Liquid Metal Heat Sink for High-Power Laser Diodes [a,b]

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ABSTRACT

We report on the development of a novel, ultra-low thermal resistance active heat sink (AHS) for thermal management of high-power laser diodes (HPLD) and other electronic and photonic components. AHS uses a liquid metal coolant flowing at high speed in a miniature closed and sealed loop. The liquid metal coolant receives waste heat from an HPLD at high flux and transfers it at much reduced flux to environment, primary coolant fluid, heat pipe, or structure. Liquid metal flow is maintained electromagnetically without any moving parts. Velocity of liquid metal flow can be controlled electronically, thus allowing for temperature control of HPLD wavelength. This feature also enables operation at a stable wavelength over a broad range of ambient conditions. Results from testing an HPLD cooled by AHS are presented.

Keywords: High-power laser diodes, thermal management, heat sink, solid-state laser, alkali vapor laser

1. INTRODUCTION AND BACKGROUND

Operation of high-power laser diodes (HPLD) results in generation of a significant amount of waste heat that must be efficiently removed to ensure proper function and to prevent catastrophic failure. HPLD generates waste heat (up to several hundred watts) at high heat flux (approaching 1,000 W/cm^2) while it must be maintained at a uniform and precise temperature (typically within 1°C). This challenge is compounded by the ongoing drive toward higher optical output per HPLD bar requiring a removal of heat at ever increasing fluxes. As seen in Figure 1, thermal management of HPLD is much more demanding than that of traditional solid-state electronics.

Traditional active heat sinks for thermal management of HPLD may use liquid-cooled microchannels, liquid-impingement jets, and evaporative sprays. Such devices require a dedicated external flow loop with pumps, heat exchangers, and plumbing. This greatly increases the size, weight, cost, and power consumption of the entire application system. As a result, the installation of HPLD in many applications, especially on mobile platforms, becomes more complex. Passive heat sinks and heat spreaders are simple and compact, but they have a large thermal resistance, which undesirably contributes to elevated junction

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temperatures. In addition, passive heat sinks have a large thermal inertia and are not conducive to accurate temperature control under varying operating or ambient conditions.

Hence, there is a critical need for improved heat sink technologies for HPLD that offer ultra-low thermal resistance and compatibility with existing electronics and photonics packaging / interfacing technologies. We have previously introduced an innovative, liquid metal-based active heat sink (AHS) for HPLD offering unparalleled capacity in high-heat flux handling and temperature control [1, 2, 3]. The AHS receives diode waste heat at high flux and transfers it at reduced flux to environment (e.g., air), coolant fluid, heat pipe, or structure. When pumping solid-state or alkaline vapor lasers, the diode wavelength can be precisely temperature-tuned to the absorption features of the laser gain medium. This paper presents results from testing HPLD cooled by AHS.

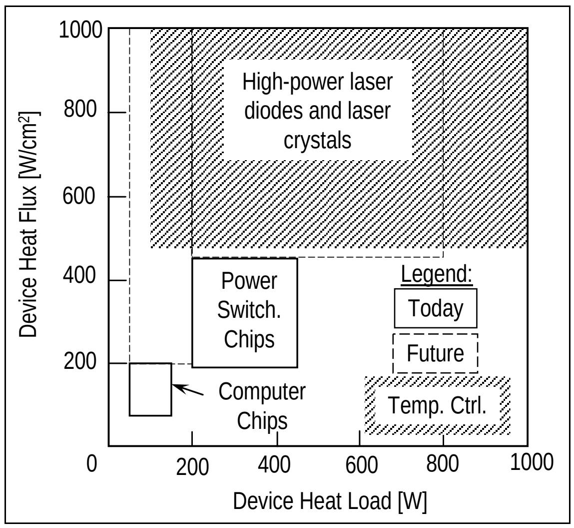

Figure 1: Typical heat loads to selected electronic and photonic components

2. ADVANTAGES OF LIQUID METAL COOLING

Metals have a thermal conductivity several orders-of-magnitude greater than water and organic liquids. Liquid (molten) metals have a viscosity comparable to that of water. High electrical conductivity and chemical stability of liquid metals makes it possible to advantageously flow them by magneto-hydrodynamic (MHD) pumps without any moving parts. These features make liquid metals excellent candidates for high-performance cooling in many demanding applications, especially where heat must be removed at high heat flux. Initially, liquid metal cooling was developed for thermal management of nuclear reactors (in particular, on submarines) since the 1950s. These large systems use eutectic alloy of sodium and potassium (also known as NaK) and in some cases, eutectic alloys of lead and bismuth.

