Compact and Robust Refilling and Connectorization of Hollow Core Photonic Crystal Fiber Gas Reference Cells

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IEEE LEOS 2007        WS2
Outline

- HC-PCF overview
- HC-PCF gas reference cells
- Applications/Current Status
- Proposed refilling/connectorization technique
  - Optical coupling
  - Evacuation and refilling
  - Sealing
- Results
- Issues
- Conclusion
Hollow Core Photonic-Crystal Fibers (HC-PCF) allow optical propagation in air, vacuum, or other gas over long distances

- Fiber types:
  - Standard (index-guiding) – higher-index core and lower-index cladding confine light via total internal refraction
  - Holey Fibers – index-guiding with air holes in cladding
  - Photonic crystal fibers (a.k.a. photonic bandgap fibers) use photonic bandgap – entirely different confinement principle

- Photonic Crystal Fibers:
  - Hole pattern and dimensions determine range of wavelengths for which light is confined
  - Can have unique properties, e.g. dispersion, birefringence
  - No index-guiding => core can be hollow, >95% of light propagates in air, vacuum, or other gas
  - Commercially available for popular λ.s, attn < 0.1 dB/m
HC-PCF Gas Reference Cell

Objective: HC-PCF instead of standard gas cell

Gas-filled HC-PCF offer numerous advantages over conventional gas cells
- Long propagation distance – particularly important for weaker lines
- Compatible with all-fiber locking loop implementation (other key components fiber-compatible as well)
- Compact and robust
Applications, Current Status

- Applications of frequency-stabilized lasers:
  - Coherent lidar
  - Metrology sources, e.g. for interferometers, formation flying
  - Coherent optical communications

- Filling HC-PCF with acetylene, methane, ammonia, etc has been successfully demonstrated

- Published experimental efforts did not focus on connectorization viable for space deployment
  - Early experiments (Benabid, 2002) – no connectorization, both HC-PCF ends inside gas chambers, free-space coupling
  - Later experiments (Tuominen, 2005) – splice to SMF on one end of PCF, mechanical splice on the other end inside a vacuum chamber
  - Splice both ends (splicer in gas or expose the end)

- HC-PCF particularly advantageous for space/aircraft deployment, due to mass, size savings
Optical Coupling [1]

- **Goal:** evacuate, refill, seal, and connectorize HC-PCF to produce a robust, compact package suitable for space

- HC-PCF input end fusion spliced to SMF
- Typical splice excess loss = 1.5 dB

![Photonic Crystal Fiber](image)

**Photonic Crystal Fiber**

**Single-Mode Fiber**
Optical Coupling [2]

- Challenge: one end must be optically coupled to, yet offset from, standard fiber for gas access and simultaneous optical monitoring, then sealed preserving alignment.

HC-PCF (other end fusion-spliced to SMF)

Si V-Groove

Seal perimeter with epoxy

AI support plate (for easy handling)

Light from laser

Quartz tube connected to gas chamber

Align fibers, secure with low-shrinkage epoxy

MMF

Torch-seal here

Light to detector

10/23/2007
Evacuation and Refilling

- HC-PCF and MMF actively aligned in Si v-groove:
  - Transmission – up to 80%
  - Gap ~50 µm
- Secured with low-shrinkage epoxy

- Quartz filling tube mounted above the gap
- Hermetically secured with epoxy
Sealing the Cell

- Filling tube put into ultra-Torr connector
- Fiber evacuated, refilled with gas to desired pressure
- Filling tube torch-sealed
Results

- 500 Torr of CO₂ in 4 m of HC-PCF (Crystal Fibre HC-1550-02)
- Transmission through (2201–0000) band of CO₂
Issues

- Fresnel reflection can be a problem – sets up multiple Fabry-Perot cavities causing intensity fluctuations
- In mechanical splices can be solved by angle-cleaving fibers
  - as in APC connectors, but angle needs to account for different NA
- Angled fusion splice recently reported in the literature

- V-groove channel designed for SMF and MMF (cladding $\varnothing = 125 \, \mu m$) $\Rightarrow$ HC-PCF (cladding $\varnothing = 120 \, \mu m$) is slightly offset
- Can lead to difficult coupling and undesired mode excitation
- Custom-designed v-grooves will solve this problem
Conclusion

- Gas-filled HC-PCFs are very appealing reference cells for laser frequency locking, particularly for aerospace applications and weaker absorption lines.
- HC-PCF cells have been demonstrated, but an attractive refilling/connectorization approach is needed.
- Proposed and demonstrated a simple connectorization approach utilizing mechanical splice of HC and regular fibers and torch-sealable filling tube.
- Approach successful, currently used for frequency locking.

10/23/2007