Main Reference is:

Physics of

OPTOELECTRONICS

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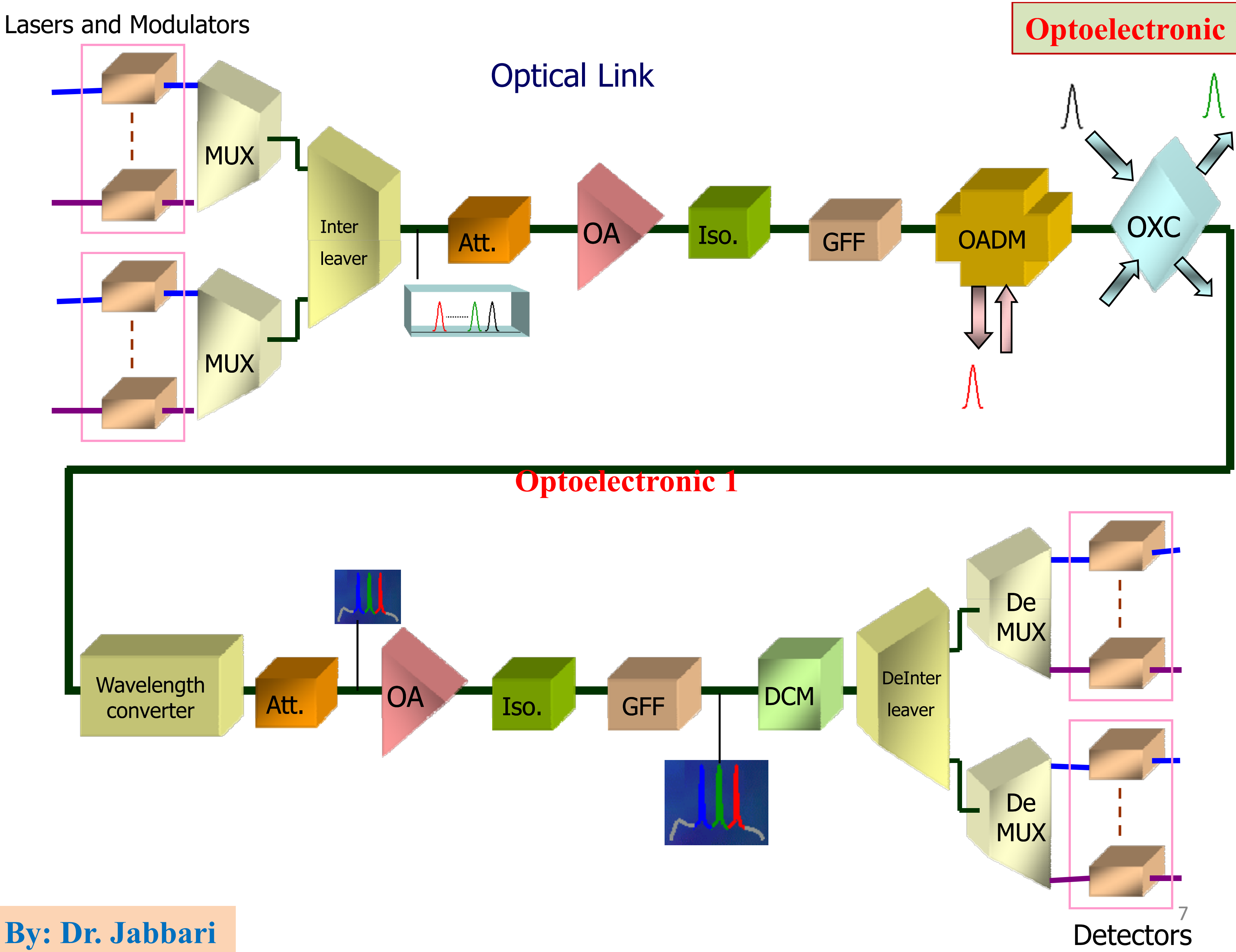
Chapter 1

Introduction to Semiconductor Lasers

By: Dr. Jabbari

Semiconductor lasers have important applications in:
communications,
signal processing and medicine,
including optical interconnects,
RF links,
CD ROM,
gyroscopes,
surgery,
printers,
and photocopying

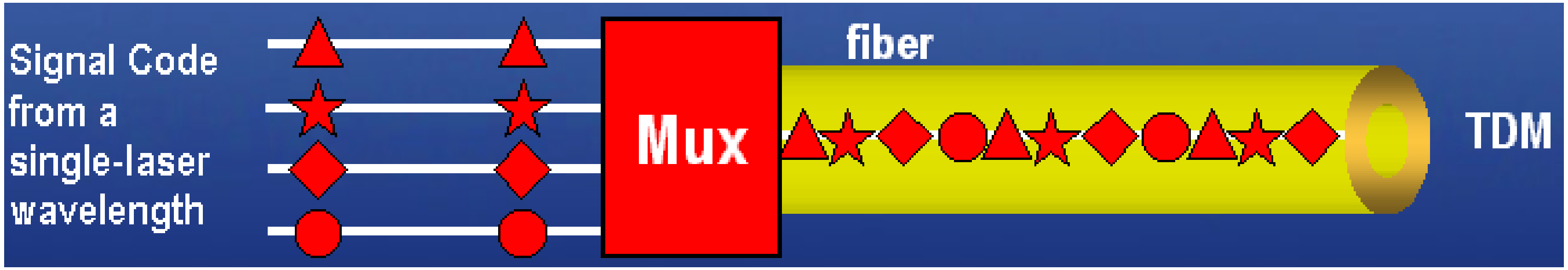


By: Dr. Jabbari

Wavelength Division Multiplexing

Increasing transmission capacity in optical fiber communication systems:

- laying new fibers
    - costly
- Increasing the effective bandwidth of existing fibers
    - Increasing the bit rate
    - Increasing the number of wavelengths on a fiber



SDH is the standardized TDM based hierarchial model where the following transmission rates are defined:

STM-1: 155 Mbps
STM-4: 622 Mbps
STM-16: 2.5 Gbps
STM-64: 10 Gbps
STM-256: 40 Gbps

Gigabit Ethernet: 1 Gbps, 10 Gbps

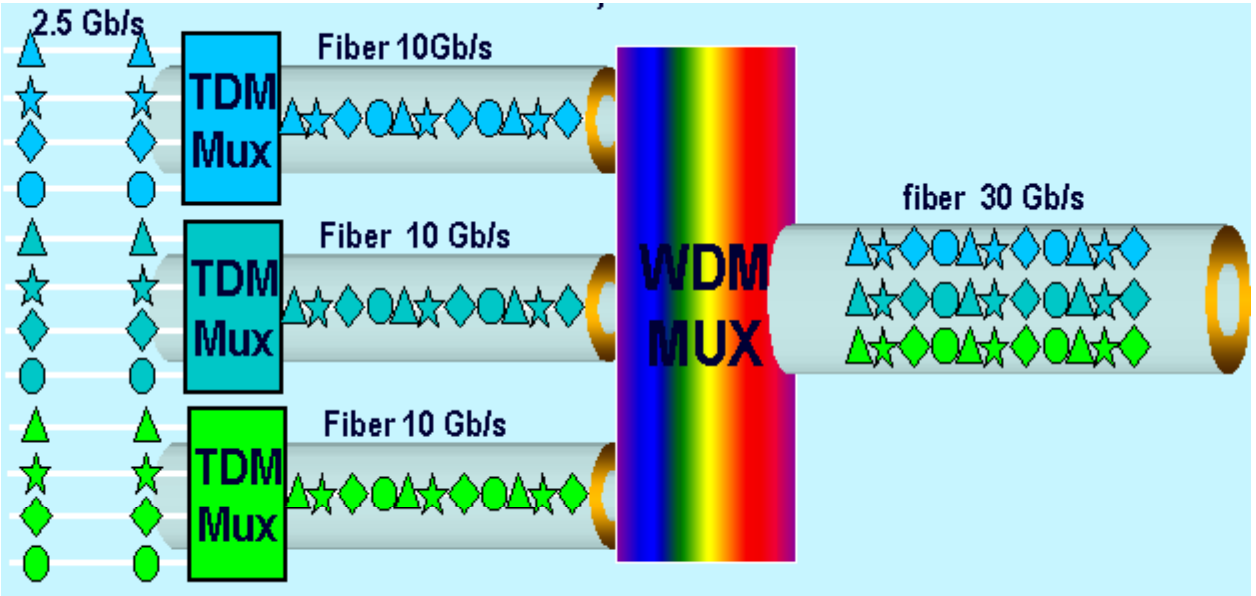
problems for high bit rates

- complex and costly
- chromatic dispersion
- nonlinear effects
- Polarization Mode Dispersion

So

combining many wavelength onto a single fiber using:

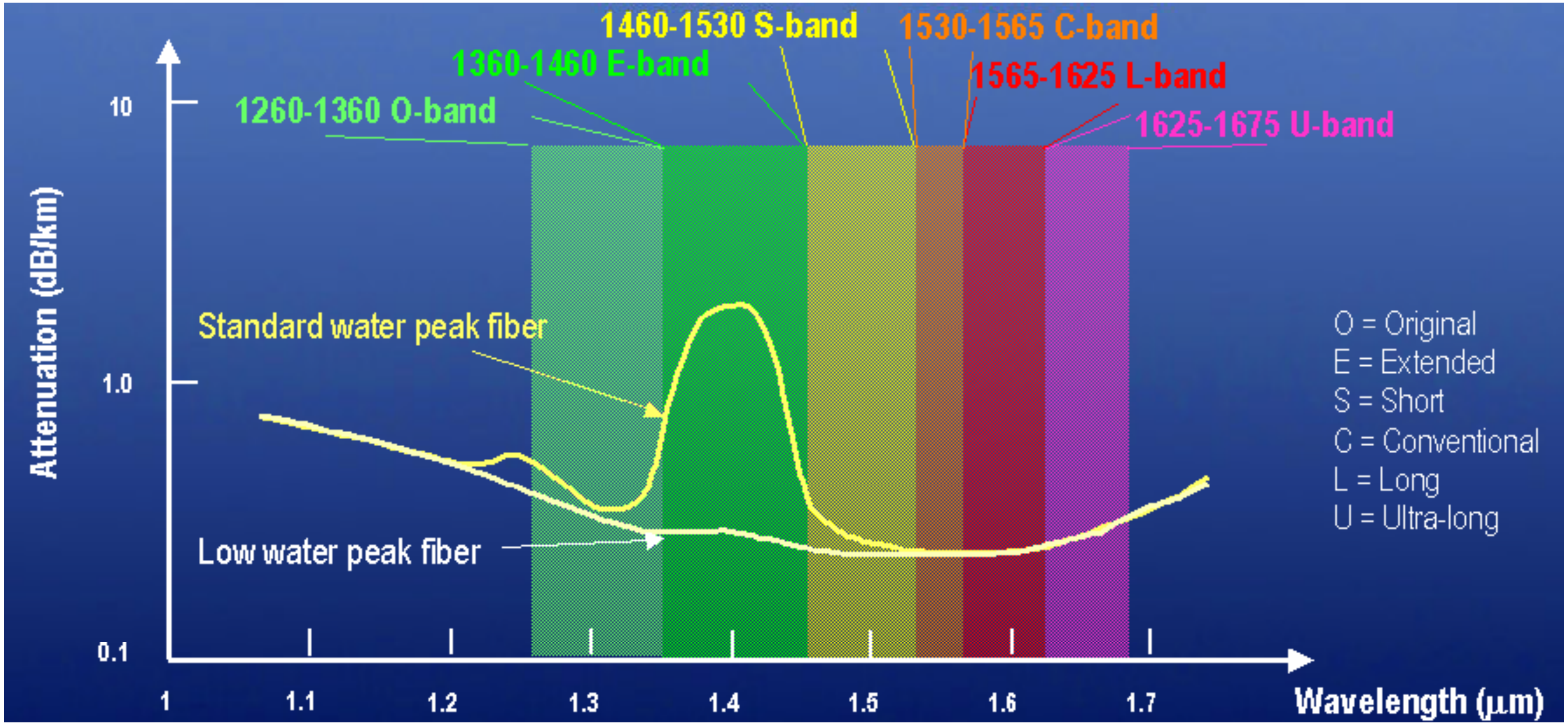
Wavelength Division Multiplexing(WDM)



