Development of High Operating Temperature (HOT) Pump Diodes

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Outline

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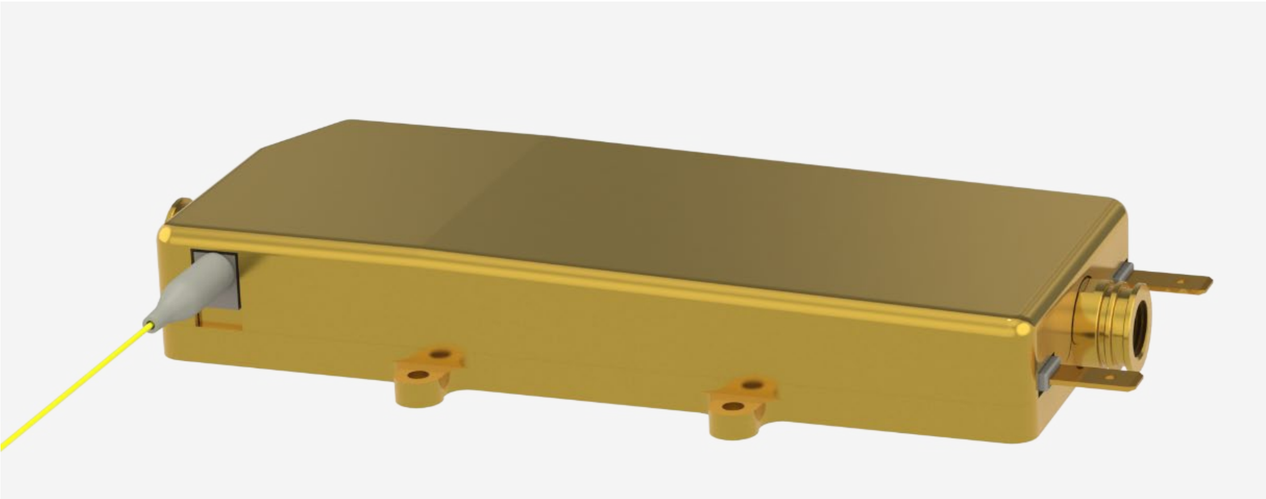
4. Corrosion Analysis
5. Summary



HEL System on the USS Ponce, Exposed schematic of HOT Diodes Package, Prospective HOT Diodes product

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Problem Statement and Benefits

Issue Description

- High Energy Laser (HEL) weapon systems require **large thermal management systems (TMS)** and piping to **dissipate significant heat loads** from the **laser diode pump modules** operating near room temperature.
- These significant cooling requirements can be reduced by operating diodes at a higher temperatures (50°C). This results in a projected 25% **reduction in system SWaP from TMS reduction** in EGW-cooled systems[1].
  - On a naval vessel, this entirely removes the need for any cooling system (compressor, condenser).
- Additional system SWaP can be realized with increases in pump diode electrical-to-optical efficiency
  - Largest component of this reduction is **driven by battery SWaP** but also **TMS**
  - 1 – 2 % SWaP reduction per 1 % increase in efficiency in the range of interest
- Manufacturing processes need to be developed to integrate high operating temperature (HOT) pump diodes into amplifiers.

Increasing laser pump diode operating temperature and increasing laser pump diode efficiency are effective means to reducing overall HEL system SWaP.

[1] Mitre Technical Report – Ground and Sea Platforms HEL High Temperature Diode SWaP Impact. 108 Pages. December 2021.

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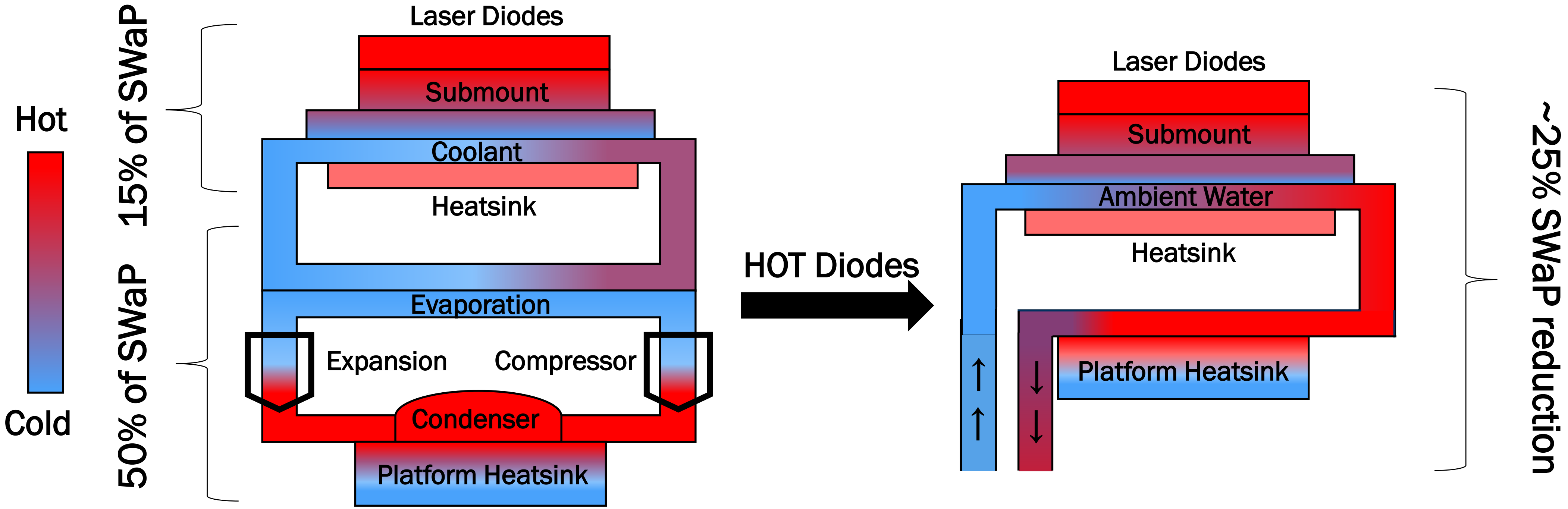
Problem Statement and Benefits

