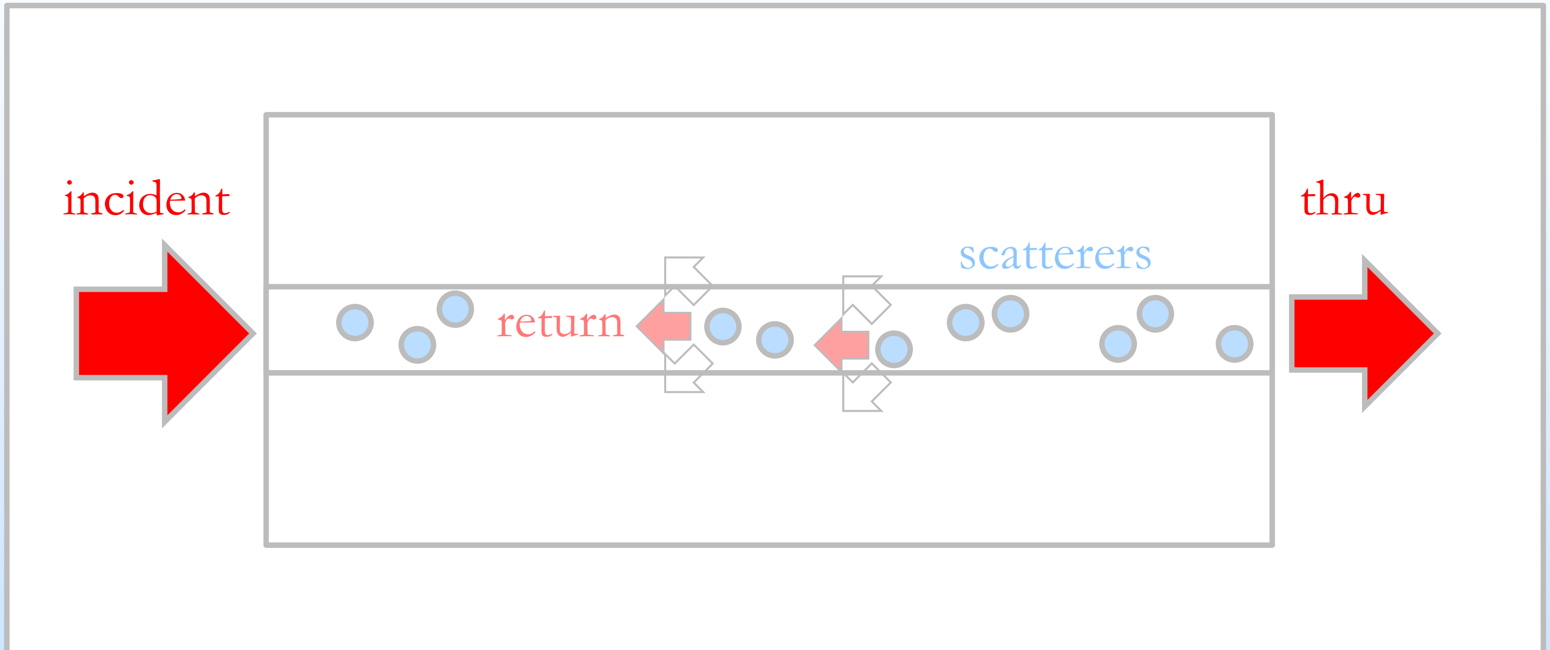
Raw data from LLNL's home-built DAS unit. Signal fading is due to distributed nature of backscatter, and to drift in the probe light's polarization state

Sensitivity of DAS is within a factor of ten of the sensitivity of a hydrophone array



From Willis, Erdemir, Ellmauthaler, Barrios,. Barfoot (2016)

