Topic 20

20 Semiconductor laser diodes

- 20.1 Introduction
- 20.2 Requirements for laser diodes
- 20.3 Laser structure
- 20.4 Gain and loss
- 20.5 Optical confinement and threshold
- 20.5 Design of laser diodes
- 20.6 Examples of semiconductor laser diodes

Introduction (i)

- WDM system requires an optical source with a **high modulation speed** and a **narrow spectral line width**

- Major advantages of LDs over LEDs:

(1) **Modulation speed** (lifetime of carrier recombination)

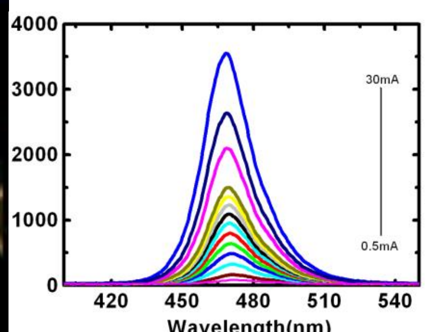
LD: $f \sim 1/\tau_{stim}$, $\tau_{stim} \sim 10ps$, $f \sim 100GHz$

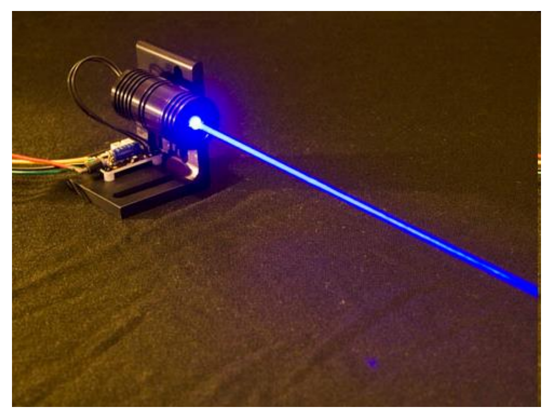
LED: $f \sim 1/\tau_{spon}$, $\tau_{spon} \sim 10ns$, $f \sim 100MHz$

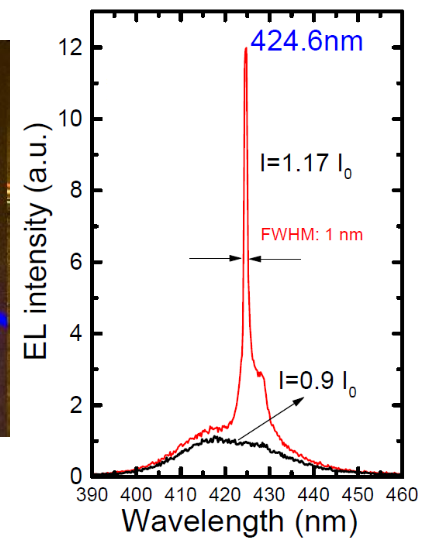
(2) **FWHM**

LEDs: ~100nm

LDs: FP Laser (~1nm); DFB Laser (~ 0.0001nm); VCSEL laser (<1 nm)







Introduction (ii)

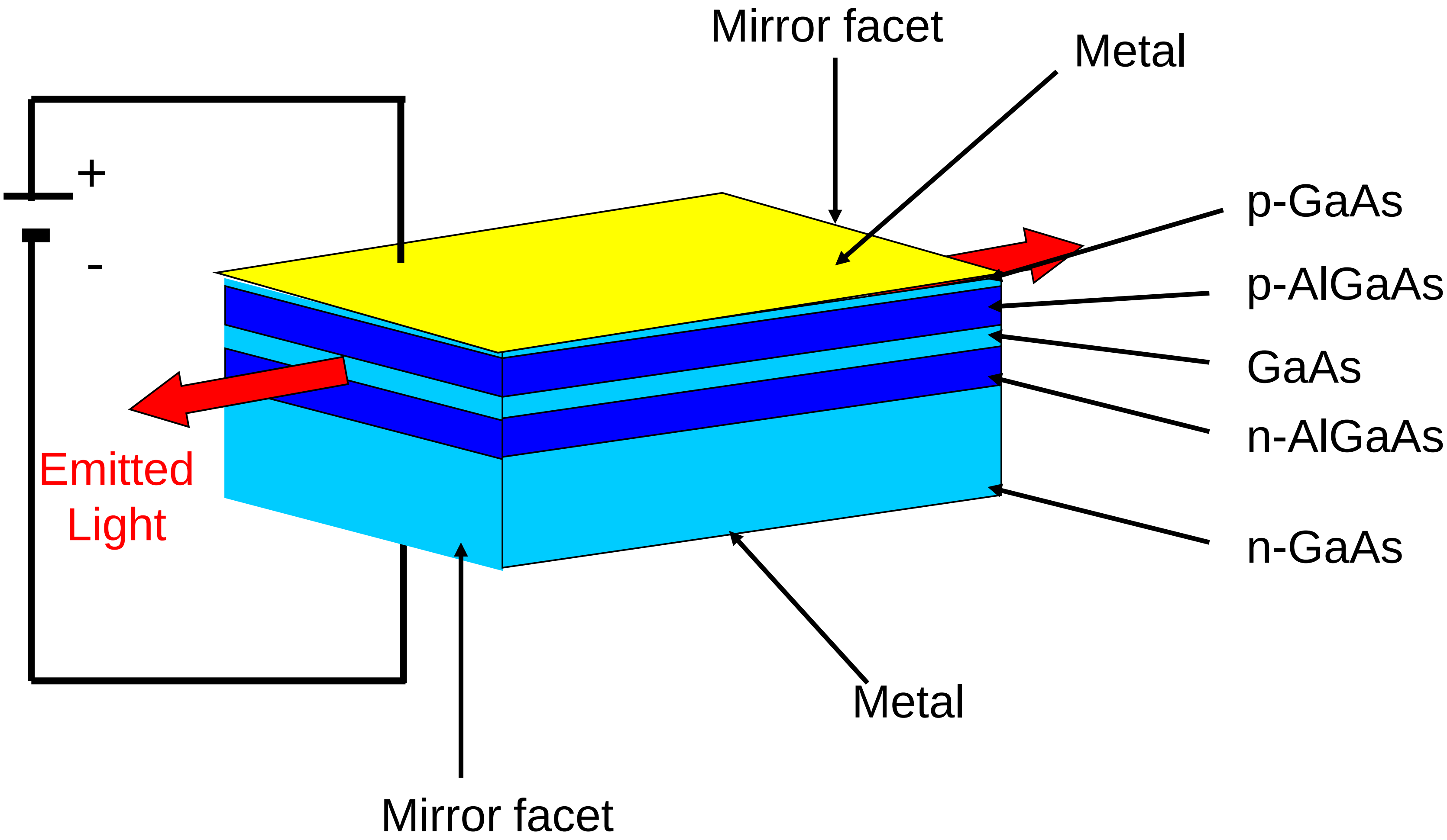
Laser stands for "**L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation".