- The **warmest water temperatures** around the world during the **warmest month (August)** reaches a maximum of **35°C.**
  - This is NOT implying or suggesting that seawater be directly pumped into the system.
    - The diode package cooling loop would be separated from seawater cooling lines by a heat exchanger
- With correct thermal package engineering, ≥ 15°C ΔT should provide adequate cooling at reasonable flow rates to cool laser diodes to 50°C.
- This program focuses on developments to the **pump laser diodes**, **submount**, **package**, and **amplifier.**



Problem Statement and Benefits

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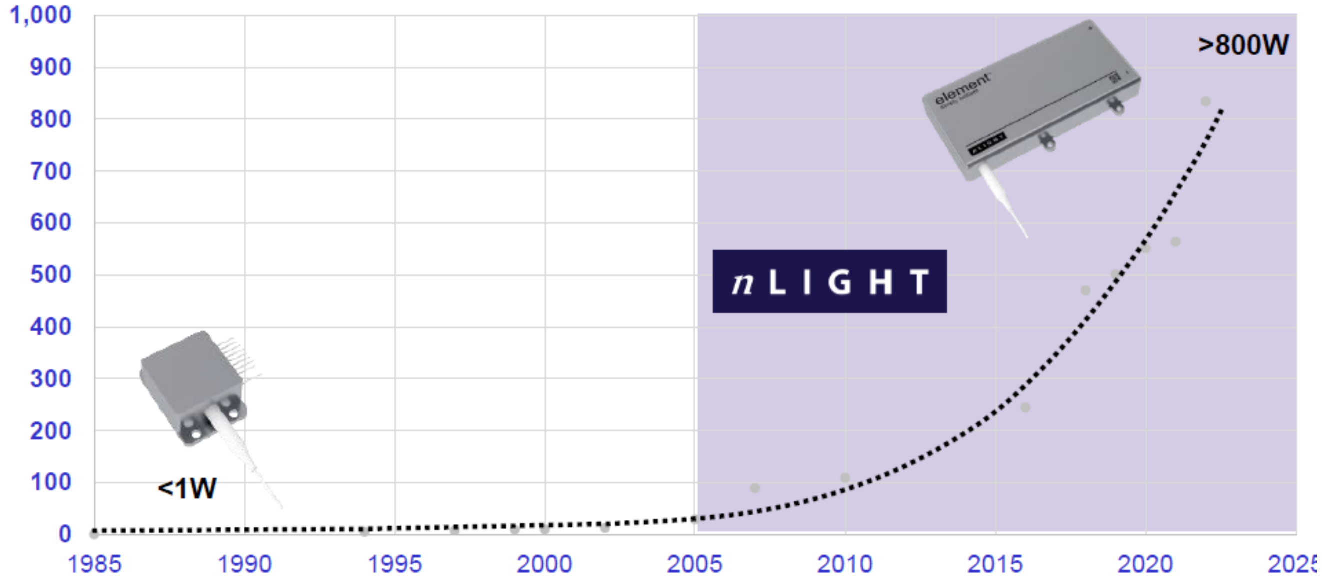
- **nLight** is the primary technical performer for this program
  - Their laser technology serves **defense**, semiconductor, industrial, and medical areas.

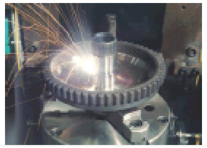
High-Power Semiconductor Laser Power
Watts coupled into 200 µm fiber



Semiconductor
- Flat Panel Display
- Semiconductor
- Photo Voltaic

Defense
- Countermeasures (IRCM)
- Rangefinders & Targeting
- LIDAR and Space

Industrial
- Welding (plastic & thin metal)
- Precision Marking
- Heat Treating



Medical
- Surgery
- Hair Removal (spa and home)
- Skin Rejuvenation

HOT Diodes Program

Semiconductor Device → Semiconductor Laser → Optical Fiber → Fiber Amplifier → DE High Energy Laser → Beam Control

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Problem Statement and Benefits

- **Industrial pump diodes** are not viable for **Directed Energy Applications**
  - HOT Diodes addresses all of these issues

Too heavy > > 1 kg/kW → Size / Weight (Package)

Too large > > 1 cm^3/W → Size / Weight (Package)

Not efficient ≤ 50% (e-o) → Size / Weight (System), Power

Power is too low (400 W) → Size / Weight (System), Power

Cannot operate at high temperature (50 °C) → Size / Weight (System)

