Packaging diode laser arrays. Why and how

Edge-emitting semiconductor laser arrays (or laser bars) are surely the best-known and still the most widespread architecture of high power diode lasers (HPDLs). Under an electron-pumping scheme, these structures are nowadays capable of generating up to 500 W of CW optical power within an overall active material volume below 0.01 mm^3. Although the electro-optical efficiency of such devices can easily surpass 50 % (especially for diode lasers based on GaAlAs and InGaAs), the portion of energy not converted into light is almost equally high. This translates into a huge amount of energy that must be dissipated from the laser device in the form of heat. Otherwise, the active medium would melt in a few microseconds. For this reason, heat dissipation is probably the major concern in HPDL mounting technology. The heat generated is firstly transmitted by conduction to the surrounding substrate volume, which is normally between 1 and 4 mm^3. However, the heat rate is too high for such a small volume, and further dissipating steps are mandatory in order to spread the heat through a larger volume of material before it can be finally removed by the environment (typically forced convection towards air or water). Moreover, this needs to be a fast enough process to avoid excessive temperature rise at the active medium. Copper is the natural choice for such application, since it allows excellent electron conductivity, and shows the second largest thermal conductivity among all metals ($\kappa \sim 385\ W \cdot m^{-1} \cdot K^{-1}$). It is slightly surpassed by silver ($\kappa \sim 405\ W \cdot m^{-1} \cdot K^{-1}$), but silver is not an option for obvious commercial reasons. From the beginning of semiconductor laser technology, copper has been used as the preferred sub-mount material, but then the next technical challenge appeared: how to establish a proper interface between the laser bar and the copper heat sink? Soldering was the first answer, and it is still the most adopted technology. But soldering brings along several inherent problems...

The interface material chosen for soldering purposes must have a melting temperature well below the melting points of both the laser bar and the heat sink. Besides, it must be high enough to guarantee thermal and mechanical stability over the operation temperature of the laser diode (typically between 15 ºC and 80 ºC). Indium was the first material employed with this purpose ($T_{melt} \sim 157$ ºC). However, the soldering process implies to create a solid joint between the laser bar and the copper heat sink around the indium melting temperature, and since the three material involved show different coefficients of thermal expansion (CTE), the device will always present a residual stress when it cools down to room temperature[1].

[1] $CTE_{In} = 33\ \mu m \cdot m^{-1} \cdot K^{-1}$; $CTE_{Cu} = 17\ \mu m \cdot m^{-1} \cdot K^{-1}$; $CTE_{GaAs} = 5\ \mu m \cdot m^{-1} \cdot K^{-1}$

Smile in laser diode arrays. A serious problem

One of the most important implications of this is the appearance of the *smile* phenomena, which means that bar suffers a curvature, causing the emitters within the array not lasing perfectly parallel to the horizontal axis. Instead, a separation in height ranging from 2 μm to 5 μm (typically) appears from the bottom to the top emitter (see Figure 1). This distance is usually the best measure to define *smile* magnitude. The *smile* in laser bars is critical whenever external resonator configurations are required or simply if maximum brightness is demanded from the fast axis.