Liquid metals for small applications such as cooling of electronics and photonics are preferably room-temperature-melting alloys of gallium. Pure gallium offers 68 times higher thermal conductivity than water, but its high freezing point restricts its use to above 30°C. Many room-temperature-melting alloys of gallium, whether ordinary or eutectic, are non-toxic, stable in air, and they wet well many materials [4]. A non-toxic eutectic liquid metal alloy known as “galinstan” (68.5% gallium, 21.5% indium, and 10% tin) is particularly attractive because of its relatively high thermal conductivity (~30 times higher than water) and low melting point (-19°C) [5]. Recently, a class of Ga-In-Sn-Zn alloys having a melting point as low as -36°C has been reported [6]. Figure 2 compares physical parameters of selected liquid metals.

Parameter	Units	Coolant		
		Water (reference)	Galinstan*	Ga-In-Sn-Zn
Melting Point	°C	0	-19	-36
Thermal Conductivity	W/m-°C	0.598	16.5	~15
Density	kg/m^3	998	6,440	~6,500
Dynamic Viscosity	Ns/m^2	10.0×10^{-4}	24×10^{-4}	$\sim 25 \times 10^{-4}$
Kinematic Viscosity	m^2/s	10.0×10^{-7}	3.73×10^{-7}	$\sim 4 \times 10^{-7}$
Specific Heat	kJ/kg-°C	4.183	~0.3	~0.3
Prandtl No.	-	7.0	0.044	~0.05

*) based on information from [5]

Figure 2: Physical parameters of selected liquid metals

In contrast to conventional coolants such as water, ethylene glycol, Freon®, or Fluorinert®, the comparably high thermal conductivity of liquid metals makes it possible to acquire high-flux heat with low thermal resistance and at relatively low flow velocities. In particular, the coefficient for heat transfer between flowing coolant and a solid wall can be calculated as

$$h = Nu\ \kappa\ /\ D_H \qquad (1)$$

where Nu is the Nusselt number, κ is the thermal conductivity of the coolant, and D_H is the hydraulic diameter. It can be easily see that using liquid metal coolant, heat transfer coefficients on the order of 10 W/cm^2-°K can be obtained with the liquid metal flowing in a laminar flow through a relatively large channel. This means that for a given cooling task, the required liquid metal coolant flow rates are much smaller than for traditional coolants.

We conducted comparative experiments on a test article heat sink with water and liquid metal coolants. The unit was operated with a resistor heat load generating about 144 W at a heat flux of 288 W/cm^2. Resistance of the test article was inferred from the temperature of the resistor. A plot of the heat sink resistance versus coolant flow velocity for each set of tests shown in Figure 3 indicates that with liquid metal cooling, a given thermal resistance value is attained at 6 to 7 times lower flow velocity than with water.

Reduced coolant velocity translates to reduced pump power necessary to maintain the coolant flow. In particular, the motive power required to pump a coolant through a heat sink scales linearly with pump head (pressure) and pump throughput. The former also scales as v^2/ρ, where v is flow velocity and ρ is the coolant density, while the latter scales linearly with velocity. Therefore, the motive power required to operate the flow loop scales as $v^3/\ \rho$. Despite the higher density of the liquid metal, the power savings over conventional coolants in operating the thermal management system can be quite high. Figure 4 shows the inferred pump power required to feed coolant through the referenced test article based on the test data in Figure 3. Reduction in pump power can be of critical importance in certain power-limited applications on airborne or space platforms.

Other benefits of low flow velocity include reduced erosion of the flow loop walls and reduced flow induced vibrations. The latter is of importance in vibration sensitive optical systems, especially on space platforms.

The challenges of using gallium-based liquid metal coolant include susceptibility to corroding metal parts and negative coefficient of expansion upon freezing. In particular, gallium in pure and alloyed form tends to fuse with other metals to form amalgams. This requires careful selection of the AHS materials and/or a use of anticorrosion coatings.

