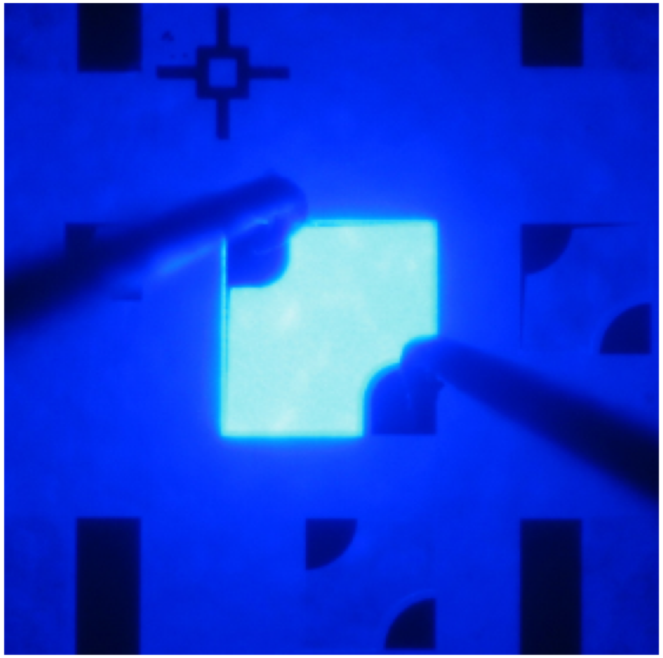
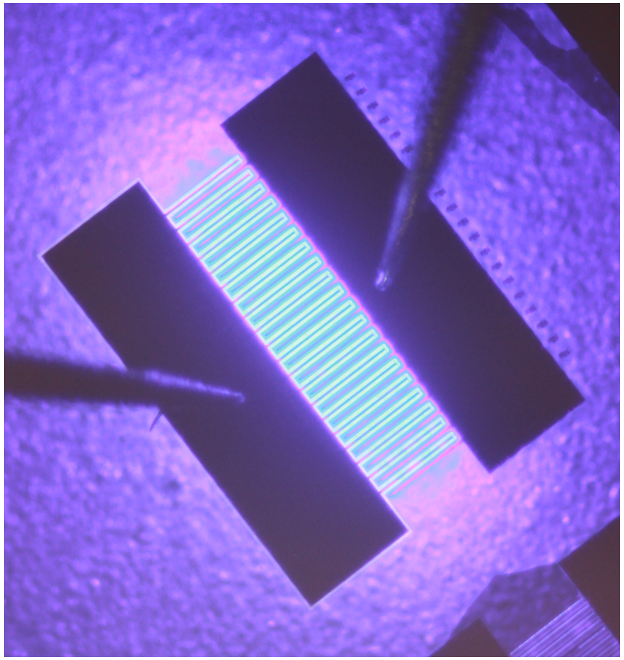
Optoelectronics
ELEC-E3210





Lecture 4

Outline

1 Lateral confinement: index and gain guiding

2 Surface emitting lasers

3 DFB, DBR, and C3 lasers

4 Quantum well lasers

5 Mode locking

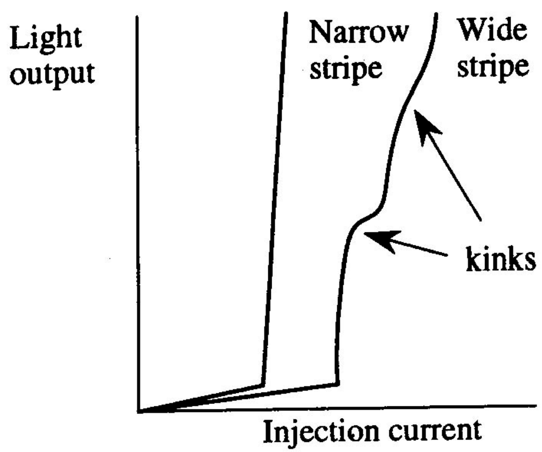
P. Bhattacharya: chapters 6&7
J. Singh: chapter 10&11

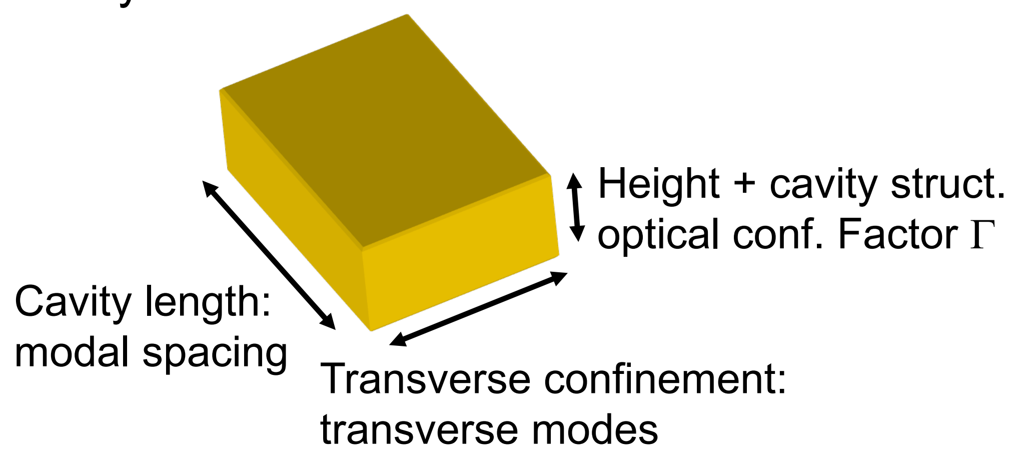
Lateral confinement

- The Fabry-Perot cavity has a certain lateral dimension which determines the transverse modes of the light that is emitted → there may be several transverse modes with closely spaced frequency
- To avoid ”kinks” in the output power a strong lateral confinement has to be ensured
- Lateral confinement may be achieved by two approaches

  1) **gain guided cavities** (lateral variation of optical gain): stripe and ridge geometries

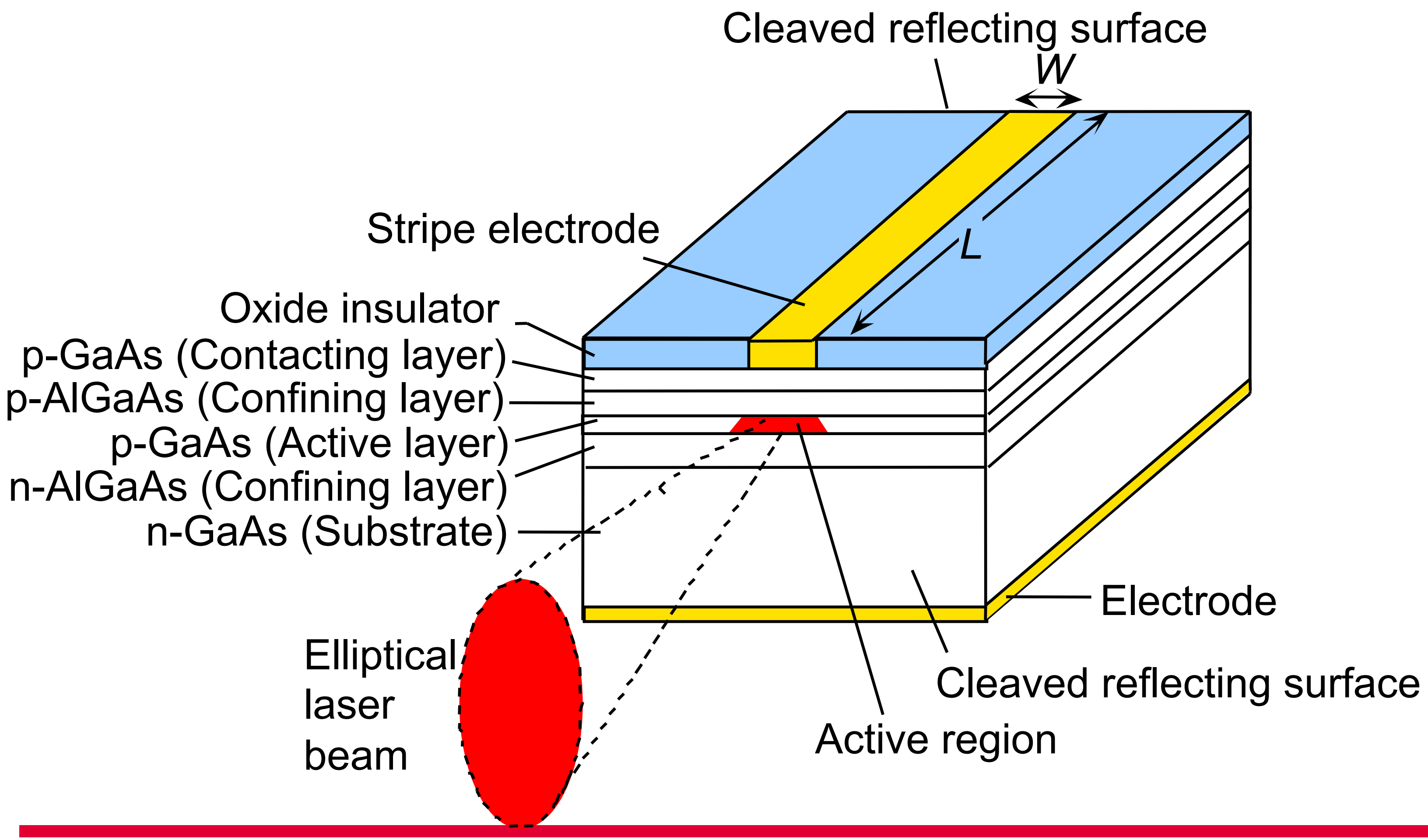
  2) **index guided cavities** (laterial variation of refractive index): buried heterostructure geometry



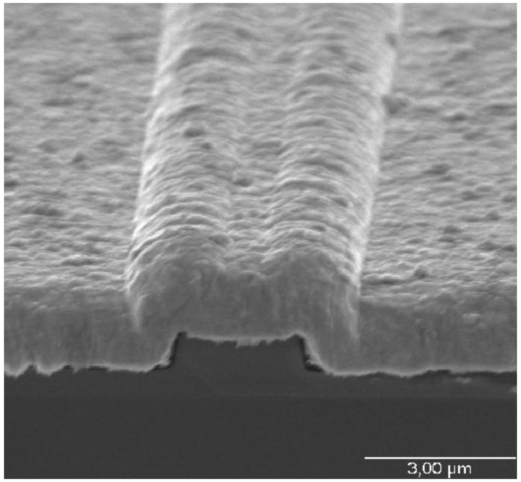


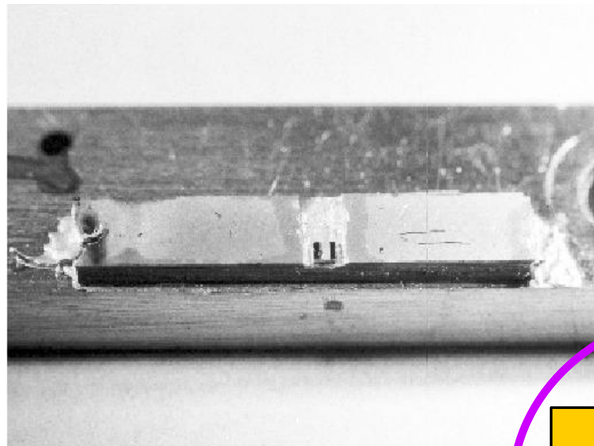
Gain-guided lasers: stripe geometry

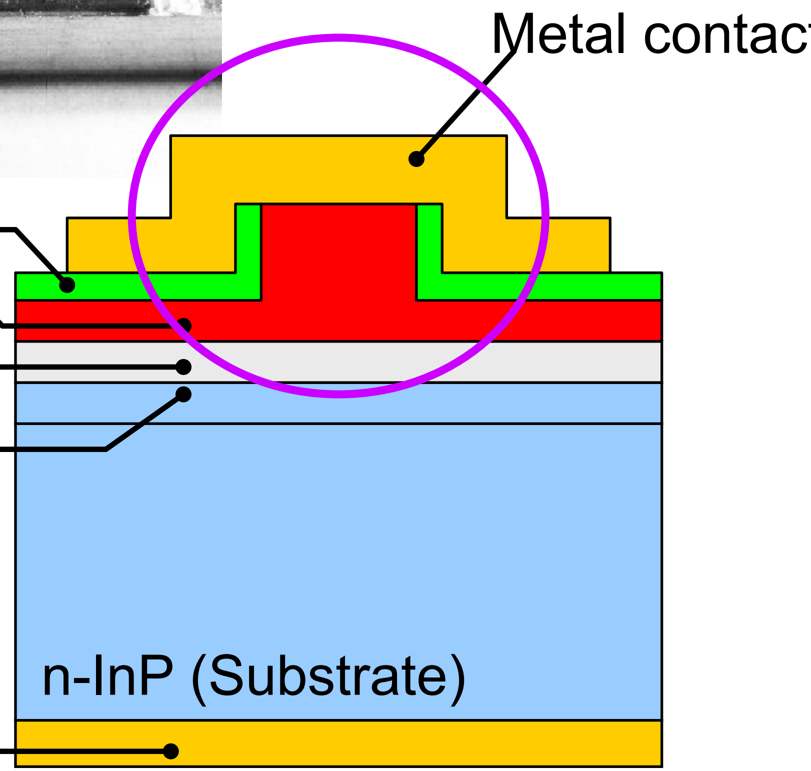
Transverse dimension of the active region 1 – 10 um



