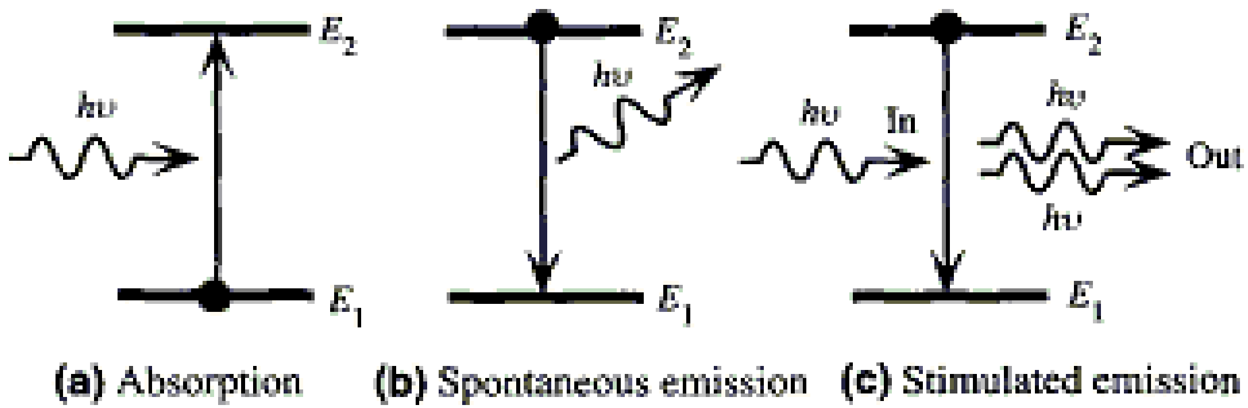
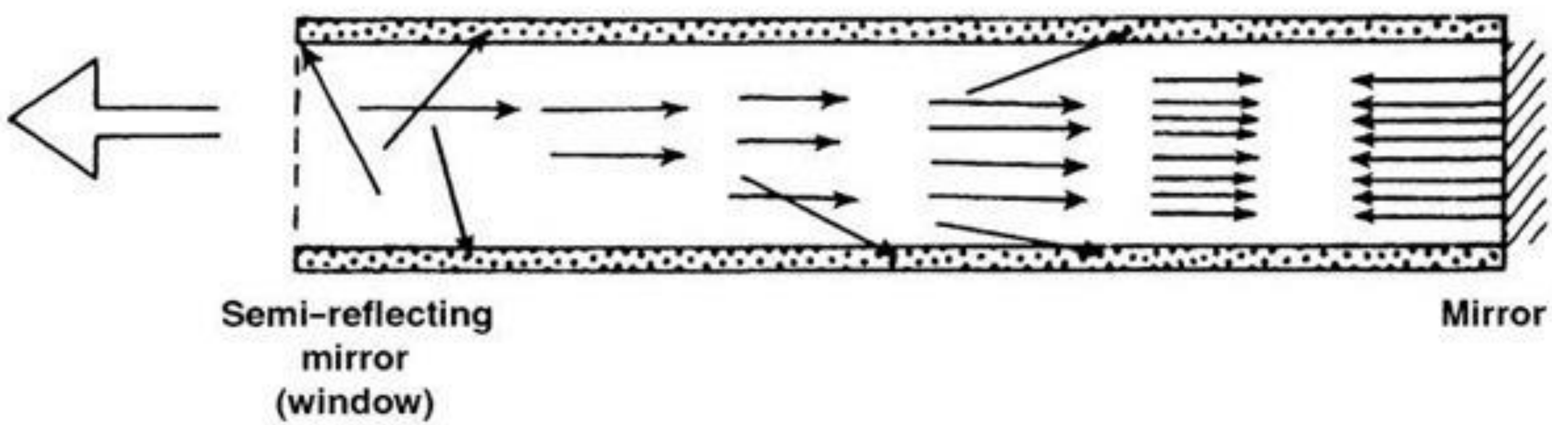
DYNAMICS OF MODE-LOCKED SEMICONDUCTOR LASERS

John Gerard McInerney
Physics Dept/Tyndall National Institute, UCC
College of Optical Sciences, University of Arizona

Photonics and semiconductor lasers
Mode-locking and ultrashort pulses
Stabilization by optical feedback and injection
Novel scalable optically pumped VECSEL experiments

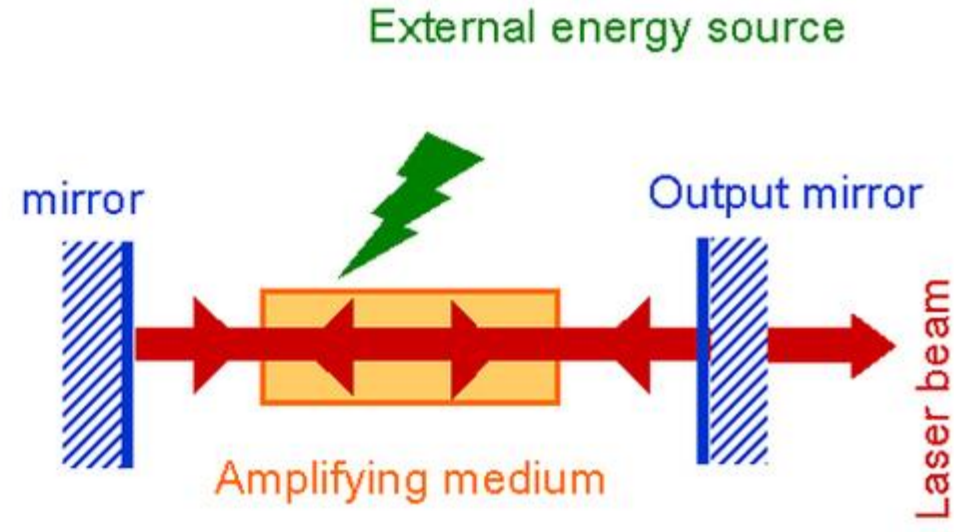
Radiative processes in 2-level systems

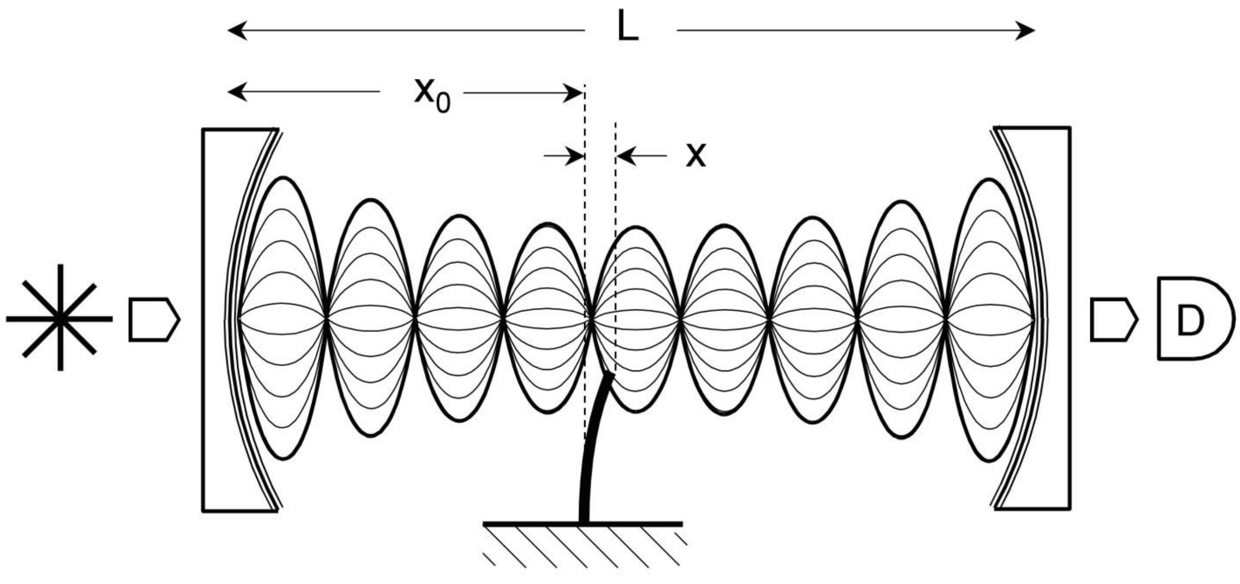




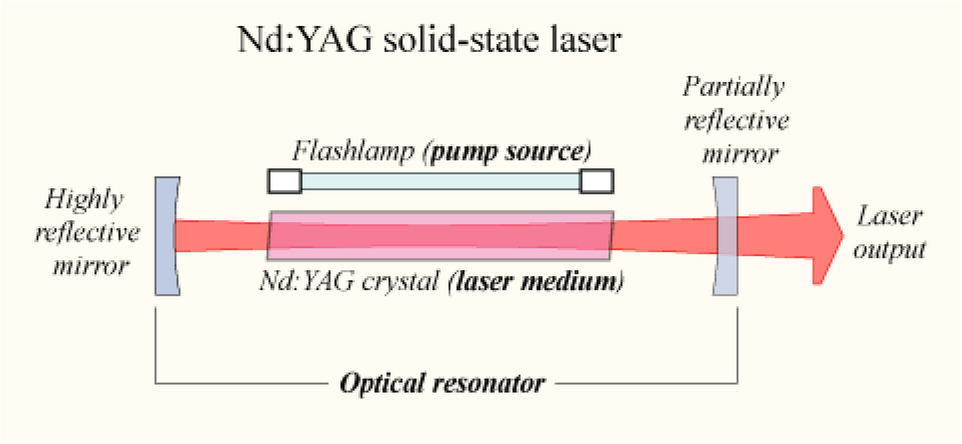
Strong stimulated emission requires population inversion + cavity

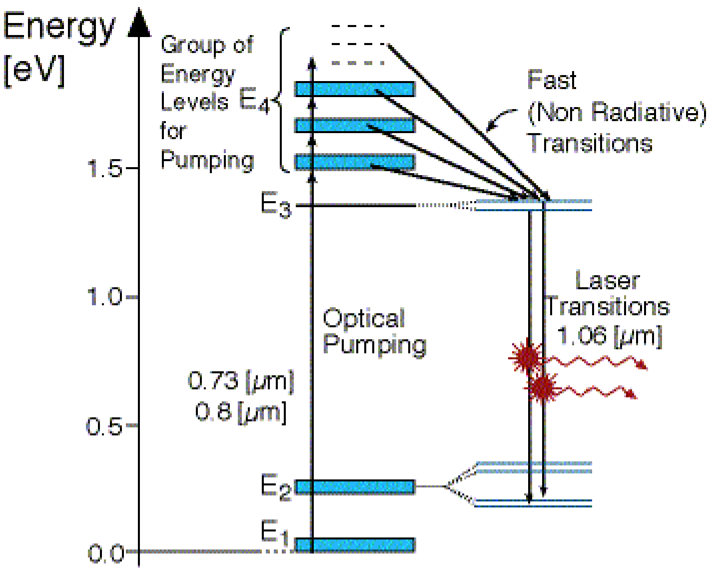
Laser = pump + amplifier + cavity

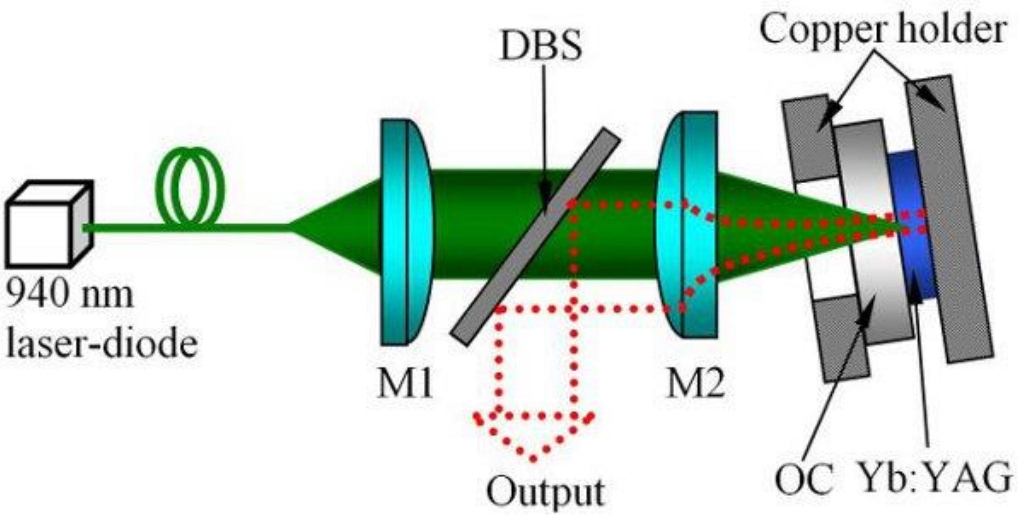




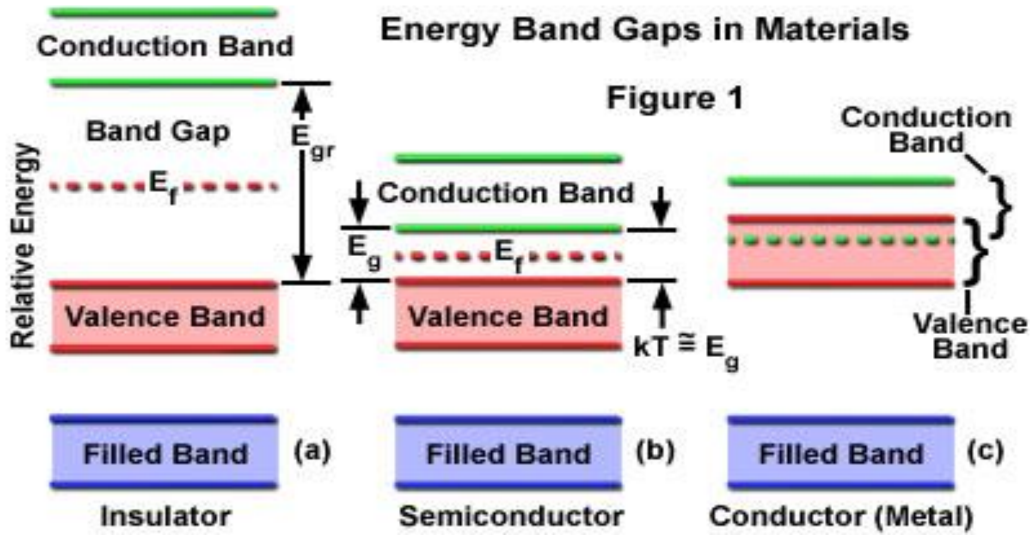
Typical lasers: solid state (Nd:YAG)