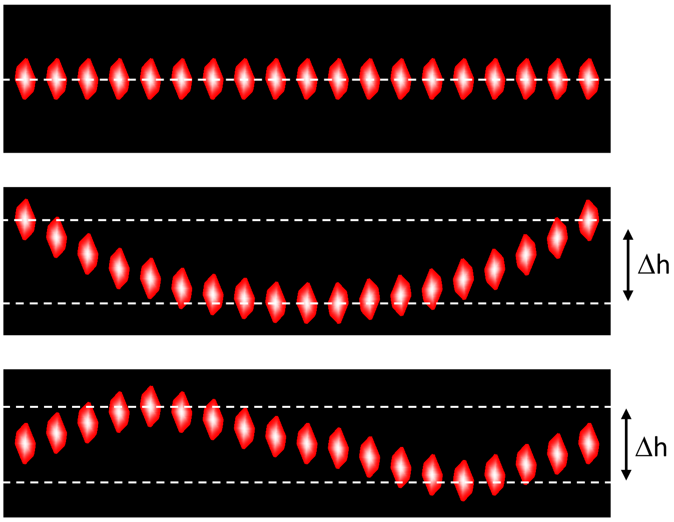

Figure 1. Theoretical emission intensity pattern after fast axis collimation and slow axis imaging of a 19-emitter laser bar. Top image corresponds to a *smile*-free laser bar. The two bottom images correspond to two different kind of *smile* effect.

External resonator configurations

To build an external resonator using a laser bar is an appealing strategy used mainly to increase power brightness or spectral brightness of the laser bar itself. High spatial brightness (W·cm^{-2}·sr) is pursued in high power diode lasers when industrial applications like metal cutting, drilling or soldering come into play. Besides, high spectral brightness (W· cm^{-2}·sr·nm^{-1}) and low wavelength thermal shift (nm·K^{-1}) are typically related to solid state laser pumping applications. In the case of power brightness, the external feedback is created with a reflective diffraction Bragg grating (see Figure 2). The result of such approach is the effective spatial superimposition of all the laser beams outcoming from the laser bar, as if all the intensity was coming from a single emitter within the laser bar. As a consequence, the spatial brightness is increased by an order of magnitude. However, this can be achieved at the expense of enlarging the emission bandwidth (lower spectral brightness) and admitting a certain percentage of power and optical losses (ranging from overall 20 % to 40 % reduction in power w.r.t. free beam operation). Inherent (and unavoidable) optical losses are attributed to the efficiency of the diffraction grating and the transmission of the lenses. But most importantly, optical losses are also affected by how the laser beam hits back the emitter after part of its intensity is bounced back at the outcoulping mirror (feedback emission from the external resonator). The larger the *smile* effect, the higher the losses (see Figure 3 and Figure 4).

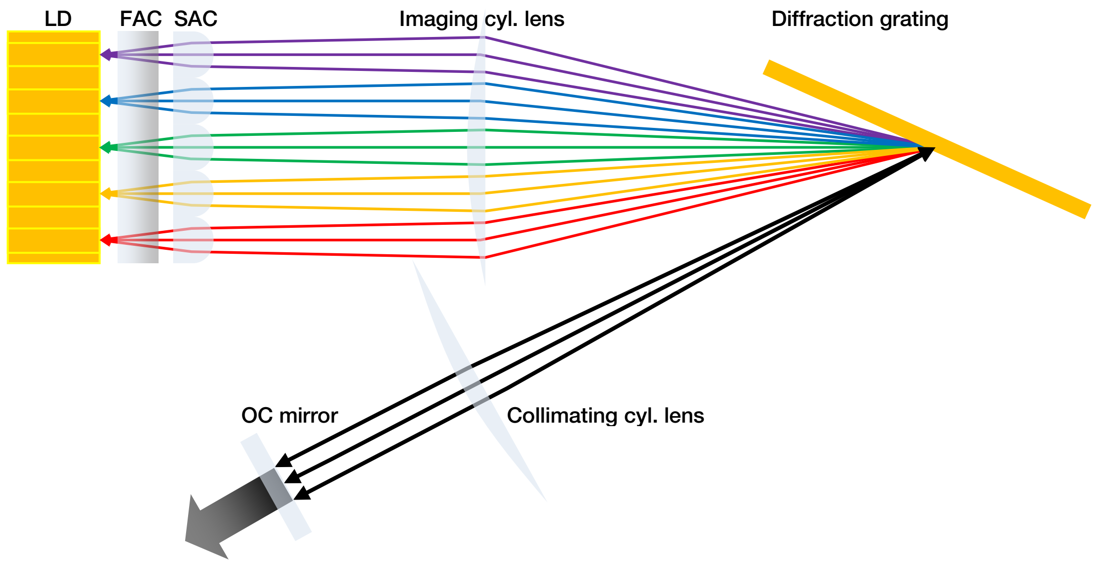

Figure 2. Basic scheme illustrating the spectral beam combining principle. Spatially separated emitters emitting at slightly different wavelengths impinge the diffraction grating at different incident angles. However, the diffracted angle is common to all of them (different colours are used here just to illustrate the difference in wavelength but they are not representative of the wavelength itself).

