A PRECISION, KINEMATIC, LOW MECHANICAL STRESS METHOD TO STACK LASER-DIODE BARS ATTACHED TO WATER COOLED HEAT-SINKS

A Thesis Presented

By

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to

The Department of Mechanical and Industrial Engineering
in partial fulfillment of the requirements for the degree of

Master of Science

in the field of

Mechanical Engineering

Northeastern University
Boston, Massachusetts

April 2015
Abstract

Laser-diode systems are moving towards higher power, higher brightness, higher efficiency, and smaller size. High power was achieved by the development of a laser-diode (LD) bar which is a monolithic component consisting of many individual emitters. The small-size requirement resulted in the invention of first a water-cooled heat-sink to remove the heat generated by the LD-bar. Subsequently, optical power was further increased by constructing a two-dimensional (2D) stack of LD-bars, each attached to a water-cooled heat-sink. In stack construction, the mechanical stress, which controls the lifetime of the LD-bar, is not controlled. Additionally, to reduce manufacturing cost, the mechanical alignment of the bars is imprecise, reducing brightness.

We present a novel, high-power stack of 20% fill-factor, 980nm, laser-diode bars, each directly attached to a copper-based, water-cooled, micro-channel heat-sink. For precision alignment, the heat-sink's surfaces are lapped to submicron variations. The external dimensions are lapped down to micron variations. For precision stacking of LD-bars attached to the heat-sinks, the heat-sinks contain mounting screws that form a kinematic mount to minimize detrimental mechanical-stress on the diode bars. There are two types of heat-sinks, each with a different screw patterns to allow stacking of the heat-sinks.

A stack of 18-bars, emitting 2.54 kW, was constructed to validate this technology. Using standard optics and a polarization multiplexer, a 320µm diameter, 0.3NA focus is achieved with a 6-bar stack that robustly couples 450W, with a ~67% coupling efficiency, from a passive, 400µm, 0.46NA double clad fiber.
Acknowledgements

This project could not have been accomplished without the help and support of my employer, Dr. Jonah Jacob, president of Science Research Laboratory (SRL). He provided encouragement, technical advice and financing to pursue this master degree in mechanical engineering. To my friends at Northeastern University and co-workers at SRL for the countless times of giving me the strength to continue when times were tough. I also thank my advisor, Dr. Gregory Kowalski, for the useful comments, remarks, and engagement through the process of writing this master thesis.
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1. Introductions

1.1 Description of Laser Diode Bar

A laser-diode bar (LD-bar) [1], as shown in Fig. 1, is a monolithic semiconductor-device, typically 10mm-wide, by approximately 100-to-150μm-thick, by 1-to-5mm deep. The depth, i.e. the spacing between the laser mirrors, is the cavity length of the LD. To control the optical output, the LD-bar is divided into numerous, individual emitters that are electrically in parallel. The anode (p-surface) of the LD-bar is usually attached to a heat-sink since the light-emitting regions, which generate several kW/cm$^2$ of heat, are located only a few microns from the anode surface. Depending on the laser-diode bar will result in different heat generation. A 0.5cm deep LD-bar with a 0.01cm width emitter, gives an area of 0.005cm$^2$; and a typical LD-bar's efficiency of 50%, a LD-bar produces an optical output power of 100W equally generates 100W of waste heat. The heat generated would be 100W divided by 0.005cm$^2$, equaling 20 kW/cm$^2$.

Figure 1. Schematic of a typical, high-power, laser-diode bar.
1.2 Properties of Laser Diode

The empirical thermal, electrical, and optical characteristics of a LD are briefly presented here in order to describe the thermal-management requirements. The basic device physics of a LD is beyond the scope of this study and the reader is referred to reference [2] for further information.

In brief, a laser consists of a medium with certain optical properties contained within an optical cavity that contains a portion of the light as shown in Fig. 2A. The medium may be a solid, liquid or a gas. The simplest optical cavity, known as a Fabry-Perot cavity, consists of two parallel mirrors that reflect any light along the optical axis back and forth within the cavity. Practically, one mirror has a high reflectivity, Mirror 1 in Fig. 2A and the other mirror has a lower reflectivity, Mirror 2 in Fig. 2A. This configuration forces the laser beam to exit the optical cavity from Mirror 2.

As illustrated in Fig. 2B, any light that is not along the optical axis walks off the mirrors after a few reflections. The optical cavity gives the laser beam a precise directionality along the optical axis that is perpendicular to the two mirrors.

