

**MATERIALS ISSUES AND ENGINEERING DESIGN CONSIDERATIONS FOR
DEVICE PACKAGING OF HIGH POWER EDGE EMITTING
SEMICONDUCTOR LASER ARRAYS AND MONOLITHIC STACKED LASER
DIODE BARS**

Technical Report

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MATERIALS ISSUES AND DESIGN CONSIDERATIONS FOR DEVICE PACKAGING OF HIGH POWER EDGE EMITTING SEMICONDUCTOR LASER ARRAYS AND MONOLITHIC STACKED LASER DIODE BARS

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Abstract

This technical report examines the unique design constraints, materials selection and performance demands encountered in device packaging of high power edge emitter linear laser bars and stacked laser arrays with hundreds of Watts optical power output. We describe the materials technology that forms the basis of new packaging designs and mounting constraints for these devices. Increased demands for device reliability and high power output make it necessary to use novel packaging and mounting methods including advanced materials and structures for thermal dissipation of high heat loads during operation in harsh CW/pulsed time regimes and environments. Thermal performance challenges are mitigated by using such novel materials as Copper-Tungsten heat sinks; CVD diamond and Boron Nitride heat spreaders. The use of die bonding methods for attachment of laser bars using fluxless Gold-Tin solders is examined. Packaging and materials engineering issues are examined when linear bars are integrated into “cigarette-pack” modules producing 600 Watts. Device packaging, reliability issues and component constraints in this regime become truly challenging but are mitigated by using actively cooled copper and silicon microchannel heat sinks. The device integration and mounting of linear arrays on microchannel cooled packages to produce high reliability devices is outlined.

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1. Introduction: Laser Diode Array Technology and Applications of semiconductor laser arrays

Laser Diode Array Technology is based upon AlGaAs diode laser structures that are grown by MOCVD or MBE processes in a wide variety of waveguide structures. Devices have been developed with a wide variety of wavelengths ranging from 630 nm to 2000 nm for a myriad of applications; laser diode arrays find widespread use in biomedical laser systems, laser based systems for materials processing, optical pumping of solid state lasers, military communications and tactical systems as well as telecommunications applications. Laser Diode Arrays are operated in various temporal modes; Continuous Wave (CW) laser diode arrays are utilized in CW laser systems – either direct diode laser based or indirectly used in CW diode pumped laser systems and in moderate to high repetition rate (10 kHz to 100 kHz pulse repetition frequency or PRF) diode pumped laser systems across a wide range of wavelengths. The same diode laser array structure can be run in pulsed or Quasi-Continuous Wave (QCW) mode with partial duty cycles that can range from sub 1% to 50%; as an example, if a linear laser diode array is operated with 60 Watts peak optical power, the same array run at 400 microseconds pulse lengths at 100 Hz pulse repetition rate (4% duty cycle), operates with 2.4 Watts average power. The same array operated at 400 microseconds pulse length and at 1000 Hz PRF (40% duty cycle) delivers 24 Watts of average power.

In materials processing applications such as Drilling, diode laser arrays find indirect use as pump lasers for diode pumped lasers produce UV 266 and UV 355 nm output; these utilize 20-50 Watt laser diode linear bars and arrays operating in CW mode. In direct Laser Welding and Joining applications, High brightness CW 20-50 Watt linear

diode array bars that are beam shaped and can be polarization multiplexed and wavelength multiplexed have been built to produce tens of Watts multi-wavelength optical power focused down to high power densities for welding of aluminum and stainless steel. In Cutting applications, UV and green and infrared Q-switched lasers that are diode pumped use pulsed or CW laser diode linear bars and stacks; these lasers operate at either high energy, short pulse regimes for photoablation or in lower pulse energy, high average power, high pulse repetition rates for precise cutting and scribing applications.

In complete turn-key laser systems, such as used for scientific, remote sensing and spectroscopy applications, laser diode arrays are used as optical pump sources for Nd: YAG, Nd: YLF, Nd: Glass and a wide variety of solid state laser systems. For diode pumping applications in solid state laser design, laser diode arrays or linear diode bars are currently available at the low end of the power spectrum from 1-5 Watts of CW power; laser diodes linear bars that are 1-2 cm linear width dimensions are also capable of producing between 5-50 Watts with multiple incoherent emitter structures in moderate power applications. As discussed subsequently in this report, higher power linear diode arrays have been built for operation in the 100-250 Watt range by fabricating dense fill factor linear bars.

Diode Laser Array technology also finds ready utilization in Military, Aerospace, Space-Qualified and Laser Communications systems. High power all solid state lasers that are diode pumped for space-qualified and air-borne qualified laser ranging, direct laser communications platforms as well as remote sensing of trace-gas concentrations and pollutants all utilize high power laser diode arrays in both CW and pulsed mode,

depending upon the time scales of the laser output desired. In CW or low energy, high repetition rate laser systems, CW laser diode arrays are utilized; in high energy, short pulse length laser systems, pulsed or QCW laser diode arrays are used.

One of the most critical application areas for use of laser diode array technology has been the use of laser systems for Biomedical surgical applications. Biomedical applications of laser diode array technology range from Infrared diode pumped lasers for photoablation (using QCW diode laser arrays for high energy, short pulse laser systems); frequency doubled visible lasers (using both CW and QCW diode laser arrays) as well as direct diode laser applications (using both CW and QCW laser arrays) for photocoagulation and photodynamic therapy especially at visible wavelengths between 630 and 980 nm. All of these medical applications utilize high power linear diode laser arrays and bars in either free space application mode or in fiber coupled laser bars that are coupled to electro-optical and fiber-optic systems for beam delivery to the target area of the human body.

2. Device and package design of laser diode arrays

Monolithic and linear laser diode bars and arrays are small sized laser structures with high current and optical power density at the emitting facets. They typically consist of 1 centimeter array length (although longer array lengths with larger numbers of emitters have been developed as well) with anywhere from 19 to 25 emitters (low and moderate power) and between 25-70 emitters (high power) arranged in linear fashion along the length of the laser bar; The emitter size typically encountered is 100-150 microns wide and 1 micron high; the emitter spacing center-to-center along the length of the bar is 500 microns to achieve a uniform fill-factor along the length of the bar[Sakamoto, Bhatia].

The output power can range from a moderate/low value of 5 Watts CW to as high as 70-80 Watts CW [Sakamoto, Bhatia] from a linear diode array or bar; still higher output powers have been reported between 100 Watts [He] to the highest of 270 Watts [Mikulla] from a linear diode array using optimized thermal dissipation technology and highly efficient materials for heat transfer.

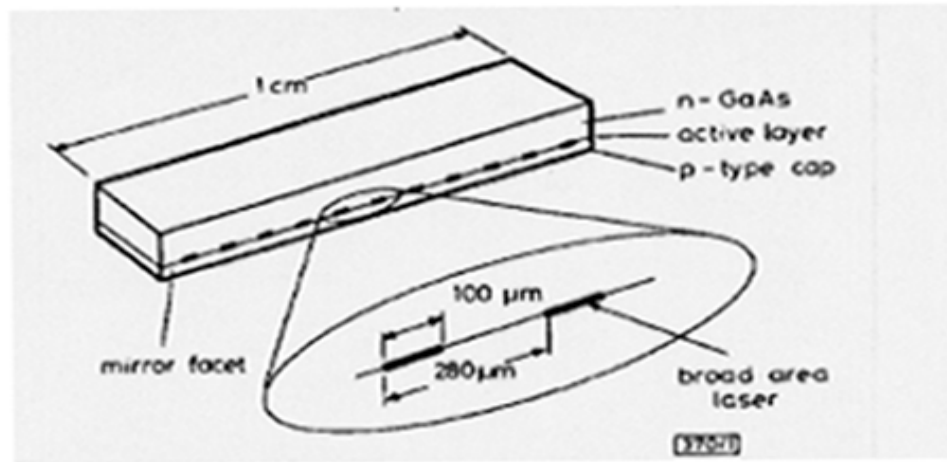


Figure 1: Typical laser diode linear array architecture showing linearly arranged high power individual emitters arranged along the width of a 10 mm bar. Bar width is not a limitation; in high packing density/fill factor arrays, upto 20 mm wide bars have been fabricated. [Sakamoto]

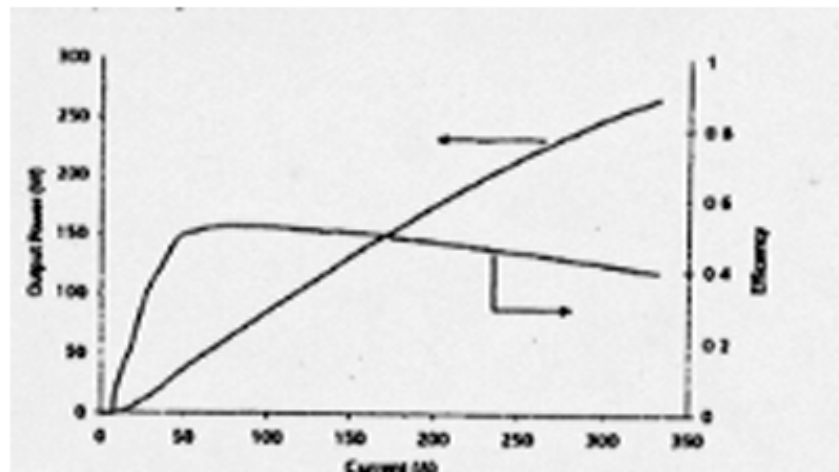


Figure 2: Recent record high power from a semiconductor linear diode laser array; the output power was 267 Watts with over 50% electrical to optical conversion efficiency [Mikulla]

The Electrical to optical efficiency of laser diode arrays is high (up to 50% of the electrical input can be converted to optical output) [Treusch]. Even so, with 20-60 Watts (say an average of 40 Watts per bar; and using a 40% efficiency figure, the typical compliance voltage is 2 V and drive currents are 50 Amps thereby requiring 100 Watts of electrical input. Of this, 40 Watts optical output is produced thereby generating 60 Watts of heat load to be dissipated [Bhatia]. As can be seen from the above “back-of-the-envelope” systems efficiency calculation performed for illustrative purposes, laser diode arrays generate highly intense and quite localized thermal loads that need to be dissipated.

As can be expected, the optical performance characteristics of laser diode bars and arrays as well as power output and reliability are highly dependent upon operating temperature. Matters are yet more complicated due to the demands of higher average power. For example, in the case of a typical operation of a multi-bar pulsed diode laser array or “sub-system”, assuming a 3 bar diode array stack (vertically integrated diode bars in a contiguous package) and 60 Watts per bar, 400 microsecond pulse width; the peak optical power is 180 Watts; at a typically used 30 Hz repetition rate for military systems; this means an average power of only 0.2 Watts. As repetition rate (Pulse Repetition Frequency or PRF) is increased in laser systems typically operated even at moderate 2 kHz, such as those used for industrial materials processing, the duty cycle becomes 80% and the average power increases dramatically to 144 Watts.

As device degradation occurs, due either to long term ageing effects or thermally induced degradation mechanisms arise, the thermal resistance of the laser diode structure as well as the complete laser diode module and heat sink changes; degradation

mechanisms also affect the over-all conversion efficiency from electrical to optical output (it takes higher drive currents and higher compliance voltages to keep producing the same output optical power as the device ages and undergoes thermal degradation). In addition, the shift of the optical spectrum to the longer (redder) wavelengths takes place and is particularly indicative of thermal degradation mechanisms [Harnagel, Bhatia].

In linear diode arrays with moderate to dense fill factors (higher number of laser emitters per same length of bar, packed closely together) laser arrays, these thermal degradation issues can be alleviated by enabling low interface thermal impedance between the laser array junctions and passive (heatsink) or active coolant (liquid cooling).

