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Understanding of Laser, Laser diodes, Laser diode packaging and its relationship to Tungsten Copper

What is LASER?

Light amplification by stimulated emission of radiation, or laser in short, is a device that creates and amplifies electromagnetic radiation of specific frequency through process of stimulated emission. In laser, all the light rays have the same wavelength and they are coherent; they can travel long distances without diffusing.

To understand how lasers work, we must understand how an atom gives out light. An atom is the smallest particle in the world, and it contains electrons. By introducing extra photon into the atom, the electrons are forced to move into a higher energy level, and now the atom is at an excited state. However, the excited atom is unstable and the electrons always tries to get back to its ground state, therefore releasing the excess energy it originally gained, as a photon of light radiation. This process is called spontaneous emission, as shown below in Figure. 1.

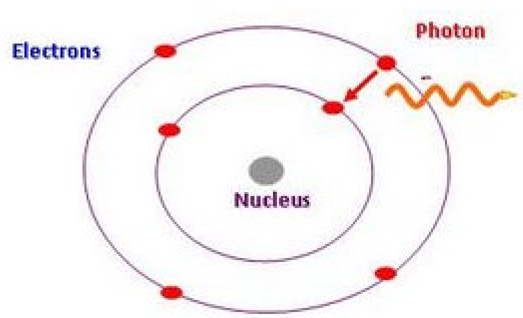

Fig. 1 Emission of photon as light energy

The laser contains a chamber in which atoms of a medium are excited, bringing their electrons into higher orbits with higher energy states. When one of these electrons jumps down to a lower energy state, it gives off its extra energy as a photon with a specific frequency. By introducing more photons into the system, the photons will eventually encounter another atom with an excited electron, which will stimulate that electron to jump back to its original state, emitting two or more photons with the same frequency as the first and in phase with it. This effect cascades through the chamber, constantly stimulating other atoms to emit yet more coherent photons, and this process is called stimulated emissions. In other words, the light has been amplified, as shown below in Figure 2, created by Al-Kashef.

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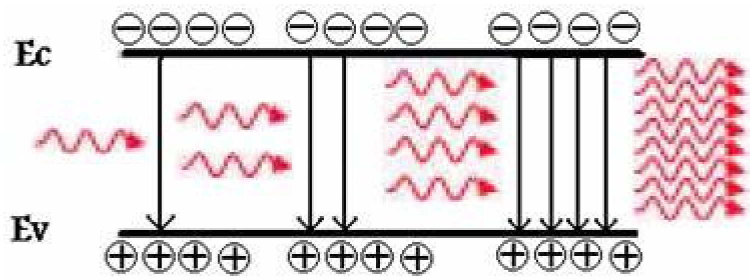

Fig. 2 Stimulated Emission of photons

Furthermore, mirrors at both ends of the chamber cause the light to bounce back and forth across the medium. One of the mirrors is partially transparent, allowing the laser beam to exit from that end of the chamber. By maintaining a sufficient number of atoms in the medium by external energy source in the higher energy state, thee emissions are continuously stimulated, and this process is called population inversion. Ultimately, it creates a stream of coherent photons which is a very concentrated beam of powerful laser light. Lasers have many industrial, military, and scientific uses, including welding, target detection, microscopic photography, fiber optics, surgery, and etc.

Types of Laser:

There are many different types of lasers and below are the five major types.

1. Gas lasers – ex. HeNe gas laser, and CO2 lasers which emit hundreds of watts of power. They are usually used for cutting and welding in industries.

2. Chemical lasers – powered by chemical reaction which permits large amount of energy, mainly for military use and of very high wavelength. Ex. Hydrogen fluoride laser 2700nm.

3. Solid-state lasers – optically pumped through use of solid medium that is doped , such as ion doped crystalline or glass. An example would be a laser pointer.

4. Fiber lasers – light is guided due to internal reflection in optical fiber. They are widely known nowadays for their high output power and high optical quality as well as long lifespan. The reason is due to the properties of fibers that give high surface area to volume ratio, which allows for efficient cooling when supporting kilowatts of continuous output power. Fiber's wave-guiding properties help maintain signal strength and minimize distortion. Fiber lasers are widely used nowadays for telecommunication that spread across regions several kilometers long.

5. Semiconductor lasers – electrically pumped

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a) Light-emitting diodes (LEDs) - In a diode formed from a direct band-gap semiconductor, such as gallium arsenide, carriers that cross the junction emit photons when they recombine with the majority carrier on the other side. Depending on the material, wavelengths (or colors) from the infrared to the near ultraviolet may be produced. All LEDs produce incoherent, narrow-spectrum light. LEDs can also be used as low-efficiency photodiodes in signal applications. An LED may be paired with a photodiode or phototransistor in the same package, to form an opto-isolator.

b) Laser diodes - When an LED-like structure is contained in a resonant cavity formed by polishing the parallel end faces, a laser can be formed. Laser diodes are commonly used in optical storage devices and for high speed optical communication.

