High Power Diode Lasers

Low Power Lasers

(below tenth of mW)

- Laser as a telecom transmitter;
- Laser as a spectroscopic sensor;
- Laser as a medical diagnostic tool;
- Laser as a write-read tool;
- Laser as bar code reader,

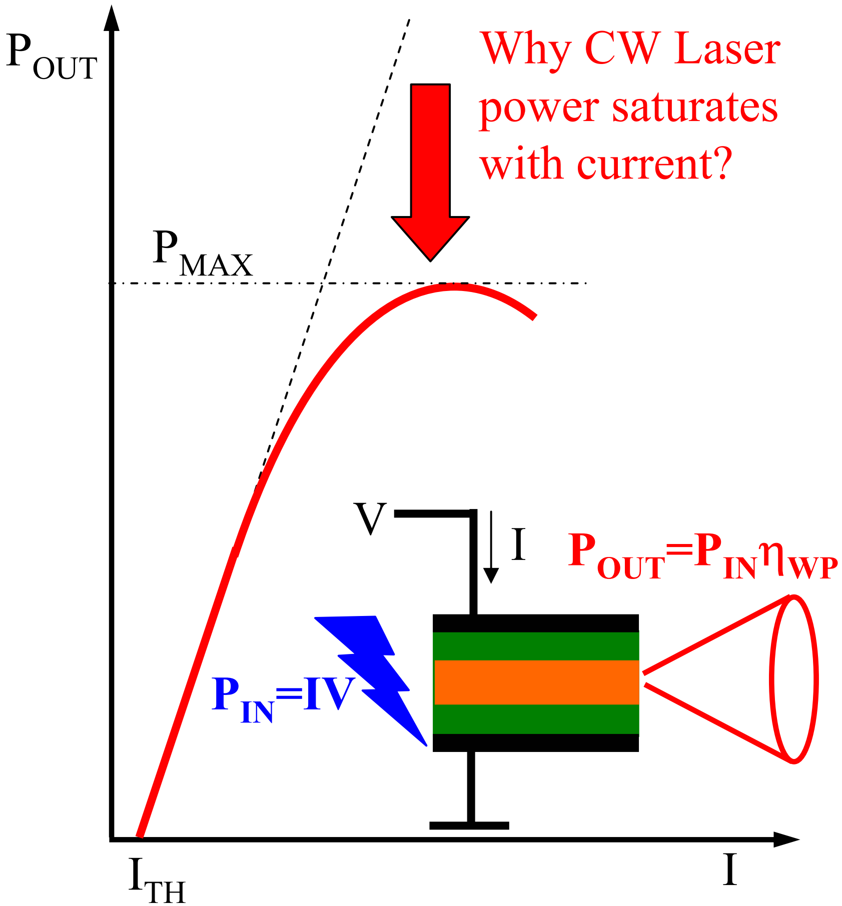
etc.

High Power Lasers
(up to tens of kW)

- Laser as a industry tool;
- Lasers as a pumping source;
- Laser as a surgery instrument;
- Laser as a weapon;
- Laser as a free space transmitter,

etc.

What limits diode laser CW output power ?



Power conversion efficiency (η_{WP}) for diode lasers is the highest among all other types of light emitters but it is still below ~ 60%

$$\eta_{WP} = \frac{P_{OUT}}{P_{IN}} = \frac{\frac{h\nu}{q} \cdot \frac{\alpha_m}{\alpha_m + \alpha_i} \cdot \eta_i \cdot (I - I_{TH})}{I \cdot V}$$

The part of P_{IN} will be dissipated in the form of heat.

Heat must be removed by proper heatsink with given thermal resistance R_{TH}.

$$R_{TH} = \frac{\Delta T}{P_{IN} - P_{OUT}}$$

ΔT – laser overheating

$$\Delta T = R_{TH} \cdot (P_{IN} - P_{OUT}) = R_{TH} \cdot (1 - \eta_{WP}) \cdot P_{IN}$$

Laser threshold current increases and efficiency decreases with ΔT. At certain current, rise of the threshold and reduction of efficiency will outweigh pumping increase and laser output power will start to go down with current. There is the current which corresponds to maximum power (P_{MAX}).

How to increase P_{MAX} ?