Today, DAS signal is generated by Rayleigh scattering



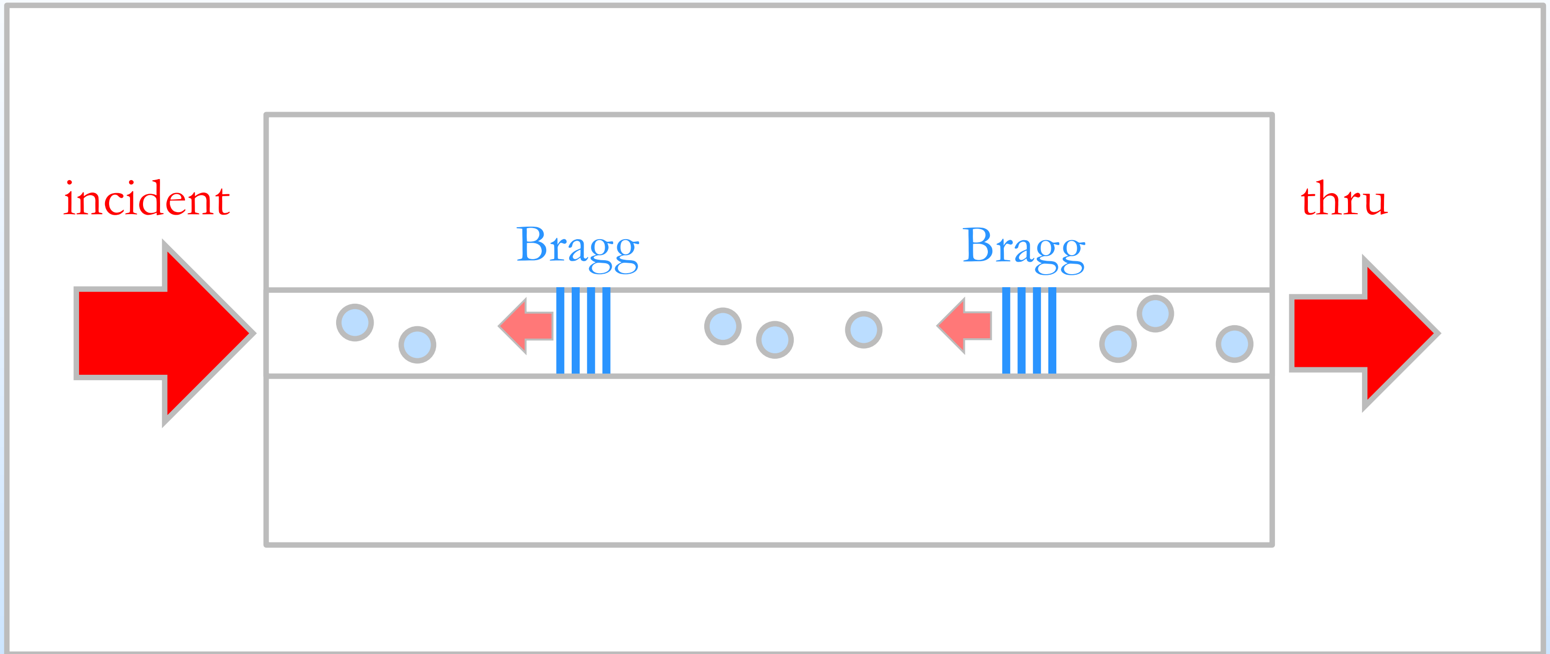
Rayleigh scattering is weak

- A 10m section of telecom fiber scatters only 0.05% of the light that passes through it, and captures and returns only 0.4% of that

Returned power is spread across pulse's width

- Since scattered amount varies with position, so does returned power

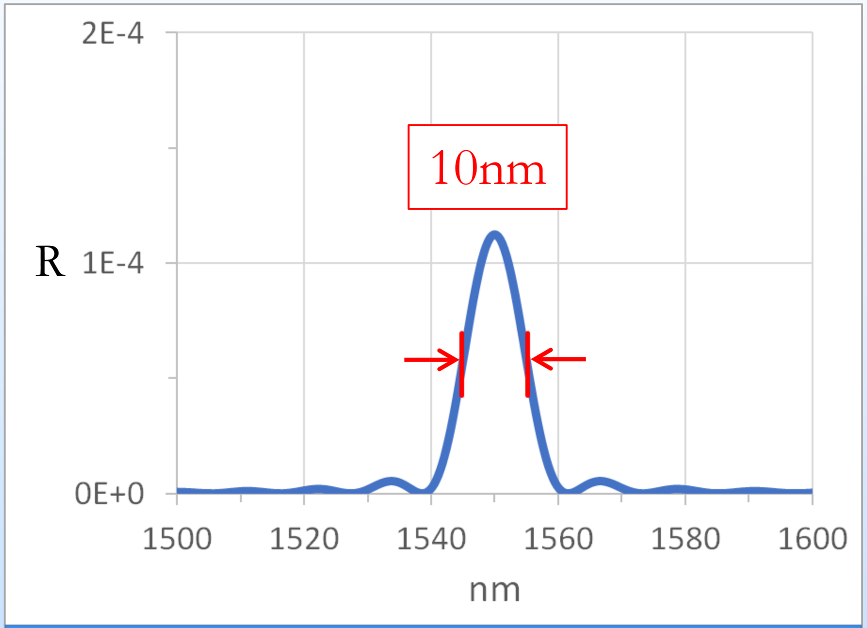
Bragg reflectors might enhance DAS signal ten-fold



