Topic 21

21 Characteristics of laser diodes

21.1 Estimation of threshold current

21.2 Temperature effect

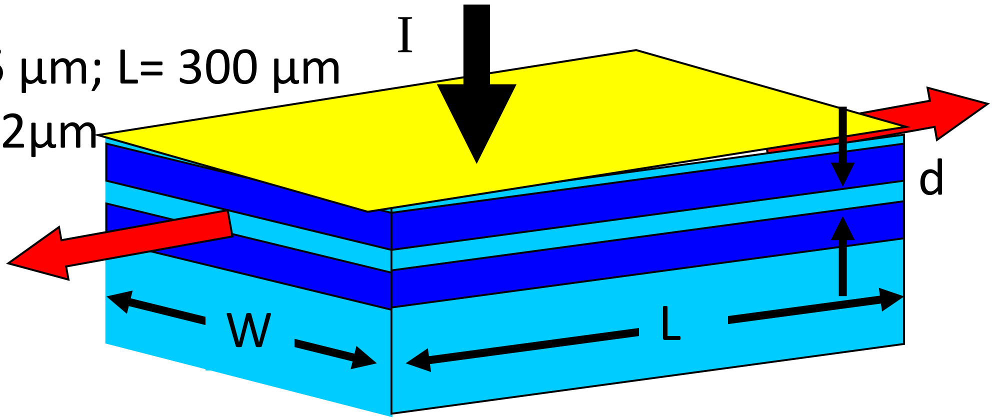
21.3 Phase conditions and laser modes

21.4 Lateral confinement lasers

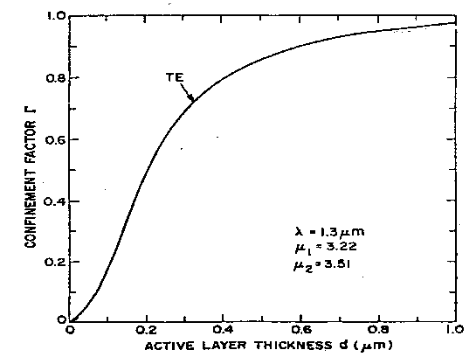
21.5 Coupling light to an optical fibre

Threshold gain and current density (i)

W=5 µm; L= 300 µm
d=0.2µm



For d=0.2µm; Γ ~0.4



- Previous slide: $$g_{th} = \frac{1}{\Gamma}[\alpha_i + \frac{1}{2L}\ln(\frac{1}{R_1 \cdot R_2})]$$

- Previous slide shows an example:

  for λ=1.3 µm LD (GaAs-based) and assuming the cavity loss =20 cm^{-1} and as cleaved facet, **g_{th} can be easily estimated**

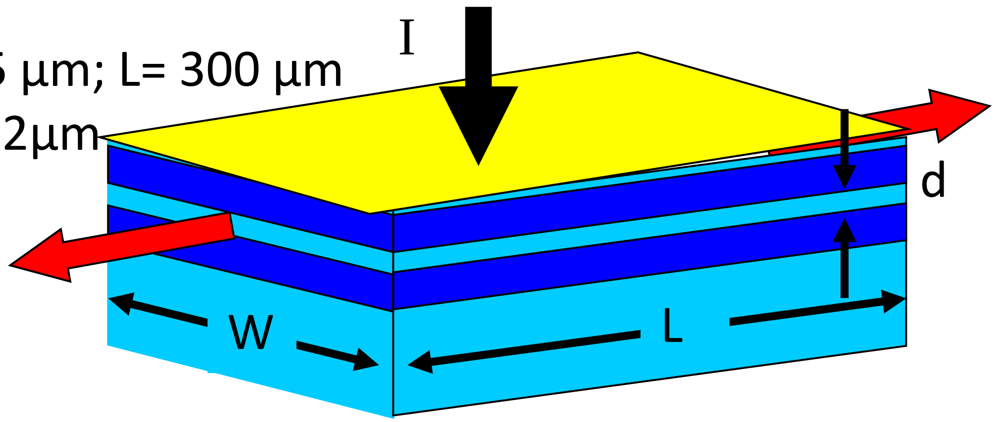
For a laser structure with a strong carrier confinement, the threshold for lasing in terms of carrier density required can be well approximated by:

$$g_{th} = \beta J_{th}$$

β: gain factor (please look at John Senior's book page 321)

J_{th} : threshold current density in order to generate lasing at the threshold

Threshold gain and current density (ii)



- **Please use an example in John Senior's book page 322**

- Based on the above structure: g_{th} ~150 cm^{-1};
- We have known: $\mathbf{g_{th} = \beta\, n_{th}}$ (β: const. ~$10^{-16}cm^2$)

$$I_{th} = e\left(\frac{n_{th}V}{\tau}\right) \quad \text{(why ?)} \Rightarrow \quad I_{th} = eBn_{th}^2 wld$$

τ : radiative recombination life-time,

τ ~1/Bn; expressed in terms of radiative recombination rate

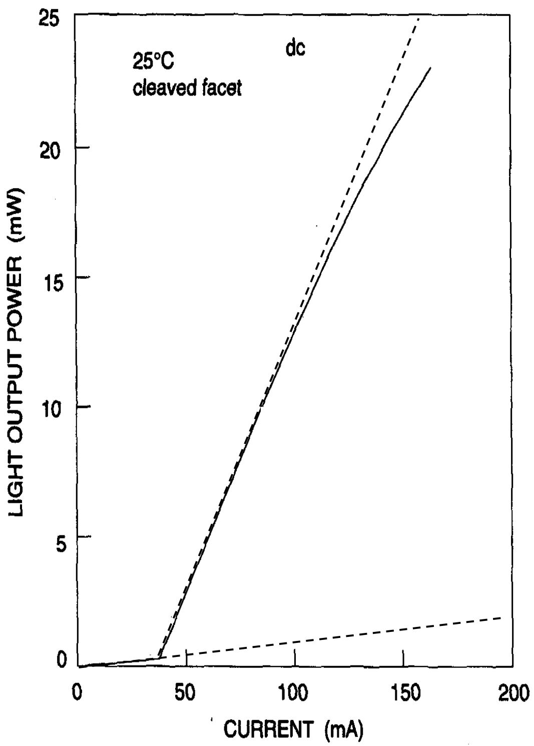
B: radiative recombination coefficient; and radiative recombination rate: Bn

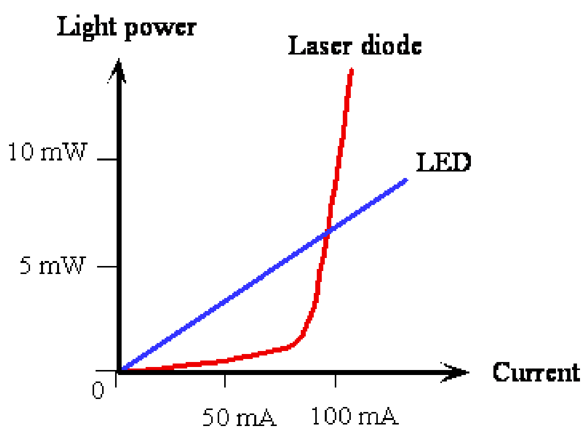
B: $10^{-10}cm^3s^{-1}$

e: 1.6×10^{-19}C

Therefore, the threshold current for lasing is ~20 mA

Optical output vs. drive current





- **Below threshold**:
  spontaneous emission, behaving as LED
  Output power linearly increases with injection current

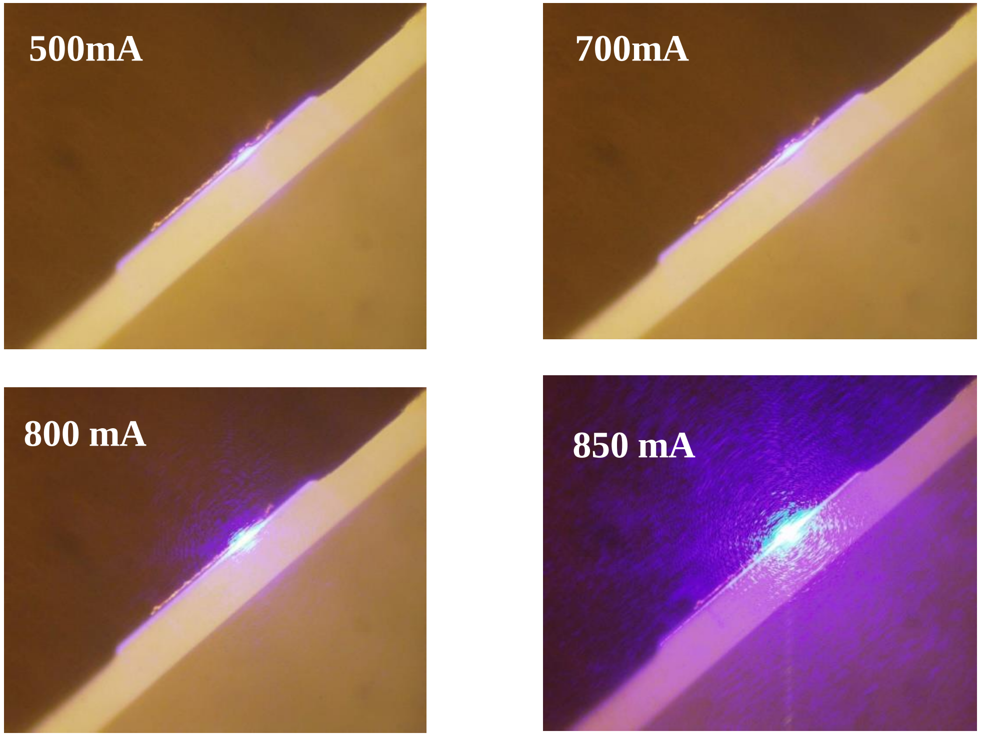
- **At threshold**: turning point, where spontaneous emission is turning into stimulated emission (optical amplification)