![Figure 2A. Generic Fabry-Perot laser. 2B. Walk off of light not parallel to the optical axis.](image)

The required optical properties consist of four energy levels as shown in Fig. 3. Energy level 1 (E1) is the ground energy state for an electron within the medium. E2, E3 and E4 are higher energy states. Initially, the electrons in the medium are in the ground energy state, E1. Next,
the electrons are excited into a high energy state E2. The excitation may be optical or electrical in nature. The duration that an electron stays in an energy state is called the lifetime of that state. The E2 lifetime is short, typically nanoseconds, and electrons quickly drop into energy level E3 which is slightly lower in energy than E2. The E3 lifetime is long, typically milliseconds. Several things can now happen. One is that the electron returns to the ground state, E1, giving off heat, i.e. non-radiative transition. Another possibility is that the electron transitions from E3 to E4, producing a spontaneous photon, i.e. radiative transition. A third possibility is that a spontaneous photon (P1) from one atom in the medium interacts with the electron of another atom in energy state E3, resulting in stimulated emission of a photon (P2). Photons P1 and P2 are identical in energy, phase, and propagation direction. As photons are emitted spontaneously or stimulated within a Fabry-Perot cavity, the photons are forced by the cavity to propagate along the optical axis that is perpendicular to the mirrors shown in Fig. 2B. The percentage of non-radiative transitions determines the amount of heat generated by the laser. The efficiency of the laser is the amount of energy in the laser beam divided by the excitation energy.
Figure 3. Energy schematic of a four level laser.

Figure 4. Light output and voltage as a function of operating current.
Figure 4 shows the various empirical-properties of a LD. As the operating current increases, the output power and the voltage increase. As for all diodes, there is a turn-on voltage ($V_{TO}$), i.e. current does not flow until a certain voltage is reached. $V_{TO}$ is related to the wavelength of the light (L) emitted from the LD. For the 980nm LD in Fig. 4, $V_{TO}$ is ~1.35V.

There is also a turn-on current ($I_{Th}$) [threshold current], i.e. no coherent (laser) light is observed until a certain current is reached. $I_{Th}$ is related in part to the lateral emission width of the LD and the cavity length. For the 980nm LDs in Fig. 4, $I_{Th}$ is ~10A. Once $I_{Th}$ is achieved, L is proportional to current, i.e.

$$L = I \times \eta$$

where $\eta$ is the slope efficiency. (1)

However, $\eta$ depends on the LD temperature (T) through the relationship $\exp(-T/T_1)$, where $T_1$ is a constant. For sufficiently high temperature, e.g. ~130°C for the 980nm laser diodes in this study, the LD will stop functioning, i.e. stop emitting laser light.

### 1.3 Water Cooled Micro-Channel Heatsink

Optical sources based on LD-bars are useful to optically pump other solid-state lasers, such as Nd:YAG lasers, Yb-doped fiber-lasers, or as direct-energy sources [3,4]. For LD-bars operating at high power in the continuous-wave (CW) mode, the LD is generally attached to a water-cooled, micro-channel cooler (MCC) [5] as shown in Fig. 5. The MCC has a water inlet and a water outlet and corresponding water seals to prevent the water from leaking.
As discussed above, the high-power LD-bars in this study have a slope efficiency (\(\eta\)) of approximately 1W/A. These LD-bars are limited to operation at approximately 100-200W due to thermal or reliability limitations to the device performance. Thus, the operating current is in the range of 100-200A. All electrical connections need to have sufficiently high electrical-conductivity to handle such large electrical-currents.

### 1.4 Stacks of Laser Diode Bar

As shown in Fig. 6a, the LD-bars are used individually as a one-dimensional (1D) source of high optical-power or more importantly, in a stack as a two-dimensional (2D) source of high optical-power. LD-bars, each attached to a MCC, can be stacked so that the LD-bars are electrically connected in series to form a spatially-compact, 2D-array of light emitters. Referring to Fig 6b. for picture of an actual completed 2D-Vertcial Stack LD-bar assembly, and Appendix A for more references.

For solid-state laser pumping applications, the spatial location of the emitters relative to each other is not critical. However, 2D LD-bar stacks can be most useful when the optical power is coupled to an optical fiber. The efficiency of coupling optical-power from a 2D stack of LD-bars into an optical fiber depends critically on the placement and pointing accuracy of the LD-bars relative to each other as illustrated in Fig. 7
Figure 6a. Schematic of a stack of laser-diode bars.

