Optimized biasing of pump laser diodes in a highly reliable metrology source for long-duration space missions

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Outline

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  - Heterodyne metrology
  - Metrology laser source
- NPRO pump reliability limitations
- Laser diode reliability primer
- Selecting optimal biasing scheme
- Monte-Carlo numerical simulations
  - Approach
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- Conclusions
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SIM Lite Overview

SIM Lite:

- 6 meter science Michelson Stellar Interferometer with 50 cm science siderostat apertures
- Visible wavelengths (450-950nm)
- Earth-trailing solar orbit, 5 year mission

Science objectives:

- Finding Earths
- Precision Stellar Astrophysics
- Dark Matter & Galaxy Assembly
- Supermassive Black Hole Astrophysics
SIM Lite Metrology

- Astrometric interferometer requires measurements of the starlight fringe, the internal path difference, and baseline length.
- Heterodyne optical metrology used to measure baseline, internal path difference.
Metrology Source Laser

- Nd:YAG-based Non Planar Ring Oscillator (NPRO) lasers at 1319 or 1064 nm are attractive due to:
  - unidirectional ring cavity provides intrinsically narrow linewidth
  - Low intensity noise
  - Compact and robust

- NPRO lasers are appealing as metrology sources for space applications:
  - Flew in TES (Tropospheric Emission Spectrometer)
  - Planned metrology source for LISA
  - Planned metrology source for SIM Lite
Why Single Mode Pumps?

- Nd:YAG absorption spectrum peaks ~808 nm
- Pump laser diodes fabricated from GaAs/AlGaAs/InGaAsP family of materials
- Multi-Mode (MM) pump diodes:
  - Higher power
- Single-Mode (SM) pump diodes:
  - Bragg grating in fiber pigtail
  - Narrow spectrum – pump Nd:YAG absorption peak only for greater efficiency
  - Spectrum stable as temperature, bias current change (0.02 nm/°C SM vs. 0.3 nm/°C MM)

Nd:YAG absorption from Fan and Byer, IEEE JQE 7, © 1988 IEEE
Reliability of NPRO lasers is limited by the reliability of 808 nm laser pump diodes.
Laser Diode Reliability [2]

- Arrhenius relations transform distribution parameters from the rated condition to a different operating condition:

\[
T_{m,o} = T_{m,r} \cdot \exp \left( \frac{E_a}{k} \cdot \left( \frac{1}{T_o} - \frac{1}{T_r} \right) \cdot \left( \frac{P_r}{P_o} \right)^n \right)
\]

\[
\frac{1}{\lambda_{r,o}} = \frac{1}{\lambda_{r,r}} \cdot \exp \left( \frac{E_a}{k} \cdot \left( \frac{1}{T_o} - \frac{1}{T_r} \right) \cdot \left( \frac{P_r}{P_o} \right)^n \right)
\]

To extend diode lifetime beyond rated value:
1. Reduce operating temperature
2. Reduce output power
Reliability Requirements

- SIM-Lite power / lifetime / reliability requirement:
  - 1.9W of pump power w/ 99.7% reliability over 5.5yrs
- COTS 808 nm laser diodes have $T_m$ 5,000 - 100,000 hours
  - If $T_m = 100,000$ hours, 76% of diodes survive 5.5yrs – inadequate

To meet requirements:
- Share load among multiple redundant lasers at de-rated conditions
- Combine their outputs using a high-port count, all-fiber coupler
Simulation Parameters

- Key parameters used in SIM-Lite mission simulation (conservative interpretation of literature/vendor data):
  - Rated temperature: \( T_r = 298 \, K \)
  - Rated pump power \( P_r = 100 \, \text{mW} \)
  - Maximum rated power \( P_{\text{max}} = 150 \, \text{mW} \)
  - Random failure rate \( \lambda_R = 2,000 \, \text{FIT} \)
  - Wear out: median diode life \( T_m = 15,000 \, \text{hrs}, \sigma = 1 \)
  - Wear out activation energy \( E_a = 0.45 \, \text{eV} \)
  - Random failure activation energy \( E_a = 0.35 \, \text{eV} \)
  - Power exponents \( n_R = n_w = 1.1 \)

- Note: power exponents \( n \) not well characterized, reported values range from 2.8 to 5
  - Use ultra-conservative value, try to minimize solution sensitivity to this parameter
Optimal Biasing Approach