number of wavelength channels > 16

Dense WDM ⟶ DWDM

G. 692 standard: 81 channel in C band (1530-1565 nm)
Channel spacing= 50 GHz(0.4 nm)



ITU-T NOMINAL CENTER FREQUENCIES

central frequencies(wavelengths) for 100 GHz spacing

$$f_c = 193.1 \pm m \times 0.1 THz$$

$$\lambda_c = 1552.52 nm \pm m \times 0.8 nm$$

central frequencies(wavelengths) for 50 GHz spacing

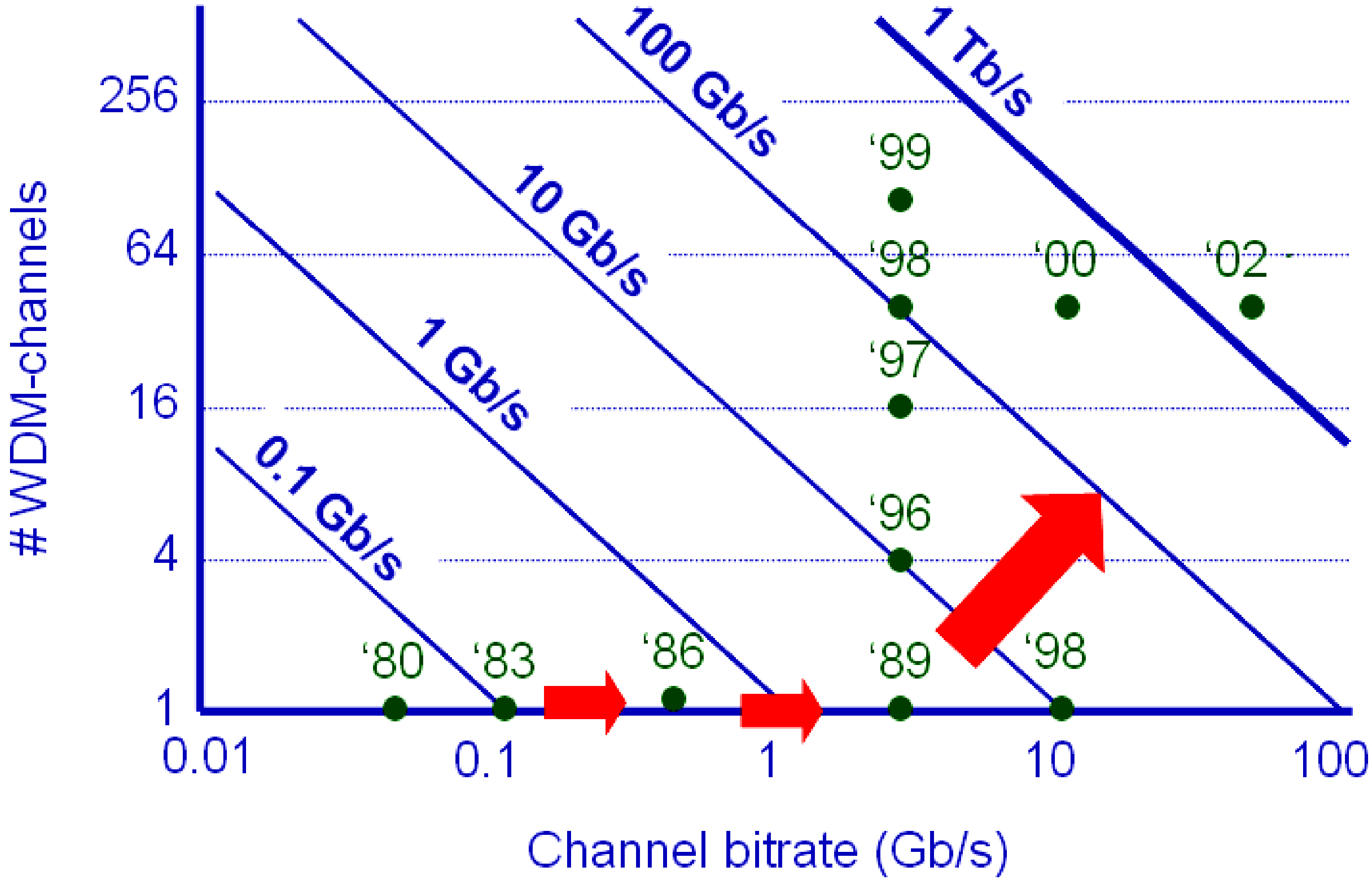
$$f_c = 193.1 \pm m \times 0.05 THz$$

$$\lambda_c = 1552.52 nm \pm m \times 0.4 nm$$

Channel Spacing(GHz): 400, 200, 100, 50, 25, 12.5

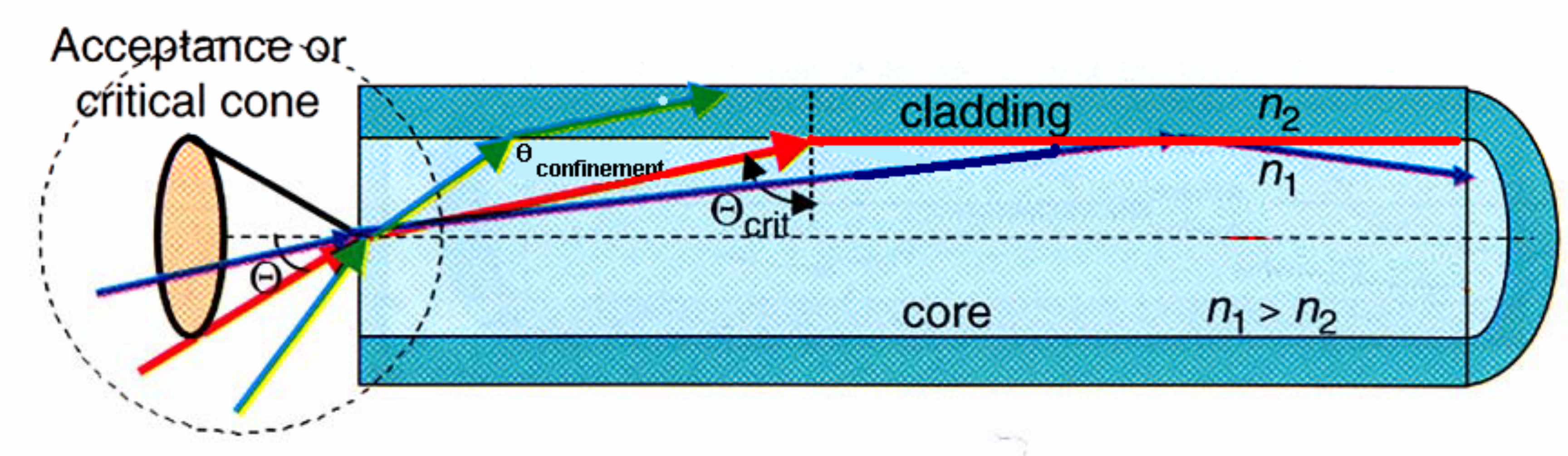
Channel Number:4, 8, 16, 32, 64, 128, 256, 512

transmission capacity growth



Optical Fiber

the transmission of light in optical fiber is commonly explained using the principle of *Total Internal Reflection.*



- Critical angle inside fiber is

$$\theta_{crit} = \arcsin\left(\frac{n_{cladding}}{n_{core}}\right)$$

- Confinement angle is the maximum angle that a ray of light can have, measured with respect to the axis of the fiber, in order to propagate in the fiber.
- From geometry:

$$\theta_{confinement} + \theta_{crit} = 90°$$

Acceptance Angle

- Total angle over which light in the air at the end of the fiber can propagate into the fiber.
- Often the half-acceptance angle is used.
  - Angle measured from axis of the fiber

$$\sin \theta_{half\text{-}acceptance} = NA$$

$$NA = \sqrt{n_{core}^2 - n_{cladd}^2}$$

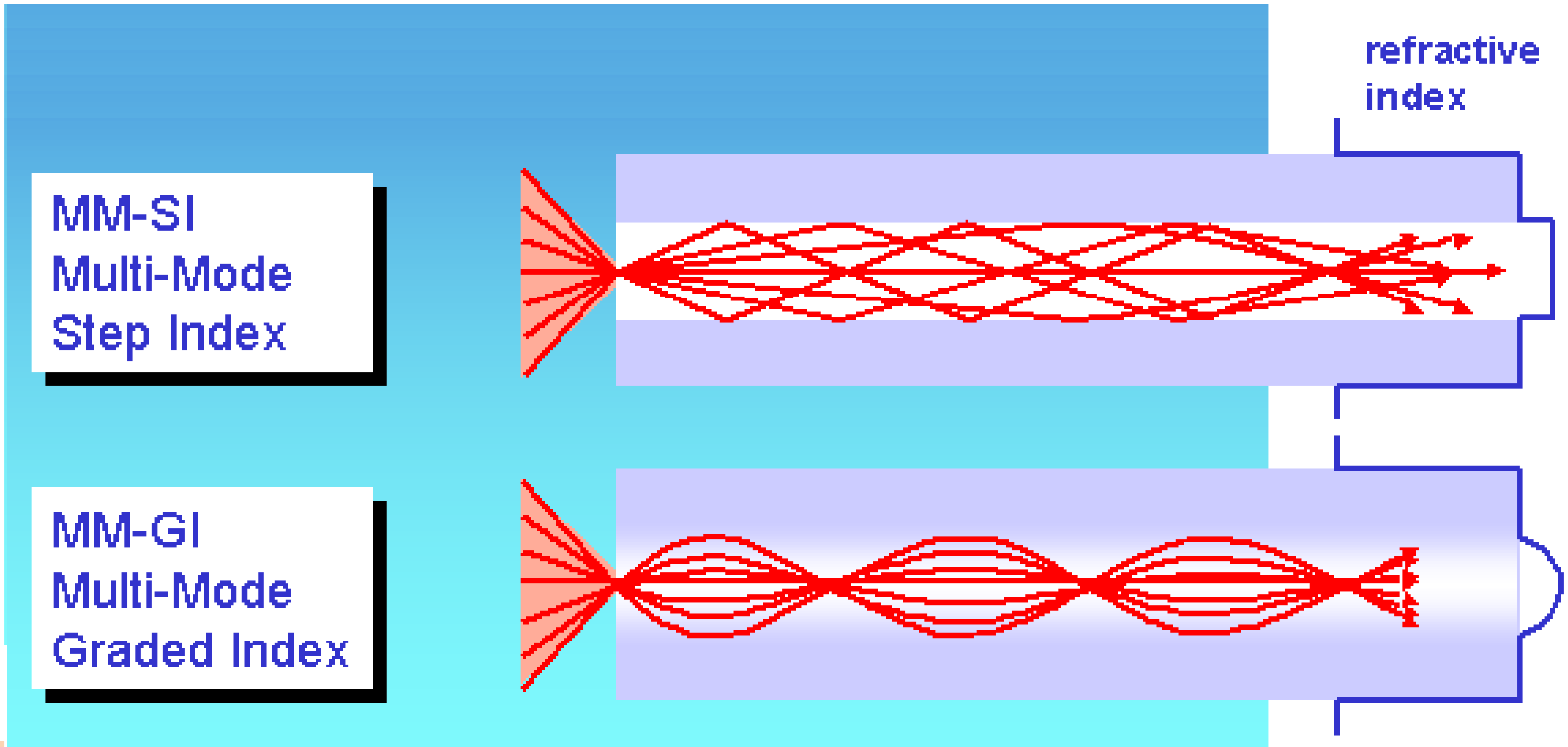
Types of Fibers:

Multimode

(Core diameter: 50 or 62.5 μm Cladding diameter: 125 μm)

Step-index

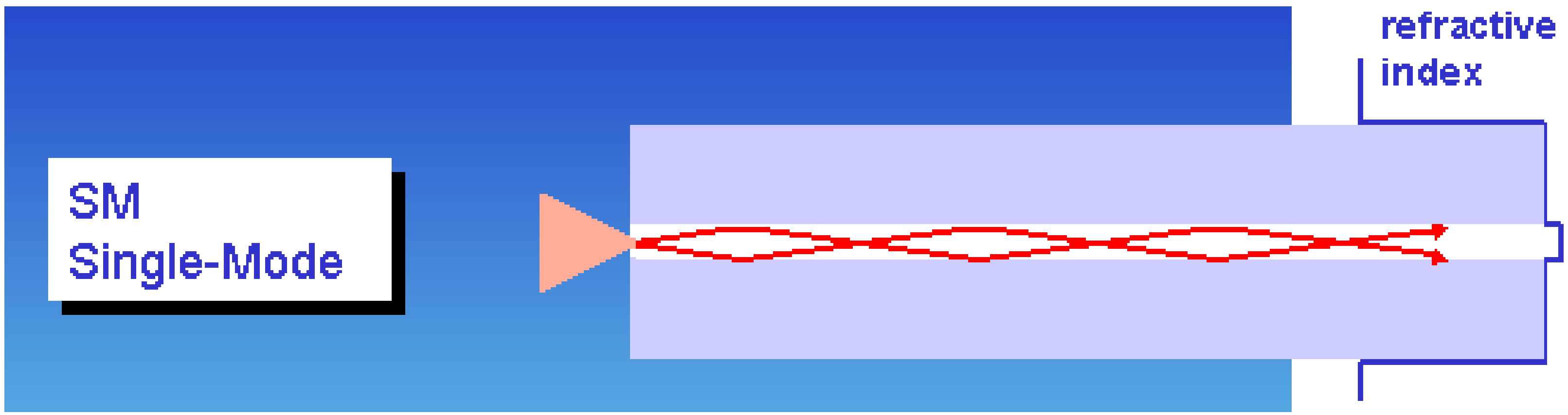
Graded-index



Single-mode

(Core diameter: 8-12 μm Cladding diameter: 125 μm)

If the fiber core is very narrow compared to the wavelength of the light in use then the light cannot travel in different modes and thus the fiber is called "single-mode" or "monomode".