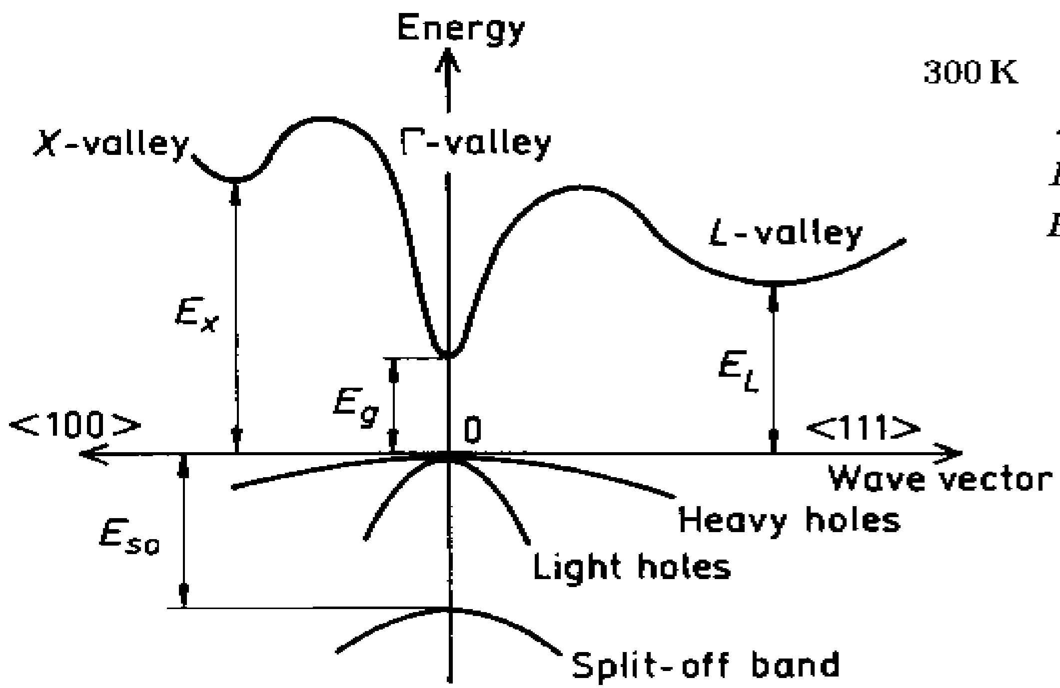






Semiconductor gain media eg GaAs





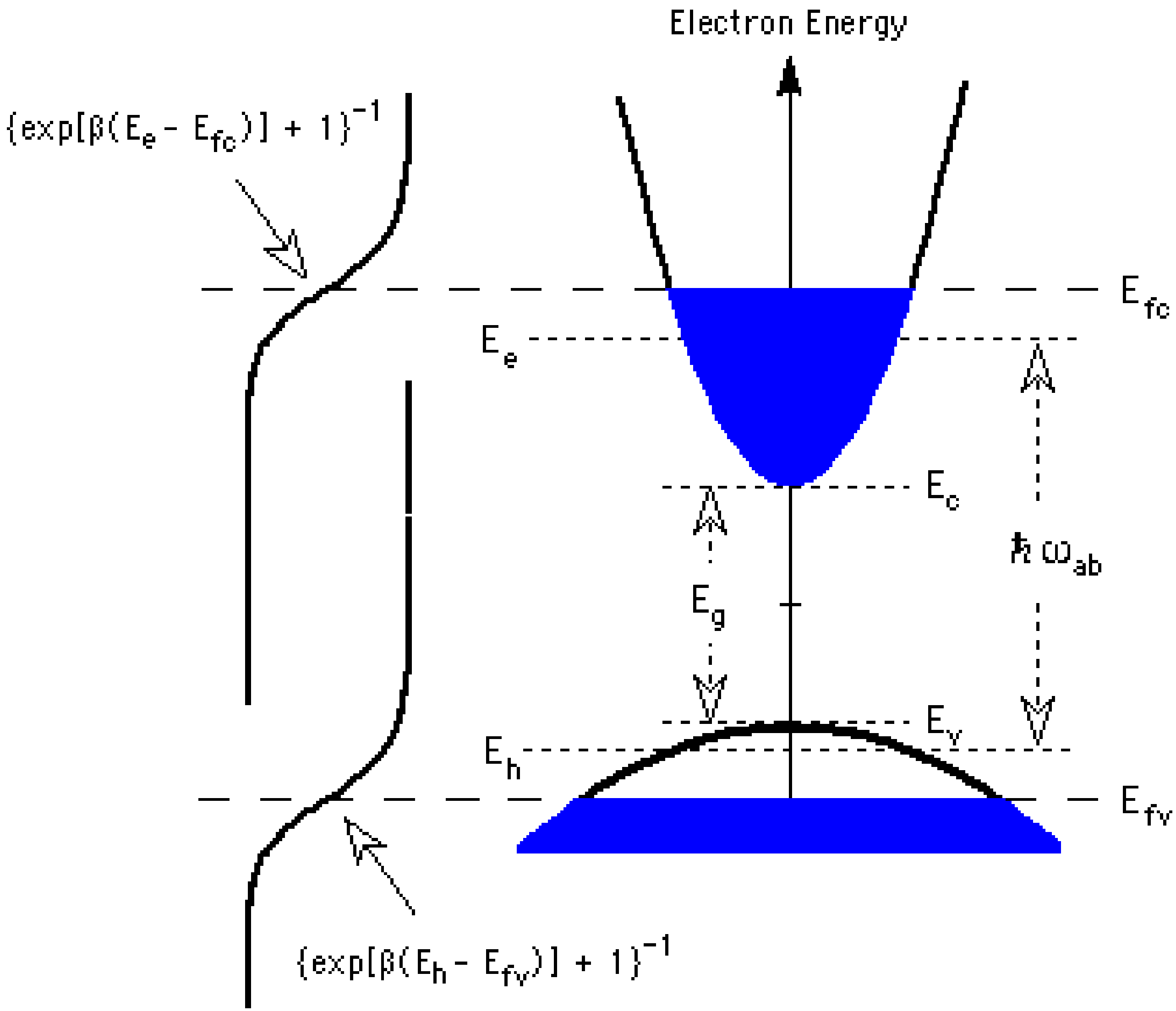
300 K $E_g = 1.42$ eV

$E_L = 1.71$ eV

$E_X = 1.90$ eV

$E_{so} = 0.34$ eV

Pumping semiconductor lasers



P-n junction laser

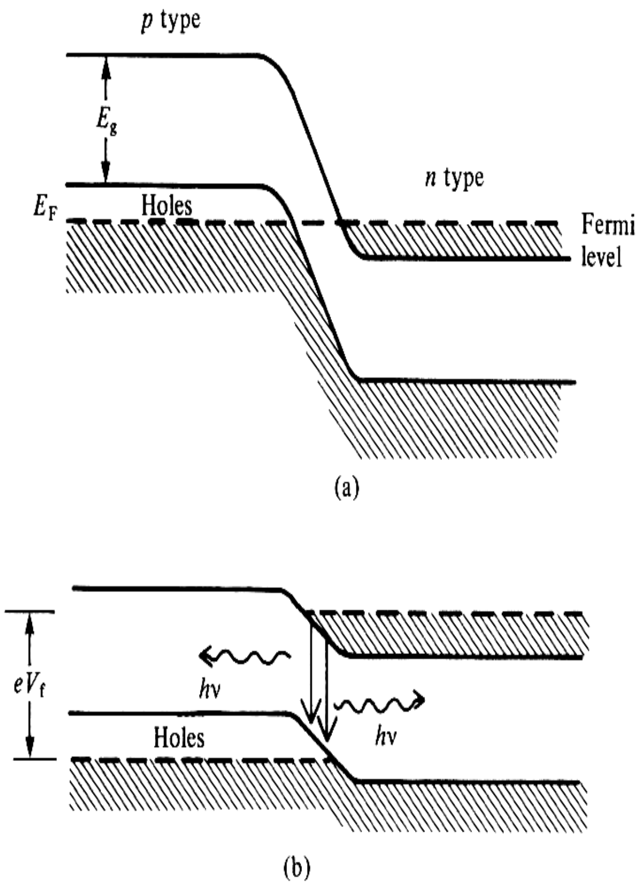
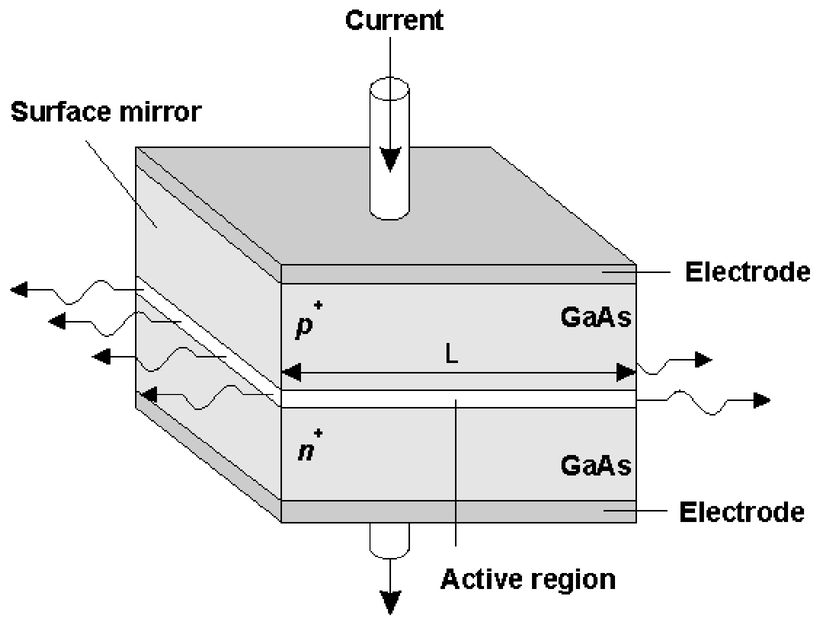
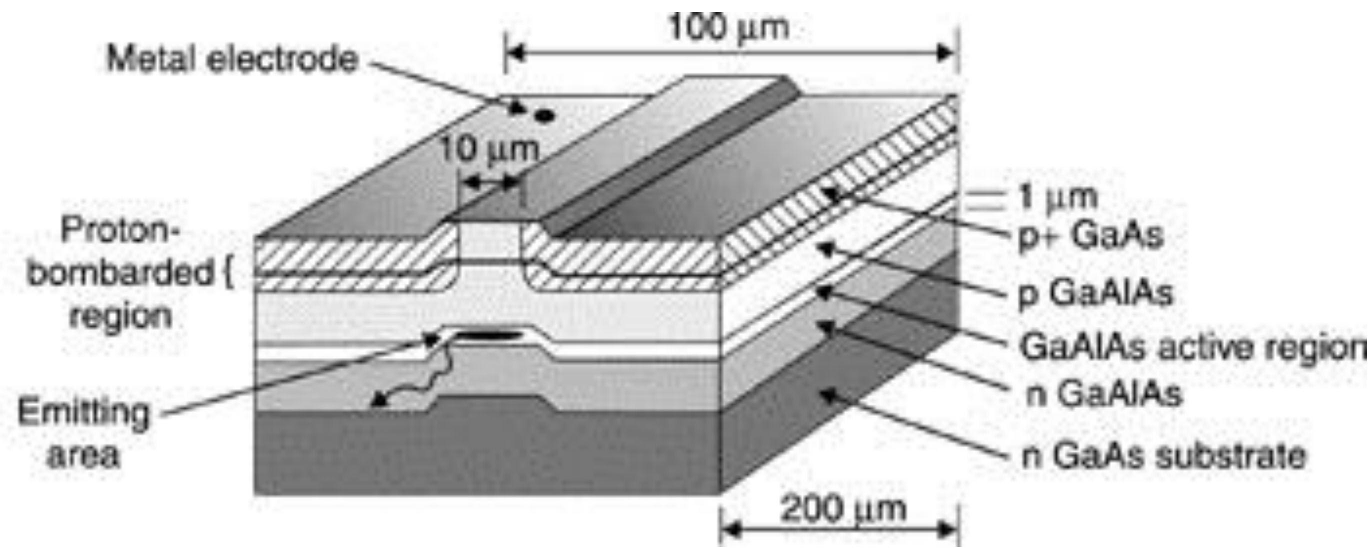


Fig. 5.18 Heavily doped *p*–*n* junction: (a) in equilibrium and (b) with forward bias (tl
broken lines represent the Fermi level in equilibrium (a) and with forward bias (b))