Laser: a combination of an optical cavity, which provides **feedback** and optical gain region, leading to an **stimulated emission**.

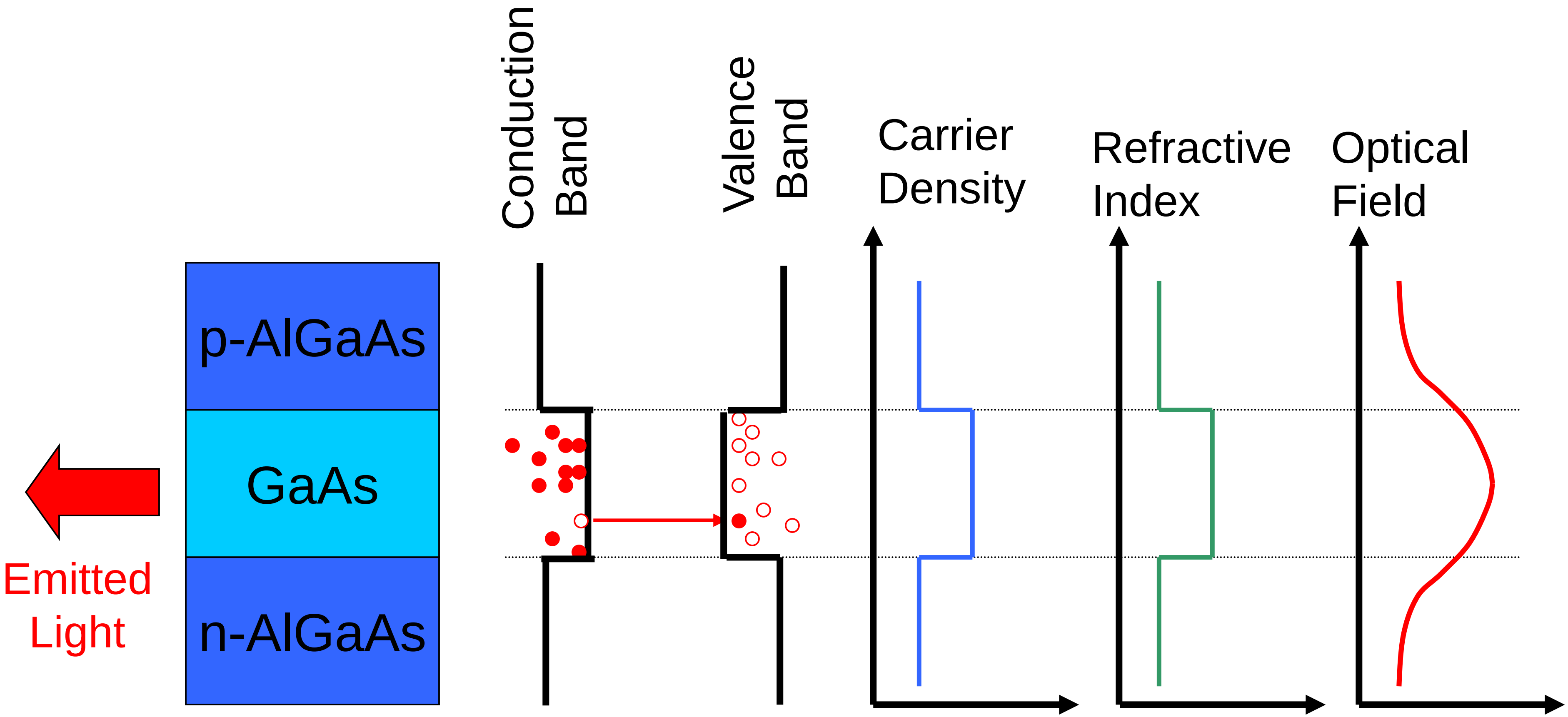
Lasing: takes place when **internal gain**, produced by stimulated recombination of injected carriers, is stronger than the **optical loss**.

The allowed emission wavelengths are those that return **in phase** after a round trip of the optical cavity.

Heterostructure Laser

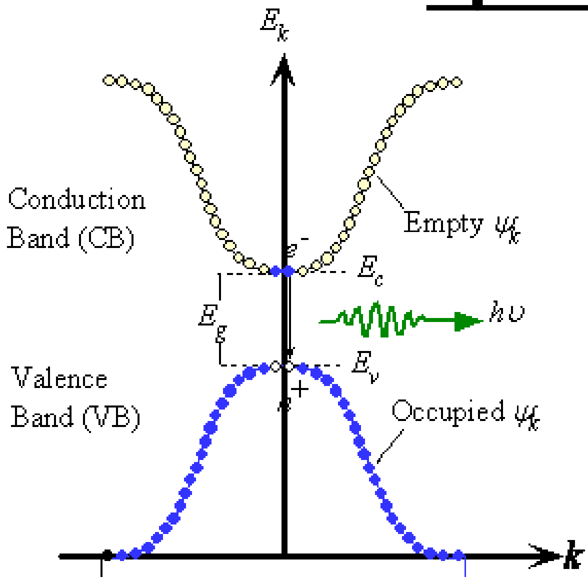


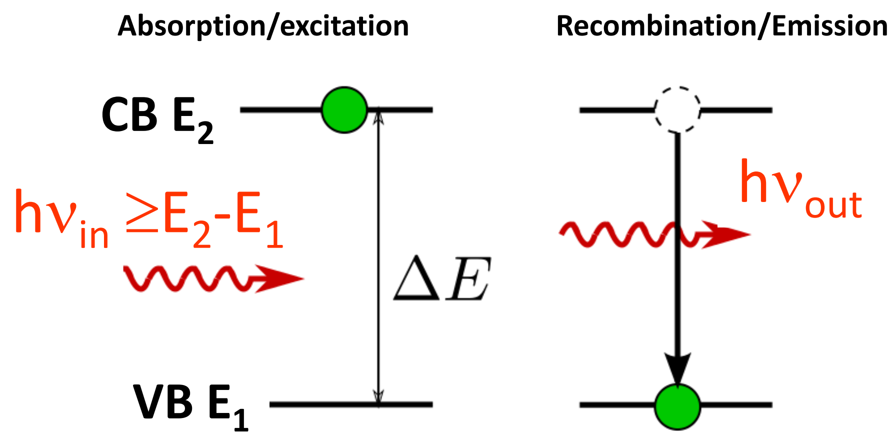
Heterostructure Laser Cross-section



Sandwich structure:
- **Optical confinement: different refractive indices**
- **Carrier confinement: different band-gaps**

Spontaneous Emission





$h\nu_{out}=E_g=E_{CB}-E_{VB}$ (Bulk case)

- **Spontaneous emission:**

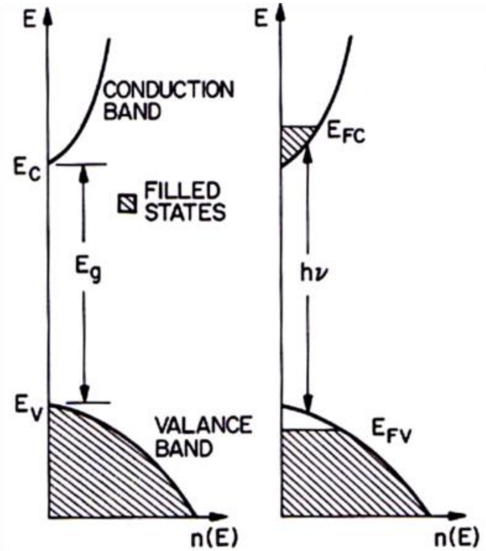
  After an optical or electrical excitation, electrons undergo a transition from VB to CB and then emit a photon.

