Modulating Retro-reflector Links for High Bandwidth Free-Space Lasercomm

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Product 2 – Modulating retro-reflector (MRR) communications terminals

The MRR terminal contains in very general terms:

- 1. A multiple quantum well (MQW) based MRR (transmitter) and a photodetector (receiver) for two-way communications
- 2. MRR driver electronics
- 3. Modem for communication between the lasercomm link and USN/USMC network

Items 1 & 2 in Product 2 will be supplied as government furnished equipment (GFE) for integration into lasercomm systems developed in this program. Item 3 will be developed as part of this program.
Modulating retro-reflector links

- Uses transmitter optics, laser, pointing and tracking, receive optics at one end of the link
- Uses a passive retro-reflector with modulator at the other end
- Asymmetric comms
  - Good when very little power/weight capability at one end of the link
  - Appropriate for unattended sensors or disadvantaged users
  - Link falls off as $1/R^4$
  - Ranges of a few kilometers to tens of kilometers depending on link
  - Data rates of up to 10 Mbps (corner cube) or 10's Mbps (cat's eye)
Multiple Quantum Well Modulators

- Coupled quantum well structure requires ~ 5V drive
- Approximately 3 dB extinction
- Capacitance of 5 nF/cm², Sheet resistance of 5-10 Ohms
- Power consumption ~ CV²f, where f is the drive frequency
- Absorption of light changes when voltage is applied
- NRL GFE devices operate in telecom c-band
- Data rates limited by RC time
Retroreflector Types

- Corner cubes: prisms

- Cat’s eyes: optical systems using lenses and mirrors
Corner Cube MRRs

INTERROGATING RECEIVER

Laser Receiver

Interrogation Beam

Modulated Beam

Returned Data

REMOTE TRANSMITTER

Data In

Amplitude Modulator

Retroreflector

Data rate determined by modulator switching rate
Corner Cube Retro-reflectors (CCR)

- Simple, rugged, inexpensive
  - Single component, no possibility of misalignment

- $D_{\text{modulator}} \approx D_{\text{aperture}}$
  - Bandwidths < 10 MHz

- Only design parameter is index of refraction
  - High index materials $\Rightarrow$ larger field of view (FOV)
Cat’s Eye Retroreflectors (CER)

- Light focused onto a mirrored surface

Entry angle determines focal point location

Array of modulators/detectors
Cat’s Eye Retro-reflectors (CER)

- Complex, custom optical design
  - Requires multiple optical elements for practical MRRs
  - Can achieve bandwidths of 10’s of MHz
  - Field of view: 5°-20°
- $D_{\text{modulator}} \ll D_{\text{aperture}}$
  - Allows small (fast) modulators in long links
LINK BUDGETS
MRR Link Budgets

\[ P_{\text{sig}} = P_{\text{Las}} L_{\text{Tx}} G_{\text{Tx}} L_{\text{R}} T_{\text{atm}} G_{\text{MRR}} L_{\text{MRR}} M L_{\text{R}} T_{\text{atm}} G_{\text{Rx}} L_{\text{Rx}} \]

- **Interrogator Laser Power**
- **Laser collimation and pointing**
- **MRR Antenna Gain:**
  \[ G_{\text{MRR}} = \left( \frac{\pi D_{\text{retro}}}{\lambda} \right)^4 S \]
- **Interrogator receive aperture**
- **Interrogator Laser Power**
- **Laser collimation and pointing**
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- **Interrogator receive aperture**

*Geometric propagation losses*

\[ \frac{1}{R^2} \]

\[ \frac{1}{R^4} \]

\[ \frac{1}{R^2} \]

\[ \frac{1}{R^4} \]

**Weather losses**


\[ P_{\text{sig}} = P_{\text{Las}} L_{\text{Tx}} G_{\text{Tx}} L_{\text{R}} T_{\text{atm}} G_{\text{MRR}} L_{\text{MRR}} M L_{\text{R}} T_{\text{atm}} G_{\text{Rx}} L_{\text{Rx}} \]

