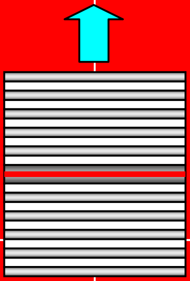

About semiconductor lasers

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(Electrical Engineer/Test Engineer)

■ **The operating condition of the semiconductor lasers**

■ ■ **Type of the semiconductor lasers**

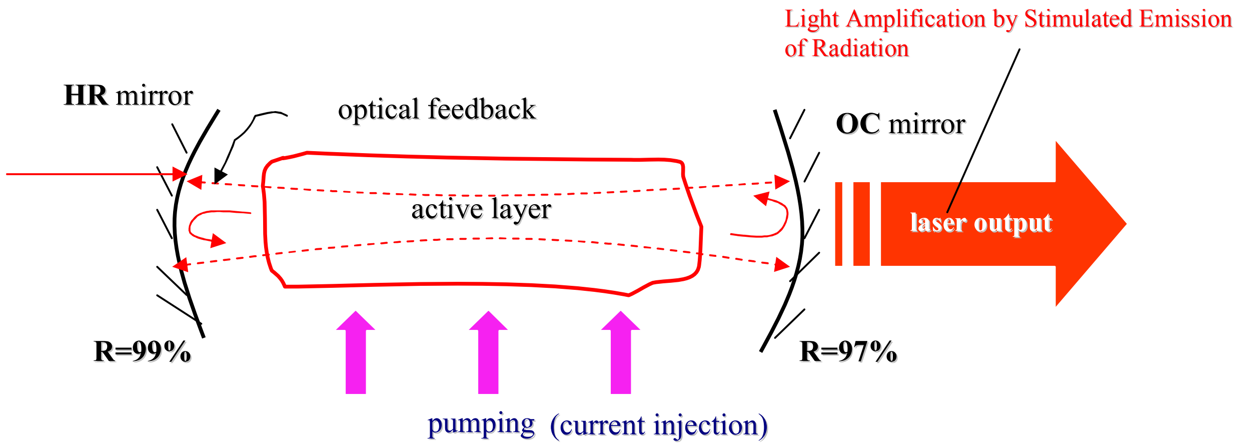
■ ■ ■ **Intensity modulation of the semiconductor lasers**

■ ■ ■ ■ **Layer structure of the semiconductor lasers and the operating wavelength***

■ ■ ■ ■ ■ **Erbium Dopped Fiber Amplyfier***

■ The operating condition of the semiconductor lasers

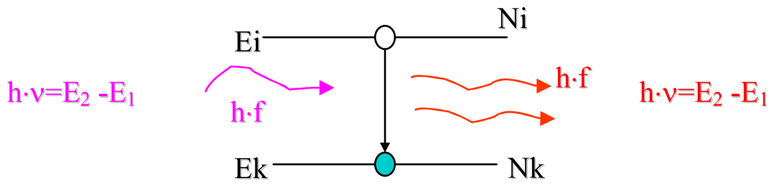
The principle of the laser operation



During the oscillation process, the light is attenuated and amplifyed in the gain material and the light beams with **same wavelength are coupled out on the** OC **mirror.** The output of a laser is a *coherent electromagnetic field*.

where, **HR** = high reflection mirror*,* **OC**= output coupler mirror *(semitransparent mirrors)*

The principle of the stimulated emission



First the electon is on the higher level and *the effect of the incomming stimulating photon* will be that the *electron will be emitt a clone (a new photon)* which will be exactly same with the incomming photon in modul, in polarization and in the phase.

For the laser operation are neccessary the following conditions:

1. ***Active layer*** *(gain material)* which working on the base of the *stimulated emission*.

