Office of Nonproliferation and
Verification Research and Development

University and Industry Technical Interchange (UITI2011) Review Meeting

Mid-Infrared Spectroscopy and Beam Delivery Using Hollow Fibers

7-December-2011

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20 YEARS 1991 - 2011

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Mid-IR Hollow Fibers – Project Team

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DOE / NNSA / Remote Sensing
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National Nuclear Security Administration

Mid-IR Hollow Fibers – Project Overview

National Nuclear Security Administration

Motivation: Improve convenience, utility, and performance of infrared spectroscopy, calibration, and quantum cascade laser (QCL) based systems

Problem: Commercial fibers do not have adequate transmission and beam quality, particularly at longer wavelengths, $\lambda \sim 10\ \mu m$

Solution: Hollow-core Glass Waveguides with reflective/dielectric coatings

Status: Phase II STTR 8/2010 to 8/2012

Results: Fabricated single-mode hollow fibers
Developed custom solutions for PNNL
Improving fiber performance

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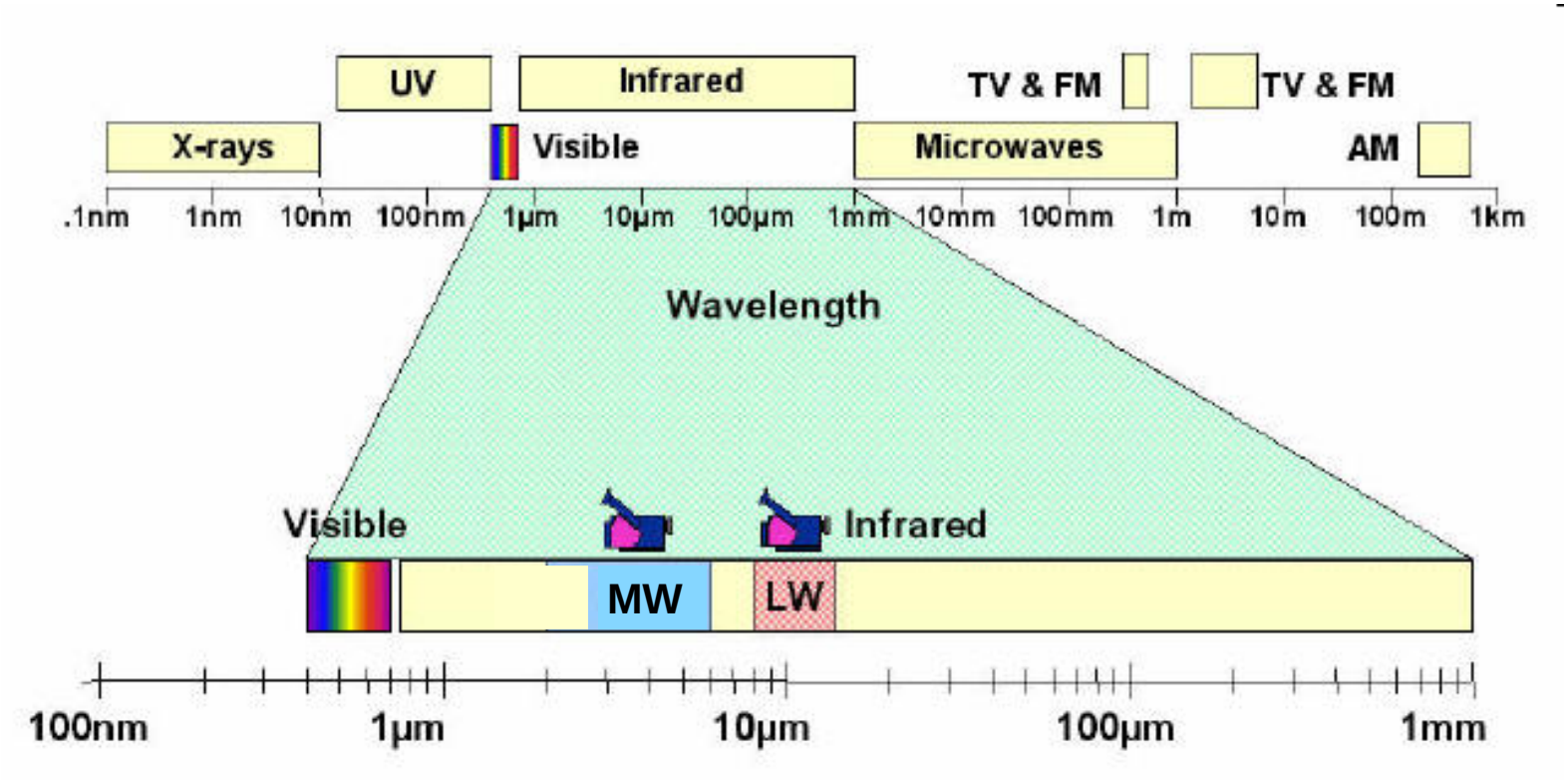
Infrared Wavelength Region



- Long-Wave Infrared (LWIR): 7 to 14 µm
- Mid-Wave Infrared (MWIR): 3 to 6 µm
- Mid-Infrared: 2 to 25 µm (5000 to 400 cm^{-1})

