Modulating Retro-Reflector Cubesat Payload operating at 1070nm for Asymmetric Free-space Optical Communications

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Modulating Retro-Reflectors would provide high data rate optical communication without strict pointing constraints

Goal: Provide high-speed comm. to low fidelity spacecraft

Advantages to standard RF and optical communications:
High-rate communication for CubeSats and larger:
  a. Low on-board power consumption
  b. Coarse on-board pointing requirements (±15°)
  c. Solves RF spectrum allocation issues using tight beam communications
  d. Improved security due to tight beam

Relevance:
Advances in comm. without imposing additional requirements to spacecraft
→ potential for crosscutting benefits to multiple missions
A non-modulating Retro-Reflector aboard PhoneSat 2.4 has been laser tracked by EOS Space Systems.

Passive Retro-Reflector (7mm diameter)

EOS Laser debris ranging station

Source: EOS Space Systems
Tracking results allow distinction between reflections from solar panels and the retro-reflector.

Source: EOS Space Systems
Link Budget for Modulating Retro-Retroreflector is challenging for ground stations

\[
P_{\text{rec}} = P_{\text{laser}} G_T L_T L_R T_{\text{atm}} G_{\text{MRR}} M L_R T_{\text{atm}} G_{\text{rec}} L_{\text{rec}}
\]

- \(P_{\text{rec}}\) = received signal power
- \(P_{\text{laser}}\) = transmitter power laser
- \(G_T\) = transmitter optical antenna gain
- \(L_T\) = transmitter losses
- \(G_{\text{MRR}}\) = MRR optical antenna gain
- \(L_{\text{MRR}}\) = MRR optical losses
- \(M\) = modulation efficiency
- \(G_{\text{rec}}\) = receiver optical antenna gain
- \(L_{\text{rec}}\) = receiver losses
- \(L_R\) = range losses
- \(T_{\text{atm}}\) = atmospheric transmission

**Example:**
700km dist., 10kW laser, 30 \(\mu\)rad divergence, 1cm MRR, 1.5m receiver, 1Mbps

<table>
<thead>
<tr>
<th></th>
<th>dB</th>
<th>linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx Power (dBm)</td>
<td>70.0</td>
<td>10000</td>
</tr>
<tr>
<td>Tx Loss (dB)</td>
<td>-1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Tx Gain (dB)</td>
<td>105.5</td>
<td>3.6E+10</td>
</tr>
<tr>
<td>Range Loss (dB)</td>
<td>-258.3</td>
<td>1.5E-26</td>
</tr>
<tr>
<td>Atmospheric transmssison (dB)</td>
<td>-0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Retro reflector gain (dB)</td>
<td>178.7</td>
<td>7.4E+17</td>
</tr>
<tr>
<td>Modulation efficiency (dB)</td>
<td>-7.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Atmospheric transmssison (dB)</td>
<td>-0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Range Loss (dB)</td>
<td>-258.3</td>
<td>1.5E-26</td>
</tr>
<tr>
<td>Velocity aberration</td>
<td>-2.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Receiver Loss (dB)</td>
<td>-3.0</td>
<td>5.0E-01</td>
</tr>
<tr>
<td>Receiver Gain (dB)</td>
<td>132.9</td>
<td>1.9E+13</td>
</tr>
<tr>
<td>Received Power (dBm)</td>
<td>-44.7</td>
<td>3.4E-08</td>
</tr>
<tr>
<td>Receiver Sensitivity (dBm)</td>
<td>-67.0</td>
<td>2.0E-10</td>
</tr>
<tr>
<td>Margin (dB)</td>
<td>22.3</td>
<td>169</td>
</tr>
</tbody>
</table>

### Particularities of the MRR link:
- Transit the atmosphere twice: path losses \(\alpha\) distance\(^4\)
- MRR acts as a receiver and transmitter: \(G_{\text{MRR}} \alpha\) Diameter\(^4\)

Detector quantum efficiency: 0.5 photons per bit

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Currently, MEMS and Multiple-Quantum-Well implementations of MRR are available.

Advantages
- Broadband
- High contrast

Disadvantages
- Speed ~100kHz
- 100V+ operating voltage

MEMS

<table>
<thead>
<tr>
<th>Advantages</th>
<th>MQW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadband</td>
<td>Speed: MHz+</td>
</tr>
<tr>
<td>High contrast</td>
<td>Power: 0.2W</td>
</tr>
</tbody>
</table>

Disadvantages
- Speed ~100kHz
- 100V+ operating voltage
- Temperature control required

Decision: to explore MQW for current effort, because of higher speed.

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ISDEFE prototyped a MQW device at 1064 nm in order to utilize available kW class fiber lasers.

**MRR design goals**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1064 nm</td>
</tr>
<tr>
<td>Contrast</td>
<td>3:1</td>
</tr>
<tr>
<td>Modulation eff.</td>
<td>-7.8 dB</td>
</tr>
<tr>
<td>Data rate</td>
<td>5 Mbps</td>
</tr>
<tr>
<td>Driving Voltage</td>
<td>&lt; 10 V</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt; 1 W</td>
</tr>
</tbody>
</table>

*Source: IPG Photonics*

- Diffraction limited performance
- 1070nm wavelength
- YAG fiber
ISDEFE has a capability to simulate and optimize the optical properties of MQW

- Number of Quantum Wells: typically >50
- Active region (QWs):  
  - Engineered accounting for quantum and excitonic effects  
  - (In,Ga)As/(Al,Ga)As structure  
  - Wells: High InAs mole fraction (>21%)  
  - Barriers: designed to improve confinement (Al >10%)
- Added Anti-Reflex Coating and contacting

Simulation results:
ISDEFE’s MQW MRR prototype modulates at 1064 nm, but material needs further optimization.

Tests at various temperatures:

Proof-of-concept that MQW at 1064 nm and 1070 nm is possible.
MRR driver design goals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Min/max voltage</td>
<td>Variable, 0…12 V</td>
</tr>
<tr>
<td>Form factor</td>
<td>1U compatible</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt; 1 W</td>
</tr>
<tr>
<td>Capabilities</td>
<td>1. Comm. interface</td>
</tr>
<tr>
<td></td>
<td>2. Independent payload</td>
</tr>
</tbody>
</table>
Driver electronics were developed to act both as an independent payload, or as a communication system.

**Carrier board:**
- Hosts Raspberry Pi (main processor)
- Data connection to S/C (USB & UART)
- s/c power conversion (5..14V input)

**Driver board:**
- High speed current driver
- Sensor readout
- Hosts optional photodiodes
- Can be placed elsewhere
Summary
1) Multiple Quantum Well modulation at 1064nm is possible with (In,Ga)As/(Al,Ga)As structures.
2) High performance operation of MRR will require further material optimization.
3) Versatile driver electronics can be fitted into cubesat form-factor.

QUESTIONS?

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