Wavelength tolerance is insufficient → Capability

Problem Statement and Benefits

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- Project is designated as a **capability acceleration** but **cost avoidance** is also expected.
  - With a SWaP reduction of 25%, $10,000 – 20,000 in material costs per TMS (HEL) system.
  - $750,000 – 1,000,000 in savings related to a required change in piping size to install an HEL system on a ship platform[2].
  - Other funded ManTech efforts bring manufacturing costs of HOT diodes down (Army)

Technical Challenges:

- **Joule heating** impact on laser diode **quantum efficiency**
  - Specifically design epi-stack to have a higher intrinsic efficiency at high temperatures
- **Increased operating temperature** impacts **emission wavelength**
  - Integrate **Bragg grating** onto chip for **instant locking with no alignment challenges**
  - It is advantageous to **maximize the spectral overlap** between the **emission of the pump diode** and the **absorption band of the host medium**
- Reliability reduces at higher temperature operation (**MTBF**)
  - Current MTBF can be reduced by understanding system realistic lifetime to **MTBF to 1,000 hours**
- At higher operating temperatures, there is a need to remove heat more quickly
  - Very high thermal conductivity / low thermal resistance (**High TC**) submounts and packages

[2] PEO IWS 2.0

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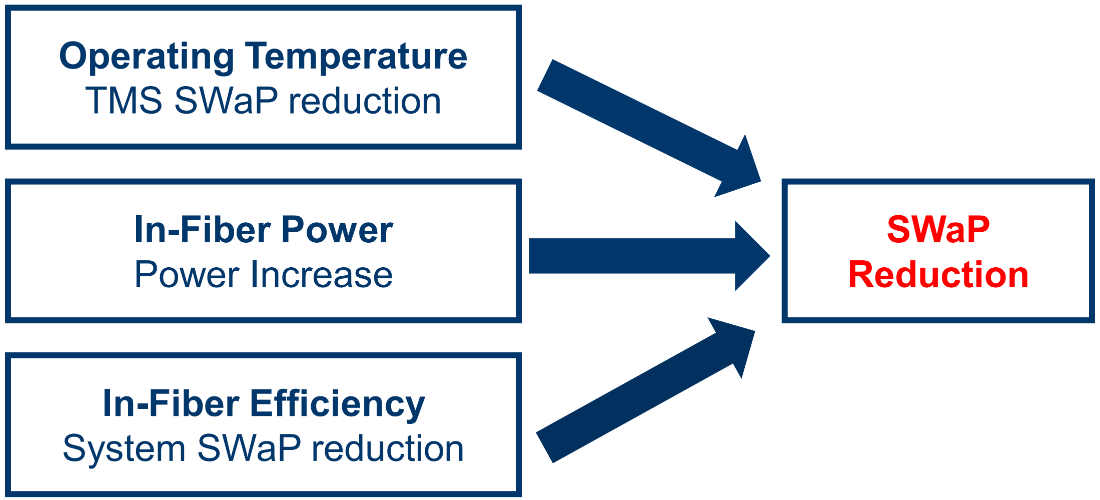
Program Objectives

- Detailed project metrics were developed to drive towards projected **SWaP reduction**
  - **TMS SWaP reduction**is a **system – level metric** and not being directly evaluated in this program.
  - Progression in TRL / MRL levels of technology
    - nLight intends to field a product with an orderable product number
  - Mean time before failure (MTBF)
  - **Operating Temperature of 50°C** enables a projected 25% system SWaP reduction
  - In-fiber power increase enables higher power packages for HOT Diodes
  - In-fiber efficiency enables projected system SWaP reduction



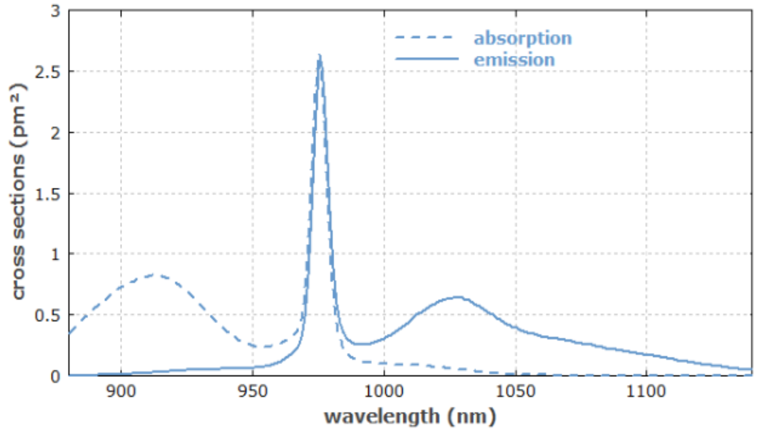
Metric	Units	Initial	Threshold	Goal
TRL	Numeric	3	5	6
MRL	Numeric	N/A	5	6
MTBF[1]	Hours		1000	1400
Operating Temperature	°C		50 ± 8	50 ± 8
In-Fiber Power	Watts		500	550
In-Fiber Efficiency	%		53	56

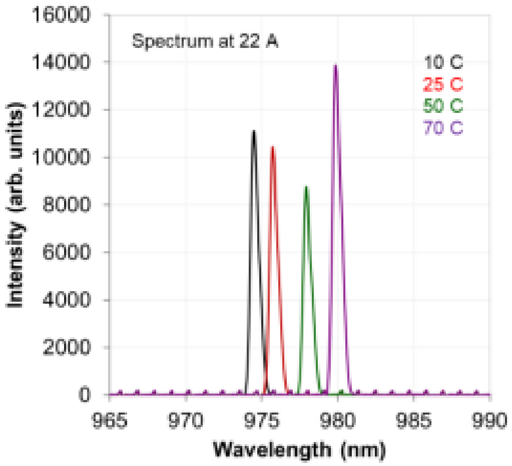
[1]MTBF corresponds to active laser pulsing on-time. ~1000 hours = 100,000 30-second on-times