Long-Wave Infrared Spectroscopy

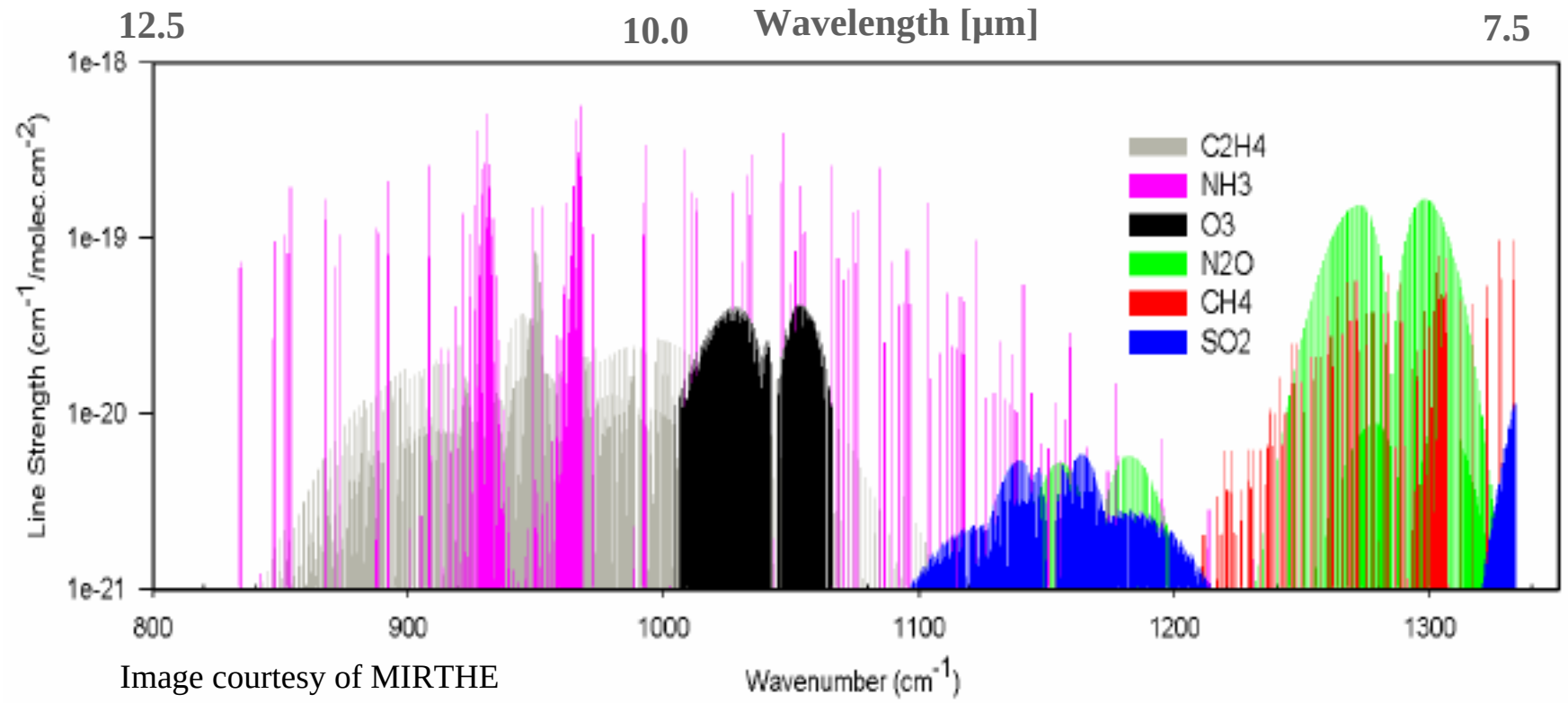


Image courtesy of MIRTHE

Molecular Finger Print

- Defense / security (e.g., WMD)
- Biomedical diagnostics
- Environmental monitoring
- Isotope ratio measurements

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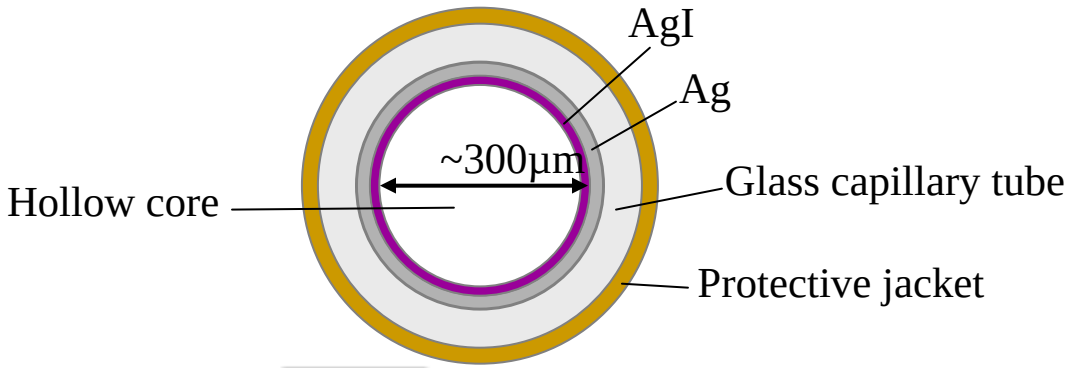
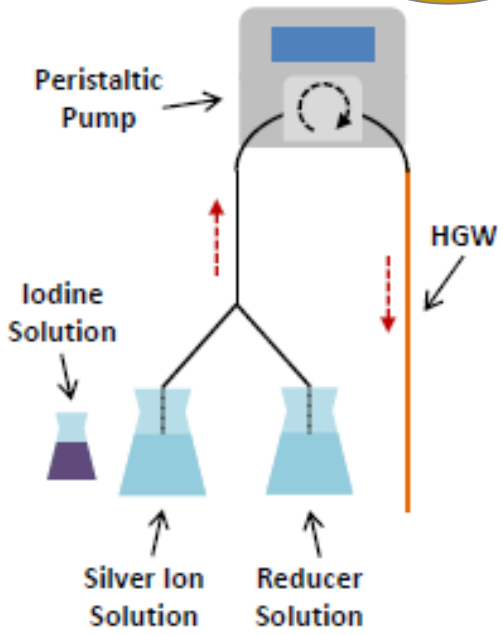
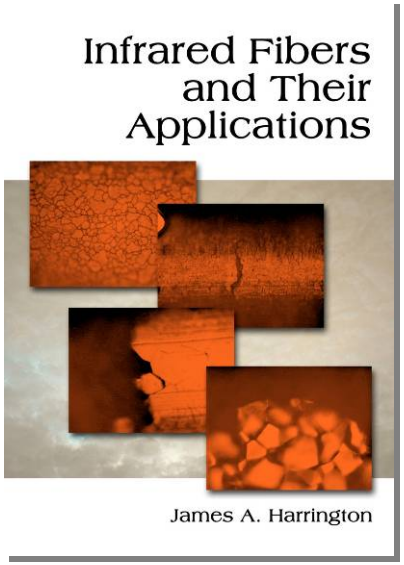
Hollow Core Glass Waveguides (HGW)







Hollow Core Glass Waveguides:

- Excellent Infrared transmission out to 20 µm
- Proven single mode delivery for bore size ~ 30λ
- No end reflections
- No cladding modes
- High damage threshold
- Very Robust
- 20+ years of experience at Rutgers

