Radiation Effects in Integrated Silicon Photonic Systems

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This work was supported by JPL, NSF, and NRL
Why Optical Communications in Space?

Optical Communications Systems

- Increased Bandwidth
- Can Operate Over Long Distances
Silicon Integrated Photonics for Space

- Optical Communications Have Inherent Advantages Over RF
  - size, power, bandwidth
- Silicon Photonic Integration
  - further reduce size and power (and cost)!

Legacy: Discrete, Bulky

Silicon Photonics:
Integrated, Compact

More Science!
Typical Integrated Si Photonic Transceiver

**Transmitter**

- CW Laser
- Electrical Signal Stream
- Voltage Controlled Phase Shifter

**Receiver**

- Photodiode
- Receiving Optics
- Pointing Optics
- Space
How does radiation affect each of these components individually AND in the context of a communications system?
Optical Single-Event Transients
Heavy Ion Strikes in Photonic Waveguides

Simulations

Waveguides Can Be Sensitive to Heavy Ion Strikes!

G. Tzintzarov, NEPP ETW, 2021

Optical Single-Event Transients (OSETs)

- OSETs Fundamentally Different Than Electrical SETs
  - SETs in electronics generate carriers that get collected by electrical terminals
  - OSETs in waveguides generate carriers that perturb the laser light going through the waveguide… no charge collection!

- OSETs Cannot Be Measured Directly… Must Be Inferred Through Photodiode
Recent OSET Results

Waveguide and PD

No Light

With Light

Example Transient

Transmission

Time (ns)

pin PD

Waveguide
Recent OSET Results

Waveguide and PD

No Light

With Light

Example Transient

- Waveguide Width 0.35 um
- Scanning Spot Size 1 um
- Detected Transients 1.35 um

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pin PD

Waveguide

2-D Scan

Example Transient
Recent OSET Results

Waveguide and PD

No Light

With Light

- Waveguide Width: 0.35 um
- Scanning Spot Size: 1 um
- Detected Transients: 1.35 um

Confirmed OSETs Can Perturb Optical Signal
Optical Single-Event Transients Within Communications System
Pulse-Position Modulation

- Pulse-Position Modulation (PPM)
- Proposed Modulation Scheme for Space

Example – 8\text{th} Order PPM

<table>
<thead>
<tr>
<th>Bit Slot</th>
<th>Bit Pattern</th>
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<tbody>
<tr>
<td>1</td>
<td>000</td>
</tr>
<tr>
<td>2</td>
<td>001</td>
</tr>
<tr>
<td>3</td>
<td>010</td>
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<td>4</td>
<td>011</td>
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<td>5</td>
<td>100</td>
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<td>101</td>
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<td>7</td>
<td>110</td>
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\[ \tau_F \]
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How Might a Heavy Ion Strike Affect PPM Communications Systems?
OSET Impact on Optical Pulses

\[ \tau_x = 80 \text{ ns} \]

\[ \tau_s = 100 \text{ ns} \]

\[ M = 8 \]
OSET Impact on Optical Pulses

\[
\tau_x = 80 \text{ ns}
\]

Strike at 350 ns

\[
\tau_s = 100 \text{ ns} \\
M = 8
\]
OSET Impact on Optical Pulses

Monte Carlo Simulation
With 1000 Strike Locations
OSET Impact on Optical Pulses

Monte Carlo Simulation With 1000 Strike Locations

Identical Result with Cross-Correlation between OSET and PPM Signal
Window of Vulnerability

- Worst-Case Strike Occurs at Start of Pulse
- Window of Vulnerability is Time Where Signal Can Be Corrupted – transient duration + signal duration ($\tau_X + \tau_S$)
- Result Applies to Any Arbitrary PPM System
The PPM Channel

• PPM Channel Modeled by Poisson Distribution
  – expected signal photons ($K_s$)

• Background Light Increases Probability of Symbol Error
  – number of background photons is $K_b$
  – $K_b = 0$ is quantum limited case

• OSETs Can Significantly Increase Probability of Symbol Error
Effect of Bitrate

- $M^{\text{th}}$-Order PPM Symbol Contains $\log_2(M)$ Bits
- Bitrate is Dependent on Order and Pulse Width ($\tau_s$)
- Probability of Symbol Error is Dependent on Target Bitrate

![Graph showing probability of symbol error vs. $K_s$ (photons) for different $K_b$ values and target bitrates.](image)
Effect of Bitrate

- $M^{th}$-Order PPM Symbol Contains $\log_2(M)$ Bits
- Bitrate is Dependent on Order and Pulse Width ($\tau_s$)
- Probability of Symbol Error is Dependent on Target Bitrate
- Space System Designers Can Optimize Communications Systems for SEE Hardness
Other Radiation Effects Efforts
Radiation Effects in Ge Photodiodes

TID (X-ray)

DD (neutron)

Ge Photodetector Both TID and DD Radiation Tolerant!

Photodiode SET Response

• Experimental Method
  – similar to OSET
  – use heavy-ions
  – laser testing is too complex
Photodiode SET Response

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Do SETs within the photodiode corrupt the conversion operation? How?
Photodiode SET Response

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Come See Me at NSREC Next Month, Poster Session I (late news)
Laser/Ion Comparison of Induced OSETs

Laser-Induced OSETs

How do these two compare?

Ion-Induced OSETs
Summary

Integrated Si-Based Photonics is Exciting for Space Systems

BUT ...

Much Remains to be Done to Understand Radiation Effects

- OSETs in nm-scale waveguides have been predicted and observed, and are a potential concern for space communications systems (specifically PPM-based)
- Ge photodetectors are TID and DD Hard, as built, BUT, potentially sensitive to SETs (NSREC 2021)
- Experiments in collaboration with JPL are on-going to identify difference between laser- and ion-induced OSETs

Exciting Stuff, But Much to Be Done!