A closer look at laser diodes

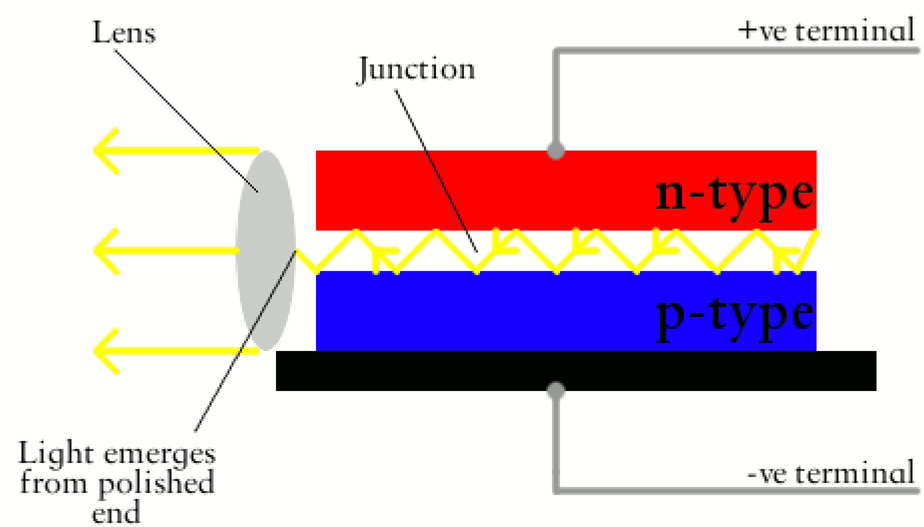

Fig. 3 The laser diode converts electrical energy into energy in form of light. (Credit to Explainthatstuff.com)

Laser diode is a laser where the medium is a semiconductor, formed by a p-n junction, as shown in Fig. 3, and powered by electric current. For different types of laser diode structures, please refer to Appendix 3. Basically, a laser diode is a combination of semiconductor chip that emits coherent light and a monitor photodiode chip for feedback control of power output, in a hermetically packaged and sealed case.

The semiconductor materials that are used to create p-n junction diodes that emit light today are: Gallium arsenide, indium phosphide, gallium antimonide, and gallium nitride. The reason that these are being used is because of the three-five compound properties on chemical periodic table. The

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materials have to be heavily doped to create P – N regions, which rules out others, leaving groups three-five the ideal options.

Below is a table of several typical substrate materials used in various laser applications.

Laser diode substrate material	Typical wavelength (nm)	Applications
GaN / InGaN	350 - 500 (UV - blue)	Blu-ray disc, Biomedical fluorescence
GaAlAs / GaAs	530 - 980 (red - near infrared)	DVD, CD, biomedical, printing, industrial aligning, sensing, cosmetics, laser projection, bio-analysis (spectroscopy)
InP / InGaAsP	900 - 1650 (infrared)	Range-finder, fiber optics, telecommunication, data transmissions, network, optical pumps.

Table 1. Laser substrates, their corresponding range of wavelength and applications.

Their wavelengths can be adjusted by changing the ratio of composition. For instance, the wavelength of the laser beam produced by InP substrate can be increased by increasing the Indium content or lowering the Phosphate content percentage. Longer wavelength usually indicates a longer travel distance.

According to Wikipedia, Laser diodes are numerically the most common type of laser, with 2004 sales of approximately 733 million diode lasers, as compared to 131,000 of other types of lasers. Laser diodes find wide use in telecommunication as easily modulated and easily coupled light sources for fiber optics communication.

Laser Packaging

In order to protect the laser diode materials or any laser devices from any mechanical and thermal stress, because the laser material, for example, Gallium Arsenide is very fragile, laser packaging is required for almost every diode laser or any other laser devices. Imaging the laser diode as a pizza, the packaging mount serves the purpose of pizza box that holds the pizza inside.
Additionally, the hermetically package sealing method prevents dust, or other contaminations from entering the laser; smoke, dust, or oil cause immediate or permanent damage to the laser. Most importantly, as technologies advance, the emergence of high power diode lasers require a sophisticated packaging design to help release the heat dissipated during operation through submounts and mounted heatsinks.

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Usually, the laser die is mounted on a submount of material with similar CTE(coefficient of thermal expansion) that matches with the CTE of the die. The submount serves as a heat spreader, which gets further mounted onto a TEC (thermal electric cooler) for rapid heat transferring. The entire assembly is then mounted onto a pure copper or copper/tungsten heatsink for advanced heat dissipation and cooling as shown below.

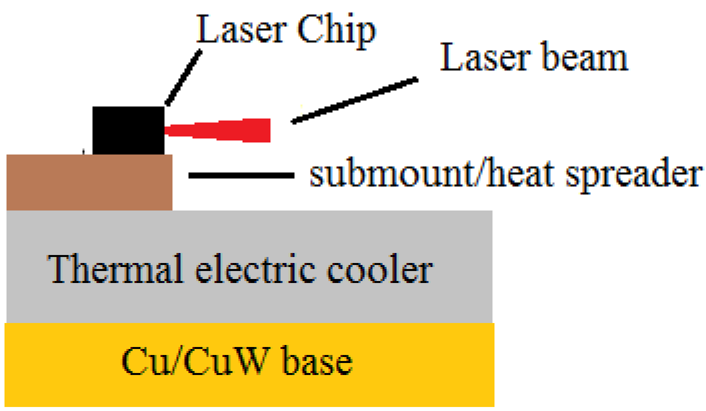

Fig. 4 Integration of submount in Laser packaging.

High power laser diode or laser devices convert electric energy into light energy at about 10% - 50% efficiency. The rest are generated as waste heat and must be dissipated within a short amount of time or else it would cause thermal stress on the laser diode bar, and eventually cause irreversible damage to the laser.