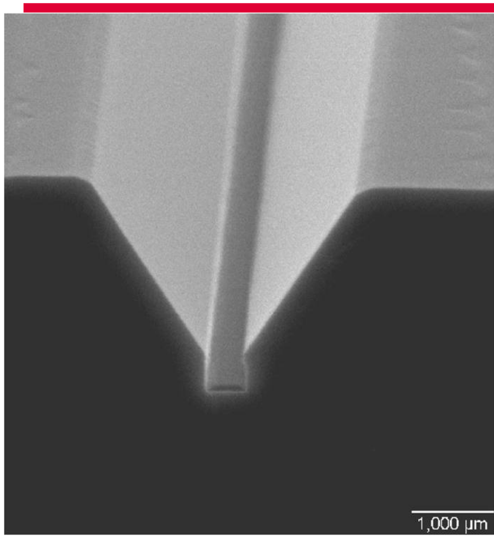
Gain-guided lasers: ridge geometry



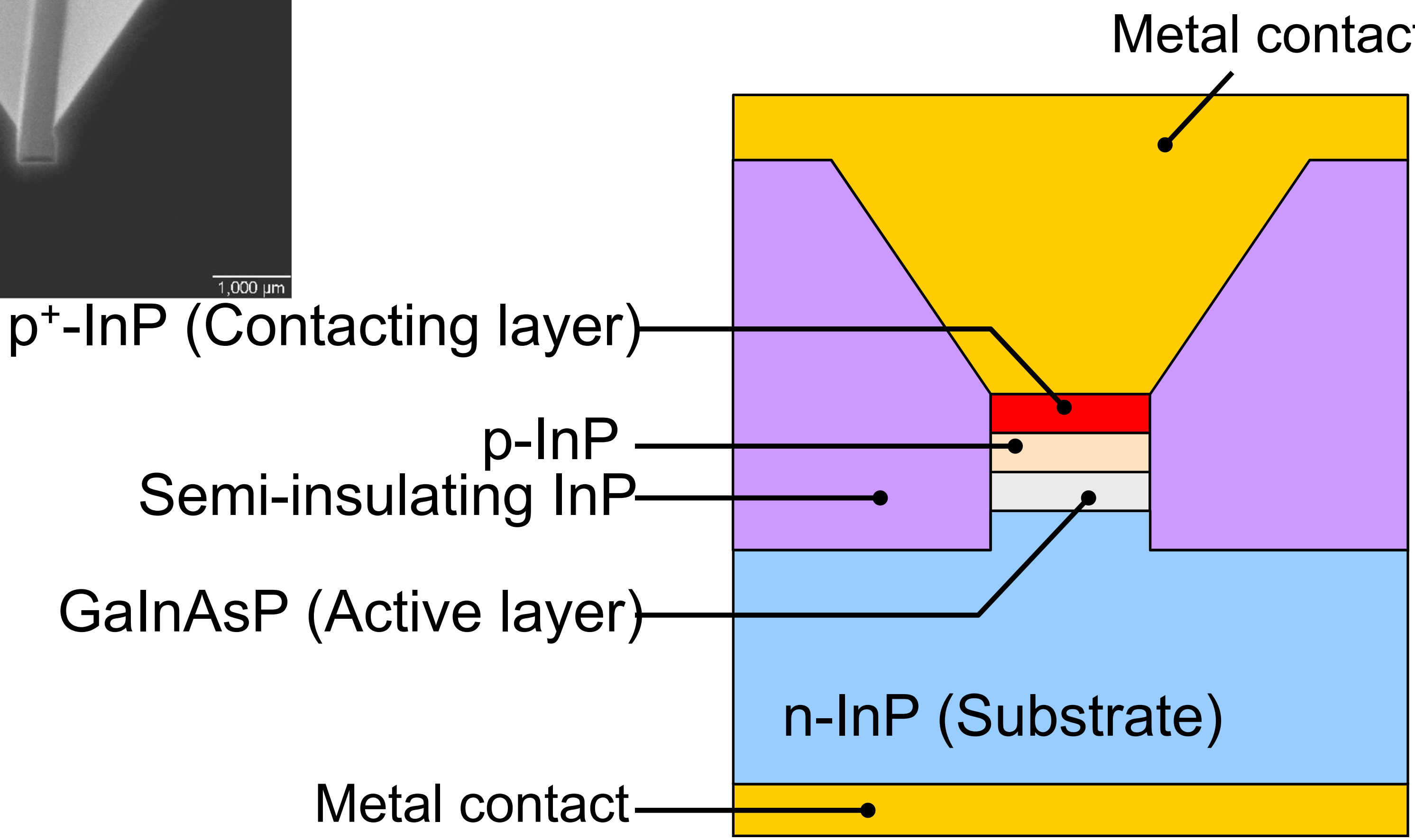




Index-guided lasers: buried heterostructure



Mesa-etching + re-growth



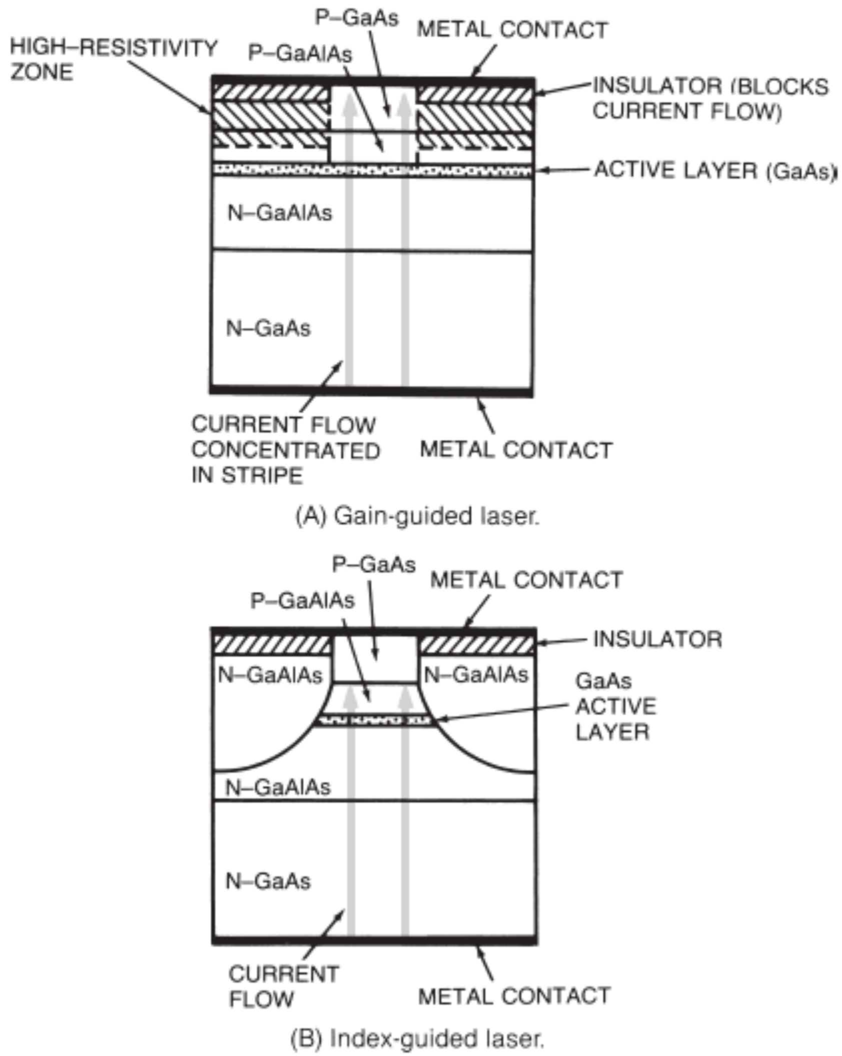


Figure 9-12. End views of gain-guided and index-guided lasers.

- Gain-guided lasers are simple to make
- Index-guided lasers confine light better, producing better beam quality

Images of real packaged lasers

A packaged laser diode with penny for scale

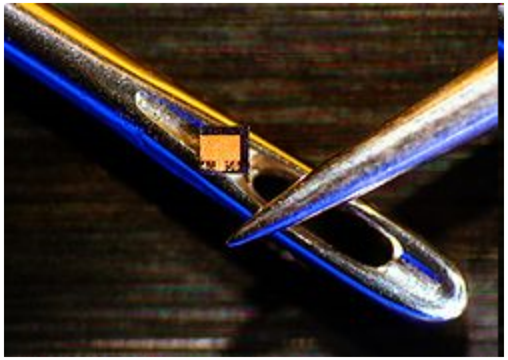
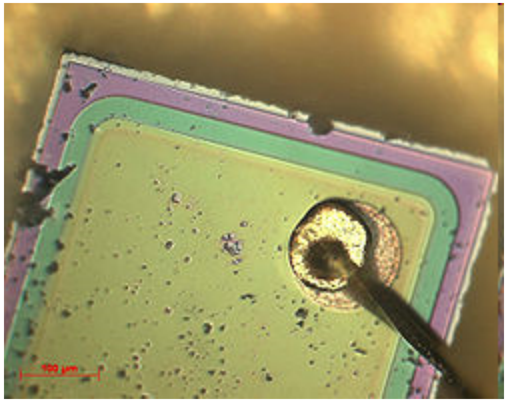


Image of the actual laser diode chip (shown on the eye of a needle for scale) contained within the package shown in the left image.



A visible light micrograph of a laser diode taken from a CD-ROM drive. Visible are the P and N layers distinguished by different colours. Also visible are scattered glass fragments from a broken collimating lens.