1. To decrease $\Delta T = R_{TH} \cdot (P_{IN} - P_{OUT}) = R_{TH} \cdot (1 - \eta_{WP}) \cdot P_{IN}$

-Development of highly efficient heatsink technologies and laser mounting techniques to reduce R_{TH}

-Improve laser wall-plug efficiency

$$\eta_{WP} = \frac{P_{OUT}}{P_{IN}} = \frac{h\nu}{qV} \cdot \frac{\alpha_m}{\alpha_m + \alpha_i} \cdot \eta_i \cdot \left(1 - \frac{I_{TH}}{I}\right) \qquad * V = V_{QW} + I \cdot R_{SER} = \frac{h\nu}{q} + I \cdot R_{SER}$$

-Reduce extra voltage drop across the laser heterostructure;

-Reduce the laser internal loss, $\alpha_i \rightarrow 0$;

-Improve laser injection efficiency, $\eta_i \rightarrow 100\%$;

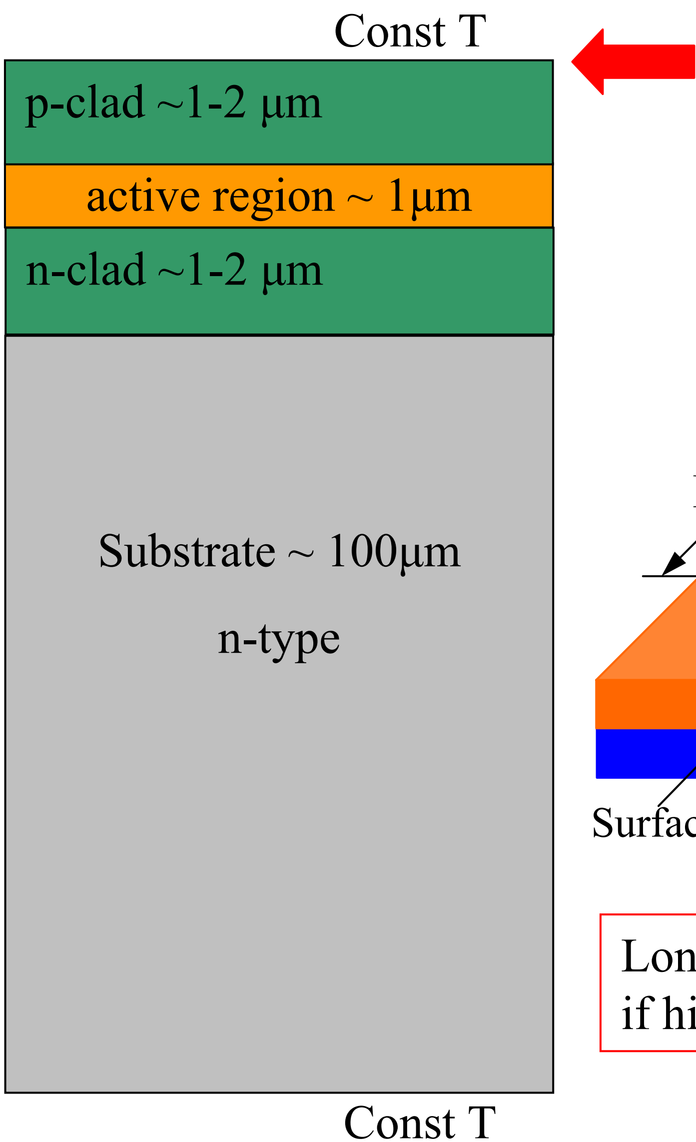
-Reduce Threshold current, $I_{TH} \rightarrow 0$

2. To decrease laser temperature sensitivity

-Suppress carrier leakage that is responsible for temperature dependence of η_i, i.e. increase T_1

-Minimize effect of nonradiative recombination on threshold concentration, i.e. increase T_0

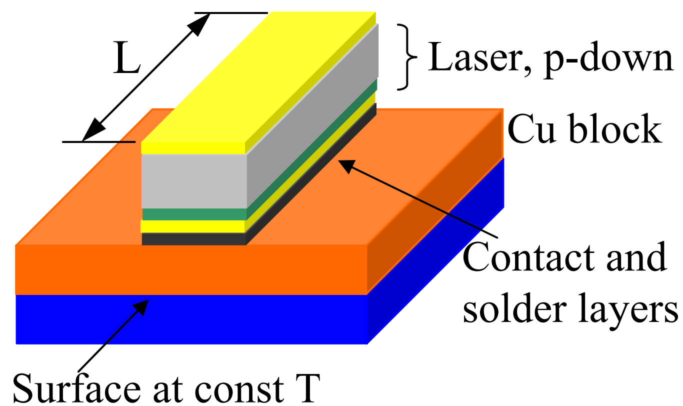
Laser mounting and heatsinking



To eliminate the substrate thermal resistance we have to mount laser p-side down.

For high power operation p-side down mounting is a must!

The thermal resistances of solder layer and heatsink itself must be taken into account – typical value of net thermal resistance is of order of several K/W per 100μm-wide laser diode.



$$R_{TH} \propto \frac{1}{\text{cavity length, } L}$$

Long cavity lasers are preferable for high power operation, if high laser efficiency value can be preserved.