Inefficient cooling packaging design will result in poor product quality as temperature of the device core has a direct influence on output wavelength and band gap. It is proven in practical situations, that for every three deg. C of change, the wavelength of the diode laser can change nearly 1 nm. Also the output power of the laser will decrease as temperature increases.

To help dissipate the heat, the conventional method of laser diode packaging is to solder laser bar onto a heatsink, which is made of copper due to its high thermal conductivity, namely, faster heat transfer. Traditionally, soft indium solder is used to bond the heatsink to laser material Gallium Arsenide (GaAs) because the thermal expansion coefficient of copper don’t match with the laser material well enough. The indium has a higher ductility than copper, provides more reliability for continuous wave (CW) and quasi-continuous wave (QCW) (Please see appendix for definitions).

However, the repeat on-off cycle/hard pulse in laser operations can cause mechanical stress, which leads to material cracking / indium migration, further leads to failure. It happens in direct-diode, and solid state pump diode. Usually, low powered lasers can last longer before reaching its demise. High powered lasers often encounter such issues and fail much quicker, as they have much larger contacting surface between die and heatsink, thermal expansion of heatsinks is always a major issue.

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With increasingly advanced technology, many laser R&D companies have developed more sophisticated high power and high performance diode laser arrays suitable for both CW & QCW operations. CW & QCW powers in excess of 900W+ have been demonstrated at varies laser companies, ex. Princeton Optronics. Yet, the mounting of these laser bars still have not changed much in performance in terms of heat conduction, resistance, expansion, and etc. While the higher thermal conductive copper heatsink submount offers a cost effective solution, the mismatching thermal expansion rate with laser materials remains an issue and the problem is being magnified as the devices start to produce more heat. The reason for that is due to the material property of copper, which tends to expand as temperature increases, causing mechanical stress on the laser diode. Apparently, the pure copper heatsink can no longer keep these products within thermal expansion tolerance.

Using Tungsten Copper as submount and heatsinks

The tungsten copper, alternatively, provides much lower thermal expansion rate compared to pure copper while maintain a necessary thermal conduction rate. Tungsten copper is a copper and tungsten alloy that usually consists of 10 to 50 percent of its weight in copper and the remaining portion is made out of tungsten. The higher the tungsten content, the lower its thermal expansion rate is.

The Copper/Tungsten heatsink submount with gold/tin solder is a very cost effective method that provides both good thermal conductivity and thermal expansion that matches the silicon ceramic, and gallium arsenide materials used to make circuits for semiconductors and for both high powered and low powered laser diodes and bars.

Shown below are the comparison graphs with descriptions by Dr. Yuen from coherent.com. Clearly, you can see that the tungsten copper significantly helped increase the laser die chip lifetime during operations.

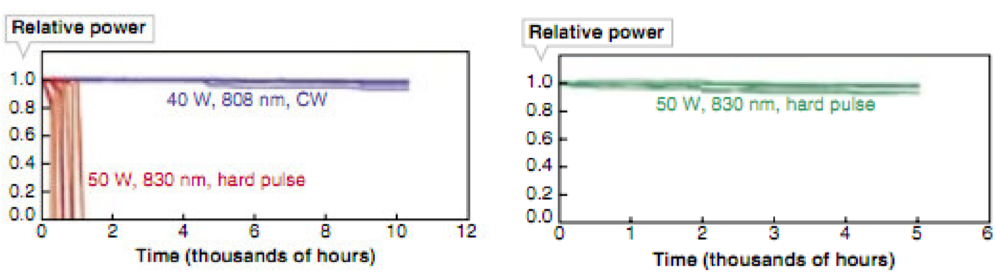

Fig. 5 - The lifetime is seriously degraded in QCW/pulse laser operations as shown on the left, while the lifetime is significantly better using improved submount made from CuW, as shown on the right.

The current trend of increasing die size and power dissipation requirement has made CuW the ideal material of choice for laser diode packaging. In addition, the conventional CuW heatsink submount provides a thermal conductivity from 180-230 W/mK with a coefficient of thermal expansion from 6.5-9.0 ppm/deg. C that matches die of laser diode. And with the newly improved solution such as finite boundary value method and functionally graded materials, the thermal conductivity of Copper Tungsten can be pushed up to around 320 W/mK. All of these thermal management solutions can be pursued and achieved using tungsten copper, which is one of the common, readily available materials.

Using Tungsten Copper as submount and heatsink in High Power Diode Arrays

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The technologies for high power diode lasers have been rapidly developed during recent years, however, the packaging technology still remains as a bottleneck for the advancement of high power semiconductor lasers.

In addition to the usage of CuW submount in single emitter laser packaging applications, tungsten copper is also a thermal management solution for high power diode lasers, which are created by combining several single emitters in an array. These high power diode arrays are applicable in pumping of solid state laser systems for industrial, commercial, military and medical applications as well as material processing applications such as welding, cutting, and surface treatment.
Shown below is a picture comparison between a single emitter and an array of emitters

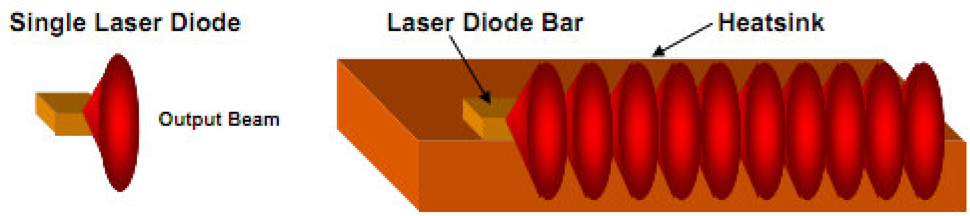

Fig. 6 Image of diode laser bars consists of multiple single emitters on a single substrate, from Coherent.com.