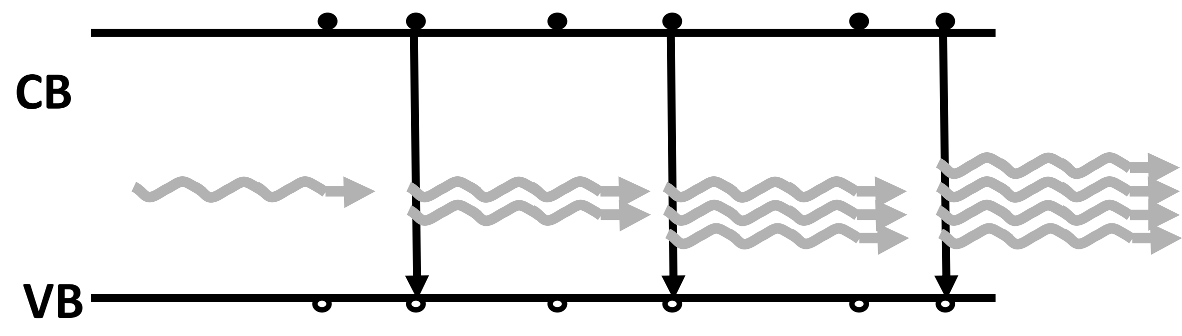
- **Conditions for optical absorption**
  (1) $h\nu_{in} \geq E_{CB}-E_{VB}$; (2) Empty states in CB and occupied electrons in VB

- **Normally, the electron population (N_2) in CB is less than N_1 in VB:**
  $N_2/N_1=\exp(-E_g/KT)$-----Bolzmann Statistic

- **Photons created via spontaneous emission: random direction and phase**

Stimulated Emission





• **Population inversion:**

More electrons in the CB than electrons in VB

In this case, $E_{Fn} > E_{FP}$

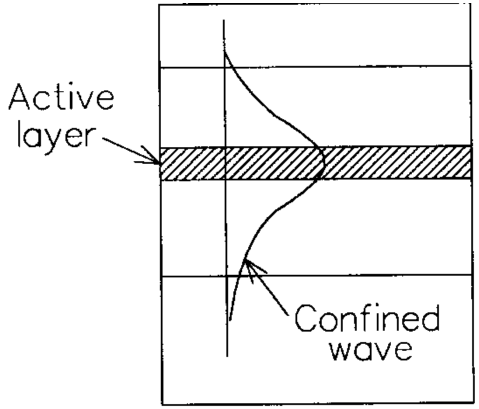
• Any incoming photon with the energy of E_C-E_V cannot be absorbed as there is no any empty space on CB. (Transparent conditions)

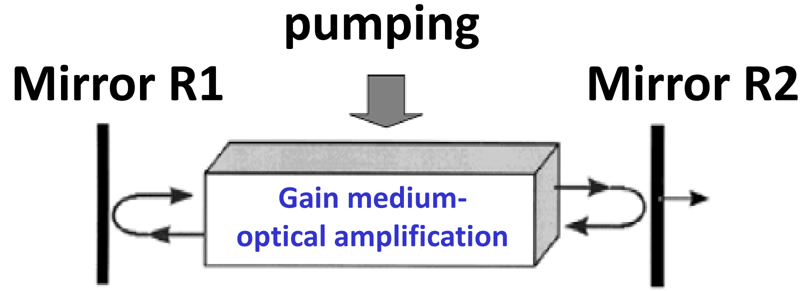
The photon can stimulate ***recombination***, causing an electron to fall down from CB to VB. This is an stimulated emission. The number of photons with the same energy will exponentially increase. **Optical amplification!**

• Photons created are identical in energy, phase, direction

•The initial stimulus is provided by any spontaneous emission

Optical Feedback





Laser = Gain medium + Cavity

• The emitted light in the active region can be amplified, meaning "obtaining **optical gain**". However, a single amplification is not enough.

⇒ **Optical feedback is necessary: optical cavity**

⇒ Elevate the intensity of stimulated emission

• **Optical cavity:**

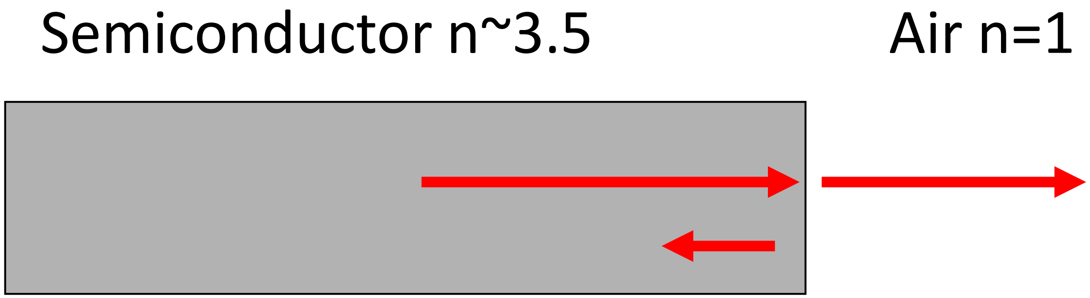
(1) Provided by a resonator (**F-P cavity**)

(2) Multiple passes in the medium due to the reflectors: amplification is substantial

(3) **Gain obtained** in the medium and also loss occurring during the optical feedback process