Figure 6b. A full assembled six LD-bar precision push pull 2-D stack with cap, u-shape, and top cover. In front of each LD-bar assembly are adhered fast-axis and slow-axis micro-lenses for the first step to fiber-coupling. Again the penny is used as a scale.
1.5 Thermal Management of a Laser Diode Bar

The power-conversion efficiency (PCE) is defined as (L) divided by the electrical input-power (I x V). As shown in Fig. 8, the value of PCE is near zero for currents below \( I_{\text{Th}} \) and reaches a peak value slightly above \( I_{\text{Th}} \). After reaching a peak value, PCE decreases since the rising temperature decreases the slope efficiency.
To maintain a high value of PCE, the thermal management needs to be optimized. Presently, the best thermal management involves:

1. Water cooling since water has been found to have the best thermal properties of commonly available liquids [6], refer to Appendix B for comparison.
2. A copper-based heat-sink since copper is a metal with a high electrical-conductivity and the highest thermal-conductivity of common metals [5]. High electrical-conductivity is desirable to reduce Joule heating at the high operating-currents of high-power LD-bars, refer to Appendix C for comparison.
3. Attachment of the LD directly to the copper-based heat-sink. Any material interposed between the LD and the heat-sink reduces the LD thermal-conductivity.

1.6 Optical-Mechanical Requirements for a Laser Diode Bar Stack

LDs are small. For the LD-bars in this study, the light is emitted from multiple regions that are ~100µm wide by ~1µm high. As shown in Fig. 9, since the wavelength is ~0.98µm, approximately the same size as one of the emission dimensions, the laser beam from the LD-bar is not collimated as it is for lasers with much larger emission-apertures, e.g. HeNe lasers. Since the emission regions are highly asymmetrical (~1µm x ~100µm), the beam has significant astigmatism [5]. The full-width half-maximum (FWHM) divergence along the 10mm direction (slow axis [SA]) is ~10° whereas the FWHM divergence in the perpendicular direction (fast axis [FA]) is ~50°.
Figure 10 is an example of the optics required [7] to efficiently couple the light from a 10mm wide LD-bar into a small core, e.g. 1mm diameter, optical fiber. The optics for a single bar and a stack are shown in Fig. 11a and 11b, respectively. The design of the optics is beyond the scope of this study. The critical optical-element is the fast-axis lens that must capture the light from the LD-bar and collimate the beam along the FA. Since the light is quickly diverging along the FA, the lens must be placed close to the facet of the LD (~100µm) to capture the majority of the light. The effective focal-length of the FA lens is ~1mm. To collimate the light, the emission region is located at the focus of the lens. This geometry magnifies the image of the emitter along the FA-direction by 1000 and consequently reduce the FA-divergence by 1000, i.e. from FWHM ~50° or (436mrad) to FWHM ~ 5 x 10⁻² degrees or (0.43mrad).
Figure 10. Optics used to couple light from a laser-diode bar into a small-core optical-fiber
Figure 11a. Optics used to couple light from a stack of laser-diode bars into a small-core optical-fiber.

Figure 11b. Side view of laser-diode with fast-axis micro-lens to collimate beam along the fast-axis.

Figure 10 assumes that the LD-bar is flat, i.e. that the emitters are along a straight line. However, the LD-bar is attached to the copper-based MCC using a soldering process. The laser diode is essentially a crystal of GaAs that has a coefficient-of-expansion (CTE) of ~5.6ppm. The copper-based MCC has a CTE of ~ 17ppm. Indium, often used as the attachment solder, melts
at 156°C. At the melting temperature of the solder, the LD-bar and the heat-sink have the same dimensions. However, as the attached LD-bar cools to room temperature, the MCC shrinks ~3 times the amount as the LD-bar. The attached LD-bar at room temperature is distorted in an uncontrollable and non-reproducible manner as shown in Fig. 12.

Figure 12 presents an image of the emitters of three LD-bars attached to an MCC. The image is expanded along the FA to show the deviation from a straight line along the SA. The LD-bar “smile” is the peak-to-valley deviation of the emitters along the fast-axis due to the CTE mismatch between the LD and the MCC. Values of smile can be several tens microns but the smile must be ≤1µm for high coupling efficiency. The actual images of three LD-bars with ~1µm smile are shown in Fig. 12 using a special die attach developed to reduce smile [8]. This die attach was used for all devices in this study.

![Figure 12. "Smile" of a laser diode bar.](image)

1.7 Present Method of Stacking Laser Diode Bars Attached to Micro-Channel Coolers
The LD-bar stack was developed to address the increasing demand for optical power and optical power-density for pumping solid-state lasers. The stacking method generally used by industry has been the same since it was first presented by Hendron et al. [5]. As shown in Fig. 13, this method starts with a single assembly consisting of a LD-bar soldered to a “wafer thin”, ~1 mm thick, MCC. In reference [5], the MCC acts as the anode and as a mechanical holder for a FA micro-lens. The cathode for this assembly is a thin metal foil which is electrically insulated from the MCC. Multiple wire-bonds, attached by thermo-compression bonding, are used to electrically connect the MCC-cathode to the LD-cathode. When forming a stack, a rubber o-ring is placed as a flexible water seal between individual assemblies to channel the water from one assembly to the next.