Clearly, the array is a combination of multiple single laser diodes, therefore, more power and heat are produced. Also, the multiple beams emitted form a near field and its linearity(or "smile") is an important parameter in determining the overall coupling efficiency between the diode lasers and the fiber or optic lens. The near field linearity depends much on the degree of CTE mismatch between the die and bonding materials, which will be discussed later.

In simple words, performance and longevity of the laser array depend much on the thermal management of the laser package. To achieve high efficiency and high power, the heatsink submount has to have the capability of transferring heat at a very fast speed while maintain a relatively close thermal expansion rate with the die material. Tungsten copper is often used in situations like this, due to its high thermal conductivity and good CTE match with die material(GaAs), and electrical active property to act as a P-side. The CuW submount is often bonded to a pure copper or thermal electric cooler for advanced heat dissipation.

CuW in comparison with AlN and BeO in submounts:

Typically, CuW, AlN, and BeO are used as submounts in packaging laser diodes. The CuW is a metal composite, while the AlN and BeO are ceramic; they serve different purposes. The CuW composite is typically used for heat spreading purposes, while AlN and BeO are dielectric materials which are used for electrical insulation purposes. Below is a comparison table showing the ups and downs of each material selection.

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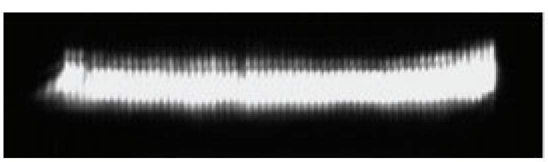
	CuW	AlN	BeO
CTE (ppm/deg. C)	6.5 - 9.0	4.5	7
Thermal conductivity (W/mK)	180 - 230	170 – 200	280
Density (gm/cc)	14.9 - 17	3.3	2.9
Material information	Metal composite, electric conductive and can act as P-side in P-N junction, strong and durable, CTE matches well with GaAs	Ceramic, electric insulation, good high frequency response*, CTE matches well with InP, easy for gold plating(tracing) for programming the diode	Ceramic, electric insulation, high thermal conductivity, CTE matches well with GaAs, toxic

Table 2

*AlN is suitable for high frequency wave applications due to ceramic material property, it help minimize the signal distortion and interference.

CTE (coefficient of thermal expansion) plays an important role in determining the overall performance and degradation time of the diode laser product. Materials expand in size due to increasing temperature. Slight degree of CTE mismatch could cause "smile" which results in poor performance of lasers. A "smile" is a non-linearity of the near-field of emitters. Shown below on the left is an image of a typical good diode-laser array in comparison with images of diode-laser arrays that have various "smiles", from Dr. Liu's experiment.



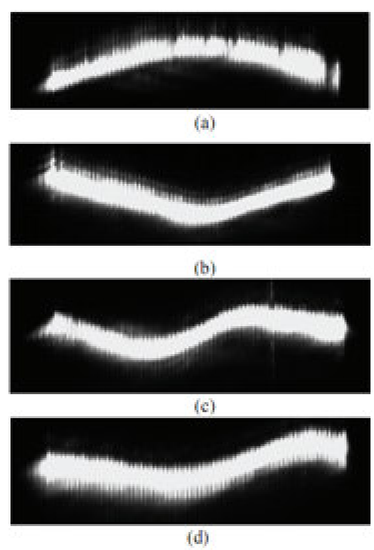


Fig. 7 Left image shows an enlarge "smile" of a good diode-laser array, while the image on the right are examples of various "smile" due to CTE mismatch between diode-laser arrays and the bonding submount/heatsinks.

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High degree of mismatch in CTE between bonding materials could cause the laser die to crack during sintering or brazing. To prevent such catastrophe, bonding layers should always have a close CTE match to the laser die. Sophisticated thermal management help the device maintain strong signal and better product quality.

Types of Laser Diode Packaging that require CuW material:

1. **C-mount packages**

   Used for lasers and laser-based systems, laser measurement and control, precision optics. Typical wavelength is from 680nm to 980nm, with output power rating up to 7W.

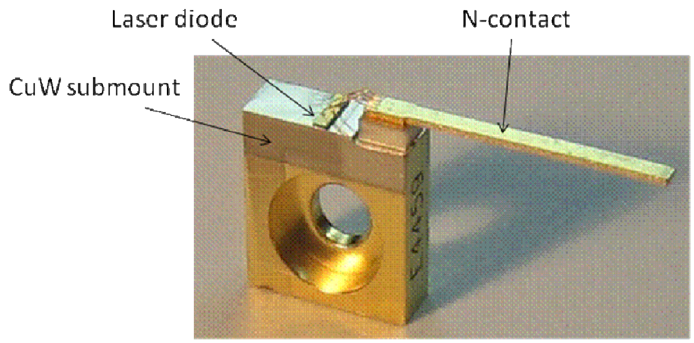

Fig. 8 C-mount laser diode

The laser diode is directly soldered onto the copper tungsten heat sink, which acts as a P-side, and the other side of diode cavity is wire bonded to a metal contact, which is the cathode. The hole in the middle is used for mounting purposes.