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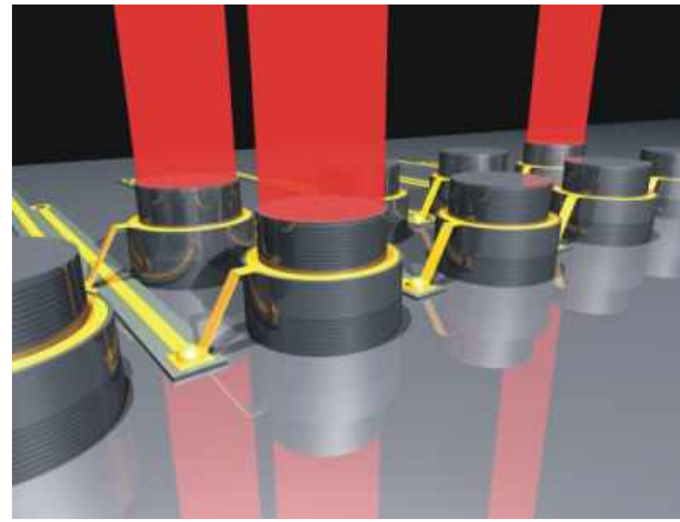
Vertical Cavity Surface Emitting Laser (VCSEL)

- In a **Vertical Cavity Surface Emitting Laser** (VCSEL) light is emitted perpendicularly to the layered structure

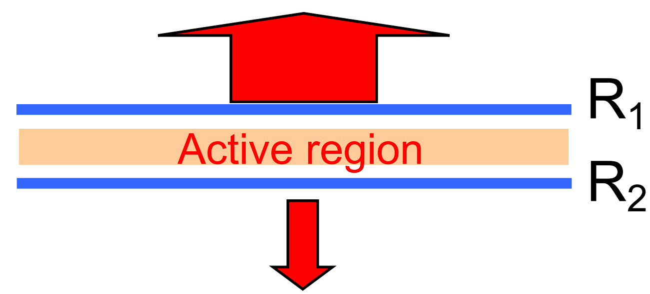
- The resonant cavity is particularly short ($L<\lambda$) and the active region has a very small volume.



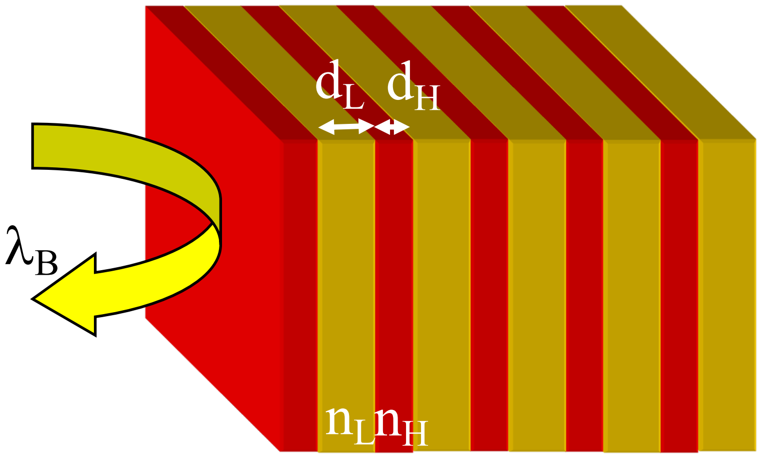
$$\Gamma g_{th} = \alpha - \frac{1}{L}\ln(R_1 R_2)$$ and L small

R_1 and R_2 need to be close to 100% in order to achieve reasonable threshold gain

~~Metal mirror?~~ ~~High reflectivity coating?~~



Distributed Bragg Reflector (DBR)



$$R = \left(\frac{1 - \left(\frac{n_L}{n_H}\right)^{2N}}{1 + \left(\frac{n_L}{n_H}\right)^{2N}} \right)^2$$

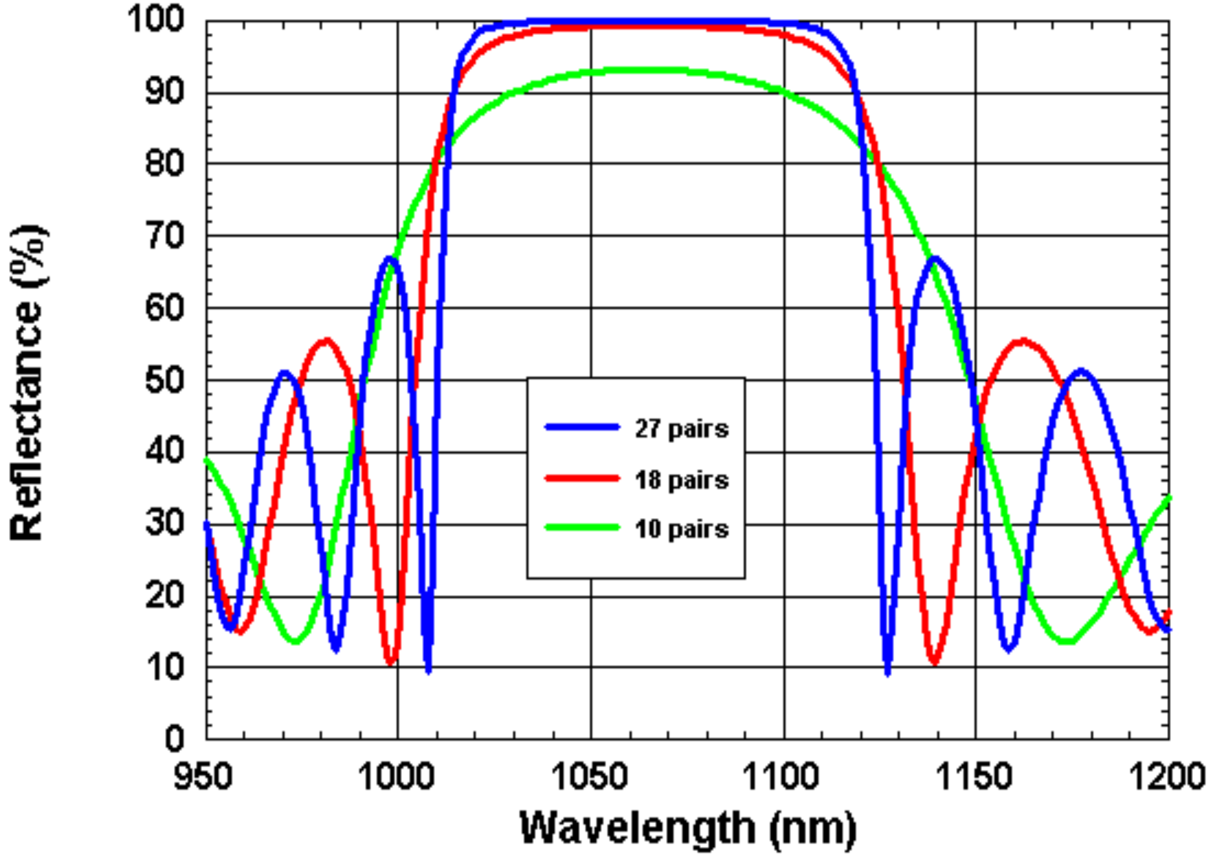
$$n_L d_L + n_H d_H = \frac{\lambda_B}{2}$$

- DBR: multilayer-stack of alternate high- and low-index films
- Basic principle: constructive reflection of light at a series of subsequent interfaces
- High reflectivity around Bragg wavelength λ_B
- Design rules:

1. $d_L = \frac{\lambda_B}{4n_L}$ $\quad d_H = \frac{\lambda_B}{4n_H}$
2. Odd number of layers
3. R has to be higher than 99%
4. Mirror has to be transparent to the laser

DBR

Example: AlAs/GaAs reflector

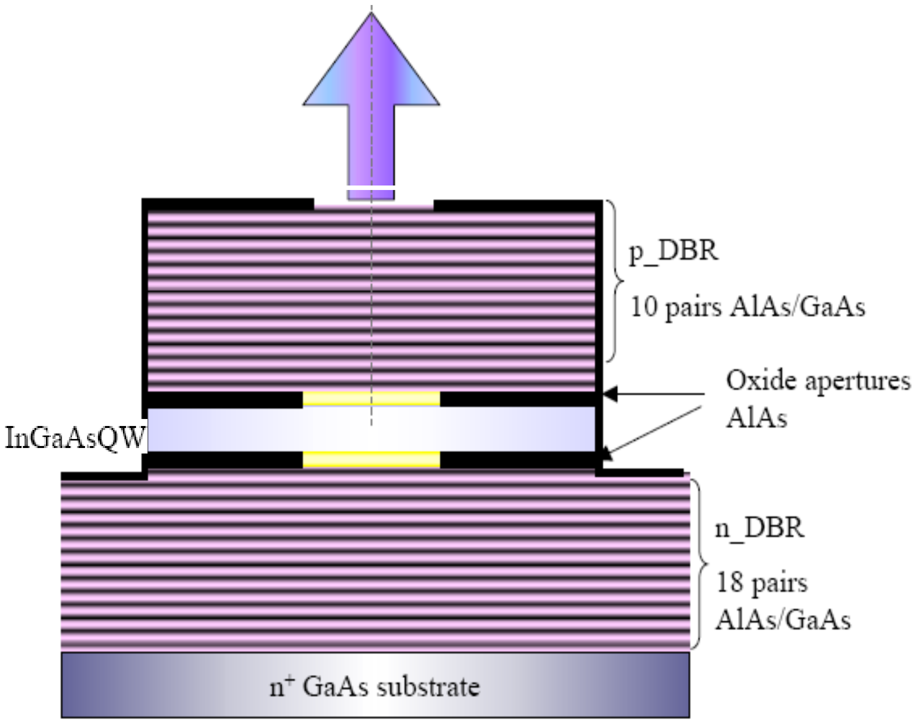


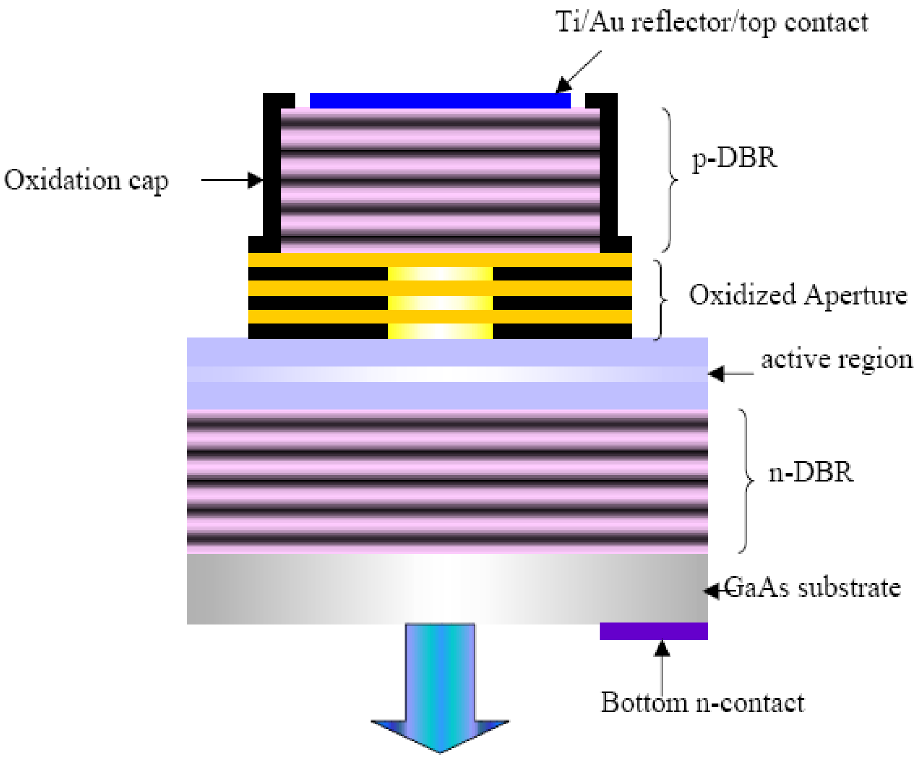
Constructive interference leads to the formation of a stopband