Stacking of single bar assemblies to form a 2-D stack is illustrated in Fig. 14 which shows a clamping-manifold fixture, clamping spacer, and an alignment plate.

Hendron et al. [5] designed the stack for easy assembly as well as easy dis-assembly to replace damaged or poor performing LD-bars. This was achieved by creating a clamping manifold which bolted to an alignment block with integrated water inlet and outlet. The alignment block was precision made. Once the clamp/manifold and alignment block are together, LD-bar assemblies
are put in place with the back of the MCC cooler on the back of clamp/ manifold and left side of
the MCC cooler on the alignment block. Next, there is an integrated seal, consisting of an
anodized aluminum retainer and ethylene propylene gaskets. The retainer electrically isolates
each LD-assemblies from each other, prevents the seal from being over compressed by
absorbing any forces that is greater than the amount required, sets the LD-assembly spacing,
and holds the seals from moving during LD-stack assembly. Before the clamping bolts are
tighten, a clamping spacer is placed on top of the stack to spread mechanical forces.

Figure 14. Side view of fixture used by Hendron to stack single bar assemblies.

1.8 Summary of the Introduction and Problem Statement

A laser diode bar (LD-bar) is a linear optical source. Due to its small size, approximately 10mm
wide, by approximately 100-to-150 micron thick, by 1 to 5mm deep, the density of the heat
generated is high. The anode (p-surface) of the LD bar is usually attached to a heat-sink since
the light emitting region is where the LD-bar generates several kW/cm^2 of heat. A typical LD-
bar's efficiency of 50%, a LD-bar produces an optical output power of 60W equally generates
60W of waste heat [9]. for the LD-bar to operate at its high power conversion efficiency, the
junction temperature must be below ~60°C. LD-bars operating at high power in the continuous wave mode mostly are attached to a water cooled micro channel cooler to keep the LD bar running at high efficiency. LD-bars attached to water cooled micro channel coolers can be stacked and connected in series to form a spatially compact 2-D array of light emitters for extremely high optical output power. The present method of stacking LD-bars attached to water cooled micro channel coolers, was developed by Hendron et al.. The locations and pointing of the emitters in these stacks do not have sufficient accuracy for applications where the light from the stacks are coupled into a small optical fiber. Additionally, this stacking method applies an uncontrolled mechanical stress on the bar that may decrease device lifetime.

In this study, we present a novel method of stacking LD-bars. Each heatsink has individual push-pull screws at three locations forming a kinematic mount. The push-pull screws can be adjusted to precisely align each bar as well as control the mechanical stress on the bar.

2. **Problems with Present Stacking Method**

The prior art stack shown in Fig. 14 has many deficiencies in mechanical precision. While the stack in Fig. 14 is easy to assemble and repair, the stack assembly fixture only mechanically aligns one side edge and the back edge of each of the heatsinks. Since these heatsinks are intended for low cost, the external dimensions have standard fine machining tolerances, estimated to be ±0.0254mm. However, such tolerances are inadequate for efficient coupling of the optical power into an optical fiber.

When trying to couple laser light into an optical fiber, there are two kinds of light: the useful light is guided in the fiber core, whereas non-useful light (loss) is not guided in the fiber core. Losses can damage the fiber and by definition, reduce coupling-efficiency. As shown in Fig. 15a, light from the incident beam that does not strike the fiber core is clearly lost. In Fig. 15b, light that exceeds the numerical aperture (NA) of the fiber, even when the light is within the core,
also lost. The NA is the maximum angle for which light entering the fiber core will be guided by the core. Figure 15c illustrates useful light which incident within the fiber core and within the fiber NA.

![Diagram of fiber coupling](image)

Figure 15. Overfilling the core of a fiber (a) Overfilling the NA of a fiber (b) Ideal fiber coupling (c)

The Beam Parameter Product (BPP) is used to determine the coupling efficiency of an incident optical beam. BPP is defined as:
BPP = \( \frac{1}{2} \times D \times (NA) \)  

(2)

where "D" is the width or height of the LD-bar chip, and the "NA" is the numerical aperture. The NA characterizes the range of angles over which the system can accept or emit light. To calculate NA, the formula is:

\[ NA = n \times \sin \Theta \]  

(3)

where "n" is the index of refraction of the medium (for air \( n=1 \)), and "\( \Theta \)" is the half angle of the maximum cone of light that can enter the detector (fiber core) or exit the source (laser diode).

In the case of an optical fiber with core diameter of 200µm and NA of 0.22rad, the BPP is 22mm-mrad. Since we are using LD-bars, the beam profile emitted is a rectangle. To have the highest fiber coupling efficiency, the laser beam at the fiber core is a square with a BPP of 15.52mm-mrad on each side as shown in Fig. 16.