2. **TO3 package**

   The number of pins is up to 6 or 8. The base material is either CRS or CuW.

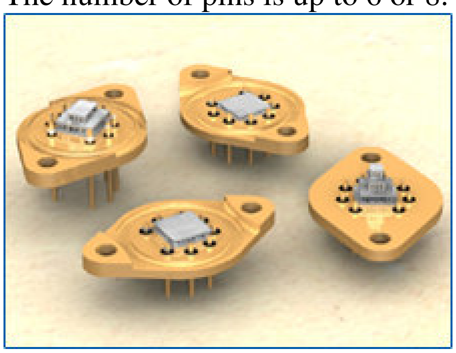

Fig. 9 Image of TO3 packages from RMT Ltd.

3. **VCSEL sub-module package**

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The vertical-cavity surface-emitting diode lasers are becoming popular during past three decades, due to its low cost and high reliability.
They are a great choice for short range data communications and networks.
Their output power and wavelength vary depending on application requirements.
Shown below on the right is the architecture of a VCSEL, the P-contact is a submount that is usually made of heatsink materials that have high thermal conductivity and close CTE match to the CTE of the GaAs die substrate, such as CuW, CuMo.

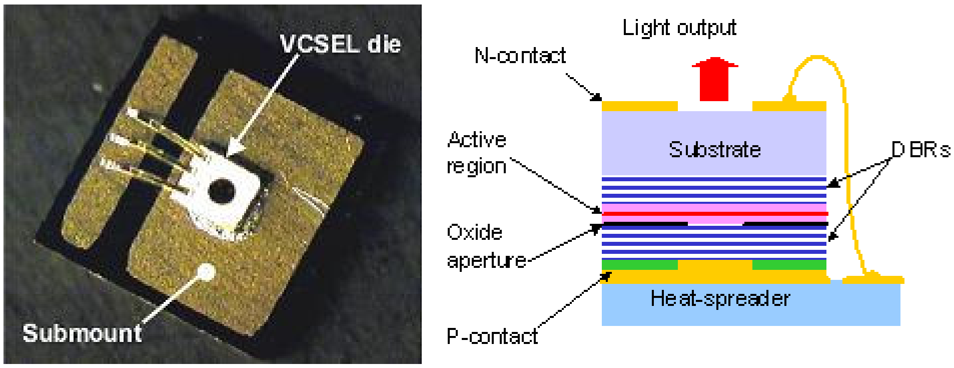

Fig. 10 On the left is an image of a high power VCSEL sub-module package from Princeton Optronics. Submount is 2x2mm and output power is >2W.

4. BTF (Butterfly) package

Butterfly packages is the standard format for optical Telecom transmissions and laser diode pumps. Below is a typical 14 pin butterfly package, in which the laser die sits on AlN submount. The AlN submount is mounted on a TEC, which is attached to a baseplate that is made of CuW, Kovar, or CuMo.

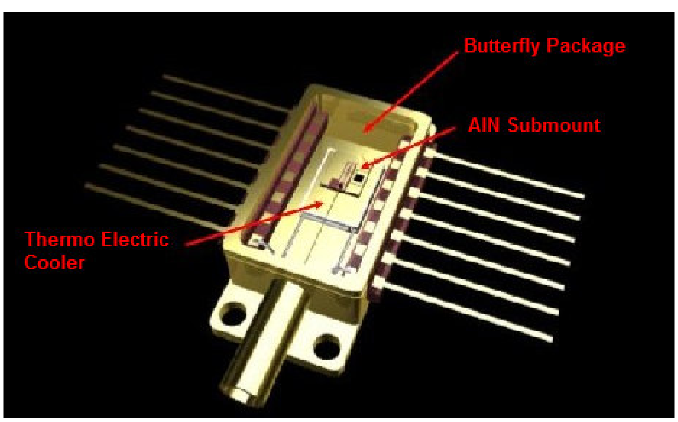

Fig. 11 Sample Butterfly package from Hitachi-HiTech.

5. Mini-DIL package

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The dual in line (DIL) packages is promising for Telecomm applications, and usually have 6 – 8 pins. The base can be various: CuW, CRS, or Alumina.

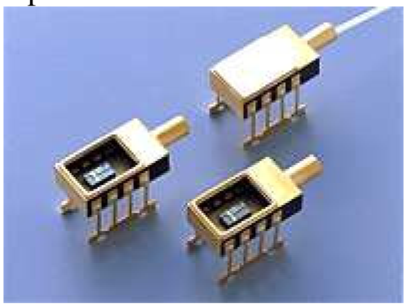

Fig. 12 Mini-DIL package from Hitachi-Hitech

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6. TOSA package

TOSA/ROSA package or transmitter/receiver optical sub-assembly are mainly for use with transceivers and transponders for data transmission purposes. Shown below is an example from Hitachi-Hitech. Their base are typically made of Copper Tungsten to accommodate the heat dissipation.