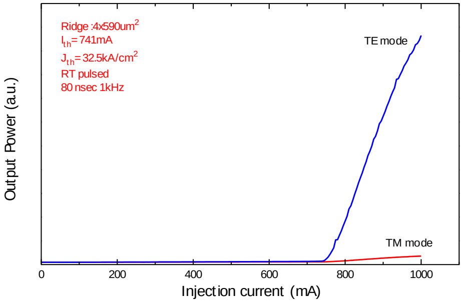
- **Above threshold**:
  highly efficient (>50%) conversion of electrical power to optical power

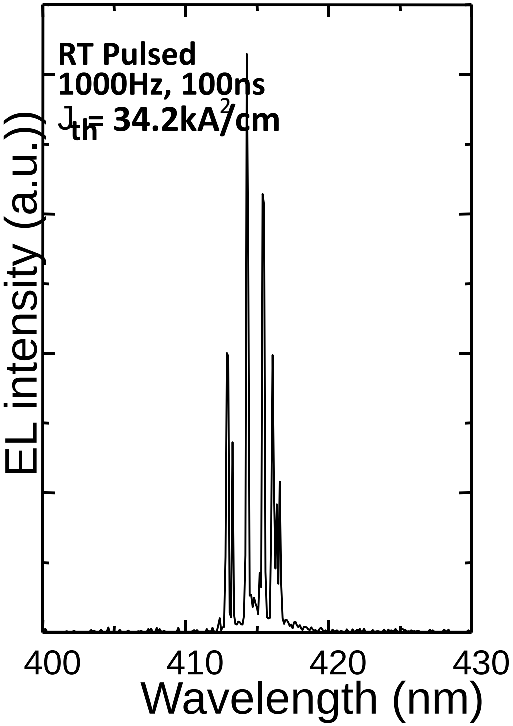
- **At high currents**

– reduction in efficiency, mainly due to heating of the device (heat sink is required)

GaN-based violet/blue LD

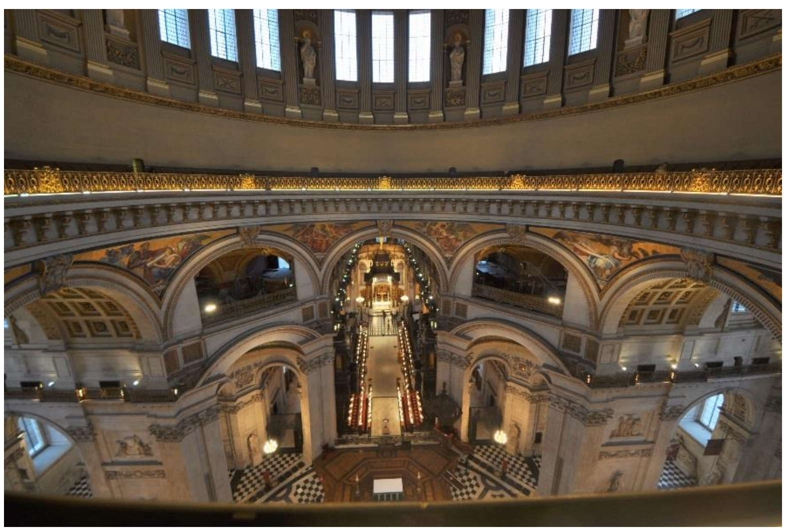


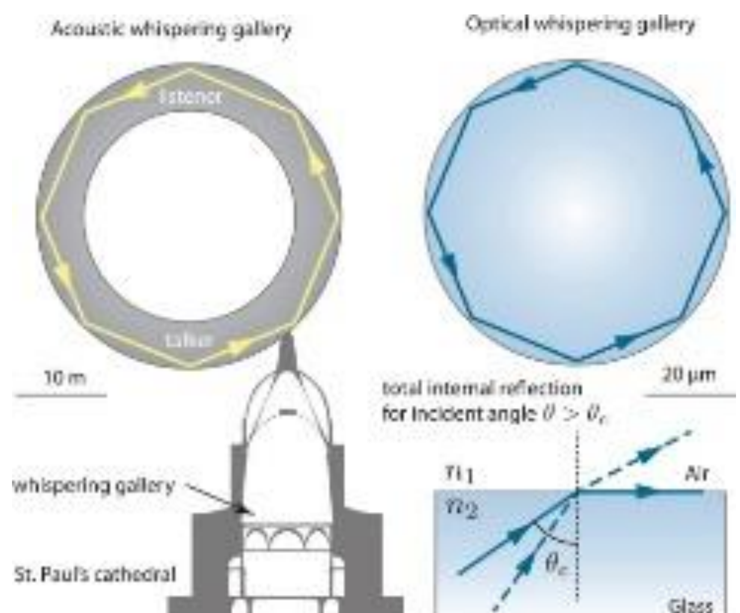




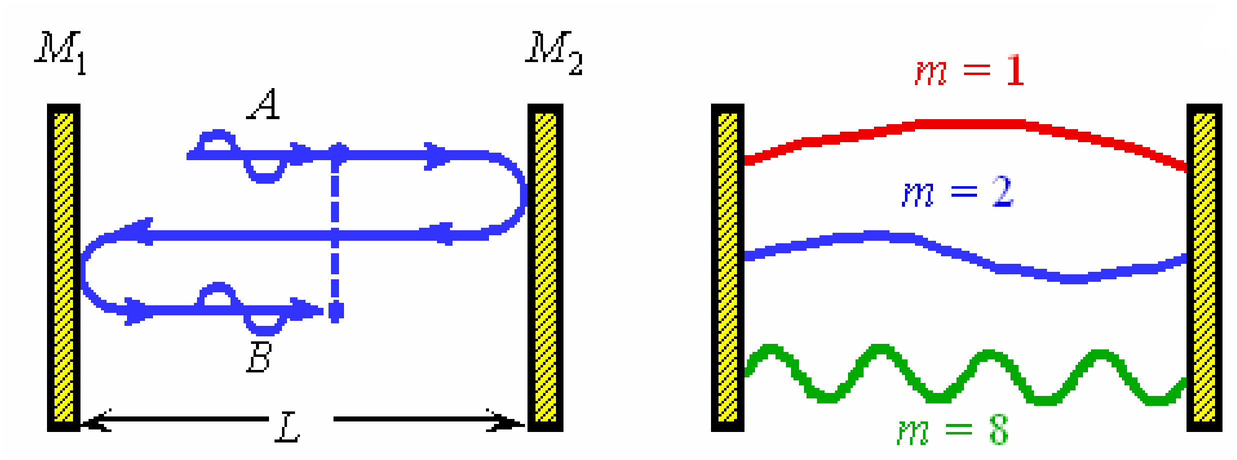
- Above the threshold, multiple emission-peaks with a narrow line width have been observed
- Laser modes

Mode formation in a cavity





Laser modes



- Phase of propagating light after a round trip must coincide with an initial phase – determined by Fabry-Perot geometry: only **standing waves with certain wavelengths** are allowed in the cavity
- Standing waves set up between two mirror facets

$$m\lambda_m/2 = L$$

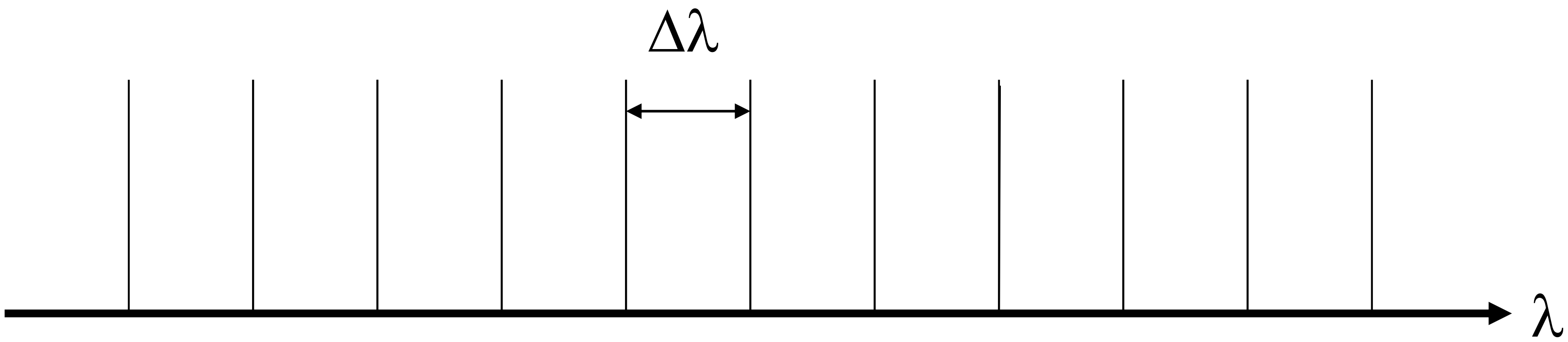
m: integral number, i.e., **mode number**