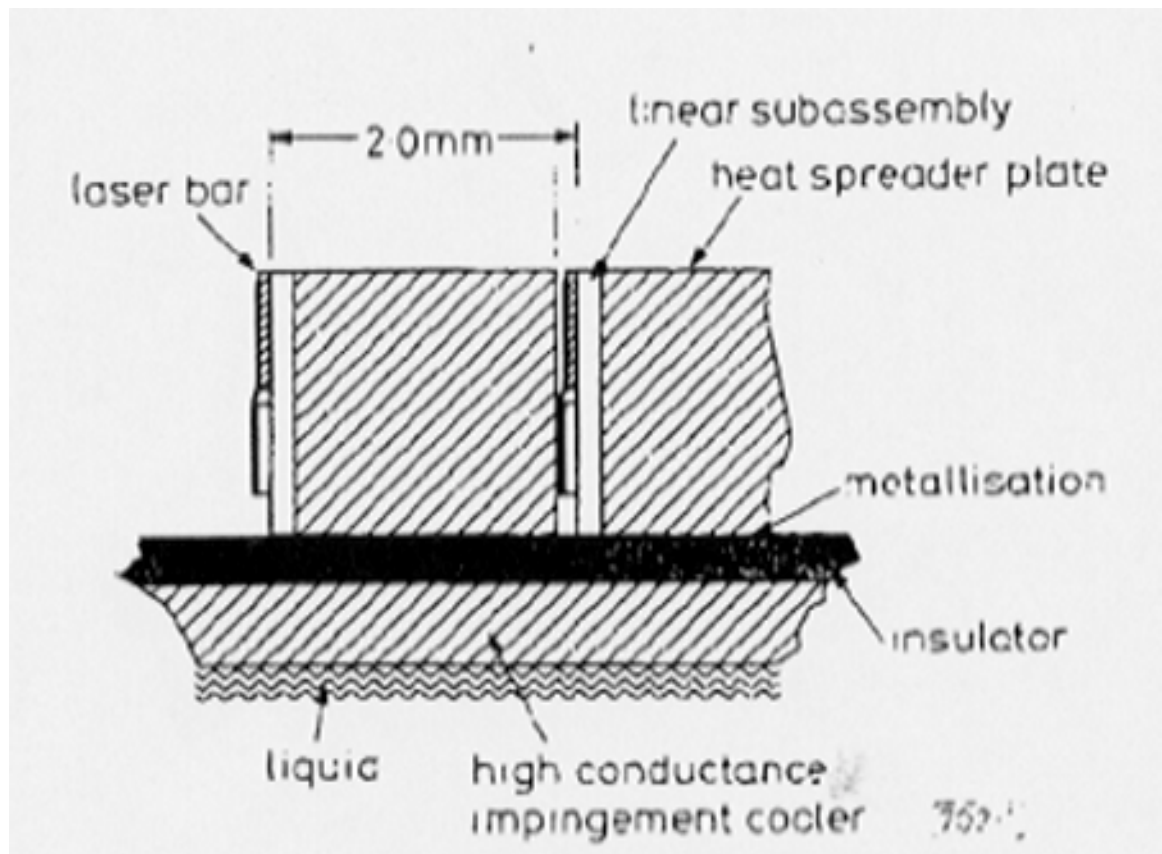


Figure 3: Laser Diode Array sub-assembly as part of a monolithic stacked array; vertical pitch of the laser arrays within the 2-D array is 2 mm. [Harnagel]

Figure 3 illustrates a typical laser array structure fabricated by Harnagel et al. In this design, laser diode arrays have been mounted onto a laser sub-assembly which are spaced 2 mm apart (vertical pitch) and have an interface of heat spreader plates inserted between them. The heat spreader plates, typically BeO, dissipate the thermal load from the laser arrays and can be used for heat storage in the “off” cycles during the partial duty cycle operation.

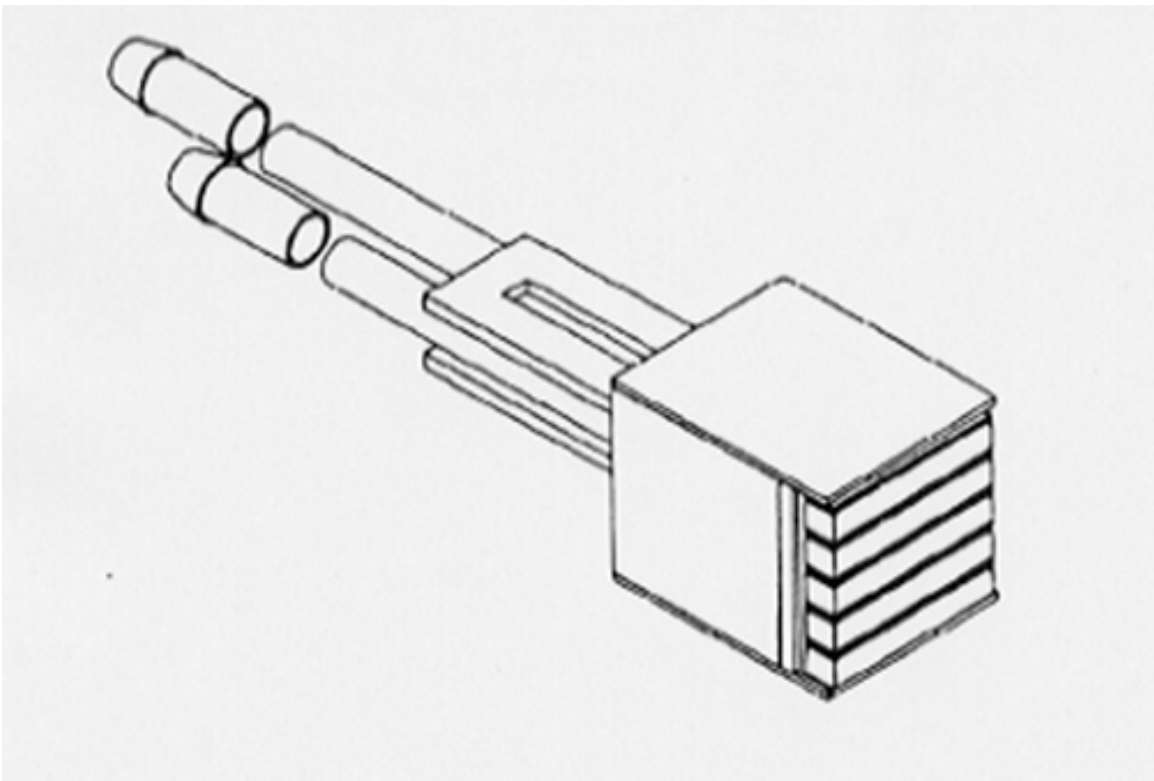


Figure 4: Compact, integrated laser diode array package showing the cooling lines and electrical interconnections; [Harnagel]

3. Customer operating requirements for Laser Diode Arrays:

The Price per Watt needs to remain low for most laser diode array applications; for example, the cost of a 50 Watt bar in 1998 was \$2000; \$40/Watt; today that same bar of

the same package and chip quality and reliability can be purchased for \$1000; ie \$20/Watt; in 5 years time, the price has had to decrease to \$20/Watt from \$40/Watt[Endriz, Bhatia]. At the same time, the power output requirements per bar keep increasing; also the push to have the same device lifetimes as well as device and package reliability keeps increasing.

With regards to output power requirements, since most laser system applications now utilize novel wavelengths as well as higher operating power at the fundamental wavelengths, the corresponding laser diode array output power requirements keep increasing, especially for materials processing, scientific, telecommunications and aerospace/military applications. High operating power is also required for biomedical surgical applications and as pump sources for high power laser systems. As an example, in the 1995 time-frame, customers expected 20 Watts CW from a linear 10 mm bar; by 2000, that had increased to 50 Watts per bar and in 2003 has climbed on to 70-80 Watts per bar from a linear 10 mm array[Bhatia]. In addition, for some applications, more compact or higher density fill-factors are utilized; this serves to exacerbate the already dramatic thermal load dissipation challenges.

As the output power needs and price per Watt pressures have grown to be more demanding, the need for high reliability on the other hand has remained steady and indeed has become more stringent as well. This is especially true in high power manufacturing applications such as laser based materials processing and laser based thermal plate printing applications, where a single device failure can shut down a production/manufacturing operation virtually for days. Reliability requirements for other demanding applications such as for aerospace/military/space-qualified instruments and

hardware are even more stringent with device lifetimes for CW laser diode arrays running into thousands of hours of continuous operation; in pulsed mode, these devices are expected to provide output power without degradation for more than one billion shots.

Enhanced expectations of Device and Package lifetimes have also accompanied increased utilization of laser diode arrays in systems design and direct applications. In the 1995-96 time-frame, device lifetimes were expected to be about 5000 hours. In the 2000 time-frame, the same device was expected to last 10,000 hours. Moreover, in the 2003 time-frame, the same waveguide based device structure and overall device package is expected to last 10,000 plus hours with almost a 25% increase in output power from the 50 Watt output power level. [Bhatia]. The same type of diode laser array device structure when operated in 60-100 Watts peak power and in Quasi-CW (pulsed) mode for military and space-qualified operation is expected to provide up to 2 billion shots. [Kraniak]

4. Operating Parameters & Thermal Management of laser diode arrays

a. Typical operating parameters

P_{out}; output power: As outlined above, the typical output powers for CW laser diode arrays or linear bars lie between 5 to 10 Watts for low power applications; Moderate power applications require 10-30 Watts from the laser diode bar in CW mode. Mid-power applications such as pumping of solid state laser systems typically require between 35 to 70 Watts of optical output power. In the author's experience, most pulsed (Quasi-CW) laser diode arrays are operated at the 60 Watts per bar peak power level; higher power versions of these devices can be fabricated by vertical integration or stacking of linear 60 Watt peak power bars with intermediate thermal spacers up to 10 bars within the stack (600 Watts peak). Yet higher array packing densities have been

fabricated for materials processing applications as well and have operated reliably up to several kilowatts of optical output power. As described above, in Quasi-CW mode, these devices are operated with partial duty cycles (dependent upon the pulse width and pulse repetition frequency) of between 1 and 50%

Spectral characteristics: The spectral characteristics of laser diode arrays whether operated in CW or Quasi-CW mode consist of a wide multi-mode laser diode spectrum with several tens to hundreds of individual lasing modes since the device structure essentially consists of individual laser emitters, each with its own gain bandwidth which is quite broad to begin with since the device is a semiconductor quantum well. Typical spectral characteristics include operation at 630-670 nm for the AlGaInP material system; 770-900 nm for the AlGaAs material system; 905-1050 nm for the InGaAs material system. These are the most commonly encountered devices for commercial and industrial applications although other devices are possible in the 1100-2000 nm range as well.

Spectral line-width: The spectral linewidth of the optical output is measured at the 50% points and is generally several nanometers wide. An indication of device ageing as well as thermal degradation generally is the widening of the emission spectrum as a function of device lifetime. The spectral linewidth is also increased as the duty cycle in pulsed laser diode arrays is increased. For example, a 5 bar stacked array with 300 Watts peak optical power exhibited a 2.9 nm linewidth operating at a 1% duty cycle; the same device exhibited a 3.6 nm linewidth when operated at a duty cycle of 8% [Bhatia].

Temperature tuning: Laser Diode array output optical spectra can be tuned or shifted to a desired emission spectrum or peak wavelength. The temperature tuning characteristics of AlGaAs upon GaAs materials are 0.3 nm of tuning for every 1 degree C

of temperature increase. This tuning characteristic is seen in laser diode arrays and two dimensional diode array stacks in AlGaAs between 750 – 900 nm lasers; in InGaAs laser diode materials, approximately the same characteristic tuning range holds between 900-1100 nm devices.

Laser Diode Array LIV Curves: The LIV curves typically depict the compliance voltage range as well as the laser diode drive current and optical output power of the device. The LIV curves are typically utilized to observe the onset of lasing threshold as well as any explicit kink regions where a roll-off of laser output power is observed as a function of increasing drive current.

Laser Diode Array Kink Free Power: Kink free power refers to the region in the output power curves where a linear dependence of output optical power is seen with increasing diode drive current; when there is a roll-off in output optical power (output optical power saturates and does not increase linearly as laser drive current is increased), this indicates a region with “kinks”. It is preferred to operate in the kink free region due to the unpredictability of roll over characteristics as well as a preference on the part of laser systems designers to operate with extra current margin below the kink region for increases in drive current experienced as the device ages over a period of time.

b. Mounting considerations to achieve operating parameters

Typical mounting methods for laser diode linear arrays and bars utilize the laser diode bars or laser chips with intermediate spacers that are thermally conductive as well as can provide electrical conduction. These are mounted on a high thermal conductivity heat spreader or heat sink that is electrically insulating. The heat sink in turn can be mounted on either a passive surface or actively cooled with air flow or liquid cooling.

