Generation of Broadly-Tunable Mid-Infrared Radiation in Periodically-Poled Lithium Niobate Waveguides

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Strategy for Achieving Broad Tunability

• For a target idler frequency \( (\nu_1) \) calculate signal frequency \( (\nu_2) \) which satisfies the following equation:

\[
n_1 + \nu_1 \frac{\partial n_1}{\partial \nu_1} = n_2 + \nu_2 \frac{\partial n_2}{\partial \nu_2} \rightarrow \frac{\partial (\Delta k)}{\partial \nu_2} = 0
\]

• Mix the tunable laser with appropriate fixed-frequency pump laser to generate broadly tunable mid-IR radiation centered on the target frequency

• Alternatively, use the tunable laser as the pump laser, mix it with a fixed-frequency signal laser to generate broadly tunable mid-IR radiation. In this case the following equation is satisfied:

\[
n_1 + \nu_1 \frac{\partial n_1}{\partial \nu_1} = n_3 + \nu_3 \frac{\partial n_3}{\partial \nu_3} \rightarrow \frac{\partial (\Delta k)}{\partial \nu_3} = 0
\]

• This strategy has been used in the past for bulk DFG (Goldberg et al., Tittel et al.); this work extends it to waveguides
**Pump/Signal Combinations for Broad Tunability**

- Once idler wavelength is chosen, wavelength of the tuned laser is fixed by the Sellmeier equations.
- The tuned laser can be the signal or pump laser.

- Broadly tunable output wavelength near 3.3, 4.3 \( \mu \text{m} \) requires tunable lasers near 1100 nm, 850 nm, respectively.
Process Steps: Waveguide Fabrication

Deposit SiO₂ → Spin PR → Soft-Bake PR → Align Mask, Expose → Develop PR

Proton Exchange → Plasma Ash → Strip PR → Dice → Etch

Anneal
Index Profiles After Proton Exchange: Glycerol versus Benzoic Acid

- Glycerol: 25 hours at 231.6 C; benzoic acid: 96.5 hours at 160 C

- Glycerol produces smaller surface index step
Index Profiles After Annealing: Glycerol versus Benzoic Acid

- Glycerol: 6.4 hours/230°C exchange, 40 hour/340°C anneal
- Benzoic acid: 17.5 hour/160°C exchange, 40 hour/340°C anneal

- Both recipes produce the same index profile
Waveguide Designs, Device Efficiencies

- Best device efficiencies obtained by coupling directly into mixing region, bypassing mode filter and taper
- Optimizing mode filter/taper design, increasing mixing region length, should improve device efficiency significantly (5-10×)

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Exchange Medium</th>
<th>Exchange Time (hours)</th>
<th>Exchange Temperature (°C)</th>
<th>Anneal Time (hours)</th>
<th>Anneal Temperature (°C)</th>
<th>Best Device Efficiency (%/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L6-1</td>
<td>benzoic acid</td>
<td>8.0</td>
<td>160</td>
<td>24</td>
<td>340</td>
<td>0.93</td>
</tr>
<tr>
<td>L6-2</td>
<td>benzoic acid</td>
<td>17.5</td>
<td>160</td>
<td>40</td>
<td>340</td>
<td>0.96</td>
</tr>
<tr>
<td>L6-5</td>
<td>glycerol</td>
<td>6.4</td>
<td>230</td>
<td>40</td>
<td>340</td>
<td>1.25</td>
</tr>
</tbody>
</table>

\[ \eta_{\text{dev}} = \frac{P_1}{P_2P_3} \]
Several pump, signal lasers available (767 to 1100 nm)

Setup used for waveguide testing (phase-matching, device efficiency) and spectroscopy
Effective Sample Length (Pump Laser Tuning)

- Signal laser fixed at 1064 nm, tunable pump laser
- Coherence length equals physical length of mixing region: good waveguide uniformity
- Absorption lines of atmospheric water vapor can be seen
Phase-Matching Curve: Pump Laser Tuning

- Pump wavelength 800 to 805 nm, signal wavelength 1064 nm
- QPM period 19.5 µm, 23 C, 22 mm chip length, 16.5 mm mixing length
- Tuning range ~ 7 cm⁻¹
Phase-Matching Curves: Signal Laser Tuning

- Tuning of >200 cm\(^{-1}\) demonstrated with proper choice of pump wavelength, signal wavelength (1050 to 1090 nm), temperature
- Unexpected dip observed in middle of tuning range; power normalization needed

- Broad tuning can be achieved in waveguides
Related Work: Broad Tuning Near 4.3 µm

- Tunable pump laser mixed with signal laser fixed at 1064 nm
- As PPLN waveguide temperature increases, phase-matching bandwidth increases to >150 cm⁻¹

Absorption spectrum of ambient CO₂ (L = 40 cm) can be seen
Absorption Spectrum - Methane

- 20 Torr CH₄, buffered with N₂ to 750 Torr, 4 cm path length
- Pump laser 803.85 nm, signal laser 1050 to 1088 nm
- PPLN temperature 25 to 55 C

- Well-resolved lines demonstrate narrow laser linewidth (<1.5 GHz)
Methane Spectra: DFG versus FTIR

- Good agreement with FTIR spectrum; saturation, linewidth effects could change relative line intensities
Absorption Spectrum: Industrially Important Mixture

- 2.8% CH₄ (M), 9.3% C₂H₄ (EY), 4.9% C₂H₆(E), balance N₂, 772 Torr
- Pump laser 803.86 nm, signal laser 1050 to 1088 nm
- PPLN temperature 25 to 55 °C

Speciation is possible
## Gas Analysis Results

<table>
<thead>
<tr>
<th>Species</th>
<th>Line Position (cm⁻¹)</th>
<th>Calculated Fraction (from Peak Height)</th>
<th>Certified Fraction (from Manufacturer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>3105</td>
<td>17.4%</td>
<td>16.5%</td>
</tr>
<tr>
<td>Ethane</td>
<td>2976</td>
<td>31.1%</td>
<td>28.8%</td>
</tr>
<tr>
<td>Ethylene</td>
<td>3125</td>
<td>51.5%</td>
<td>54.7%</td>
</tr>
</tbody>
</table>

- Good agreement using simple measurement of three peak heights; more sophisticated analysis will yield more accurate results.
Practical Wavelength Combinations

- Tuning provided by grating-stabilized diode lasers

- Coverage from 2300 to 3100 cm⁻¹ possible
Summary and Conclusions

- DFG with tuning range of 250 cm$^{-1}$ in 3.4-micron wavelength region demonstrated in waveguides with proper choice of pump, signal wavelengths

- Phase-matching curves show unexpected structure, but overall tuning range agrees with predictions for bulk DFG

- New fabrication process (proton exchange in glycerol) demonstrated, offers practical advantages over the established benzoic acid process

- Tunability exploited to perform speciation on hydrocarbon mixtures

- Future plan: develop portable gas analyzer for petrochemical industry based on waveguide DFG