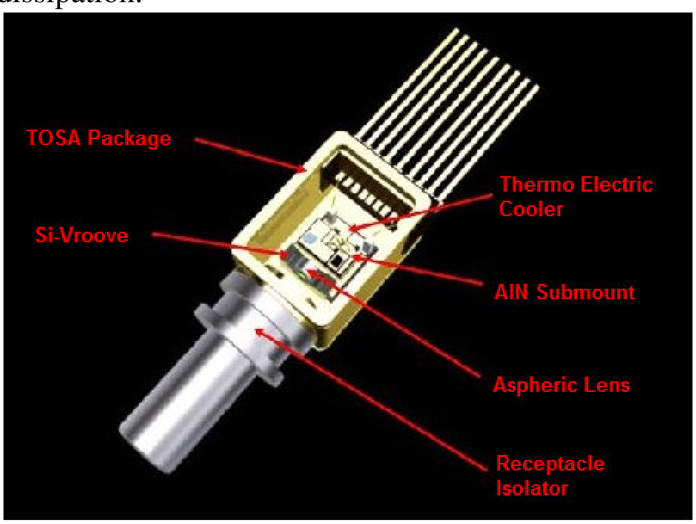

Fig. 13 Sample TOSA package from Hitachi-Hitech

7. HHL Package

HHL or High Heat Load packages are the largest standard laser diode packages available. They are designed for high power diode laser applications, and usually have 9 pins. The base material can be various: kovar, CuW, or CuMo.

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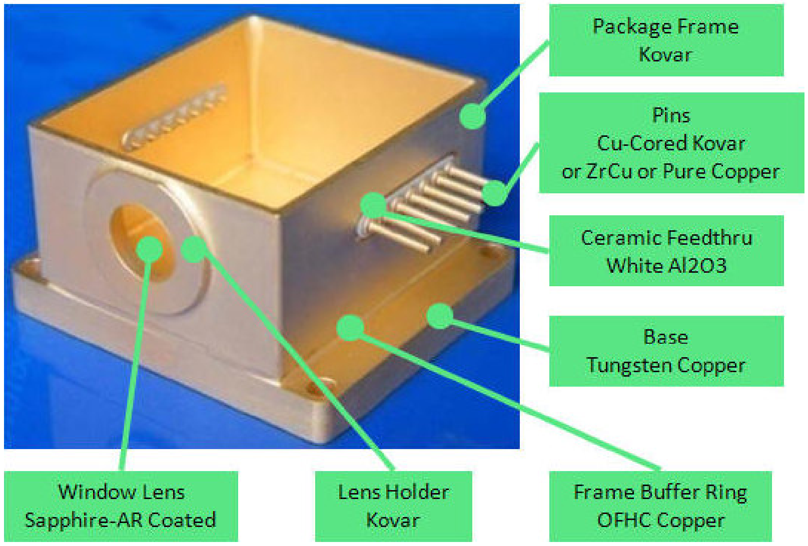


Fig. 14 Architecture of HHL package from Streamtek.

8. Golden/Silver Bullet Laser Array Submodules (ASM package)

Application: Typically used for solid state laser pumping
Typical wavelength: 803-808nm, 880nm, 885nm, 940nm (Golden bullet package)
800-1550nm (Silver bullet package)
Output power: 20-40W (CW), 50-300W (pulsed)

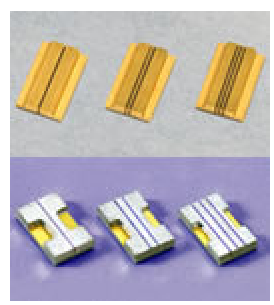


Fig. 15 Top are Golden Bullet packages and bottom are silver bullet packages. There are 1-bar, 2-bar, and 3-bar designs. The base is usually of ceramic coolers while the end-blocks on both sides are made of CuW for both thermal and electrical conduction.

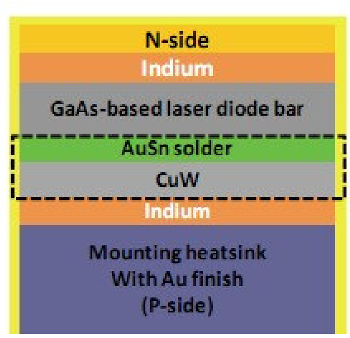
9. CCP Package (CS-mount)

Application: Conduction-cooled packaging (CCP) method for diode laser bar, used in laser systems or direct-diode application.

Typical wavelength: 806nm, 880nm, 885nm, 940nm

Output power: 20-40W(CW), 100 – 1600W(pulsed)

Typical material layer schematics:



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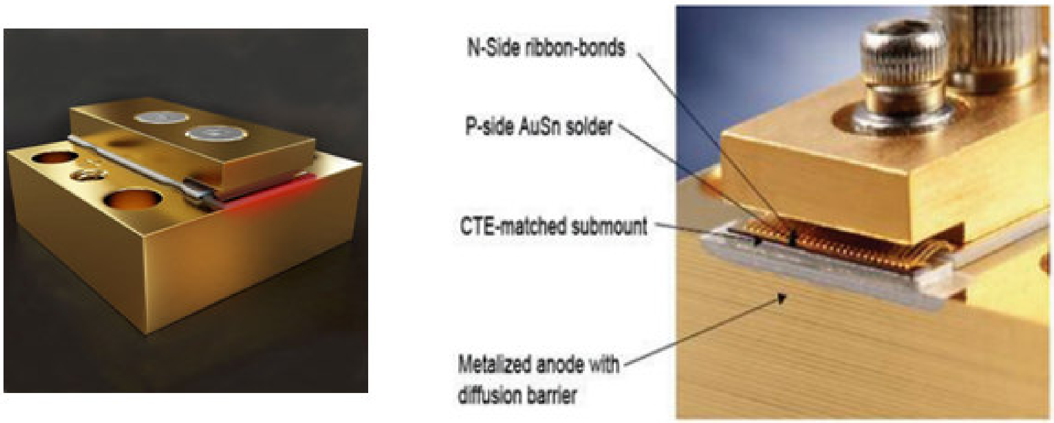

Fig. 16 Schematics of CS-mount.