![Figure 16. 200um, 0.22NA fiber core with a 15.52mm-mrad square.](image)

A LD-bar emits a beam that is 10mm wide (X-direction) by ~1µm high (Y-direction). The slow axis divergence angle is ~8 degree and the fast axis divergence angle is ~50 degrees. The calculated BPP\( _X \) in the X-direction is 349.7mm-mrad and the BPP\( _Y \) in the Y-direction is 3.5mm-mrad. BPP\( _X \) greatly exceeds the BPP of the fiber and indicates that the coupling would be poor.
However, the areal $\text{BPP}_A$ of the diode is $\text{BPP}_X \times \text{BPP}_Y = 122.5 \text{ (mm-mrad)}^2$. The areal BPP of the fiber is $(\pi/4)(22\text{mm-mrad})^2 = 380\text{(mm-mrad)}^2$. Efficiently coupling can occur if the “BPP shape” of the laser beam is rearranged without changing the areal BPP.

As explain in section "Optical-mechanical Requirements for a Laser Diode Stack", a micro-lens is needed to rearranged the areal-BPP of the LD-bar beam. Using an appropriate microlens, the FA divergence is reduced from $\sim 50^\circ$ to $\sim 8^\circ$ and the SA divergence is reduced from $\sim 8^\circ$ to 8mrad. The microlensed modified beam has a $\text{BPP}_X$ of $\sim 14.25\text{mm-mrad}$ and a $\text{BPP}_Y$ of 3.45mm-mrad, resulting in a micro-lensed LD-bar that couples efficiently into the 200µm, 0.22NA optical fiber.

In a 4 LD-bar vertically stacked perfectly would have a BPP in the X-direction about 14.25mm-mrad and in the Y-direction would be 13.8 mm-mrad, with an outcome fitting in our optical fiber, and proper fiber coupling, refer to Fig. 17 for clarity.

![Figure 17. Optical Fiber Core with a 15.52mm-mrad square with 4 perfectly vertical stacked LD-Bar beams, fitting into optical fiber core](image)

However adding in the fine machining tolerances on the lensed micro-channel cooler and the o-ring retainer, estimated to be $\pm 0.001$" or $\pm 0.0254\text{mm}$. We could have a $\pm 0.0508 \text{ mm}$ lateral shifts and a $\pm 0.0508\text{"}$ longitudinal shift to the laser beam. In the worst case scenario the micro lens of 9.5mm goes to 9.551mm wide by 0.1mm goes to 0.151mm high. The calculated BPP in the X-direction would be 14.32mm-mradian, and the Y-direction would be 5.26mm-mradian. In a 4 LD-bar vertically stacked would have a BPP in the X-direction about 14.32mm-mradian and in the Y-direction would be 21.04 mm-mrad, with an outcome not fitting in our optical fiber,
leading into damage to the fiber if losses are not removed or poor fiber coupling efficiency, refer to Fig. 18 for clarity.

Figure 18. Optical Fiber Core with a 15.52 mm-mrad square with 4 vertically stacked LD-Bar beams with added in machine tolerances, not fitting into optical fiber core

Also, depending on the exact dimensions of the various parts, the stack is subject to significant mechanical errors.

The following parameters, illustrated in Fig. 19, are critical for efficient fiber coupling. These parameters are uncontrolled in the stack in Fig. 14 and are the items which our new stack improves:

- Fig. 19a: There is a large "smile", as described in "Optical-mechanical requirements for a laser diode stack", which is further increased by the uncontrolled compression of multiple LD-bar assemblies in forming the stack.
- Fig. 19b: Spacing variations (y-axis in Fig. 14) of the LD-bars.
- Fig. 19c: The relative yaw of the LD-bars (rotation about the y-axis in Fig. 14).
- Fig. 19d: Lateral shifts (x-axis in Fig. 14) of the LD-bars
- Fig. 19e: Pistoning of the LD-bars (z-axis shifts in Fig. 14)
Figure 19a. Increased Smile due to uncontrolled compression of LD-Bar Stack Assembly

Figure 19b. Relative Spacing of LD-Bar Stack Assembly

Figure 19c. Relative Yaw of LD-Bar Stack Assembly
3. **Push Pull Stack Construction and Solution**

To address the mechanical deficiencies in the present LD-bar stacking procedure, we developed a novel kinematic stacking method with significantly improved mechanical precision. We refer
to this new stacking procedure as a push-pull stack (PP-stack)

Figure 20. Comparison of push-pull heatsinks (a) with a standard micro-channel cooler (b). Alignment of the heatsinks are illustrated in (c).