(4) **Saturation is reached when gain=loss**

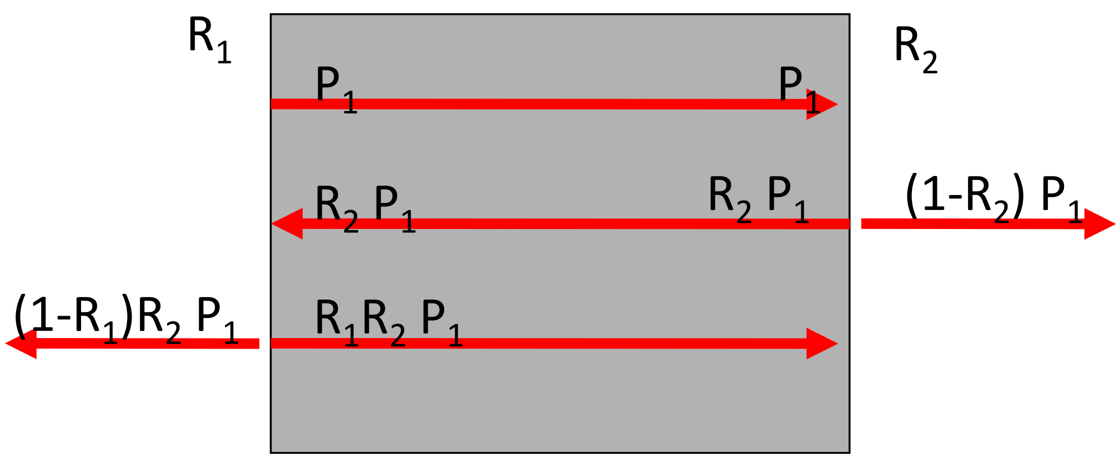
Optical Loss due to Fresnel Reflection



Reflected Power

$$I_R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

As Cleaved Semiconductor Facets - Reflectivity ~30%

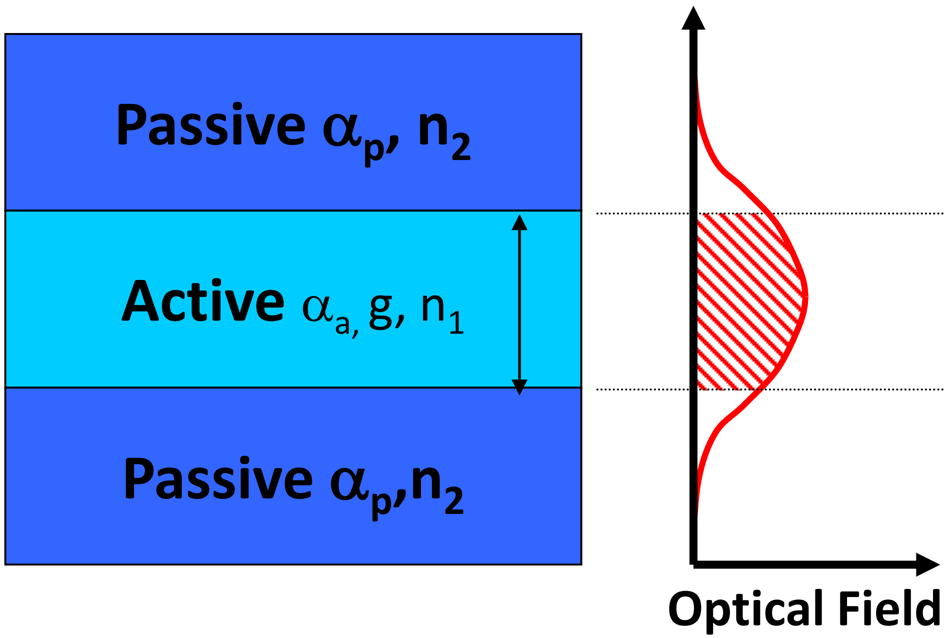


mirror loss

$$\alpha_m = \frac{1}{2l} \ln \frac{1}{R_1 \times R_2}$$

In 1 round trip only **9% of the original power** is left if no any other loss

Optical Confinement (Γ)



- Only in the active region can the light be "amplified". Therefore, it is important to confine light in active region
- Optical confinement factor Γ: **the fraction of the optical field in the gain region**

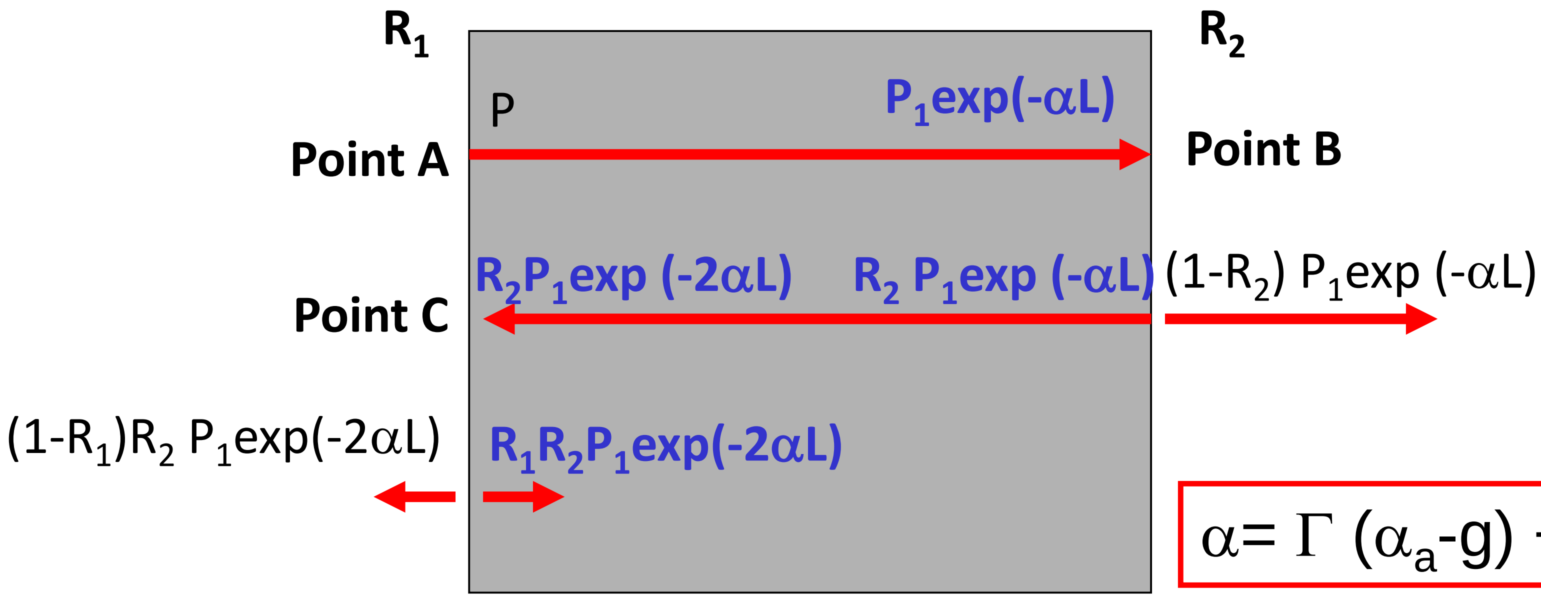
$$\boxed{\Gamma \cong 1 - e^{-C \bullet \Delta n \bullet d}}$$

- Δn: contrast of refractive index
- d: thickness of active region
- C: constant

Net loss coefficienct: $\alpha = \Gamma\,(\alpha_a - g) + (1-\Gamma)\,\alpha_p$

α_p = passive loss coefficient e.g. free carrier absorption
α_a = active loss coefficient, e.g. scattering at active/passive interface
g = gain in active ("material gain")