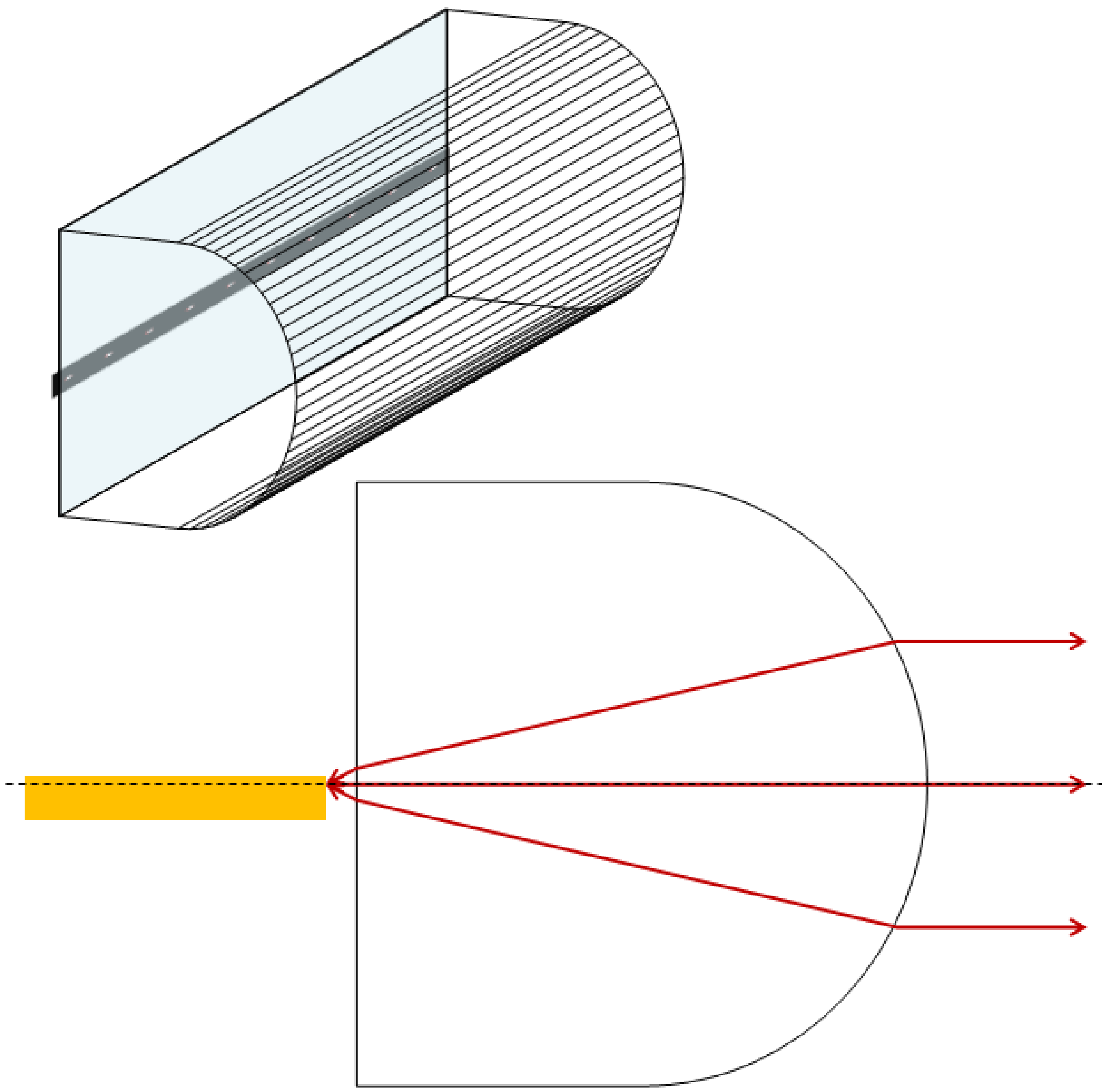

Figure 3. The emitters of a laser bar with no *smile* are contained within the plane defined by the fast axis and the optical axis of the system. As a consequence, the emitted laser beams and its partially-reflected counterpart (feedback) are spatially coincident in an external resonator configuration.