DBR

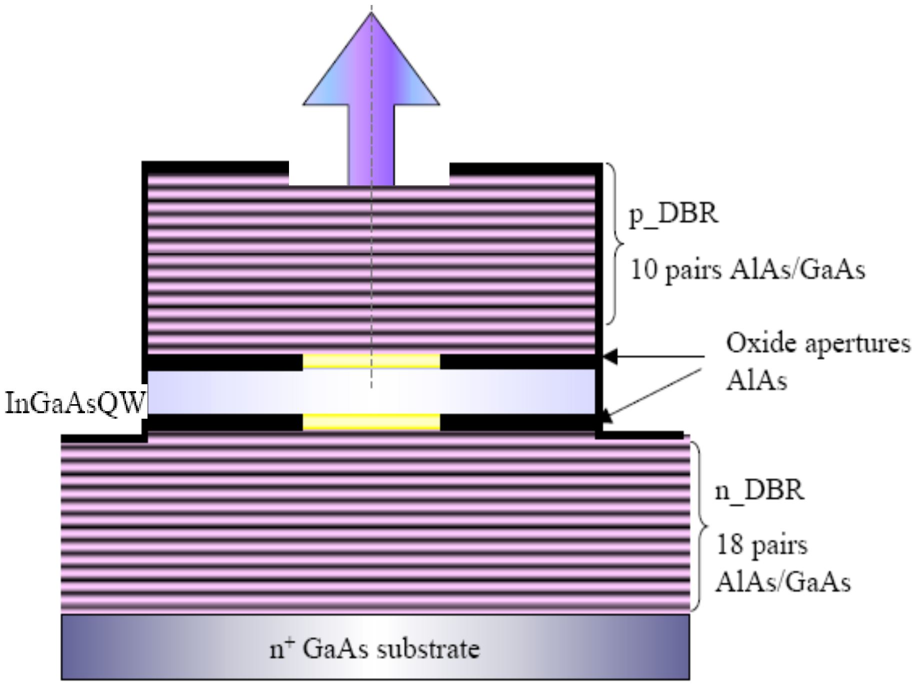
- Several possibilities exist to make DBRs of the III-V's:
  - AlGaAs/GaAs
  - InGaAsP/InP
  - AlGaInP/AlInP
  - GaP/AlGaP
- DBRs serve as pathways for the injected current
- Mirror design is a compromise between good optical characteristics and low electrical resistance; heterobarrier offsets in the DBR layer cause high resistance especially in the p-side
- Several modifications reducing the offsets have been introduced (for example compositional grading and doping profiling in the interfaces)

VCSEL structure





VCSEL structure



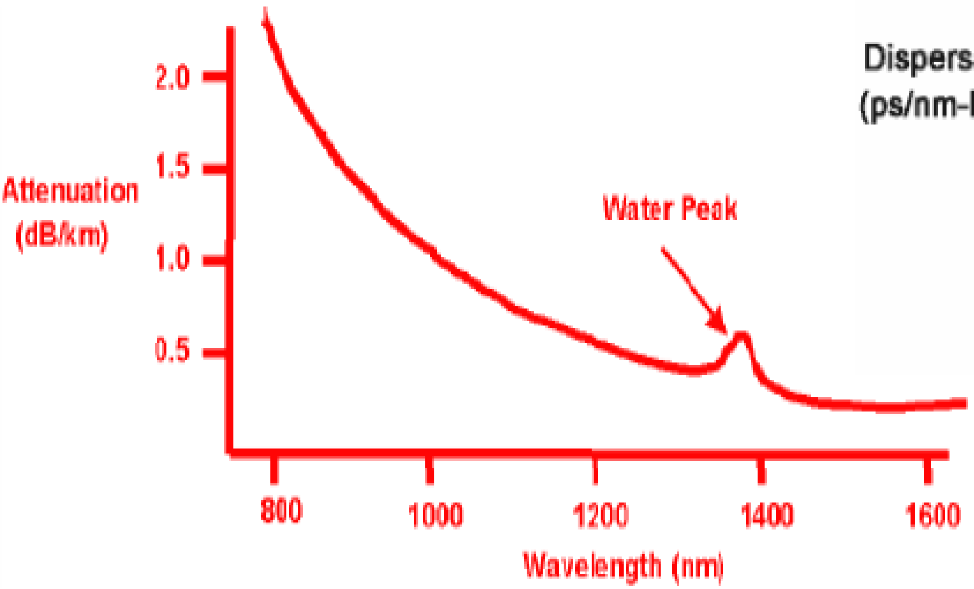
+ implant defined devices

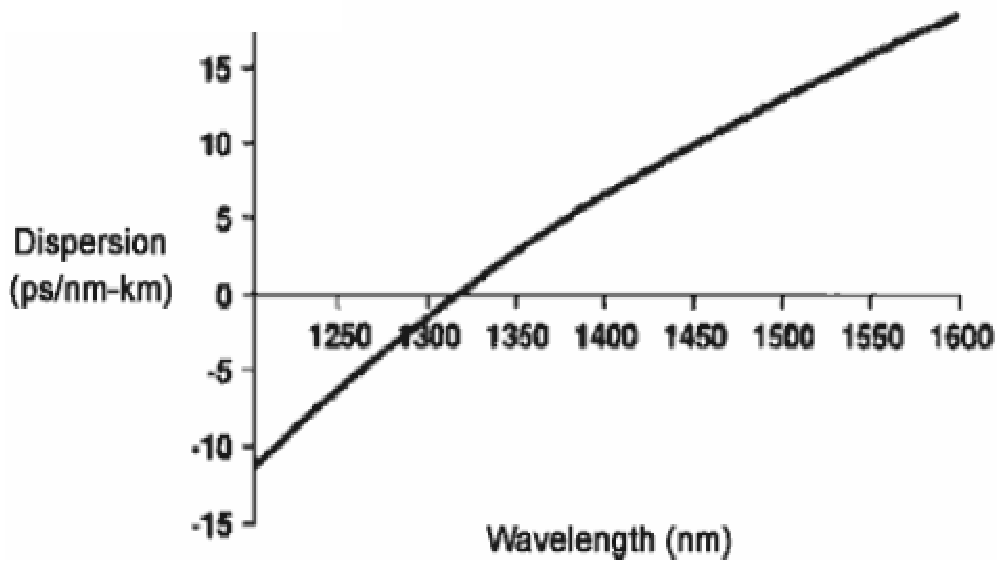
+ intra-cavity contacted devices

- **Oxide-confined design** in an example of index-guiding
- In Al-containing alloys oxidation is highly selective: in GaAs-based structures the oxidation rate is highest for $Al_xGa_{1-x}As$ with $x > 0.98$.
- Formation of Al-oxide reduces the refractive index
- A partially oxidised AlGaAs layer forms an efficient current aperture that can be placed close to the active region to provide strong current confinement

VCSELs for 1.3-1.55 μm

- Long wavelength VCSEL
  - 1310nm- lowest dispersion in fiber
  - 1550nm- lowest loss



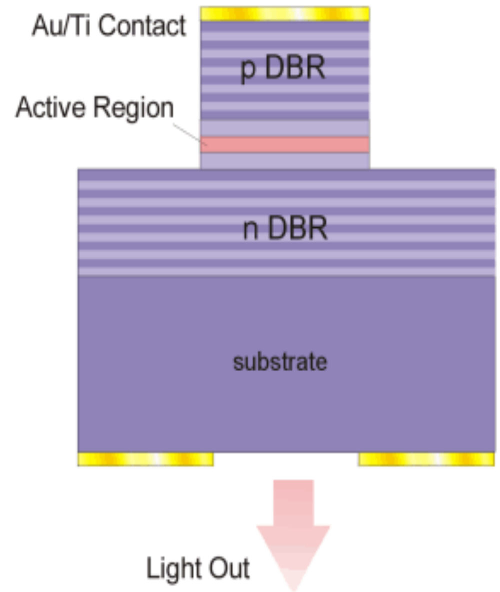


VCSELs for 1.3-1.55 μm

Approaches for long wavelength VCSEL

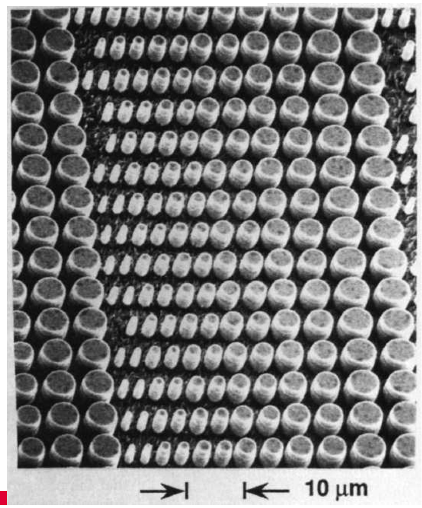
Wavelength	Active/DBR Materials	Comment
1310 nm	GaInAsP/AlGaInAsP on InP	Monolithic DBR have low index contrast—need may periods Low modal gain from quatum well
	GaInAsP/AlGaAs (wafer bond)	Excess voltage?
	GaInAsN/AlGaAs	Material gain : As N increases, radiative efficiency decreases
	InAs quantum dots	Sufficient material gain?
1550nm	GaInAsP/AlGaInAsP on InP	Monolithic DBR have low index contrast—need may periods Low modal gain from quantum well
	GaInAsP/AlGaAsSb on InP	Extremely reactive Sb-containing DBRs.
	InGaAsN/AlGaAs	Sufficient gain at long wavelength?
	InAs quantum dots	Sufficient gain at long wavelength?

VCSEL advantages



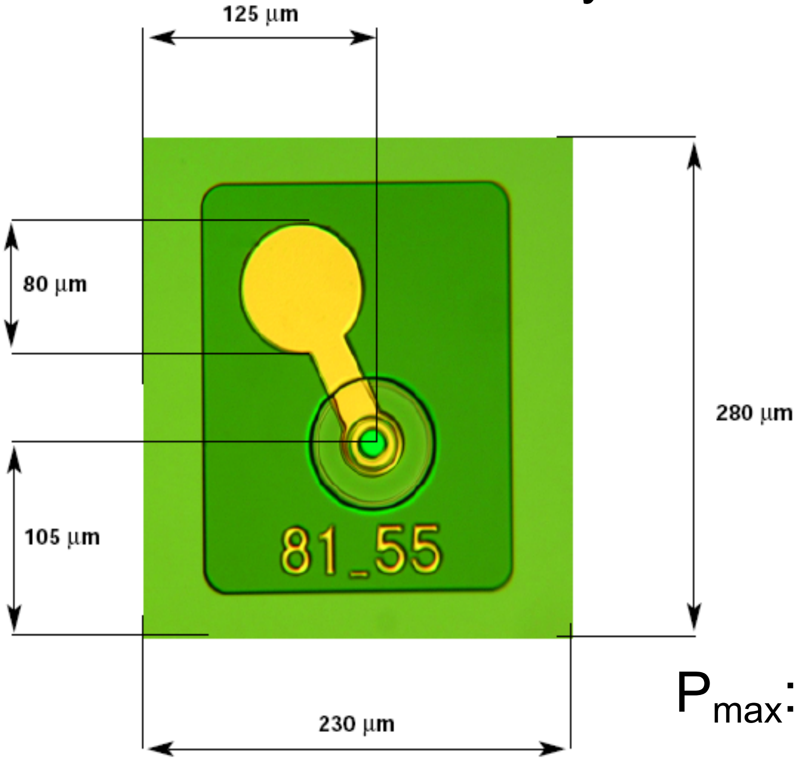
<ins>Advantages of VCSELs</ins>

- **Monomode operation** due to the short cavity
- Low threshold currents
- Low beam divergence
- On-wafer testing possible (reduces costs)
- 2D VCSEL arrays possible
- Can be easily coupled (circular beam), surface-normal emission
- Low drive current needed (thin active region)
- High transmission speed with low power consumption