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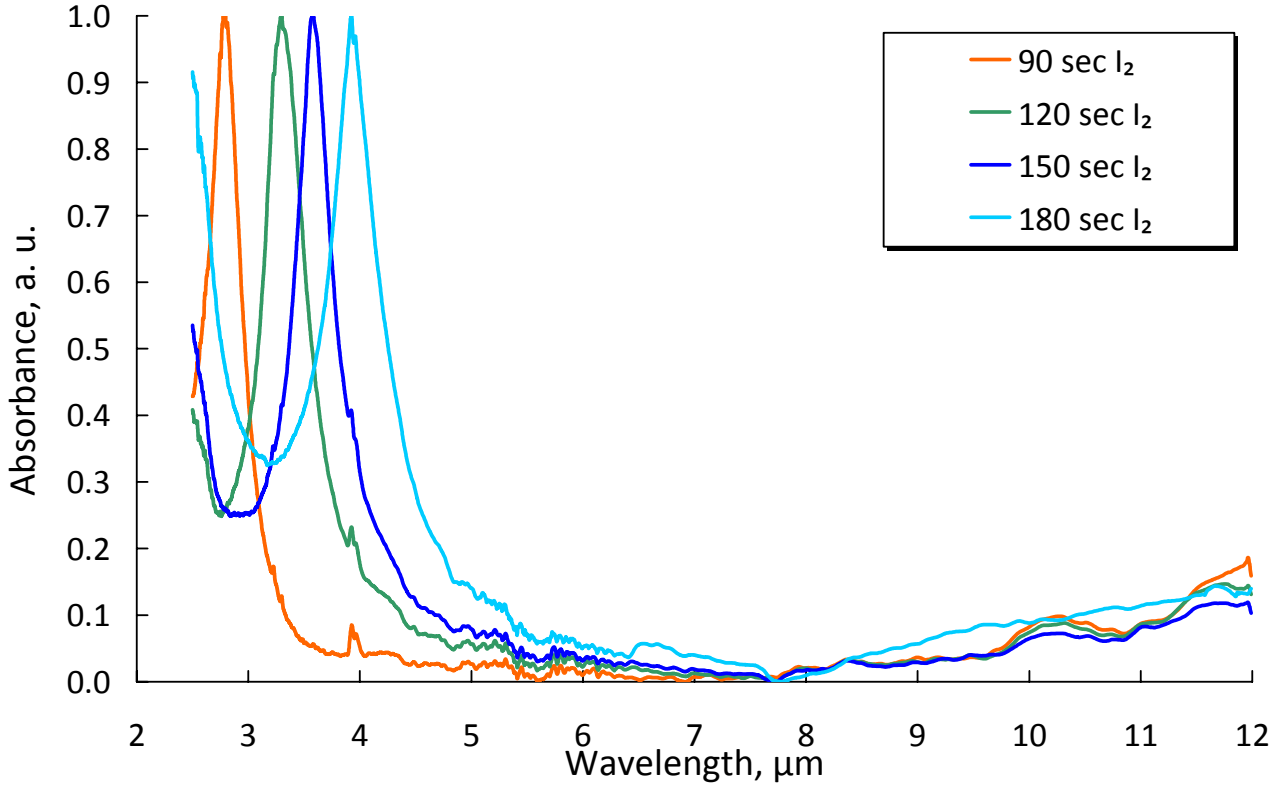
Spectral Transmission



- Spectral range is determined by dielectric thickness / deposition time
- Loss is relatively low even at longer wavelengths up to λ = 20 μm
- Coatings can also be tailored for shorter wavelengths including visible

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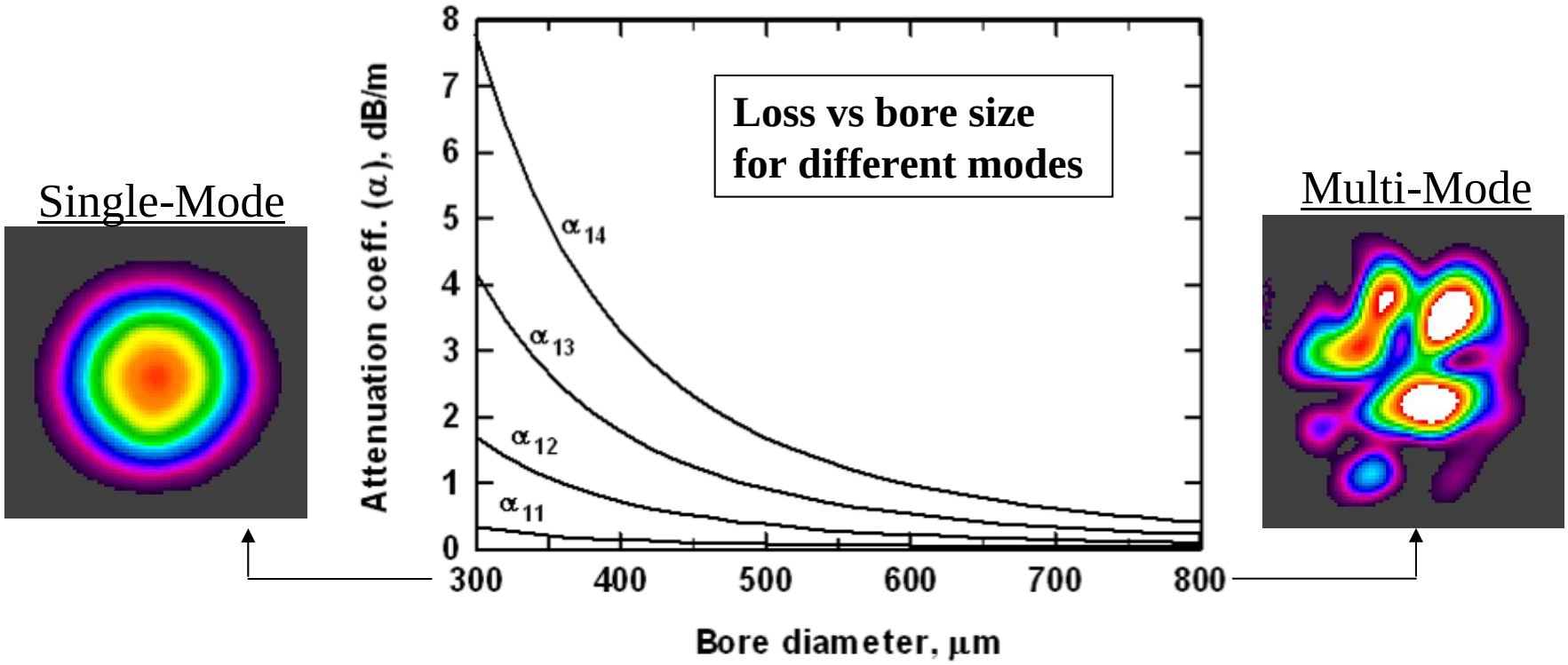
Losses for Hollow Glass Waveguide