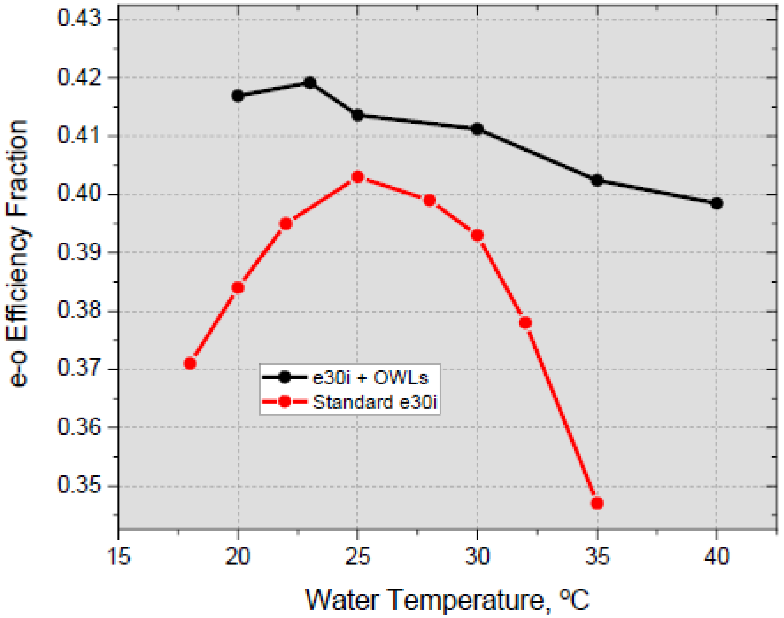
Technical Approach

- Efficiency of pump laser diodes **decreases** with **increasing temperature** due to **Joule heating.**
  - This reduces the **quantum efficiency** and ultimately **electrical-to-optical efficiency.**
- Emission wavelength of laser diodes varies with temperature due to **material bandgap modulation**
  - Epitaxial stack **(material composition)** engineers the specific emission wavelength.
- **Spectral width** and **wavelength drift with temperature** cannot be directly engineered through epitaxy modulations alone.
- **Yb absorption** occurs at **976 nm** with a **FWHM < 5 nm**
  - **Pump diode emission wavelength** shifts from **0.2 – 1.0 nm/°C**

The mismatch between Yb absorption and diode emission wavelength at elevated temperatures causes a significant reduction in efficiency







Prior work nLight demonstrated significant efficiency improvements of OWL technology.

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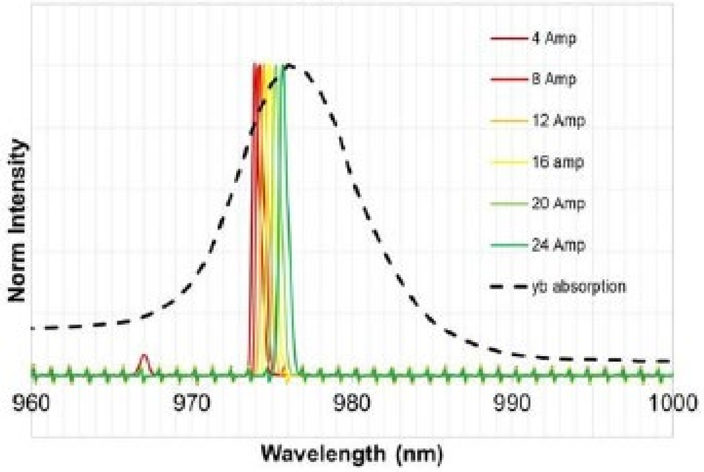
Technical Approach

- nLight's **On-chip Wavelength-stabilized Laser (OWL) technology** significantly reduces shift in diode emission wavelength with temperature .
  - Embeds a Bragg Grating on-chip to limit wavelength shift to **0.065 nm/°C**
  - Enables 100% power in the band at all operating powers/currents with a locking over 50°C temperature range.

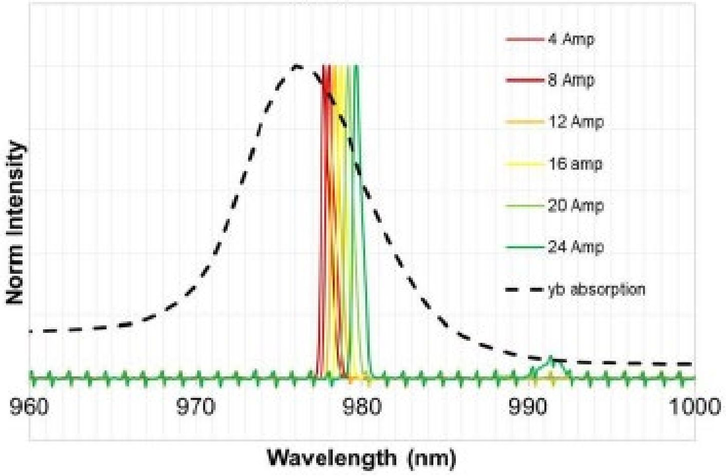
Due to SWaP-considerations, nLight has developed internal Bragg grating technology On-chip Wavelength stabilized Laser (OWL) technology enabling instant on (1 ms)