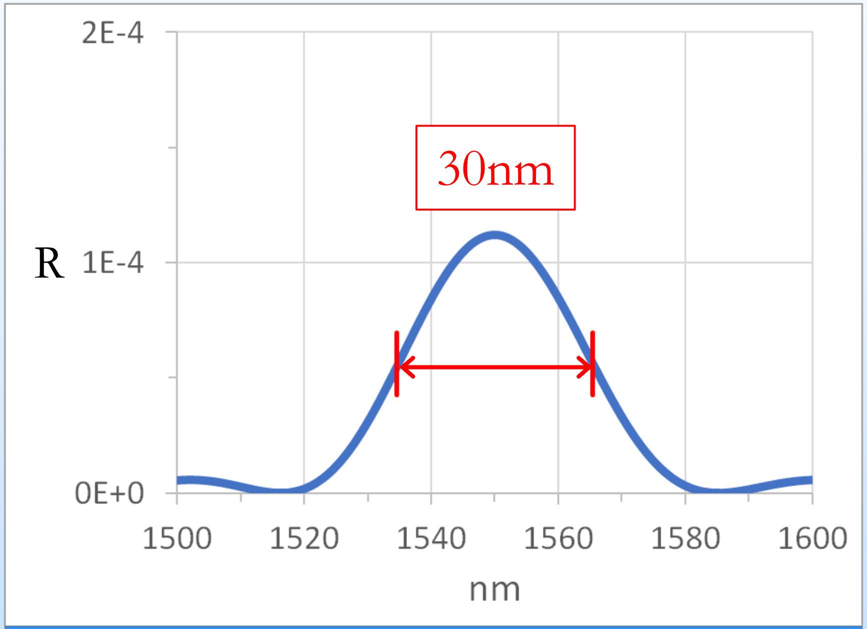
UV light can permanently modify the refractive index of glass by 10^{-3}, enough to write wavelength-resonant Bragg gratings into a waveguide

Proof-of-principal goal is to write and detect > 10 gratings along a > 500m length of fiber

Bragg reflectors for DAS should be relatively weak and spectrally broad



$\Delta n = 1 \times 10^{-3}$, 29 regions



$\Delta n = 3 \times 10^{-3}$, 9 regions

In contrast, telecom Bragg gratings have 1000 regions, with $R > 0.999$ and width < 0.1nm

Accomplishments to Date

1) Attempted to write gratings with UV LEDs already mounted on tower
   - ✓ Tested, but unsuccessful
2) Attempted to write gratings with LLNL's on-site lasers
   - ✓ Searched, but found no appropriate lasers
3) Writing gratings with program-purchased laser
   - ✓ Purchased, installed, and commissioned UV Excimer laser
   - ✓ Purchased, installed, and commissioned custom off-line rewinder
   - ✓ Write gratings (began writing on 19-Aug-2019)
4) Fabricate custom fibers
   - ✓ Fabricated UV-sensitive fiber
   - ✓ Fabricate custom fiber having UV-transparent coating
5) Design, commission, and field-test DAS cable

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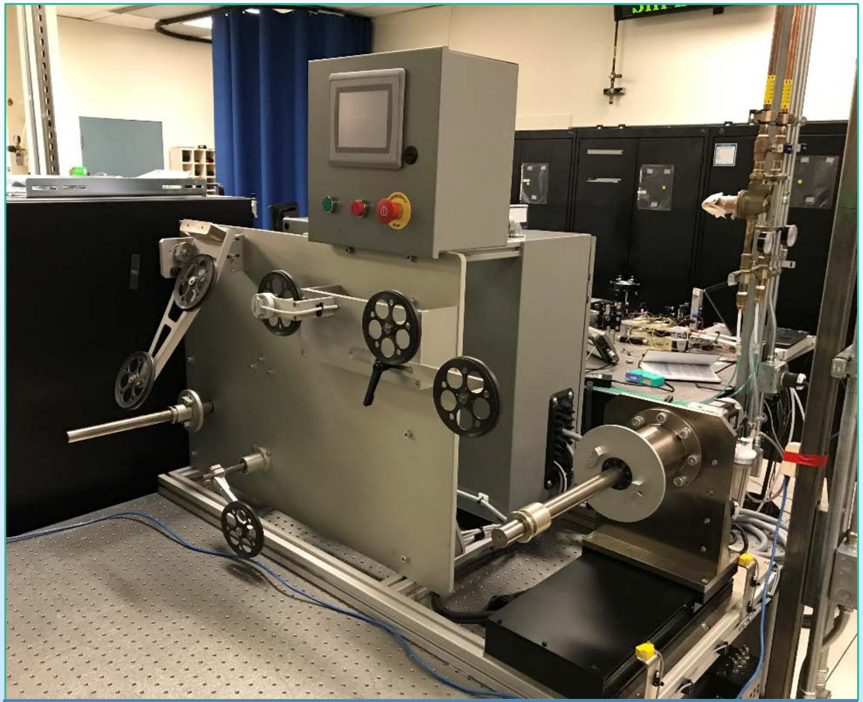
We have purchased and commissioned a UV excimer laser and a custom rewinder