λ_m: wavelength of the mode m in the optical cavity

L: cavity length

Medium with a refractive index n in an optical cavity: **$m\lambda/2 = nL$, where λ is the wavelength in the vacuum**

Fabry-Perot Modes (i)



•**Standing wave**: $m\lambda/2 = nL$, where n: refractive index; and L: cavity length;

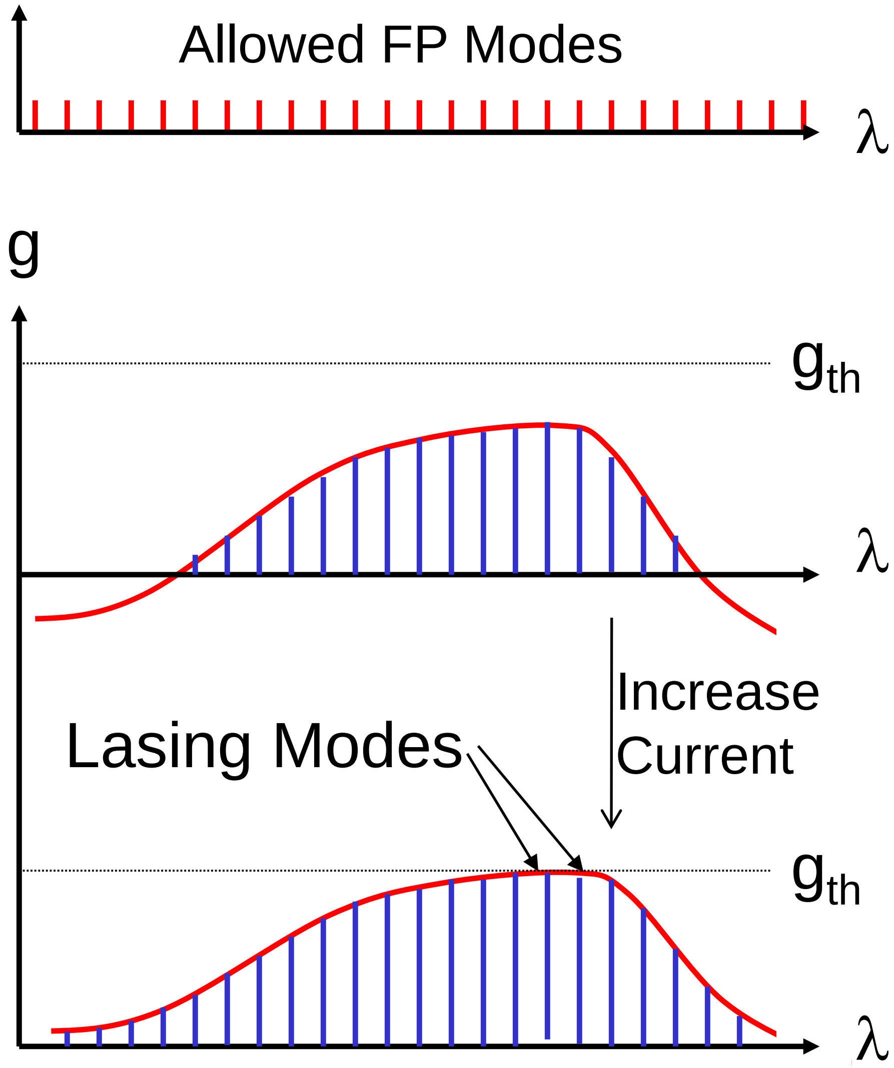
•For next (m+1) mode: $(m+1)[\lambda - \Delta\lambda]/2 = nL$

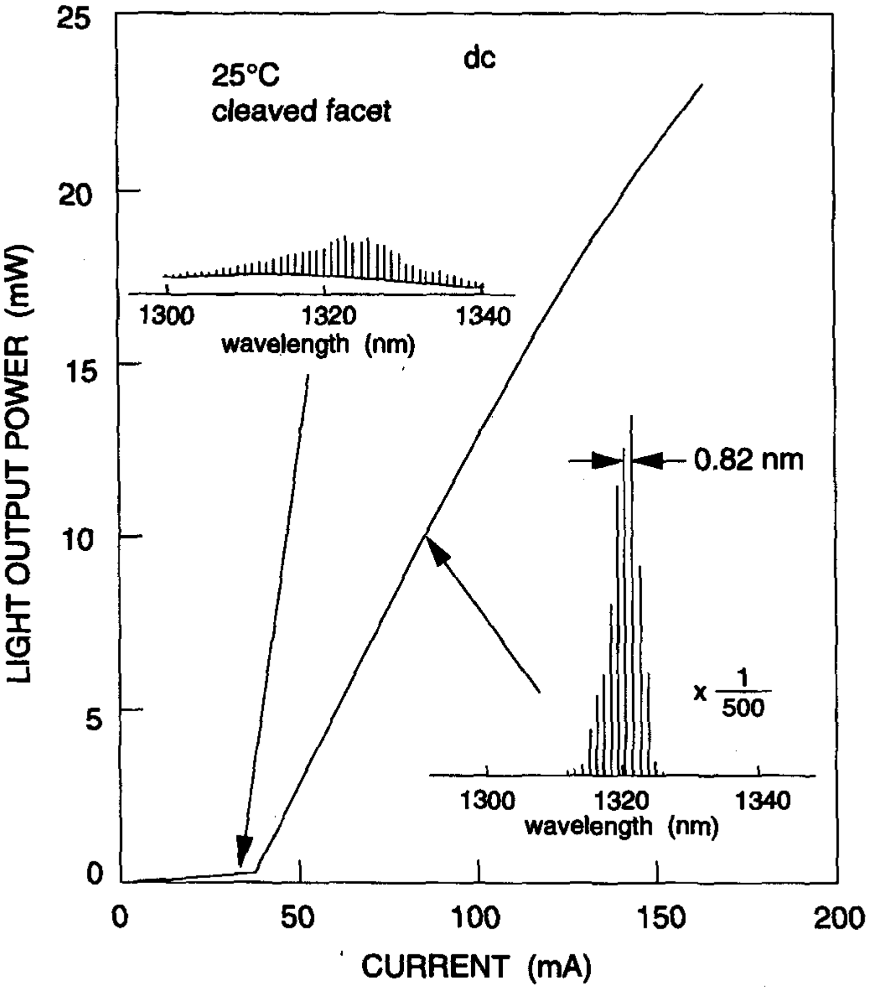
Therefore, we can obtain **mode separation**, i.e,

$$\Delta\lambda = \lambda^2/2nL$$

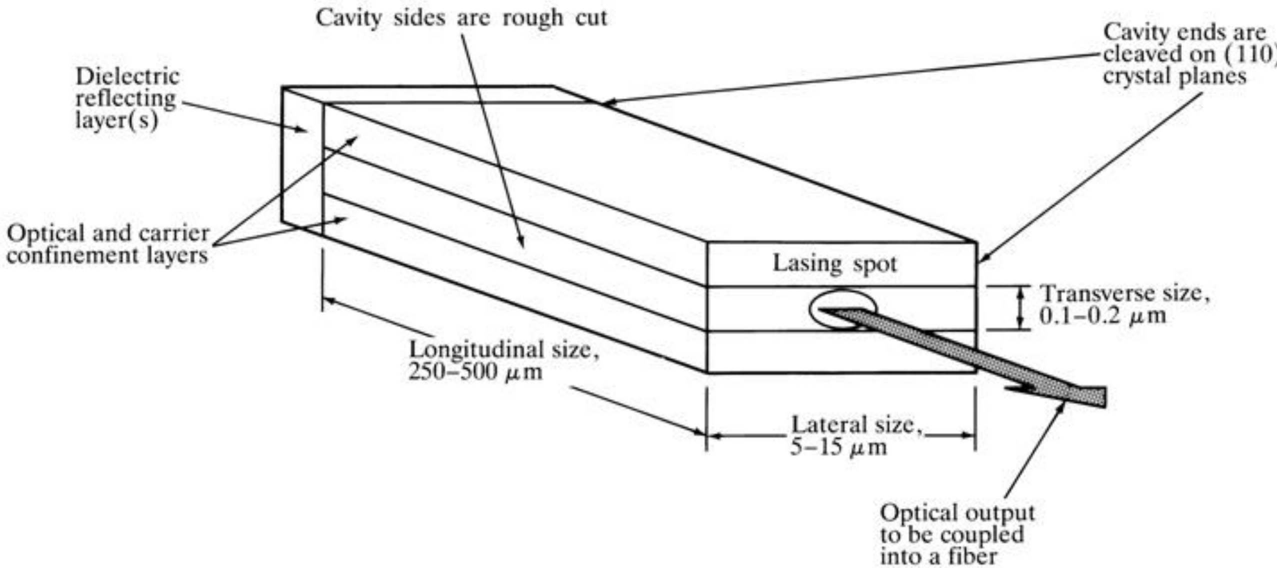
High order modes: long length
Large mode separation: short length, potentially avoiding high order modes