Limitations in Fibers

Attenuation

- Absorption, Scattering

Dispersion

- Modal, Chromatic, PMD

Nonlinear effects

- SPM, XPM, FWM, SBS, SRS

Attenuation

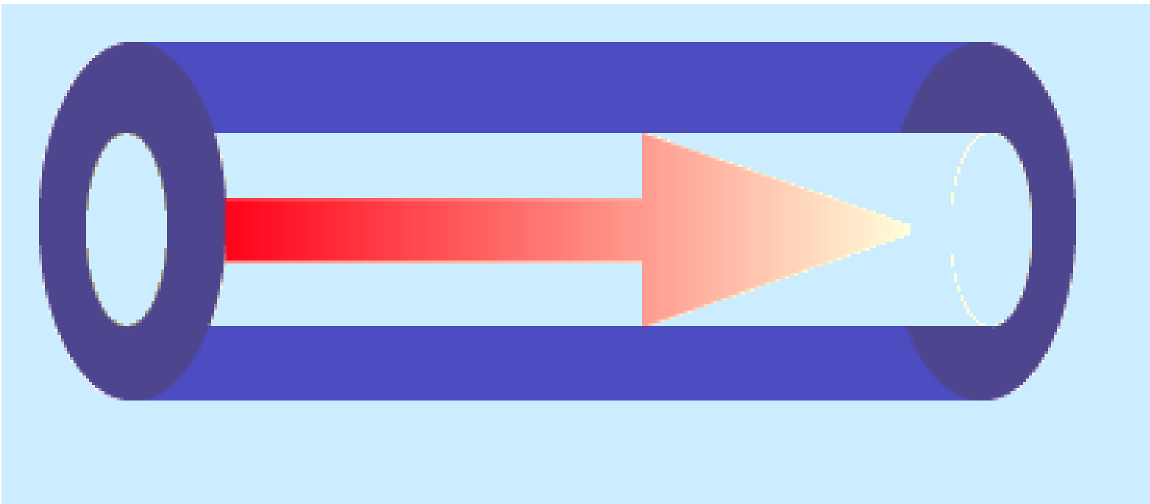
- **Optical attenuation** is the **loss** of signal strength due to transmission along the fiber.
- Attenuation in optical fiber is caused by **intrinsic factors, primarily *scattering* and *absorption*, and by extrinsic factors, including stress from the manufacturing process, the environment, and physical bending.**
- Light can leak from a fiber that is coiled too tightly or kinked
- Microbends inside fiber jacket also cause losses

Absorption

caused by:

- intrinsic properties of the material
- impurities
- atomic defects in the glass

Varies depending on wavelength



peak at 1400 nm due to the OH^- ions in the fiber

Scattering

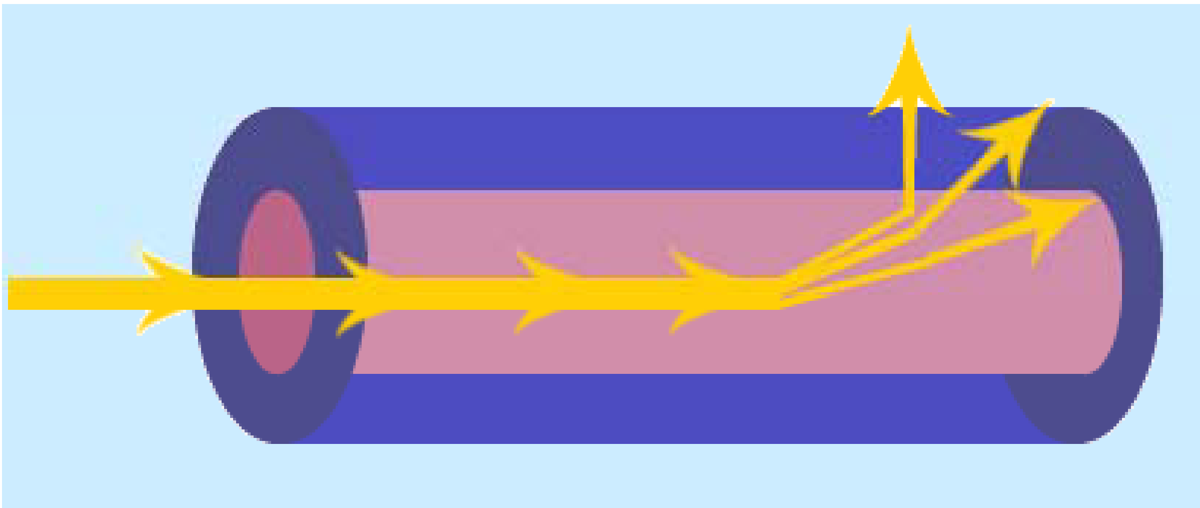
Rayleigh scattering:

- caused by small variations in the density of glass as it cools

Causes a change in direction which usually causes light to escape from the core

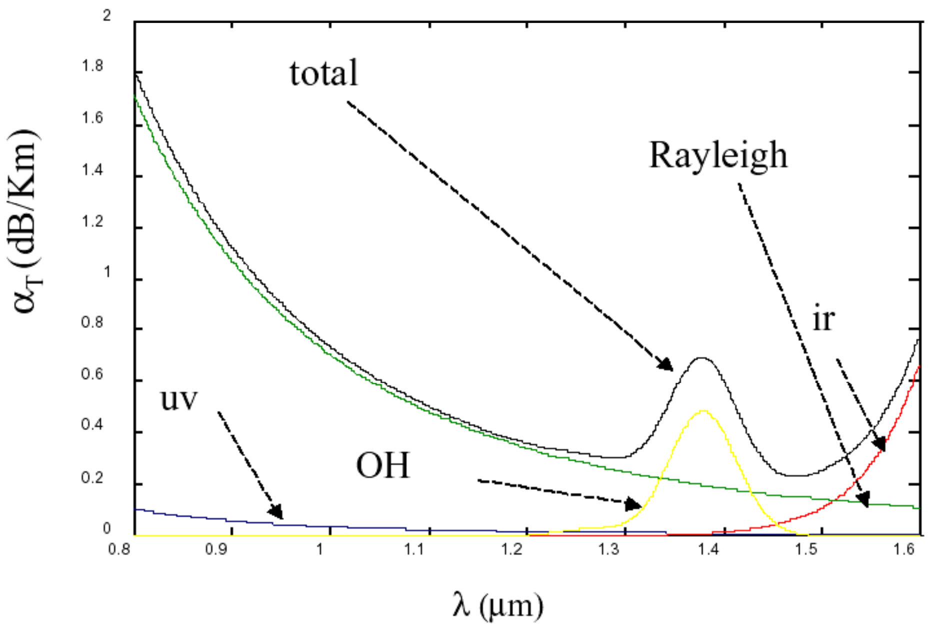
- more scattering at shorter wavelengths

Scattering varies inversely with 4th power of wavelength



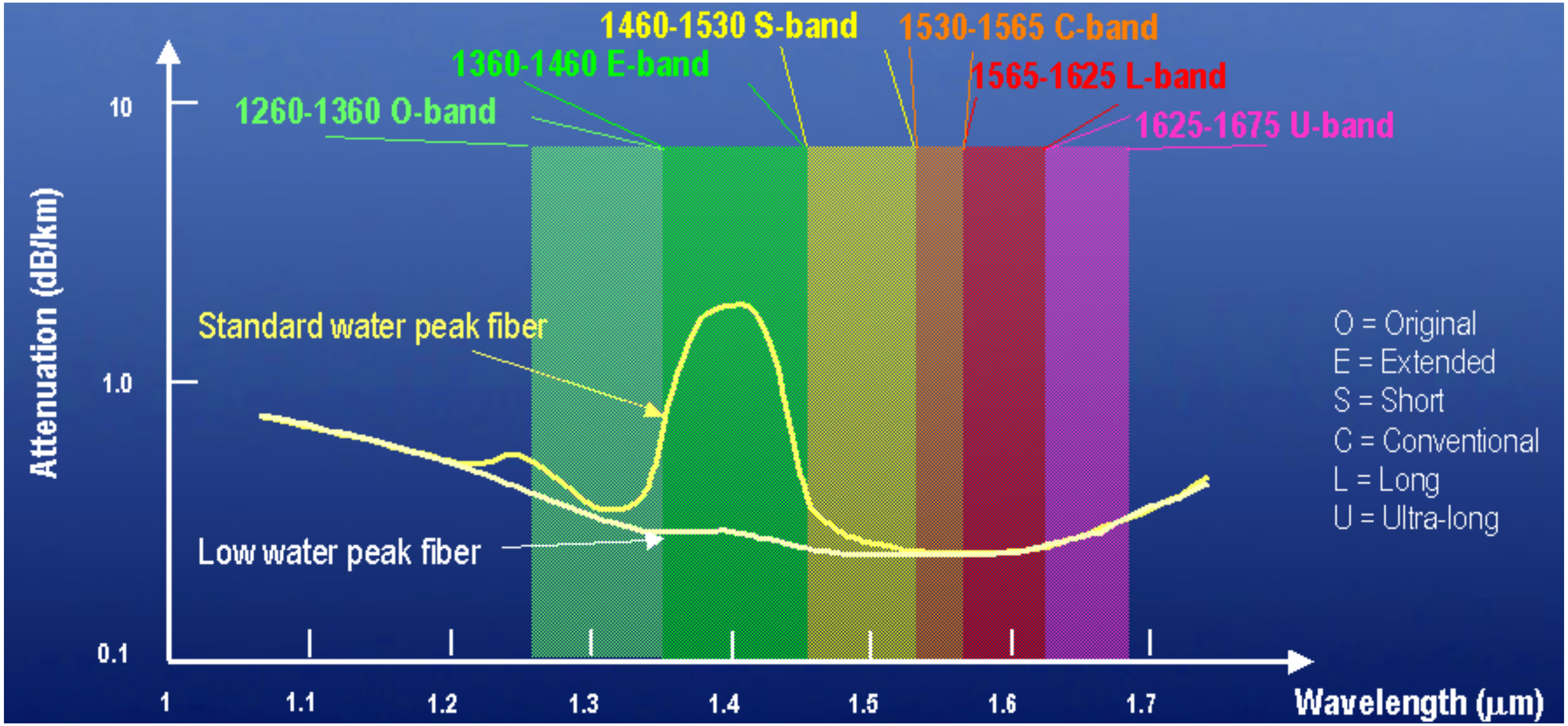
- **Losses due to absorption and scattering add**
- **The primary factors affecting attenuation in optical fibers are the length of the fiber and the wavelength of the light.**