The mounting method utilized for the laser bar is junction side or p-side down on the heat sink; the diode array bar is then metallized and is mounted in contact with the thermally conductive spacer. Wire bonding is performed on one side of the diode bar; the other side is soldered to the heat sink. The critical characteristic for high reliability and high power operation of laser diode arrays is the need for a low thermal resistance between the laser gain material (AlGaAs quantum well on a GaAs substrate). This in turn requires an excellent Coefficient of Thermal Expansion (CTE) matching between the GaAs substrate of the laser chip or array and the material of the heat spreader or heat sink.

The critical parameter that indicates high efficiency thermal management is the Junction temperature; this can be calculated using the thermal resistance values usually estimated at the center of the laser bar or array. As an example, in devices fabricated in the early 1990s by [Sakamoto]; for a heat sink thermal impedance estimated at the array center of 0.8 Watts per degrees C, the Junction temperature is calculated to be 54 degrees C for 25 degrees C ambient or heat sink temperature; the same junction temperature undergoes a dramatic increase to 120 degrees C when the heat sink is kept at an ambient temperature of 70 degrees C. This illustrates the challenge posed by the dramatic increase in laser bar/array junction temperature and the need to have the overall device package thermally stabilized for use in practical application environments.

c. Current mounting techniques:

- i. 5-50 Watt and 50-100 Watts CW laser diode bar mounting on passively cooled Copper heat sinks

The higher power versions of monolithic linear diode bars and arrays within the 5-50 Watts range are all mounted on Tungsten-Copper submounts to conductive copper

heatsinks. These typically contain 19 to 25 emitters each with an aperture size range of 100-150 microns. As an example of the mismatch of the Coefficient of Thermal Expansion (CTE), for the material of the laser diode arrays, Gallium Arsenide (GaAs); the CTE is 5.8 ppm/degree K. The CTE of copper, commonly used as a heat sink material is 17.8 ppm/degree K. There is thus a high degree of mismatch between GaAs and Copper. Soft solders are commonly used in current technology (including the Eutectic Pb-Sn or Indium based solders). The migration of solder into the laser chip structure leading to catastrophic failure as well as whisker generation at the bond lead to long term reliability concerns

Higher power laser arrays operating at the 50-75 Watts level are typically mounted junction side down on a standard submount which typically consists of copper metallized with Nickel and Gold layers; the other alternative is to mount the array on a heat spreader (BeO was used in earlier devices) that acts as an intermediate carriage between the laser array and the copper submount. BeO has been superseded by the use of diamond and silicon heat spreaders. The typical mounting and array packaging architecture used for the heat spreader and the Copper submount is described below in Table I[from Puchert, R et al; 1997 Electronic Components and Technology Conference]. The Copper heat sink or mount used was 10 mm x 20 mm x 6 mm high; the heat spreaders used were 500 microns x 500 microns x 300 microns.

Component	Thickness in microns	Thermal Conductivity; W/mK	Density	Heat Capacity J/(Kg*K)
Laser Diode Bar mounted on a Copper Heat sink without Heat spreader				
Solder	10 microns	25.5	7300	235
Submount/Carriage	6000	384	8940	383
Laser Diode Array on Copper Heat Sink with intervening Diamond Heat Spreader				
Solder	10 microns	25.5	7300	235
Diamond /Carriage or submount (Lateral)	300	1100	2200	510
Diamond Carriage or submount(Perpendicular)	300	1200	2200	510
Laser Diode Array on Copper Heat sink with silicon Heat spreader				
Solder	10	25.5	7300	235
Silicon Carriage or Submount	300	138	2330	686

Table I: Material and Geometry parameters of mounting configurations used to mount high power 10-50 Watt laser diode arrays; [Puchert, R et. al, p 1254-1259]

ii. 50 Watts plus bar mounted on a water/liquid cooled heat sink

Laser arrays operating at the 100 Watt level and higher have been fabricated and mounted with metallization on to an intermediate carriage or heat spreader which in turn is mounted on a microchannel cooler with active (liquid) cooling. These devices have used CVD Diamond as the heat spreader material. Mikulla et al at the Fraunhofer Institute-Freiberg have fabricated long cavity length (2 mm resonator length) laser diode arrays and mounted them on microchannel cooled heat sinks that have thermal resistance of less than 0.3 Watts/K. They provided additional cooling to the n-side of the laser array and were able to operate their devices at a record 270 Watt power level on the actively cooled heat sink. [Mikulla]

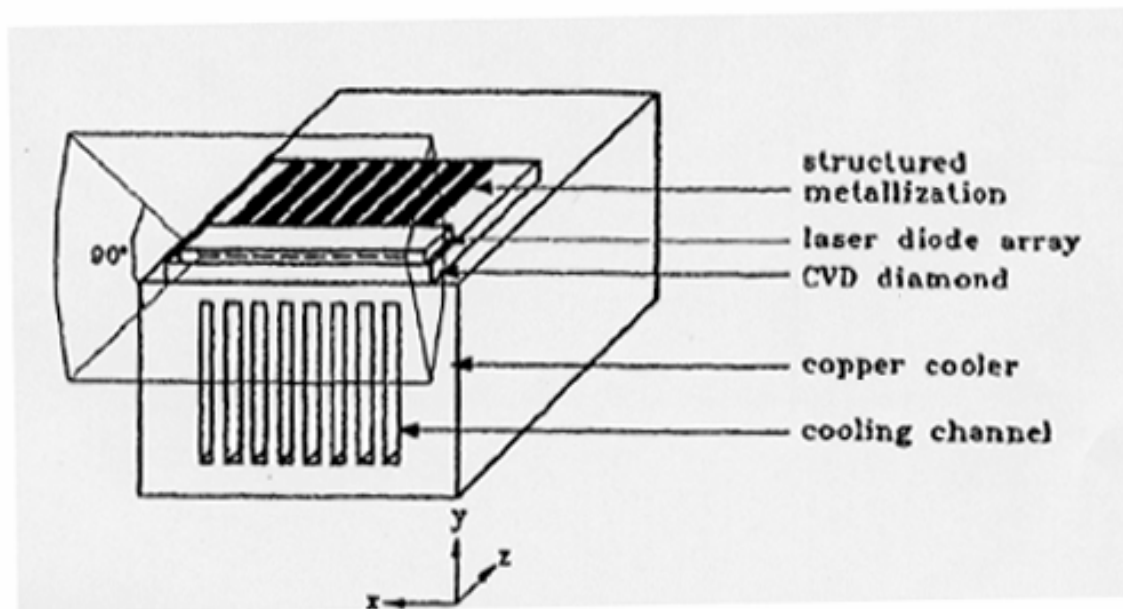


Fig. 5: Mounting of high power laser diode arrays on intermediate heat spreaders and microchannel based actively cooled heat sinks. [Lorenzen]

d. Influence of packaging design upon optical, electrical and thermal operating parameters

The device design and operating regimes of laser diode arrays make it critical that thermal dissipation at high operating power levels needs to be optimized from the active area of the device to the heatsink since at the high power levels, the corresponding power densities are of the order of kWatts/square cm of mounting area [Merritt].

In particular, the thermal resistance of the interface created at the laser die attach to the heatsink is quite critical; the laser die material is mounted with the epitaxial or p-side down toward the heatsink or heatspreader surface. However, this p-side or epitaxial side down mounting also decreases the overall process yield since the process is more susceptible to solder creep induced electrical shorts on the electrical interconnects or optical contamination of the laser facets. In addition, the substrate and waveguide materials have inherently low fracture strengths and are prone to damage due to mechanical mounting stresses encountered in the manufacturing process and device integration. High reliability operation of these devices requires that the thermal resistance should be low; in addition, the devices when they are mounted must be free of any voids created during the die bonding process and any subsequent solder process steps. The location of the laser die material relative to the heatsink, the flatness of the interface between the laser die surface and the heatsink surface and the thermal transfer properties of the die attach process are all critical in order to prevent site specific local heating due to the mounting induced mechanical deformation. Mounting stress in high power laser arrays is also caused by the disparity or mismatch between the Coefficient of Thermal Expansions of the heatsink and laser die material; this can be somewhat alleviated by use

of soft and low melting point solder materials such as Indium and Indium alloy solders. The yield stress of Indium and Indium based solders are relatively low; however a price is paid by an increasing tendency of the soft solder bond to creep over a period of time; this too can be alleviated by use of harder eutectic solders such as Gold-Tin that have low creep tendency and higher reliability [Weiss, Lorenzen]. The melting points of Gold-Tin solder compositions are higher as compared to Indium and Indium based solders; moreover, the mounting stresses created during the use of Gold-Tin solders are much higher.

5. Current and future generations of Laser Diode Arrays: Operating Conditions and Performance

a. Current generation of device technology in commercial use: 5- 50 Watts per bar

Current generation of high power solid state lasers for industrial and military applications call for doubling the power of laser diode arrays and bars as well as monolithic stacked array structures. These bars or linear arrays are mounted on intermediate carriages (the legacy material used was BeO for its excellent thermal conductivity but due to toxicity issues has been superseded largely by Copper-Tungsten or Silicon) which in turn are mounted on to Copper heat sinks. These heat sinks are passively cooled by air flow or by mounting the complete heat-sink/laser array assembly onto thermoelectric cooler modules or even water cooled chiller plates.

b. State-of-the-art devices with high output powers: Up to 70-80 watts per linear bar

Higher power laser arrays are currently being developed by increasing the drive current capability of each individual laser emitter within the bar as well as a lengthened cavity or resonator size. In addition, the number of emitters has undergone an increase from the “typical” 19-25 per 10 mm of laser array length to as many as 48 on a single bar. [Lorenzen]

c. Next generation devices: Relentless push for higher output powers: 80 to 250 Watts per linear laser diode array

Various fabrication efforts world-wide have focused on the highest power output from monolithic 10 mm wide AlGaAs/GaAs laser arrays. X. He et al [He] have demonstrated 155 Watts CW power which until the recent Mikula devices was the highest CW Optical Output Power reported to date.

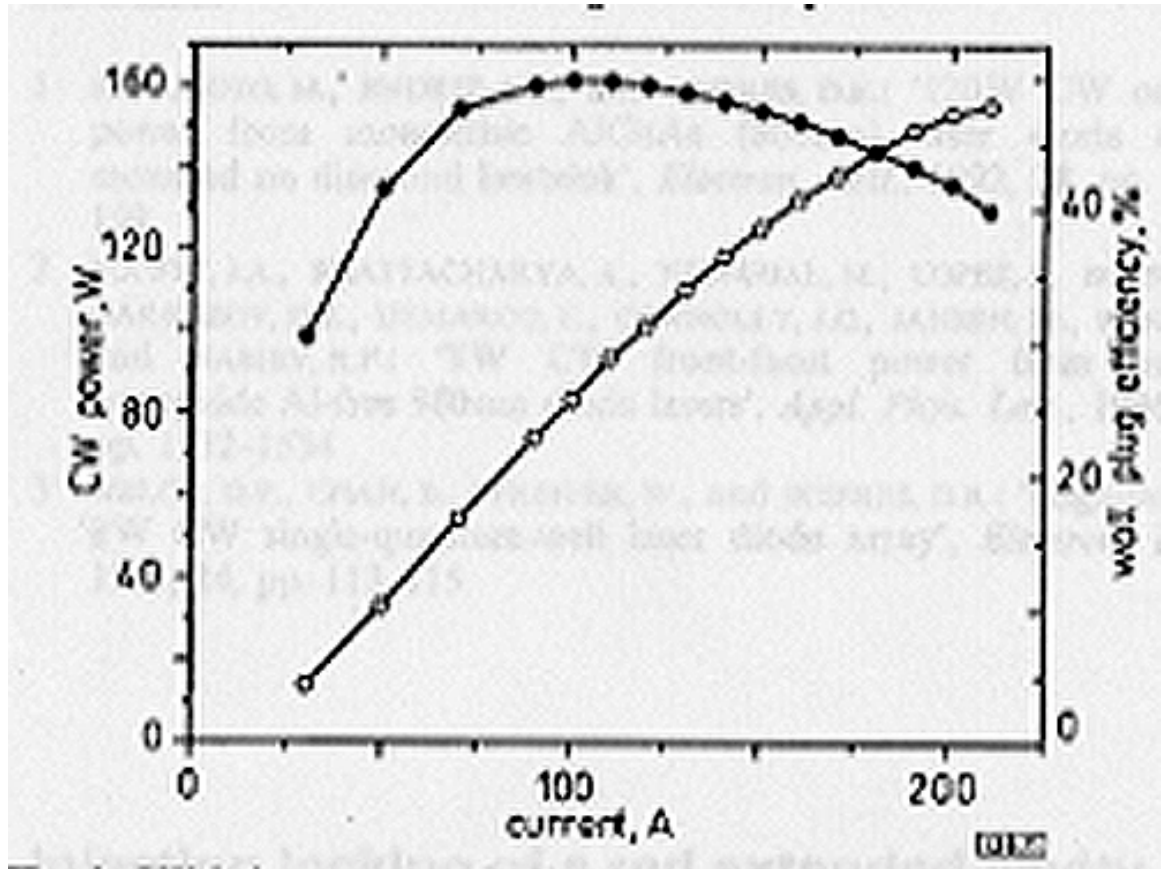


Figure 6: Recent high power semiconductor laser array developments with 155 Watts of Optical output power [He]

The laser diode arrays were mounted junction side down on a water cooled microchannel package and the complete device package was operated at very high ambient temperature extremes apparently without any degradation in optical output power. The electrical to optical efficiency realized was peaked at 50%.