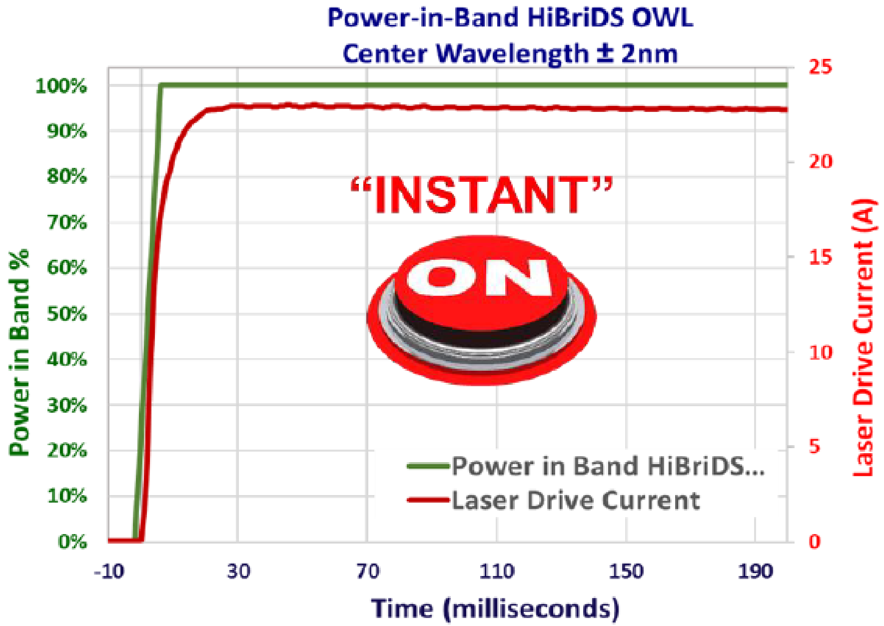
OWL Technology:

15 °C



65 °C





Technical Approach

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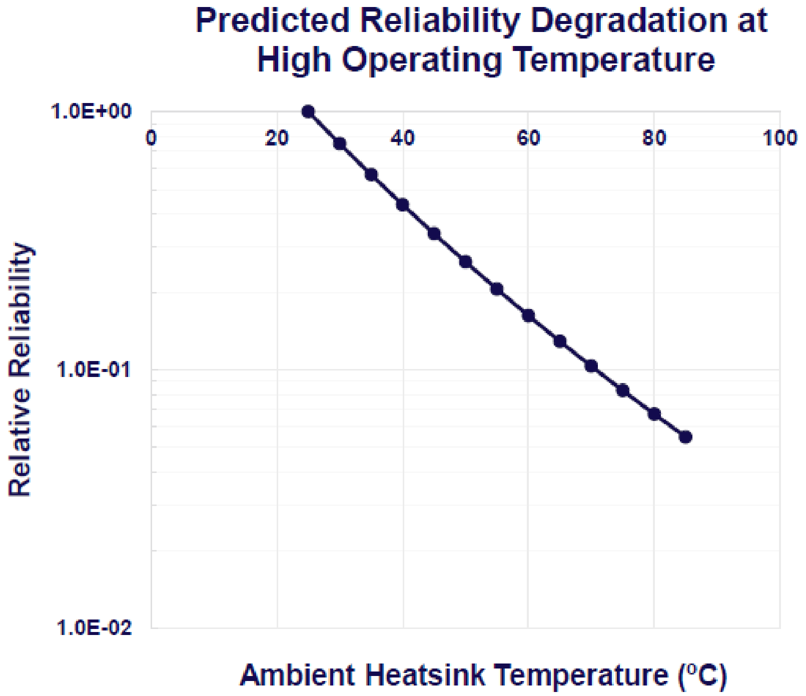
- Higher temperature operation results in a significant reduction of diode reliability through an Arrhenius relationship.

$$Reliability \propto I^m P^n e^{-\frac{E_a}{kT_j}}$$

- Current operating temperature of diodes at **25°C** results in a **MTBF ~ 10,000 hrs**
  - o Largely important for commercial applications
- Operating pump diodes at **50°C** results in a **projected 2 – 5x reduction in MTBF**
- Specifically, by understanding mission profile and system usage, an expected **MTBF of 1,000 hrs of on-time** is acceptable
  - o On-times are generally short >30 seconds equating to ~ 100,000 hours
- CW testing of OWL chips is underway for required 1,000 hrs