Broadened waveguide design

Increase of the cavity length, L, reduces R_{TH} but affects laser efficiency.

$$\alpha_m = \frac{1}{2 \cdot L} \cdot \ln\left(\frac{1}{R_1 \cdot R_2}\right)$$

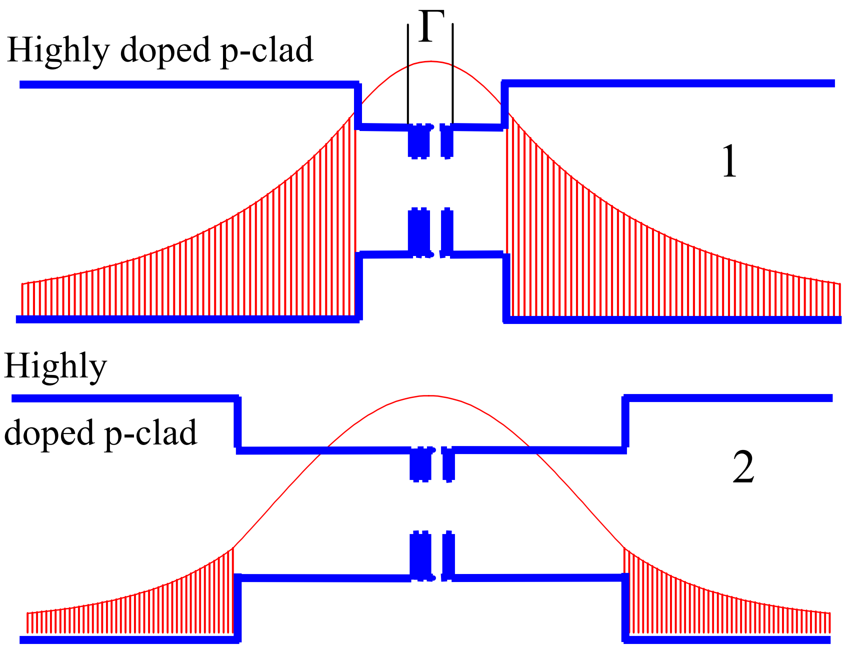
$$\eta \propto \frac{1}{1 + \alpha_i / \alpha_m}$$

As mirror losses decrease relative role of internal loss increases and laser efficiency drops down

The laser internal loss

The internal losses are related to free carrier absorption. An important absorption mechanism is “intervalence band absorption” (IVBA) related to transitions between HH and SO valence subbands.

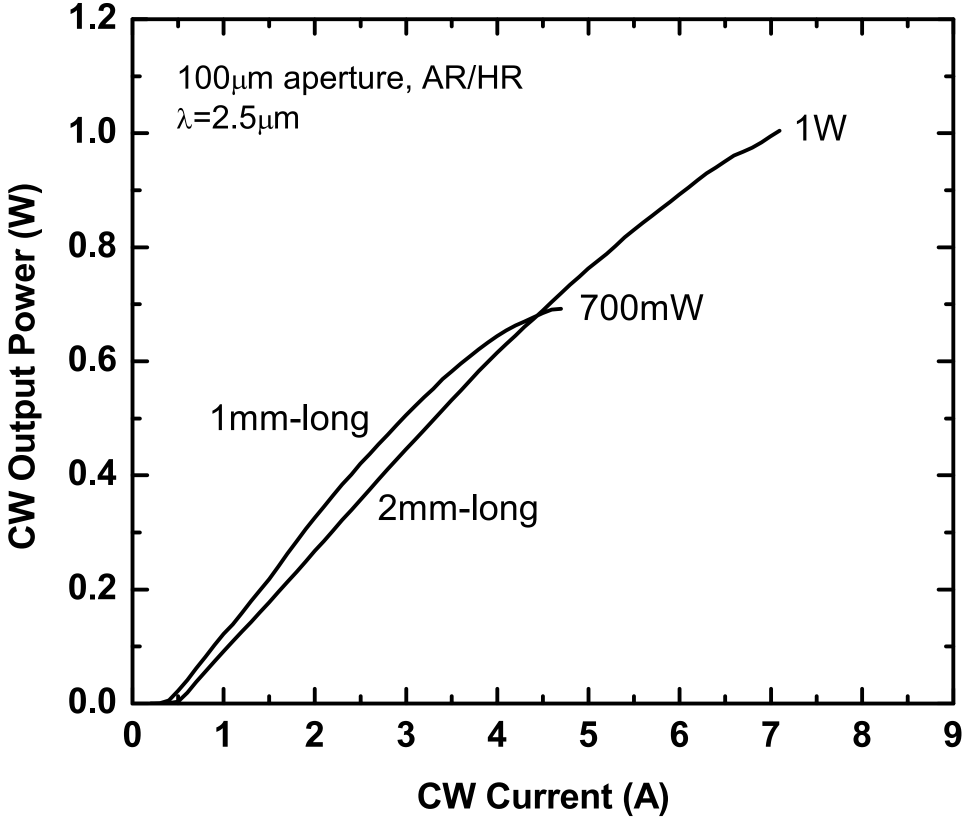
The main contributions into the net internal loss comes from absorption within highly doped cladding regions



Confinemnt factor Γ for broadened waveguide devices is slightly reduced but the losses decrease dramatically resulting in net decrease of the threshold current density.