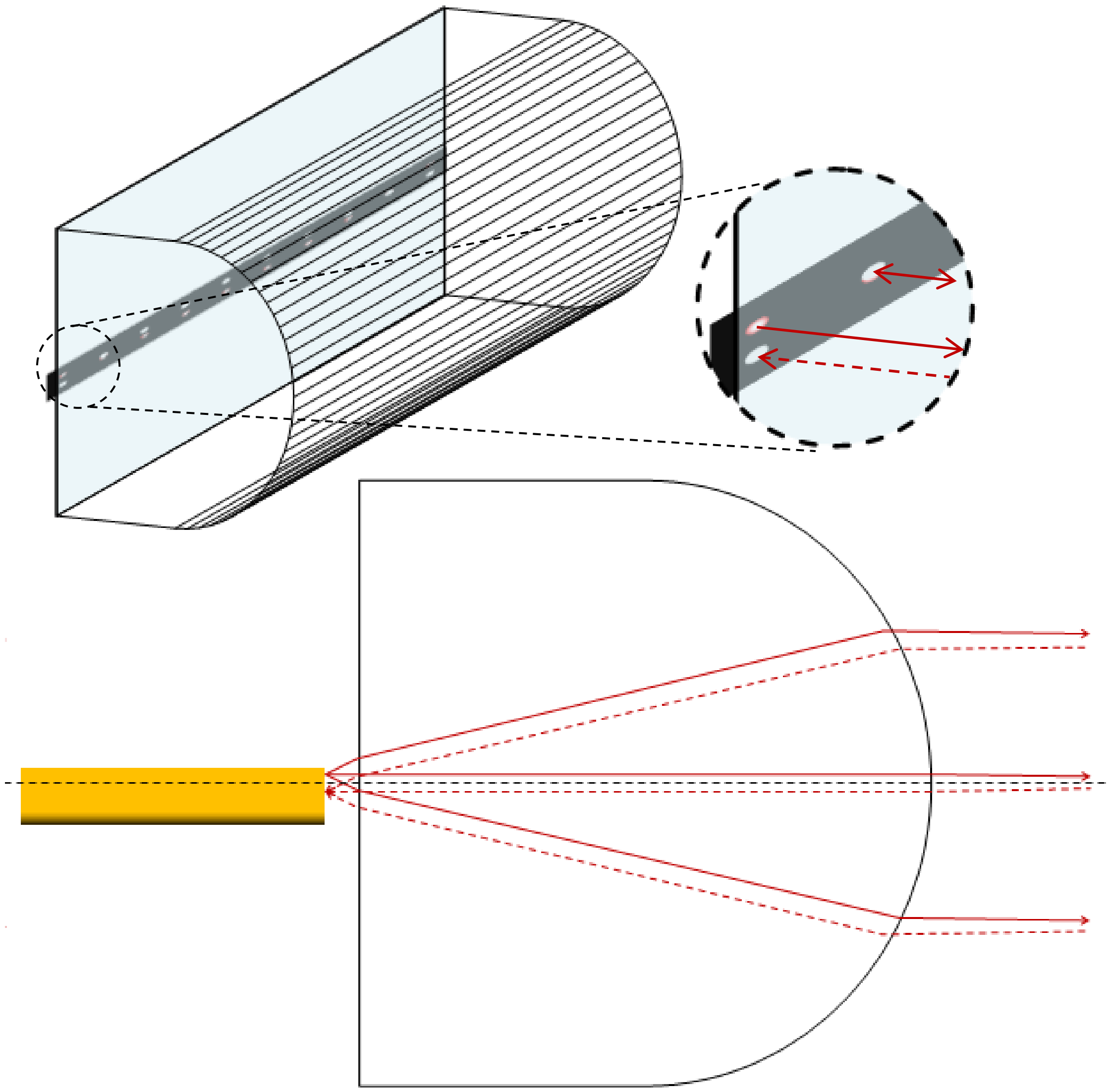

Figure 4. Most of the emitters in a laser bar with *smile* are partially or totally out of the plane defined by the fast axis and the optical axis of the system. This results in a partial lack of optical feedback in an external resonator configuration (most of the emitted and feedback beams are partly or totally non-coincident).

In the case of spectral brightness improvement, usually volume Bragg gratings (VBGs) are placed in front of a fast axis collimated laser bar. Again, an external feedback is required by the Bragg grating, which now acts narrowing and "locking" the emission wavelength of the whole laser bar. The effect is a remarkable reduction in the wavelength shift w.r.t. temperature, from 0.3 $nm \cdot K^{-1}$ to less than 0.08 $nm \cdot K^{-1}$, in a similar way as it happens with distributed feedback lasers (either applied on the diode structure itself or by an optical fibre coupled to it). The question here is that having a laser diode array, the absence of *smile* is crucial in order to have uniform feedback on each emitter, especially if we consider that the optical elements are common to all the emitters (see Figure 3).