VCSEL applications

Commercial VCSEL by Avalon Photonics



AVAP-850SM

Standard 850 nm singlemode VCSEL chip

P_{max}: 3 mW

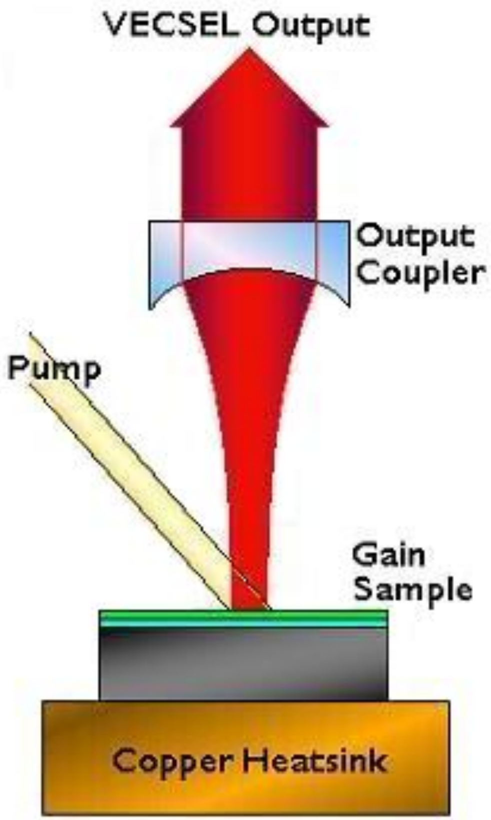
I_{th}: 1-4 mA

T_{op}: 0 - 70°C

Applications

- Replacing edge-emitting lasers such as Fabry-Perot and DFB
- 1x12 arrays, 2D arrays, 3D arrays of a variety of VCSELs all coupled together driving a big set of parallel fibers
- Long haul, Metropolitan, LAN, Storage area Network
- Fiber-to-the home and two dimensional arrays for MEMS

VECSEL



- The **external cavity** enforces a low-divergence, circular, near-diffraction-limited, high quality output beam.
- In the gain sample, a Bragg reflector is grown behind the active region.
- **Optical pumping** of the gain sample allows high power operation avoiding the problems of carrier filamentation and post-growth processing associated with electrical pumping.
- Access to external cavity allows manipulation of the laser output. Frequency doubling, mode-locking and spectroscopy are amongst these manipulative applications.

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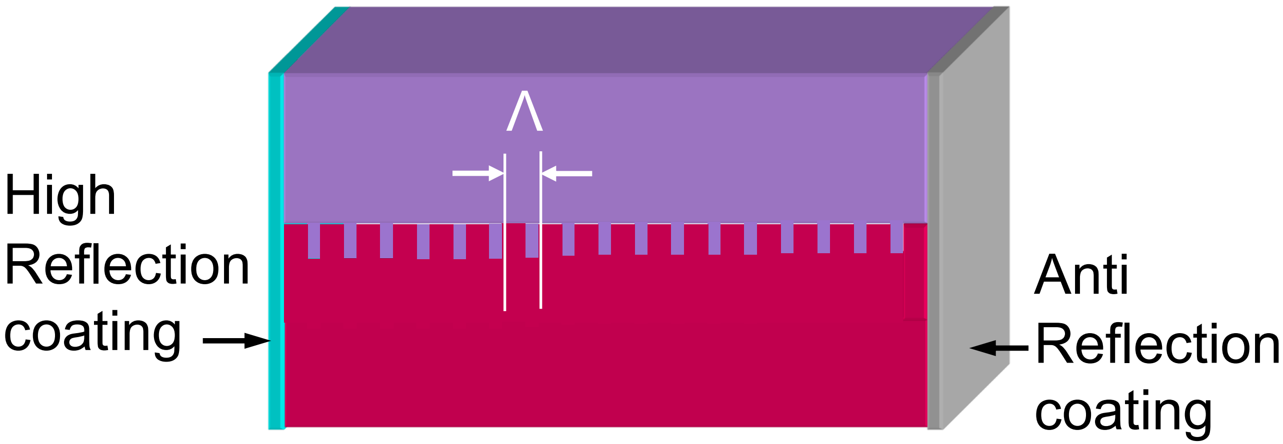
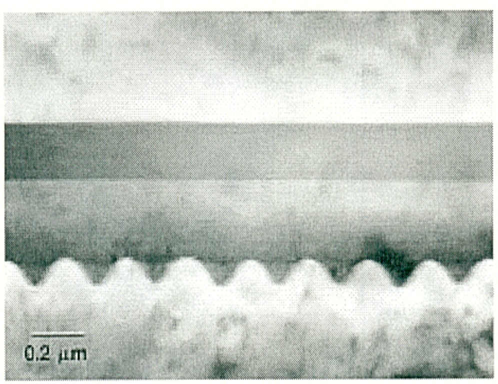
Distributed FeedBack (DFB) Laser



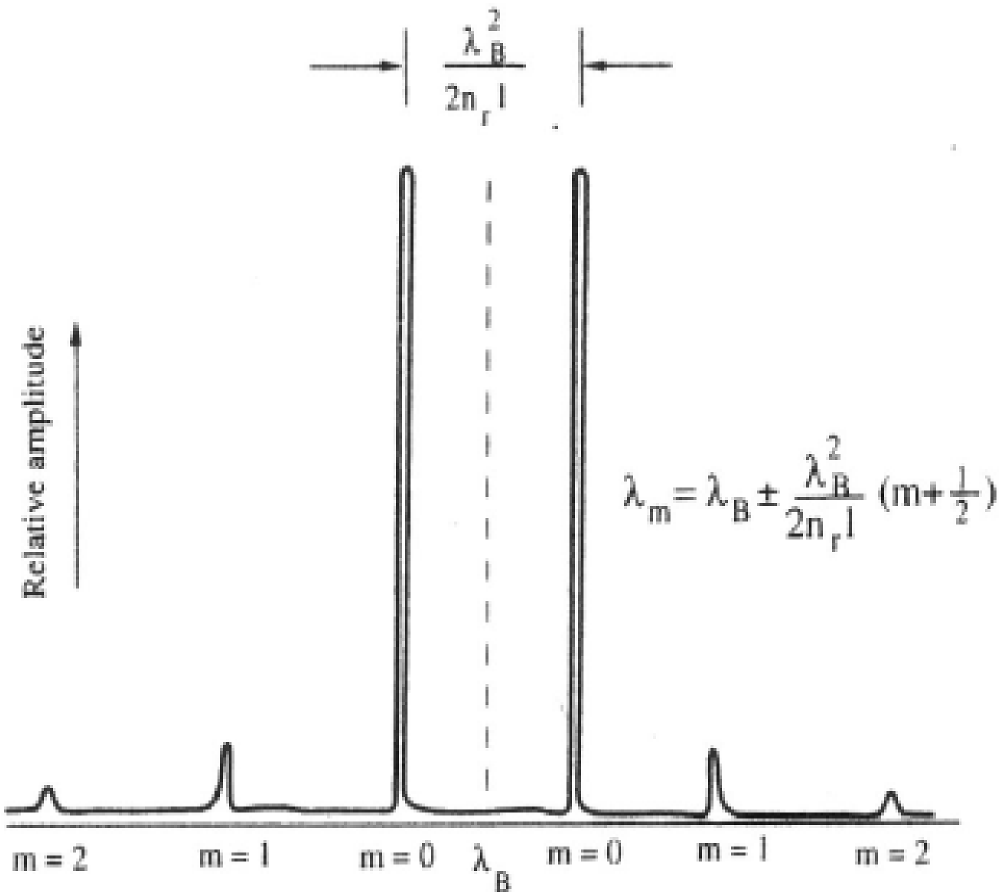
Periodic variation of refractive index along the propagation direction



Feedback occurs due to the energy of the wave propagating in the forward direction being continuously fed back in the opposite direction by Bragg diffraction at the corrugation, or grating.

Distributed FeedBack (DFB) Laser

The longitudinal modes of an idealized DFB laser

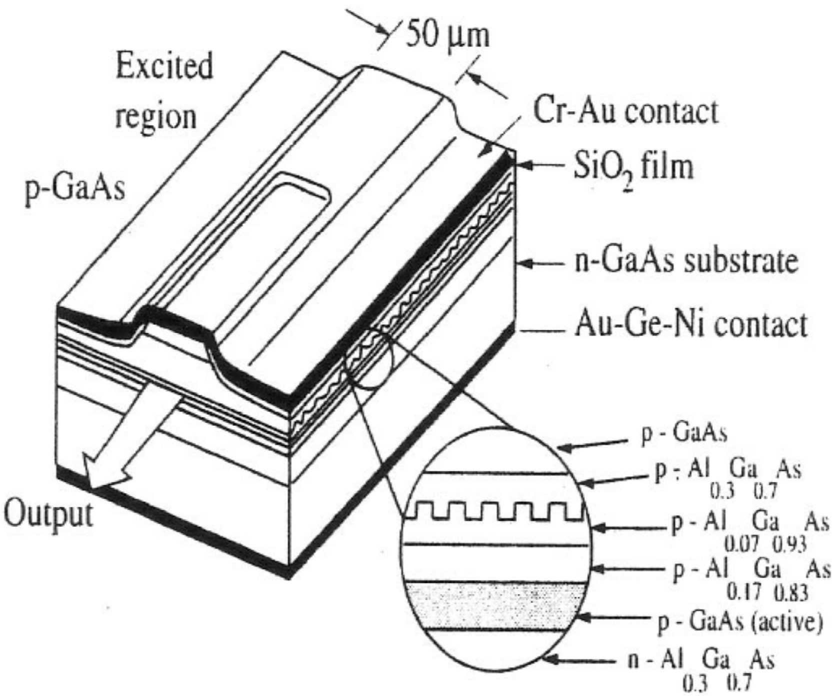


(p = diffraction order)

$$\lambda_B = \frac{2n_{eff}\Lambda}{p}$$

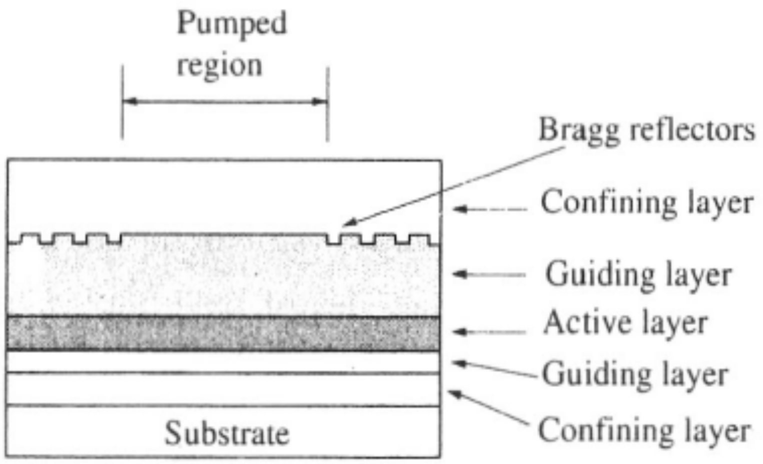
- **feedback is f-dependent:** cavity loss is different for different longitudinal modes!
- two modes on either side of Bragg resonance are the strongest
- emission is stabilized at one of these modes when the gain curve overlaps them