Total Optical Loss in an Optical Cavity



$$\alpha = \Gamma(\alpha_a - g) + (1-\Gamma)\alpha_p$$

- P undergoes **net loss** $\Rightarrow P\exp(-\alpha L)$
- Undergoes loss due to a **reflector** $\Rightarrow R_2 P\exp(-\alpha L)$
- Under goes another **net loss** $\Rightarrow R_2 P\exp(-2\alpha L)$
- Undergoes another loss due to a **reflector** $\Rightarrow R_1 R_2 P\exp(-2\alpha L)$

After a round trip Gain and Loss balance light power will have to be the same as the initial optical power: $R_1R_2P\exp(-2\alpha L)=P$

Therefore, lasing Condition: $R_1R_2\exp(-2L\alpha)=1$

Threshold Gain

- Previous slides tell you about lasing conditions, and thus the lasing threshold

$$R_1R_2\exp(-2L\alpha)=1$$

- Previous slides also tell you: **Net loss per unit length**:

$$\alpha=\Gamma(\alpha_a-g)+(1-\Gamma)\alpha_p$$

- We can have

$$\alpha=(1/2L)\ln(R_1R_2)=\Gamma(\alpha_a-g)+(1-\Gamma)\alpha_p$$

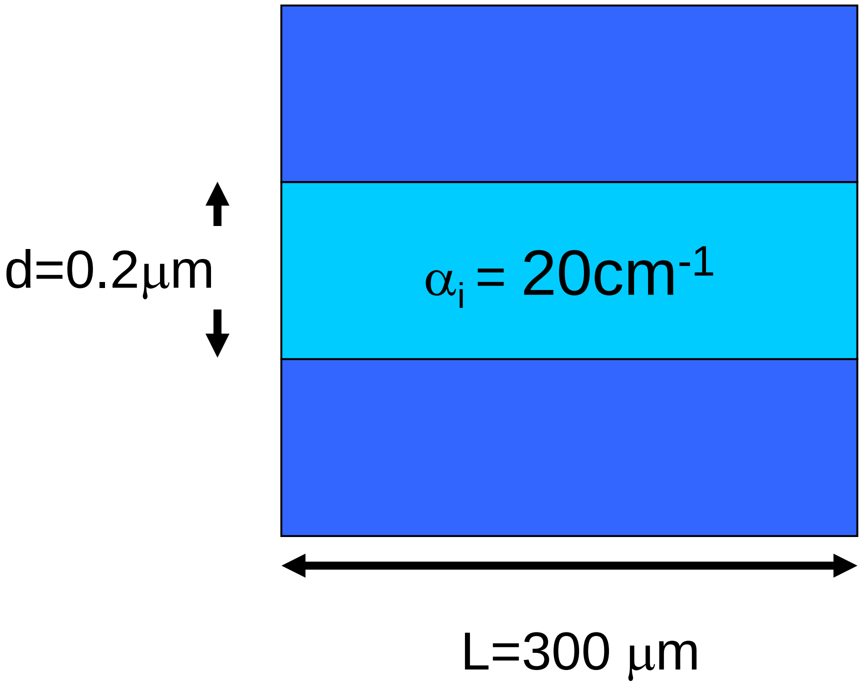
- **Gain coefficient at the lasing threshold, g_{th}:**

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

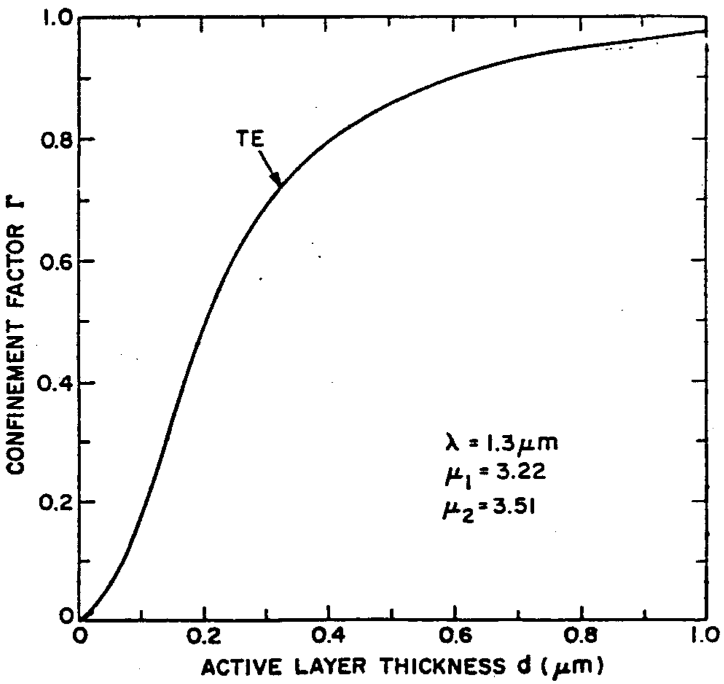
- where the total **cavity loss α_i** = $\Gamma\alpha_a+(1-\Gamma)\alpha_p$ and L: cavity length

Typical Values

$R_1 = R_2 = 0.32$



For d=0.2μm $\Gamma \sim 0.4$



$$\boxed{g_{th} = \frac{1}{\Gamma}[\alpha_i + \frac{1}{2L}\ln(\frac{1}{R_1 \cdot R_2})]}$$ (keeping dimensions in cm)

= 1/0.4[20-(1/2x0.03)ln$(0.32)^2$] = 2.5x[20+2.27/0.06] = 2.5x58

g_{th} ~150cm^{-1}

Reducing Threshold Gain

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

Reduce losses α_a and α_p

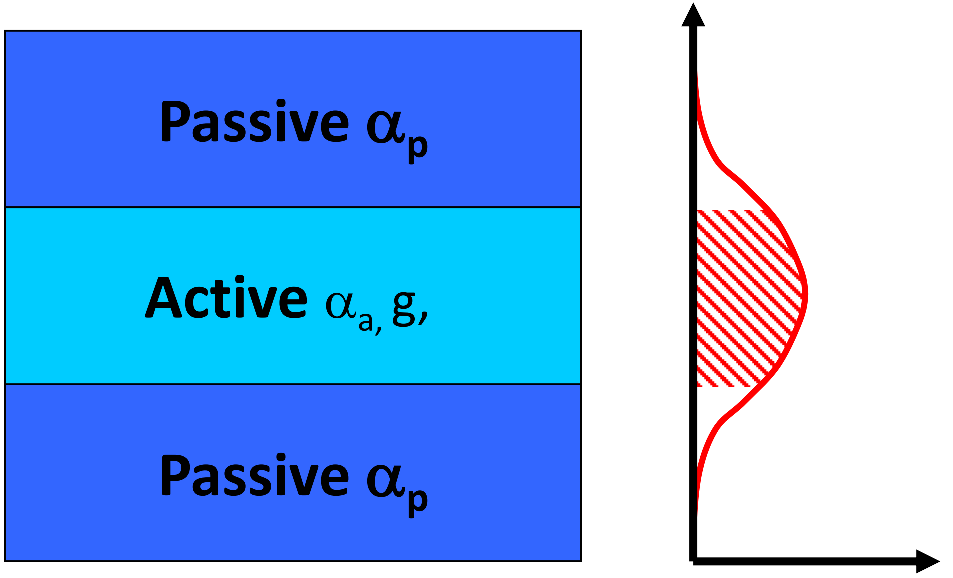
- Increase Γ :