- Loss ~ 1/(Bore Size)^3 => greater loss for smaller waveguides
- Loss higher for higher order modes => mode filtering

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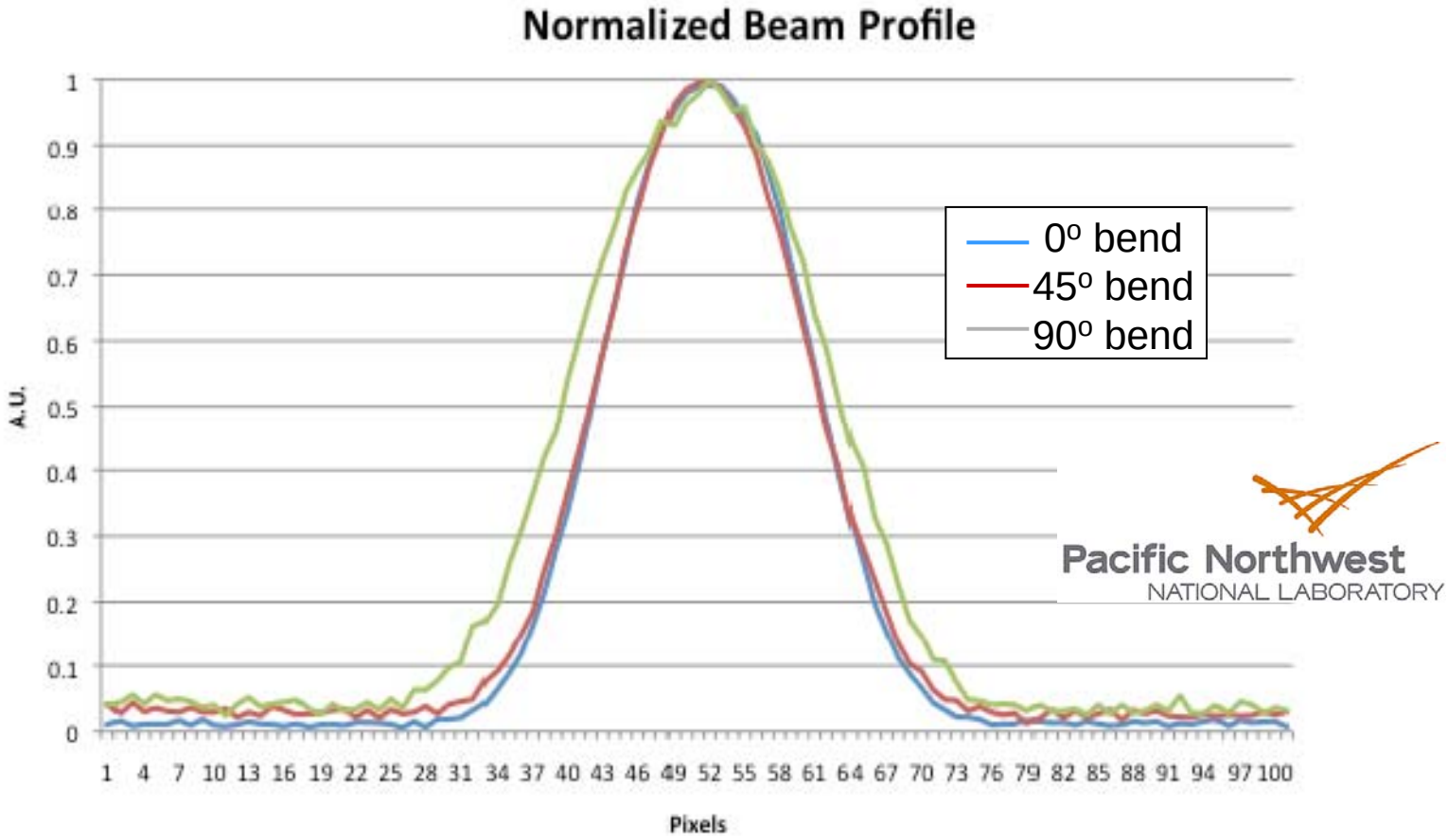
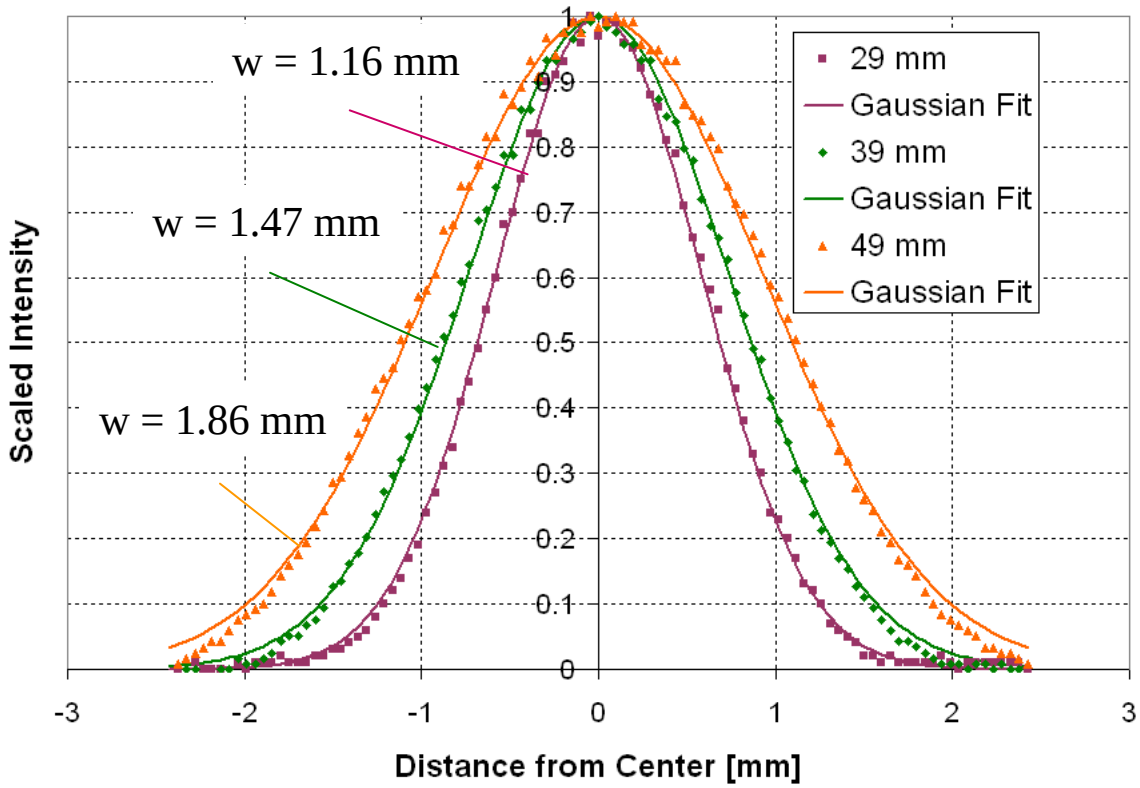
Gaussian Output – CO_2 laser (9.3 μm)