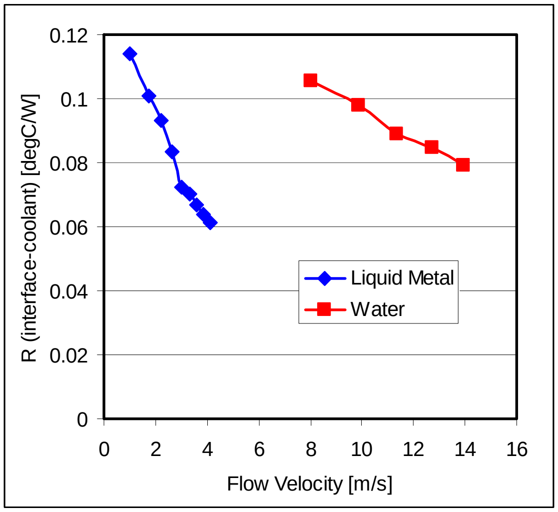

Figure 3: Thermal resistance of a test article heat sink vs. flow velocity for each water and liquid metal coolants

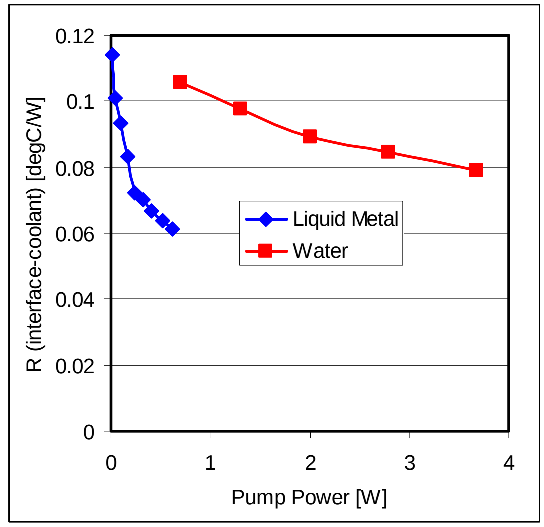

Figure 4: Thermal resistance of a test article heat sink vs. net pump power for each water and liquid metal coolants

3. ACTIVE HEAT SINK (AHS) CONCEPT

Aqwest is developing a novel class of liquid metal-based AHS for thermal management of current and future high-power density electronic / photonic devices, namely HPLD. As shown in Figure 5, the AHS uses a miniature closed and sealed flow loop of liquid metal comprising three basic regions: 1) heat extraction region adapted for mounting or thermally contacting a component (e.g., a semiconductor chip) requiring cooling; 2) heat transfer region adapted for transferring heat at reduced flux to a system heat sink, which may be a component or a fluid; and 3) a pump region containing a MHD pump for inducing the liquid metal flow. In the heat extraction region, the AHS has a thin wall separating the HPLD bar and the liquid metal flow. This feature allows for very effective removal of waste heat with very low thermal resistance.

Waste heat from the HPLD is conducted through the thin wall under the diode bar, it is acquired by the liquid metal flow, and transported to the lower portion of the AHS where it is conducted through the wall and transferred at 10 to 100 times lower heat flux to a suitable primary heat sink, which may be the environment, a primary coolant fluid, a heat pipe, or a structure. The heat transfer surface of the AHS may be adapted for contact heat transfer or it may be equipped with fins for heat transfer to a suitable fluid. Because the flow loop is very simple and smooth, the round trip pressure loss is low, which allows for a modest size MHD pump. As a result, the AHS can be configured in a compact package allowing for interfacing with existing electronics and photonics integration technologies, Figure 6.

4. AHS TESTING

AHS test articles were equipped with either 804- or 880-nm HPLD bars of various cavity lengths. Depending on the thermal interface of the heat rejection segment, the AHS test articles were either conductively cooled by a cold plate cooled by a liquid, an air-cooled heat sink, or by heat pipes, Figure 7. Some AHS test articles were directly cooled by liquid (50-50 mixture of ethylene glycol and water).

The operating temperature of HPLD junctions was inferred from the central, wavelength of the emitted light according to a known wavelength shift relationship. Thermal power dissipation in the HPLD was inferred from the diode current according to a calibrated slope efficiency relationship. Temperature of the AHS body was measured by a thermocouple. Thermal resistance of the AHS inferred from the above parameters versus MHD pump (drive) current is shown in Figure 8 for several values of diode current. Figure 9 shows the same thermal resistance versus MHD pump current for corresponding values of heat flux at the HPLD-AHS interface.