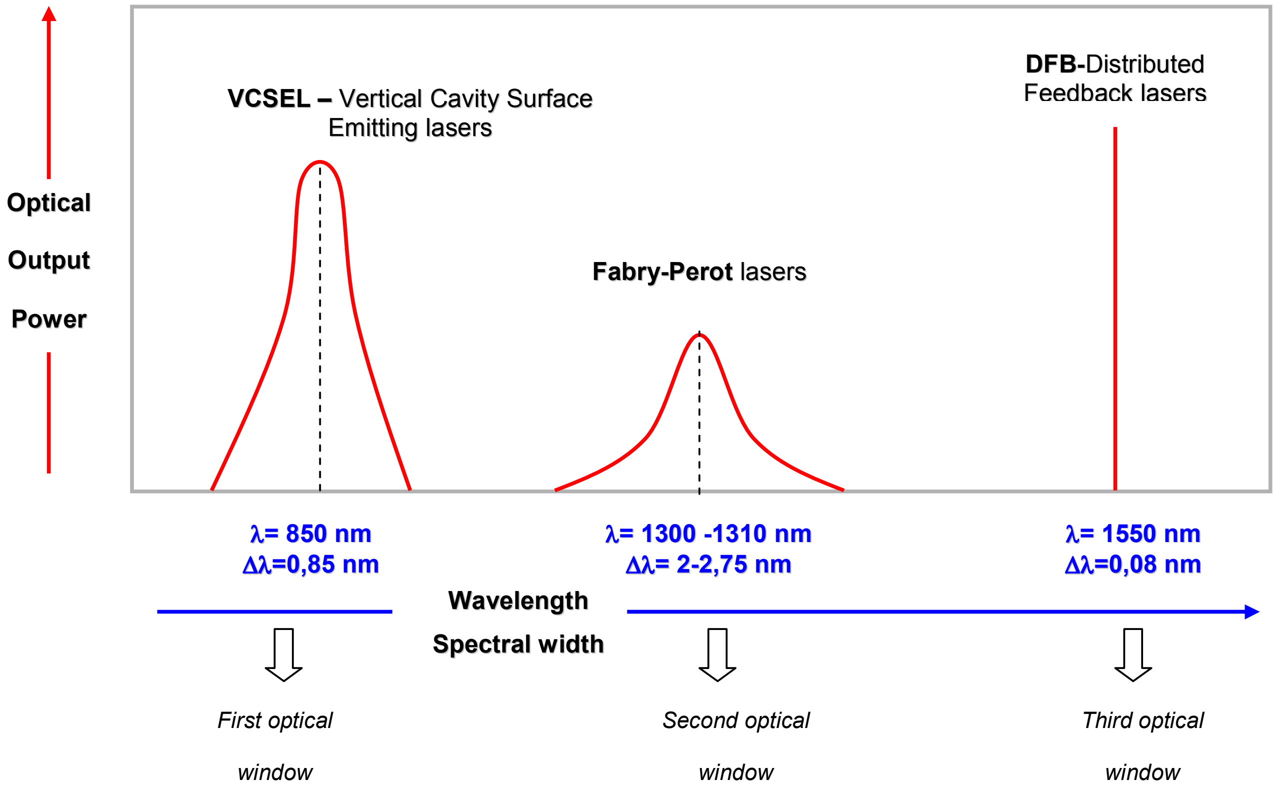
2. *Pumping power* which change the material to active state with ***population inversion****

3. ***Optical feedback*** which usually is created with *Fabry-Perot rezonator** with *(optical rezonators)*

The function of the rezonator is the *creation of the high optical energy density* and the *hard frequency-selective dealing* namely the assurance high spectral purity.

Generally the number of the atoms in base state is higher as the number of the excitated.
For the laser operation the loading state of the energy levels must be change , namely *in the active layer of the laser it needs to be reached* the self-styled ***population inversion***. This state in case of the semiconductor laser is created by *injection of the electrical particles* (with current injection). In case of the *solid state lasers* is used the *optical pumping*. (for example in case of **Nd: YAG** -yttrium-aluminium-garnet glass lasers or *ruby laser*)

■ ■ Type of the semiconductor lasers



Operating wavelength and the *spectral line width* for different laser types as **VCSEL, FP** and **DFB**

- **VCSEL** – ***Vertical Cavity Surface Emitting*** lasers:
  They are the type of the seciconductor lasers with a monolithic laser resonator, where the emitted light leaves the device in a direction perpendicular to the chip surface.
  The resonator (cavity) is realized with two semiconductor *Brag mirrors* and between these mirors is an *active region* (gain structure). The active region is electrically pumped with circa **50 mW** (tens of milliwatts) and generated an output power in the range **0,2 – 5 mW** . The current is applied through a *ring electrode*.