- Gaussian profile maintained in presence of bend

Gaussian beam profile in far-field



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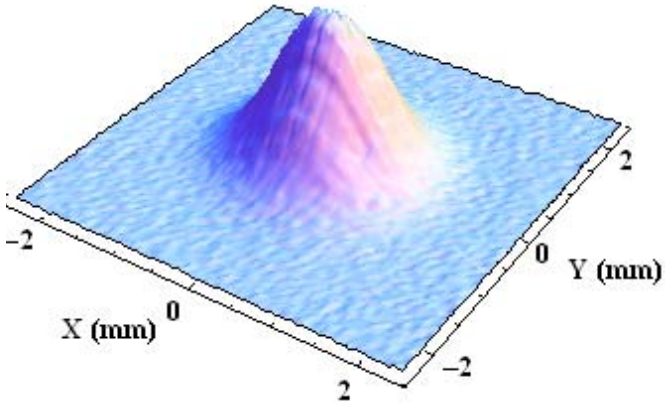

Beam profile at d = 29 mm

- Gaussian profile maintained in far-field
- Hollow fibers have small numerical aperture, NA ~ 0.04 at λ = 10 μm

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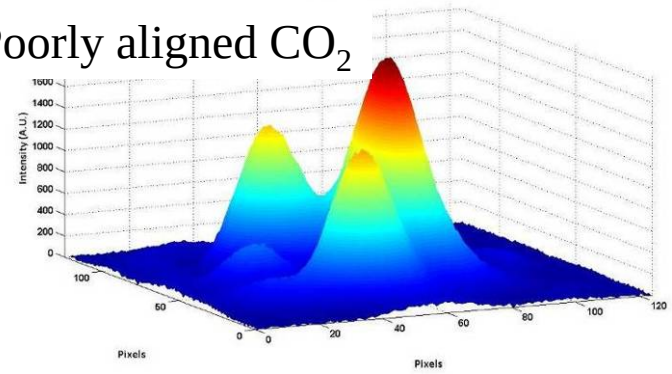
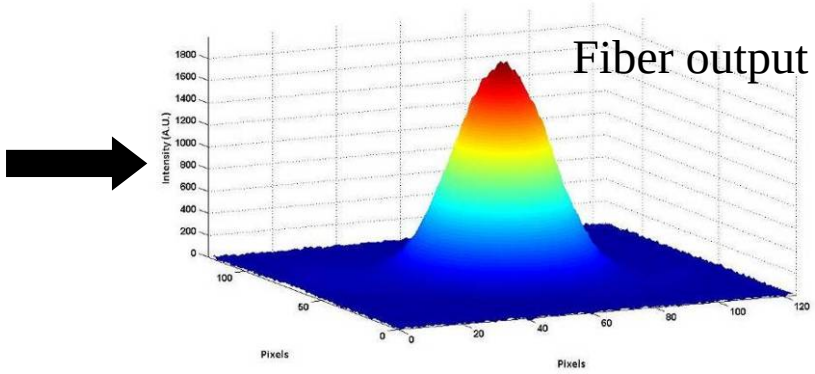
Mode Filtering

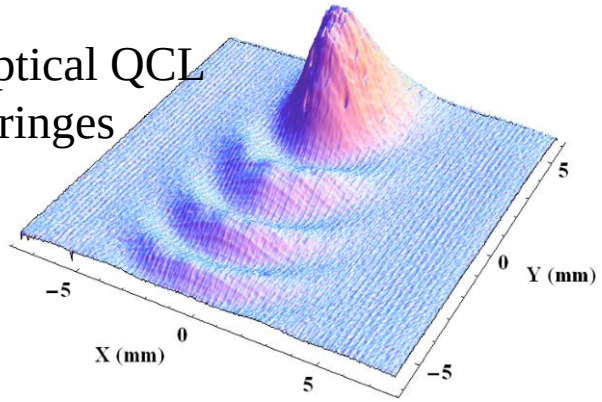
Poorly aligned CO_2

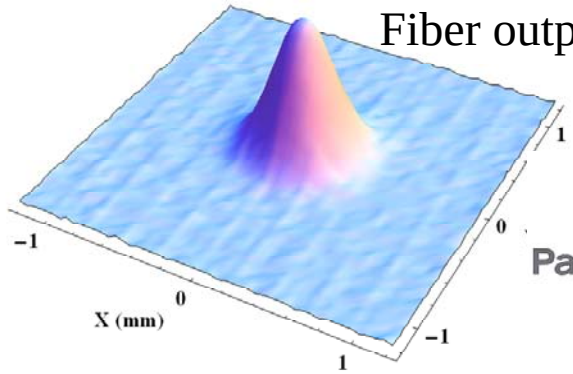




Fiber output

Elliptical QCL
w/ fringes





Fiber output

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- Higher order modes damped by waveguide, i.e., “Mode Filtering”
- Hollow fibers can be used to “clean-up” QCL beams