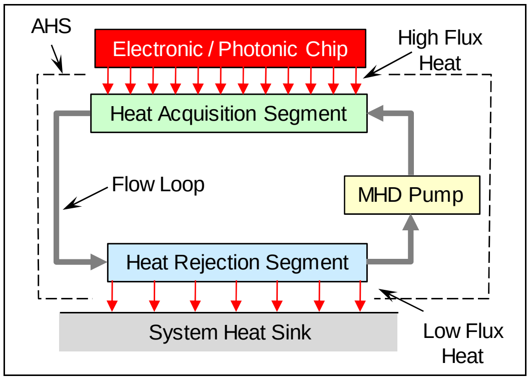

Figure 5: AHS liquid metal flow loop concept

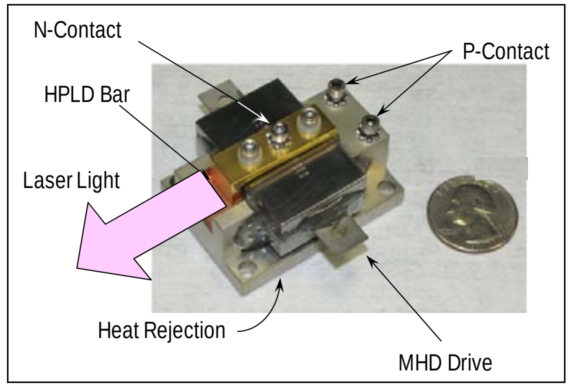

Figure 6: Exemplary AHS for cooling HPLD

Wavelength tunability of HPLD by control of the AHS current was also demonstrated. Figure 10 shows that the HPLD wavelength can be tuned over a range of about 5 nm by adjusting the AHS drive current from 0 to about 20 A. It was discovered that the HPLD bandwidth is beneficially reduced by increasing the AHS drive current. In particular, Figure 11 shows about 30% reduction in bandwidth when increasing the drive current from 0 to 35 A. This effect, which we did not observe in an HPDL cooled by microchannel heat sinks, is attributed to more uniform cooling afforded by liquid metal.

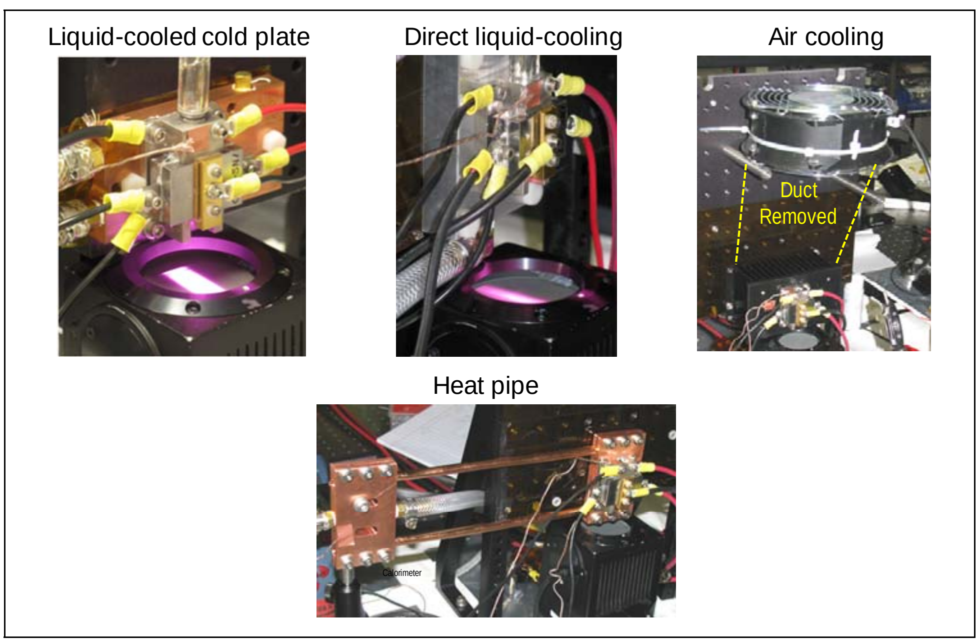

Figure 7: Configurations for testing AHS with HPLD

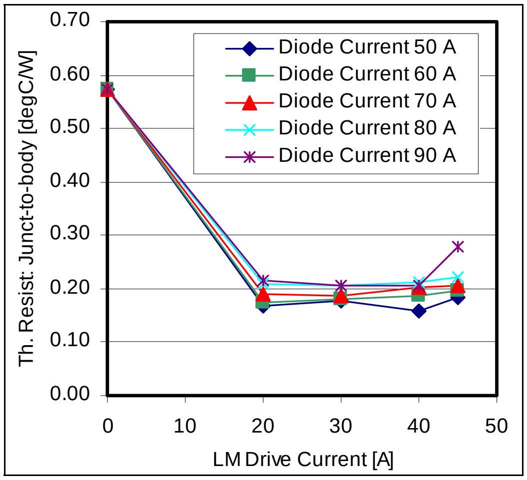

Figure 8: AHS thermal resistance vs. the liquid metal drive current for several HPLD currents