6. High power operation of edge emitting linear laser bars and arrays

a. Limitations of current mounting techniques for scaling devices

This section examines the limitations of currently used mounting techniques and their extensions to very high operating output optical power levels of 100 Watts plus for linear bars. High power linear diode arrays and multi-dimensional stacks when operating at the

tens of Watts to hundreds of Watts optical power experience very high operating currents and even higher current densities within the structure of the waveguide and electrical interconnections.

Due to device ageing and thermal degradation, electromigration problems are experienced in electrical interconnections between the laser diode array and the substrate/package, especially in creep phenomena of commonly used solder materials. In addition the mismatch of the CTE leads to mounting induced stress which may lead to bar failure due to physical damage or cracking [Weiss]. The lifetime of the device is related to mounting induced stress in the material of the bar; soft solders such as Indium and Lead-Tin reduce the mounting induced stress after cooling but at the same time are prone to whisker growth as well.

b. *Need for new solder materials and laser die mounting processes for high power laser arrays*

i. *Optimized Gold-Tin Solder Process:* New solder metallurgy has been developed for reliable attachment of moderate and long cavity length laser arrays that uses Gold-Tin solders that have been optimized for a particular process. As Pittroff has outlined[Pittroff 2002], the optimized Gold-Tin solder process relies on the application of an extra Gold layer on the side of the laser die material; this dissolves in the molten solder during the reflow process. When the laser die material reaches the soldering temperature, the excess Gold starts to dissolve and creates a Gold rich phase; the Gold rich phase has a melting temperature beyond 500 degrees C. It therefore flows uniformly and uses up the whole molten solder in such a way as to form a bond that comprises of a pure Gold rich content Gold-

Tin solder; this yields optimum thermal stability, high reliability and high process yield using linear diode arrays mounted on passive heat sinks.

ii. Indium-Tin Solder and Process

Merritt et. al. [Merritt] have proposed the use of Indium-Tin solders for high reliability laser die material attachment and bonding to heatsinks; their process exhibited increased reliability due to precise control and reflow behavior of the solder used. The Indium-Tin alloy system used in laser die attachment experiments exhibited low incidence of voids in the laser die material to solder and the solder to heatsink interface. The 51% Indium-49%Tin solder used exhibited eutectic behavior at 118 C; evaporation of a 2 micron thick tin layer was performed on a OHFC Copper heat sink with 2.5 micron thick layer of Indium evaporated on the epitaxial side of the laser die material; the presence of an Indium layer directly on the laser die material prevented the occurrence of solder voids in close proximity to the high heat load laser array. During the thermal cycling process to create the attachment of the laser die to the heatsink, the heatsink surface temperature was increased to melt the Indium at 157 C but was stopped before the tin melting point of 232 C.

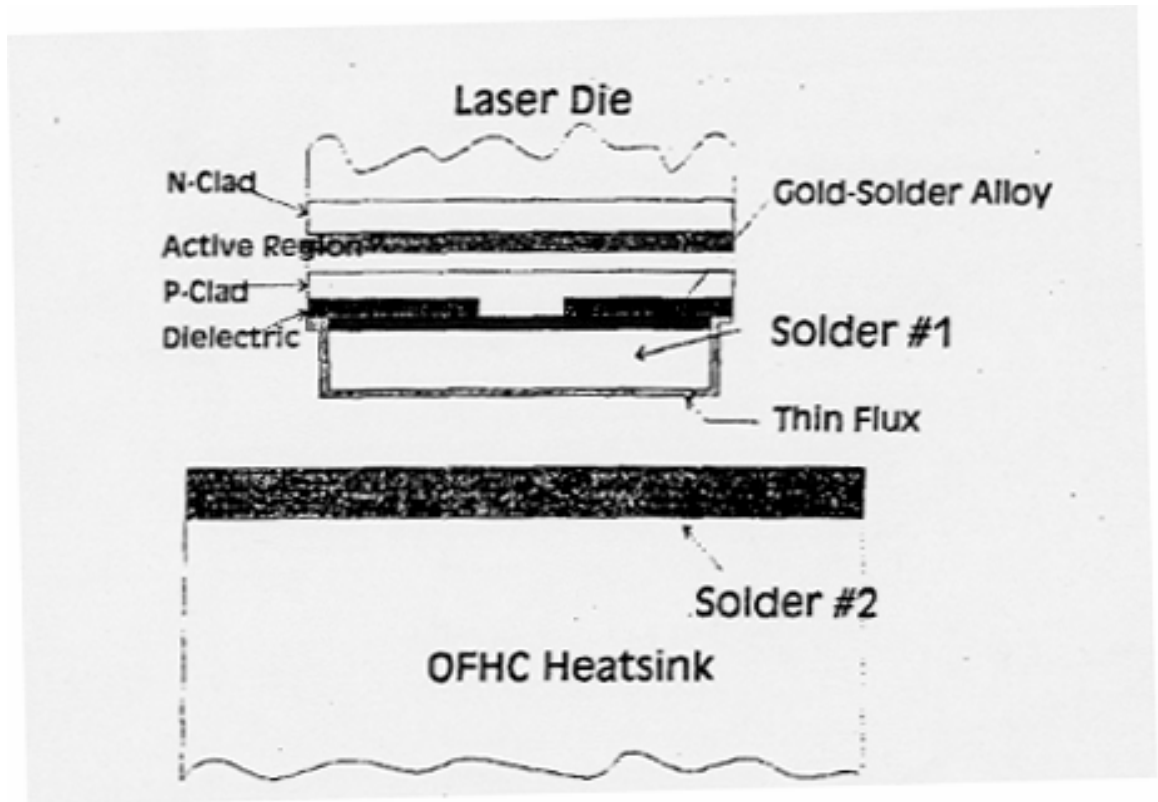


Figure 7: Laser Die Attachment to an OFHC Copper heat sink using solder #1 (Indium) and solder No. 2 (Tin); this technique produces high reliability laser die attachments due to lack of voids on the laser die epitaxy side. [Merritt]

This resulted in higher reliability laser die bonding since the solder creep and resulting device damage due to shorting was reduced. Upon reaching the Indium melt temperature, the Indium-Tin inter-diffusion creates the alloy which has a lower melting point than the Indium; the diffusion of the two metals therefore completes the solder bond. A large amount of the Indium was transferred along the surface of the laser die as the diffusion process progressed and the compression forces were applied to attach the laser die to the heatsink. [Merritt]

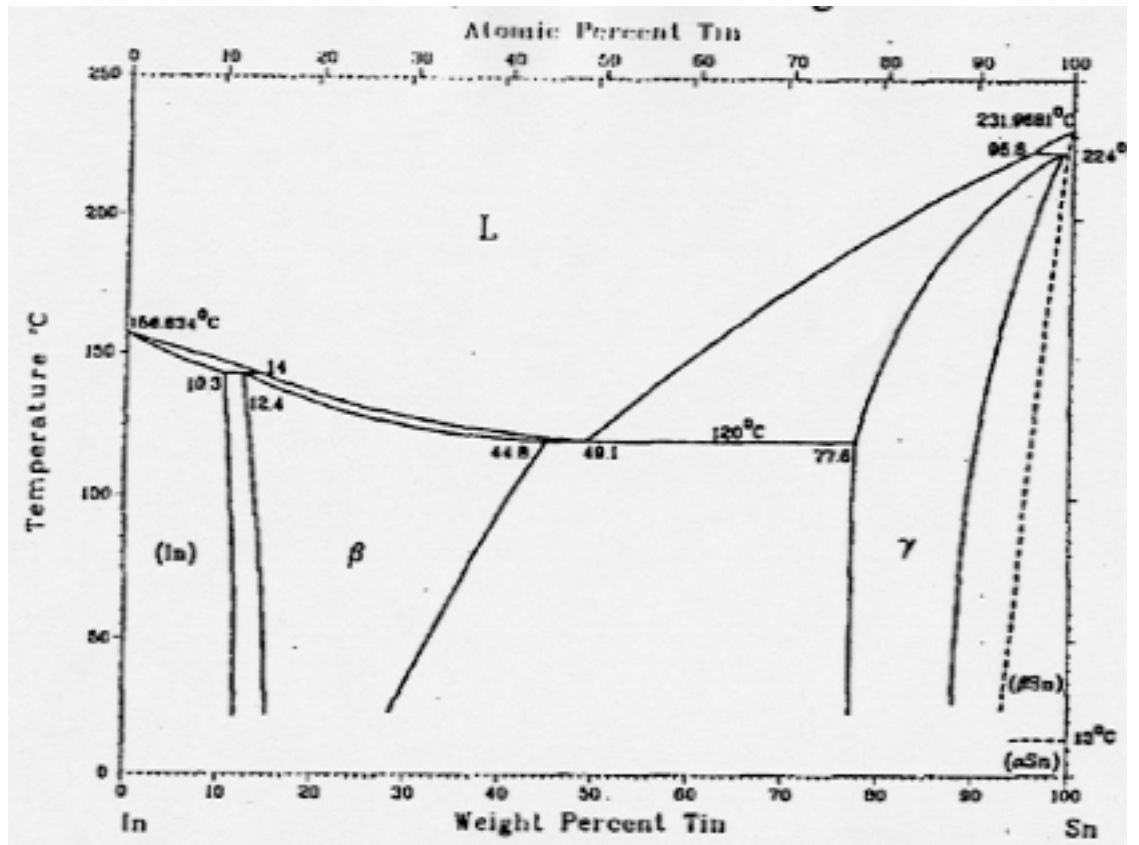


Figure 7: Indium-Tin phase diagram with reference to Indium-Tin solder process for mounting high power laser diode bars with increased reliability. [Merritt]

1. Materials considerations for package design of high power Laser Diode Arrays

a. New Heat sinks and Heatspreader materials

i. Use of Copper-Tungsten heat sinks and heat-spreaders as submounts

Copper-Tungsten heatsinks with W-10 are currently being utilized for high power linear diode arrays; the CTE of Copper-Tungsten is $6.4 \cdot 10^{-6}/\text{degree K}$. The maximum degree of tensile stress encountered by the GaAs substrate when it is mounted on a copper-tungsten heat sink is 6 Mpa. In the case of Copper-Tungsten with heatsinks with W-20, the CTE value is $8.3 \cdot 10^{-6}/\text{degree K}$. In this case, the Maximum Tensile stress encountered by the GaAs laser array substrate is -43 Mpa [Weiss].