<table>
<thead>
<tr>
<th>Term</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{\text{Las}}), Transmit Power</td>
<td>Measured</td>
</tr>
<tr>
<td>(L_{\text{Tx}}), Transmitter loss</td>
<td>Measured</td>
</tr>
<tr>
<td>(G_{\text{Tx}}), Transmitter antenna gain</td>
<td>(\frac{32}{\theta_{\text{div}}^2})</td>
</tr>
<tr>
<td>(L_{\text{R}}), Range loss</td>
<td>(\left[\frac{\lambda}{4\pi R}\right]^2)</td>
</tr>
<tr>
<td>(T_{\text{Atm}}), Atmospheric transmission</td>
<td>Measured</td>
</tr>
<tr>
<td>(M), MRR Modulation efficiency, (L_{\text{MRR}}), MRR loss</td>
<td>(\sim 0.25)</td>
</tr>
<tr>
<td>(G_{\text{MRR}}), MRR Antenna gain</td>
<td>(\left[\frac{\pi D_{\text{MRR}}}{\lambda}\right]^4 S)</td>
</tr>
<tr>
<td>(G_{\text{Rx}}), Receiver antenna gain</td>
<td>(\left[\frac{\pi D_{\text{Rx}}}{\lambda}\right]^2)</td>
</tr>
<tr>
<td>(L_{\text{Rx}}), Receiver loss</td>
<td>Measured</td>
</tr>
</tbody>
</table>

Definitions:
\(\theta_{\text{div}}\): Tx divergence 
\((1/e^2 \text{ full})\)
\(\lambda\): laser wavelength
\(R\): range
\(D_{\text{MRR}}\): MRR diameter
\(S\): MRR Strehl ratio
\(D_{\text{Rx}}\): Receiver diameter
<table>
<thead>
<tr>
<th>Term</th>
<th>Parameter</th>
<th>Formula</th>
<th>dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Power</td>
<td>5 Watts</td>
<td>Measured</td>
<td>37 dBm</td>
</tr>
<tr>
<td>Transmitter loss</td>
<td></td>
<td>Measured</td>
<td>-1.0</td>
</tr>
<tr>
<td>Transmitter antenna gain</td>
<td>Full angle $e^2$ divergence</td>
<td>$\frac{32}{\theta_{div}^2}$ Gaussian beam underfilling transmit aperture</td>
<td>85.5 dB</td>
</tr>
<tr>
<td>Range loss (interrogator)</td>
<td>Range, $R=7$ Km</td>
<td>$\left[\frac{\lambda}{4\pi R}\right]^2$</td>
<td>-215</td>
</tr>
<tr>
<td>Atmospheric transmission</td>
<td>$16$ Km visibility</td>
<td></td>
<td>-1.5</td>
</tr>
<tr>
<td>MRR Modulation efficiency, $M$</td>
<td>Coupled-well modulator</td>
<td>$e^{-\alpha_{off}} \cdot \left[ C_{MOW} - 1 \right]$</td>
<td>-7.0</td>
</tr>
<tr>
<td>MRR loss</td>
<td>Loss due to anti-reflection</td>
<td>Measured</td>
<td>-0.7</td>
</tr>
<tr>
<td>MRR T/R Antenna gain, $G_{retro}$</td>
<td>$D_{retro}=1.6$ cm, $S=0.4$</td>
<td>$\left[\frac{\pi D_{retro}}{\lambda}\right]^4 S$</td>
<td>177</td>
</tr>
<tr>
<td>Range loss (retro return)</td>
<td>$7$ Km</td>
<td>$\left[\frac{\lambda}{4\pi R}\right]^2$</td>
<td>-215</td>
</tr>
<tr>
<td>Atmospheric transmission</td>
<td>$16$ Km visibility</td>
<td></td>
<td>-1.5</td>
</tr>
<tr>
<td>Receiver antenna gain</td>
<td>$D_{rec}=15$ cm</td>
<td>$\left[\frac{\pi D_{rec}}{\lambda}\right]^2$</td>
<td>108</td>
</tr>
<tr>
<td>Receiver loss</td>
<td>Fiber coupling loss</td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>Predicted received power</td>
<td>$0.28$ $\mu$W</td>
<td></td>
<td>-35.0 dBm</td>
</tr>
<tr>
<td>Actual received power</td>
<td>$0.4$ $\mu$W</td>
<td></td>
<td>-34 dBm</td>
</tr>
</tbody>
</table>
GFE MRR Options
Some MRR Configurations