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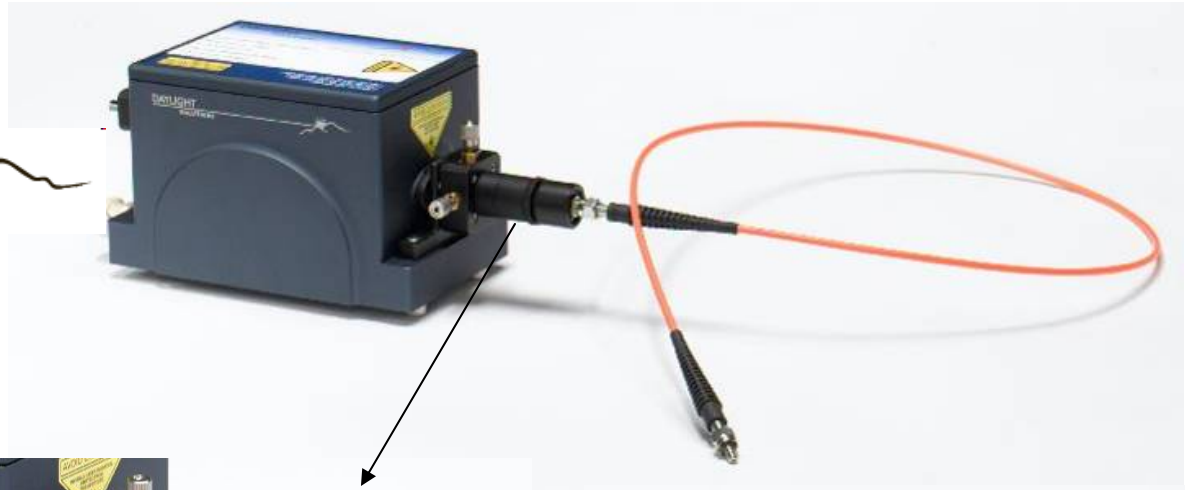
Fiber Probes and Optics for QCL's

- Fiber probe for single-mode delivery of LWIR lasers
- Custom mount and coupling optics for Daylight Solutions lasers
- Custom collimation and focusing optics



Coupling mount & optics

Collimation optics

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3-to-1 Fiber Probe for PNNL

- Inputs for 3 separate Mid-IR laser sources
- Common output
- Intended for PNNL calibration system

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Tanya Myers
Bruce Bernacki

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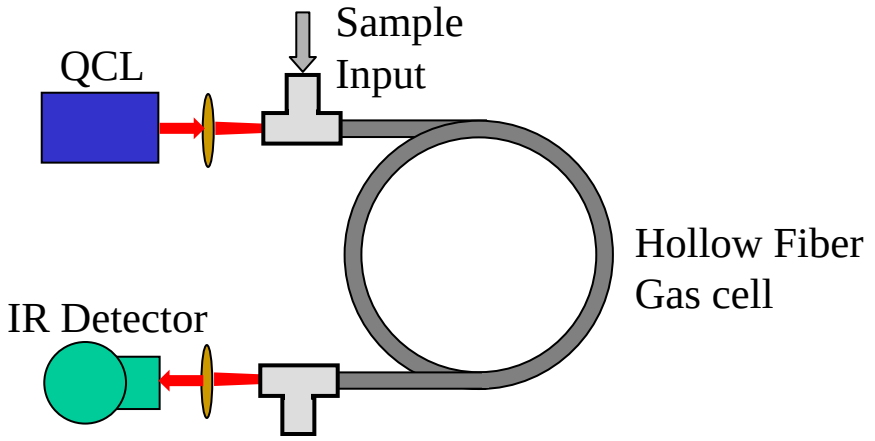
Hollow Fiber Gas Sensor

Benefits of hollow fiber gas sensors:

- Extremely small volume
- High sensitivity to small quantities
- Small size, weight, and power



Applications of hollow fiber gas sensor:

- Isotope analysis (e.g., $^{13}CO_2$ / $^{12}CO_2$)
- Gas detection
- Breath analysis (e.g., biomarkers)

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Jim Kelly
Capillary Absorption Spectrometer (CAS)

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Hollow Fiber CO_2 Isotope Analyzer

- Attribution/ carbon cycle/ sequestration
- Atmospheric monitoring
- In situ soil / water sampling
- Biological analysis

Institution / Method	Total Vol. (mL)	Press. (Torr)	CO Conc (ppm)		
Picarro / CRDS	30	300	300	1.6×10^{-7}	0.5 /100 s
Los Gatos / ICOS	120	300	300	6.4×10^{-7}	0.25 / 60 s
Aerodyne / Herriott	300	25	300	1.3×10^{-7}	0.2 / 1 s 0.03 / 300 s
PNNL / CAS	0.63	2	390	2.0×10^{-11}	1.0 / 1000 s
OKSI-PNNL / CAS (proposed)	0.10	2	390	$\sim 3 \times 10^{-12}$	~ 0.4 / 10 s

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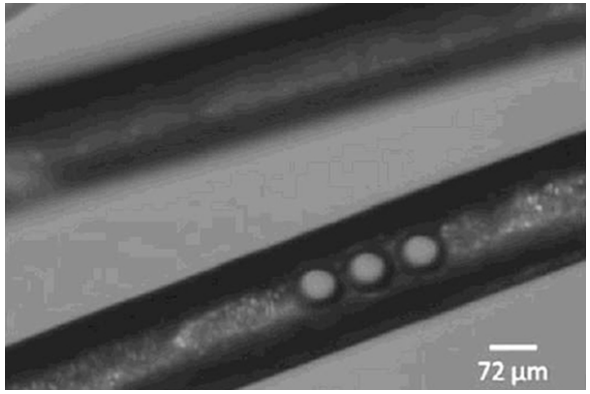
PNNL CO_2 Isotope Analyzer

- Used with laser ablation to analyze ultra small samples
- Fiber-based CAS replaces much more expensive and bulky mass spectrometer
- Biological / forensic applications

