Optical filter assembly for interplanetary optical communications

Y. Chen and H. Hemmati
Jet Propulsion Laboratory
California Institute of Technology
• Objective and rationale

• Existing filter technologies

• Requirements

• Options

• Lab experiment results

• Conclusions
OBJECTIVE AND RATIONALE

Objectives:

– Develop narrowband filter for Deep-space Optical Terminals (DOT) Ground Terminal
– Validate in laboratory and in the field
– Remove uncertainty on actual values for filter’s transmission and filtering bandwidth

Rationales:

– Background can easily overwhelm signal in a deep space link
– Wide range of wavelengths need to be eliminated since nanowire detectors (NbN and $a-W_xSi_{1-x}$) have wide spectral responsivity
– Off-the-shelf filters meeting DOT’s requirements are not available
Based on the flight terminal transmitter and orbital operation requirements, ground receiver design and Earth atmospheric effect, the ground receiver filter requirements are derived and shown in the Table below:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Requirement</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Center wavelength (nm)</strong></td>
<td>~1550</td>
<td>DOT requirement</td>
</tr>
<tr>
<td><strong>Tunability (pm)</strong></td>
<td>±150</td>
<td>• ±80 pm, from expected post-launch shift (10% ITU grid of 100GHz)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ±40 pm, from max Doppler shift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ±10 pm (=0.1(\frac{d\lambda}{dT})), from laser chamber temperature drift of 0.1°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ±20 pm, assumed margin</td>
</tr>
<tr>
<td><strong>Bandwidth (noise equivalent - nm)</strong></td>
<td>0.17±0.03</td>
<td>DOT requirement</td>
</tr>
<tr>
<td><strong>Transmission efficiency (%)</strong></td>
<td>&gt;80</td>
<td>DOT requirement</td>
</tr>
<tr>
<td><strong>Minimum clear aperture (mm)</strong></td>
<td>&gt;23</td>
<td>To cover 2 to 12m telescope apertures; and FOV=50 µrad of atmospheric seeing for daytime operation (DOT require. L3-GLR3.8)</td>
</tr>
<tr>
<td><strong>Acceptance angle (FOV - degree)</strong></td>
<td>≥1.5</td>
<td>Same as above</td>
</tr>
<tr>
<td><strong>(d\lambda/dT) (pm/^\circ C)</strong></td>
<td>&gt;10</td>
<td>Not too small requiring large temperature variation for tuning, but not too large causing big change with small temperature variation (instability)</td>
</tr>
<tr>
<td></td>
<td>&lt;85</td>
<td></td>
</tr>
<tr>
<td><strong>Out-of-band rejection range (nm)</strong></td>
<td>1,000 to 3,000</td>
<td>Nanowire detector has response over all the wavelengths with peak around 1550nm. BK7 and silica will be placed in front of the detector to remove noise/unwanted signals below 1µm and above 3µm</td>
</tr>
<tr>
<td><strong>Ratio of integrated power within the signal band to that outside the signal band</strong></td>
<td>&gt;3 or 10</td>
<td>Contributions (radiance, stray light, noise) outside the band can be comparable to those within the band, because photon counting detectors follow Poisson statistics</td>
</tr>
<tr>
<td><strong>Operating temperature (ºC)</strong></td>
<td>5 to 80</td>
<td>Temperature likely experienced by filter</td>
</tr>
<tr>
<td><strong>Surface quality (scratch &amp; dig)</strong></td>
<td>40-10</td>
<td>Negligible scattering</td>
</tr>
<tr>
<td><strong>Surface flatness (at 633nm)</strong></td>
<td>&lt;(\lambda/4)</td>
<td>Negligible scattering</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>Meet spec for any polarization</td>
<td>Depolarization/polarization must be less than 1%</td>
</tr>
</tbody>
</table>
EXISTING FILTER TECHNOLOGIES

• **Dielectric (interference) filter**
  – Can be designed for high quality filtering
  – Difficulty to fabricate for uniformity with high transmission efficiency
  – Typically work only over ~200nm

• **Fabry-Perot Etalon (FPE)**
  – Relatively easy to make
  – Free Spectral Range is a limitation

• **Volume Bragg Grating (VBG)**
  – High quality filtering within the transmission band
  – Low suppression outside transmission band
  – Limited by side lobes outside the transmission band