Lasing Spectrum - Function of Current





Fabry-Perot Modes (ii)



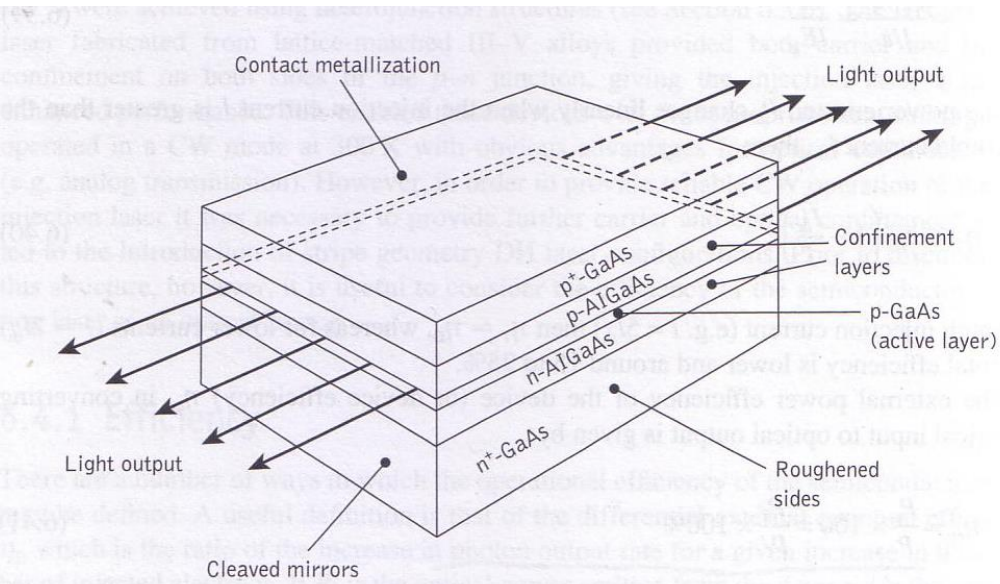
- Laser diodes have three kinds of modes along different direction, **longitudinal, lateral and transverse** modes.

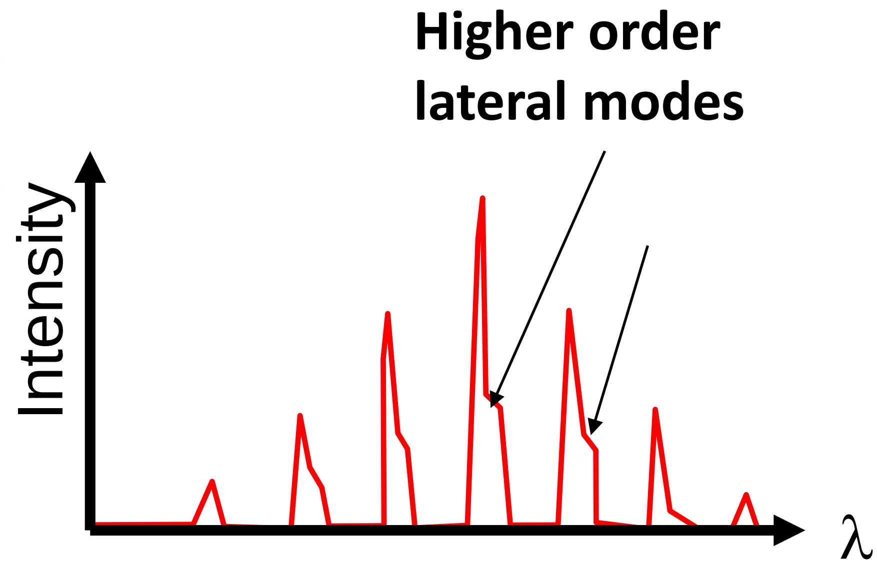
1. **Longitudinal Direction**: normally called optical **cavity length**
2. **Lateral Direction** (perpendicular to the longitudinal direction): normally called cavity width, generating extra modes, called **lateral modes**

   Lateral confinement - ~>1 micron **(should be avoided),** controlled

   by a device fabrication
3. **Vertical confinement** (**Transverse Direction**) – sub micron , controlled by an epitaxial process (**no concern**)

Fabry-Perot Modes (iii)



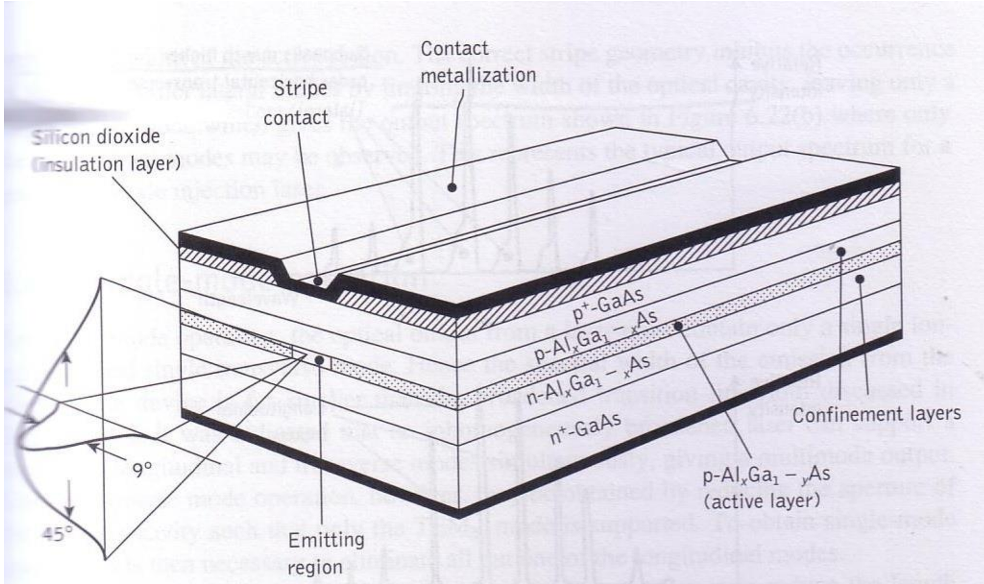


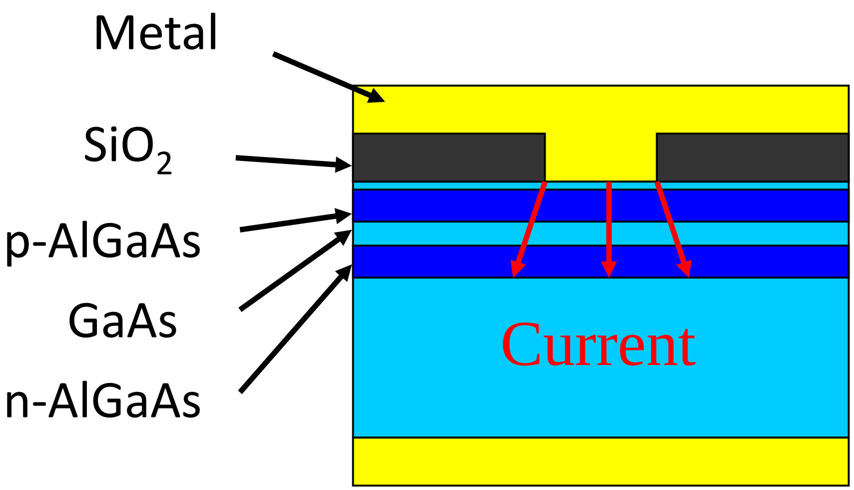
- **For broad area laser diodes:**

  Lateral direction: **Roughen sides** to suppress reflections from sides

  Not so efficient, in particular, under a high injection current– **still get lateral mode effects**

Lateral Current Confinement (i)