Shown above is an example of laser die bonding in a CS type mount; a CTE-matched submount is added between the die and heatsink to serve as a buffer layer. The diode bar is bonded to CuW submount using gold/tin solder, which is mounted on a copper heatsink, acting as the P-side. The N-side is wired bonded to the P-side. The typical output power is 60-300W in either CW or QCW mode, makes it well suitable for solid-state pumping, direct-diode materials processing, medical, reprographics, and illumination applications.

10. CCP stacks (G-mount)

Applications: The high output power is suitable for applications such as military uses, rangefinding, sensing, and medical applications.
Typical wavelength: 808nm, 880nm, 885nm, 940nm
Output power: 20W (CW), 100-5200W (pulsed)
Below is the architecture of Coherent's Vertical diode laser array. Each diode bar is soldered to the CuW submount with AuSn solder on the P-side. N-side is connected with indium solder.

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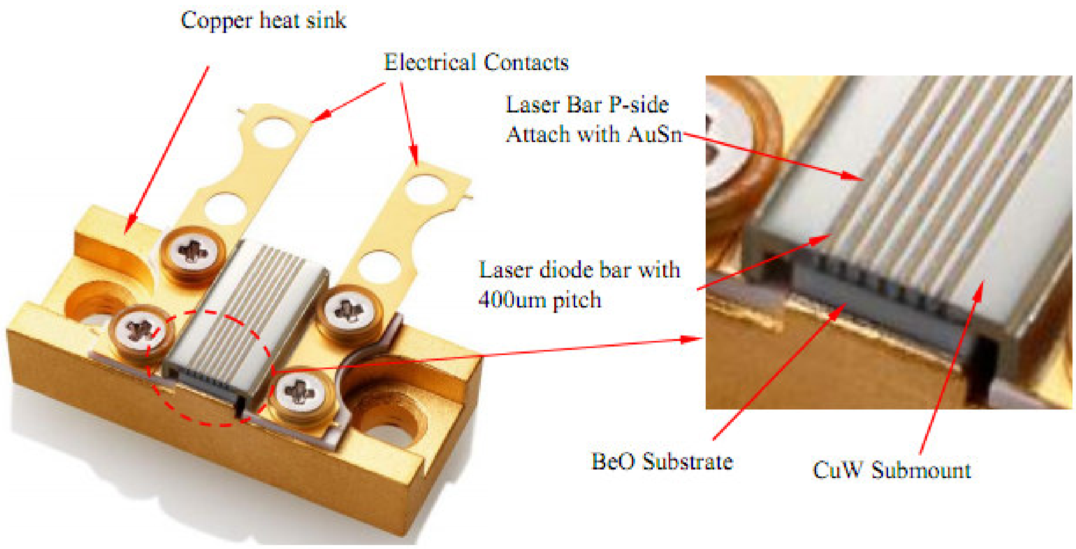

Fig. 17 Architecture of Coherent's 7-bar Vertical Array. Maximum peak power 1400W (200W/bar)

The submount is made of CuW composite due to its perfect thermal expansion match with the laser diode material(GaAs). The BeO layer allows for quick heat transferring onto the copper heatsink, while help maintain electrical insulation between diode and the heatsink.

11. Microchannel cooled package (MCCP)

Application**:** The high output power achieved by these packages can be used in laser pumping, military (rangefinding, light detecting), or medical applications.
Typical wavelength**:** 806-808nm, 880nm, 980nm
Output Power**:** 100-900W
Due to excellent thermal and electrical conduction of the CuW submount, and close CTE match with die material GaAs. The MCC package allows stacking of several high power laser diodes in an array using gold/tin solder, and the sub-assembly is then cooled using water cooling channels, as shown below.

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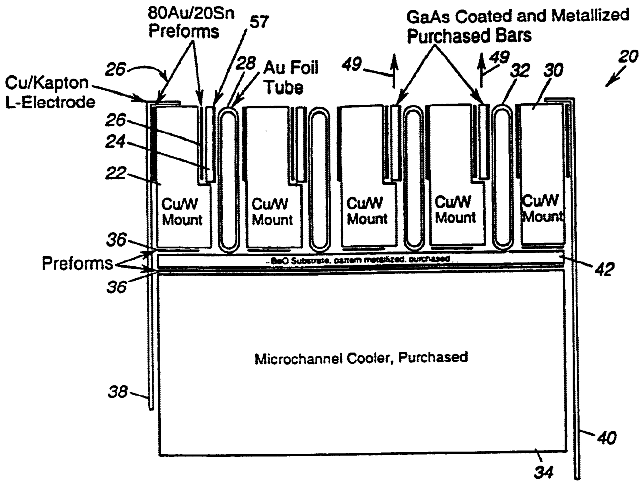

Fig. 18 Schematic Drawing illustrates a Micro-channel cooled diode-laser array by Pinneo, G..

Fig. 19 An example of a 6-bar MCC package from NG/CEO. Available both in CW or QCW bars with maximum power rating of 1800W.