The assembly of the PP-stack is illustrated in detail in Fig. 20c. The start of the PP-stack begin with the manufacturing of two distinct and precision machined water cooled heat-sinks, labeled "XX" and "YY" with laser diodes (LD) directly attached to them, see Fig. 20a for clarity. These heat-sinks have three sets of screw-holes which are designed into the heat-sink to form a kinematic mount, and all surfaces have been lapped to a micron to minimize the parameters discussed in Figures.19. For the XX-heatsink, the three sets of screw holes are (X1, X3, and X5), (X2, X4, and X6), and (X7, X8 and X9). Similarly, For the YY-heatsink, the three sets of screw holes are (Y1, Y3, and Y5), (Y2, Y4, and Y6), and (Y7, Y8, and Y9). In each group, there is one through hole for a pull screw and two tapped holes for a push screw. (X1, X2, and X7) and (Y5, Y6, and Y8) are through holes. On the "XX" heat-sink, notice the screws holes X3, X4, and X9;
and on "YY" heat-sink screw holes Y3, Y4, and Y9 are offset to prevent interference of the screws in adjacent heat-sinks.

Referring to Fig. 21a and starting with an "alignment block" bolt onto the base. The "alignment block" prevents the relative yaw, lateral shift, and pistoning of the vertical stack. Place in o-rings to the base to prevent water leakage during operation. Second, with a "XX" heat-sink, use thru holes X1, X2, and X7 place in three metal machine screws to bolt onto the base of the fixture, referring to Fig 21b; making sure the front and left side surfaces are pressed against the "alignment block", referring to Fig 21c. This step must be done for either "XX" and "YY" heat-sinks with LD. The base of the fixture becomes the electrical anode for the LD-stack.

Figure 21. Alignment Block Mounting to Base (a) Mounting of XX Heatsink to Base, Alignment Block removed for clarity (b) Contact Surfaces of Heatsink XX

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Referring to Fig. 22, after bolting on "XX" heat-sink to the base fixture to configure the stack to be in electrical series we need to place in nonconductive ceramic pads and ceramic o-ring retainer. These nonconductive ceramic pads are place on top surface of "XX" heat-sink where the metal push screws on "YY" heat-sink would contact, preventing any electrical shorting to the LD. As for the ceramic o-ring retainer, prevents the o-rings from shifting during stacking. The o-rings in this stack prevent water leaking out during operation.

Referring to Fig. 23a, then with a "YY" marked heat-sink place push screws, generally set screws, in Y3, Y4, and Y9 and pull screws in Y5, Y6, and Y8, slotted ceramic cap screws
Figure 23. Mounting of YY Heatsink to Base, Alignment Block removed for clarity (a) Contact Surfaces of Heatsink YY (b)

The pulls screws in heat-sink "YY" will then mate with X5, X6, and X8 bring the two cooler together and the push screws in heat-sink "YY" separate the two cooler. Manipulating the push and pull screws can carefully lower the "YY" heat-sink on top of the "XX" heat-sink cooler LD to reduce the stress and smile.

Referring to Fig. 24, after lowering "YY" heat-sink on to "XX" heat-sink to configure the stack to be in electrical series we need to place in nonconductive ceramic pads and ceramic o-ring retainer. These nonconductive ceramic pads are place on top surface of "YY" heat-sink where the metal push screws on "XX" heat-sink would contact, preventing any electrical shorting to the LD. As for the ceramic o-ring retainer, prevents the o-rings from shifting during stacking. The o-rings in this stack prevent water leaking out during operation.
Referring to Fig. 25a, taking a "XX" marked heat-sink place push screws, generally metal set screws in X3, X4, and X9 and pull screws in X1, X2, and X7, ceramic screws. Ceramic screw provides electrical isolation from one heatsink to another, so as not to electrically shorted the LD.

Figure 25. Mounting of XX Heatsink to Base, Alignment Block removed for clarity (a) Contact Surfaces of Heatsink XX (b)
The pull screws will mate with Y1, Y2, and Y7 bring the two coolers together and the push screws in the heat-sink "XX" will separate the two coolers. Again manipulate the push and pull screws to slowly lower the "XX" heat-sink on top of the "YY" heat-sink cooler LD to reduce the stress and smile.

This novel stacking method, each heat-sink is mechanically coupled to the two adjacent heat sinks in a controlled and reproducible fashion.

Referring to Fig. 26, after the stack has been completed, the alignment block is removed and the water inlet and outlet of the stack needs to be capped. The cap used is fitted with o-rings to seal the water inlet and outlet and a plastic shoulder washer to center the bolt, preventing the metal screw from contacting the heat-sinks, which will cause a short to the stack.