DFB and DBR laser



DFB laser

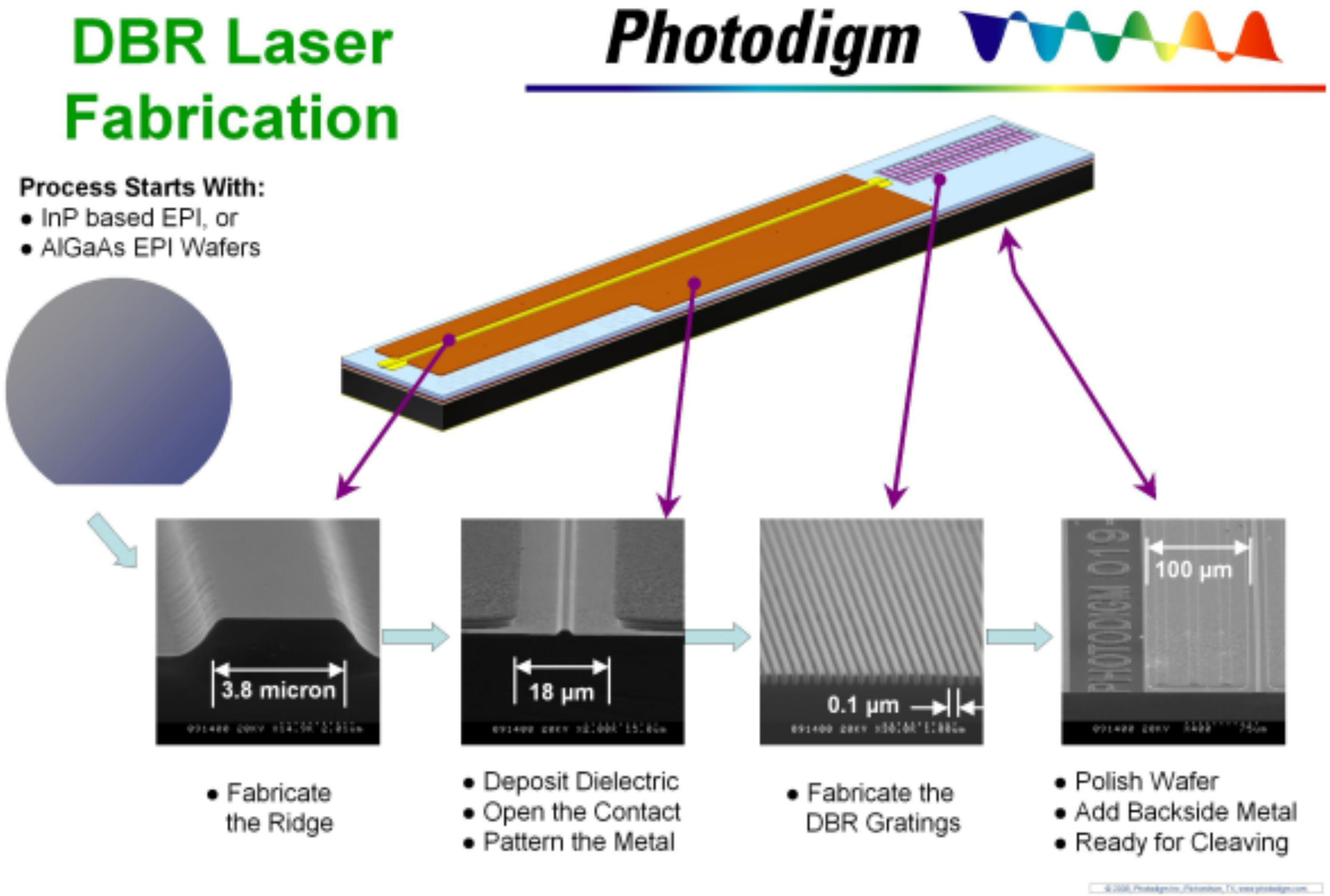
- The reflectors are within the active laser cavity



Distributed Bragg Reflector (DBR) laser

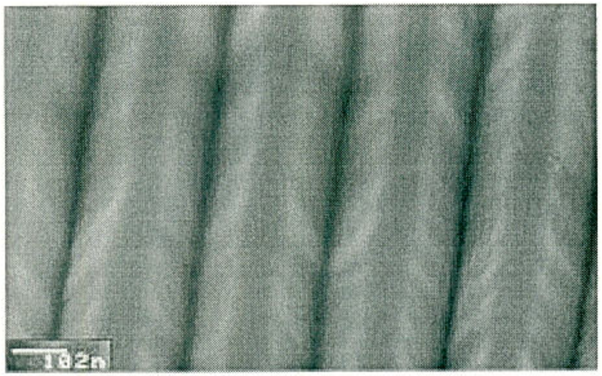
- The reflectors are outside the active cavity region = the end mirrors are replaced by gratings

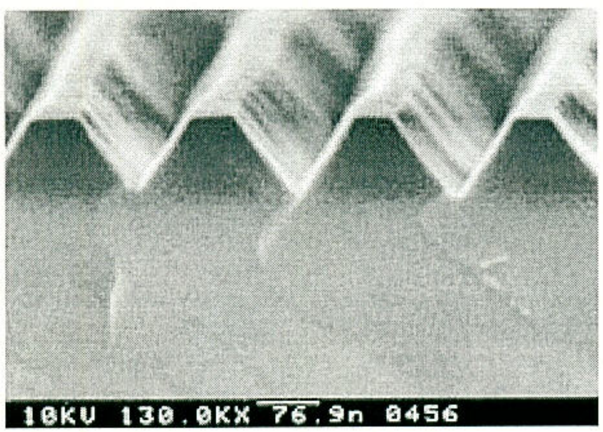
DFB and DBR laser

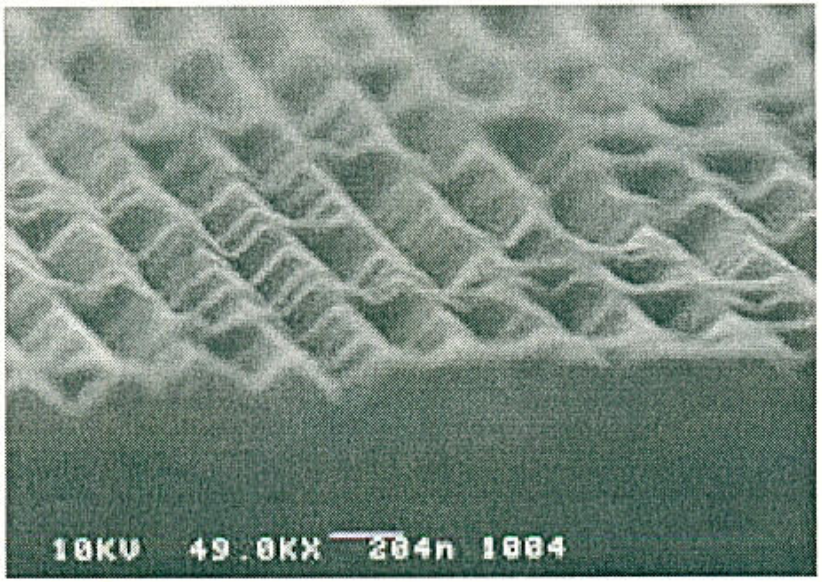


DFB grating: fabrication

DFB gratings are usually wet-etched. Epitaxial regrowth is then necessary to cover the grating.







Commercial DFB laser

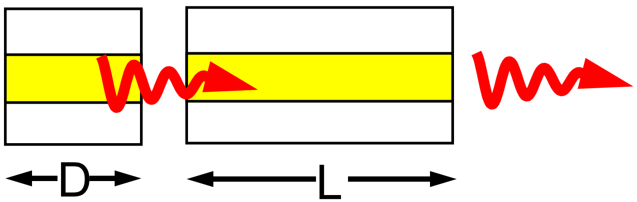
Includes

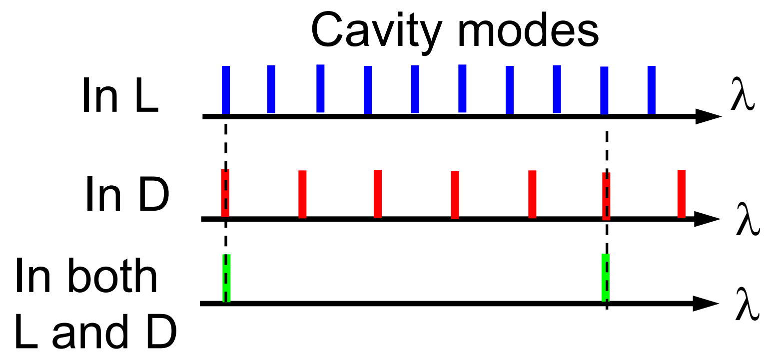
- DFB diode
- Thermoelectric cooler
- Thermistor
- Photodiode
- Optical isolator
- Fiber-coupled lens

Parameters	Symbol	Min	Typ	Max	Unit
CW Output power (25C)	P_{out}	10	---	30	mW
Threshold current	I_{th}	--	25	60	mA
Operating current	I_b	--	300	--	mA
Forward voltage	V_f	--	2.0	3.0	V
Center Wavelength	λ	1540	1550	1570	nm
Linewidth	$\Delta\lambda$	--	2	--	MHz
Operating Temperature	T_o	-20	--	65	C
Storage temperature	T_{stg}	-40	--	85	C

Cleaved Coupled Cavity (C^3) Laser

Cleaving → two shorter laser diodes with aligned cavities





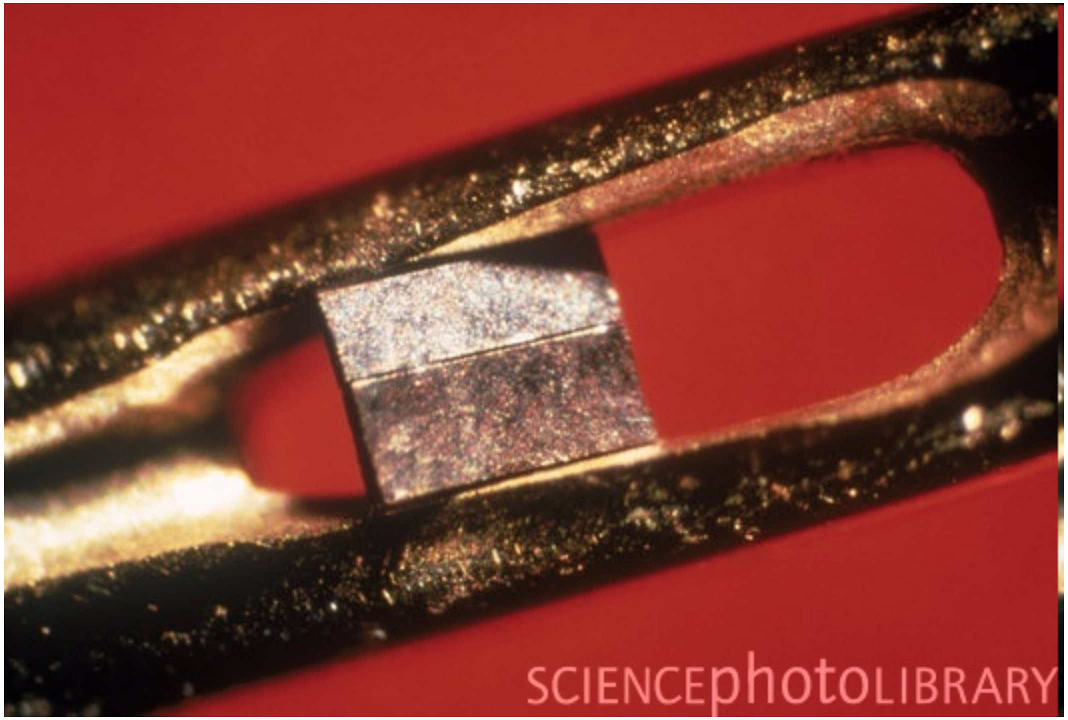
$$\lambda = \frac{2Ln}{m_1} = \frac{2Dn}{m_2}$$

Longitudinal modes are required to satisfy the phase condition for both cavities

Monomode operation is possible since there are less modes compared to the simple Fabry-Pérot structure