The efficiency of the broadened waveguide lasers are less sensitive to cavity length increase and long cavity lasers can be used for high power applications.

Effect of the L increase on maximum output power of 2μm GaSb-based laser.



CW performance of high power lasers with broadened waveguide and low internal loss < $4cm^{-1}$. Devices were In soldered p-side down on water cooled Cu blocks. Water temperature ~ 15^0C.

R_{TH} and R_S ~1/area

Laser overheating depends on operating current density J.

$$\Delta T = R_{TH} \cdot \left(I \cdot V_{QW} + I^2 \cdot R_S - P_{OUT}\right) = \\ = \rho_{TH} \cdot \left(J \cdot V_{QW} + J^2 \cdot \rho_S - P_{OUT}/area\right)$$

*ρ_{TH} and ρ_S are thermal and series resistances per unit area

The use of long cavity increases the device maximum CW output power.

R_{TH} can has more complex dependents on contact area due to edge effects.

Minimization of the carrier loss and reduction of the threshold current

$$P_{OUT} = \eta \cdot (I - I_{TH})$$

Current flowing through the lasers until threshold is reached produces only heat

Threshold current density must be minimized !

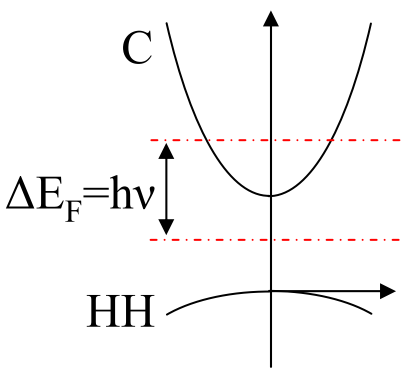
Threshold current = Transparency current + Extra current to overcome loss

Transparency current

Current required to reach transparency concentration in QWs, i.e. $\mathbf{\Delta E_F=(E_e)_F-(E_h)_F=E_g=h\nu}$

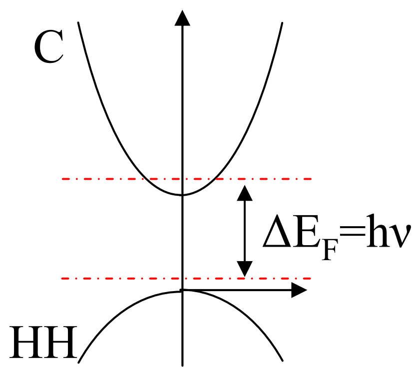
1. Number of quantum wells should be minimized because QWs are "connected in parallel".
2. Compressively strained QWs to be used to reduce difference in effective masses.

No strain, $m_e << m_{hh}$



$I_{TR} \sim n \cdot p = n^2$

Comp. Strain, $m_e \sim m_{hh}$



$n \downarrow$ and $I_{TR} \downarrow$

Extra current

Current required to reach $\mathbf{g = \Gamma G_{TH} - \alpha_{tot} = 0}$

$$G_{TH} = \frac{\alpha_{tot}}{\Gamma} = \frac{dG}{dI} \cdot (I_{TH} - I_{TR})$$

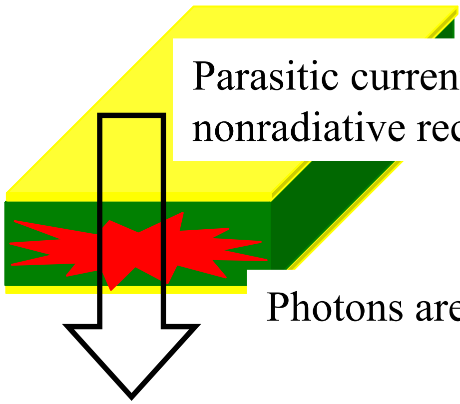
1. Threshold material gain must be reduces .
2. Compressively strained QWs must be used to reduce difference in effective masses between holes and electrons thus increasing differential gain (dG/dI)

High power laser is the low internal loss devices with minimum possible number of compressively strained QWs.