Laser ablation of horse hair



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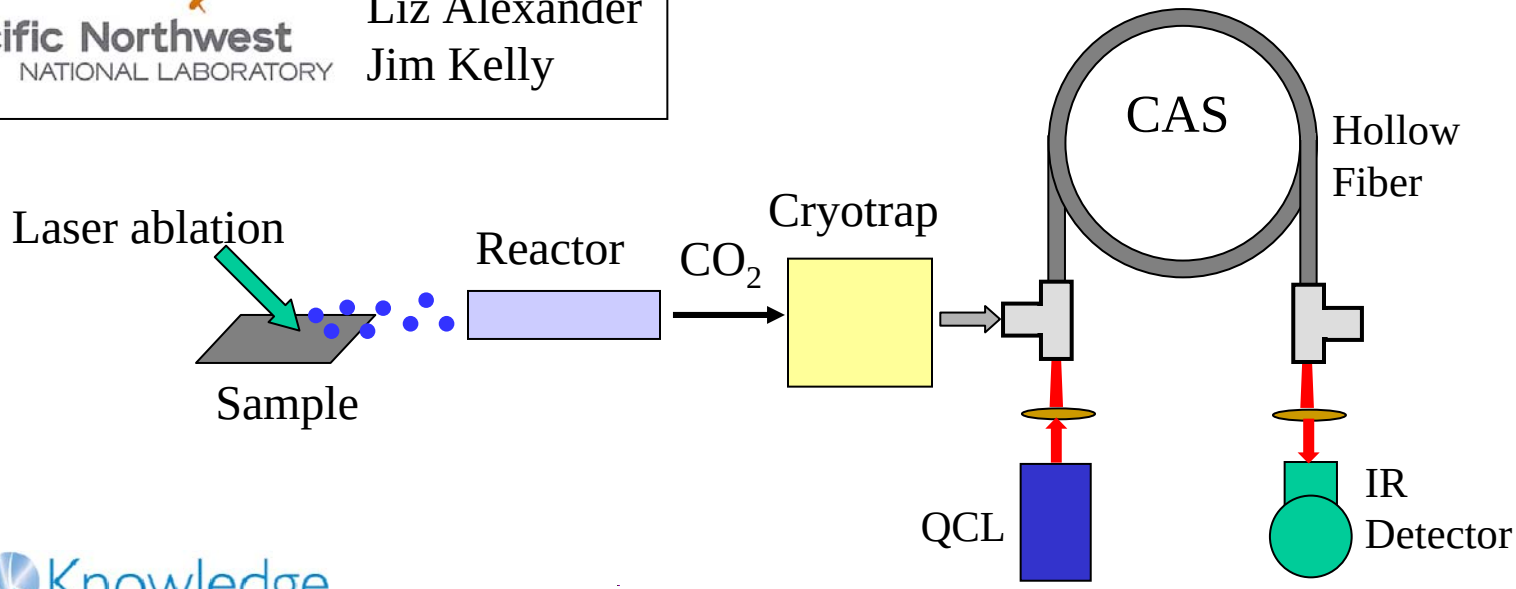
Jim Moran
Liz Alexander
Jim Kelly



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Related Projects / Applications

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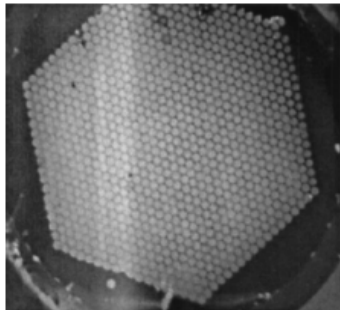
Related hollow fiber work at Opto Knowledge:

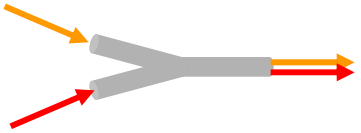
- Hollow fiber bundles for IR imaging / signal collection
- Beam delivery for high-energy short-pulsed lasers for combustion/propulsion diagnostics (visible wavelengths)

600 rigid holes



Other applications being pursued:

- BRDF measurement device for solids
- Remote IR spectroscopy analysis (penetrator)
- CO_2 laser delivery for medical & industrial applications
- IR counter measures
- Fiber beam combiner



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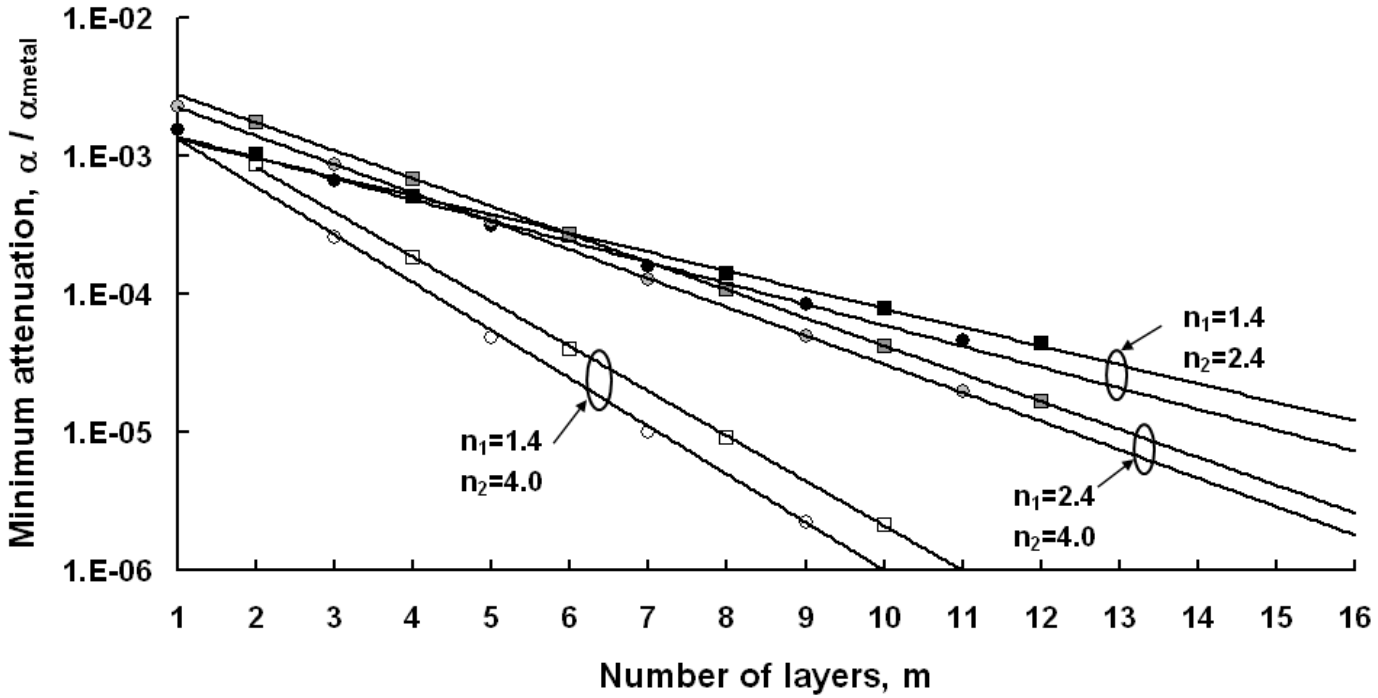
On Going R&D