Attenuation profile



$$Loss(dB/unit\ length) = \frac{10\log\left(\frac{P_{in}}{P_{out}}\right)}{L}$$

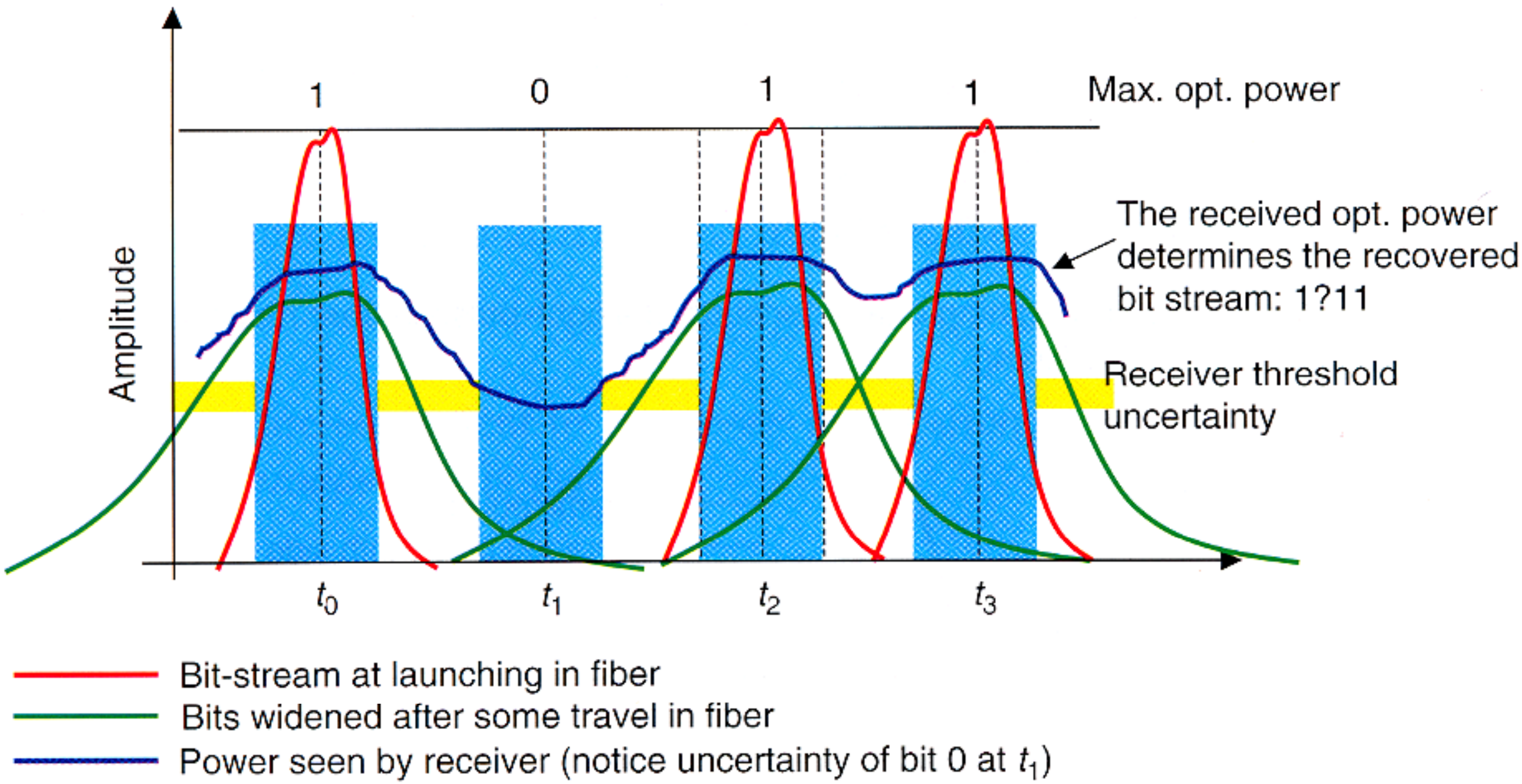
Fiber Bands


1460-1530 S-band
1530-1565 C-band
1360-1460 E-band
1565-1625 L-band
1260-1360 O-band
1625-1675 U-band
10
1.0
0.1
Attenuation (dB/km)
Standard water peak fiber
Low water peak fiber
O = Original
E = Extended
S = Short
C = Conventional
L = Long
U = Ultra-long
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)

Dispersion

- Even, the laser light consists of a range of wavelengths.
- Modulation of the light also increases its bandwidth.
- Different wavelengths propagate at slightly different velocities in a fiber.
- A short pulse will become longer due to pulse spreading (dispersion).
- When dispersion is too large, pulses run together.

- When dispersion is too large, pulses interfere with each other.

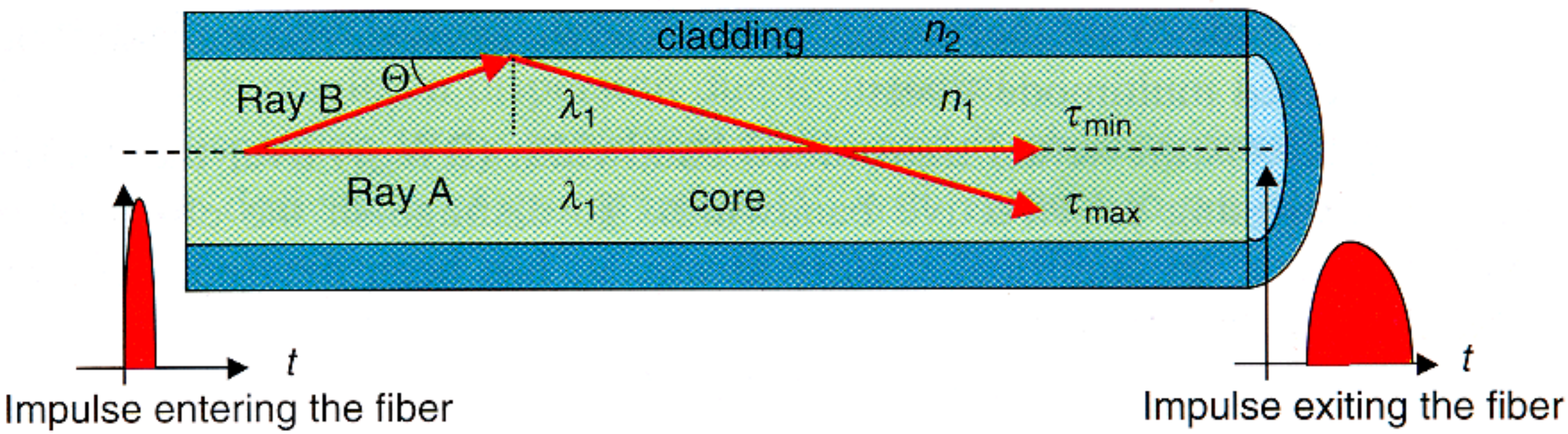


Dispersion Types

- Modal Dispersion
- Chromatic Dispersion
- Polarization Mode Dispersion

Modal Dispersion

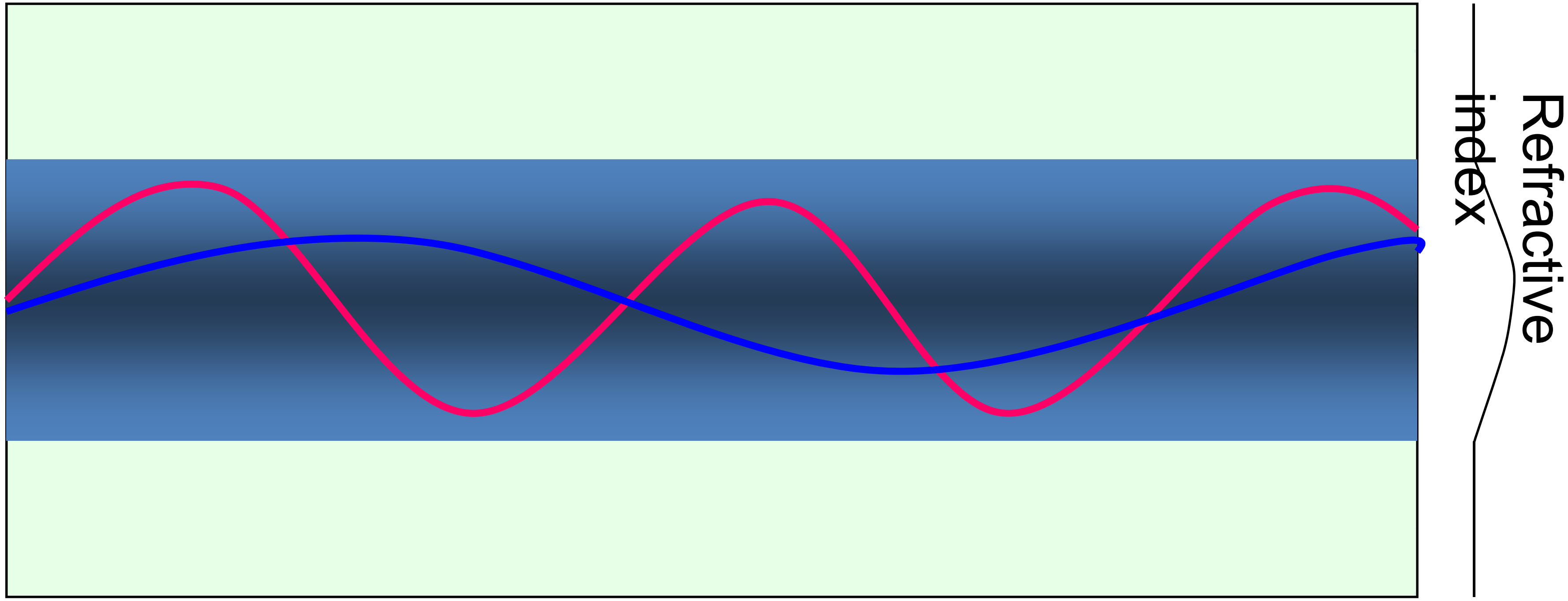
Each ray (mode) travels a different distance, so it arrives at a distant point of the fiber at a different time



Modal Dispersion is zero in Single Mode Fiber

Modal dispersion in Graded-Index Fiber

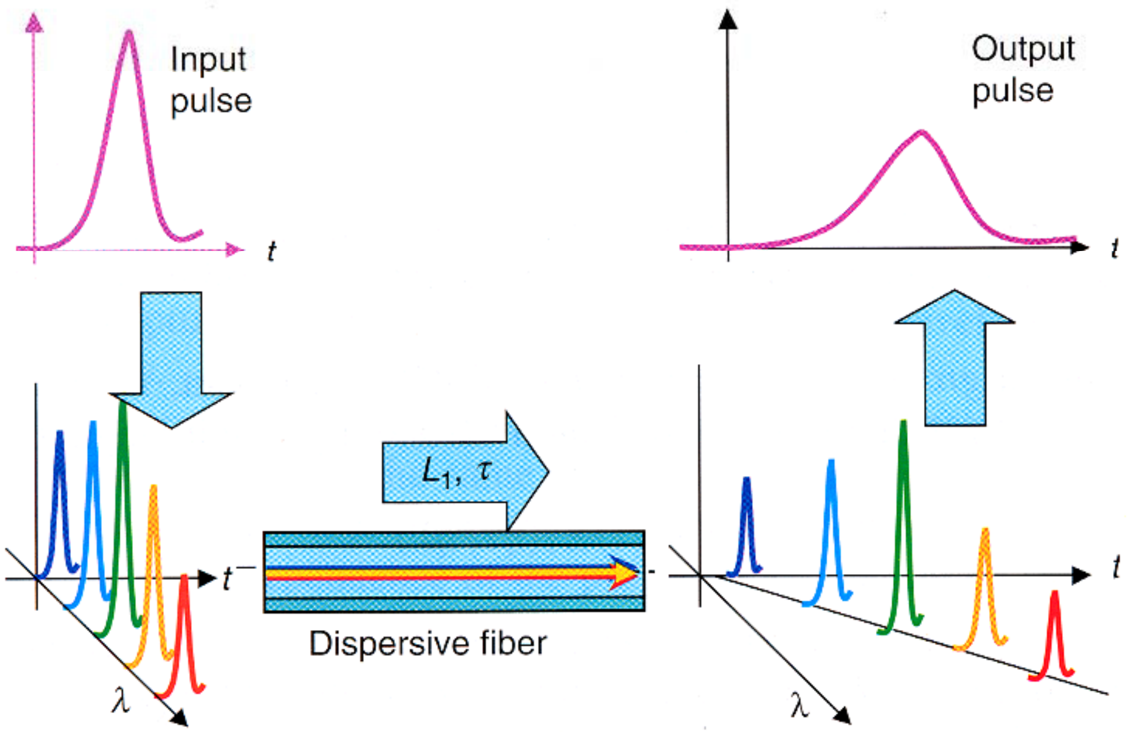
- Velocity is lowest in center of core, highest near its edges.
- The graded index increases the group velocity of higher-order modes, relative to low-order modes, reducing dispersion



Chromatic dispersion

different wavelengths propagate at different Speeds

Chromatic dispesion is measured in ps/nm/Km (picoseconds of dispersion per nanometer of signal bandwidth per kilometer of distance travelled.



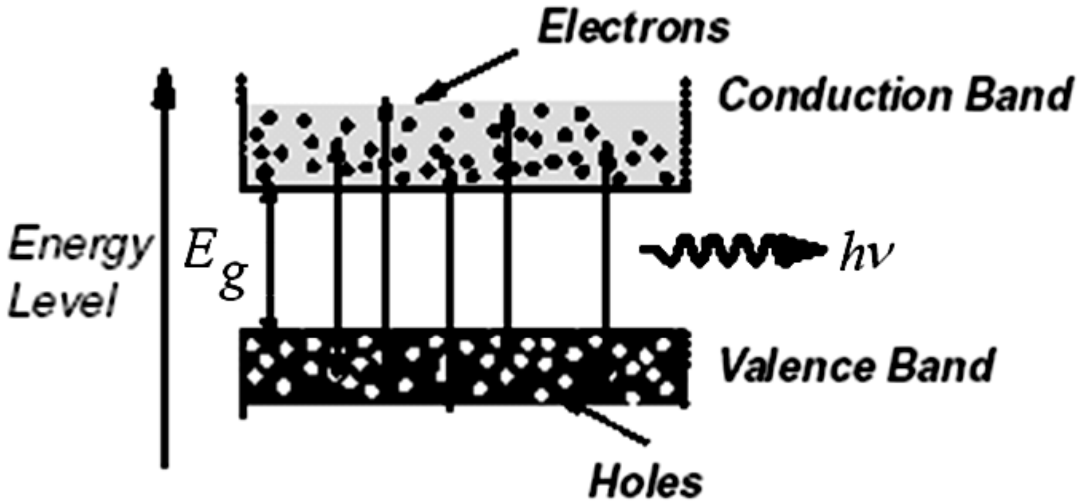
Optical Sources

The optical source converts electrical signal to optical signal.