Facet load and catastrophic optical damage, mirror passivation

By proper laser design very high value of the P_{MAX} can be achieved ~ 10W per 100µm aperture. This corresponds to power density at the output mirror of about **10 MW per cm² !!!** This power will burn and melt metals when absorbed.

What happens at laser mirror?



1. Nonradiative recombination on surface defects leads to slow mirror overheating proportional to laser operating current.
2. When semiconductor temperature in the vicinity of mirror goes up photons start to absorb effectively due to thermal decrease of the semiconductor band gap.
3. Absorption of light leads to more heat and positive feedback loop closes up melting output mirror down fast. When laser is turned off mirror cools down but initial semiconductor structure will never recover and dark regions will be formed. This effect is called catastrophic optical damage (COD).

Different semiconductor laser structures have different thresholds for COD. The most sensitive is Al containing devices. A lot of research efforts were spent to design high power lasers with Al-free active region and many approaches to passivating mirror surfaces were developed.

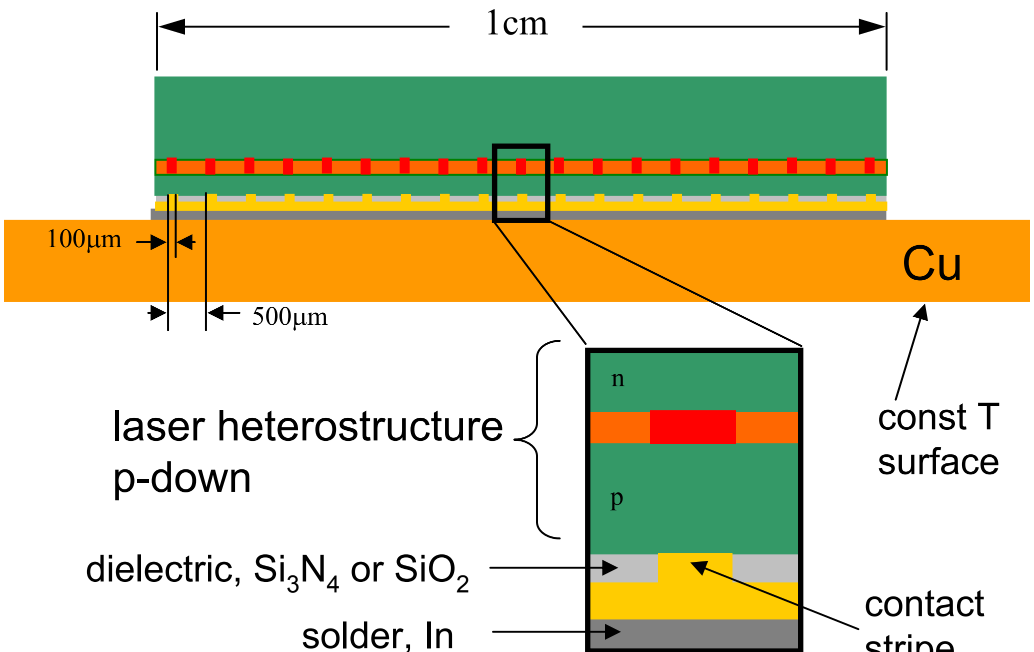
AR, $\lambda/4n$, $n = \sqrt{n_{eff}}$ - ideal

HR Bragg stack $\lambda/4n$

* Large index step is desirable to decrease number of layers

High power lasers are usually AR/HR (3-5%/95%) coated to direct all power to one mirror. The higher is the output power, the lower absorption coefficient the mirror coatings should have. Development of extra-low absorption optical coatings is now very important research direction due to numerous applications in solid state and semiconductor lasers industries.

1D diode laser arrays



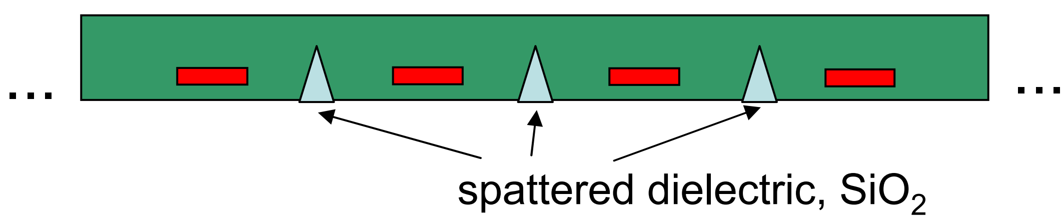
1D laser array is laser bar with emitters defined by metal contact stripes.

Important parameters is bar fill-factor. It is ratio of the net emitting aperture to bar lateral length.

The example: 20% (100µm stripe with 500µm center-to-center spacing)

The larger is the bar fill-factor the larger is the emitting aperture and the larger is total power. With current contact area increase operating current increases and overheating can take place. There is optimum value of the fill-factor determined by laser temperature sensitivity, threshold current density and hetasink performance as well as operating regime type: CW or QCW.