Fast axis brightness

Laser emission in the fast axis is inherently almost diffraction-limited ($M^2 \sim 1$). This represents an outstanding advantage in many applications where maximum brightness is demanded along a line-shaped laser spot. Such is the case of offset laser printing (computer-to-print machines). Nevertheless, the presence of *smile* effect in a laser bar can reduce overall fast axis brightness easily between 50 % and 80 %. The main reason is that the apparent height of a laser source in the fast axis gets increased proportionally to the *smile*. From a practical perspective, the consequences of placing a fast axis collimator (FAC) lens in front of the laser bar is either obtaining a higher residual divergence or a larger focused spot (see Figure 5).

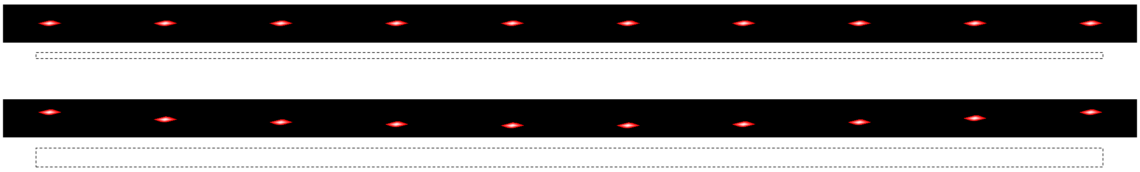

Figure 5. Near-field representation of a 10-emitter laser bar with no smile (top) and with 3 µm *smile* effect (bottom). The apparent size (represented by the dashed frames below) is enlarged in the fast axis due to the *smile*.