Narrow spectral linewidth

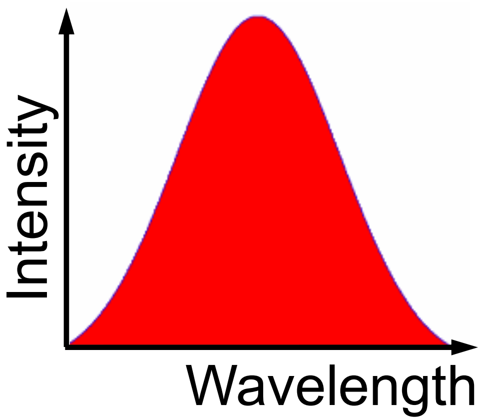
Cleaved Coupled Cavity (C^3) Laser



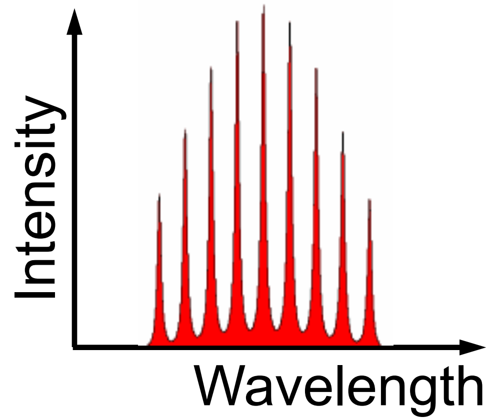
"The cleaved-coupled-cavity (C3) laser shown in eye of a needle. A semi-conductor device can be tuned to emit a range of ultrapure frequencies, having important implications for lightwave communications systems"

Spectrum comparison

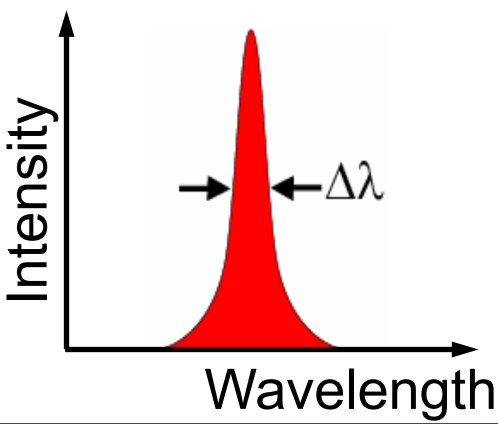
LED



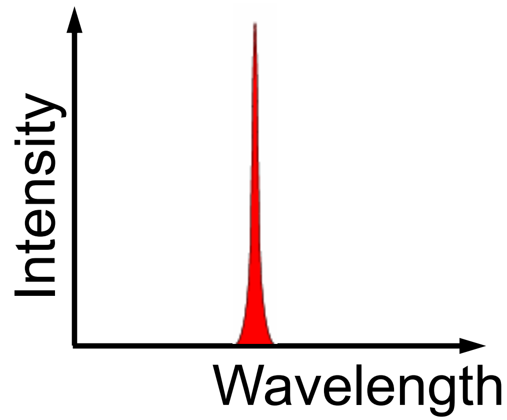
Fabry-Pérot Laser



C^3 Laser



DFB Laser



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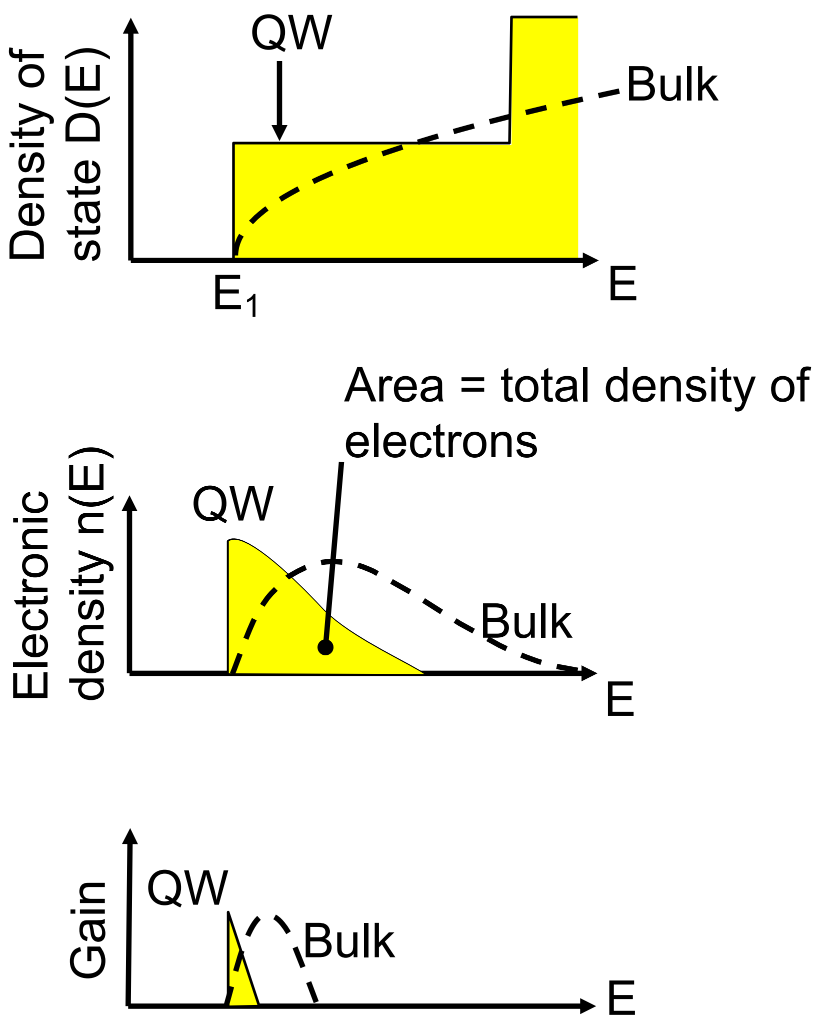
Quantum well lasers



In bulk 3D case the electrons are spread over a wide energy range with a small density at the bandedges.

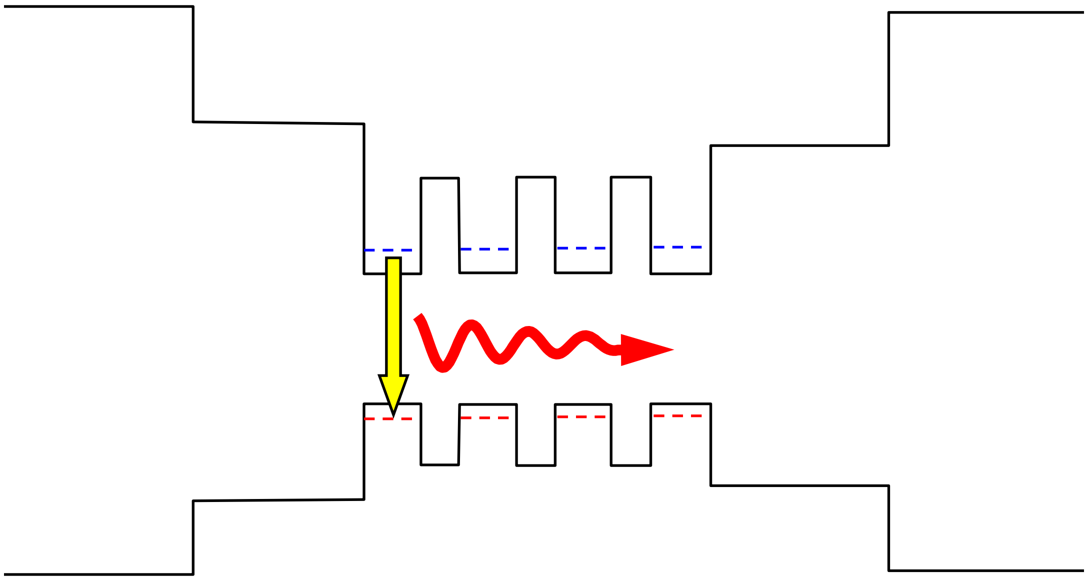
For QW lasers, the density of states is large at the edge of the conduction band, the electrons are spread over a smaller energy range with a high density at the subband edge.

→population inversion is achieved with a lower carrier density

→the modal gain curve is more peaked

→the threshold current is expected to be low in QW lasers

Quantum well lasers

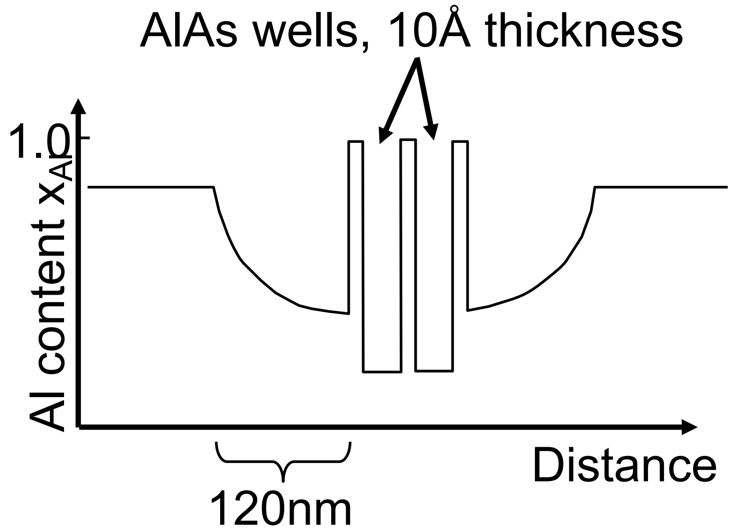


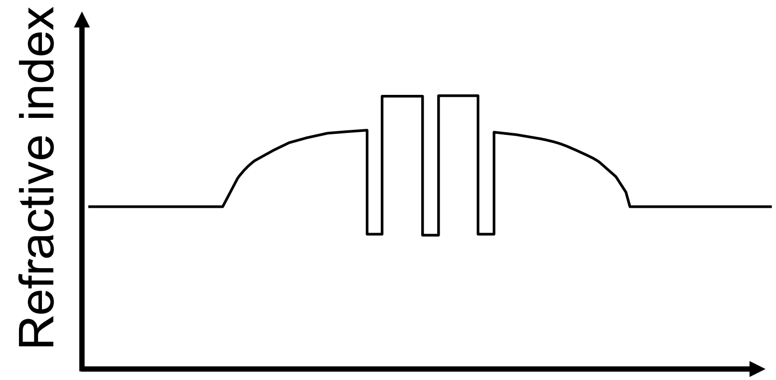
Advantages of **quantum well lasers** (QW laser)

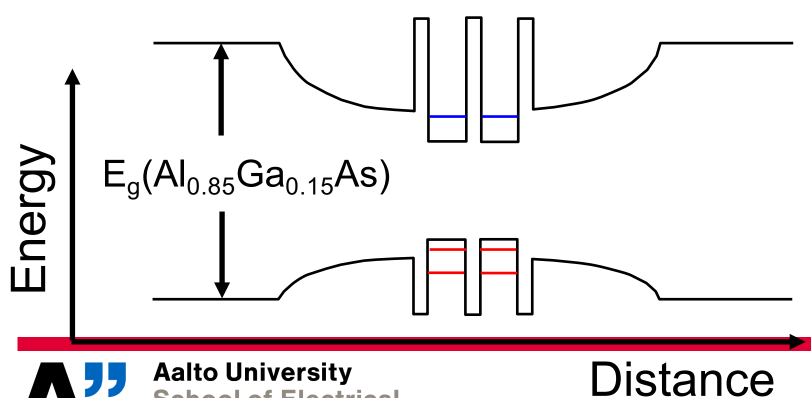
- Higher differential gain → Smaller J_{th}
- Population inversion obtained more easily → Smaller J_{trans}
- Lower temperature sensitivity
- Multiple quantum wells (MQW) coupled together increase the total thickness of active layer → higher output power

QW lasers: Graded Index Separate Confinement heterostructure (GRIN-SCH)

Single-QW lasers suffer from poor optical confinement due to small width of the gain region.