- There are two kinds of devices that are used as light sources:
  - Light Emitting Diode (LED)
  - Semiconductor Laser

Emission of light: *Spontaneous* and *Stimulated*

- **Spontaneous emission** is really the normal case. When an electron is elevated to a high energy state this state is usually unstable and the electron will spontaneously return to a more stable state very quickly (within a few picoseconds) emitting a photon as it does so. When light is emitted spontaneously its direction and phase will be random and the wavelength will be determined by the amount of energy change



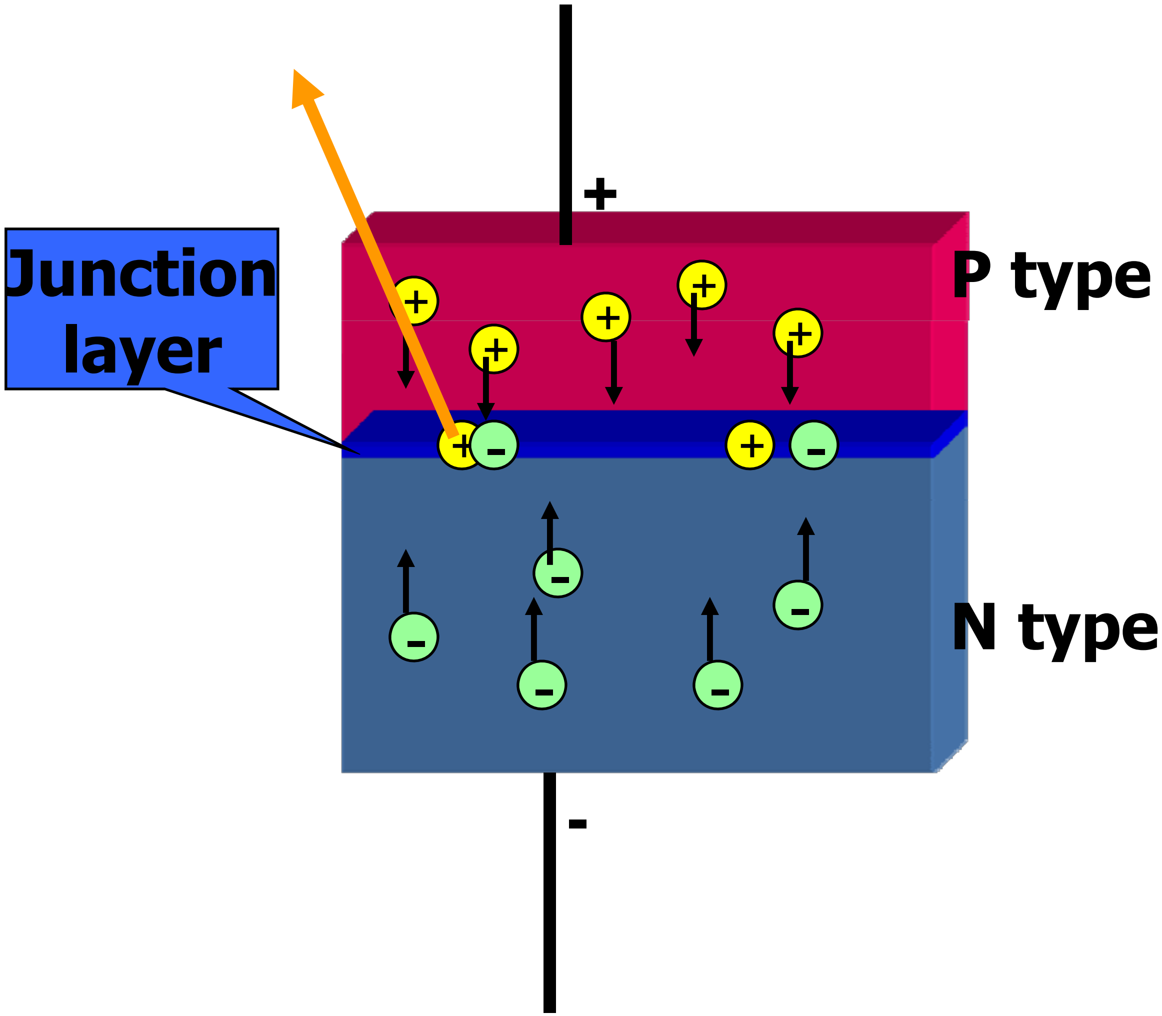
Stimulated emission is what happens in the operation of a laser. In some situations when an electron enters a high energy (excited) state it is able to stay there for a relatively long time (a few microseconds) before it changes state spontaneously. When an electron is in this semi-stable (metastable) high energy state it can be "stimulated" by the presence of a photon of light to emit its energy in the form of another photon. In this case the incident photon must have the right energy (wavelength) within quite small limits.

It is of fundamental importance to understand that **when stimulated emission takes place the emitted photon has exactly the same wavelength, phase and direction as that of the photon which stimulated it.**

For spontaneous or stimulated emission to occur, energy must be supplied to boost the electron from its low energy state to a higher energy state. The energy comes from electric current.

Light Emitting Diode (LED)

- in its most basic form an LED is just a forward biased p-n junction.
- forward bias voltage draws carriers to junction
- recombination produces spontaneous emission


Junction layer
P type
N type
+
-

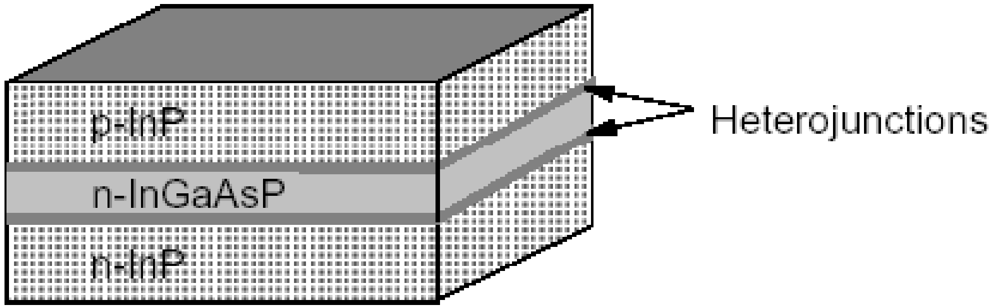
the materials of which the optical source is made determine the wavelength of light emitted.

$$\lambda(\mu\text{m}) = \frac{hc}{E_g} = \frac{1.2399}{E_g(\text{eV})}$$

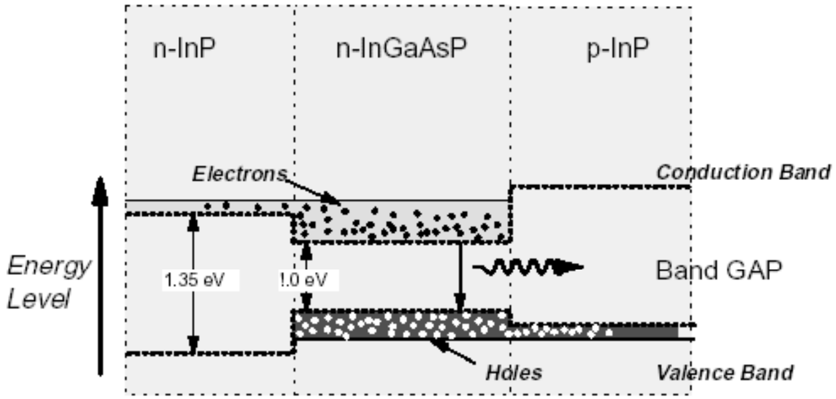
Material	Wavelength Range λ (μm)
InP	0.92
InAs	3.6
GaP	0.56
GaAs	0.87
AlAs	0.59
GaInP	0.64-0.68
AlGaAs	0.8-0.9
InGaAs	1.0-1.3
InGaAsP	0.9-1.7

Heterojunctions (Practical LEDs)

- **When a layer of material with a particular bandgap energy is sandwiched between layers of material with a higher energy bandgap a double heterojunction is formed.**



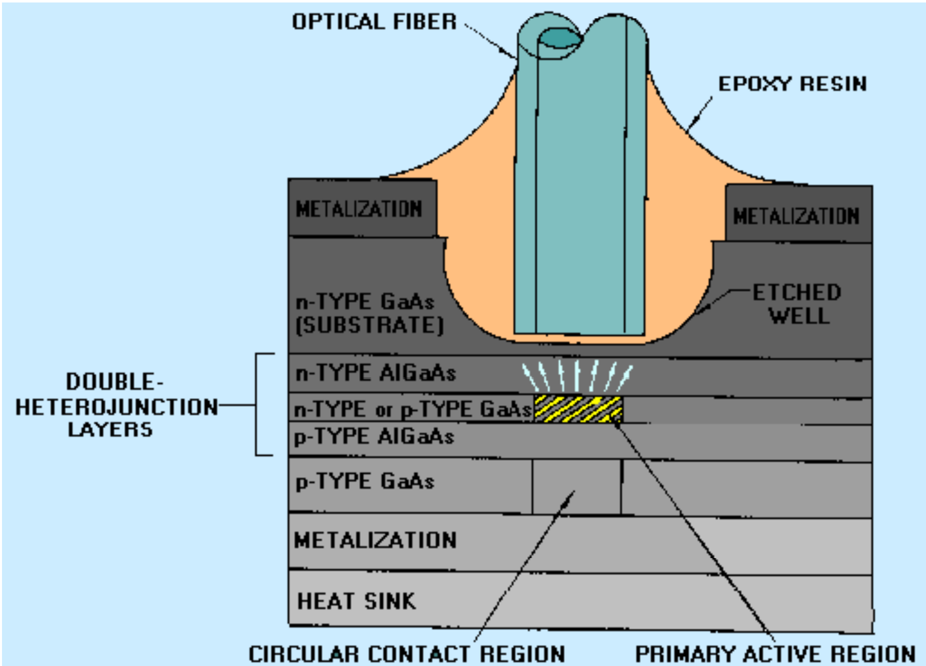
- **The double heterojunction forms a barrier which restricts the region of electron-hole recombination to the lower bandgap material. This region is then called the "active" region.**
- **Recombination takes place in the n-InGaAsP and spontaneous emission occurs.**



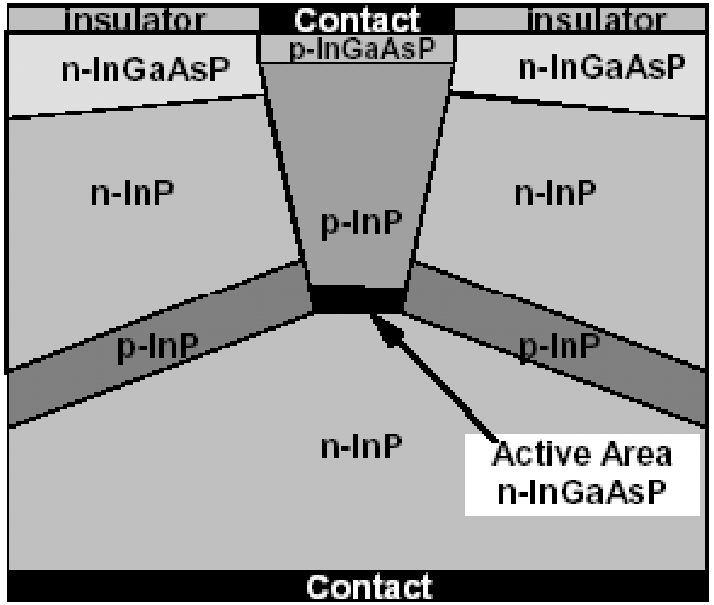
the material in the active region has a higher refractive index than that of the material surrounding it. This means that a mirror surface effect is created at the junction which helps to confine and direct the light emitted.