Programmable rewinder
Technical Development Corporation
Huntersville, NC

UV excimer laser
248nm, 150mJ
Coherent Laser Corp

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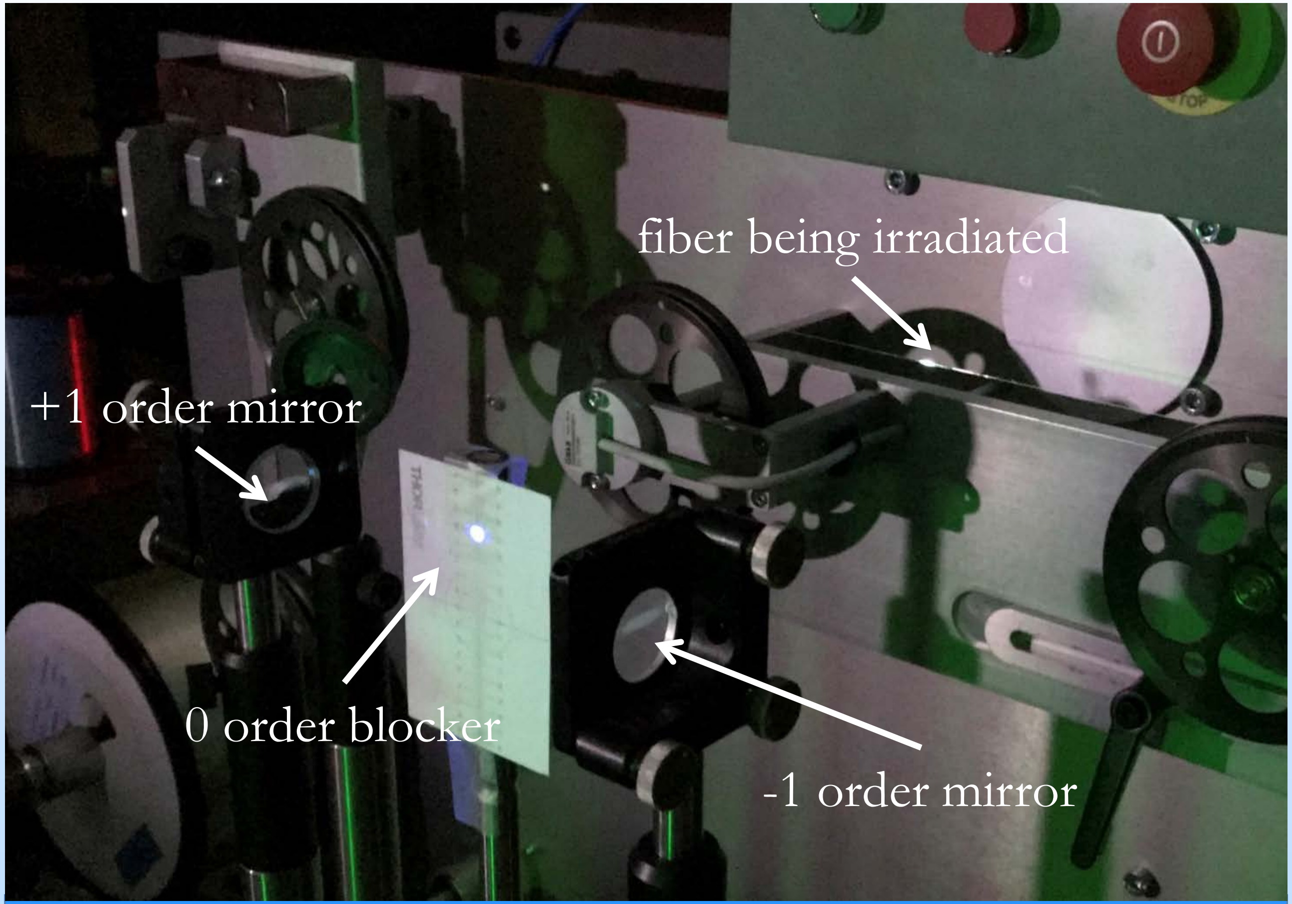
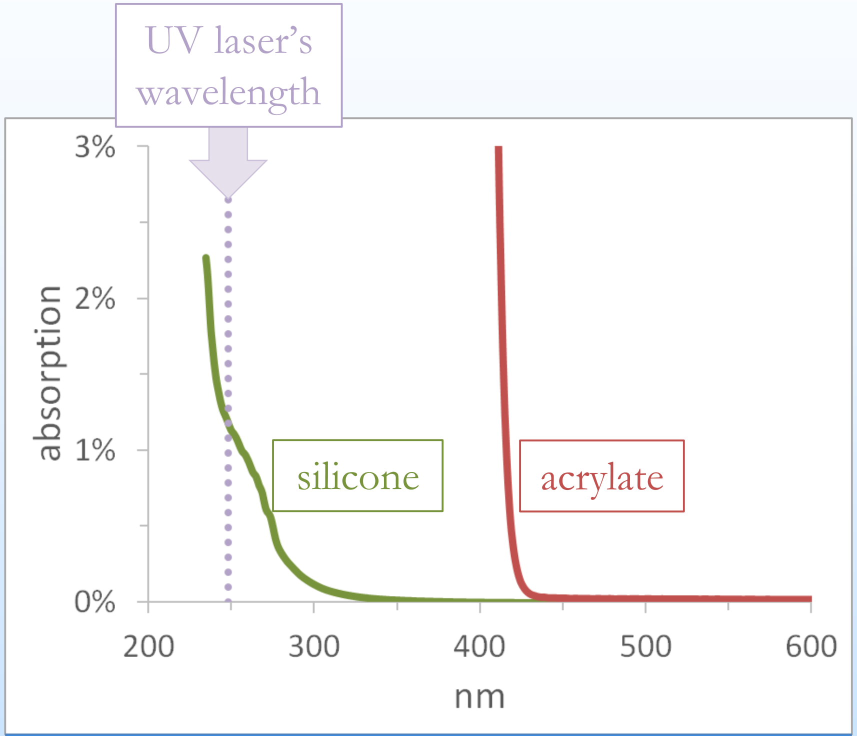
Began to write first gratings during week of Aug 19, 2019