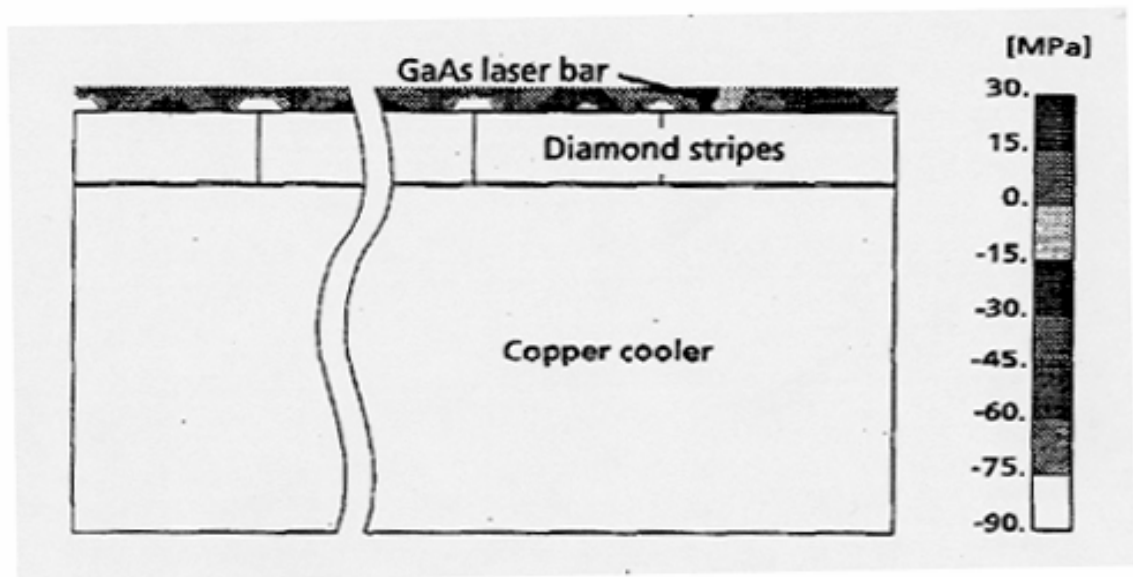


Figure 8: Profile measurements of Mounting induced Stress for a AlGaAs laser diode array mounted on CVD Diamond heatspreader strips and integrated on a copper heatsink/cooler [Weiss]

New mounting techniques have been proposed which use Cu-W heatsinks as well as CVD diamond heatsinks and heat spreaders. CVD Diamond heat spreaders are commonly now utilized between the laser array and a copper heatsink on high power laser designs approaching 100 Watt optical output powers and operating with 10000 hour lifetimes. Since both copper and diamond have large CTE mismatches to the GaAs laser material, the mounting is performed using Indium based soft solders; the inherent disadvantage in the use of Indium based solders is problems with electromigration as well as formation of whiskers over a period of time. For low to modest amounts of thermal dissipation, submounts that are better thermally matched to GaAs have been used; these include Silicon carbide and Copper-Tungsten. In particular, since Copper-Tungsten has a CTE closely matched to that of GaAs, it has been used for mounting of laser arrays with long cavity lengths producing high power. [Pittroff]

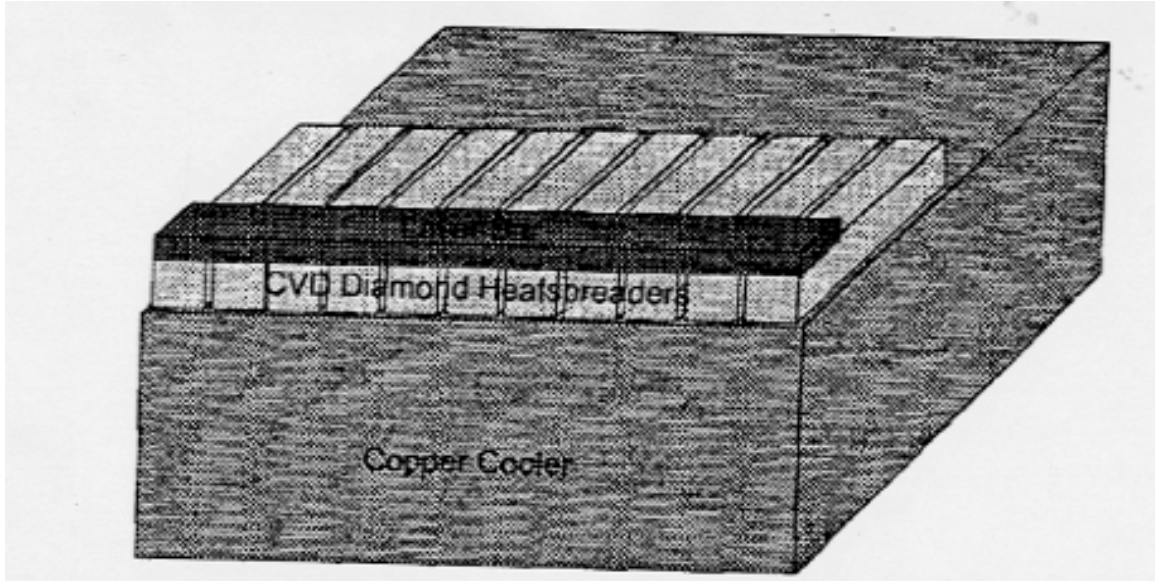


Figure 9: CVD Diamond heatspreaders mounted underneath individual incoherent emitters on a laser diode array; the heatsink is an Oxygen Free High Concentration (OHFC) Copper cooler [Weiss]

In the case of mounting of AlGaAs/GaAs laser arrays on Copper-Tungsten submounts as well, Gold-Tin solder is again used but with the composition optimized for this process. In the case of a laser array mounted p-side down on a Copper-Tungsten mount, Pittroff et al have shown that using the cavity length of 2 mm for the laser array, a emitting aperture of 100 microns and a pitch or distance between each of the 19 emitters of 500 microns and a Cu-W heat spreader thickness of 250 microns with a thermal conductivity of 180 k/W which is much lower than that of diamond, only a slight 0.1 K/W increase in thermal resistance on Copper heat sinks using the Cu-W heat spreaders. This is offset by the considerable advantage of being able to reliably attach high power laser arrays that have long cavity lengths without CTE disparity induced tensile and compressive stress in the laser die material.

ii. Use of CVD Diamond heat sinks and heat-spreaders as submounts

For yet higher CW output optical powers (120 Watts and beyond), CVD Diamond has been used for optimum thermal dissipation. The CTE of CVD Diamond is $1.2 \times 10^{-6}/\text{degree K}$; the maximum Tensile stress encountered by the GaAs laser array substrate using CVD diamond as the heat spreader material is 120 Mpa. [Weiss et al 1998]. For these high CW and high average power (pulsed or Quasi-CW case) laser diode array applications, diamond heatsinks are finding increased use and acceptance. The CTE of Diamond heatsinks is approximately 2.3 ppm/degree K or less and thus better (more closely) matched to that of the GaAs substrate material. The Thermal conductivity of the Diamond heatsinks is greater than 1000 Watts/mK; this results the laser chip lifetime being improved due to the better thermal conduction during laser operation, even under high thermal stress conditions. In addition, the spectral linewidth of the optical output of the laser chip is better controlled since thermal gradient induced changes to the laser structure (the waveguide structure as well as the substrate material) that affect the lasing characteristics and thus provide deleterious influences upon the output power and laser spectral characteristics is mitigated. In recent work over the last 2-5 years, up to 120 Watts in a linear laser diode bar structure have been operated using a diamond heatsink mount [Sakamoto].

iii. Use of Boron Nitride heat sinks and heat-spreaders

In thermal dissipation for high power laser diodes, the critical issues remains that the Coefficient of Thermal Expansion (CTE) mismatch between the laser substrate

material needs to be low whereas the Thermal Conductivity of the heat sink material needs to be high; the CTE disparity in the case of longer cavity diode lasers that are used to produce high power becomes a more crucial parameter for effective heat removal from the length of the cavity. For short cavity moderate to high power laser diode arrays, high thermal conductivity CVD diamond heat spreaders mounted on Copper heatsinks can be used. Boron Nitride and in particular Cubic Boron Nitride has been used as a heat sink material by several European research groups for longer cavity length lasers [Pittroff et. Al.]; the coefficient of thermal expansion correlation is better in translucent cubic Boron Nitride than it is in diamond. The CTE of GaAs is 6×10^{-6} 1/k; the CTE of Cubic Aluminum Nitride is 4×10^{-6} 1/k. In addition, the thermal conductivity is still quite high and the material lends itself well to use as a heatspreader. The German group at Ferdinand Braun Institute [Pittroff et al] have used long 2 mm cavity length laser diode bars and bonded them p-side down on Aluminum Nitride heat spreaders using gold-tin solders and in turn mounted them on to copper c-mounts using lead-tin solder. For electrical connections, gold wire bonding using thermosonic bonding method was used. Cubic AlN heat spreaders are commercially available and are coated with a 3 micron layer of Titanium-Platinum-Gold/Tin on one face and with Titanium-Platinum gold on the other face for better adhesion.

b. Novel bonding methods for die attachment and bonding of laser diode bars

i. Use of fluxless Gold-Tin Solders

Eutectic Indium and Lead-Tin solders can provide limited reliability laser devices with up to few thousand hours device lifetime [Mizuishi]. Soft solder migration and catastrophic failure of the laser chip becomes a concern. Whisker growth at the bond

interface as well as the use of solder flux is necessary to obtain good wetting and absence of voids in the bond interface. Eutectic Au80-Sn20 solder provides a more reliable and flux-free alternative that results in increased lifetimes

Au-Sn solders are used with high power devices but as power increases, the bonding stress needs to be low; also the thermal resistance of the interface needs to be controlled as output laser power increases. As the active region of the laser chip is exposed to a temperature increase, the laser chip lifetime and overall device lifetime is affected; heatsinks need to be used that have high thermal conductivity. Also active thermoelectric coolers need to be used that have high coefficients of thermal transfer in order to dramatically increase laser diode bar lifetimes (up to 10K hours or more for industrial, biomedical and military applications). Gold-Tin solders are used primarily for reasons of low values of thermally induced fatigue as well as higher reliability [Pittroff 2]. Pittroff et al have mounted high power laser diode bars on Copper Tungsten sub-mounts using 80-20 Gold-Tin solders; they placed an additional gold layer on the laser chip or die and observed isothermal solidification behavior since a gold rich phase on the solder was created [Selvaduray]. The complete assembly of laser diode bars installed onto Copper-Tungsten mounts was in turn mounted on passively (air) cooled heat sinks using a 37-63 Lead-Tin solder; these laser bars were run at multiple tens of Watts optical power (30 Watts for 808 nm and 45 Watts for 960 nm bars) with only 1 in 100000 hours degradation [Pittroff]

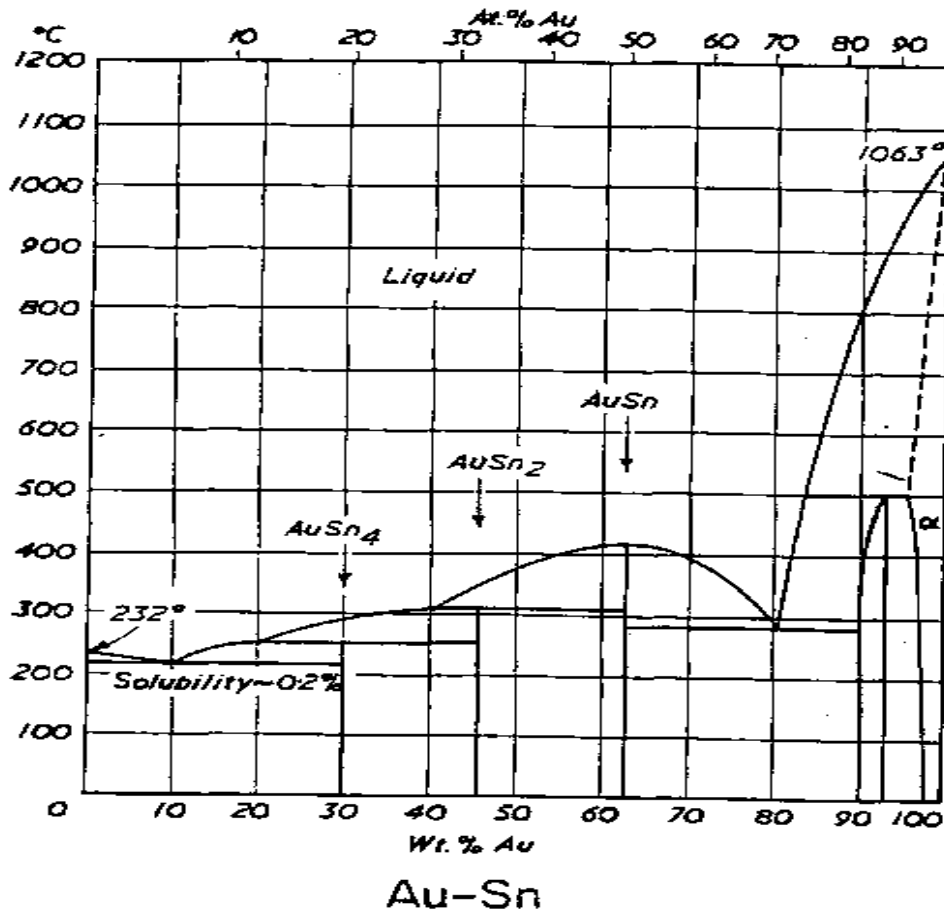


Figure 10: The Gold-Tin Phase diagram to illustrate the Gold rich layer formation in the Pittroff and Weiss laser array bonding and attachment process to heatsinks [Selvaduray]