LED Structures

- **Surface-Emitting (Burrus)**



Edge-Emitting LED

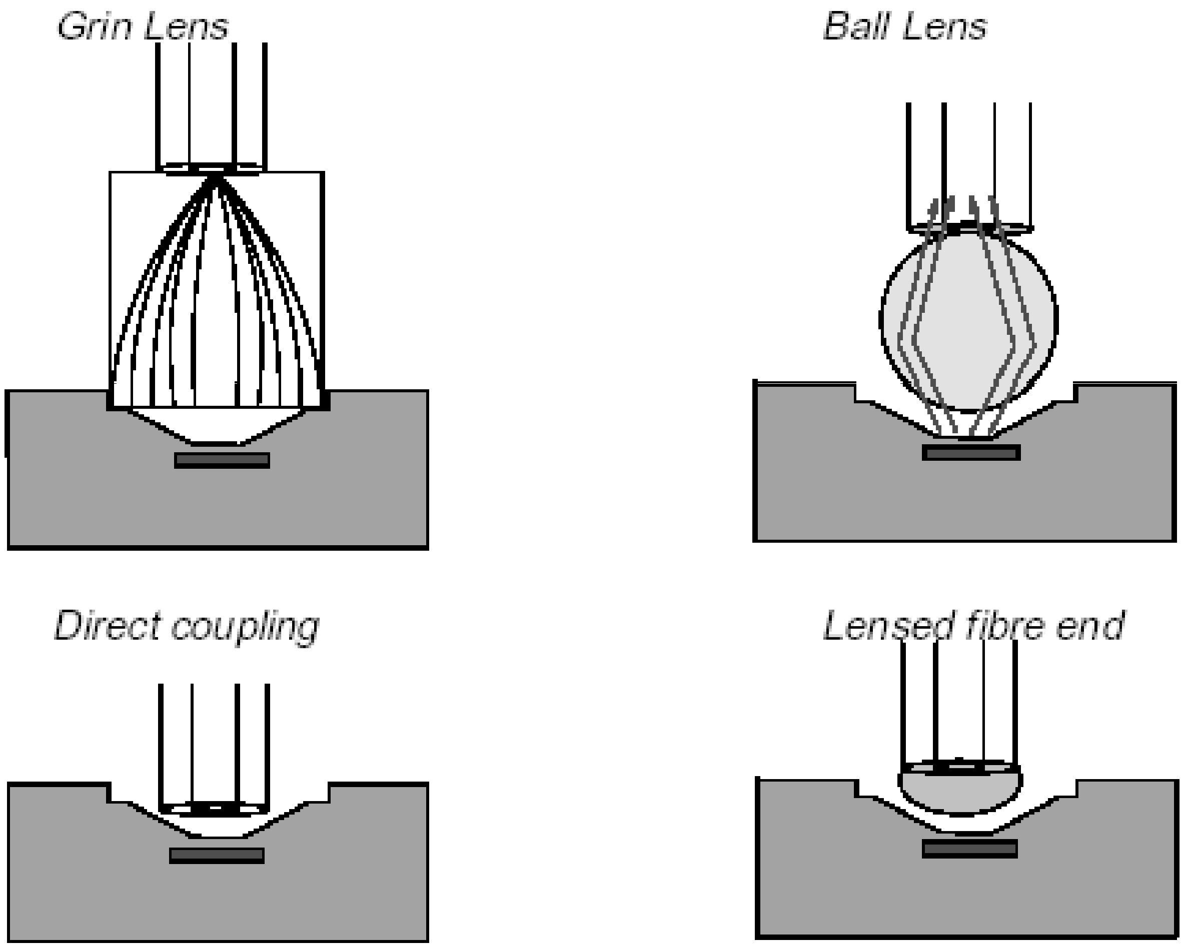


In both types of LED a combination of insulating materials and junctions is used to:

1. Guide the current flow to a small "active region" and

2. Guide the light produced out of the device and into an easy position for coupling to a fibre.

Coupling to Fiber



- **Light-Emitting Diode (LED) characteristics**

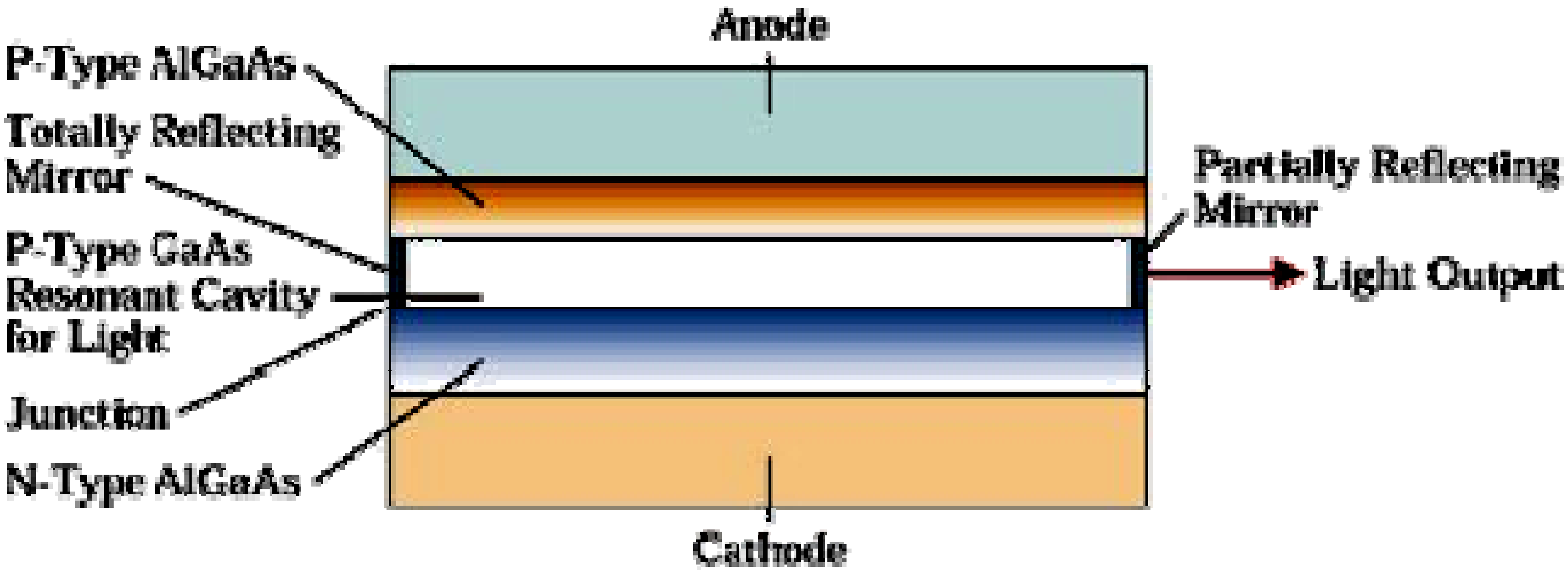
  - **Low cost.**
  - **Low power (microwatts).**
  - **Large linewidth (around 30-50 nm).**
  - **Incoherent light.**
  - **Low modulation speed (<300Mbps).**

Semiconductor laser Types

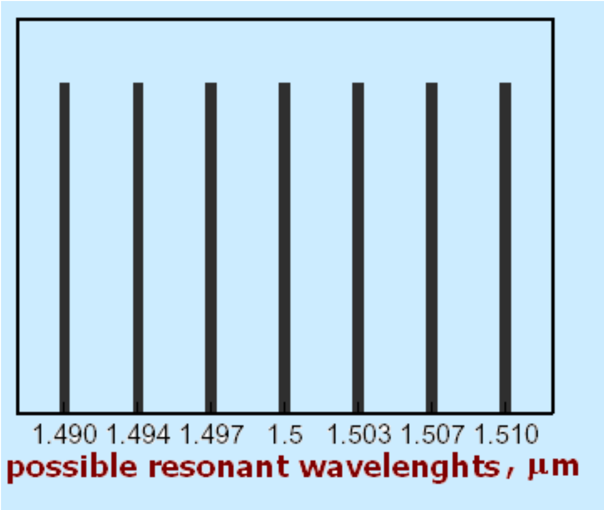
- Fixed wavelength
- Multi-wavelength
    - Laser array
    - tunable laser

Fabry-Perot (FP)

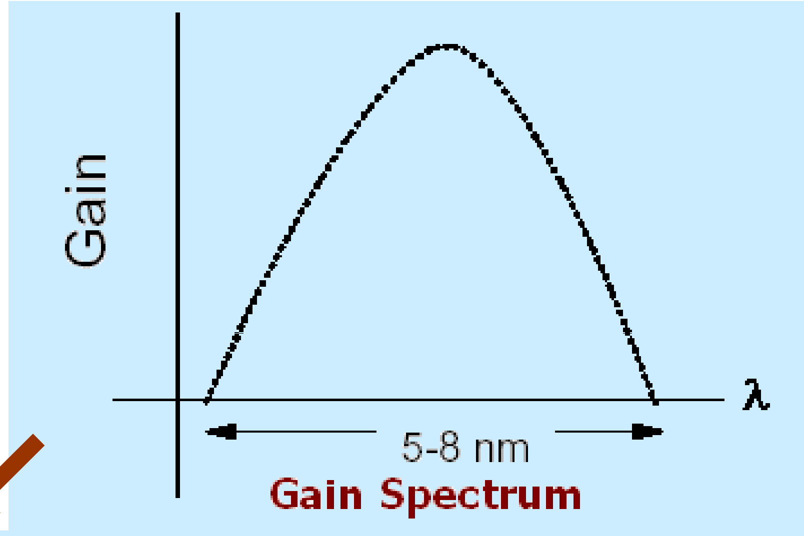
- **The most common communication laser.**
- **The Fabry-Perot laser is conceptually just an LED with a pair of end mirrors.**

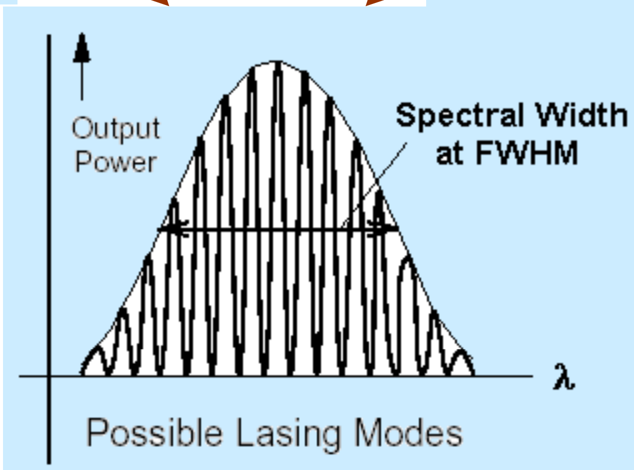


When the graph of possible resonant wavelengths combines with the amplifying characteristics of the device we get a pattern of possible modes.



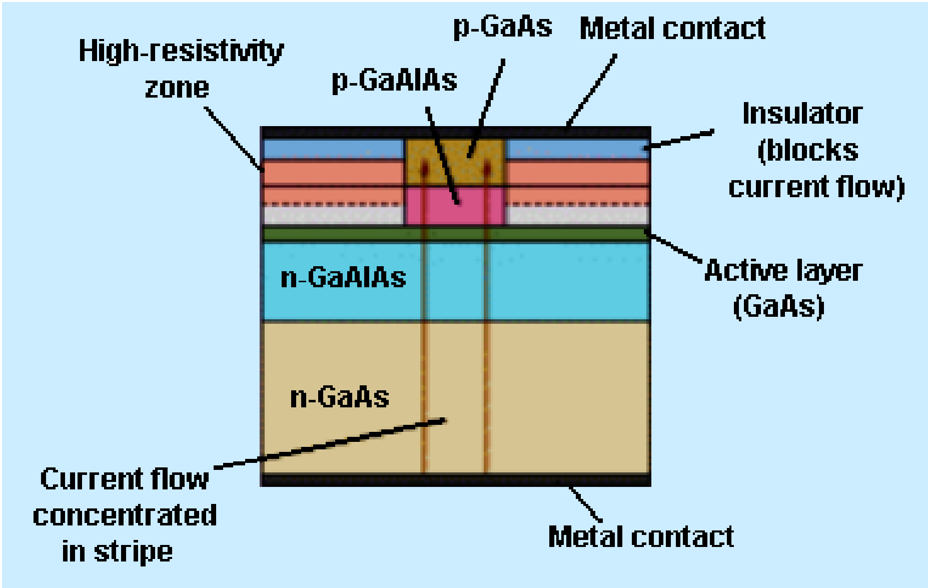
$$nL = \frac{m\lambda}{2}$$





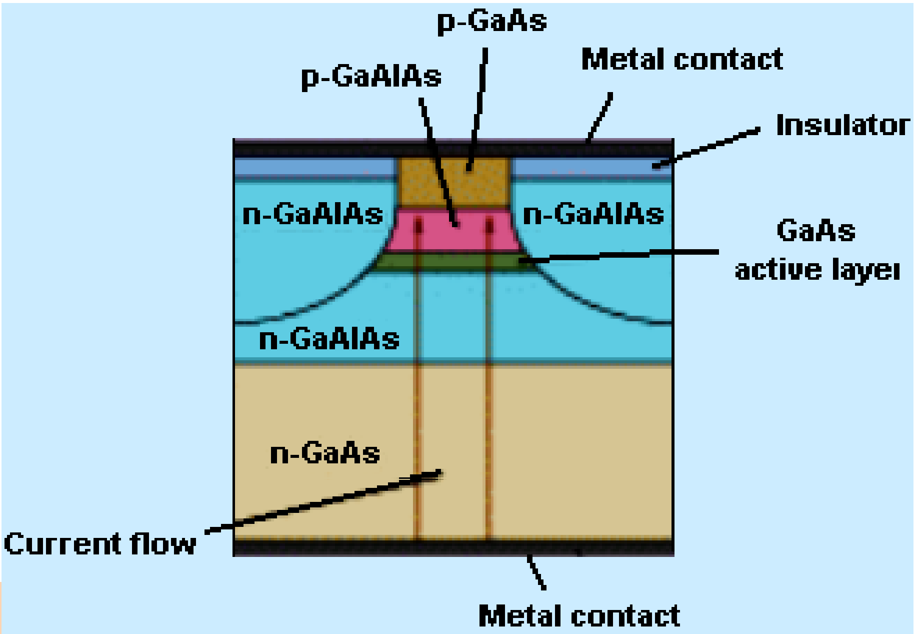
- Gain-Guided

- The typical technique used to guide power into the active region is to limit the area of electrical contact on the surface of the device.
- Gain guided FP lasers produce a spectral width of between 5 nm and 8 nm consisting of between 8 and 20 or so lines. Linewidth is typically around .005 nm.