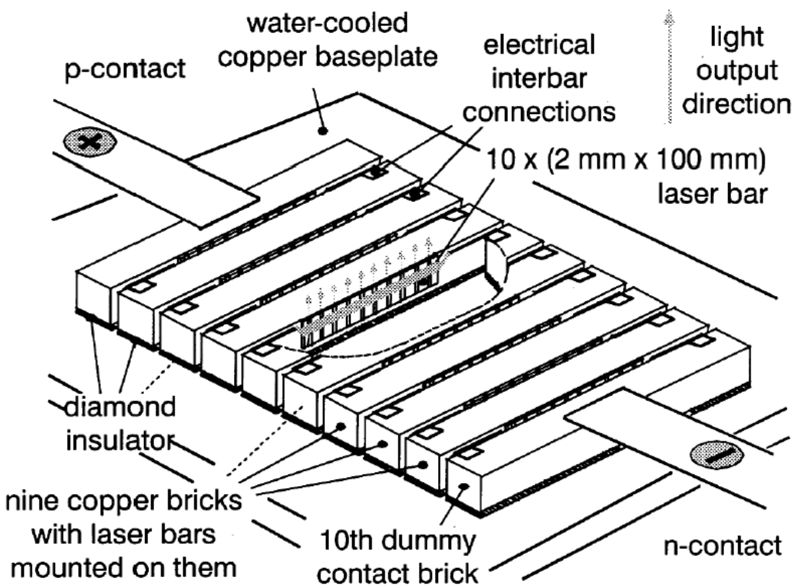
* for large values of the bar fill-factor laser bar can become transparent in lateral direction and its output power will saturate. Spoiling lateral cavity groves must be etched – additional processing step.



2D diode laser arrays

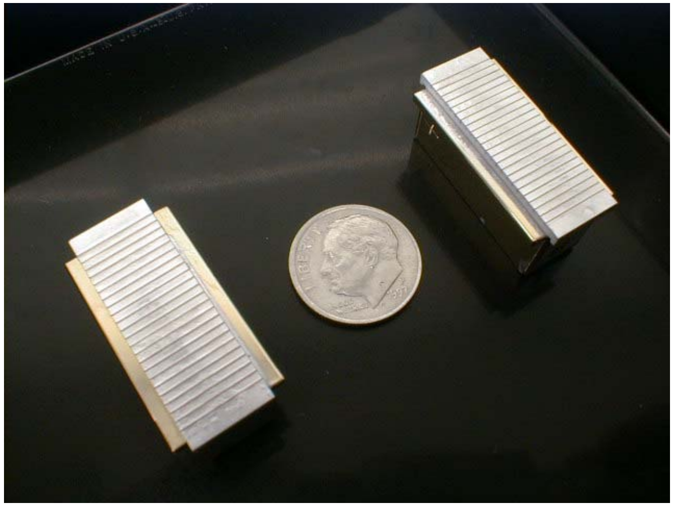
Laser bars can be stack in 2D arrays.

Rack and stack configuration

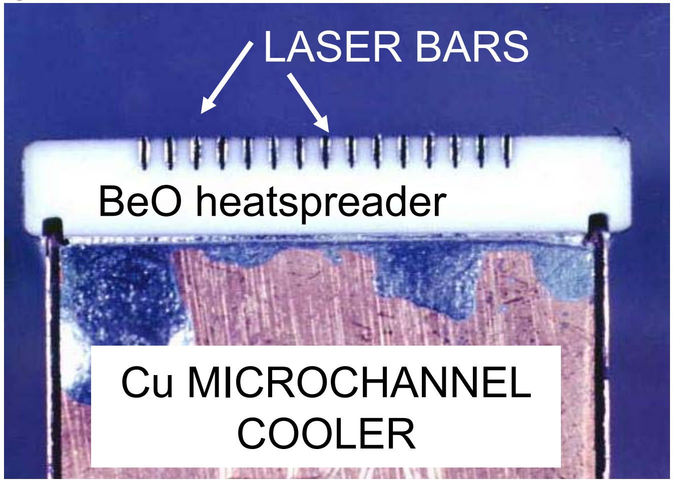


2D laser arrays can produce hundreds watt of CW output power. 2D arrays can be further combined into stacks of array and produce total power of >10kW in relatively compact package.