- **Fabry-Perot** lasers:
  A laser oscillator in which two mirrors are separated by a amplifying medium (gain) with an inverted population, making *Fabry-Perot cavity*. Standard diode lasers are Fabry-Perot lasers.
  Exist two *resonator type*: with *plan-parallel* (**R1, R2 = ∞)** and with *spherical mirrors* ***(R1, R2 = L/2)***
  The *thickness of active layer* at *heterojunction lasers, strip lasers* (mirror separation distance) is usually **d < 1 μm** or **d= 0,2 μm.**

- **DFB** – ***Distributed Feedback*** lasers :
  Are the type of the laser devices where operating with *very small spectral width* in the third optical window and the active layer of the device has integrated a *diffraction grating* which can be different special form (*normal trapezoidal, rectangular, sinusoidal*, ...etc)

  Where: $\mathbf{n_g}$ - is the group refractive index, $\boldsymbol{\lambda_B}$ - is the Bragg wavelength and **m** – is a integer number

  For **m=1** the grating is called *first-order grating*. The **DFB** lasers has *very clean spectral line width*.

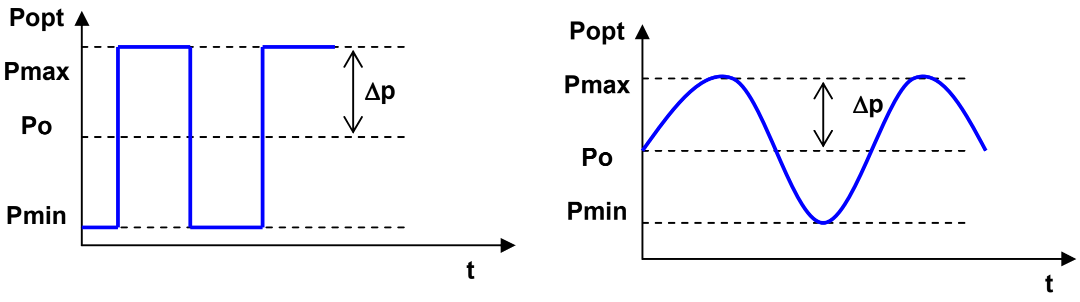
This type is used in the high speed optical communication and in the cable TV applications.

■ ■ ■ Intensity modulation of the semiconductor lasers

- In practice for the semiconductor lasers usually it is used the ***intensity modulation***

- The neccessary power for the modulation is created by a ***driver circuit***

- The key parameter of the modulation is the ***modulation index*** (*modulation deep*) $m = \dfrac{P\max - P\min}{P\max + P\min}$



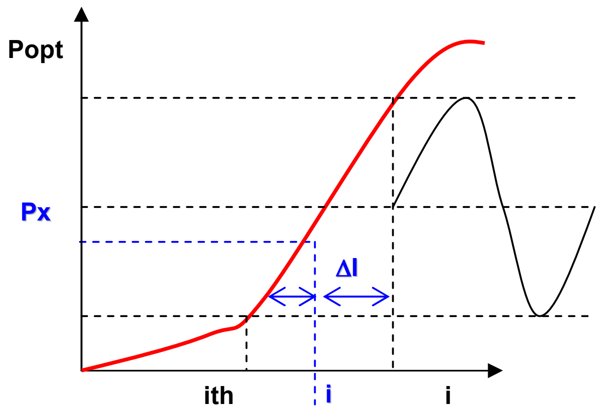
The modulation index variation during digital and sinusoidal modulation

- The main parameter of the light source is the outgoing optical power

What is the intensity modulation?

If the current of the device (laser diode) containing a modulation term, in this case <u>*the modulator current*</u> *will be change the* ***outgoing optical power*** *of the device.*

In the intensity modulation it is required that the device to be modulated at *high frequence*, which is perfect for the semiconductor lasers.



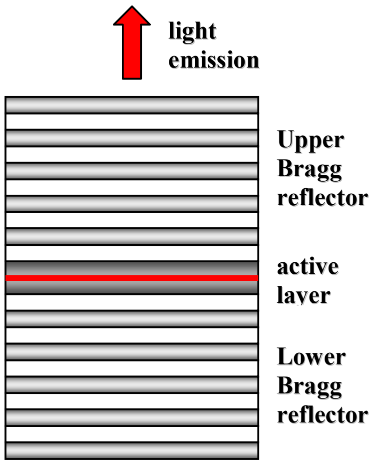
Usually the device is modulated at third part of the <u>relaxation resonance frequency</u> $\mathbf{F_M=(1/3)f_R}$

The maximal value of the *relaxation resonance frequency* today is **10 Ghz**.

The other very important is, that the device must be modulated on the *linear part of the characteristic* (after the **ith** - *treshold current*).
During the optical transfer (communication), the device is not powered down completely (totally), only until the treshold current.
The modulation process <u>is characterized by *chirp*</u> becuase during the <u>variation of the optical power</u>, is change the *value of the laser frequency*.