LLNL's setup. Yu et al (2018) have demonstrated strong gratings in telecom fibers using a similar off-line process

We are fabricating a custom fiber coated with a UV-transparent polymer

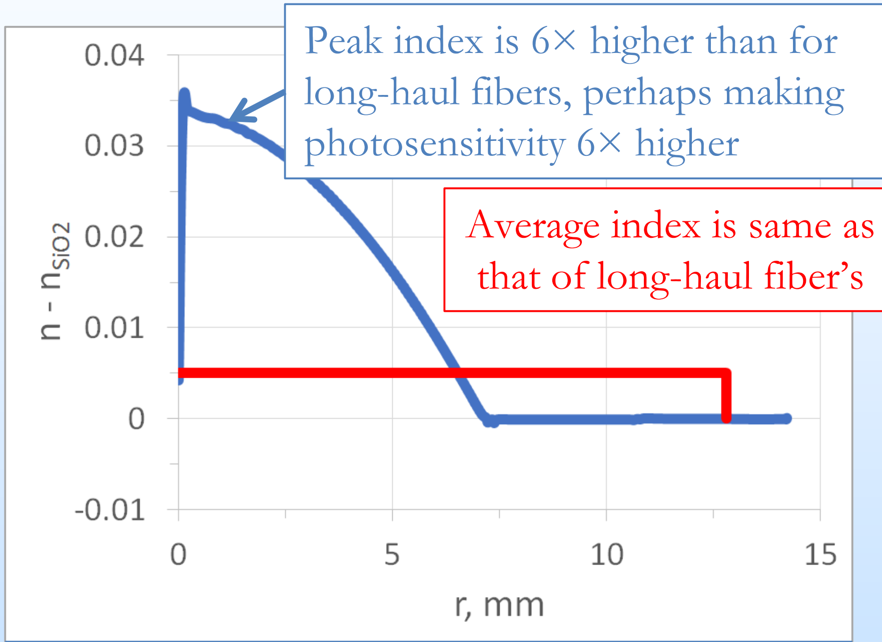
- Polymers that coat commercial telecom fibers absorb UV light
  - UV cures the polymers
- Thermally-cured coatings can have much lower UV absorption, allowing UV laser to pass through coating with little loss