(1) increasing refractive index contrast in active region and the cladding region

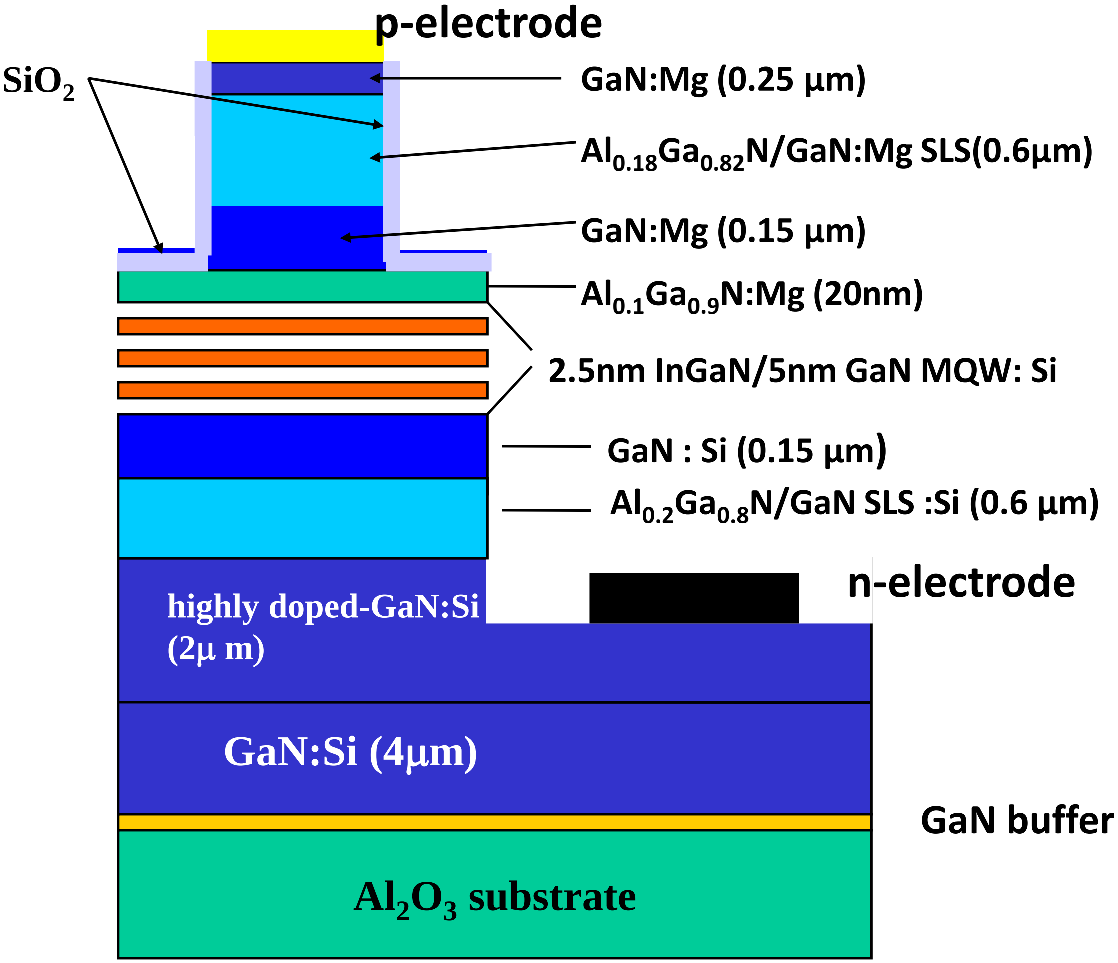
(2) Increasing the cladding layer thickness

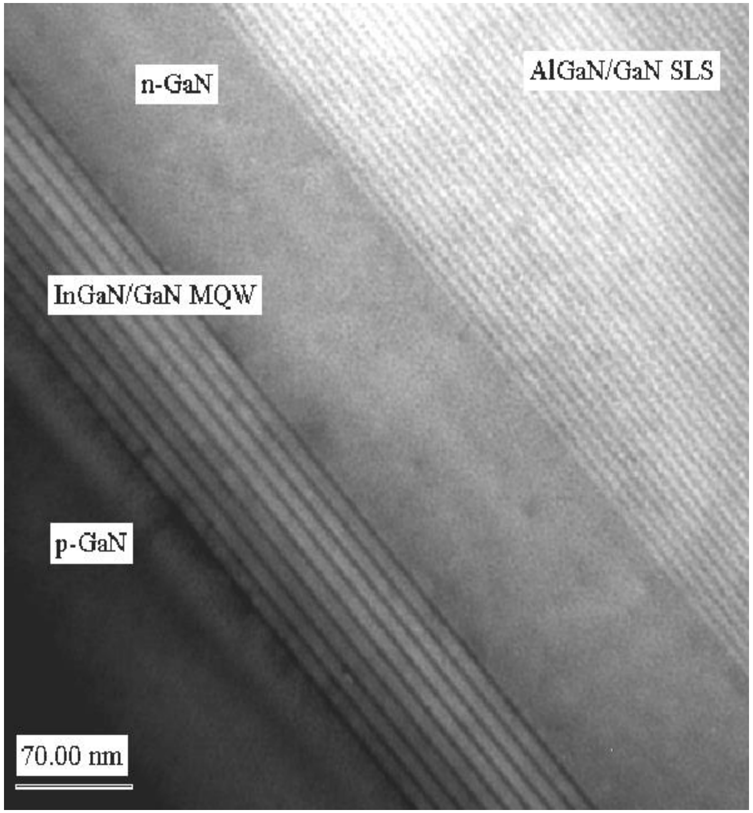
- Increase R_1, R_2 – make one mirror highly reflective - high reflectivity mirror facet: DBR~100%