![Figure 26](image)

Referring to Fig. 27, next, the U-shape will be bolted onto the base. The U-shape will be the cathode for the electrical connection. Using polyimde tape on the bottom (not shown for clarity) and four nylon shoulder washers on top to isolate the U-shape from the base; four machine screws are use to fasten the U-shape to the base.
Referring to Fig. 28, lastly, the top cover is used to complete the assembly. The top cover has the same push pull setup as the heat-sink, three sets of screw-holes which are designed into the cover to form a kinematic mount, with a cut out larger than the cap to prevent any electrical connection. Manipulate the push and pull screws to slowly lower the cover on the top heat-sinks LD bar to complete the electrical series for the push pull stack.
4. **Precision Push Pull stack Results**

The most common way to measure a "smile" on a LD-bar or on a vertical LD-bar stack is to have the assembly micro-lensed. As the assembly is being operated under power, the micro-lensed process allows for far-field images and near field images. The near field image can clearly give the "smile" of each LD-bar in the vertical stack assembly, see Fig. 29 for clarity.

Figure 29. Near-field image of 10-Emitter with very good "smile"
However, in our case for a quick and precise measurement on "smile" without micro-lensing our vertical push pull stack we set up a camera system, Fig. 30. Using a 10X high magnification camera with a 51mm focal length going thru a 25mm diameter lens with a pure green light emitting diode at 555nm for illumination, we can calculate smallest resolvable feature thru the camera, also known as diffraction limit:

$$\text{diffraction limit} = (2.44\lambda/D)\times L$$

(4)

where $\lambda$ is the wavelength of the light emitting diode, $D$ is the diameter of the lens, and $L$ is the focal length; the calculated diffraction limit equals to 2.7 microns. So with three measurements at each emitter on the LD-bar and taking the average, we can measure down to a micron by the "smile" of the precision, kinematic stack from one LD-assembly to the next. The camera system was placed on a precision three axis stage, set up by a colleague of mine, Steve Fulgum, see Fig. 30 for camera system.

Figure 30. SRL’s Camera system to measure LD-bar Stack Assembly
4.1 Results:

Stack 16, a 6 LD-Bar Assembly

Stack 16 was a six LD-bar vertical stack assembly. From the bottom up, started with LD-bar assembly CLF255-M32-007, CLF245-M32-009, CLF255-M32-006, CLF245-M32-010, CLF255-M32-005, and the top LD-bar assembly was CLF245-M32-005. Referring to Fig. 30 below, the "red" box represents if the stack was acceptable or not.

Figure 30. Stack 16, Red Box represents if Stack was acceptable
The red box starts at emitter one and ends at emitter nineteen on a 10mm long 20% fill factor bar (total of nineteen emitters). Clearly CLF245-M32-009 would not be acceptable for fiber coupling; however with one out of the six not passing, Stack 16 would be adequate for micro-lensing and used for fiber coupling.

Stack 20 was a six LD-bar vertical stack assembly. From the bottom up, started with LD-bar assembly CLF255-M34-011, CLF245-M34-020, CLF255-M34-012, CLF245-M34-012, CLF255-M34-013, and the top LD-bar assembly was CLF245-M34-011. Refering to Fig. 31 below, the "red" box represents if the stack was acceptable or not.
Reviewing the results on Stack 20, CLF245-M34-011 borders on the edge of ±1 micron tolerance, but would be acceptable. Stack 20 would be a good case for micro-lensing and for use of fiber coupling.
Stack 21, a 7 LD-Bar Assembly

Stack 21 was a seven LD-bar vertical stack assembly. From the bottom up, started with LD-bar assembly CLF255-M34-014, CLF245-M34-014, CLF255-M34-018, CLF245-M34-018, CLF255-M34-021, CLF245-M34-012 and the top LD-bar assembly was CLF255-M34-019. Refering to Fig. 32 below, the "red" box represents if the stack was acceptable or not.
Reviewing the results on Stack 21, CLF255-M34-018 and CLF255-M34-019 borders on the edge of ±1 micron tolerance, but would be acceptable. Stack 21 would be a good case for microlensing and for use of fiber coupling.

Stack 23, a 6 LD-Bar Assembly

Stack 23 was a six LD-bar vertical stack assembly. From the bottom up, started with LD-bar assembly CLF245-M35-025, CLF255-M35-024, CLF245-M35-027, CLF255-M35-028, CLF245-M35-029, and the top LD-bar assembly was CLF255-M35-032. Refering to Fig. 33 below, the "red" box represents if the stack was acceptable or not.
Figure 33.

Reviewing the results on Stack 23, would be a good case for microlensing and for use of fiber coupling.