In most recent work by the Fraunhofer Institute, Germany, laser diodes have been mounted on diamond heatsinks using Au80-Sn20 solders of a few microns thickness; the laser structures are mounted p side down and operate under severe thermal stresses and gradients especially in CW operation since the slope efficiency of the electrical to optical output is moderate to low. With standard metallization process, their mounted laser diode bar was able to operate at up to 0.4 Watts output power. The same device was able to operate at up to 1.6 Watts output power with the improved or modified metallization process

The metal layers deposited between the laser array and the heat sink material consist of Titanium, Platinum and Gold followed by a layer of Gold-Tin solder; this is followed by another Platinum, Titanium layer deposited on the heat spreader; the Titanium acts as an adhesion layer, the Platinum forms a barrier for diffusion.

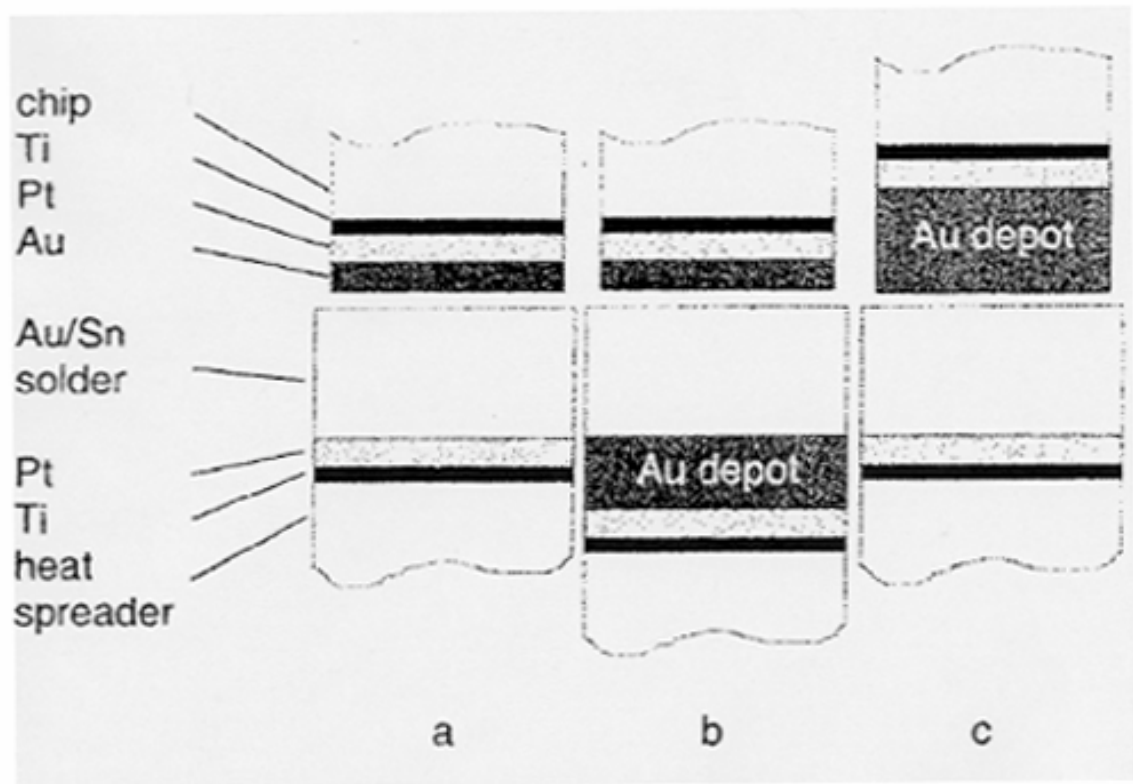


Figure 11: Metallization layers for laser die attachment to heatspreader [Pittroff]; Figure (a) shows metallization layers used in Gold-Tin metallurgy; Figure (b) shows mounting approach with Gold layer on heatspreader [Weiss]. Figure (c) shows new approach with Gold layer on laser die side. [Pittroff]

Weiss et al [Weiss] have proposed a thin Gold wetting layer on the laser array side; as the Gold-Tin solder melts, the Gold starts to dissolve and a Gold rich phase is created within the solder that migrates to the laser substrate. The metallization layer was changed with the addition of a 2 micron thick Gold layer under the 3 micron

thick Gold-Tin layer. The modified process also resulted in linewidth compression with a spectral linewidth measured at 50% or FWHM points of 1.5 nm being possible against the standard 2-3 nm at these power levels for commercial laser diode bars.

In order to prevent poor quality solder joints due to unequal heating between the laser array and the heat spreader substrate, Pittroff et al have proposed adding a Gold deposit to the laser array side instead when using the Gold-Tin eutectic solder system for mounting of high power laser diode bars on Boron Nitride heatsinks. As the Gold starts to dissolve, the Gold rich phase starts to be created only when the laser array reaches the soldering temperature. The metallic layer profiles for Gold-Tin bonding of the laser die are shown in Figure 10. Figure 10 shows the additional Titanium and Platinum layers utilized on both sides of the laser die as well as the heat spreader substrate. Figure 11 shows the standard approach and Figure 12 shows the Weiss approach with the additional Gold rich layer being formed on the heat spreader substrate which is more deleterious in not being able to get good quality solder joints; finally, Fig 11 (c) shows the Pittroff approach with the Gold layer deposited by electroplating on the laser die side. The subsequent figure, Figure 16 shows a Cubic Boron Nitride heat spreader profile after the laser array has been removed at slightly higher than the 280 degrees C Eutectic Temperature; the metallization remains on the heat spreader rather than migrating towards the laser die side.

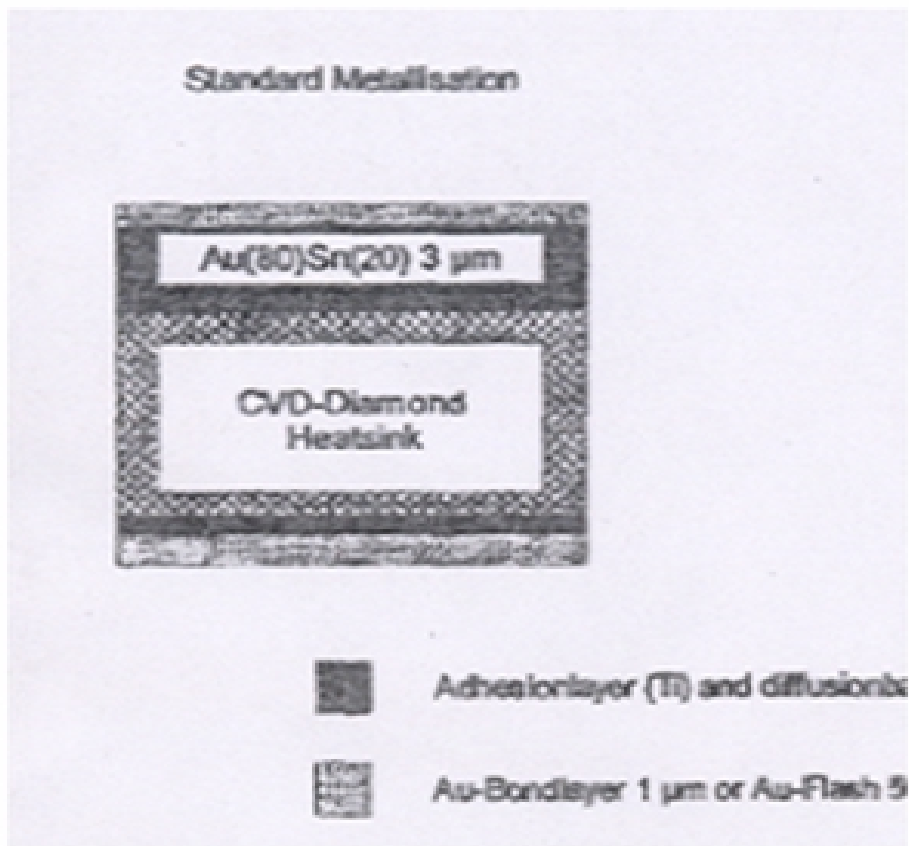


Fig 12: Standard Laser Diode mounting process on a CVD Diamond heatsink;
[Weiss]

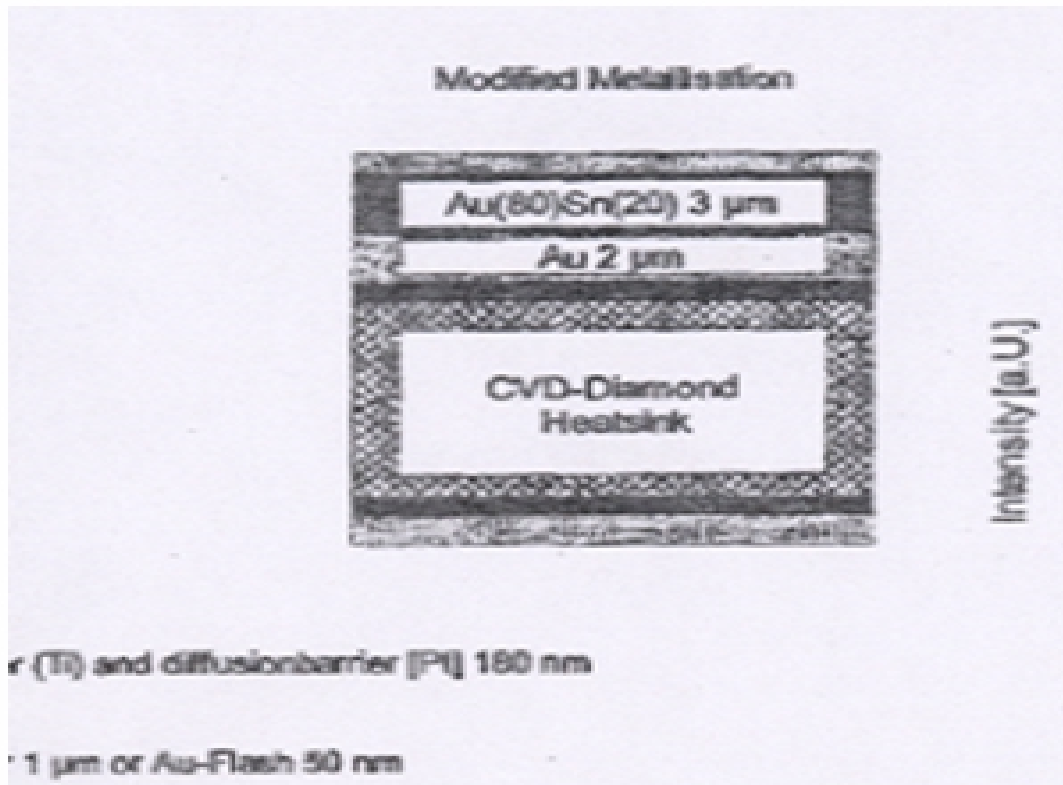


Fig 13: Structural Diagram of Modified mounting process with an additional Gold layer underneath the Gold-Tin layer [Weiss]