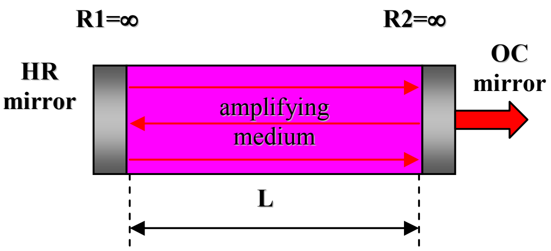
■ ■ ■ ■ Layer structure of the semiconductor lasers

VCSEL structure

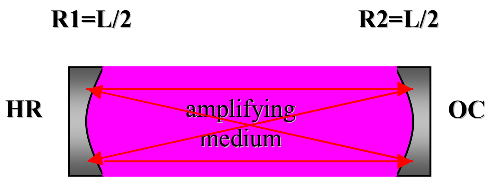


The total tichness of the active layer is usually few micrometer.

Fabry-Perot resonators



Plane-parallel resonator

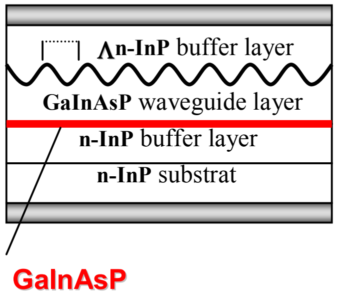


Spherical resonator

The mirror separation distance is usually L < 1 cm.

HR = high reflection mirror
OC = output coupler mirror

DFB laser structure



Uniform grating DFB laser

The *grating period* (Λ):

$$\Lambda = m \cdot \lambda_B / 2 \cdot n_g$$

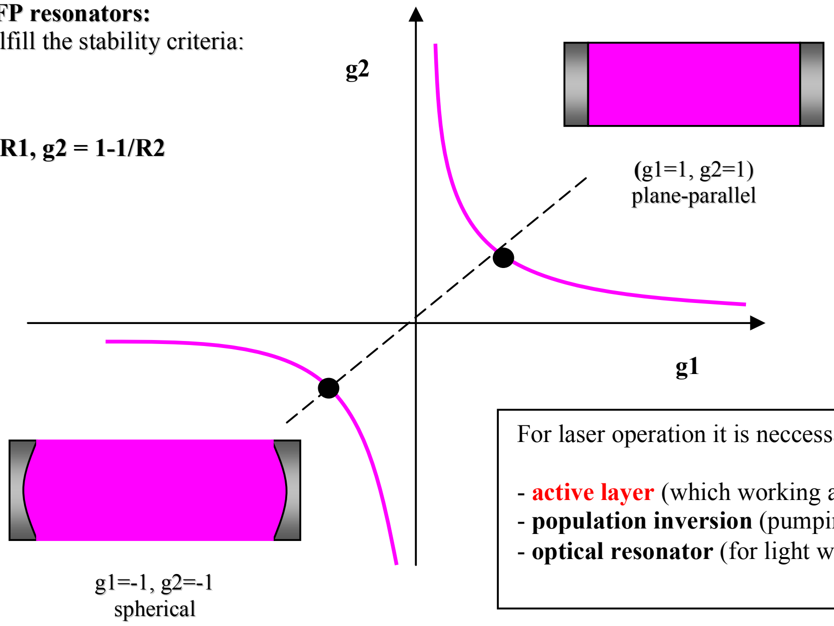
For **1,5 μm InGaAsP** laser,with first order grating the typical value of **ng=3,4** and **Λ=0,23** μm

Are used usually at 40km/2Gb or 10km/4Gb optical transfers.

Stability of the FP resonators:
They must be fullfill the stability criteria:

$0 < g1 \cdot g2 < 1$

where **g1 = 1 –1/R1, g2 = 1-1/R2**



For laser operation it is neccessary for:

- **active layer** (which working after stimulated emission)
- **population inversion** (pumping)
- **optical resonator** (for light wave amplification)

The parameters of Fabry-Perot resonator are:

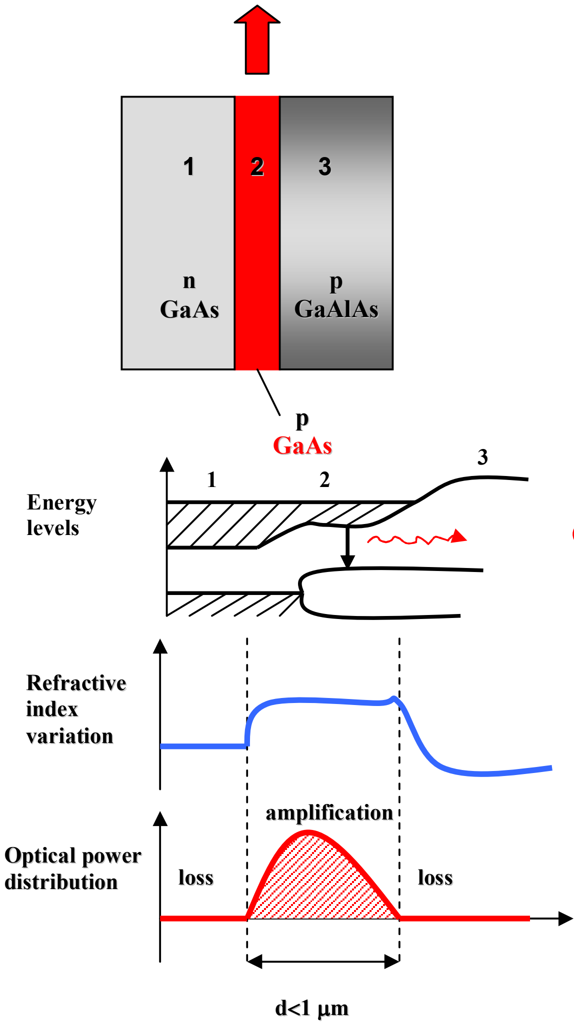
FSR = c/2·L – free spectral range, **FWHM = c/2d·[1-R/(R)$^{1/2}$]** – full width at half maximum

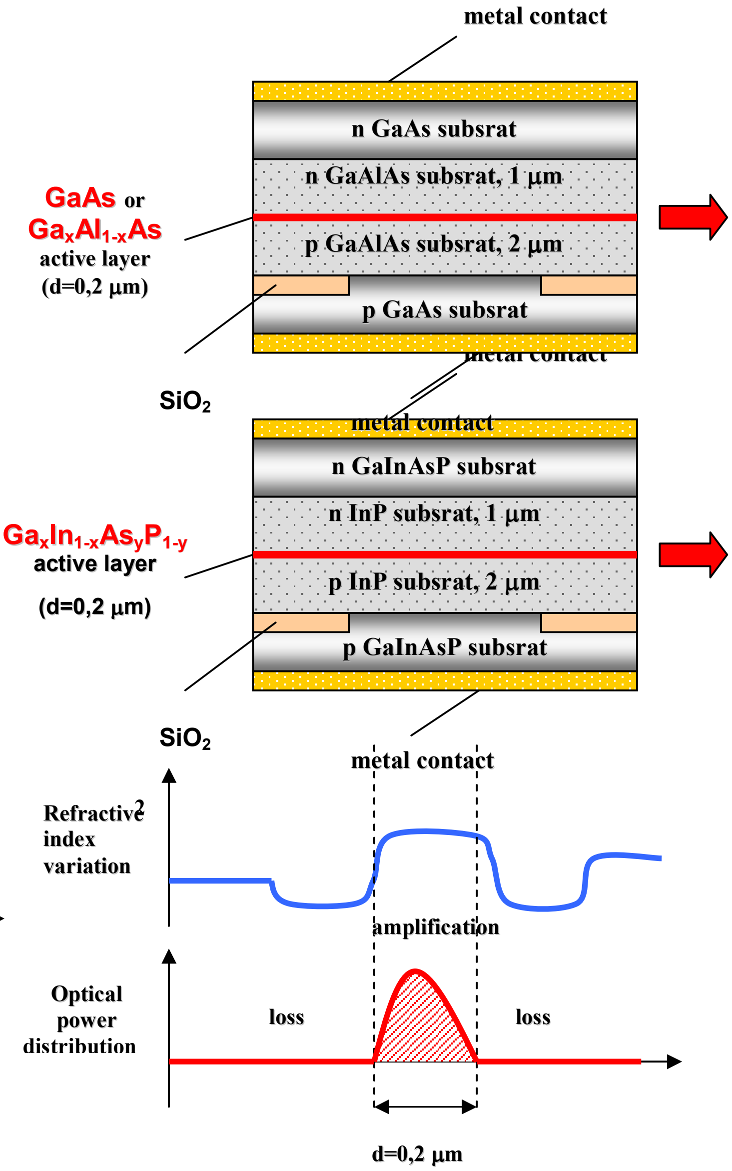
F = FSR/FWHM - finesse

Heretojunction lasers /Edge emitting laser diodes *(Fabry-Perot type lasers)*

Simple heretojunction structure

Double heretojunction structure





The **p GaAlAs** substrat <u>hold back</u> the electrons injected from the **n GaAs** substrat in the **p GaAs** active layer. The potential barrier is circa **0,53 eV**.