The graded index structure allows improving the optical confinement!

Example: $Al_xGa_{1-x}As$ laser

QW lasers: How many wells?

A number of QWs in the active region results in higher gain compared to a single QW laser. However, too many wells will give problems related to non-uniform injection and in strained laser structures generation of dislocations.

If the number of wells goes from 1 to m, the amount of gain required from each well decreases by a factor of m. Since $J \sim mn^2$, in order to benefit by using m wells, the threshold carrier density n in a well must decrease by a factor of $m^{1/2}$ as the required gain per well drops.

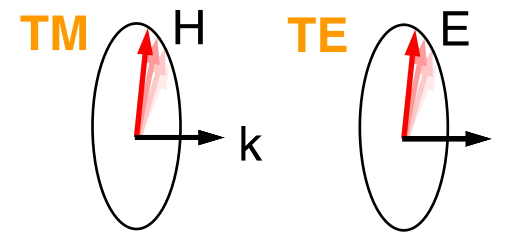
Very low threshold gain → relatively high differential gain → large reduction in gain means only a small reduction in carrier density and very small reduction in threshold current density

→MQW lasers are more favored for high-current densities!

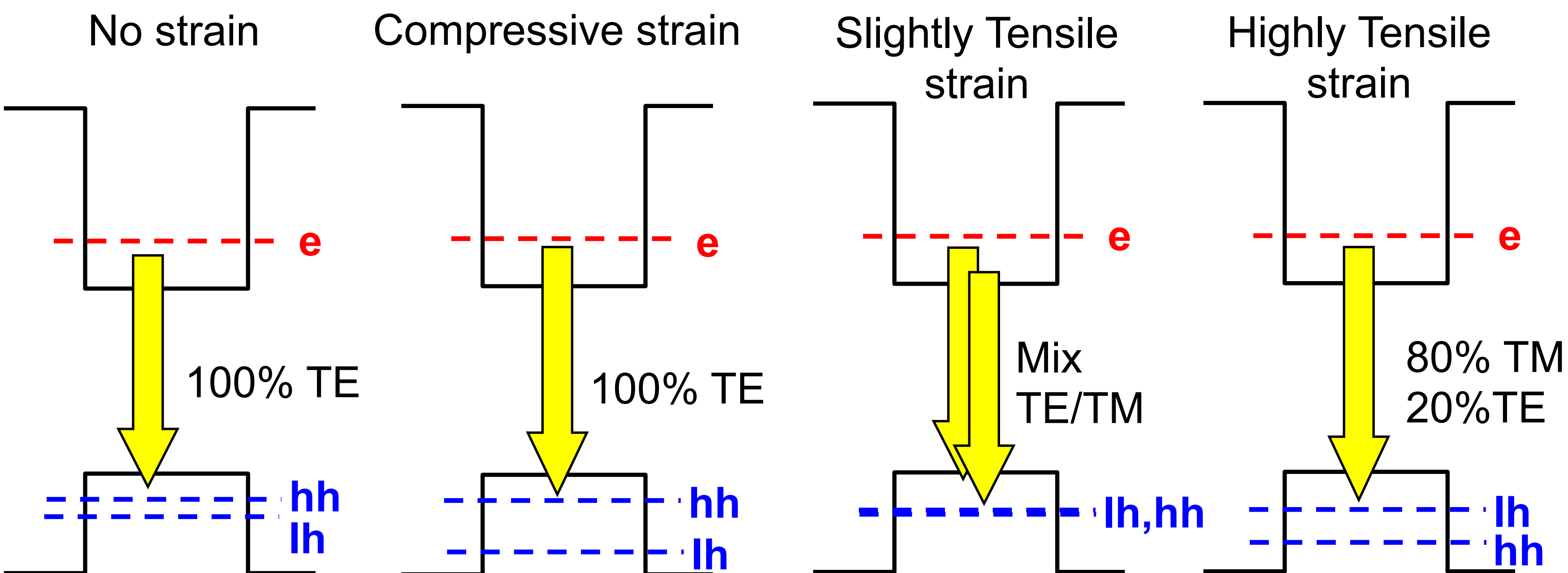
QW lasers: polarisation

Bulk lasers (without QWs) emit a mix of TE- an TM-polarized light.
The polarization of QW lasers depends on the predominant radiative recombination in the QWs:

- hh ⇨ e: 100% TE
- lh ⇨ e: 20% TE, 80% TM



The predominant recombination depends on the strain in the QWs:



Outline

1 Lateral confinement: index and gain guiding

2 Surface emitting lasers

3 DFB, DBR, and C3 lasers

4 Quantum well lasers

5 Mode locking

P. Bhattacharya: chapters 6&7
J. Singh: chapter 10&11

Mode locking

- A technique of obtaining intense narrow pulses
- The phases of mode components are locked together by external means → a periodic pulse train is formed
- Active mode-locking: a device (modulator) is inserted into the laser resonator
- Passive mode-locking: a saturable absorber is used in the laser cavity to initiate short pulse generation
- A saturable absorber is a material that has non-linearly decreasing light absorption with increasing light intensity.
- The key parameters for a saturable absorber are its wavelength range (where it absorbs), its dynamic response (how fast it recovers), and its saturation intensity and fluence (at what intensity or pulse energy density it saturates).

Semiconductor saturable absorber mirror (SESAM)

• The SESAM is a saturable absorber that operates in reflection, thus the reflectivity increases with higher incoming pulse intensity.

• The mirror in a SESAM can be either a metallic mirror or a DBR

• QWs are used as absorbers, other layers are transparent at the operation wavelength

• Recovery time should be short (photo-generated carriers should recombine before the material can absorb light again) → a certain number of crystal defects are needed in the absorber

SESAM: non-linear reflectivity

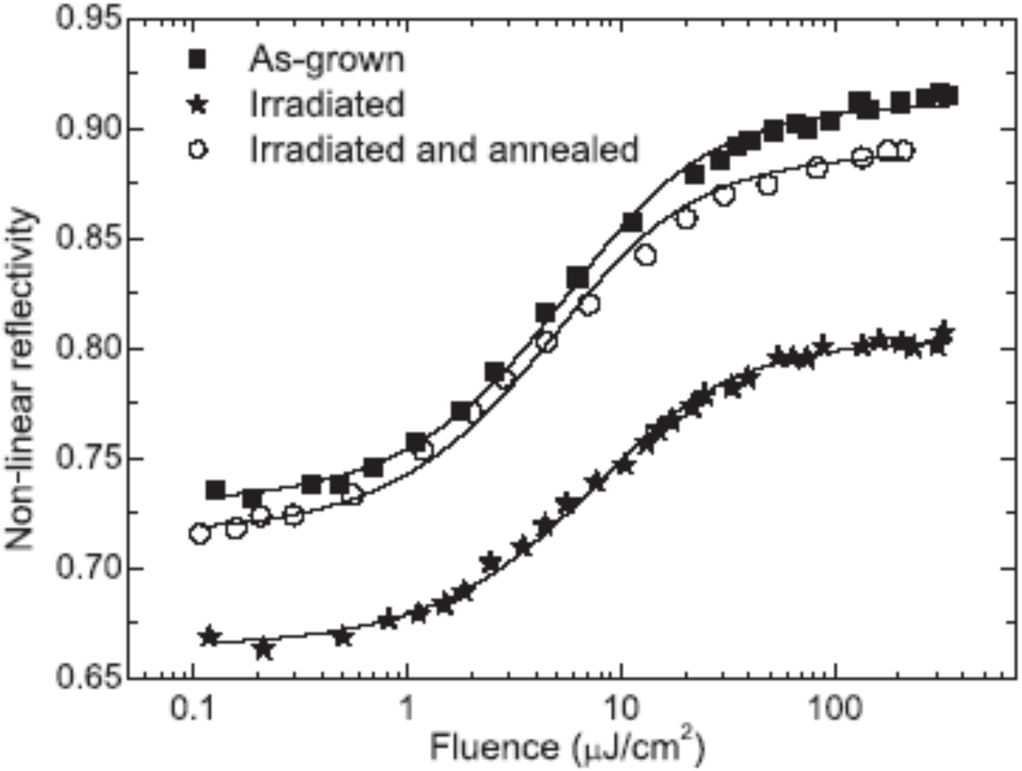


Figure 5. Non-linear reflectivity curves of as-grown, irradiated and subsequently annealed (400°C for 1 s) SESAMs. The experimental data were fitted to a theoretical model (equation (1)).

$$R = 1 - \alpha_0 - \Delta R \frac{1 - \exp(-E/E_{sat})}{E/E_{sat}}, \qquad (1)$$

InGaAs/GaAs SESAM @ 1040 nm

Ion irradiation + subsequent annealing can be used to tune the recovery time and non-linear parameters!

Table 1. Recovery time and non-linear parameters for the as-grown SESAM and for the irradiated SESAM before and after annealing. The parameters were derived by fitting the experimental data shown in figure 5 to a theoretical model.

Sample	Non-saturable loss (%)	Modulation depth (%)	Saturation fluence (μJ cm^{-2})	Recovery time (ps)
As-grown	8.7	18.3	3.3	162
Irradiated	19.5	14	4.5	0.8
Irradiated, annealed	11	17.4	2.9	1.1

where E is the pulse energy fluence, α_0 stands for the non-saturable loss, ΔR is the modulation depth and E_{sat} the saturation fluence.

T. Hakkarainen et al., J. Phys. D 38 (2005) 985-989

Mode-locked ytterbium fiber laser tunable in the 980–1070-nm spectral range

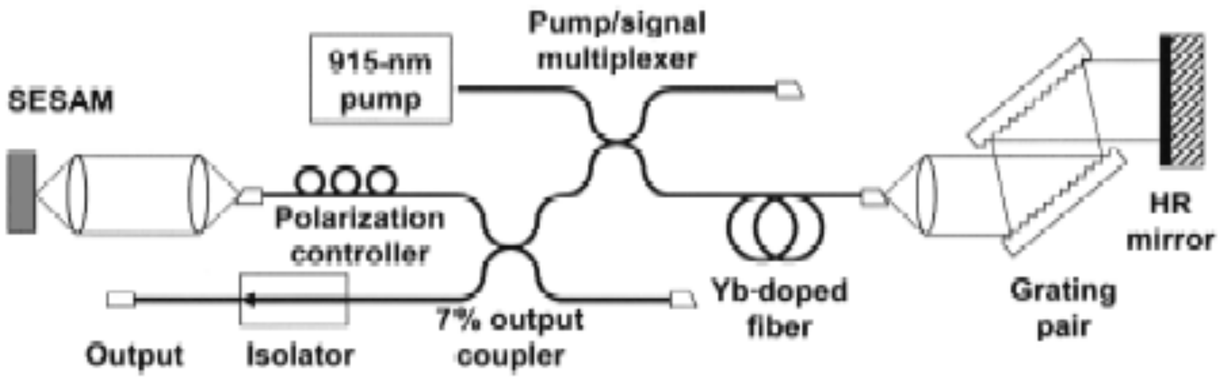


Fig. 1. Cavity configuration for a widely tunable Yb fiber laser.

Spectral tuning of a mode-locked Yb-doped fiber laser over a 90-nm range is reported. Using semiconductor saturable absorber mirrors in a fiber laser cavity incorporating a grating-pair dispersive delay line, we obtain reliable self-starting mode locking over the whole tuning range. The wide tuning range is achieved by optimization of reflection characteristics and bandgap energy of the multiple-quantum-well semiconductor saturable absorber and by proper engineering of the laser cavity. © 2003 Optical Society of America

InGaAs/GaAs SESAM
with AlGaAs/GaAs DBRs

1.6-2 ps pulse width, 3 mW output power

O. Okhotnikov et al, 1522 OPTICS LETTERS / Vol. 28, No. 17 / September 1, 2003