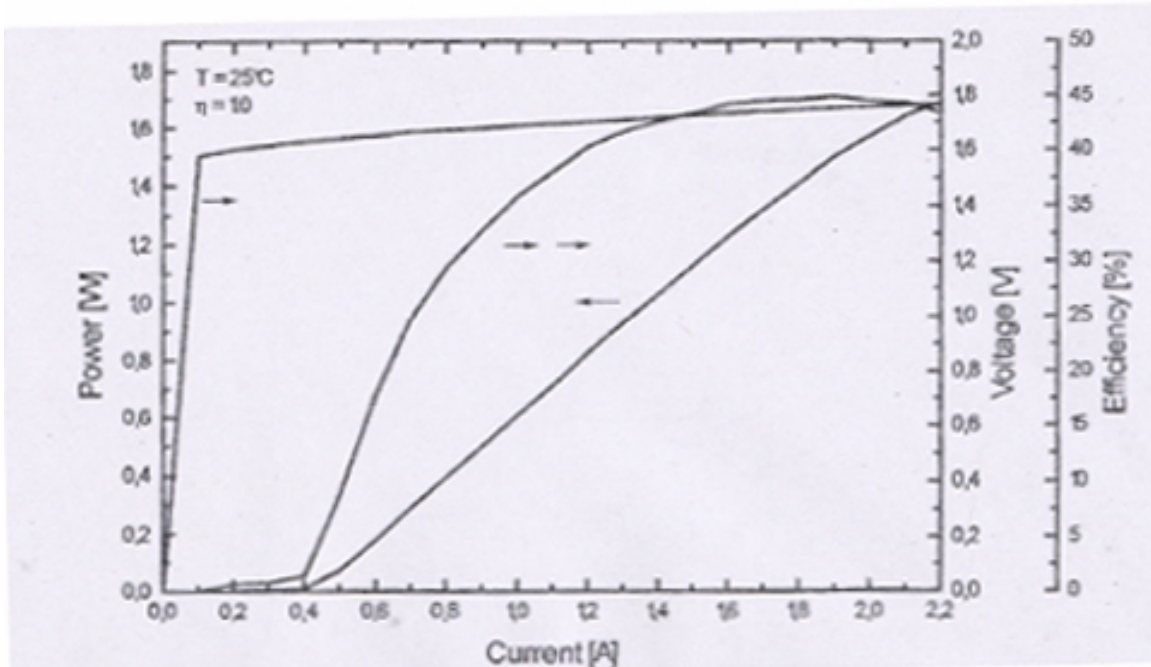


Fig 14; Laser Diode Light-Current-Voltage Characteristic (LIV) Curve with the standard mounting process [Weiss]

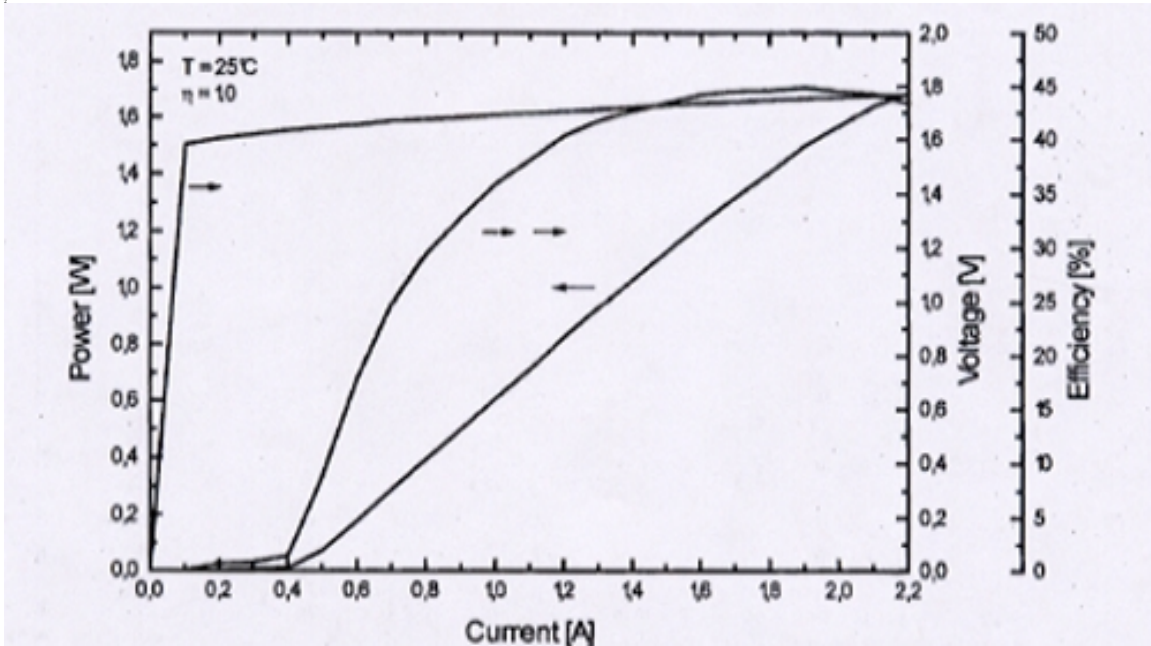


Fig 15; Laser Diode Light-Current-Voltage Characteristic (LIV) Curve with the modified mounting process [Weiss]

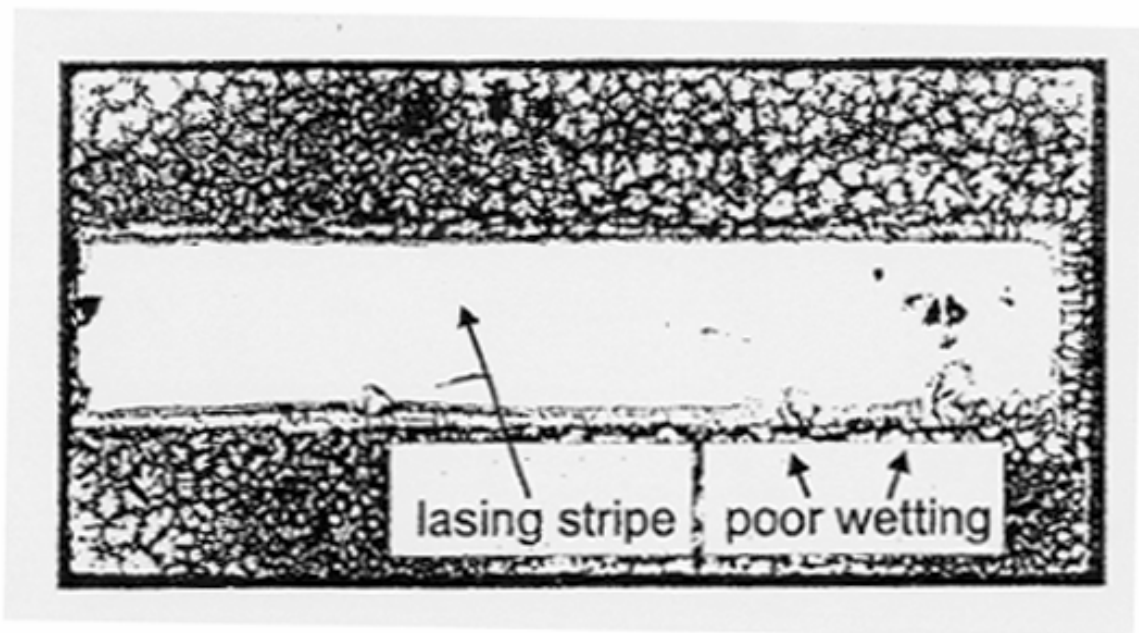


Figure 16: Cubic Boron Nitride Heatspreader showing the laser diode removal at 300 degrees C; the metallization layer remains on the heatspreader rather than migration onto the chip. The exception are the two right-hand regions where poor wetting is observed. [Pittroff]

2. Very high power stacked linear laser diode arrays and bars

a. *Mounting architecture: Transition from linear laser diode bars to monolithic stacked arrays*

As the need for higher power laser diode arrays materializes in the form of new applications, new approaches to increase the output optical power have been developed; these consist of the stacked arrays built using microchannel cooler technology as discussed below. Other approaches consist of individual laser diode linear bars or arrays mounted on water cooled plates that are stacked vertically with water inlet and outlet ports; ceramic spacers are utilized to provide electrical insulation between individual laser arrays; electrical interconnections are made using metallic contacts from the n side of one bar to the n side of an adjacent bar. In this architecture, 10 bar stacks can be constructed that operate at CW power levels of 60 Watts per bar and 600 Watts total power.

b. *Microchannel Array technology for active liquid cooling*

Microchannel cooled laser diode arrays were first developed by the Lawrence Livermore National Laboratory to achieve operation of very high power, high brightness sources [Beach, Payne]. The microchannel heat sink is a structure of 750 microns thickness of silicon-glass-silicon that contains channels fabricated through it for water flow; the channel thickness or width is 25 microns and the location of these channels is directly underneath the interface bond pad upon which the laser diode is mounted. The thermal impedance between the laser diode bar and the channel center is of very low value; this is achieved due to the narrow width of the water flow channels which constricts the return path water flow width to a lower value than that achieved in a wider

flow channel, unrestricted flow cooling system. The optimized thermal performance of these microchannel array heat sinks enable very high average power operation of the laser bars; since both the laser diode linear arrays as well as the microchannel structures can be vertically stacked, it is also possible to build vertically expandable laser diode stacked arrays that are capable of even higher average powers and have extremely compact optical radiation propagation patterns (high brightness). These microchannel heatsink structures and assemblies have been fabricated in CVD Diamond as well as in Silicon and copper [Goodson].

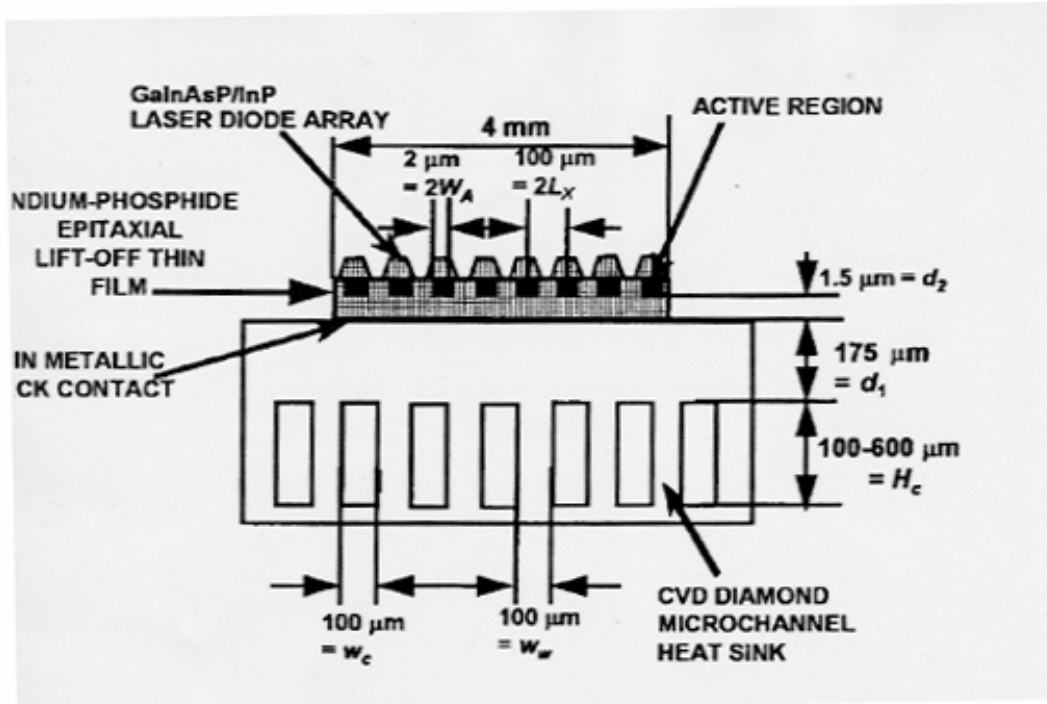


Figure 17: CVD Diamond Microchannel Heatsink indicating the flow channels and feature dimensions [Goodson]