Absorption spectra for two 30μm-thick coatings: a thermally-cured silicone and a UV-cured "telecom" acrylate

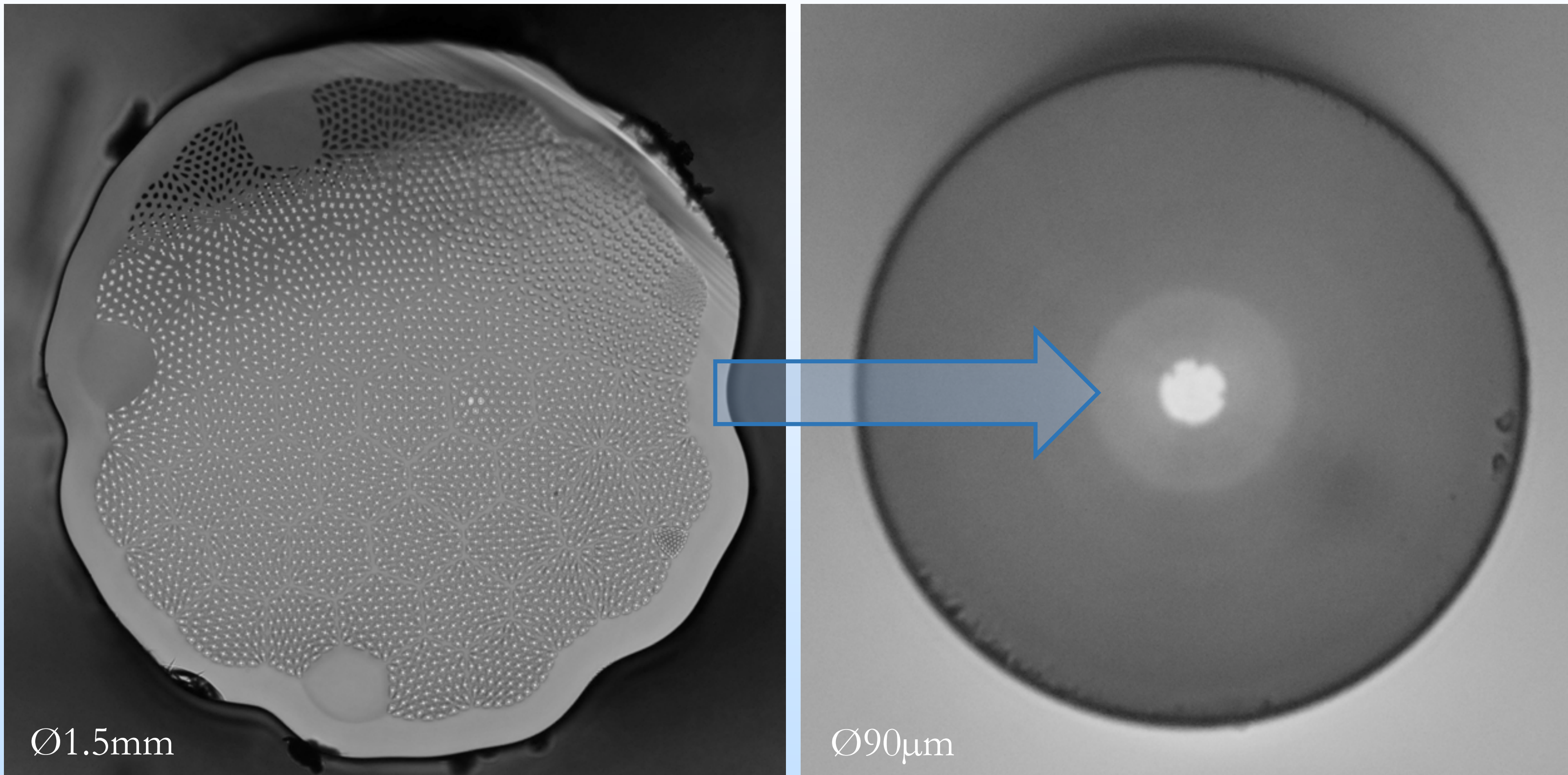
We have fabricated a photosensitive fiber

- Boron, phosphorous, and germanium are known to enhance the UV sensitivity of fibers
- For Fiber #1, we mixed highly Ge-doped glass to create photosensitive fibers having similar guiding properties as telecom fibers