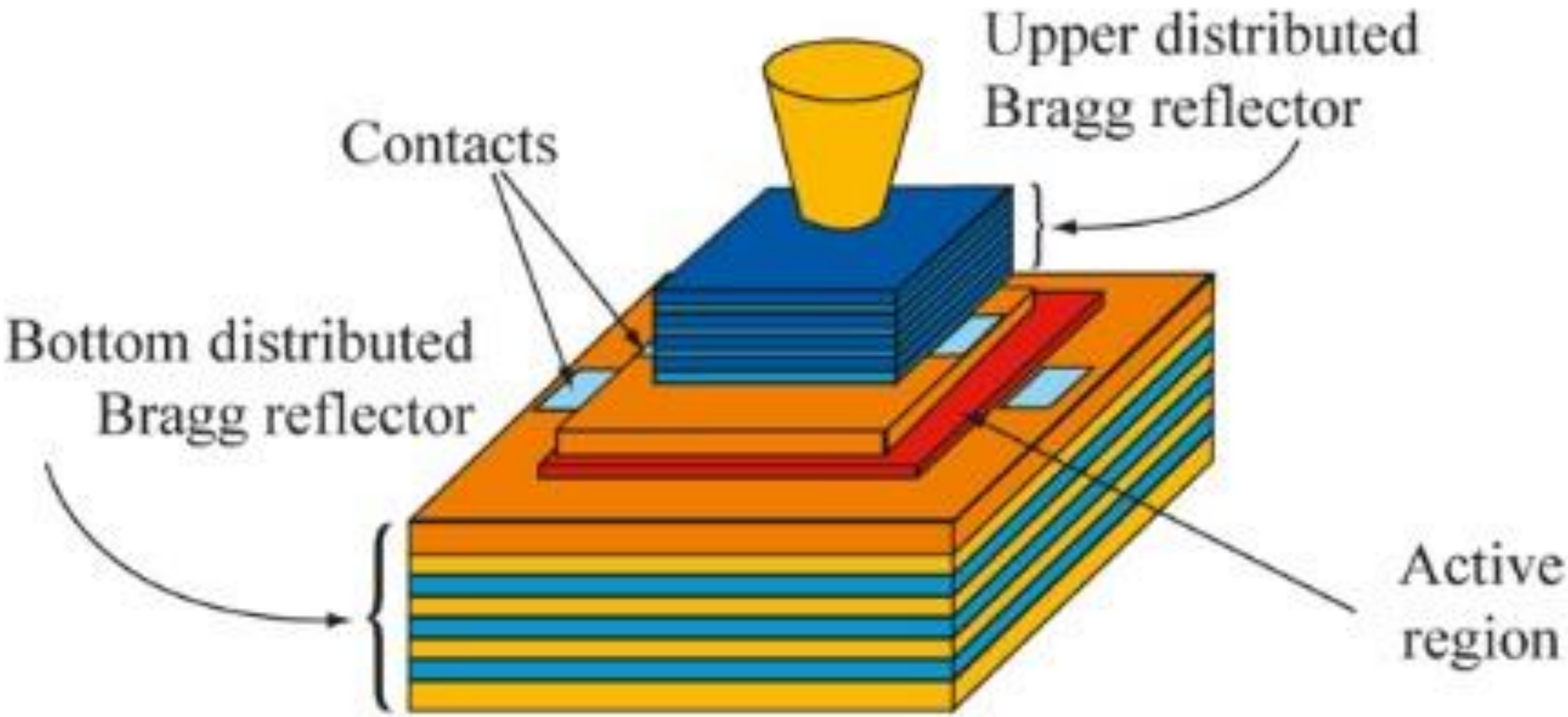
- The equilibrium and forward biased energy band diagrams for a junction formed from such degenerate materials with direct energy gap is shown.
- When the junction is forward biased with a voltage that is close to the energy gap electrons and holes are injected across the junction in sufficient numbers to cause population inversion.

Edge-emitting laser diode

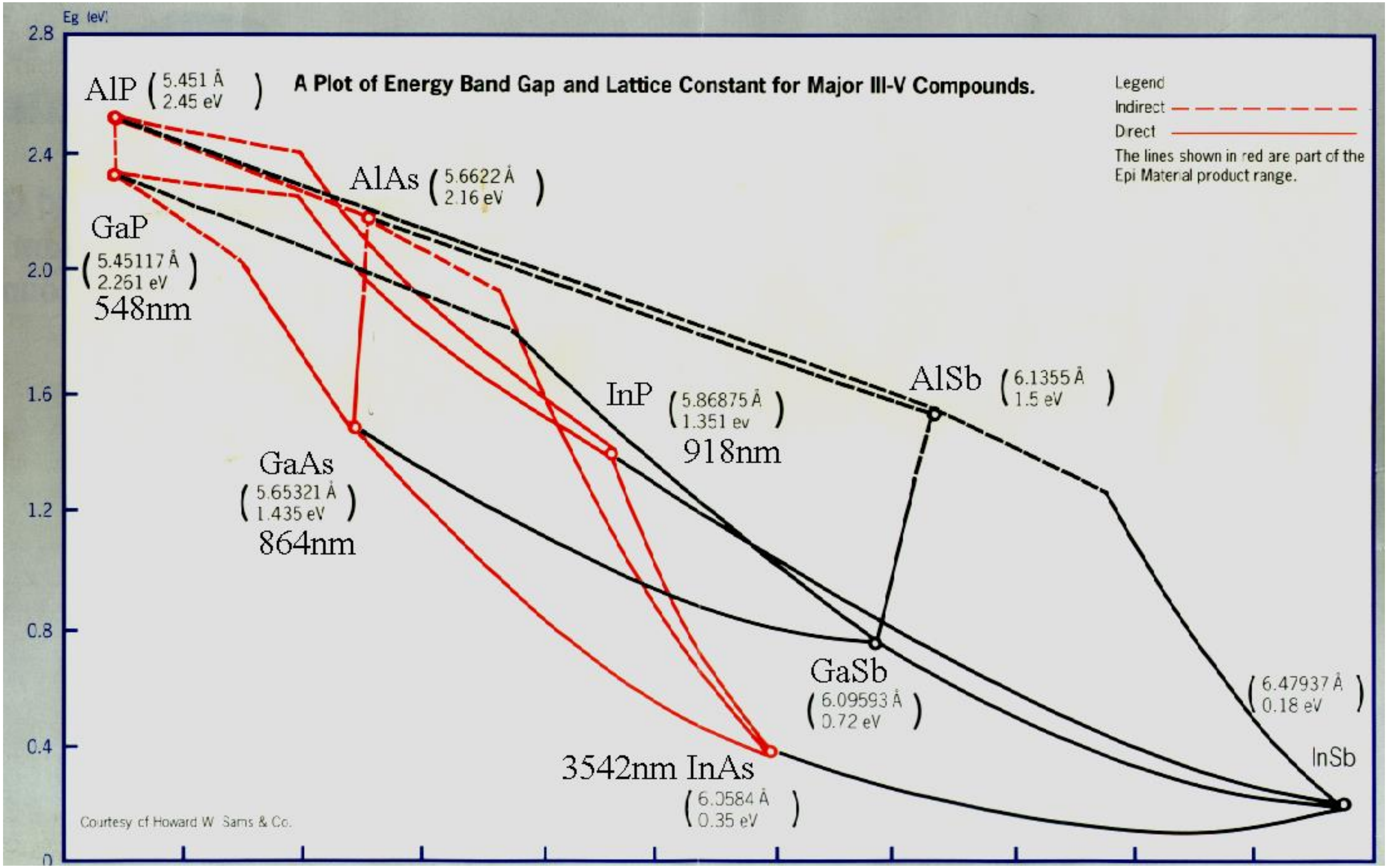




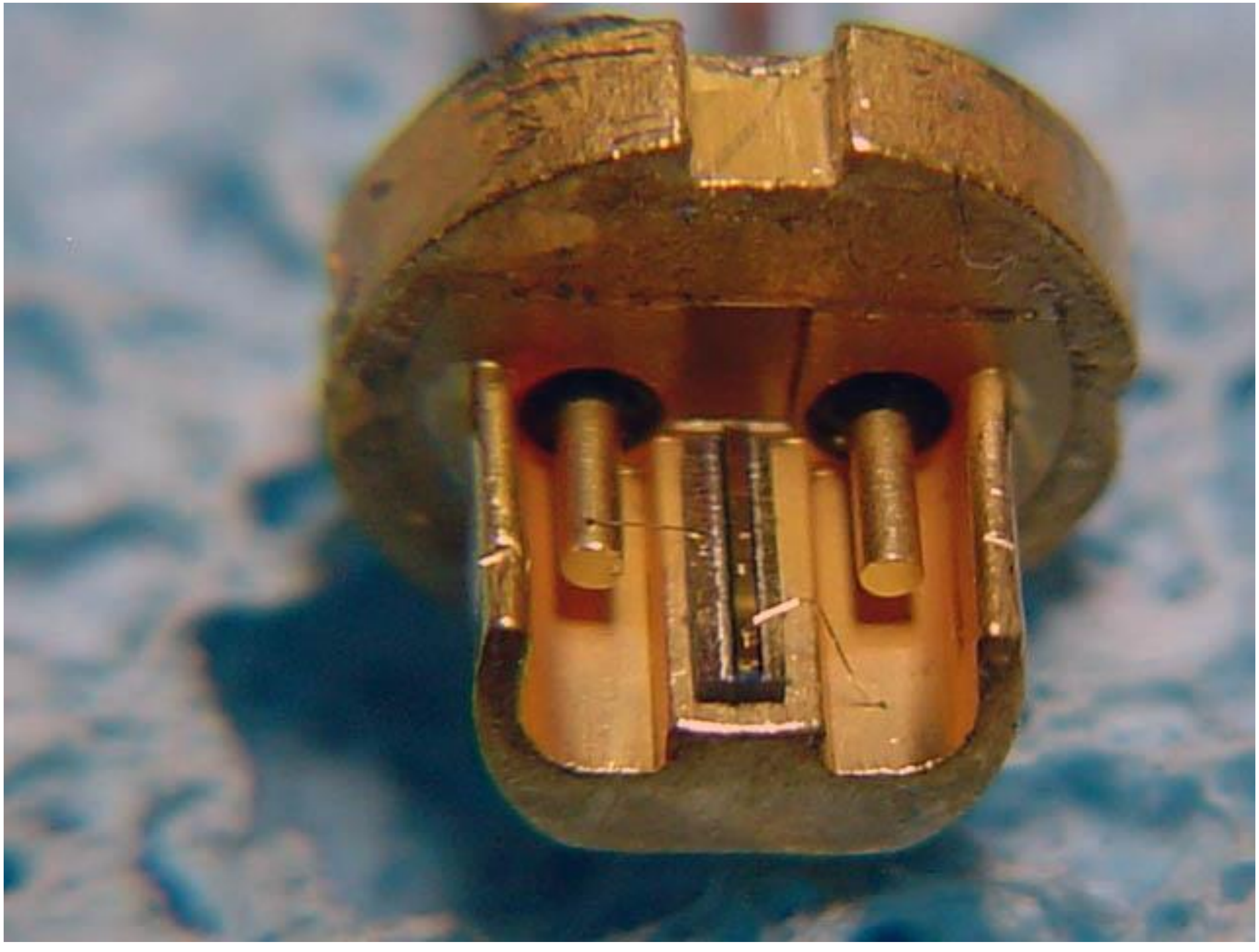
Vertical cavity surface-emitting laser (VCSEL) – most numerous