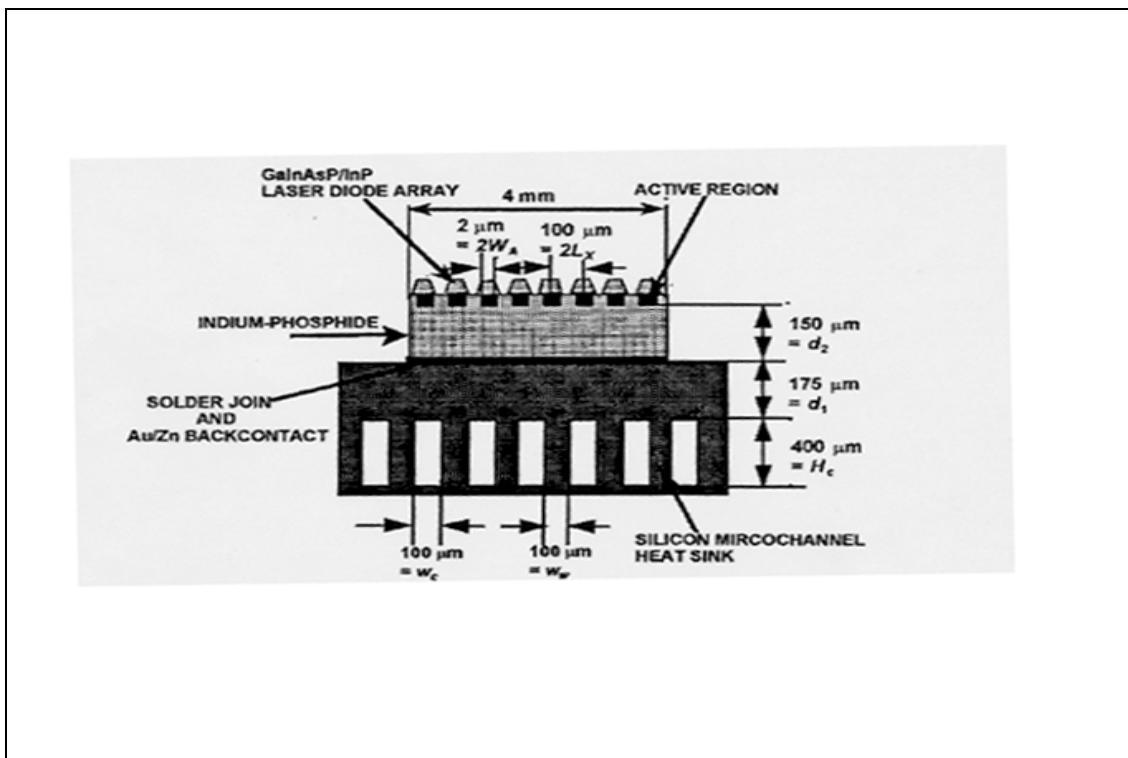


Figure 18: Similar features of Figure 10 fabricated in a silicon microchannel heatsink [Goodson]

c. *Overall package design for high power stacked LDAs utilizing integrated single stage water cooled heatsinks:*

The thermal load dissipation required by high power laser diode array stacks can be addressed in two separate approaches; the first is the use of microchannel cooled heatsinks as outlined above. The second approach consists of the use of multiple single-stage low thermal impedance water cooled sinks for individual laser diode arrays up to the 100 Watt optical output level [Treusch]. The laser bar is mounted on the front part of the heat sink. The individual single stage heat sink assemblies are bonded together in a high temperature process to obtain an integrated solid heatsink assembly. The thermal impedance of the heatsink assembly can be controlled by the flow rate of the liquid cooling; also highly critical to achieve a low thermal impedance heat sink is the use of individual ceramic spacers for the single-stage laser bar/heatsink module and electrical contact points for the complete laser bar/heatsink assembly [Treusch]. Using this approach, multiple array laser diode stacks have been fabricated that operate in the 1.5-2 kilowatt optical power range.

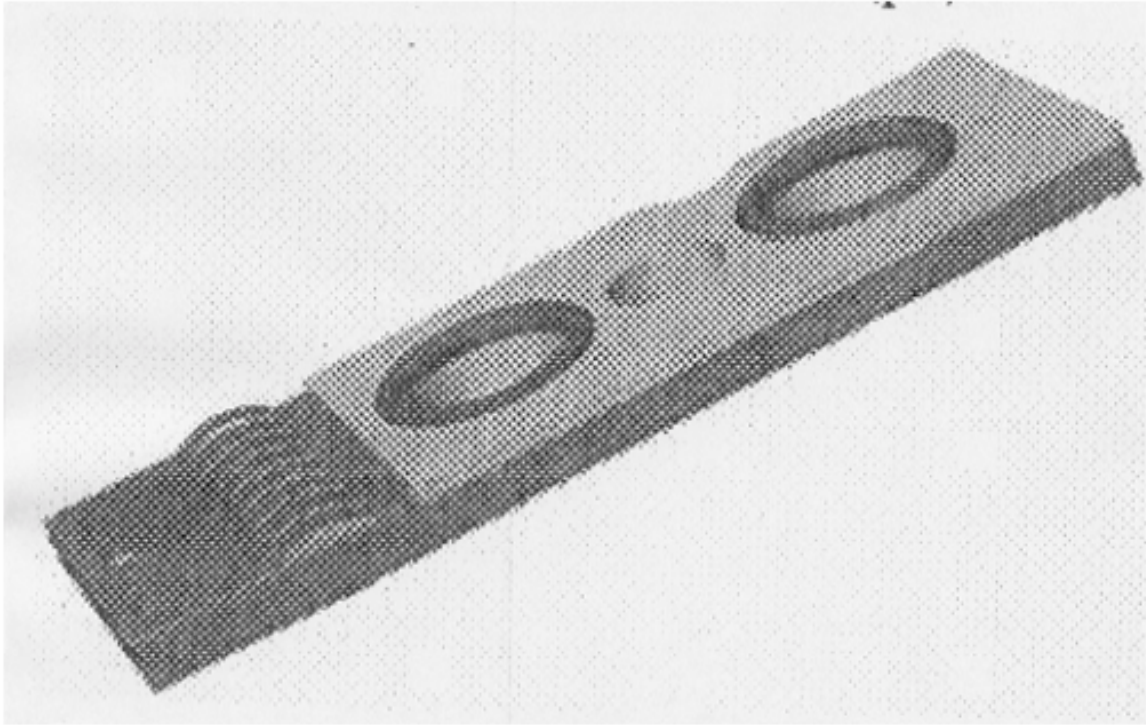


Fig 19; Single stage heat spreader (flat-plate) for stand-alone applications or for integration into 10 bar monolithic stacked array [Treusch]

d. Integration of multiple linear bars/arrays to form a monolithic stacked array

Two dimensional semiconductor laser arrays can be created for high power CW and pulsed operation using individual ceramic support members for each active laser array layer. In the case of AlGaAs diode arrays, both Silicon Carbide and Aluminum Nitride have been used for heat spreader inserts [Huang]. Due to increasing emitter density (the fill factor along the length of the laser bar) as well as the stacking density with decreasing vertical spacing between the emitting facets, thermal load dissipation becomes increasingly challenging when single-stage high power (100 Watts or higher CW) are integrated into the multi-dimensional stacked array.

Current device packaging technology has used the silicon and copper microchannel coolers, but even these are susceptible to thermal degradation and contamination over a period of time lasting a few months [Bhatia]. Laser diode manufacturers and system integrators have considered the use of CVD diamond spreader elements (the thermal conductivity of diamond is 1800 W/mK; with optimized length and thickness of the diamond heat spreaders under each single-stage high power bar, over-all single-stage bar and over all stacked array thermal impedance is reduced. When the multi-dimensional stacked arrays are assembled and optimized for deployment in laser systems pumping or other applications, the form factor resembles that depicted in Figure 20 below.

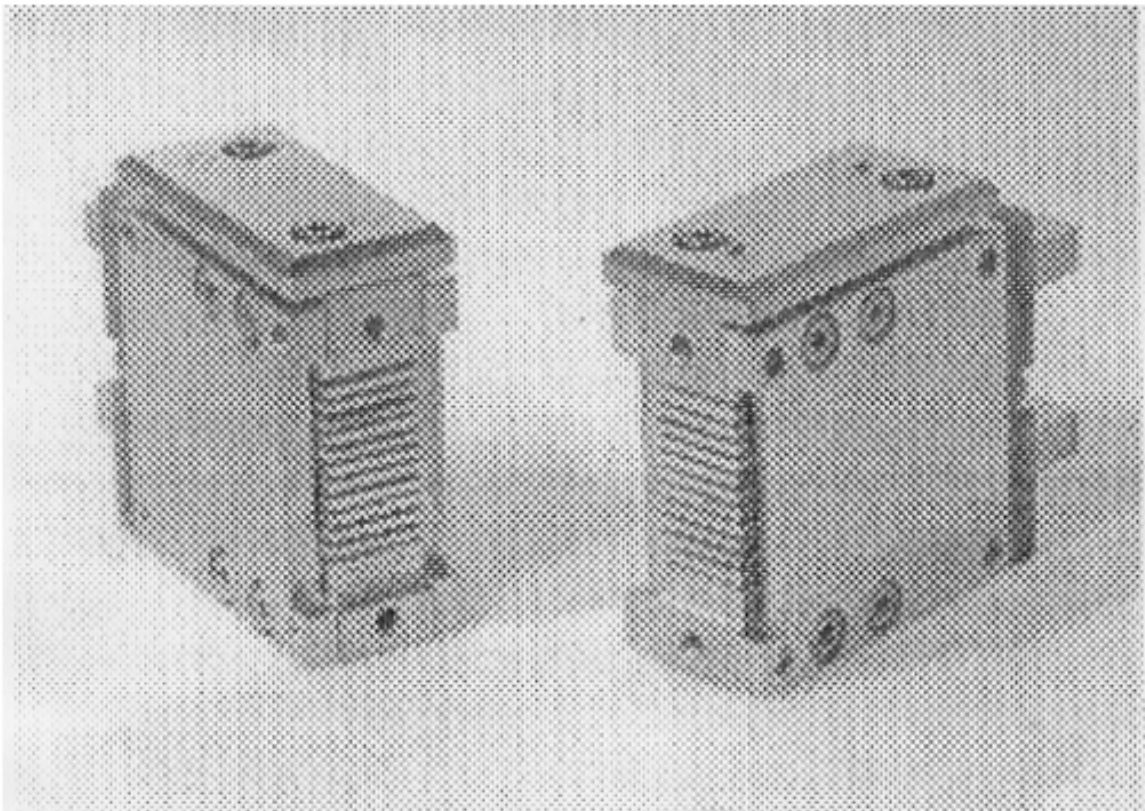


Fig 20; 60 Watts per bar, 10 bar multi-dimensional diode array stack producing 600 Watts of peak optical power {Treusch]

3. Conclusions

We have outlined the various aspects of laser diode array technology that have been developed and have come to maturity over the last few years. The thermal engineering technology that enables dramatically improved performance of semiconductor laser arrays consists of both the materials technology developments as well as new device integration techniques and methods.

These advances have enabled operation of laser diode linear arrays and bars as well as laser diode stacked two-dimensional arrays in robust device form at increasing output power levels demanded by users. In particular, the materials, devices and integration process technologies that have enabled the output powers as well as higher device and over-all package reliability have resulted in development improved heat sink and heat spreader materials such as Copper-Tungsten, CVD Diamond and Boron Nitride. New fluxless Gold-Tin solder based laser diode bonding methods have enabled laser bars to be attached to heatsink substrates and resulted in the same device being able to operate at significantly higher output power levels.

Unique thermal design constraints posed by the integration of several semiconductor laser arrays into “monolithic” two-dimensional stacked laser diode arrays have been alleviated by the development of copper and silicon microchannel based heatsinks. The 100 Watt output level linear bars when stacked in multi-level layers can result in the development of highly compact yet robust and ruggedized laser sources capable of producing optical power at 1 kilowatt and higher range; the size of these sources is such that it fits into the palm of a hand and therefore can be readily integrated into electro-optical systems for materials processing and power beaming applications.

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