Characterization of Mid-Infrared Interband Cascade Laser Coupling to a GeSbS Chalcogenide Glass Waveguide

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MIR Integrated Photonic Sensor on a Chip

- Hybrid integration of interband cascade laser (ICL), chalcogenide glass waveguide micro-resonator and polycrystalline PbTe detectors on a Si substrate
- Polymer coating for enhancing analyte concentration
- Target ppb-level sensitivity
Room Temperature
Interband Cascade Laser Operation

- **Laser Requirements**
  - Room-Temperature CW operation, Power \( \sim 10 \text{ mW} \)
  - Single-frequency emission with center wavelength \( \lambda = 3.4 \mu m \)
  - Single-spatial mode output beam, TE output polarization

- **ICLs fabricated by NRL**
  - GaSb-based device with ridge width = 7 \( \mu m \), HR/uncoated facets
  - DFB devices with corrugated sidewalls forming 4\(^{th}\) order grating
  - Beam divergence: \( \theta_{1/2} \) for fast (slow) axis = 40\(^\circ\) (30\(^\circ\))

Vurgaftman et al., IEEE JSTQE 2011
Fabrication of ChG Waveguide Structures

- Fabrication of ChG ($\text{Ge}_{23}\text{Sb}_7\text{S}_{70}$ or $\text{As}_2\text{Se}_3$) waveguide structures
  - Bulk multi-component chalcogenide glass (Clemson).
  - Waveguides were fabricated on a silicon substrate via UV contact lithography, GeSbS thermal deposition, and lift-off (MIT).

- Device structure
  - ChG waveguide (1.3 $\mu$m or 3.7 $\mu$m thick) structures
  - SiO$_2$ undercladding (3 $\mu$m thick)
  - Si substrate

Hu et al., Optics Letters 2008
Chalcogenide Glass (ChG) Waveguide Chips

Mask

Input

Output

Paper-clip

Micro-disk

Chip

100 μm radius micro-disk
NIR Characterization of Micro-Disk Resonators

- Microdisk resonators: Q and loss measurement in the NIR (λ=1550 nm)
- Based on fiber-coupling a telecom laser to the ChG waveguide
- Different radii microdisk resonators used to separate loss contributions in Ge$_{23}$Sb$_7$S$_{70}$ at 1550 nm
  - Observed high Q of up to $6 \times 10^5$ and low loss of 0.6 dB/cm in 100 µm radius resonators
  - Scattering loss due to sidewall roughness dominates
  - Found material loss in glass to be ~0.15 dB/cm

- Demonstrates low loss, high Q resonators in the NIR
MIR Waveguide Coupling – Experimental Apparatus

- **Butt-coupling**
  - Based on micro-positioning of ChG input facet next to ICL output facet
  - Ideal for compact integration but risks device damage

- **End-fire coupling**
  - Based on high-NA collection of ICL output and re-focusing on ChG input facet
  - Used for device testing
• **Butt-coupling**
  - Coupling into waveguides as small as 4.8 µm x 1.3 µm
  
  Estimate for number of TE modes supported in waveguide
  
  \[ N = \frac{\pi}{4} \left( \frac{2d}{\lambda} \right)^2 \left( n_{chG}^2 - n_{cladding}^2 \right) \]
  
  \( N \sim 4 \) TE Modes

• **End-fire coupling**
  - Coupling into 5.0 µm x 1.3 µm waveguide
  - Gaussian fit
    • \( \sigma_x = 2.8 \) µm, \( \sigma_y = 3.2 \) µm
Comparable coupling achieved for Butt-coupling and End-fire coupling

- **Butt-coupling**
  - Insertion loss vs. ICL – ChG separation
    - Insertion loss for 7 μm wide x 3.7 μm thick straight waveguide = -29 dB

- **End-fire coupling**
  - Insertion loss for 7 μm wide x 1.3 μm thick straight waveguide = -31 dB
  - Insertion loss for 7 μm to 2 μm tapered waveguide = -38 dB
Total Insertion Loss Contributions (End-fire case)

1. **Modal mismatch between the ICL beam and ChG waveguide**
   - ICL beam ~ 9.6 μm x 7.1 μm (field)
   - Modal overlap ~ −13 dB

2. **Fresnel reflection from the waveguide facets** (~14 dB)

3. **Waveguide propagation loss**
   - Straight vs. paperclip waveguides (5 μm wide x 1.3 μm thick devices)

<table>
<thead>
<tr>
<th>Straight waveguide</th>
<th>Insertion Loss = -35.0 dB ± 2.2 dB</th>
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<tbody>
<tr>
<td>length = 1.2 cm</td>
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<tr>
<th>Paperclip waveguide</th>
<th>Insertion Loss = -38.7 dB ± 2.3 dB</th>
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<tbody>
<tr>
<td>length = 2.2 cm</td>
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Assuming no loss due to bends

Propagation Loss ~ -3.7 dB/cm ± 2.6 dB/cm

Measurement limited by waveguide-to-waveguide variation
Summary

Results so far:

- Room temperature ICL operation (NRL)
- Fabrication of planar waveguide structures of chalcogenide glass (MIT / Clemson)
- Characterization of ICL coupling into a chalcogenide glass waveguide (PSI)

Next Steps:

- Characterize Q of micro-disk resonators in the MIR
  \[ Q_i = \frac{2\pi n_g}{\alpha \lambda} \]
- Demonstrate gas sensing of analyte using micro-resonator

Long-term goal:

- Integrate ICL + resonator sensing element + detector onto a chip for ultrasensitive chemical vapor detection
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