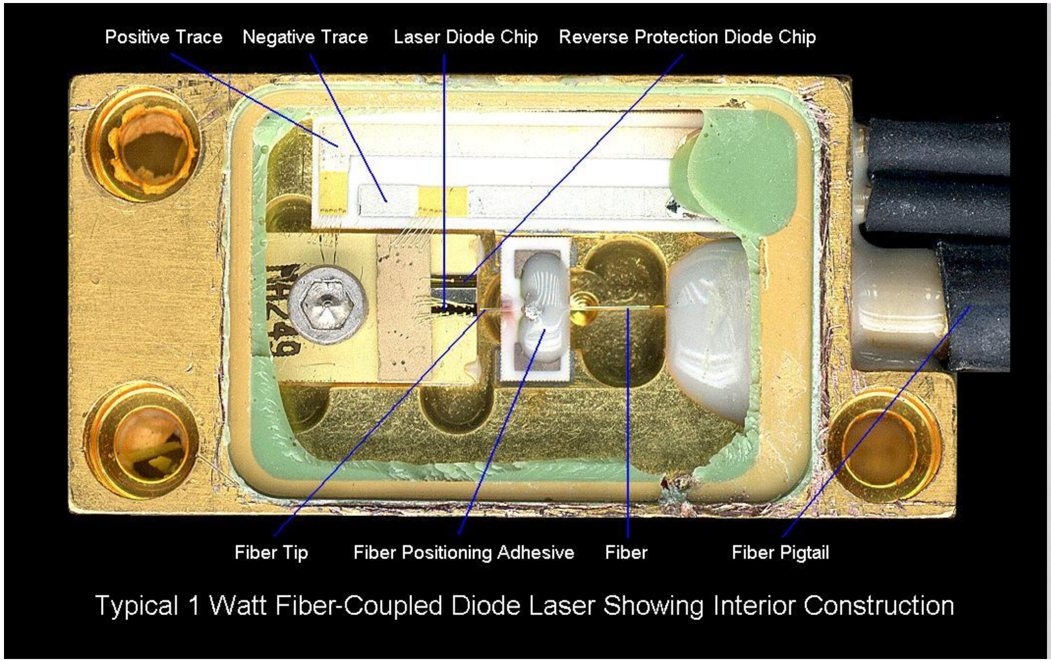
Semiconductor laser materials

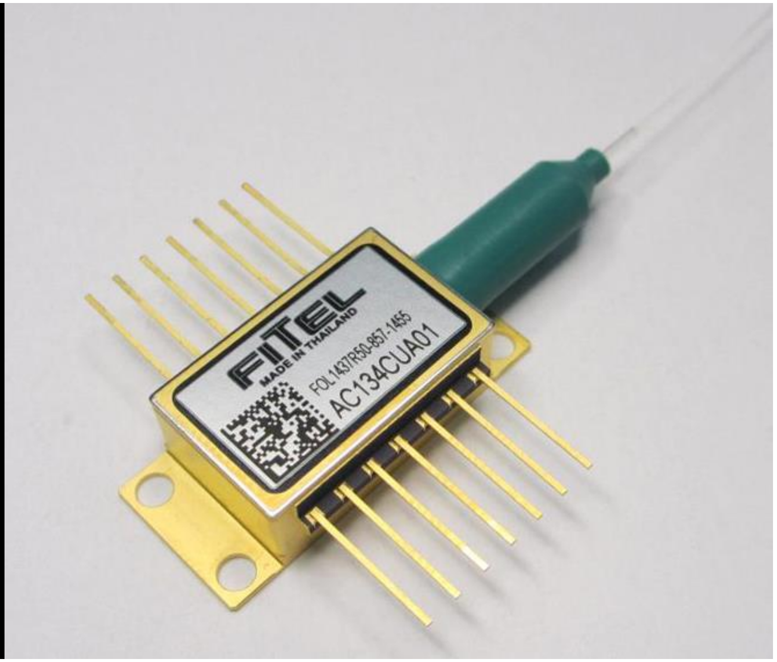


Semiconductor lasers in real life: integrated with detector in TO can



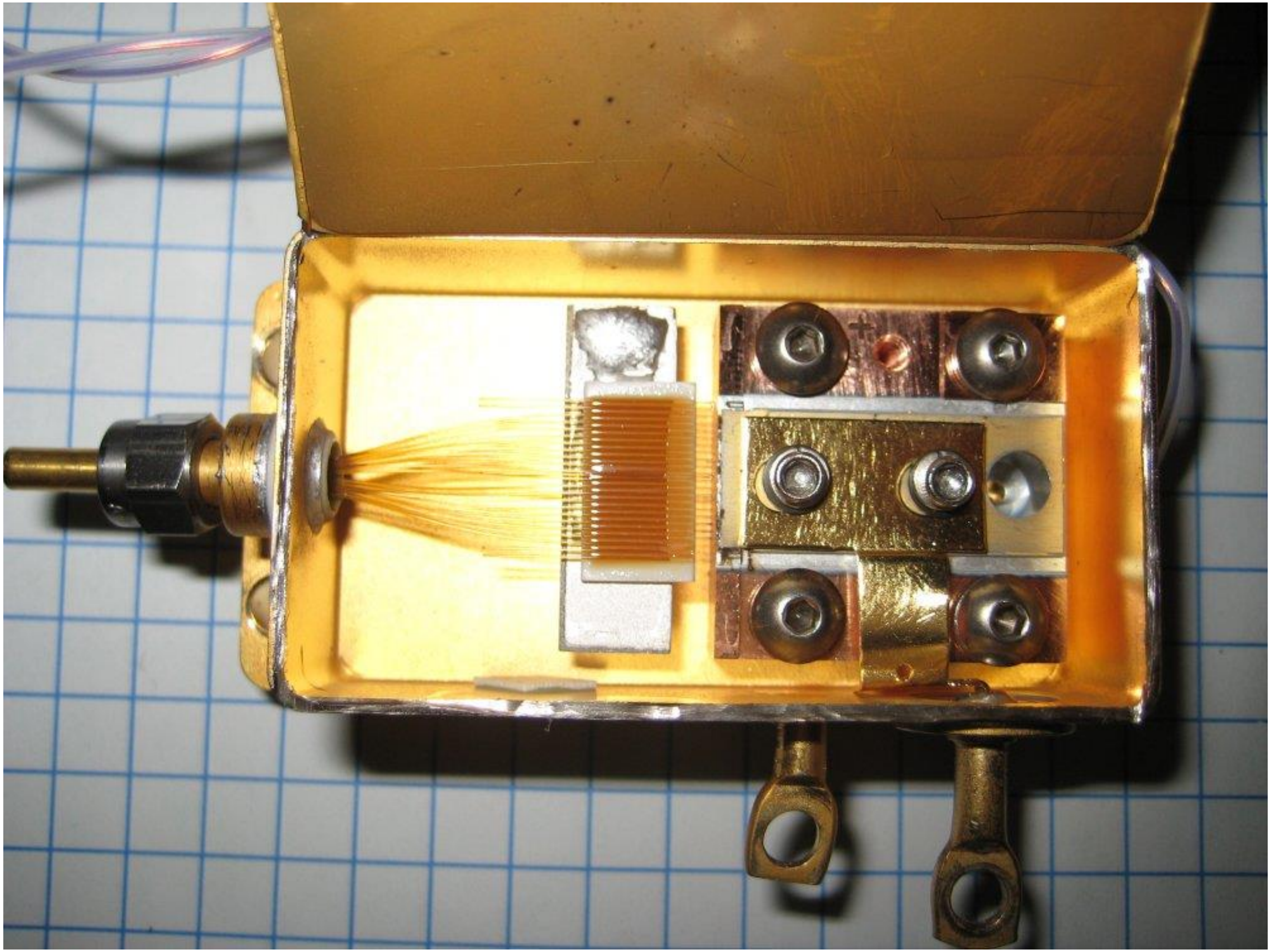
Semiconductor lasers in real life: butterfly-style telecom package



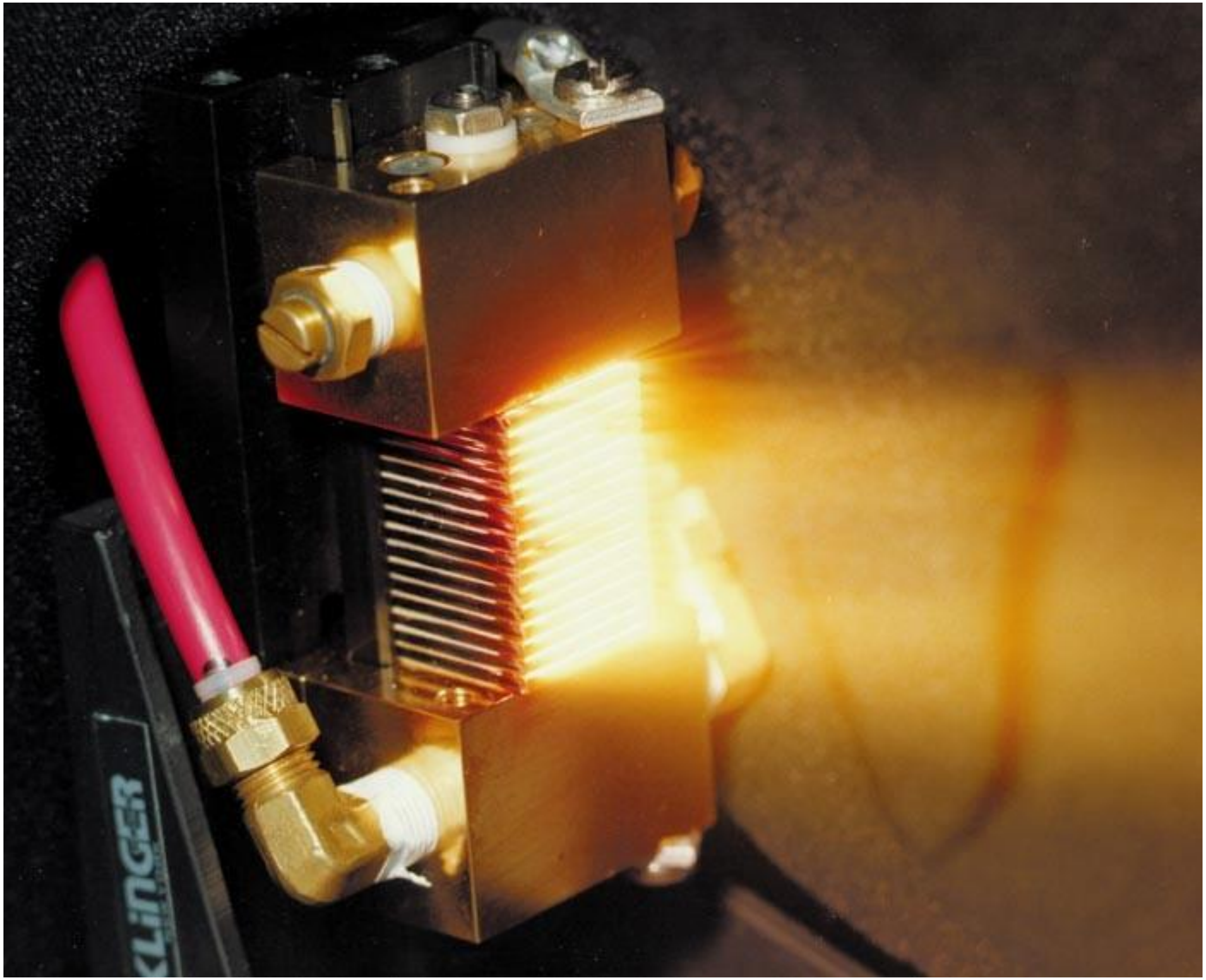


14xx nm module to pump Er-doped fibre amplifier (EDFA)
C-band (1530-1565 nm) transceivers are similarly packaged
Monolithic integration has enormous potential (see F Peters)

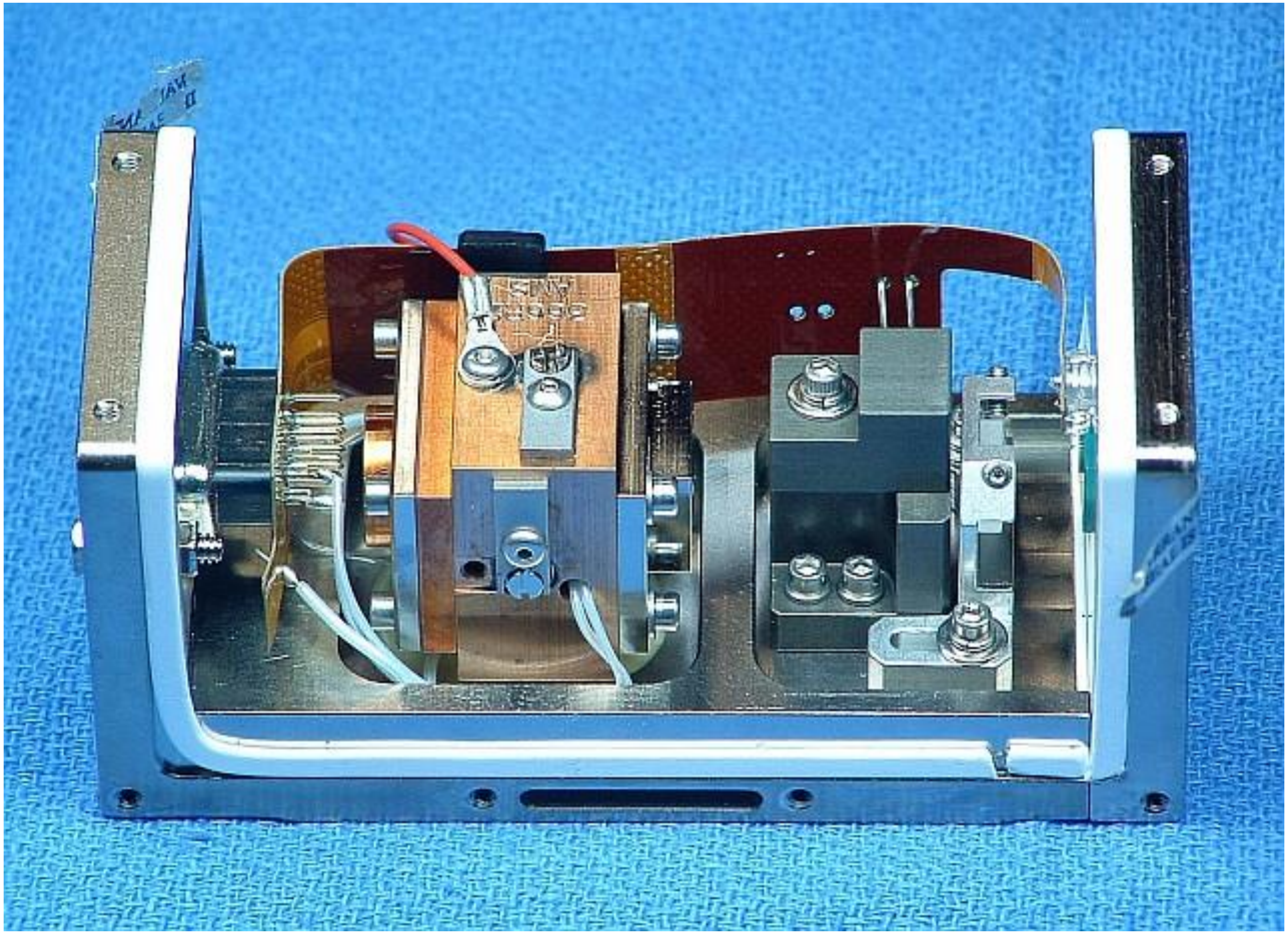
High power semiconductor laser bar



Diode bar stack aka Death Ray



5 mW 488 nm Protera (Novalux Inc, 2004)