Because of this back holding, the electrons remaining concentrated in the **p GaAs** layer the value of threshold current will be decrease and the variation of **Ithr** with temperature will be same decrease. At *<u>SH lasers</u>* the **$I_{thr} \cong 4800 \cdot d$**.

The **threshold current** for 0 Kelvin is (for *<u>DH lasers</u>*, **I(T)=0** if **T=0 K**):

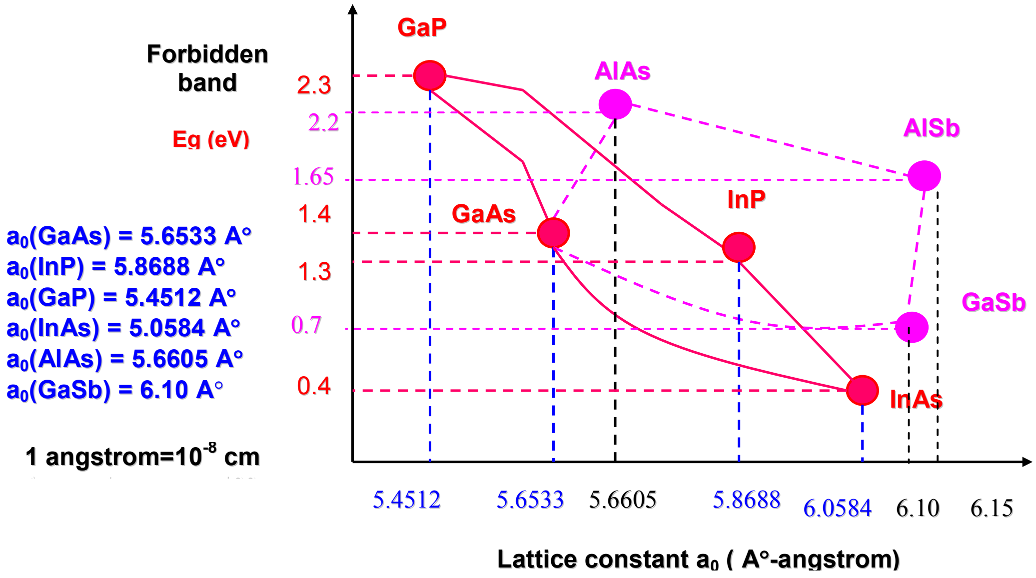
$$I_{thr}(0) = \frac{8\pi \cdot \Delta f \cdot q \cdot d}{\lambda^2 \cdot \eta_i} \cdot \left[\alpha_{in} + \left(\frac{1-\Gamma}{\Gamma} \right) \cdot \alpha_{out} + \frac{1}{2L \cdot \Gamma} \ln\left(\frac{1}{r_1 \cdot r_2} \right) \right] + I(T)$$

Temperature variation of the *threshold current*:

$I_{thr} = I_{thr}(0) \cdot \exp^{(T/T0)}$

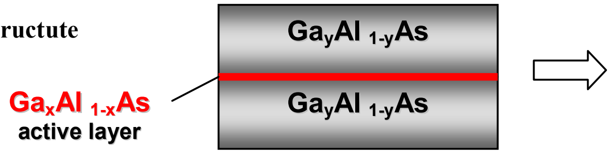
where: **L** – is the mirror distance, **d**- diffusion thickness, **α** - attenuation,
ηi – internal quantum efficiency, **n_{GaAs} = 3,6** – refractive index , **Γ**-confinement factor and
$r_1 = r_2 = r = (n_{GaAs} - n_{air} / n_{GaAs} + n_{air})^2 = 0,32$ are the reflection coefficients

Layer structure of SW and LW laser diodes and the operating wavelength



The lattice constant and the energy band gap for different materials

SW laser device layer structute



First optical window range:

λ = 820 nm – 880 nm

The active layer **$Ga_xAl_{1-x}As$** which is doped in x % in **Al**-aluminim, is lattice matched

to **$Ga_yAl_{1-y}As$** layer which is doped in **y > x %** in **Al**.