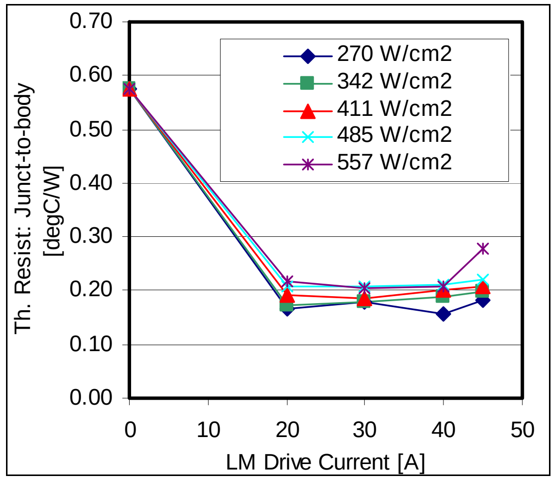

Figure 9: AHS thermal resistance vs. the liquid metal drive current for several HPLD –AHS interface heat flux values

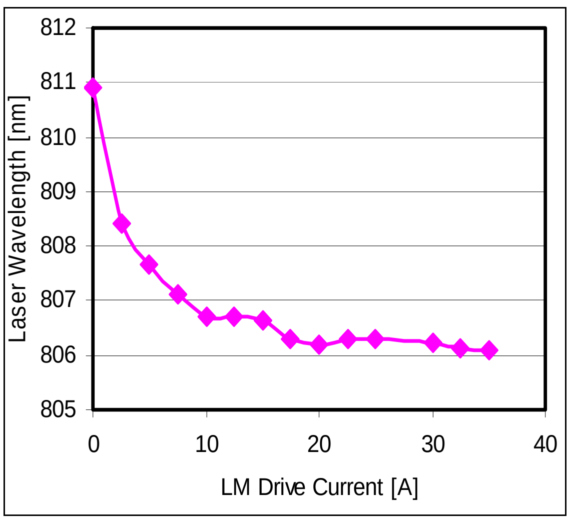

Figure 10: HPLD wavelength can be tuned over a range of about 5 nm by adjusting the AHS drive current

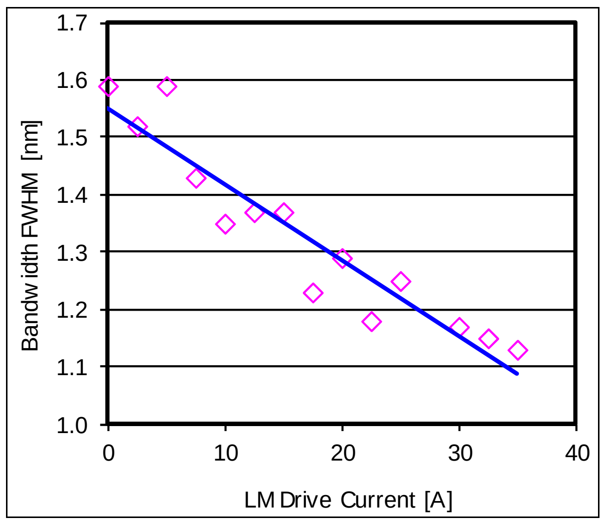

Figure 11: HPLD bandwidth is beneficially reduced by increasing the AHS drive current

6. CONCLUSION

We developed and tested an innovative liquid metal-based AHS for thermal management of HPLD. Test configurations included AHS rejecting heat to a cold plate, liquid, air-cooled heat sink, and heat pipes. Testing showed that HPLD can be advantageously cooled by a liquid metal-based AHS. HPLD wavelength tuning via control of AHS drive current was demonstrated. A beneficial reduction in the HPLD bandwidth was observed. The AHS is robust, requires very low electric power to operate, and is conducive to high-volume production.

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