- To measure the impact of different biasing configurations we developed a “total instantaneous farm aging” parameter

- Compare 3 biasing approaches w/ same number of lasers:
  1. equal load sharing among all lasers that have not yet failed (hot spares) - blue
  2. running a minimum set of lasers at rated output, while keeping spares cold until needed - green
  3. running a minimum set of lasers just below maximum rated output, while keeping spares cold until needed - red

- Approach #1 is preferable for $n > 0.44$ – all physical situations
Monte-Carlo Algorithm

• Run for N (30,000) trial missions, monitor for convergence of reliability
  ▪ Run for mission lifetime in δt steps...
    – In each time step: \( P(\text{fail}) = (\lambda_R + \lambda_W(t)) \delta t \)
    – (adaptive step size: δt set such that \( P < 1e^{-3} \))
    – N uniform random number generator: model individual diode failures. Compare to \( P(\text{fail}) \)
    – If diode fails:
      • Adjust power on remaining diodes to maintain desired output
      • Use Arrhenius to scale \( \lambda, T_m \), while maintaining continuity of reliability function \( R \)

*Mission fails when adjusted laser power exceeds max rated power

\[ R = 1 - \frac{N_{\text{fail}}}{N} \]
How Many Pump Diodes?

- Minimum number of laser diodes needed to produce 1.9 W of pump power over 5.5 years with >99.7% reliability for temperatures between -25 and -1°C:

<table>
<thead>
<tr>
<th>Operating Temperature, (deg C)</th>
<th>Min. Number Of Diodes Required To Achieve Mission Reliability &gt; 99.7%</th>
</tr>
</thead>
<tbody>
<tr>
<td>-25</td>
<td>22</td>
</tr>
<tr>
<td>-20</td>
<td>23</td>
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<tr>
<td>-15</td>
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<td>-10</td>
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<td>-5</td>
<td>33</td>
</tr>
<tr>
<td>-1</td>
<td>37</td>
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</tbody>
</table>

- We chose the warmest case (-1°C, 37 lasers) because:
  - Least sensitive to the value of exponent $n$ by far (next slide)
  - Operating at -1°C reduces required thermal radiator footprint
  - Very low loss, robust 37x1 coupler readily available
Sensitivity to $n$

- **-25deg C solution (cold solution)**
  - This solution also does NOT de-rate the diode operating power (110mW)
  - Solution very sensitive to uncertainty in $n$

- **-15deg C solution (in-between solution)**
  - Minimal de-rating as well, 95mW
  - Solution very sensitive to uncertainty in $n$ – more sensitive than cold one due to increase operating temperature

- **-1deg C solution (warm solution)**
  - This solution operates with substantial de-rating, 64mW
  - Solution works for all realistic values of $n$
Sensitivity to Temp, Number of Diodes

- At 0°C mission reliability still >99%, quickly rolls off for higher temperature
- Operate at -5°C to reduce risk
- As number of diodes at start of mission falls below 36, mission reliability below 99%
- Below 32 diodes mission reliability drops below 90%
- If >2 diodes fail during launch, mission reliability seriously impaired
Summary

- NRPO lasers are highly attractive for metrology applications
- NPRO reliability for prolonged space missions is limited by reliability of 808 nm pump diodes
- Combined laser farm aging parameter allows comparing different bias approaches
- Monte-Carlo software developed to calculate the reliability of laser pump architecture, perform parameter sensitivity studies
- To meet stringent SIM Lite lifetime reliability / output power requirements, we developed a single-mode Laser Pump Module architecture that:
  - provides 2 W of power at 808 nm with >99.7% reliability for 5.5 years
  - consists of 37 de-rated diode lasers operating at -5°C, with outputs combined in a very low loss 37x1 all-fiber coupler
Acknowledgement

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BACKUP SLIDES
SIM Lite Overview

• **Salient Features**
  - 6 meter science Michelson Stellar Interferometer (MSI) with 50 cm science siderostat apertures
  - One 4m MSI and one 30cm T-scope Guides
  - Visible wavelength (450-950nm)
  - Earth-trailing solar orbit, 5 year mission
  - SIM is a JPL, Caltech, NGAS, KSC, and SIM Science Team partnership
  - Category 1, Risk Class B mission.