---

*A Single Filter Technology DOES NOT Meet The Requirements*
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Requir.</th>
<th>A) #1 (VBG)</th>
<th>B) #2 (VBG)</th>
<th>C) #1 (FEP)</th>
<th>D) #2 (FEP)</th>
<th>E) (Interference)</th>
<th>F) (Wide band)</th>
<th>G) (Long wave blocking)</th>
<th>Option 1 A+C+G</th>
<th>Option 2 A+E+G</th>
<th>Option 3 E+F+G</th>
<th>Option 4 C+F+G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center wavelength (nm)</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
</tr>
<tr>
<td>Tunability (pm)</td>
<td>±150</td>
<td>±150</td>
<td>±150</td>
<td>±150</td>
<td>±150</td>
<td>N/A</td>
<td>N/A</td>
<td>±150</td>
<td>±150</td>
<td>±150</td>
<td>±150</td>
<td>±150</td>
</tr>
<tr>
<td>Bandwidth (nm)</td>
<td>0.17</td>
<td>0.2</td>
<td>0.15</td>
<td>0.17</td>
<td>0.17</td>
<td>3</td>
<td>&gt;50</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Transmission efficiency (%)</td>
<td>&gt;80</td>
<td>96</td>
<td>93</td>
<td>95</td>
<td>97</td>
<td>&gt;80 (85)</td>
<td>95</td>
<td>95</td>
<td>87 (-0.6dB)</td>
<td>78 (-1.08dB)</td>
<td>77 (-1.14dB)</td>
<td>86 (-0.66dB)</td>
</tr>
<tr>
<td>Minimum clear aperture (mm)</td>
<td>&gt;23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Acceptance angle (FOV - mrad)</td>
<td>&gt;26</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>dλ/dT (at 0.1°C tem. variation)</td>
<td>&gt;9 pm/ °C &lt;85 pm/ °C</td>
<td>15</td>
<td>15</td>
<td>9</td>
<td>9</td>
<td>13</td>
<td>N/A</td>
<td>N/A</td>
<td>15/9</td>
<td>15/13</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Out of band rejection range (nm)</td>
<td>850-3000 800-2800</td>
<td>800-2800</td>
<td>800-2800</td>
<td>4</td>
<td>4</td>
<td>1380-1770</td>
<td>850-1780</td>
<td>1750-3000</td>
<td>850-3000</td>
<td>850-3000</td>
<td>850-3000</td>
<td>850-3000</td>
</tr>
<tr>
<td>Out of band rejection ratio</td>
<td>&gt;10</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>7</td>
<td>12</td>
<td>3.7</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Price ($K)</td>
<td>30.9</td>
<td>36.4</td>
<td>14.3</td>
<td>14</td>
<td>66.4</td>
<td>0.622</td>
<td>3.5</td>
<td>48.7</td>
<td>100.8</td>
<td>70.522</td>
<td>18.122</td>
<td></td>
</tr>
<tr>
<td>Lead time (Weeks)</td>
<td>16</td>
<td>8-12</td>
<td>8-12</td>
<td>10-12</td>
<td>5</td>
<td>16</td>
<td>1</td>
<td>8</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>10-12</td>
</tr>
<tr>
<td>Required ovens</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
OPTION 1

A: VBG

C: FP Etalon

G: Long wave blocking filter

Option 1: A+C+G

Expanded on the left
**OPTION 2**

**A: VBG**

**E: Dielectric filter**

**G: Long wave blocking filter**

**Option 2: A+E+G**

**Expanded on the left**
**OPTION 3**

**E: Dielectric filter**

**F: 3 nm band-pass filter**

**G: Long wave blocking filter**

---

**Option 3: E+F+G**

Expanded on the left
OPTION 4

C: FP Etalon
F: 3 nm band-pass filter
G: Long wave blocking filter

Option 4: C+F+G
Expanded on the left
LABORATORY EXPERIMENT CONFIGURATION

1550nm beam

Detector

Compensator (for Earth atmospheric induced polarization drift)

PC - Polarization controller
TC - Temperature chamber

PBS
QWP
FP Etalon

OSA/Power meter

Long wave blocking filter

Controllers (for filter center wavelength tuning)

VBG
LABORATORY EXPERIMENT SETUP

- Receiver
- Long wave blocking filter
- QWP (Quarter Wave Plate)
- FP (Faraday Rotation)
- PBS (Polarizing Beam Splitter)
- VBG (Volume Bragg Grating)
- 1550nm laser
- PC (Polarization Controller)
FABRY-PEROT ETALON TEST

- **Band width** = 150pm
- **Transmission efficiency** = 94%
- Free spectrum range = 4nm
- Temperature coefficient of $|d\lambda/dT|=3.4\text{ pm/}^\circ\text{C}$ is small because FP is made of ULE
- Required $|d\lambda/dT|>10$, achievable by using fused silica or other material

Free spectrum range $\rightarrow 4\text{nm} \leftarrow$

Updated spectrum with temperature tunability measurements:

- FP center wavelength $\rightarrow 1550.14\text{ nm} \leftarrow$
- $d\lambda/dT=-3.4\text{ pm/}^\circ\text{C}$
VBG TEST

Measured spectrum of VBG

- Band width = 140pm
- Transmission efficiency = 94%
- Measured temperature coefficient $d\lambda/dT = 13\text{pm/}^\circ\text{C}$ meets our requirement
- Requiring $T>50^\circ$ to get the center wavelength at 1550.12nm
VBG + FP

Measured spectrum of VBG+FP

- Band width (FWHM) = 90pm
- Transmission efficiency = 88.4%
SUMMARY AND FUTURE WORK

- We demonstrated spectral filter assembly with a band-pass of 90 pm over a large 2000 nm operational range at telecommunication window of 1550 nm for DOT ground terminal

- Future work:
  - Design and fabrication of FP with material having large thermal coefficient
  - Design and fabrication of VBG with center wavelength of 1550.12 nm at temperature around 45°C
  - Automatic temperature tunings of FP and VBG filter center wavelengths for tracking the downlink signal wavelength
  - Automation of PC for polarization compensation
  - Custom filter ovens for automation of wavelength tuning and lifting temperature tunable range from current 60°C to 80°C
  - Exploration of Option 2 for implementation with better out-band rejection ratio and transmission efficiency