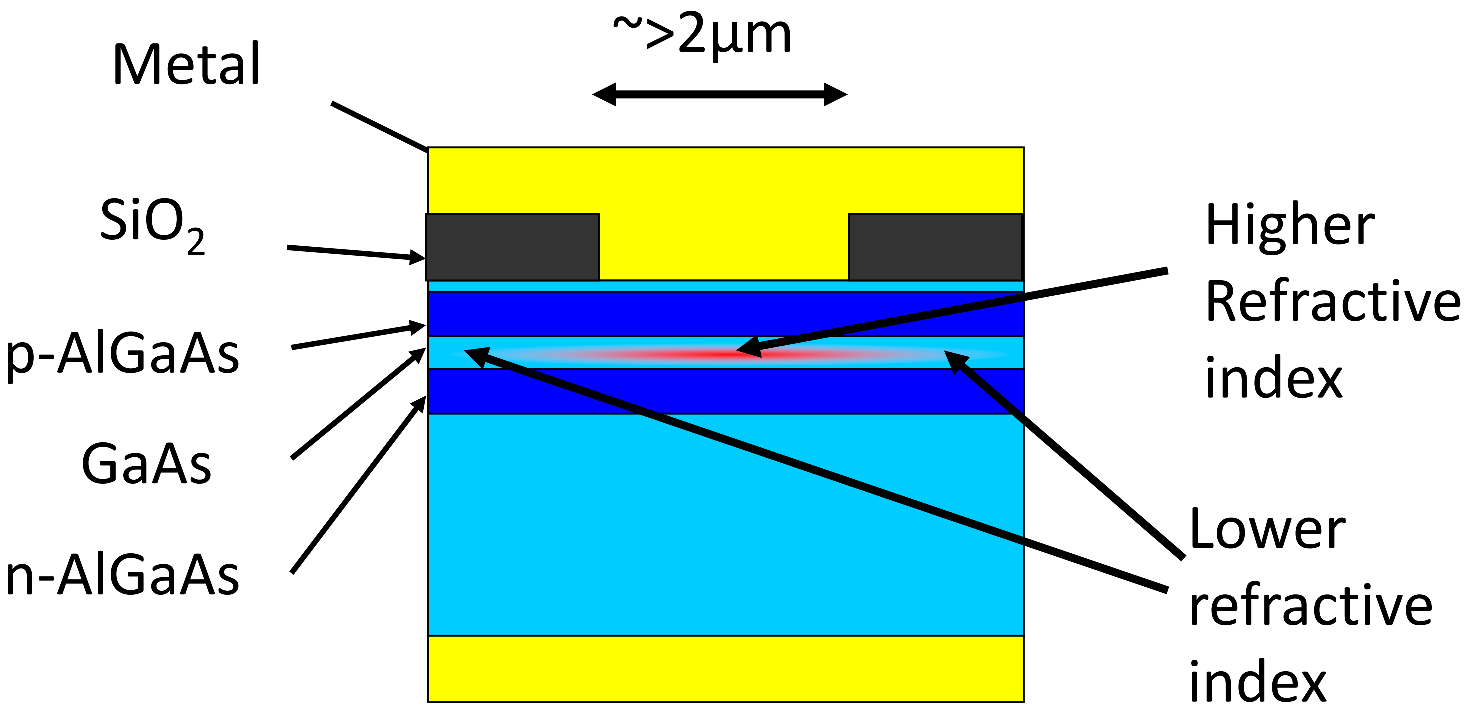




- $\boxed{\Delta\lambda = \lambda^2/2nL}$: L is small enough, causing any high order mode beyond gain curve, namely, **a lateral confinement is required**

- **Current Confinement: Oxide Stripe Laser**
  controlled by device fabrication by using standard lithography, which can be down to a few micrometers

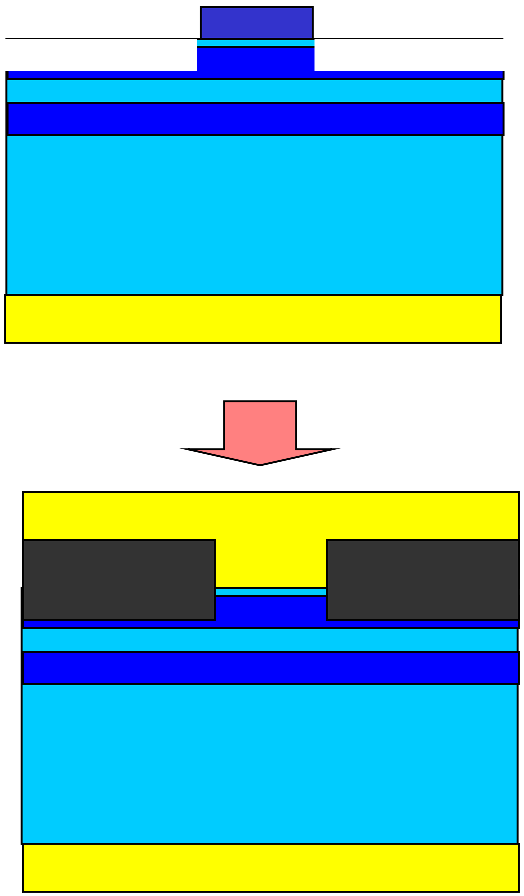
Lateral Current Confinement (ii)



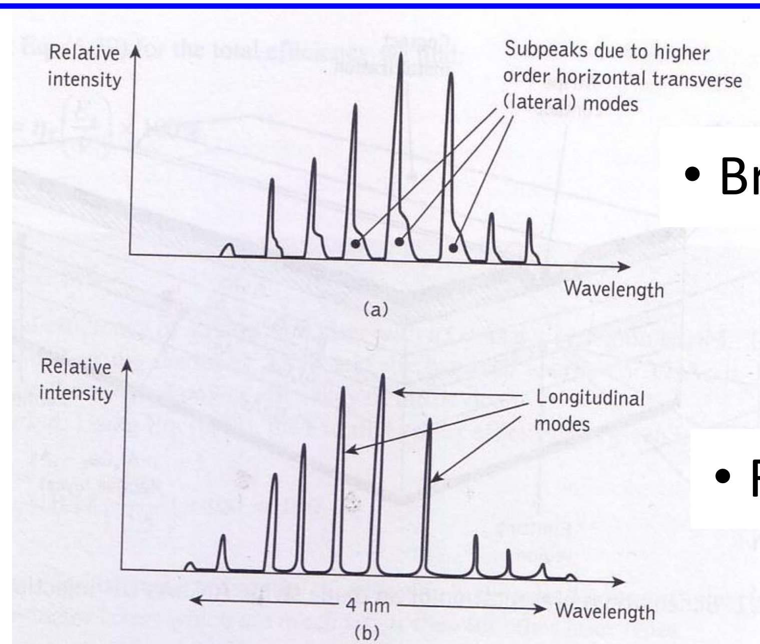
- Poor control of current spreading
  Lateral optical confinement: **larger than the oxide stripe width**

"Gain Guided" – high gain – high carrier density – higher n

Ridge Laser Structure

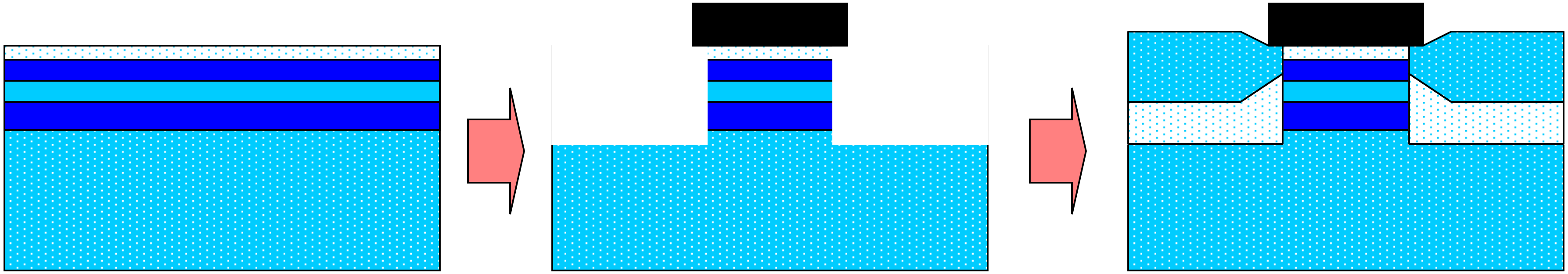


- Mask mesa and etch nearly all cladding
  Deposit oxide and metal
- Much reduced & improved control of current spreading
- Refractive index change due to dielectric leads to the lateral confinement of light