Stack 26, a 6 LD-Bar Assembly
Stack 26 was a six LD-bar vertical stack assembly. From the bottom up, started with LD-bar assembly CLF245-M36-014, CLF255-M36-027, CLF245-M36-012, CLF255-M36-026, CLF245-M36-029, and the top LD-bar assembly was CLF255-M36-032. Refering to Fig. 34 below, the "red" box represents if the stack was acceptable or not.

![Figure 34.](image)

Reviewing the results on Stack 26, CLF255-M36-032 borders on the edge of ±1 micron tolerance, but would be acceptable. However, CLF245-M36-014 would be unacceptable. Stack 26 similar to stack 20 having one out of the six not pass, would be okay case for micro-lensing and for use of fiber coupling.

5. **Summary/Conclusion**

We report, for the first time, double-side cooling of laser-diode bars in a water-cooled stack-format using a novel kinematic stacking procedure. Using 976nm, 20% fill-factor, 5mm cavity-length, laser-diode bars, operated at 20°C, we demonstrate
• a collimated 18-bar stack with more than 2.5kW @ 145A and residual divergences of 4.8mrad x 44mrad (95% power containment angle). Since the residual divergences of a collimated single bar is only 3.9mrad x 43mrad (95% power containment angle), the results of the 18-bar stack validate the LD-bar, the ELF heat-sink, and both the stacking and collimation procedures.

• an extrapolated lifetime of stacks, assembled with this novel kinematic procedure, that exceed 10khrs for 140A, 20°C operation.

• 450W coupled from 400µm, 0.46NA double-clad fiber using a 6-bar stack with an ~67% coupling efficiency.

6. References


Appendix A: Precision Push Pull Stack Pictures
An eight LD-bar precision push pull stack complete with the alignment block removed, and the water inlet and outlet of the stack capped. The penny in the picture is used as a scale and to show how well the precision push pull stack was assembled. If the stack was mis-aligned in anyway as discuss in Figure 19, the reflected image off the micro-channel coolers would be distorted.

An eighteen LD-bar precision push pull stack complete with the alignment block removed, and the water inlet and outlet of the stack capped.

Photograph of 18-bar push-pull stack with applied bias. The 980nm emission is not visible to the human eye but can be imaged with an electronic camera containing a silicon CCD imager.
This is also known as "electro luminous". When a LD-bar is operating under the threshold current, and has been assembled properly, it will emit a light (electro-luminous); if assembled improperly, the LD-bar will not emit a light, meaning the LD-bar assembly is "shorted" or damaged.

*Appendix B: Comparison of Heat Transfer Rates of Liquid Coolants*
### Material Selection Requires Tradeoffs of Several Important Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/mK)</th>
<th>Young's Modulus (PSI)</th>
<th>Tensile Strength (PSI)</th>
<th>Coefficient of Thermal Expansion (1/deg C)</th>
<th>Machinability</th>
<th>Raw Material Cost</th>
<th>Toxicity</th>
<th>Electrical Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFHC Copper</td>
<td>391</td>
<td>$17 \times 10^6$</td>
<td>32-35000</td>
<td>$17.6 \times 10^6$</td>
<td>Poor</td>
<td>Low</td>
<td>No</td>
<td>Low</td>
</tr>
<tr>
<td>Zirconium Copper</td>
<td>367</td>
<td>$17 \times 10^6$</td>
<td>49-68000</td>
<td>$17.6 \times 10^6$</td>
<td>Poor</td>
<td>Low</td>
<td>No</td>
<td>Low</td>
</tr>
<tr>
<td>Beryllium Oxide</td>
<td>250</td>
<td>$50 \times 10^6$</td>
<td>34000</td>
<td>$9.0 \times 10^6$</td>
<td>Good</td>
<td>High</td>
<td>Yes</td>
<td>High</td>
</tr>
<tr>
<td>75% W Cu (Elkonite)</td>
<td>190</td>
<td>$34 \times 10^6$</td>
<td>100000</td>
<td>$9.1 \times 10^6$</td>
<td>Poor</td>
<td>High</td>
<td>No</td>
<td>Low</td>
</tr>
<tr>
<td>Beryllium Oxide</td>
<td>159</td>
<td>$41 \times 10^6$</td>
<td>60-90000</td>
<td>$11.4 \times 10^6$</td>
<td>Good</td>
<td>High</td>
<td>Yes</td>
<td>Low</td>
</tr>
<tr>
<td>Silicon</td>
<td>140</td>
<td>$16 \times 10^6$</td>
<td>90000</td>
<td>$2.5 \times 10^6$</td>
<td>Good</td>
<td>Low</td>
<td>No</td>
<td>Semi-Conductor</td>
</tr>
</tbody>
</table>

GaAs: $6.9 \times 10^{-6}$
Close up view of the Dino-Lite Digital Microscope and the Precision Push Pull Stack with Alignment block.