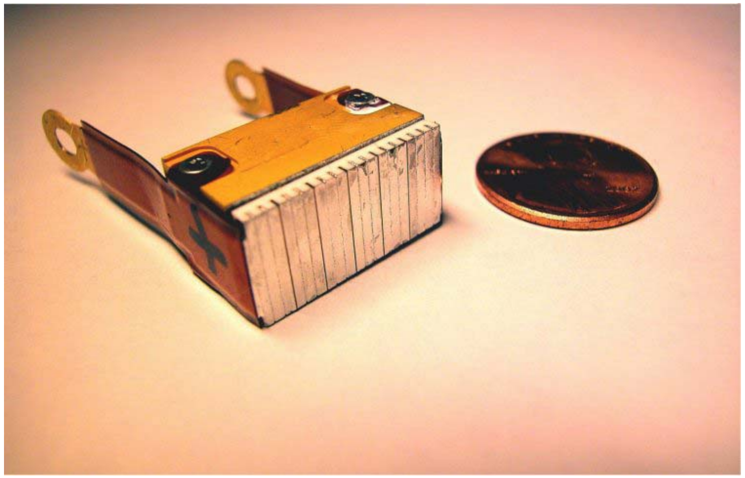
Advanced package, R_{TH}~0.4K/W

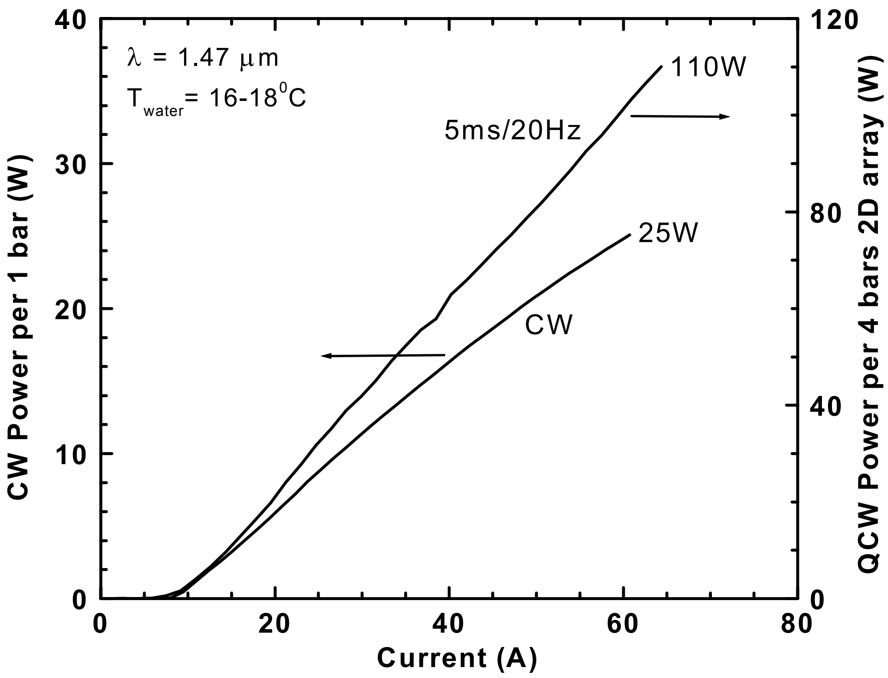


SIDE VIEW

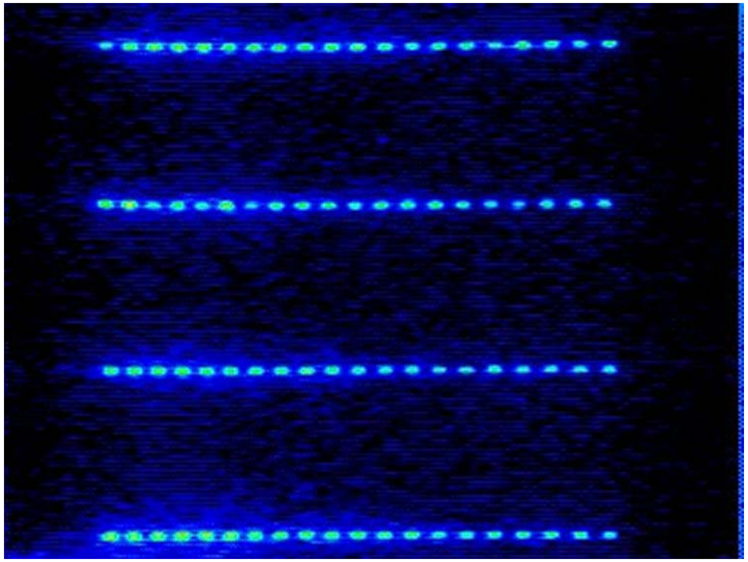


2D diode laser arrays





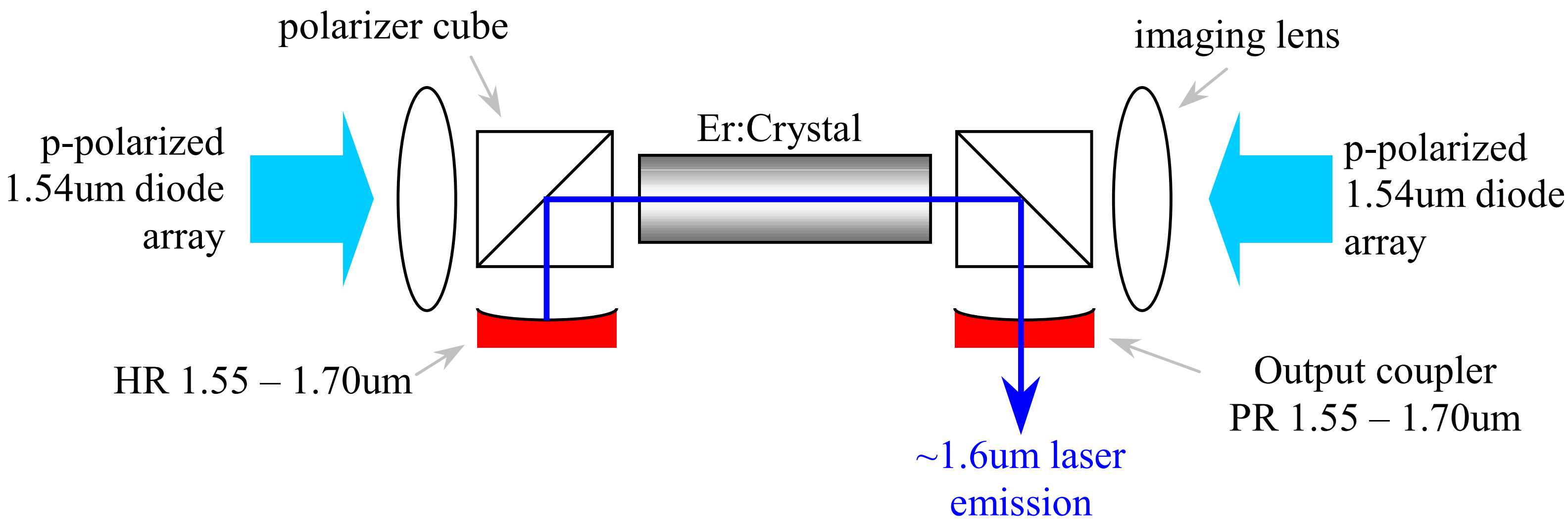
IR image of the laser array near field

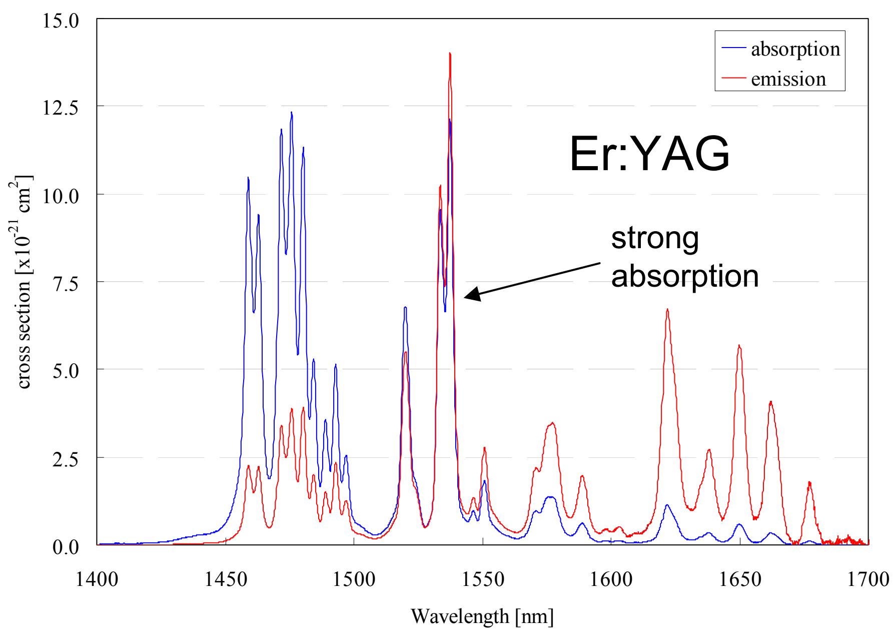


Performance of 1D and 2D 1.47µm laser diode arrays. Array were packaged into microchannel cooled heatsink and operate at CW and QCW conditions.

Bar fill-factor was 20% (100um/500um) and bars were spaced by ~1.5mm.

Diode pumped solid state laser





Novel 1.6um Er^+ laser

(research and development stage.)

Er atoms in crystal absorb 1.54um radiation provided by diode laser and then emit photons with ~1.6um wavelength.