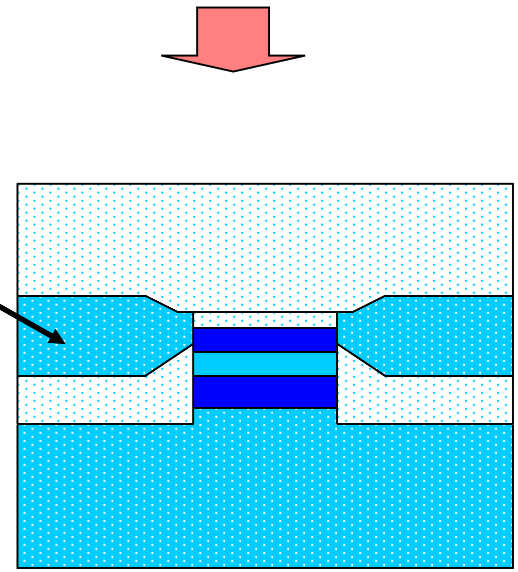


- Broad area LD
- Ridge LD

Laterally Index guided Laser - Buried Heterostructure



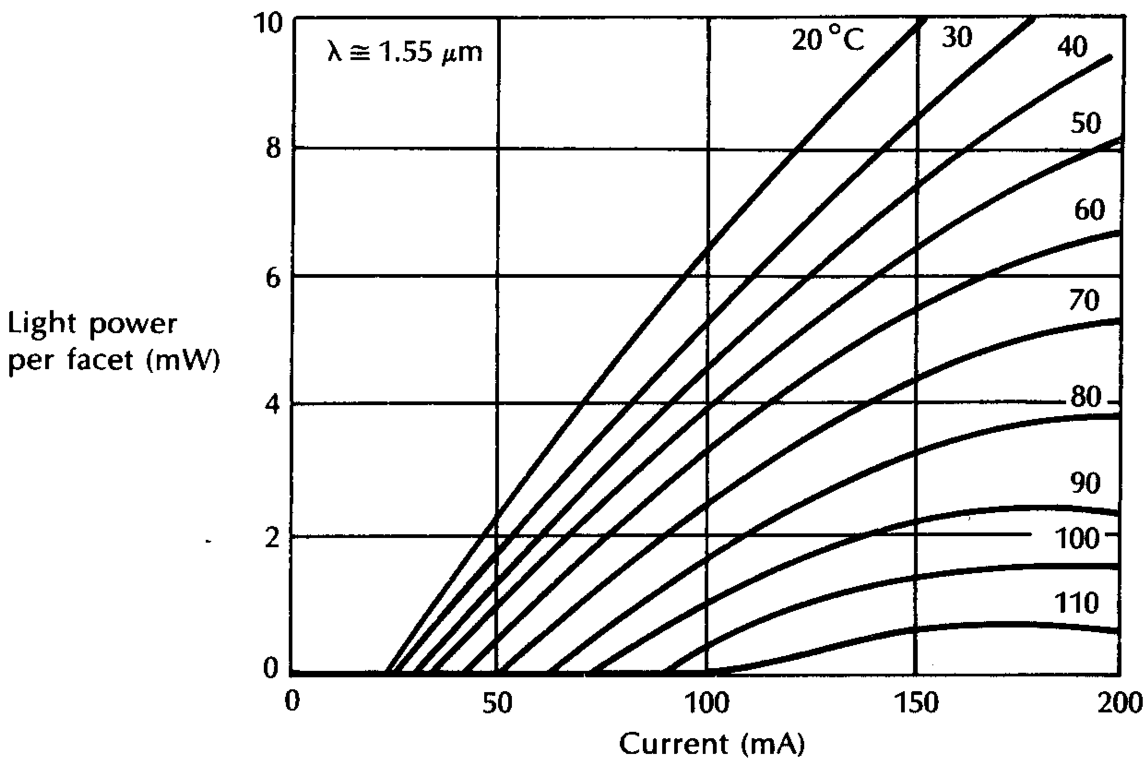
Planar growth   Mesa Etch 1^{st} Overgrowth



2^{nd} Overgrowth

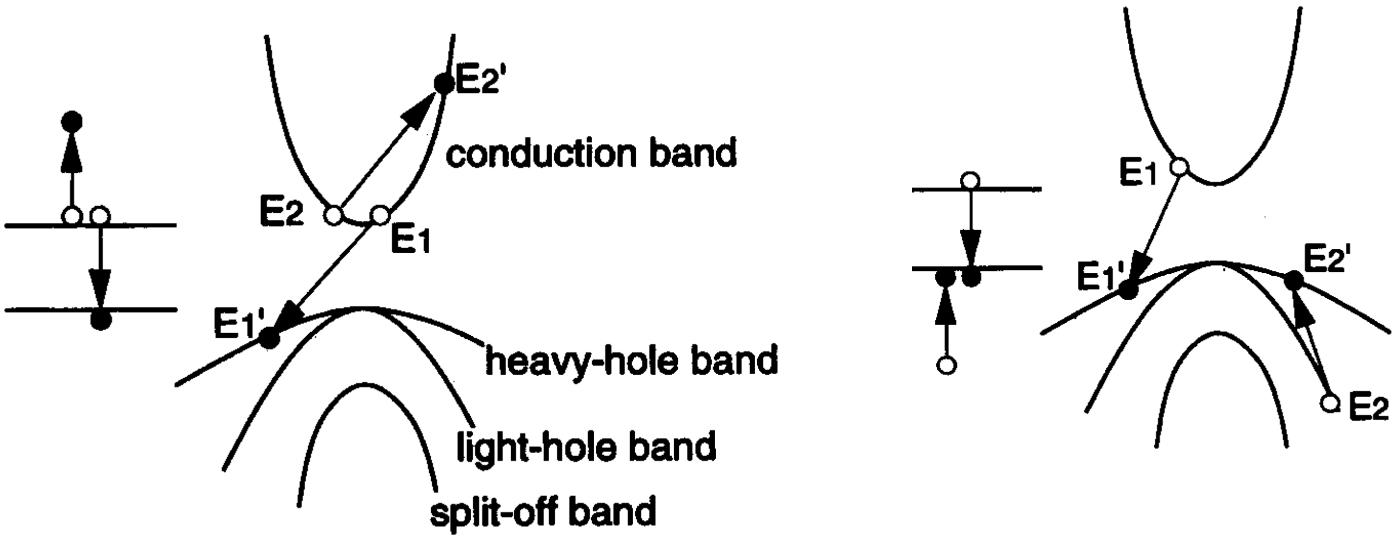
- Low index p-n-p-n blocking layers - Current and carrier confinement
- Strong lateral optical and carrier confinement low Ith, high lateral mode stability (single lateral mode at all operating conditions)
- But ! Complicated to do – But can make FP laser at ~$2 each!

Temperature Dependence of LI curve



- Increasing temperature: heats carriers higher into bands – away from band edge
- Other non-radiative effects: Auger recombination, etc
- $I_{th} \sim \exp(T/T_0)$: **threshold current increases with increasing temperature**
- Problem for setting current level for "0" and "1": Need power/temperature monitoring and feedback or accept variation in P_{launch} and extinction ratio