Single Corner cube MRR
30° FOV, 5 Mbps, 8.5 g

Corner cube MRR array
60° FOV, ~5 Mb/s
86 g, including drive electronics

Cat’s eye MRR
1.6 cm aperture
20° FOV optic, 45 Mb/s
410 g, including drive electronics

Corner cube MRR array
Tested on USNS Yukon

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### GFE MRR

<table>
<thead>
<tr>
<th>Design</th>
<th>Aperture</th>
<th>$G_{\text{retro}}$</th>
<th>FOV (degrees)</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCR</td>
<td>0.63 cm</td>
<td>163 dB</td>
<td>26-70</td>
<td>10 MHz</td>
</tr>
<tr>
<td>CCR</td>
<td>1 cm</td>
<td>171 dB</td>
<td>26</td>
<td>5 MHz</td>
</tr>
<tr>
<td>CER</td>
<td>1 cm</td>
<td>171 dB</td>
<td>20</td>
<td>5-45 MHz</td>
</tr>
<tr>
<td>CER</td>
<td>1.6 cm</td>
<td>179 dB</td>
<td>20</td>
<td>5-20 MHz</td>
</tr>
<tr>
<td>CER</td>
<td>2.8 cm</td>
<td>189 dB</td>
<td>5</td>
<td>5-45 MHz</td>
</tr>
</tbody>
</table>

**Notes:**
- Field of view for single elements; MRR arrays can broaden FOV
- CCR field of view depends on corner cube material: glass vs silicon
- Electrical input to all MRRs: 5V TTL, power consumption < 1 Watt

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Wide FOV MRR Photodetectors

- The MRR terminal photodetector must match the field of view of the MRR

- GFE design: PIN photodetector with 5 mm lens 35° FOV
  - Sensitivity at 5 MHz bandwidth~ -30 dBm

- Other variants are possible

- Note: optical fluence on the MRR terminal is much higher than on the interrogator (1/R² vs 1/R⁴)

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Other Design Considerations
MQW Temperature Dependence

- The response of the MQW modulator shifts with temperature
  - the optimal laser wavelength shifts by 0.67 nm/°C
  - Changes of less than ±10°C have a small effect
- Can use a tunable laser to compensate: more complex interrogator
- Can thermally control the MRR: more complex MRR terminal
Interrogator Considerations

- Optical power levels
  - Typical MRR links will return ~ -50 dBm to the interrogator
  - Your system must be able to track on these levels

- MQW modulator has about 3 dB extinction
  - Needs to be considered in interrogator receiver design

- Tx/Rx isolation
  - Typical Tx powers will be on the order of +30 dBm
  - => 80 dB of Tx/Rx isolation needed
  - Return beam is at same wavelength as Tx beam => No spectral isolation

- Optical scintillation is higher in a retro-reflected link
  - Modem designs must deal with deep and frequent fades
Conclusions

- MRRs can be used in your designs for asymmetric links

- Corner cube vs cat’s eye MRRs offer different advantages
  - Corner Cubes:
    - Simple and rugged
    - Easy to array for wide field of view
  - Cat’s eye:
    - Larger aperture yields high antenna gain
    - Capable of higher bandwidth

- MRR links can use the same interrogator as direct links, but have special requirements