Index profile of a preform commonly used to make graded-index fibers for local area networks

Fiber built with Ge-doped mixture



3,025-core cane
(55 groups of 55 cores)

Multicore cane becomes single core in photosensitized fiber

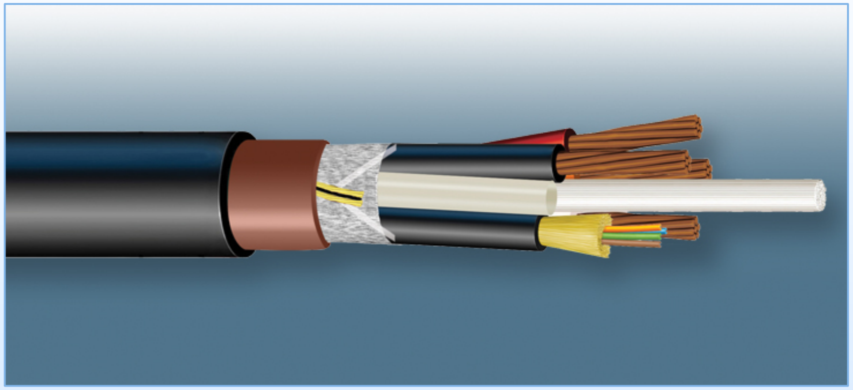
Though loss is unacceptably high (100dB/km), we will still be able to test photosensitivity

Lessons Learned

- Off-line writing, first presented by Yu el al, may greatly simplify the writing of weak Bragg gratings for DAS applications
  - Sidesteps manufacturing challenges and alleviates safety concerns
- Ge-doped glass used to enhance photosensitivity has unexpectedly high loss, limiting its use for DAS
  - Phosphorous-doped glass may be a better choice

Synergy Opportunities

- LBNL researchers will cable and field-test the DAS-enhanced fibers that the LLNL group is developing
- Carbon sequestration needs will continue to steer LBNL/LLNL research and commercialization efforts



Project Summary

Key findings

- An off-line writing process, involving a UV laser, overcomes safety concerns and should sidestep many manufacturing challenges

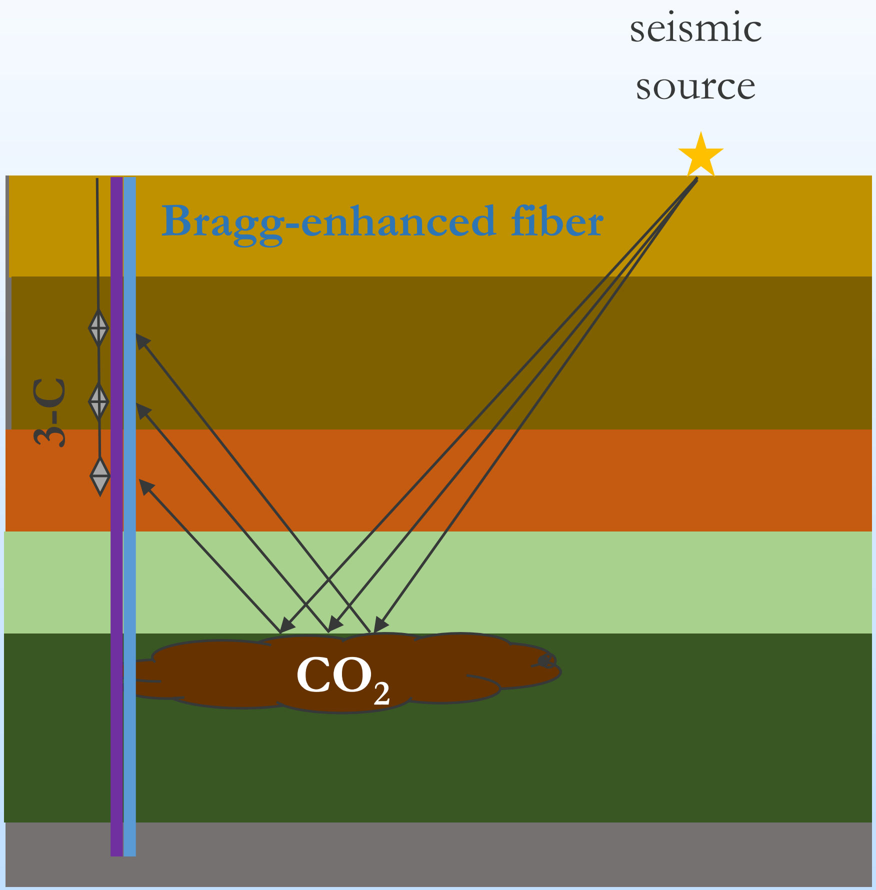
Next steps

- LLNL: Complete custom Bragg fiber and deliver to LBNL
  - Fabricate fiber having UV-transparent coating
  - Write > 10 gratings at intervals along a > 500m length of fiber, and deliver to LBNL team
- LBNL: Cable, deploy, and field-test fiber