- Increase L: Be careful, as it also increases loss in practical applications

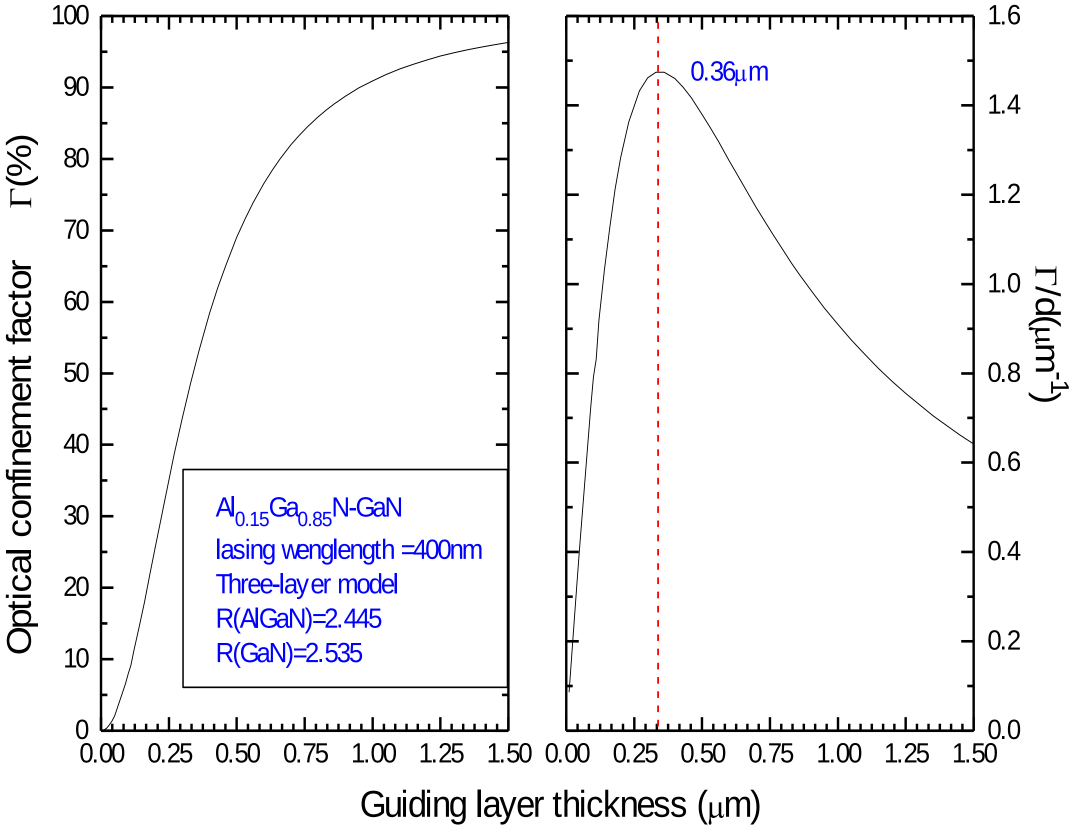


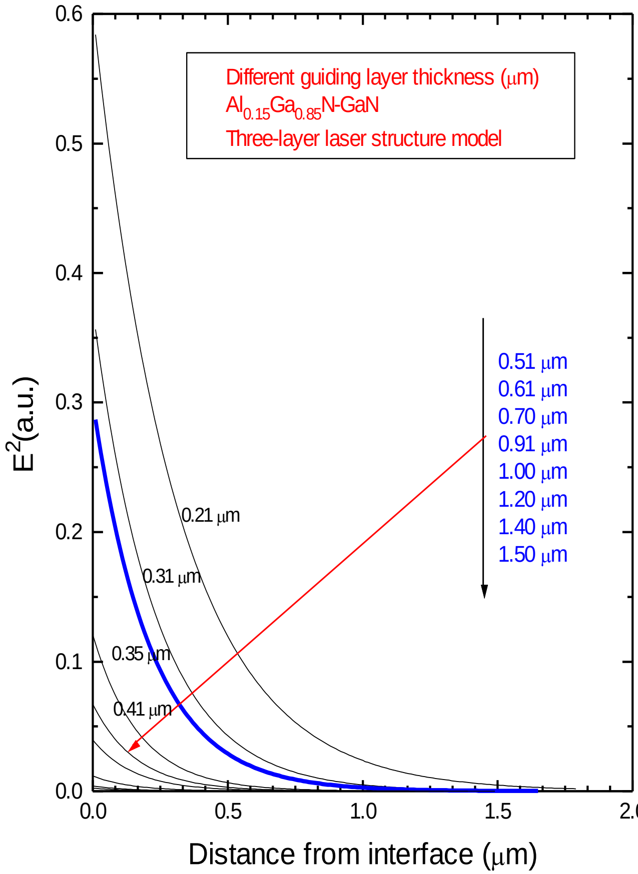
InGaN-based LD as an Example (i)



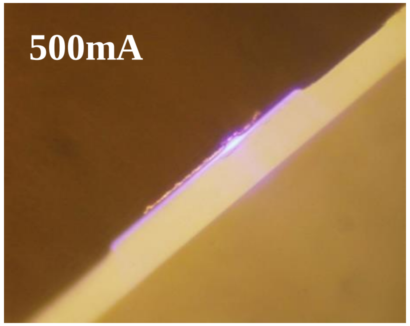


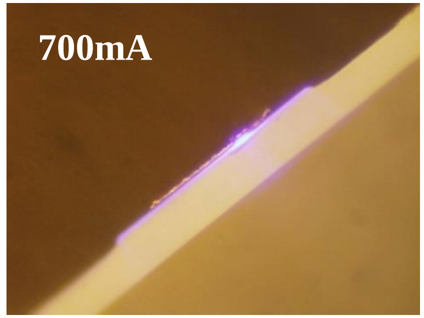
InGaN-based LD as an Example (ii)