• **Science**
  - **Finding Earths** – Reveal the population, masses, and orbits of terrestrial and giant planets around nearby stars, and the formation, evolution, and architecture of planetary systems.
  - **Dark Matter & Galaxy Assembly** – Determine the age of and probe the hierarchical formation history of the Milky Way. Map the distribution of local dark matter, and place limits on the mass of the dark matter particle. Include rotational parallaxes.
  - **Precision Stellar Astrophysics** – Precision measurements of the masses and luminosities of the highest and lowest mass stars allow testing of models of stellar evolution, from brown dwarfs to black holes.
  - **Supermassive Black Hole Astrophysics** – Understand how black holes accelerate jets, from stellar masses to galaxy central engines.
More on Wear-Out

- Wear out median life given by Arrhenius relations assumes constant operating conditions.
- However, conditions change over time as some lasers fail and others ramp up to maintain constant total output.
- Since log-normal distribution has memory, wear-out parameters depend on the past operating conditions, as well as current and future ones.
- As operating conditions change (e.g. at $t = 40,000$ hrs below), wear-out reliability function $R_w(t)$ remains continuous but experiences discontinuity in its first derivative.

![Graph showing reliability function over time](image)
Infinitely many biasing approaches are available to maintain constant output power – ranging from equal load sharing among all lasers that have not yet failed, to running a set of lasers as hard as possible, while keeping spares cold until needed.

To compare analytically compare various biasing approaches we introduce the instantaneous “laser farm aging” $A(t)$:

$$A(t)dt = \sum_{n=1}^{N(t)} \left\{ \left[ \frac{\lambda}{R_n(t)} + \frac{\lambda_W}{n(t)} \right] dt * R_n(t) + \left[ 1 - \left( \frac{\lambda}{R_n(t)} + \frac{\lambda_W}{n(t)} \right) dt \right] * \left[ R_n(t) - R_n(t + dt) \right] \right\}$$

Aging here is defined as continuous decline of wear-out reliability

$$A(t) \approx \sum_{n=1}^{N(t)} \left\{ \left[ \frac{\lambda}{R_n(t)} + \frac{\lambda_W}{n(t)} \right] * R_n(t) + f_{w,n}(t) \right\}$$
## Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td><strong>Mission Parameters</strong></td>
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<tr>
<td>Mission Lifetime</td>
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<td>Mission Lifetime</td>
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<td>Reliability At Mission End</td>
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<td><strong>Optical Power Requirements</strong></td>
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<tr>
<td>NPRO Power</td>
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<td>Pump Power</td>
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<td>W</td>
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<td><strong>Pump Diode Parameters</strong></td>
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<td>Rated Temperature</td>
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<td>Maximum Rated Power</td>
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<td>Diode Median Life</td>
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<td>Random Failure Power Exponent</td>
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<td><strong>Pump Beam Combiner Parameters</strong></td>
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<td>Coupling Coef. Per Channel</td>
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<td>%</td>
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<td><strong>Calculation Parameters</strong></td>
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<td>Threshold Probability</td>
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<tr>
<td>Optical Power Margin Factor</td>
<td>90</td>
<td>%</td>
</tr>
</tbody>
</table>
Sensitivity to $T_m, \lambda_r$

- **Strong dependence on median life** below 15,000 hrs
- **Mission reliability** $< 99\%$ for $T_m = 13,000$ hrs
- **Mission reliability approaches 0** for $T_m = 5,000$ hrs
- **Dominant failure mechanism**

- **Weak dependence on random failure rate** – as $\lambda_r$ varies from 1,000 to 10,000 FIT, mission reliability is reduced from 99.9% to $\sim 97\%$
All Fiber Combiner

- Pump Beam Combiner (PBC) has 37 single mode input fibers
  - Operating wavelength 808 nm
  - Core diameter 5 um
- The combiner has 1 output multimode fiber
  - 105 um core diameter and 0.15 NA
- Measured insertion loss < 0.5 dB for all ports
PBC Package

- Package designed to ensure PBC protection for temperature excursions from -40°C to +80°C and random vibration levels > 90g rms (5σ).
- PBC is epoxied at 2 support points into SS housing
- Ferrules at package end provide additional strain relief
- FEM simulations show PBC surviving launch conditions with required safety margin