The properties of the semiconductor compoud can be deswcribed

by **Vegards law**: **$a(Ga_xAl_{1-x}As) = x\cdot a(AlAs) - (1-x)\cdot a(GaAs)$,** where **a** - is the *lattice constant.*

The lattice constant and energy band gap value of the materials resulting from the graphic.

$$5{,}6605\cdot x + 5{,}6533 - 5{,}6533\cdot x = 5{,}6605\cdot y + 5{,}6533 - 5{,}6533\cdot y$$

$$0{,}0072\cdot x = 0{,}0072\cdot y \Rightarrow x \le y \quad (y > x)$$

For the *energy bandgap (forbidden band)* we can apply same law:

$Eg(Ga_xAl_{1-x}As) = x\cdot Eg(AlAs) - (1-x)\cdot Eg(GaAs)$ **$Eg(x) = 2{,}2\cdot x + (1-x)\cdot 1{,}4 = 0{,}8\cdot x + 1{,}4$**

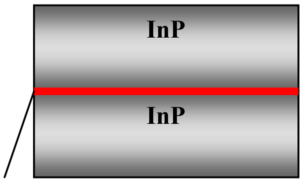
For **0,850 nm = 1.24/Eg** ⇒ for first optical window the *forbidden band* must be **Eg = 1,24/0,850 = 1,45 eV**

1,45 = 0,8 ·x +1,4 ⇒ **x = 0,0625 Al %** and y must be higher as x

From the definition of the *operating wavelength,* resulting λ for the SW-short wave operation range:

$$\lambda = \frac{c}{f} = \frac{c}{\frac{Ec - Ev}{h}} = \frac{hc}{Eg} = \frac{1{,}24}{145} = 0{,}855\ \mu m = 855\ nm$$ which is the first optical window.

LW laser device layer structure



2^{nd} optical window: λ =1285 – 1330 nm

3^{rd} optical window: λ =1525 – 1575 nm

$Ga_xIn_{1-x}As_yP_{1-y}$
active layer

The *active layer* of the LW laser device is the material system - **$Ga_xIn_{1-x}As_yP_{1-y}$** - *gallium indium arsenid phosphide* which is doped in **x % in In** – indium and **y % in P**-phosphide.
This material system can be used for the realization of lasers in the spectral window around 1310 nm and 1550 nm which are the *second* and *third optical windows*.

The properties of this *semiconductor compound* (**$Ga_xIn_{1-x}As_yP_{1-y}$**) can be described by **Vegard's law**.

$$a(Ga_xIn_{1-x}As_yP_{1-y}) = xy\cdot a_0(GaAs) + x(1-y)\cdot a_0(GaP) + (1-x)y\cdot a_0(InAs) + (1-x)(1-y)\cdot a_0(InP) =$$
$$= 5.6533\cdot xy + 5.4505x\cdot(1-y) + 6.0584(1-x)\cdot y + 5.8688(1-x)\cdot(1-y)$$

Using this law and know the semiconductor compounds **GaAs, GaP, InAs**, and **InP** it is possible to determine the coefficients **x** and **y** and the *operation wavelength* of the laser device.

$$a(Ga_xIn_{1-x}As_yP_{1-y}) = a_0(x,y) = 5.8688 - 0.4176x + 0.1896y + 0.0125xy$$

The material shystem **$Ga_xIn_{1-x}As_yP_{1-y}$** it is lattice matched to **InP** layer (with lattice constant **a(InP) =5,8688**) :

$$5.8688 - 0.4176x + 0.1896y + 0.0125xy = 5.8688 \Rightarrow 0.4176x = 0.1896y + 0.0125xy$$

For the **x %** and **y %** of **In** and **P** resulting the following relationship:

$$\boxed{x = \frac{0.1896y}{0.4176 - 0.0125y} \quad 0 \le y \le 1.0} \qquad \boxed{y = \frac{0.4176 \cdot x}{0.1896 - 0.0125 \cdot x}}$$

If **y=1** resulting **x=0.468**, but allways **y** must be higher as **x** **(y>x)**

Resulting **x <0,468** (the **In**-indium % of the active layer)

For 1310 nm $$1550nm = \frac{1.24}{Eg} \Rightarrow Eg = \frac{1.24}{1.310} = 0.94eV$$