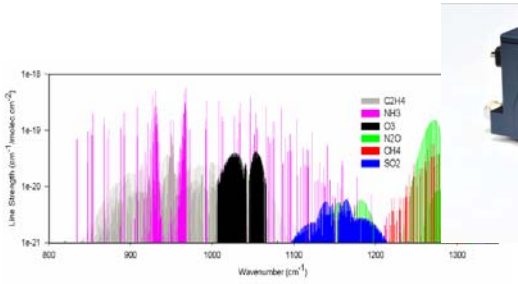
- Continue to improve standard coating and develop modified fiber structures
- Develop advanced multi-layer coatings with potentially much lower loss (e.g., single mode fibers for the 3 to 5 µm range)
- Continue to develop specific solutions for spectroscopy systems

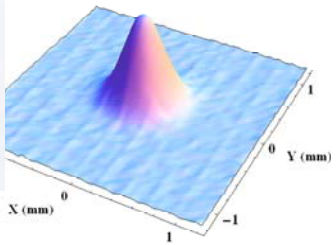


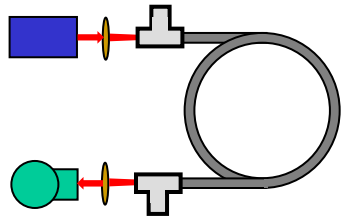
Summary

- LWIR (7 to 14 µm) spectroscopy and laser systems are important for non-proliferation and counter-terrorism applications
- Infrared laser systems can benefit greatly from fiber delivery
- Solid-core fibers have significant drawbacks particularly at longer wavelengths
- Hollow glass waveguides are a proven low-loss, single-mode delivery solution
- Current development and testing is focused on reducing loss and producing complete solutions for QCL based spectroscopy systems

- J. Kriesel, et. al. "Fiber delivery of mid-IR lasers", SPIE Newsroom (Aug. 2011).
- J.M. Kriesel, et. al., "Hollow core fiber optics for mid-wave and long-wave infrared spectroscopy", Proc. SPIE 8018, pp. 80180V, 2011. doi:10.1117/12.882840







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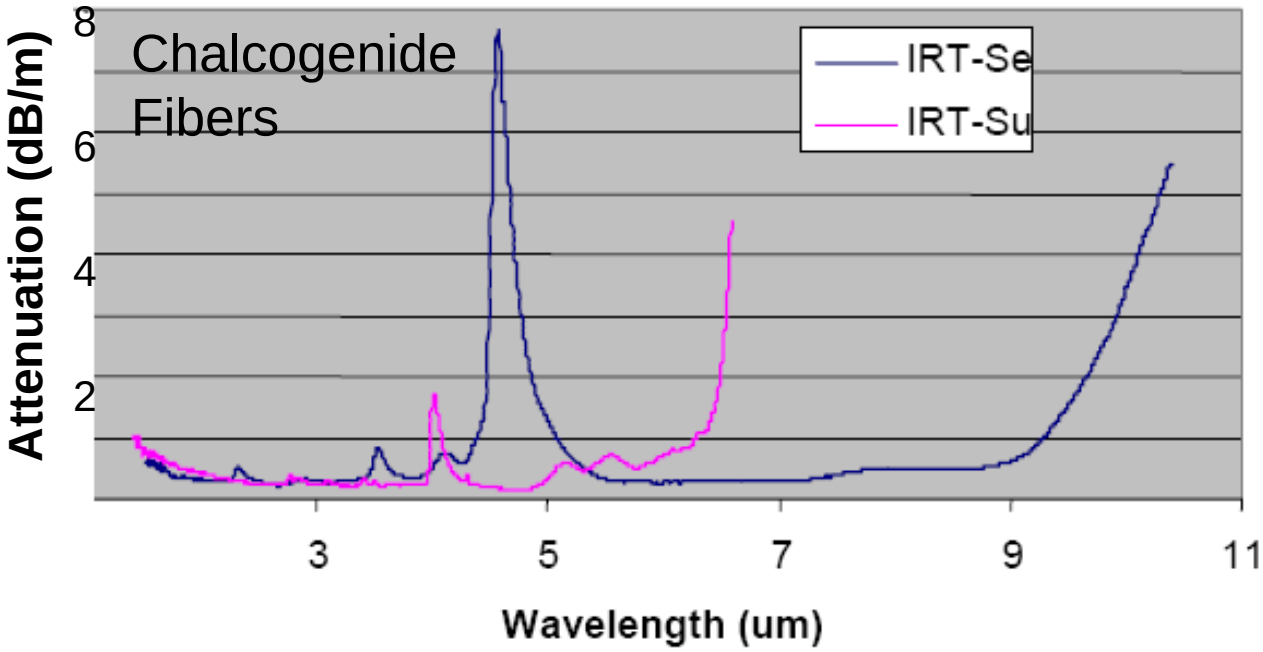
Backup

Solid Core IR Fibers



- Losses are too high in the LWIR range

- Extremely fragile and brittle
- Generally difficult to work with
- End reflections can cause laser feed back
- Cladding modes diminish beam quality

K. Krishnaswami, et.al. "Characterization of Single-mode Chalcogenide Optical Fiber for Mid-Infrared Applications", Proc. of the SPIE, Volume 7325 (2009).

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