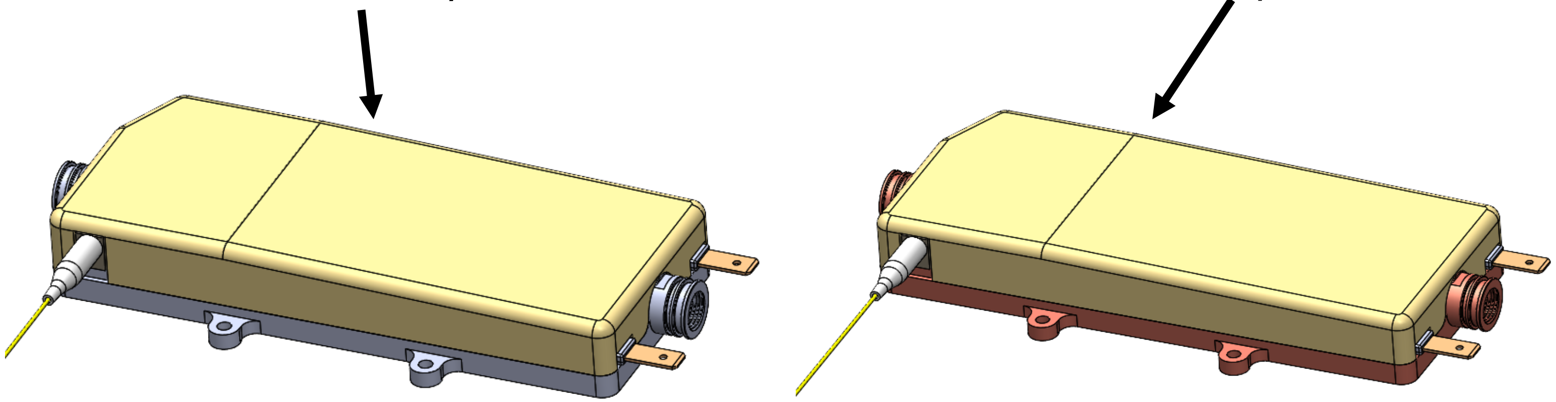
Predicted impact of operating HOT diodes on their lifetime.

Technical Approach

- Room temperature aluminum packages focus on low manufacturing cost and SWaP – C but do not have adequate thermal resistance for Directed Energy Applications.
- Copper heat sinks inserted into aluminum housings provide superior thermal conductivity and lower SWaP – C.
- T_J is reduced for Cu – insert Aluminum housing vs. standard aluminum housing
  - $\Delta T_J = 5°C \text{ @ } 22A$

All – Aluminum Package
Low manufacturing cost
Light weight (**190 g**)
$k = 237\ W/mK$

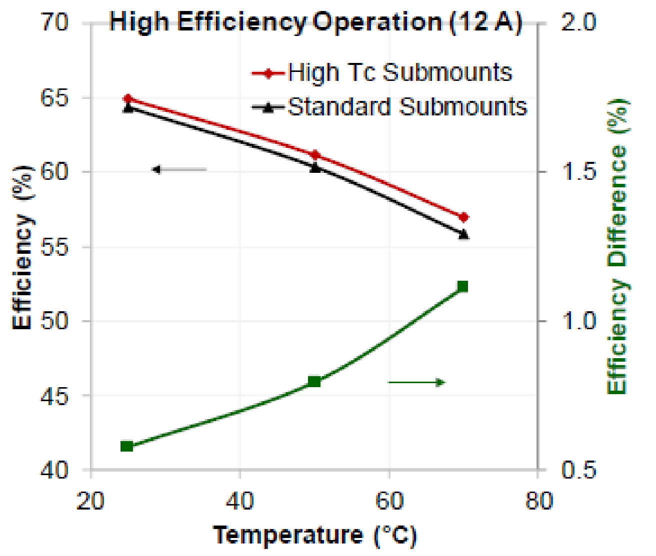
All – Copper Package
High manufacturing cost
Heavy weight (**435 g**)
$k = 401\ W/mK$



Hybrid Design being evaluated to reduce weight while maintaining thermal efficiency.
(245g & $k = 401\ W/mK$)

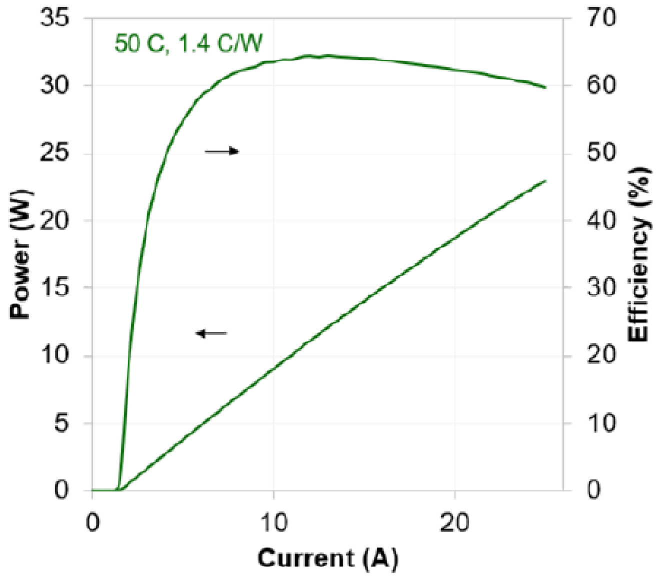
Technical Approach

- High thermal conductivity (TC) submounts enables efficiency gains
  - Thermal resistance reduction (**2.1 °C/W → 1.8 °C/W**) enables **> 1% efficiency reduction** at **50°C.**
  - Under the **HOT Diodes program**, a submount thermal resistance of **1.4 °C/W** is targeted.