Tyndall National Institute
Institiúid Náisiúnta

Quantum confined gain media: wells, wires, dots and dashes

▪

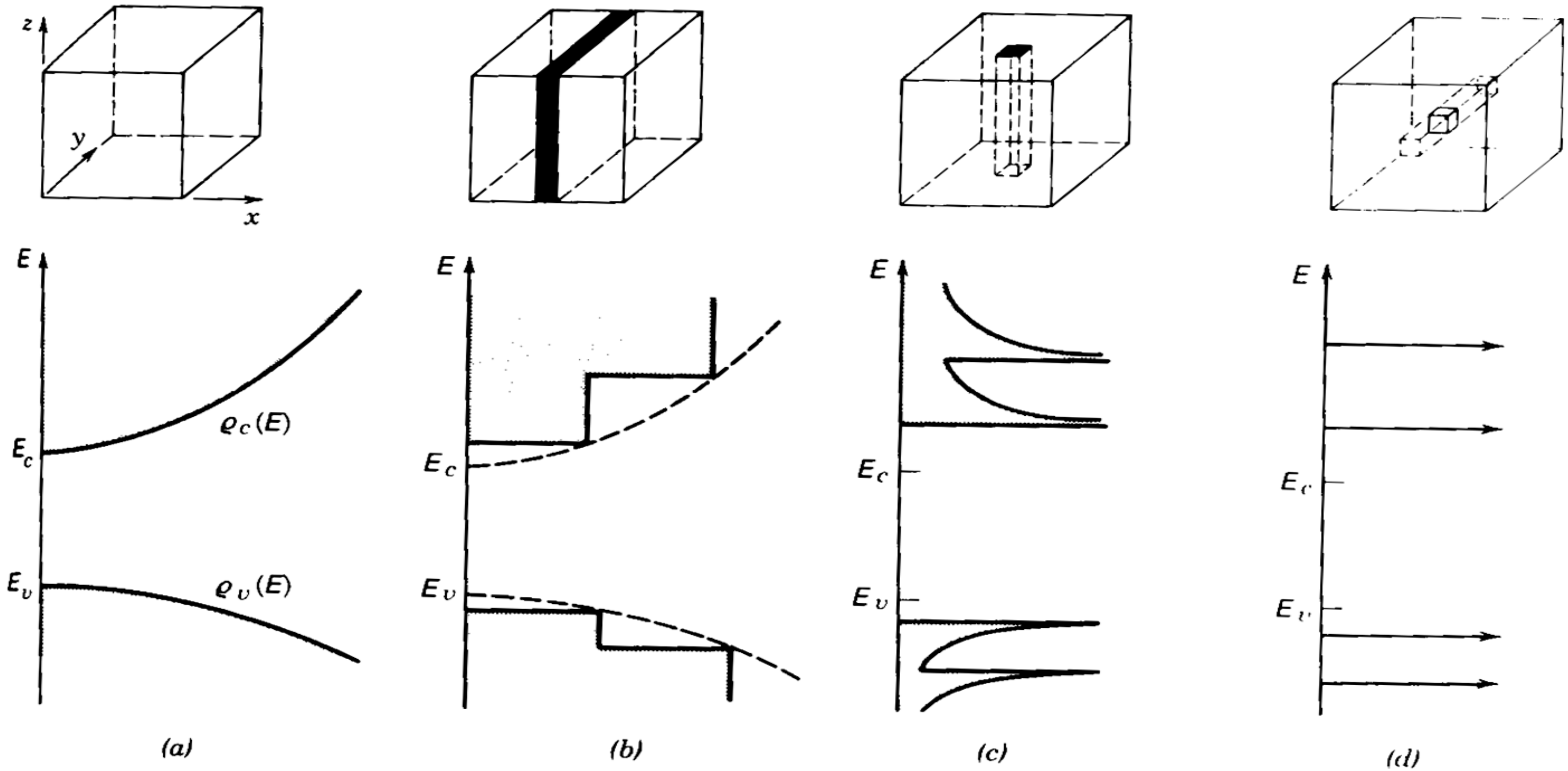
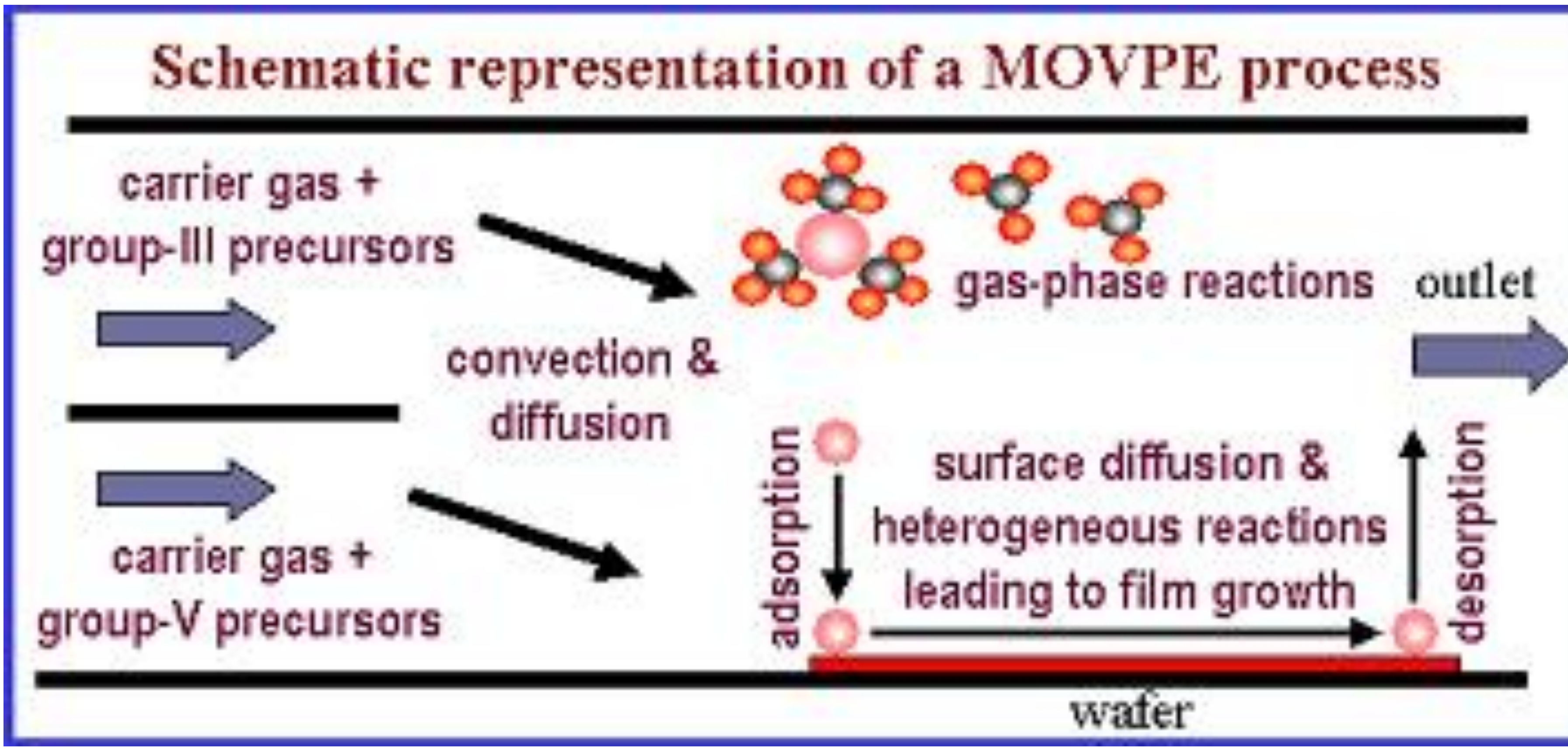


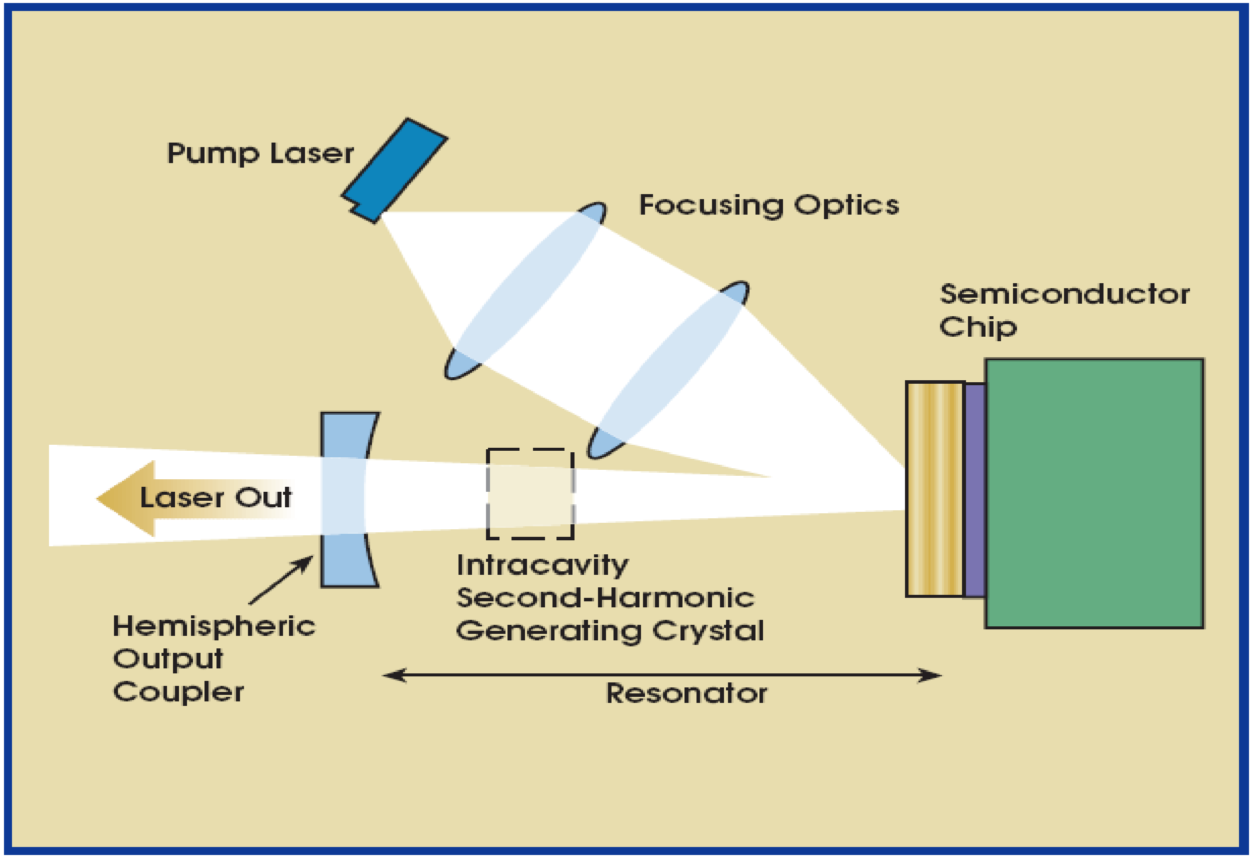
Figure 15.1-24 The density of states in different confinement configurations: (*a*) bulk; (*b*) quantum well; (*c*) quantum wire; (*d*) quantum dot. The conduction and valence bands split into overlapping subbands that become successively narrower as the electron motion is restricted in more dimensions.

MOVPE growth of doped III-V semiconductor nanostructures



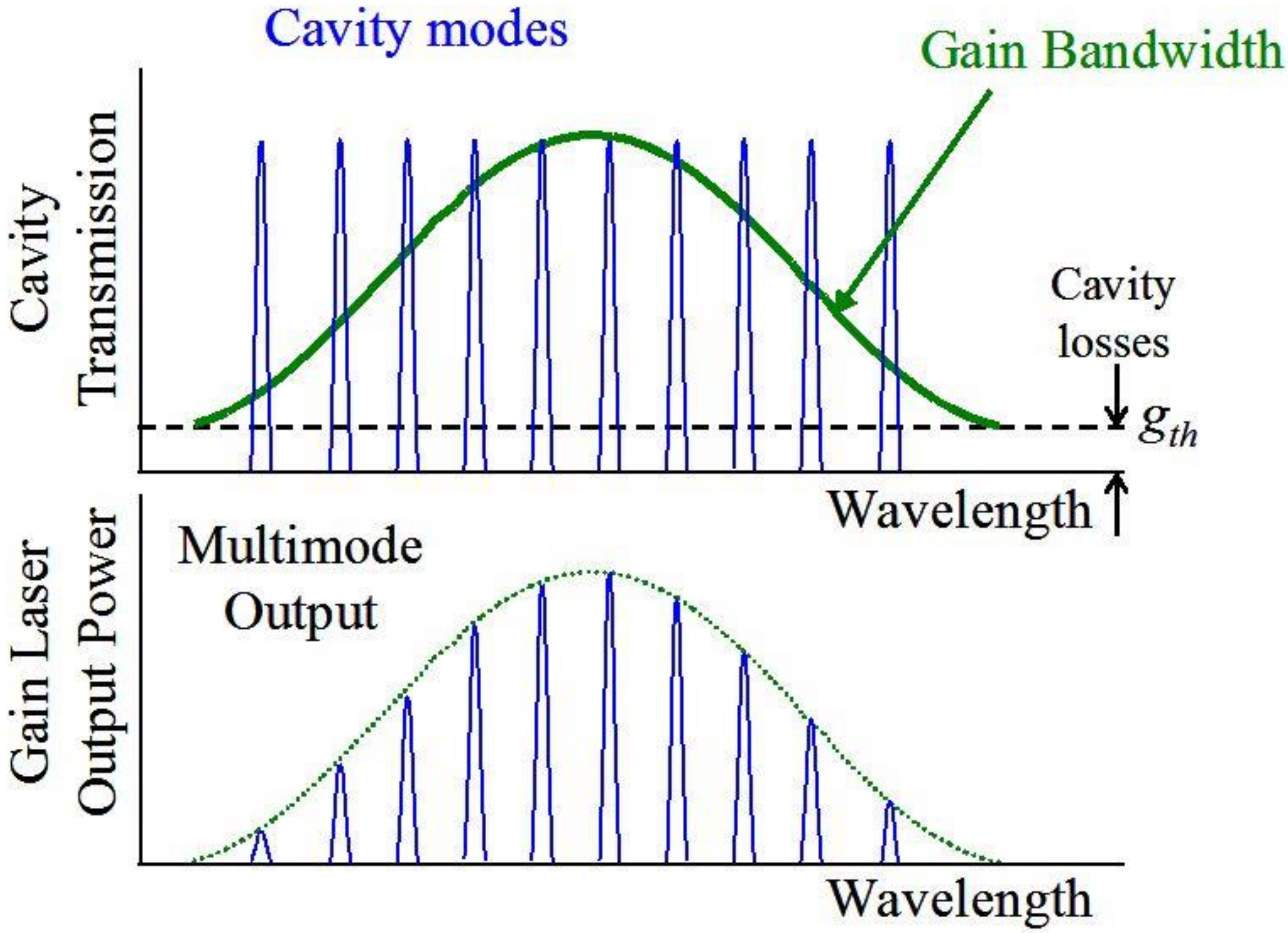
MOVPE reactor in real life

Optically pumped semiconductor laser (vertical extended cavity surface-emitting laser, VECSEL)