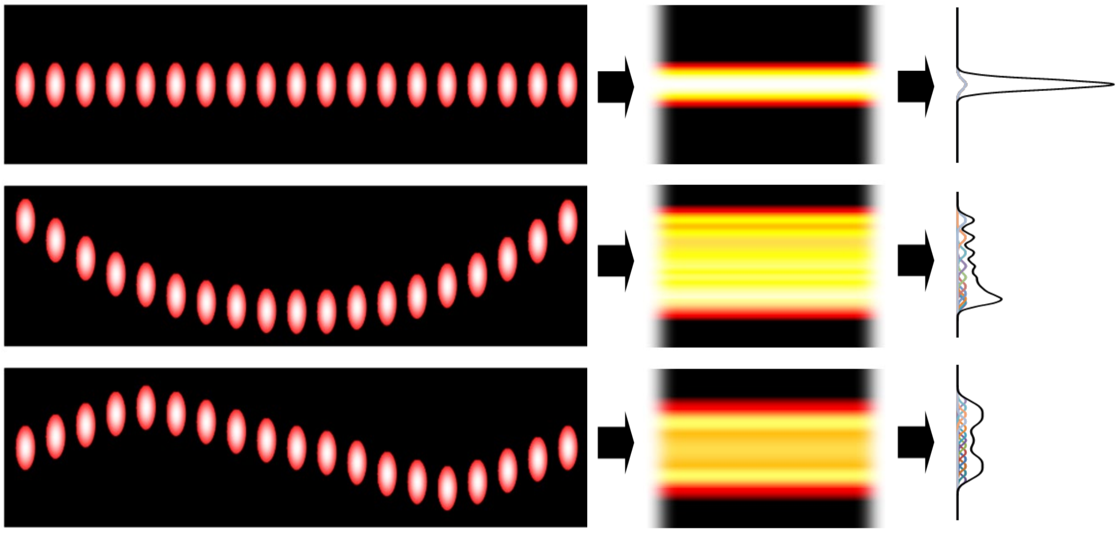

Figure 6. Different *smile* patterns (left) yield different fast axis intensity profiles under fast axis collimation (middle). The far field intensity profile along the fast axis is the result of superimposing as many line-shaped spots as emitters within the laser bar (right).

Smile suppression. What are the alternatives?

Despite the challenge, the HPDL industry found ways to overcome *smile* effect. The most extended solution is called “hard-soldering”. This consists of using a AuSn alloy as the interface material, and CuW as the heat sink[2]. This way, the CTE of the semiconductor, heat sink metal and soldering interface are much closer, the joint is even more reliable than in the case of indium, and the *smile* effect is minimized. However, nothing here is for free. CuW shows a remarkable reduction of thermal conductivity compared to copper (around 50 % lower), a far lower degree of machinability and far higher cost. As a consequence, usually CuW is used just as an intermediate volume between the laser bar and the actual heat sink, which is made of copper indeed. This adds further thermal resistance jumps to the laser diode package. In the end, the advantages of such an approach are restricted to a few set of applications.

So, what can be done apart from indium and hard-soldering? The ultimate alternative has been shown and demonstrated by Monocrom for the last 20 years, and it relies on an extremely simple concept: mechanical pressure (Clamping™). However, as the reader might guess, conceptual simplicity does not necessarily imply easy engineering, and for this reason Monocrom remains as the only company able to bring such a revolutionary approach to laser diode packaging. Clamping™ technology relies (mainly) on a superior surface finish of the copper heat sink, and the establishment of direct thermal and electrical contact with the laser bar, enhanced by the application of mechanical force. While soldered bars are contacted to the p-side by the heat sink (anode) and wire-bonding to the n-side (cathode), clamped bars are “sandwiched” from both sides by bulky heat sinks acting as the anode and cathode.