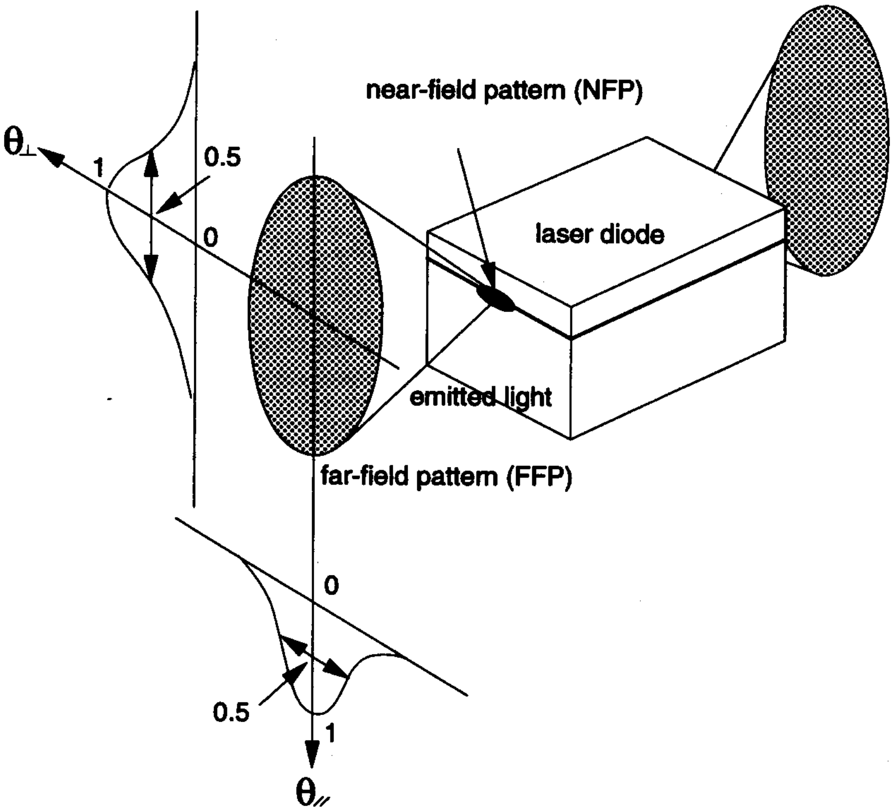
Auger Recombination

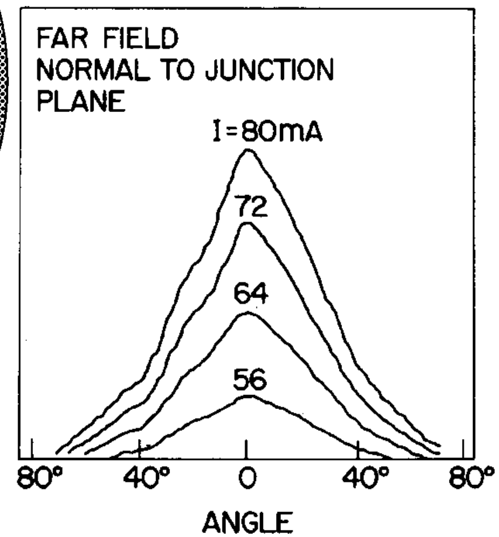


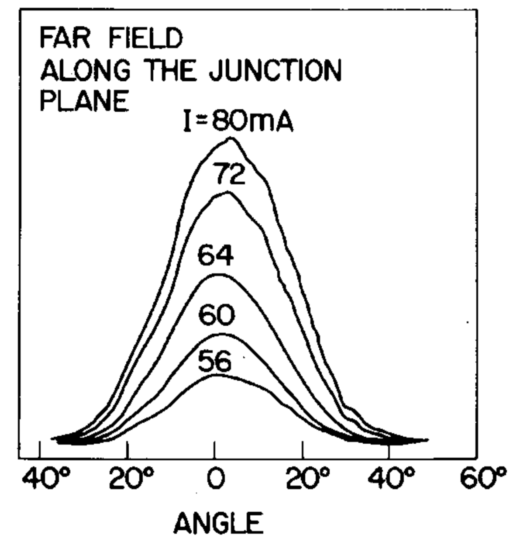
- Multi-carrier Scattering:

Carrier loses energy by giving another carrier kinetic energy– this energy is subsequently lost as heat

Far-Field and Near-Field Patterns



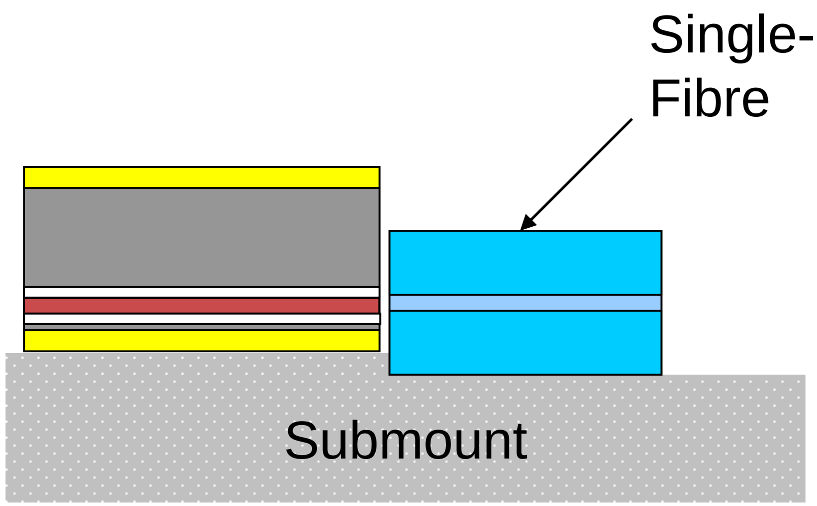




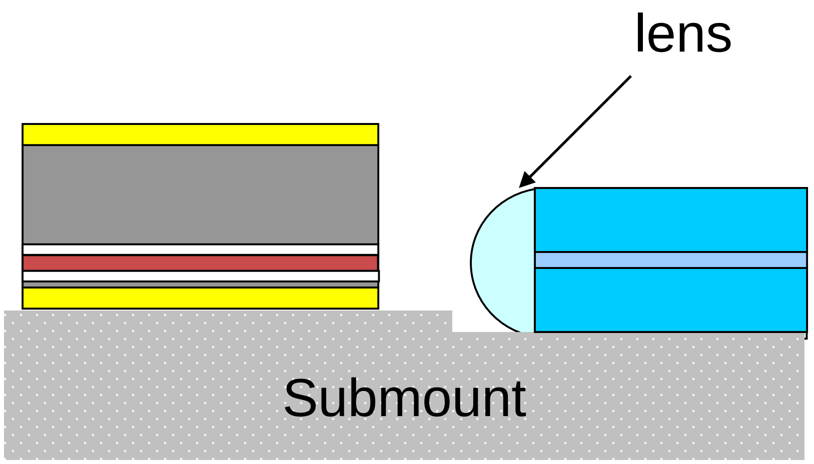
Consider emission as a diffraction of light through a slit