Large pump spot allows scaling to high power

Electromagnetic modes in lasers

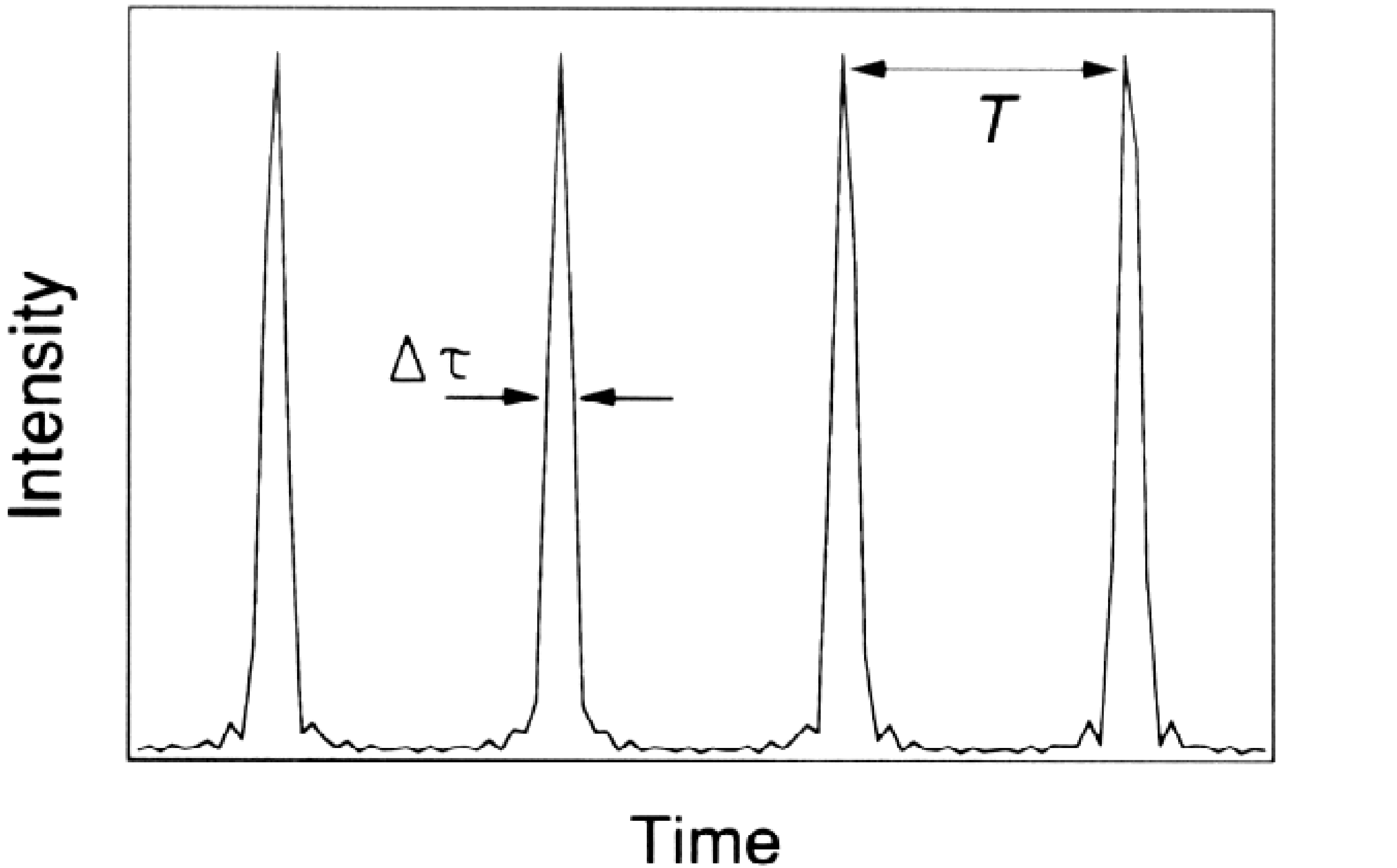


Mode locking of lasers

- Forced synchronism between spectral modes
- Result is low-entropy ultrashort pulse trains
- Pulse width limited only by gain bandwidth
- Pulse repetition rate given by cavity roundtrip
- Pulses precisely tunable in time and frequency
- Shortest, most intense man-made events
- Applied to metrology, materials, lidar, comms

Mode locked output with 10 modes

(after Vasil'ev, "Ultrafast diode lasers", Artech 1995)



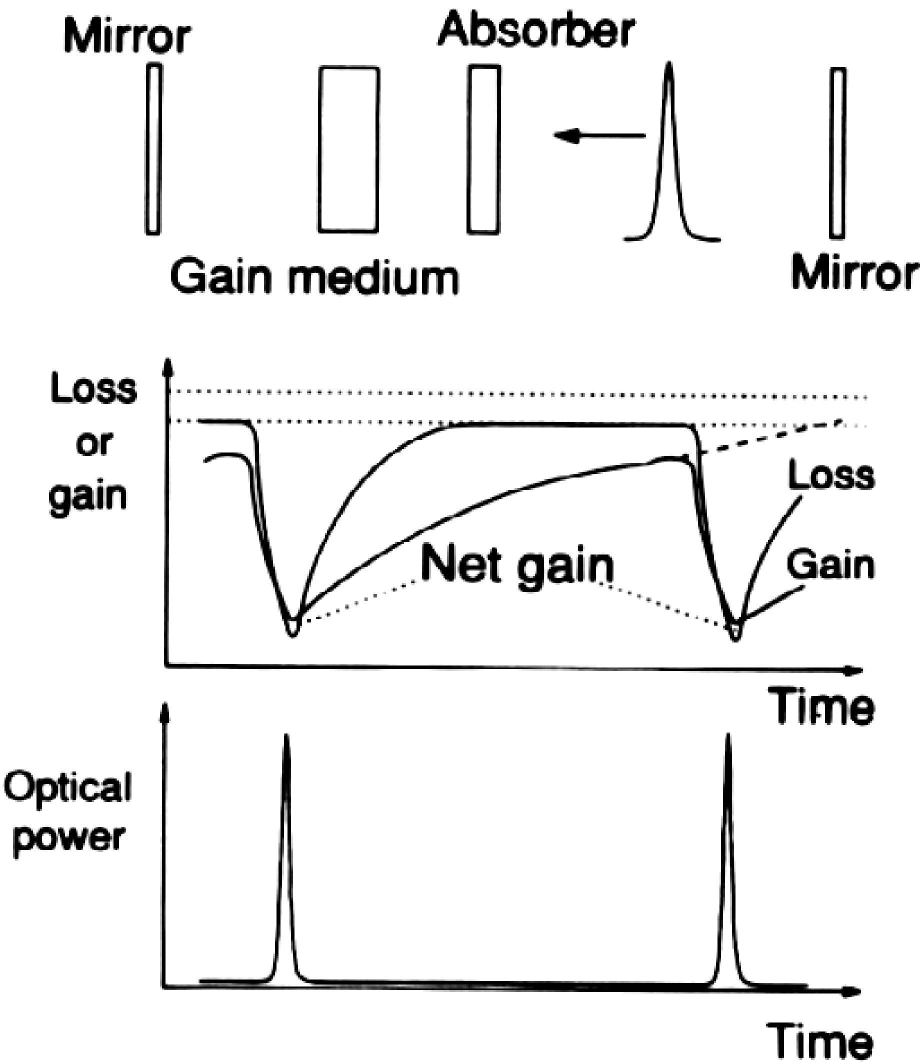
Some applications of pulsed laser diodes

Communications: clock generation, extraction
Optical data sampling, processing, storage
Imaging: THz generation and sampling
Injection locking, seeding, synchronous pumping
Time resolved scattering, coherence tomography
Frequency conversion, fluorescence sources
Precise machining, tissue ablation (high power)
Monitoring, sensing, collision avoidance

Tyndall
National Institute
Institiúid Náisiúnta

WHERE FINBARR TAUGHT LET MUNSTER LEARN

Passive mode locking in principle



No modulation required

Gain/absorption balance vital

Cavity delay ~ absorber recovery

Synchronisation difficult

Pulsewidth, coherence excellent

Pulses ltd by group delay dispn

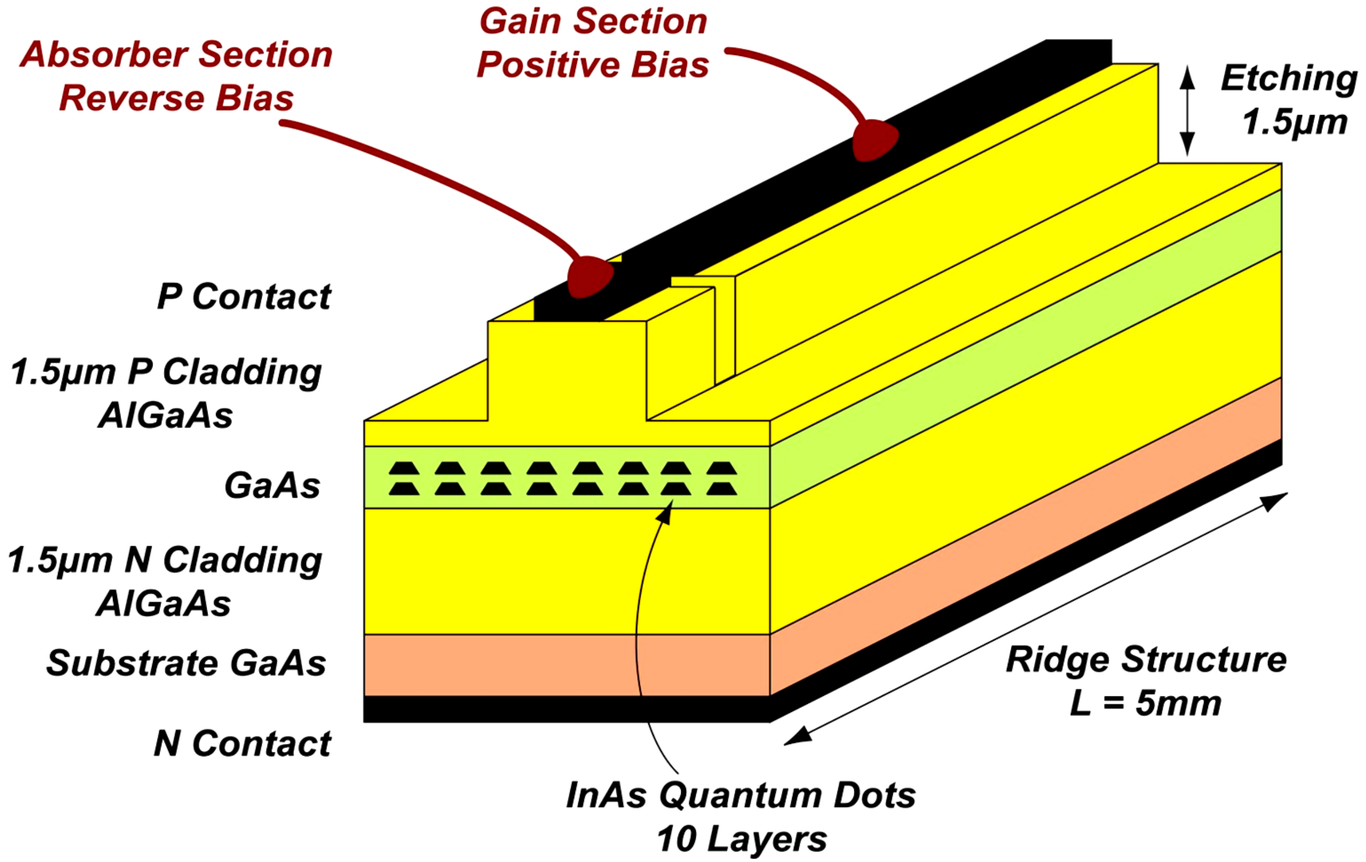
Pulse generation by mode locking: 2-section QD lasers

:

Saturable absorber channels energy into pulses
All modes synchronized into low entropy state

InAs/GaAs QDs for **1.3µm** operation

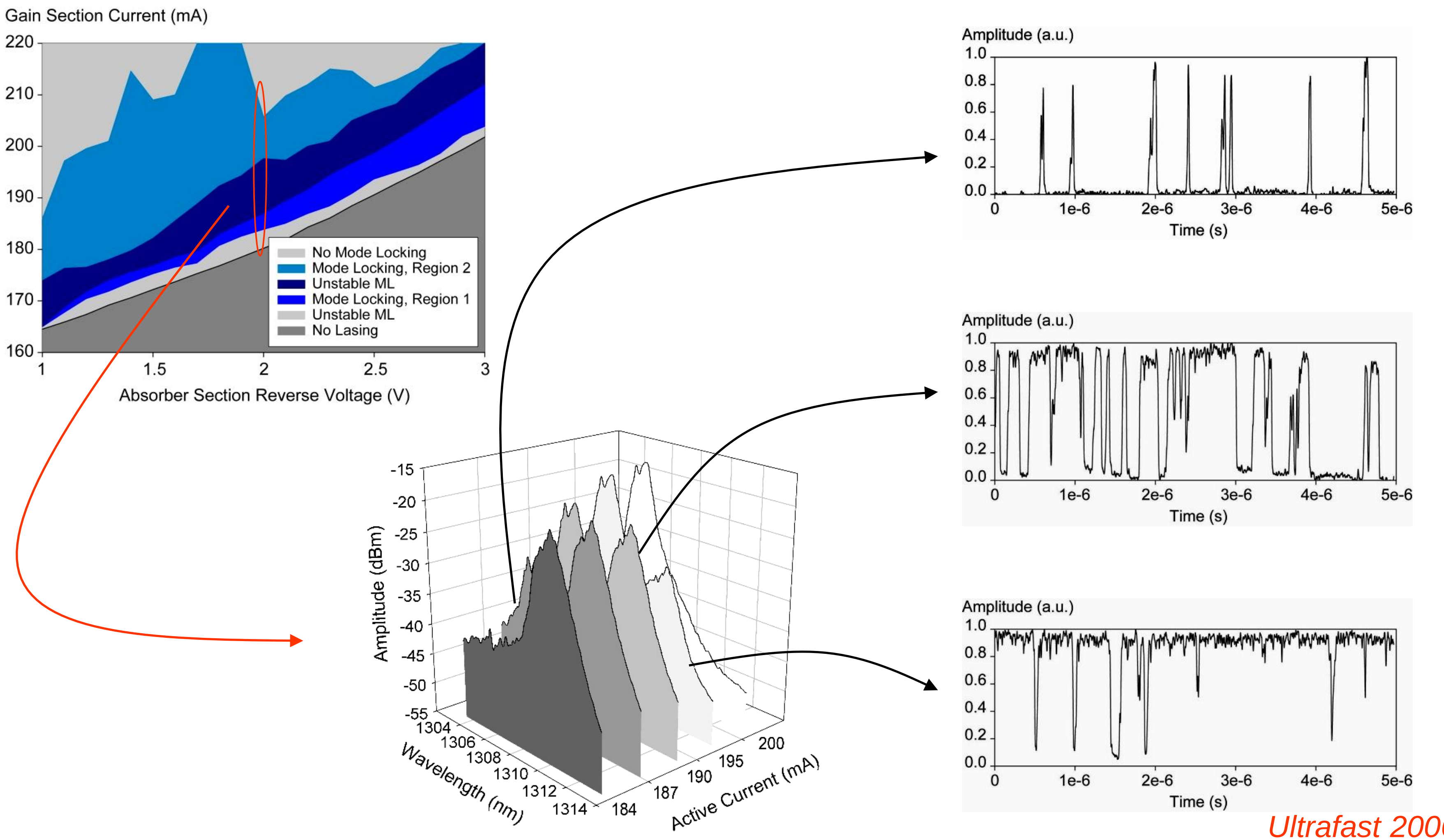
$\boldsymbol{L_{tot}}$ **= *5 mm*** for ~ **8 GHz** operation