For 1550 nm $$1310nm = \frac{1.24}{Eg} \Rightarrow Eg = \frac{1.24}{1.550} = 0.80eV$$

$$Eg(Ga_xIn_{1-x}As_yP_{1-y}) = xy\cdot Eg(GaAs) + x(1-y)\cdot Eg(GaP) + (1-x)y\cdot Eg(InAs) + (1-x)(1-y)\cdot Eg(InP) =$$
$$= xy\cdot 1,4 + x(1-y)\cdot 2,3 + (1-x)\cdot y\cdot 0,4 + (1-x)\cdot(1-y)\cdot 1,3 = 1.3 + x - 0.9y$$

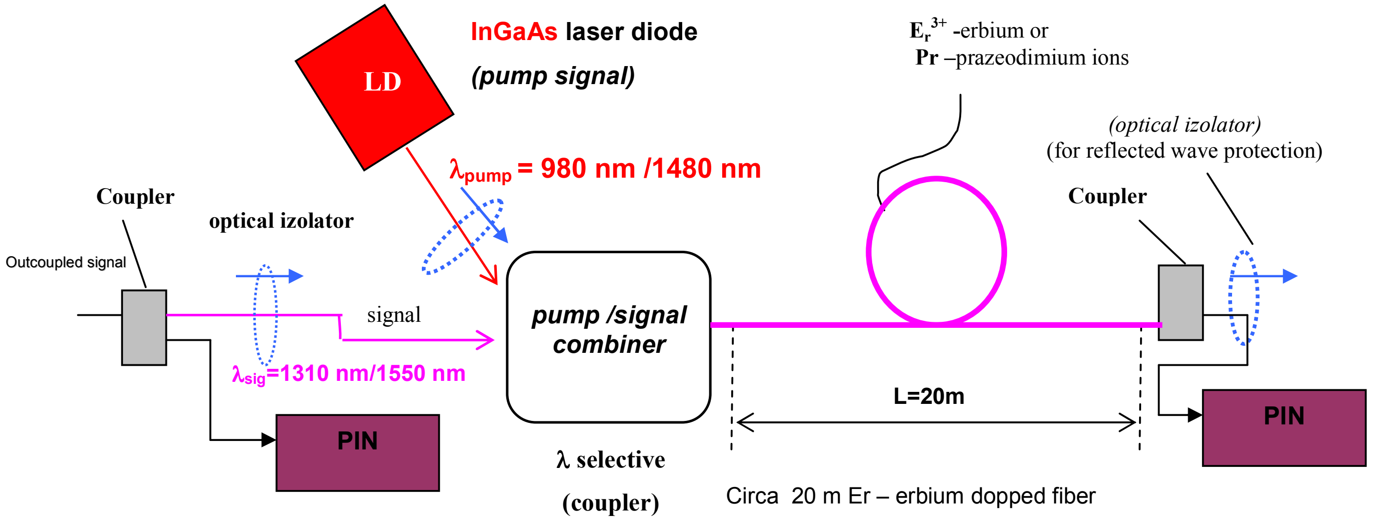
For **Eg** = **0,94** eV if **x=0,36** (In %) resulting **y=0,8** (P %) and resulting λ = 1310 nm

$0,94 = 1.3 + 0,36 - 0.9y \Rightarrow y=0,8$ λ =1.24/0,94 = 1310 nm *(2-nd optical window)*

For **Eg** = **0,80** eV if **x=0,46** (In-indium %) resulting **y=1,06** (P-phosphide %) and resulting λ = 1550 nm

$0,80 = 1.3 + 0,46 - 0.9y \Rightarrow y=1,06$ λ =1.24/0,80 = 1550 nm *(3-rd optical window)*

■ ■ ■ ■ ■ Erbium Dopped Fiber Amplyfier - EDFA



The diagram show the functional principle of the optical amplyfier (**E_r^{3+} - erbium dopped fiber amplyfier**)

In the solenoid of the **OA** – optical amplyfier the erbium ions are excited by the emitted wavelength of the laser diode. The function of the optical izolators are the insurance (cover) of the optical power in single direction *(protect the OA-optical amplyfier contra reflected waves)*

The pumping wavelength is **980 nm** or **1480 nm** because the Er-erbium ions has absorbtion o this value of the wavelength. They working only for the **III-third optical window.** (in near of the **1550 nm**)

The amplification is circa **10-20 dB**.

The bit error rate (bit error distribution probability) **OA** circa **P (bad bit)$_{EDFA} \le 1/10^9 = 10^{-9}$**

At repeaters **P (bad bit)$_{REPEATER} \cong 1/10^4 = 10^{-4}$**

The development direction of the EDFA's:

- Fine amplification

- Applying of the *"double window"* parallel coupled optical amplyfiers, in which the working bands are shifted