Mid-Infrared Spectroscopy and Beam Delivery Using Hollow Fibers

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Mid-IR Hollow Fibers – Project Team

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STTR Funding Support:
DOE / NNSA / Remote Sensing
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**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
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

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

Image courtesy of MIRTHE
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
Spectral Transmission

- Spectral range is determined by dielectric thickness / deposition time
- Loss is relatively low even at longer wavelengths up to $\lambda = 20 \, \mu m$
- Coatings can also be tailored for shorter wavelengths including visible
Losses for Hollow Glass Waveguide

- Loss $\sim 1/(\text{Bore Size})^3$ $\Rightarrow$ greater loss for smaller waveguides
- Loss higher for higher order modes $\Rightarrow$ mode filtering

Loss vs bore size for different modes

Single-Mode

Multi-Mode
Gaussian Output – CO₂ laser (9.3 µm)

- Gaussian profile maintained in presence of bend
Gaussian beam profile in far-field

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

- Higher order modes damped by waveguide, i.e., “Mode Filtering”
- Hollow fibers can be used to “clean-up” QCL beams
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
3-to-1 Fiber Probe for PNNL

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

Tanya Myers
Bruce Bernacki
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., $^{13}\text{CO}_2 / ^{12}\text{CO}_2$)
- Gas detection
- Breath analysis (e.g., biomarkers)

Jim Kelly
Capillary Absorption Spectrometer (CAS)
Hollow Fiber CO₂ Isotope Analyzer

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

<table>
<thead>
<tr>
<th>Institution / Method</th>
<th>Total Vol. (mL)</th>
<th>Press. (Torr)</th>
<th>CO₂ Conc. (ppm)</th>
<th>DL Sensitivity (moles)</th>
<th>Precision / Dwell Time</th>
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</thead>
<tbody>
<tr>
<td>Picarro / CRDS</td>
<td>30</td>
<td>300</td>
<td>300</td>
<td>1.6 x 10⁻⁷</td>
<td>0.5 / 100 s</td>
</tr>
<tr>
<td>Los Gatos / ICOS</td>
<td>120</td>
<td>300</td>
<td>300</td>
<td>6.4 x 10⁻⁷</td>
<td>0.25 / 60 s</td>
</tr>
</tbody>
</table>
| Aerodyne / Herriott  | 300            | 25           | 300             | 1.3 x 10⁻⁷             | 0.2 / 1 s
|                      |                |              |                 |                        | 0.03 / 300 s           |
| PNNL / CAS           | 0.63           | 2            | 390             | 2.0 x 10⁻¹¹            | 1.0 / 1000 s           |
| OKSI-PNNL / CAS (proposed) | 0.10      | 2            | 390             | ~ 3 x 10⁻¹²            | ~ 0.4 / 10 s           |
PNNL CO₂ 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

Jim Moran
Liz Alexander
Jim Kelly

Laser ablation of horse hair

Sample
Reactor
CO₂
Cryotrap
QCL
IR Detector
CAS
Hollow Fiber

Opto Knowledge
Converting Light into Knowledge
RUTGERS
Related Projects / Applications

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)

Other applications being pursued:
- BRDF measurement device for solids
- Remote IR spectroscopy analysis (penetrator)
- CO₂ laser delivery for medical & industrial applications
- IR counter measures
- Fiber beam combiner
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
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.

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