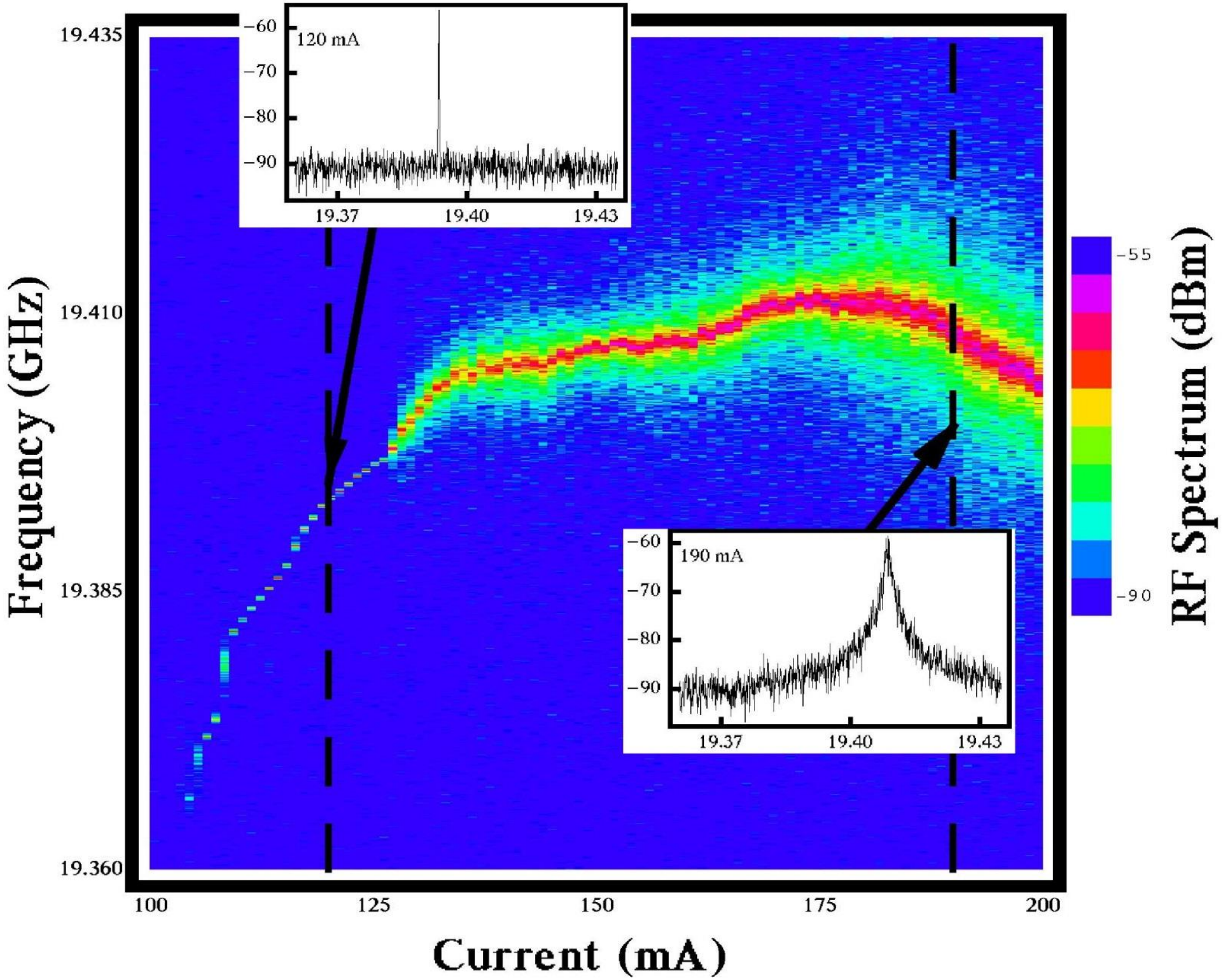
Global mapping of mode-locking characteristics

➡ Two distinct groups of ML Regions with different spectral characteristics

➡ Sub-MHz switching between groups

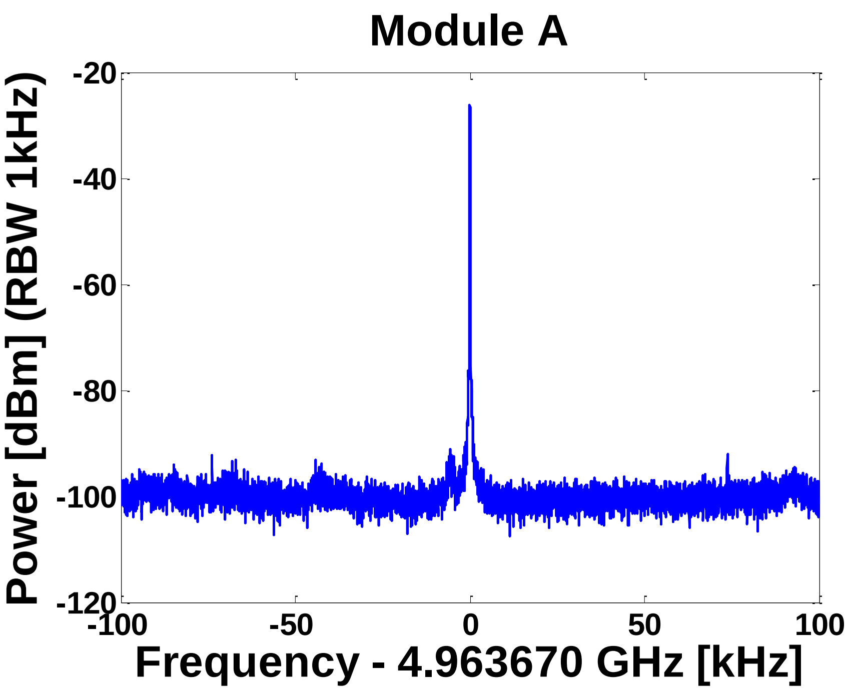


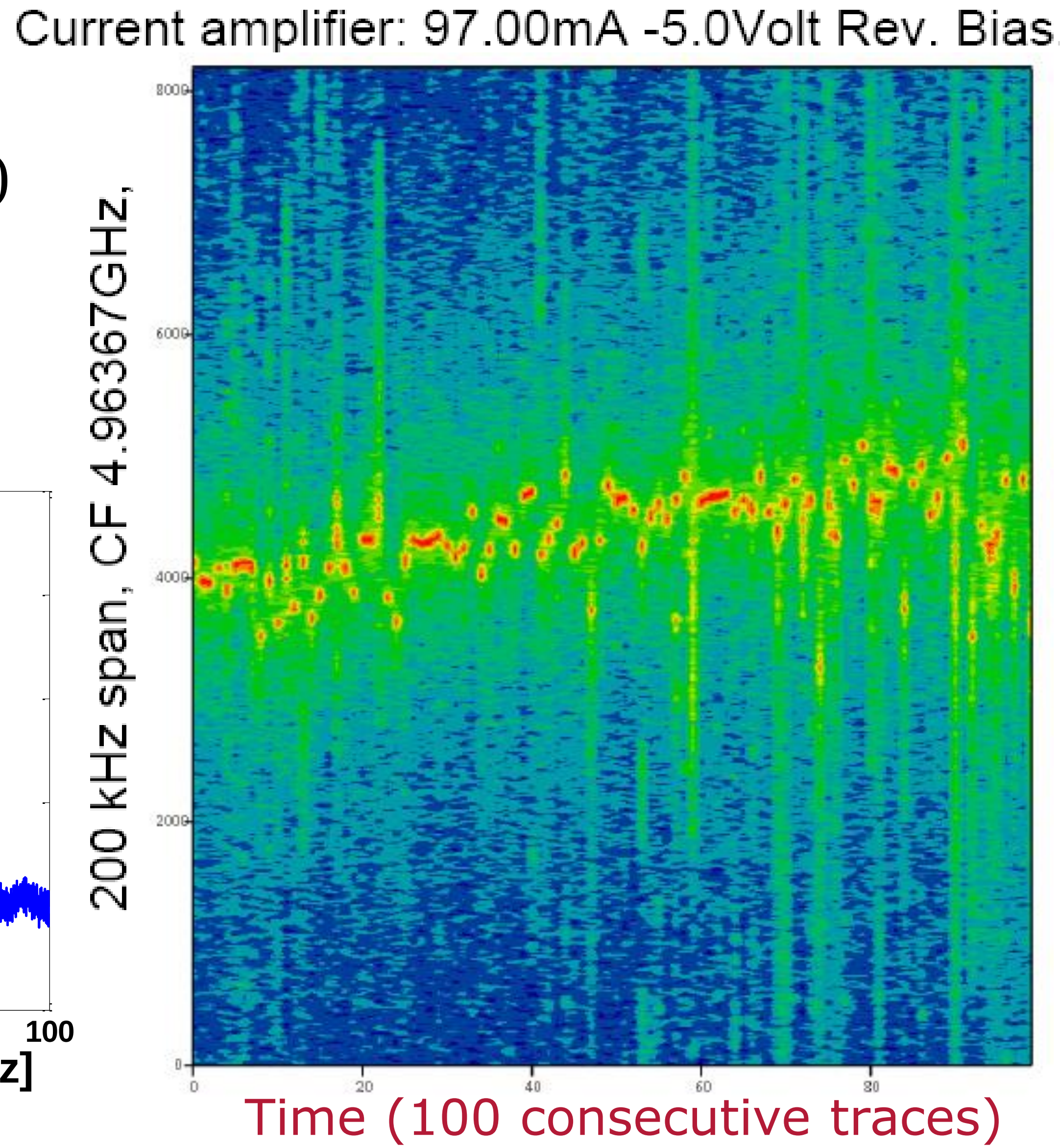
RF spectra in 20 GHz MLL



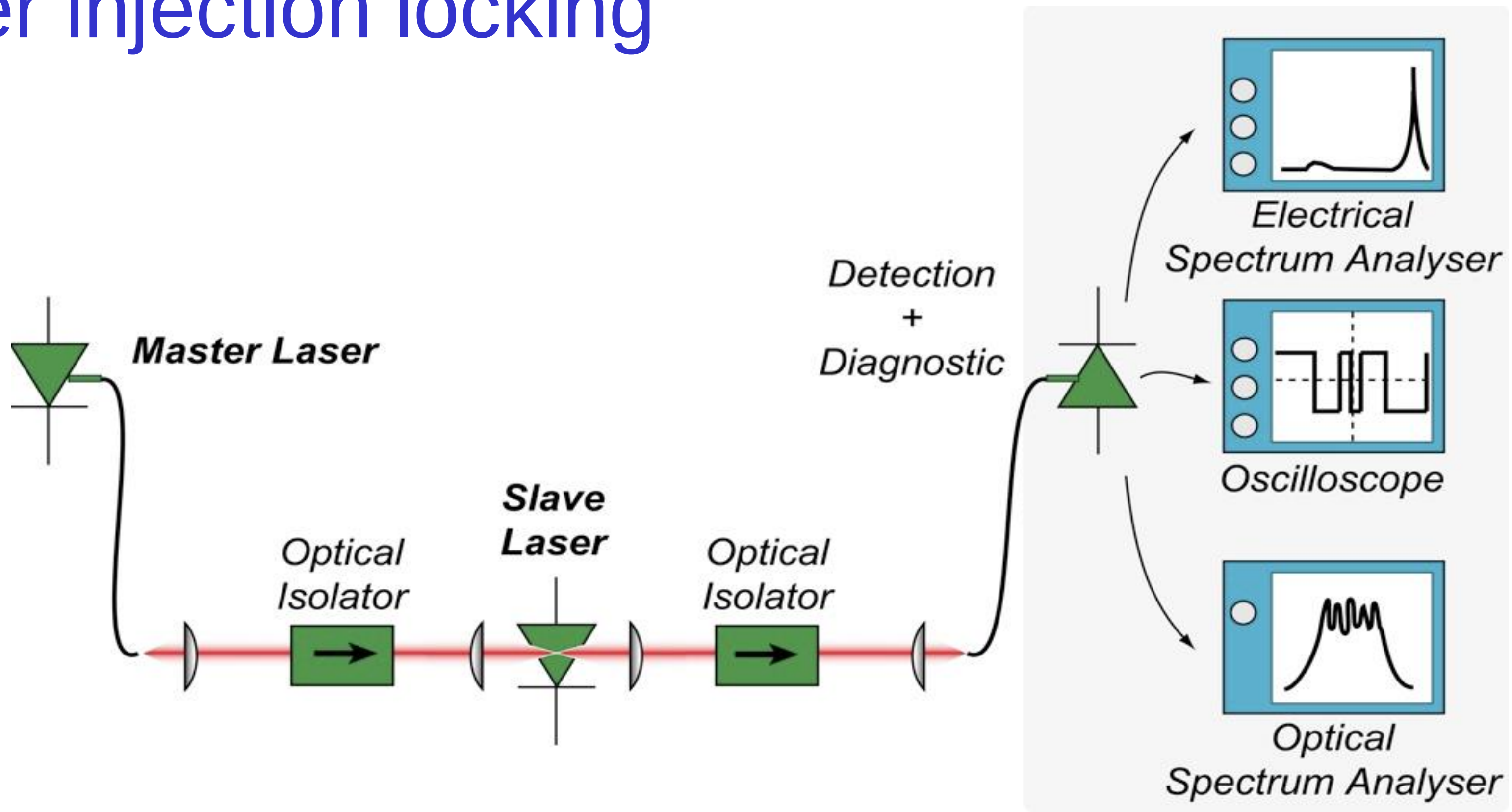
Jitter and wander

- Very low jitter
  - ~700fs (20kHz-40MHz)
- ”Significant” wander
  - Slow jitter <10Hz