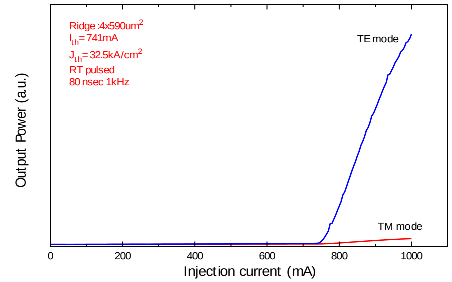


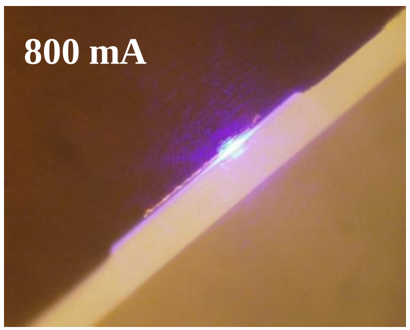


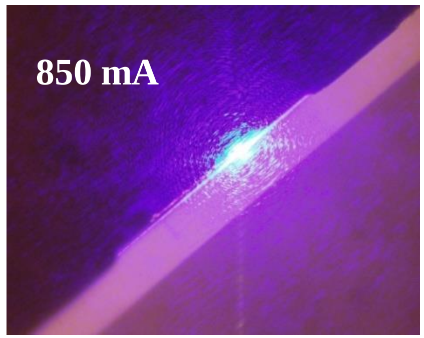
GaN-based Violet/Blue LD

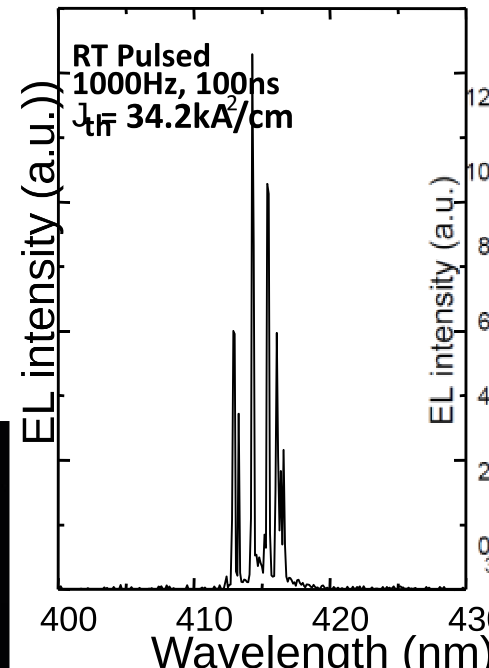


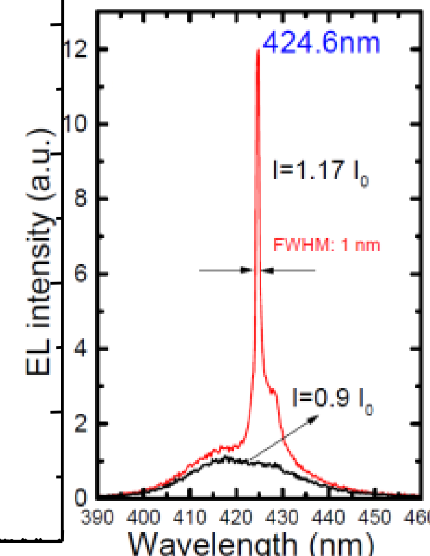


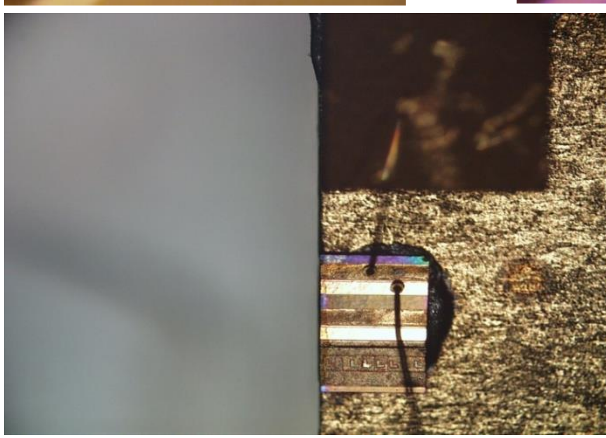


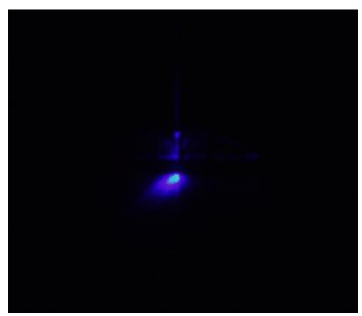




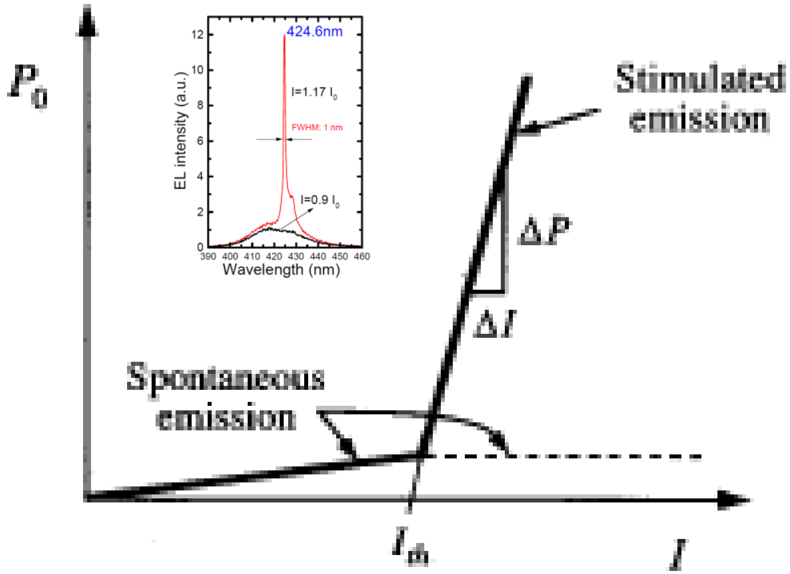








Laser Power – Differential Efficiency



(1) **Internal quantum efficiency:**
the efficiency of converting an electron-hole pair into a photon

(2) External differential efficiency
- related to internal quantum efficiency, η_i and the ratio of photons lost at mirrors and total loss

• α_a = internal loss = photons absorbed or scattered out of the cavity

• α_m = mirror loss = photons transmitted at facets = $(1/2L) \ln (1/R_1R_2)$

• Measure

– external differential efficiency

$$P_0 = \eta_d \frac{h\nu}{q}(I - I_{th})$$

$$\eta_d = \frac{q}{h\nu}\frac{\Delta P}{\Delta I}$$

• Useful laser output is coupled out through the facets, and the rest is used to overcome the loss

$$\eta_d = \frac{\eta_i \alpha_m}{\alpha_i + \alpha_m}$$

Summary – Topic 20 (i)

- Lasing takes place when the internal gain, produced by stimulated recombination of injected carriers is stronger than the optical loss, and the allowed emission wavelengths are those that return in phase after a round trip of the optical cavity
- Semiconductor laser – a combination of optical cavity and electrically pumped gain section
- A laser may be formed by two partially reflective mirrors (cleaved facets of semiconductor) and is termed a Fabry Perot (FP) laser
- Operates by stimulated emission – photons in phase, emitted in the same direction
- Considering round trip losses of a laser we can derive the gain required to achieve a round trip with no loss/gain of optical power within the cavity

Summary – Topic 20 (ii)

- Threshold gain is the sum of “mirror loss” and “internal loss”
- Below threshold – LED, above threshold – the efficient conversion of carriers to photons
- Directional stimulated emission – laser “beam” which is readily focused – high launch power
- Above threshold – we can determine the output power or differential efficiency with regard to an electron to photon conversion efficiency and the ratio of mirror loss to total loss

Tutorial Questions

T20.1 Draw and label a typical laser diode structure. Describe the requirements for lasing to take place in a semiconductor laser diode. What is meant by the terms “transparency current” and “threshold current” for a semiconductor laser diode?

T20.2 What is meant by 'population inversion'? Explain the principles of stimulated optical emission and how it is related to optical absorption.

T20.3 A Fabry-Perot laser of length L and optical confinement factor has active and passive region losses α_a and α_p and facet reflectivity R. Derive an expression for the threshold gain, g^{th}. Show that if one of the facets is silvered g^{th} is reduced by $-\ln(R)/2\Gamma L$ and if the passive region loss is eliminated it is further reduced by $\alpha_p(1-\Gamma)/\Gamma$. n

T20.4 Sketch the gain spectrum of a “bulk” laser diode as a function of current from zero applied current to lasing at room temperature. Mark on the schematic the threshold gain. Comment on the effect of raising the temperature.