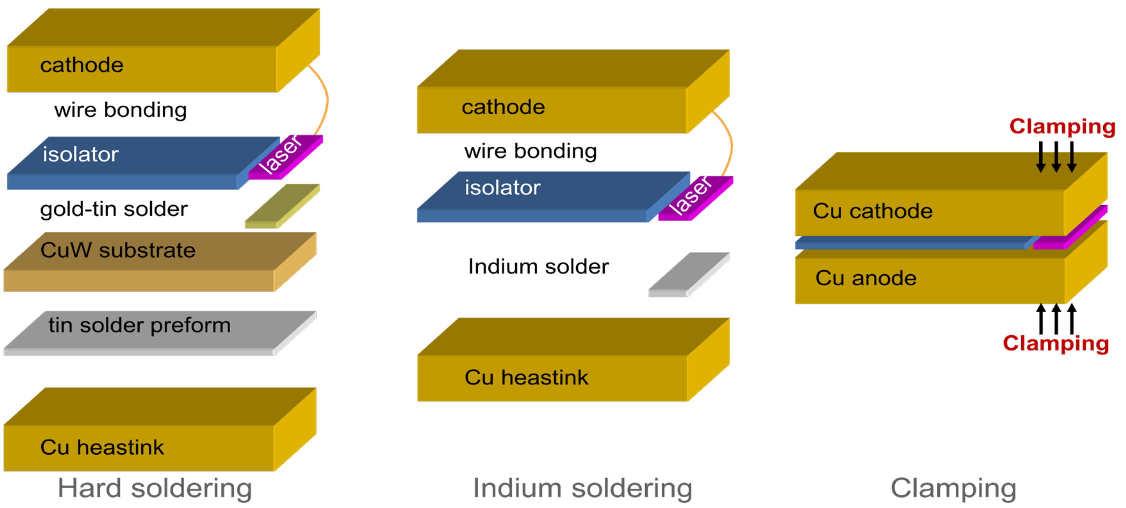

Figure 7. Comparison between the most common soldering approaches for laser bar packaging and Clamping™ technology.

The advantages of Clamping™ are numerous:

- Cold process. No residual stress is caused by dissimilar CTE, so the *smile* is limited to the surface flatness achieved in the heat sink (typically <0.5 µm over 1 cm²).

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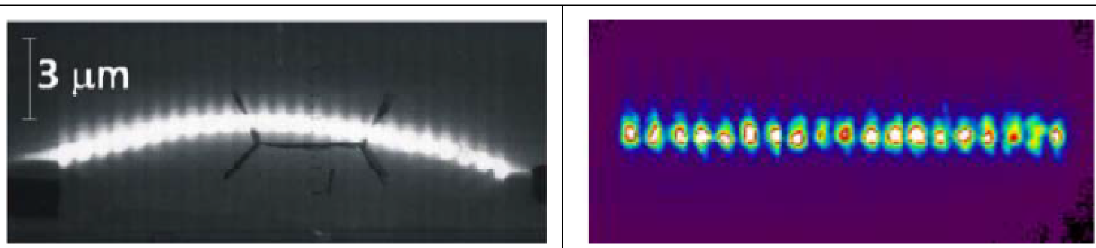
[2] $CTE_{Au(80)Sn(20)}$ = 16 µm·m^{-1}·K^{-1}; CTE_{CuW} = 5-9 µm·m^{-1}·K^{-1}

- Minimum thermal resistance jumps. Heat is directly evacuated from the laser bar to the heat sink. Only the contact resistance between copper and the semiconductor material must be accounted from a technical point of view.

- Heat is dissipated from both p and n side, adding an extra path for heat dissipation. Additionally, this allows the use of water/glycol cooling channels machined on both electrodes in the case of CW and high duty QCW operation. Likewise, this fact relaxes the requirement for micro-channel cooling. Millimetre-sized channels can be used instead, which are less corrosion sensitive and consequently allows to minimise maintenance.

- Simplicity and cost reduction. There is no interface material involved and no soldering equipment. Mechanical force is applied by the operator by means of a stainless steel screw. The key is on the perfect surface finish of the copper heat sink (but of course this is not the only one).

- Superior performance in pulsed mode. The lack of horizontal residual stress eliminates the fatigue suffered by the joint and the laser bar during successive on/off cycles, enhancing the service life of the device.



Soldered bar smile >1µm	Clamped bar smile 0,1µm

Figure 8. Typical intensity profile of the individual emitters (fast axis collimation plus slow axis imaging) within a soldered laser bar (left) and a clamped laser bar (right).

In conclusion, Clamping™ can be seen as a smart solution to a challenging packaging problem, which has been successfully implemented at Monocrom as part of the standard manufacturing process.