- Narrow slit: large diffraction angle
- Wide slit: small diffraction angle

Coupling a Laser Diode to Fibre

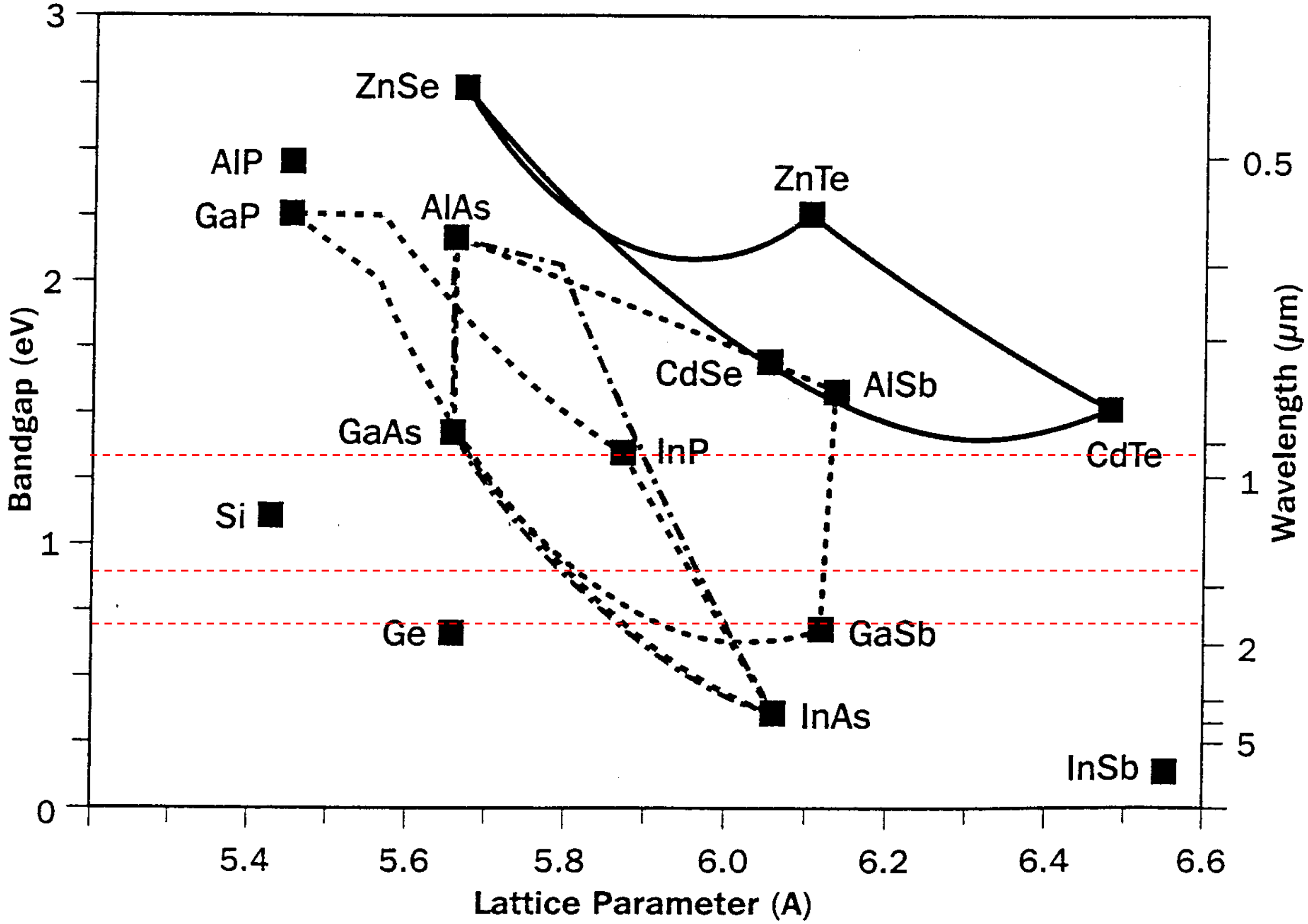


Butt Coupling
~10% Efficiency



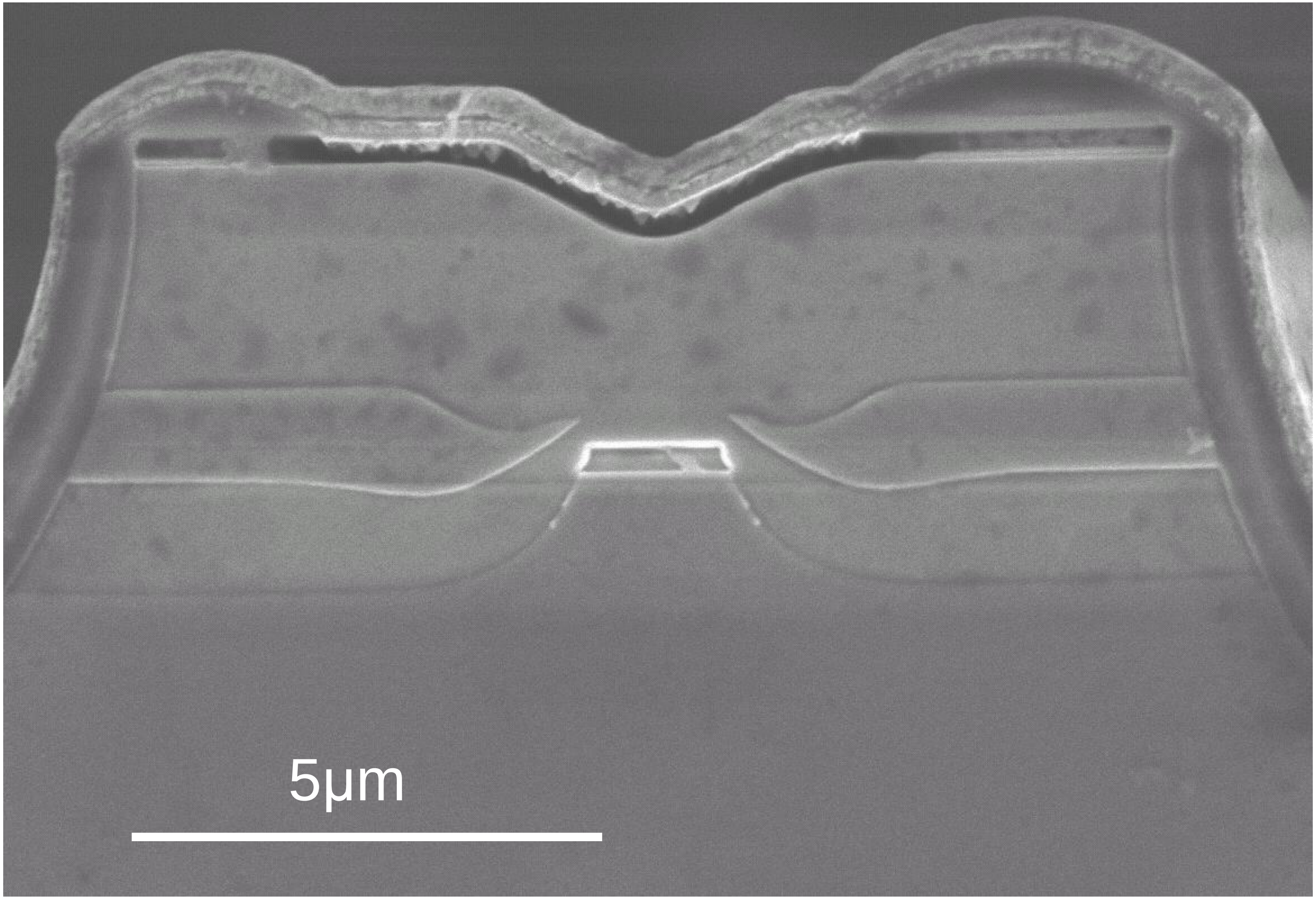
Lenses, AR coatings,
AR Gels
~85% Efficiency

Materials For Optical Communications

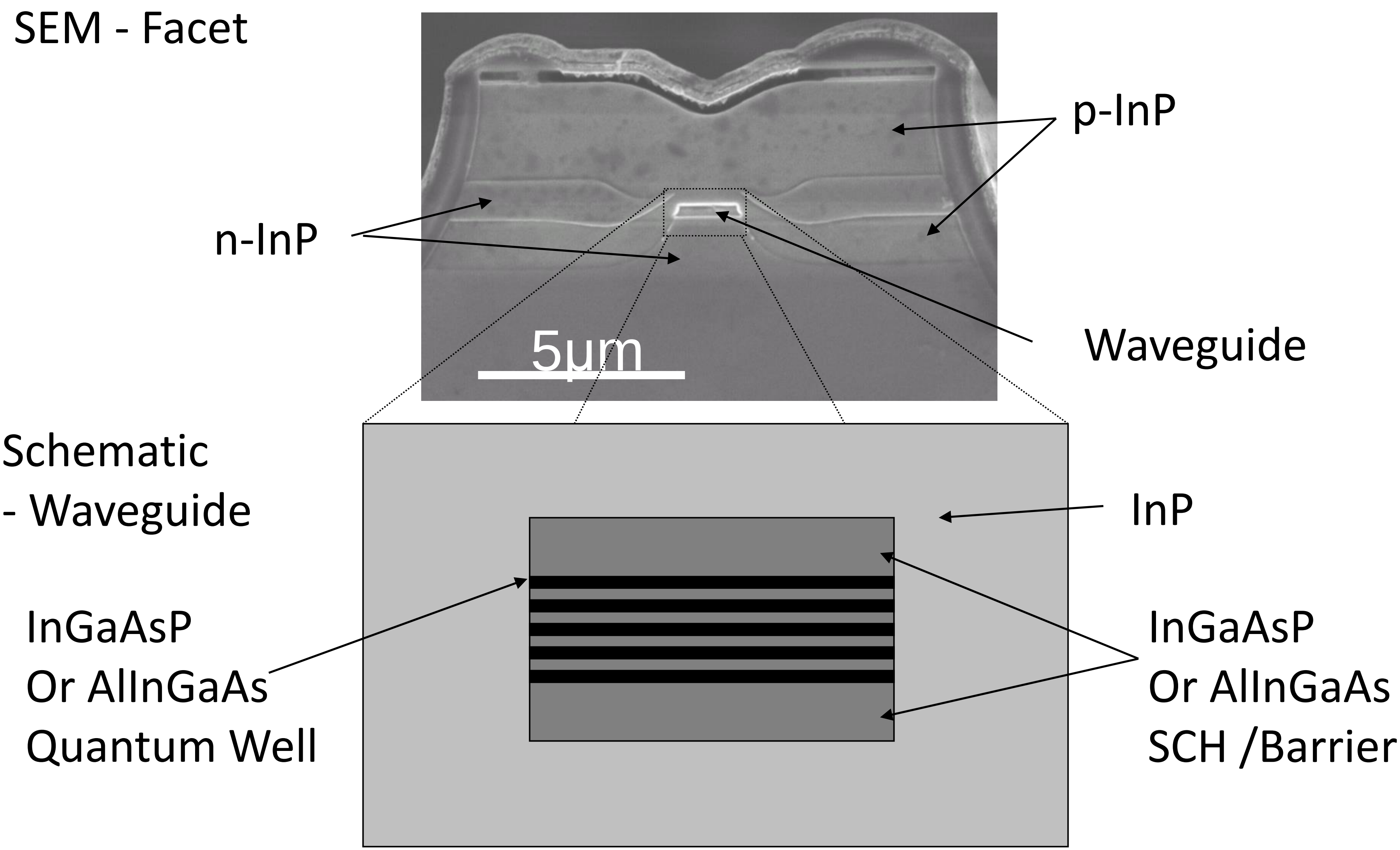


"Q" usually refers to the lattice matched emission wavelength of a quaternary alloy in microns

SEM Image of a real BH Laser



Anatomy of a Telecomms Laser



Summary Topic 21

- Get series of equally spaced modes which satisfy the phase requirements
- For FP laser get a few modes contributing - ~few nm wide emission
- For FP – have the phase requirement -a round trip is integer wavelengths for constructive interference
- For narrow lasers –get a single lateral mode – for wide lasers – get additional lateral modes – bad for fibre coupling
- Various strategies for achieving a single lateral mode
- Important parameter is the threshold *current* - reduced by reducing active volume of laser
- Threshold current is the strong function of temperature – not good for transmitter in lightwave system
- Various strategies for limiting the threshold current – some combine carrier *and* photon confinement
- Strategies include increased Reflectivity, increased Length, reduced active volume, quantum confinement, strained QWs, having trade offs w.r.t. other laser characteristics

Tutorial Questions

T21.1 Discuss the factors contributing to the temperature dependence of threshold current. Why is this dependence important?

T21.2 Draw and label the structure of a typical 1.55 μm FP laser diode, indicating possible materials. Draw the band structure under zero bias and forward bias indicating the (quasi) Fermi levels.

T21.3 Describe the problems associated with additional lateral modes. How is this overcome in a practical device?