- Index-Guided

- **Gain guidance can be further improved if we put layers of semiconductor material with a high bandgap energy (lower refractive index) around the active region.**
- **Index guided FP lasers produce a spectral width of between 1 nm and 3 nm with usually between 1 and 5 lines. Linewidth is generally around .001 nm. (Much better than the gain guided case).**



Fabry-Perot lasers have relatively wide spectral width and not suitable for :

- **extended distances**
- **wavelength multiplexing**

Therefore:

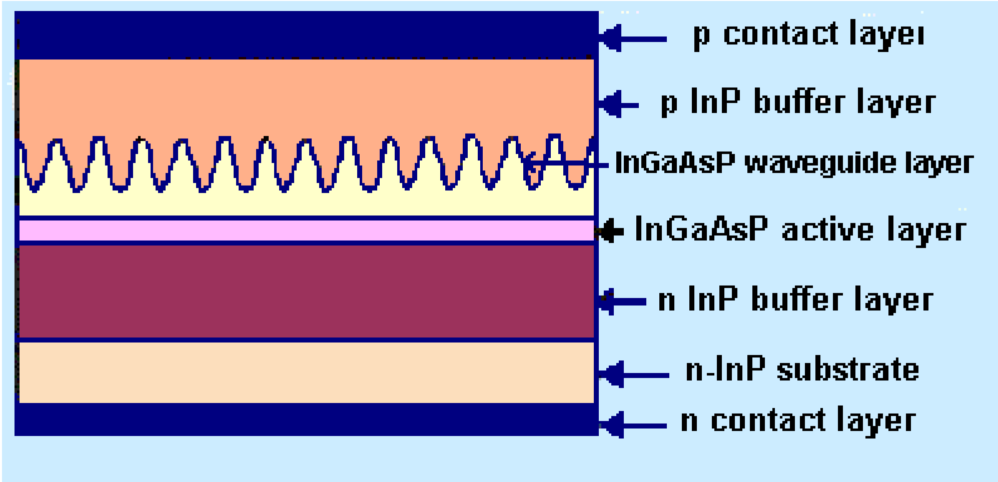
modification by placing a diffraction grating within the cavity.

Grating acts as a wavelength selective mirror.

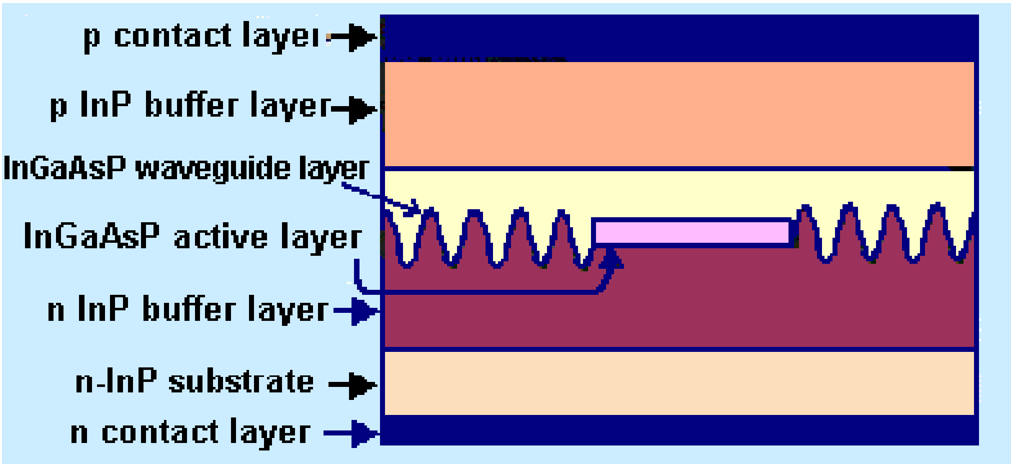
→ DFB & DBR lasers

narrow spectral linewidth, typically 0.2 to 0.3 nm.

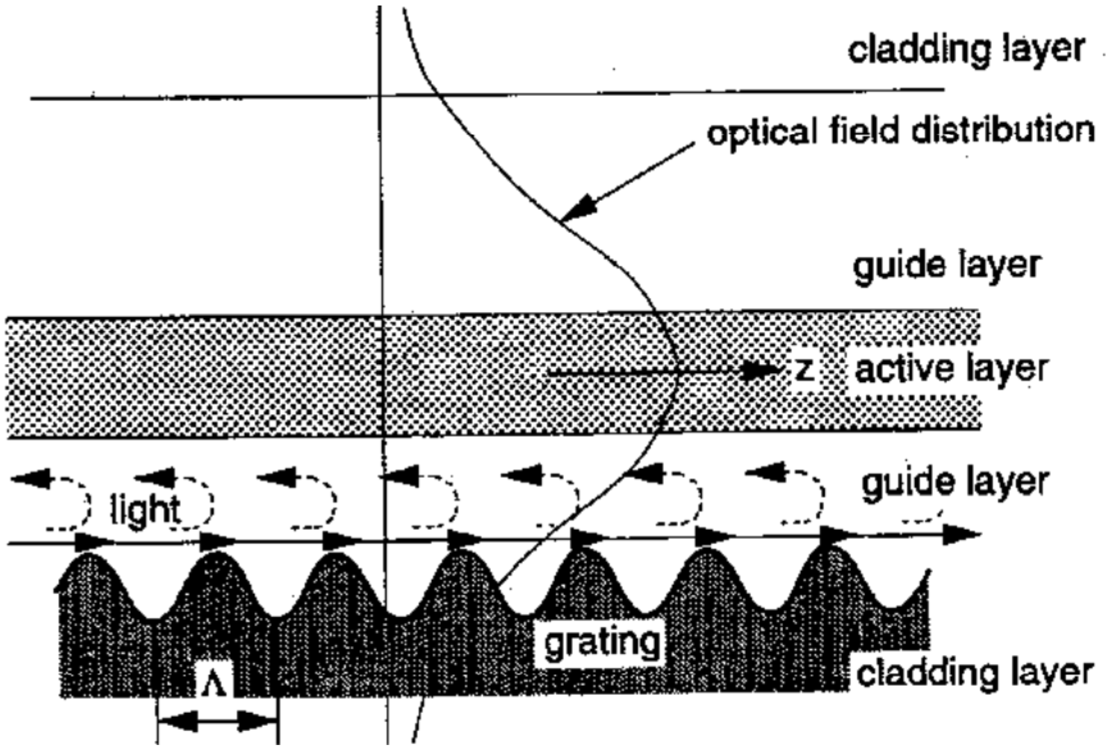
Distributed Feedback Laser (DFB)



Distributed Bragg Reflector (DBR)

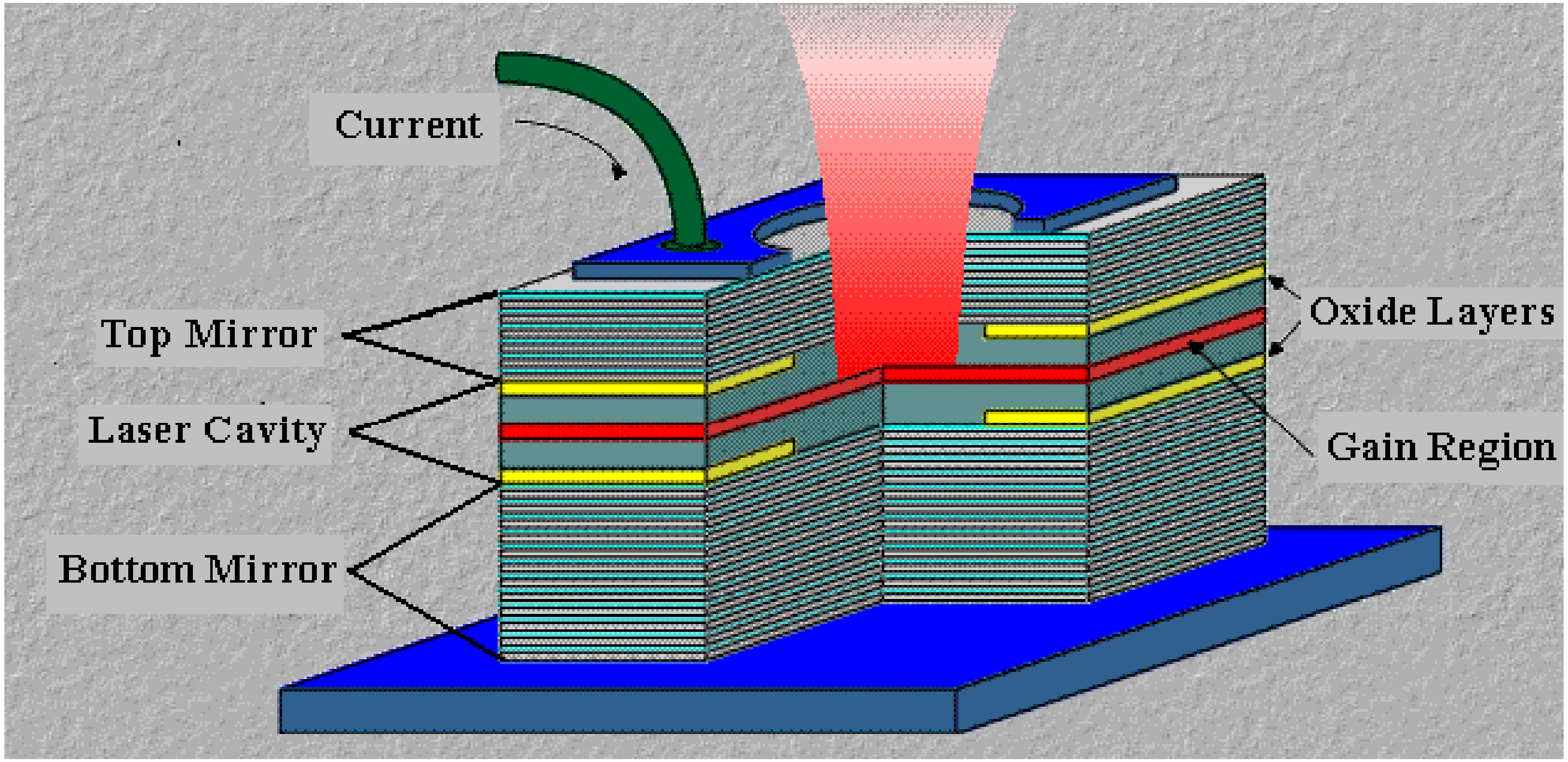


In DFB and DBR lasers, for wavelenghts close to the Bragg wavelength the reflections from the individual parts of grating are in phase and constructive interference occures.



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

Vertical-Cavity Surface-Emitting Laser (VCSEL)



The mirrors are made of alternating layers of material of different refractive indices

The stack forms a Bragg grating which is a wavelength-selective mirror.