Appendix

Benefit to the Program

- Sensitivity-enhanced DAS fiber would allow for…
  - More rapid imaging of CO_2/pressure plumes
  - Higher-resolution characterization of faults and fracture networks
  - Improved detection of fluid flows
  - Detection and diagnosis of imminent wellbore integrity problem



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Project Overview

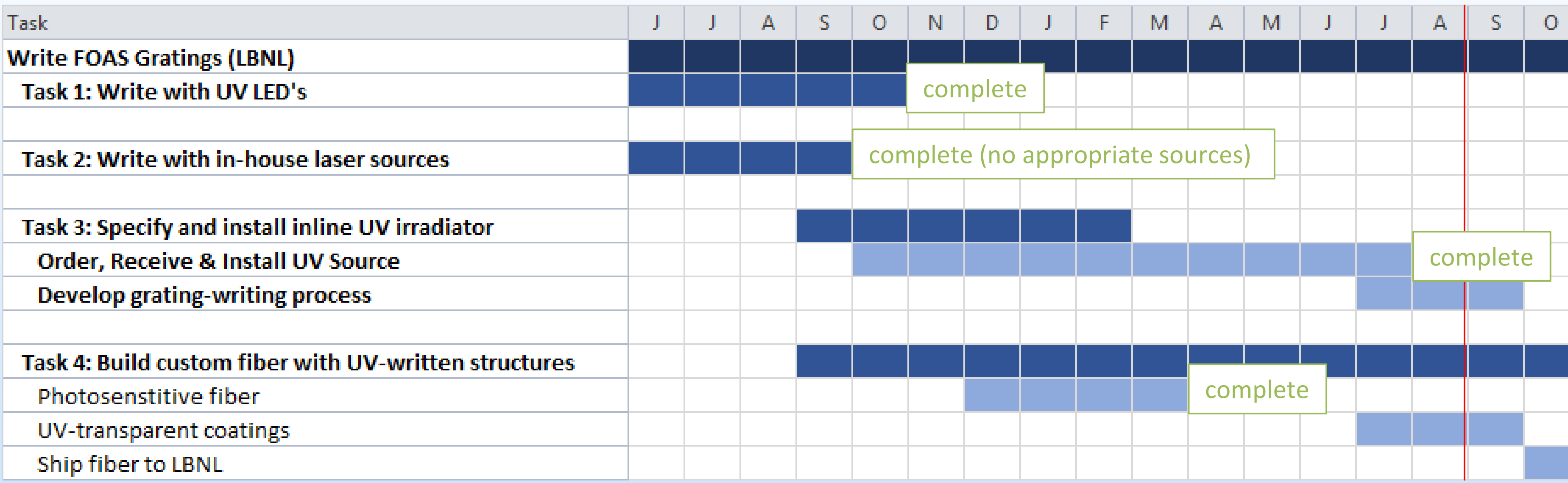
Goals and Objectives

- Goal: Combine LBNL's DAS field expertise and LLNL's optical fiber expertise to enable:
  - Rapid imaging of CO_2/pressure plumes
  - Higher-resolution characterization of faults and fracture networks
  - Improved detection of fluid flows
  - Detection and diagnosis of imminent wellbore integrity problem
- Objectives
  - Fabricate custom optical fiber, having length greater than 500m, and having more than ten weak Bragg reflectors, each reflector having reflectance greater 1/1000th
  - Cable the above custom optical fiber and field-test it, demonstrating greater than ten-fold improvement in DAS signal-to-noise ratio

Organization

- LBNL
  - Objective: Field test custom optical fiber cable
  - Lead scientists: Michelle Robertson, Julia Correa, Barry Freifeld
  - Resource Analyst: Helen Prieto
- LLNL
  - Objective: Develop fiber Bragg grating writing process, and fabricate custom optical fibers
  - Lead scientists: Robert Mellors, Michael Messerly

Gantt Chart



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- Gang Yu et al, "Micro-structured fiber distributed acoustic sensing system for borehole seismic survey," 2018 SEG International Exposition