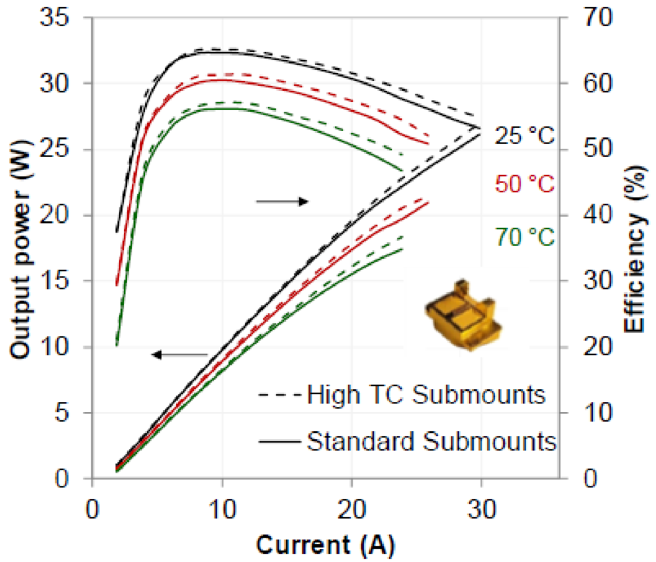


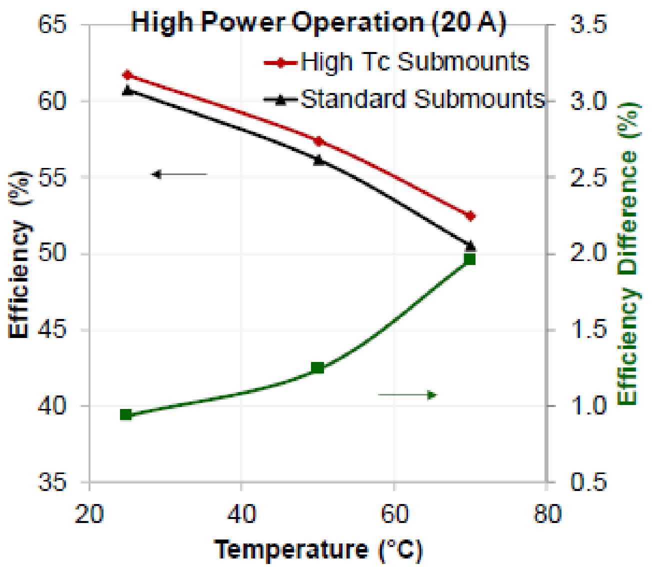
Reductions in thermal resistance with high TC submounts are poised to increase efficiency of HOT Diodes

Simulated 1.4 °C/W at 50°C



2.1 °C/W → 1.8 °C/W





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Technical Approach

- **Characterization plan** developed to adequately measure **OWL Chips on Submount** and **Fiber-coupled packages**
  - **Subcomponent metrics** developed to meet **program metrics**

Fiber-Coupled Package Metrics

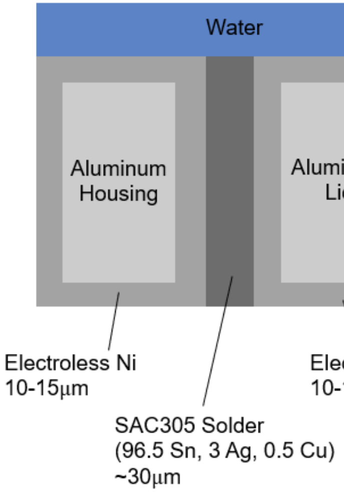
Metric	Units	Threshold	Goal
In-fiber Power	Watt	500	550
Pkg Voltage	Volt	48.3	53.5
In-fiber Eff	%	55	58
Inlet H_2O Temp	C	50	50
Specific Mass	kg/kW	<0.46	0.46
Specific Volume	cm^3/W	<0.42	0.42
Wavelength (λ)	nm	976	976
Λ- Tolerance	nm	±1	±1
Spectral Width	nm	<1	<1
NA	Numerical	<0.22	<0.2
Reliability	Hrs	1000	1000

OWL Chip Metrics

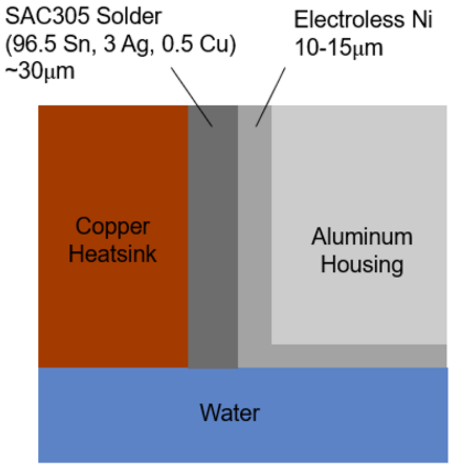
Metric	Units	Threshold	Goal
Chip Power	Watt	17.4	17.7
Voltage	Volt	1.500	1.485
Chip Efficiency	%	61	63
Temperature	C	50	50
Wavelength	nm	976	976
Center WL Tolerance	nm	±1	±1
Spectral Width	nm	<0.5	<0.5
Reliability	Hrs	1000	1000

Corrosion Analysis

- Hybrid (copper/aluminum) design creates an intermetallic interface with a high potential for **Galvanic corrosion**
- Not a theoretical concern for EGW – cooled systems, but evaluating risks of small amounts of electrolyte intrusion