Laser injection locking



- Power injected from master to slave laser unidirectionally
- Slave is InAs/GaAs quantum dot laser emitting at 1300 nm
- Feedback-insensitive design (low alpha, high damping rate)

Verification of Semiconductor Laser Bloch Theory

Prof John McInerney, Physics Dept/Tyndall Institute, University College Cork, Ireland

Technical Merits:

<u>Theory</u>: enormously challenging to describe dynamics on time scales from 10 fs to 1 us. <u>Experiment</u>: precise measurement of pulse train optical & RF parameters, high power pattern/mode spectra; detailed comparison

Relevance:

Enable new generations of portable/air- or space-borne sensors of position, velocity, docking, attitude; high power lasers which maintain brightness/beam integrity over long distances for directed energy usages

Objective(s):

- *3 ps, 10-GHz pulse trains from QD laser*
- *10 W large aperture multimode VECSEL*
- *Simulation vs experiments for both these*

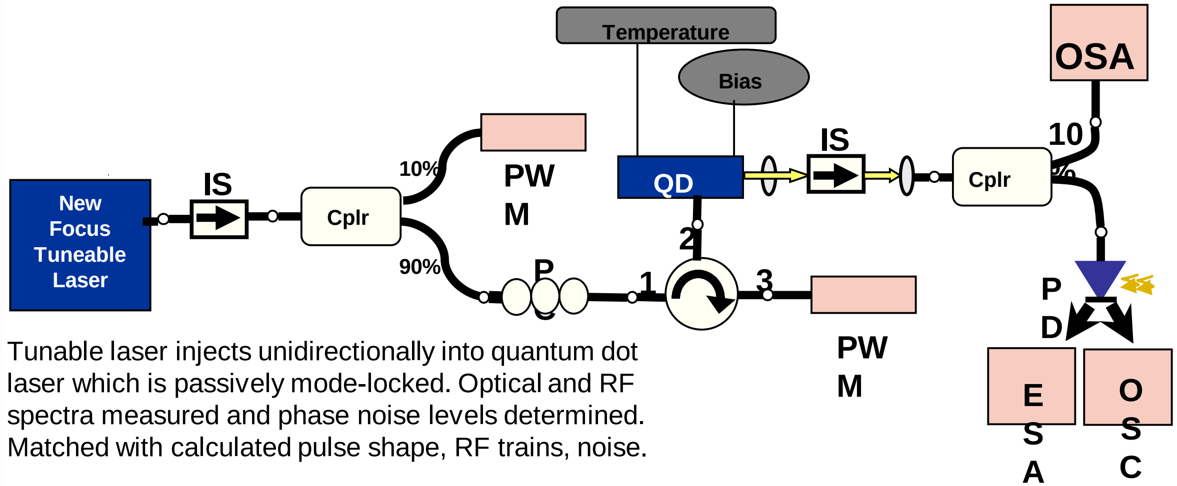
Impact (Development Potential):

Semiconductor Maxwell-Bloch theory very powerful, versatile: extend to new materials and pulsed, modulated, high power sources

Key Institutions:

U of Arizona, U Marburg, Alcatel III-V Lab, CNRS-LPN (France), TU Eindhoven, TU Denmark, U Cambridge (collaborators)

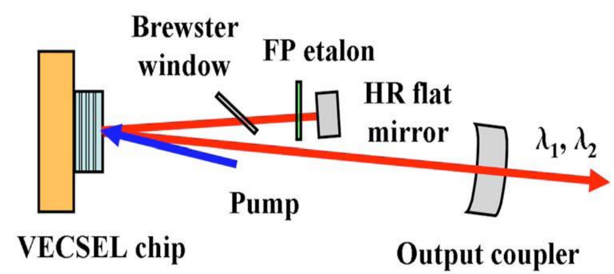
Mode/injection-locking/feedback experiment



Tunable laser injects unidirectionally into quantum dot laser which is passively mode-locked. Optical and RF spectra measured and phase noise levels determined. Matched with calculated pulse shape, RF trains, noise.

Large aperture VECSEL experiment

Vertical cavity laser (VCSEL) chip with no or incomplete top mirror optically pumped by diode array to yield high Fresnel number states which can be analyzed by spatial filtering. Single modes may also be selected for high brightness beams.

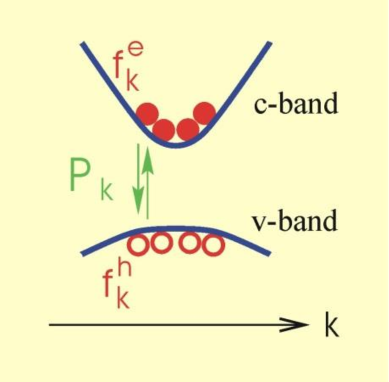


E Sooudi, J G McInerney *et al*, IEEE J Quantum Electron. <u>48</u>, 1327 (2012)

Nonequilibrium Microscopic Theory: Semiconductor Bloch Equations

$$\left[i\hbar\frac{\partial}{\partial t} - \epsilon_k^e - \epsilon_k^h\right] P_k = \left[1 - f_k^e - f_k^h\right]\Omega_k + \frac{\partial}{\partial t}P_k|_{corr}$$

$$i\hbar\frac{\partial}{\partial t} f_k^a = -\Omega_k(t)P_k^* + \Omega_k^* P_k + \frac{\partial}{\partial t} f_k^a|_{corr}$$

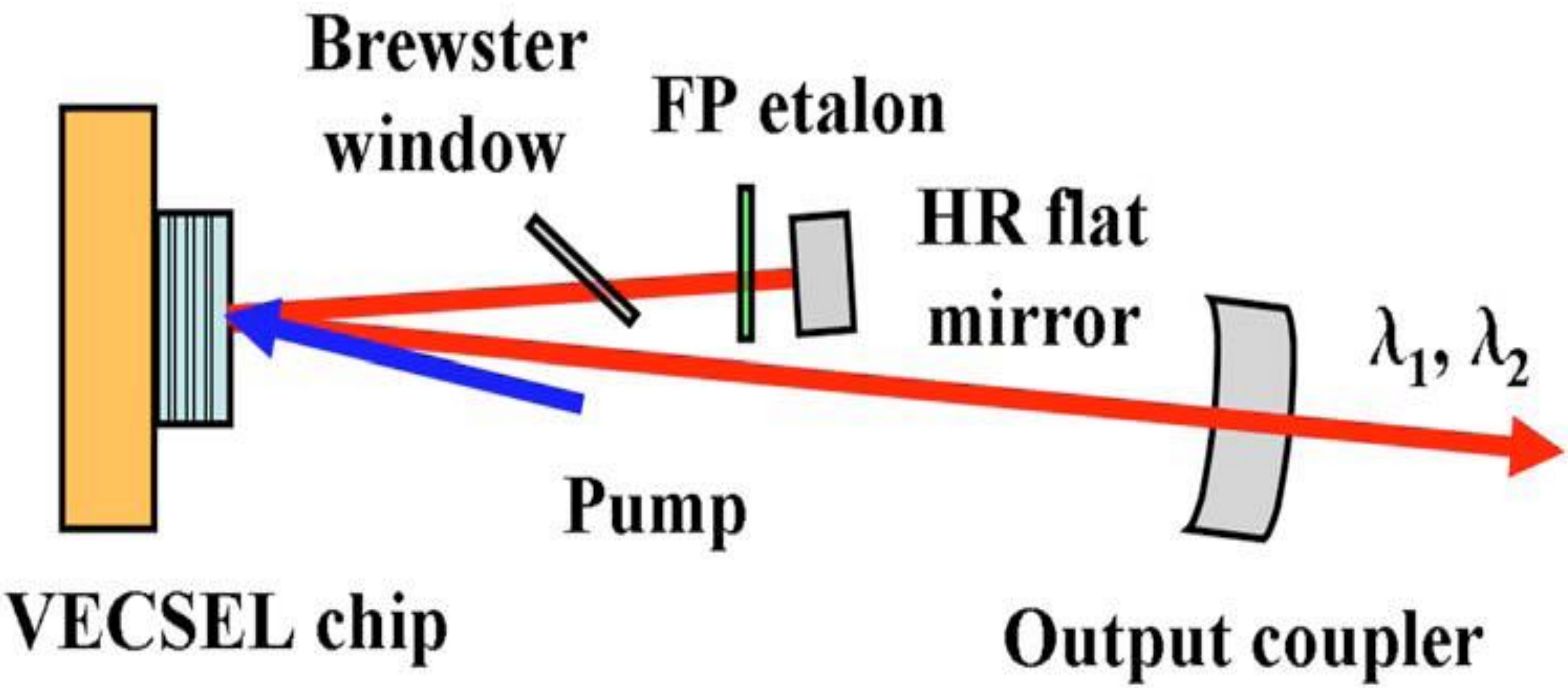


field renormalization $\quad \Omega_k(t) = d_{cv}\; E^{QW}(t) + \sum_{k'} V_{k-k'}\; P_{k'}(t)$

energy renormalization $\quad \epsilon_k^a(t) \;=\; \varepsilon_k^a - \sum_{k'} V_{k-k'}\; f_{k'}^a(t)$

- nonlinearities: phase-space filling, gap reduction, Coulomb enhancement
- correlation contributions: scattering, dephasing, screening

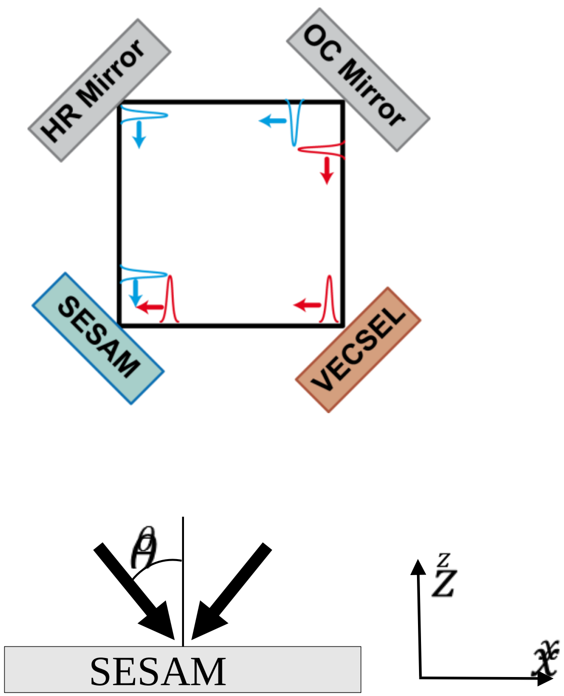
New experiment: VECSEL dynamics

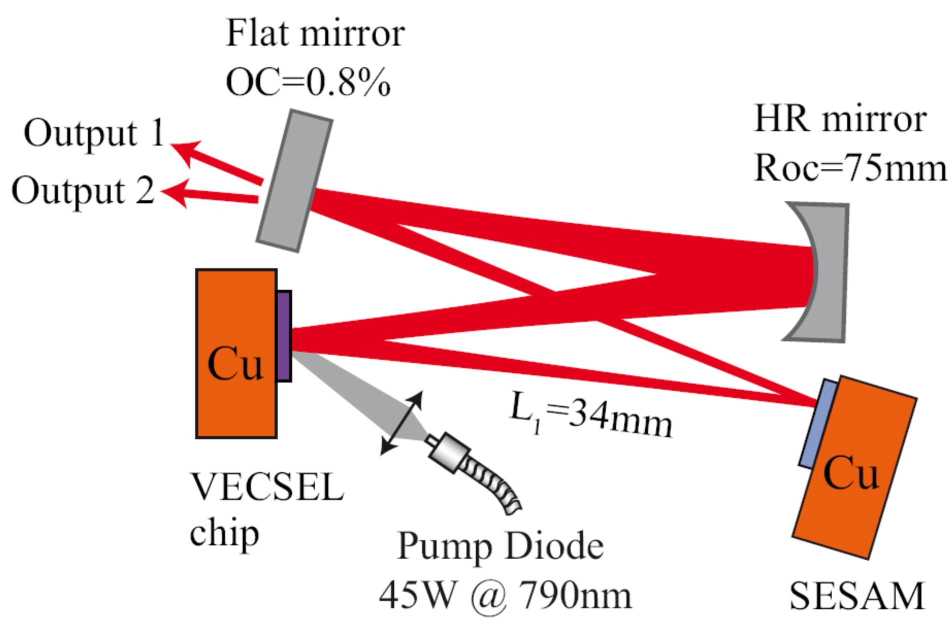


Investigate power scaling, transverse patterns, mode locking, injection & feedback dynamics, verify Bloch equation model.

Colliding Pulse Mode-Locked VECSEL

➢ Ring cavity with two counter-propagating pulses: principle and setup





A. Laurain et al., *Optica*, **7**, 781 (2016)

- Pulses synchronize on the saturable absorber: losses saturated with 2 pulses instead of one and interference grating leads to (x3) lower saturation fluence (mode ratio SESAM/VECSEL less critical)
- One pass on VECSEL, one pass on SESAM : minimize the contribution of the VECSEL on total GDD.
- VECSEL placed at 1/4th of the cavity length from SESAM: ensure a symmetric gain for both pulses.
- High repetition rate achievable with longer cavity (x2 increase).

Laser Physics Group UCC
SEMICONDUCTOR LASER DYNAMICS

Final year project options 2017-8

- Model mode-locked laser stabilisation (6wk)
- Experimental dynamics of VECSELs (12wk)

- J McInerney, Proc SPIE 9734 (2016)
- A Laurain, JMcI et al, Optica 3, 781 (2016)
- H Asghar & JMcI, Opt Lett 42, 3714 (2017)