Conclusion:

CuW is used in many places in laser packaging recently, especially in die chip submounts and heatsinks. Other techniques of joining copper tungsten to other metals such as kovar to form miniature heatsinks, sub-carriers, or sub assemblies suit applications that require light-weight design. As higher power laser diode devices emerge, the requirement for diode laser mounting is increased. Due to current technology trend in developing higher power diode lasers, the mounting substrate or heatsink has a significant impact on the performance of the diode laser system. Materials that were previously used cannot satisfy the thermal management requirement of diode lasers nowadays. Fortunately, copper tungsten provides high reliability for enclosing the electronic material from outside

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environment, as well as providing an improved thermal conductivity for mounting and integrating high power laser diode devices.

Appendix

Definition of Continuous Wave (CW) and Quasi-CW from RP Photonics

1. CW – continuous wave operation of a laser means that the laser is continuously pumped and continuously emits light. The emission can occur in a single resonator mode (→ *single-frequency operation*) or on multiple modes.

2. QCW (pulsed) - In continuous-wave operation, some lasers exhibit too strong heating of the gain medium. The heating can then be reduced by quasi-continuous-wave operation, where the pump power is only switched on for limited time intervals. Quasi-continuous-wave (quasi-cw) operation of a laser means that its pump source is switched on only for certain time intervals, which are short enough to reduce thermal effects significantly, but still long enough that the laser process is close to its steady state, i.e. the laser is optically in the state of continuous-wave operation. The duty cycle (percentage of "on" time) may be, e.g., a few percent, thus strongly reducing the heating and all the related thermal effects, such as thermal lensing and damage through overheating. Therefore, quasi-cw operation allows the operation with higher output peak powers at the expense of a lower average power.

   Pulsed operation with significantly shorter pumping times, where an optical steady state is not reached, is called *gain switching*.

   Quasi-continuous-wave operation is most often used with diode bars and diode stacks. Such devices are sometimes even designed specifically for quasi-cw operation: their cooling arrangement is designed for a smaller heat load, and the emitters can be more closely packed in order to obtain a higher brightness and beam quality. Compared with ordinary continuous-wave operation, additional lifetime issues can result from quasi-cw operation, related e.g. to higher optical peak intensities or to frequent temperature changes.

   Some doped-insulator solid-state lasers are also operated in quasi-cw operation. Such lasers are sometimes called *heat capacity lasers*.

   QCW operates at typically higher frequency kHz (ns-ms pulse) compared to pulsed Hz. Mostly, QCW is used to extend battery life or reduce heat. QCW and pulsed are usually implemented by adding laser diode driver to control the input for different applications.

3. Types of Laser diode structures from Computer Desktop Encyclopedia.

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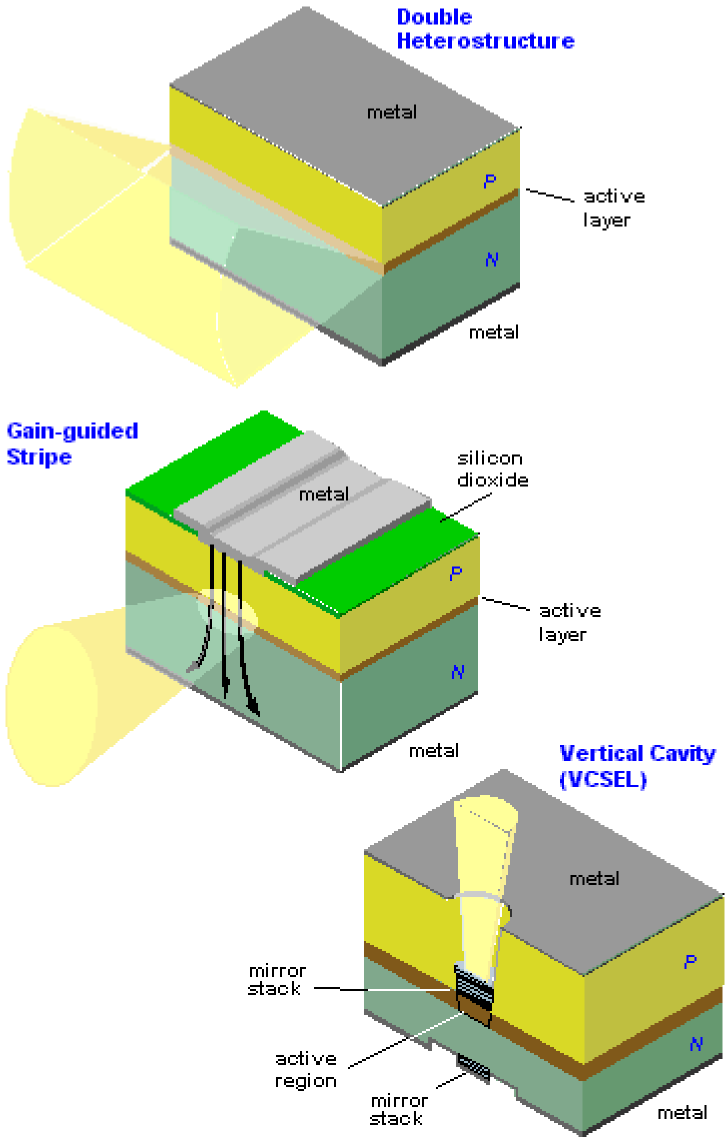

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