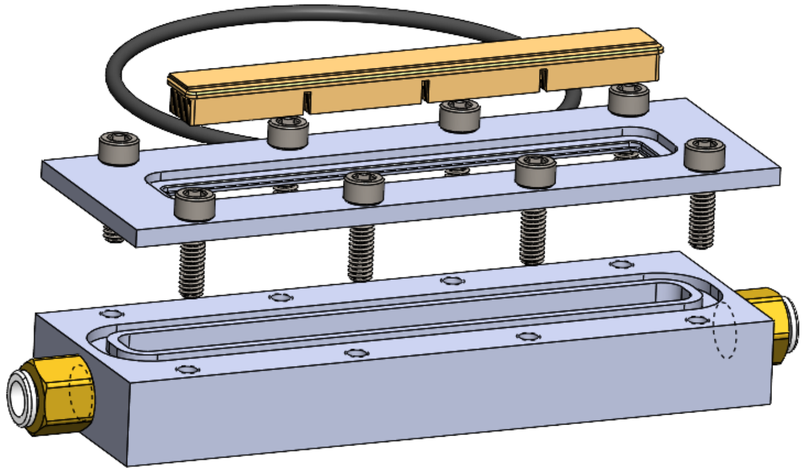
Regular Low SWaP Diode Pkg. Config.



Hybrid HOT Diode Pkg Config.

Corrosion Analysis

- Corrosion testing was executed with surrogate coupons with multiple design of experiments (DoEs) with continuous water flow at 50°C and 1.2 gpm
  - One group with 70% Distilled water / 30% ethylene glycol (EGW)
  - One group 25% ASTM seawater / 75% Distilled water
    - Aggressive water chemistry intended to accelerate corrosion formation
    - Lake Products Company LLC - "SEA SALT" ASTM D1141-98



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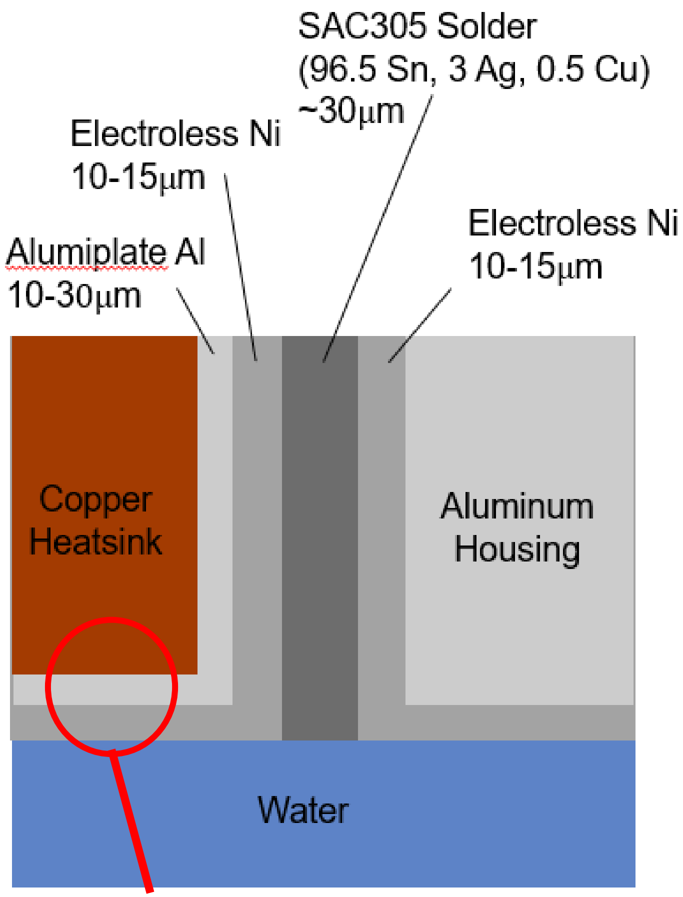
Corrosion Analysis

- EGW Samples
  - Significant corrosion observed in Al-plated copper heatsink (CaW2), failed at 455 hours
  - All other samples (CS2, CW2, AS2) did not show corrosion at
- 25% Seawater samples – 960 hour bare copper & 645 hour bare aluminum heatsinks
  - Samples holding up well - no aggressive corrosion
  - Biggest issue is clogging at fin inlet for fine straight fins – Installing filter
- 25% Seawater samples – 1200 hour bare copper & 885 hour bare aluminum heatsinks
  - Fins holding up well, but additional deterioration around seal area

Goal of testing is to develop standard operating procedures and requirement/s for monitoring systems and maintenance intervals



Failure region within fin structure

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Summary

- HOT Diodes is projected to provide significant SWaP benefits based on significant size reduction of the TMS (~25%)
  - Sea-borne vessels are intended to use the ocean as their heatsink, entirely removing the need for a compressor, condenser, and additional piping
- Additional SWaP is intended to be realized with projected increases in efficiency from OWL chip designs and thermal management solutions
- This program lays the ground work for similar HOT Diodes programs for other services (Army, Air Force)

Future Work and Programs:

- The end of this program will develop HOT diodes rated for 50°C operation but in order to field a system that operates at 50°C, an amplifier will need to be designed

Metric	Units	Initial	Current	Threshold	Goal
TRL	Numeric	3	4	5	6
MRL	Numeric	N/A	3	5	6
MTBF	Hours		1000 +	1000	1400
Operating Temperature	°C		50	50 ± 8	50 ± 8
In-Fiber Power	Watts		500	500	550
In-Fiber Efficiency	%		52	53	56

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