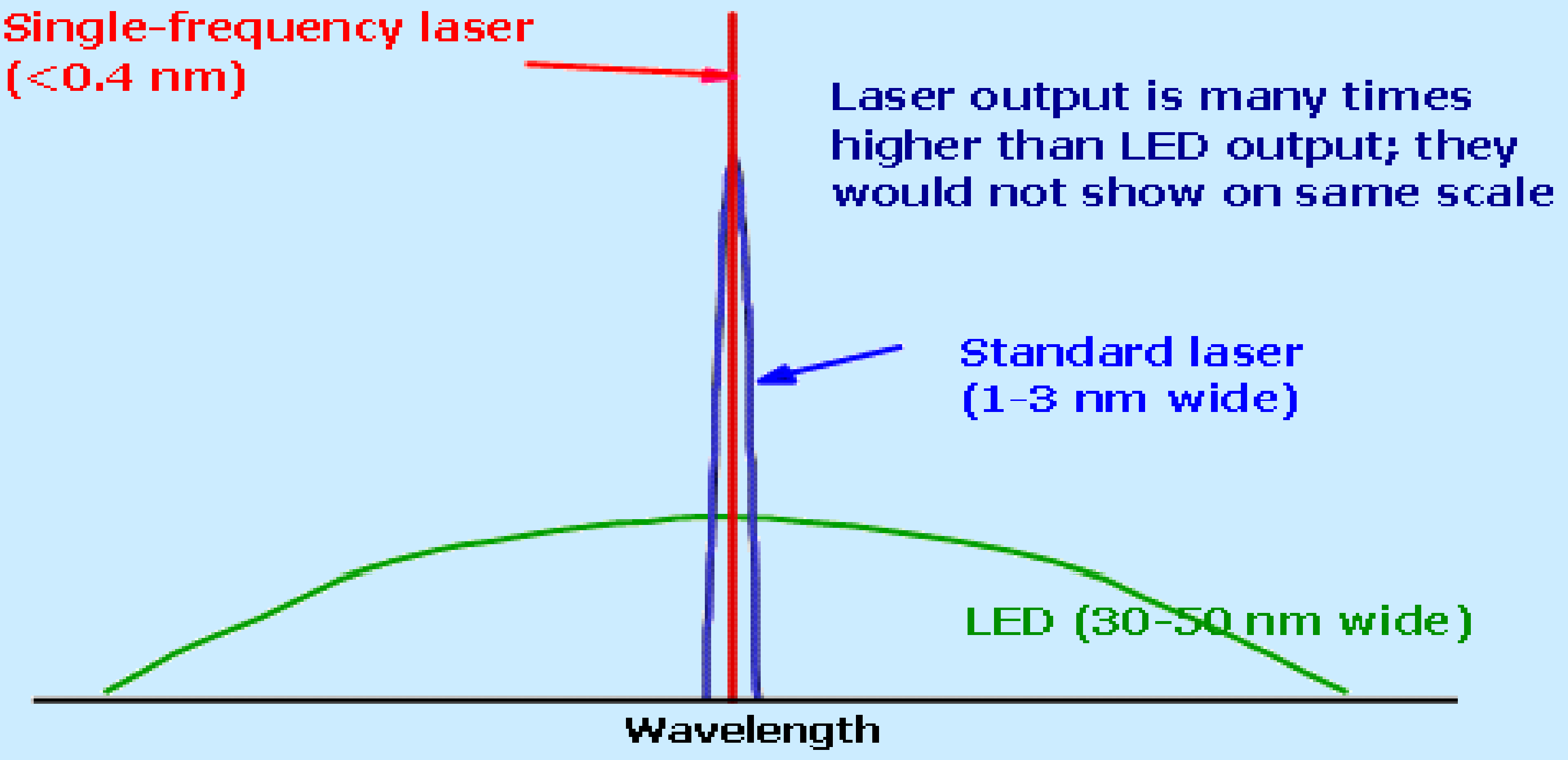
New low-cost design.

Can be used instead of LED with multimode fiber.

Used in fiber LANs.

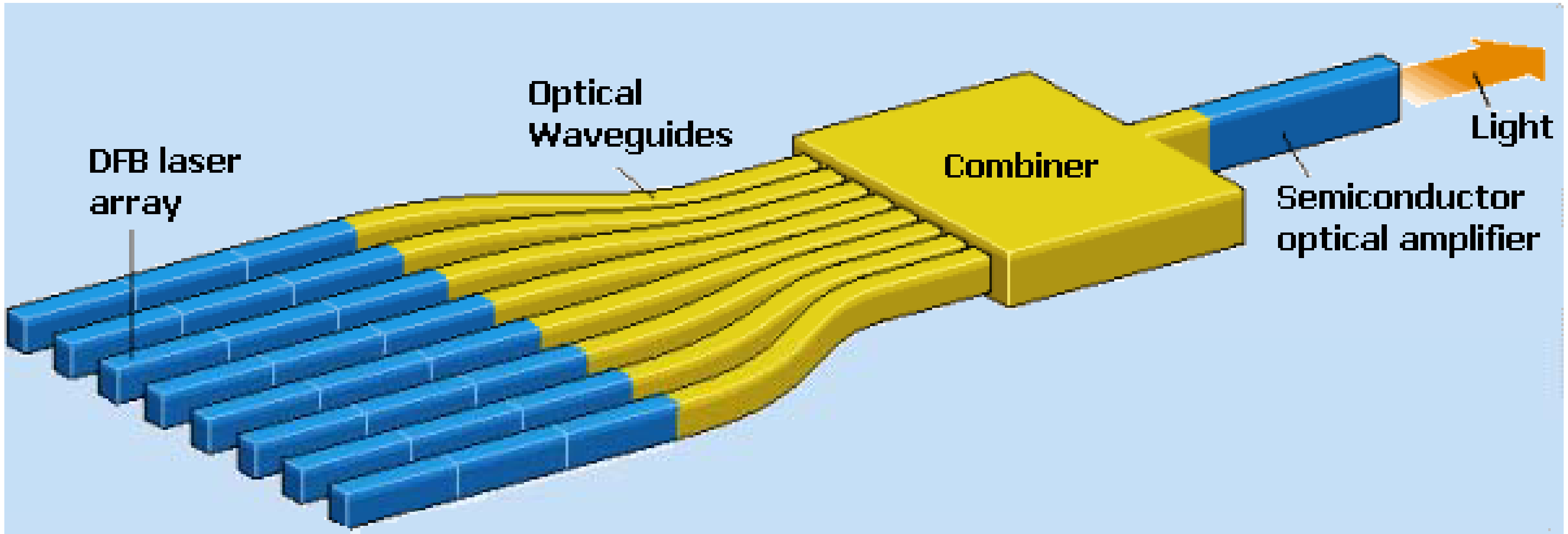
Use GaAs, emit about 750-1000nm.

LED vs. laser spectral width



Multi-wavelength lasers

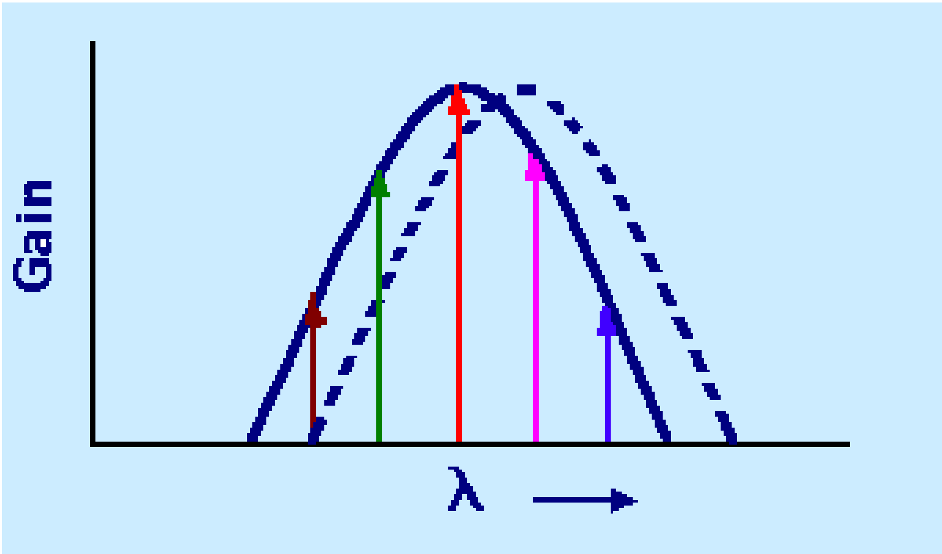
a) Laser Arrays



b) Tunable Lasers

- External Cavity tunable lasers
- Monolithic Integrated Tunable Lasers

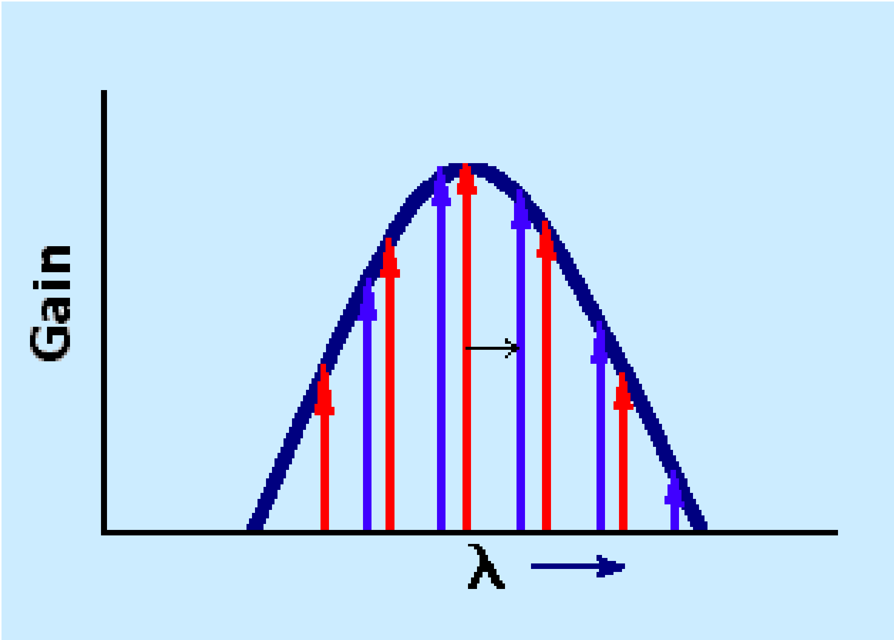
- **Tuning the laser wavelength:**
- **Changing the cavity gain characteristics**



-Varying the wavelength dependence of the active medium gain

-Using laser mirrors with a tunable wavelength-selective mirror loss

Shifting the comb-mode spectrum



- Changing the optical length of the laser cavity

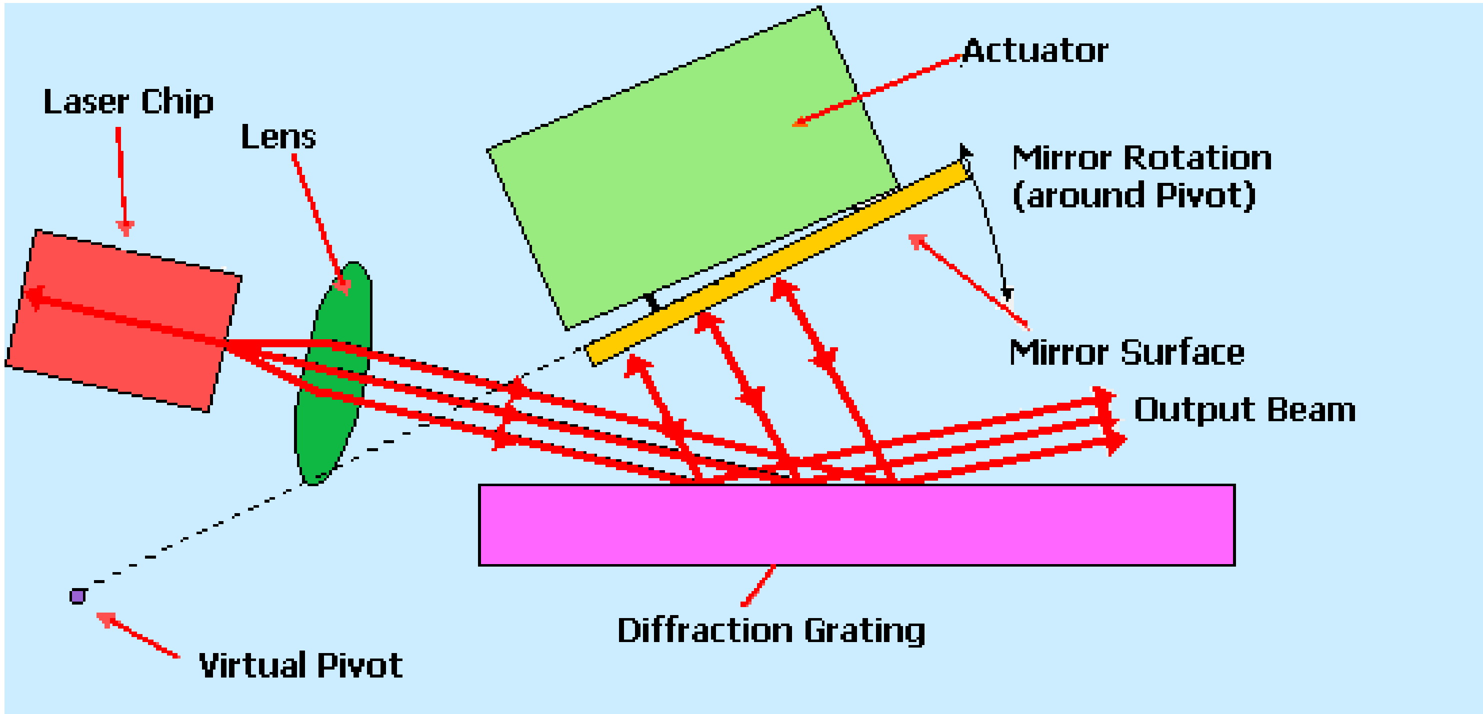
$$n'_{eff} L$$

- **Simultaneous variation of both parameters**

- External Cavity tunable lasers

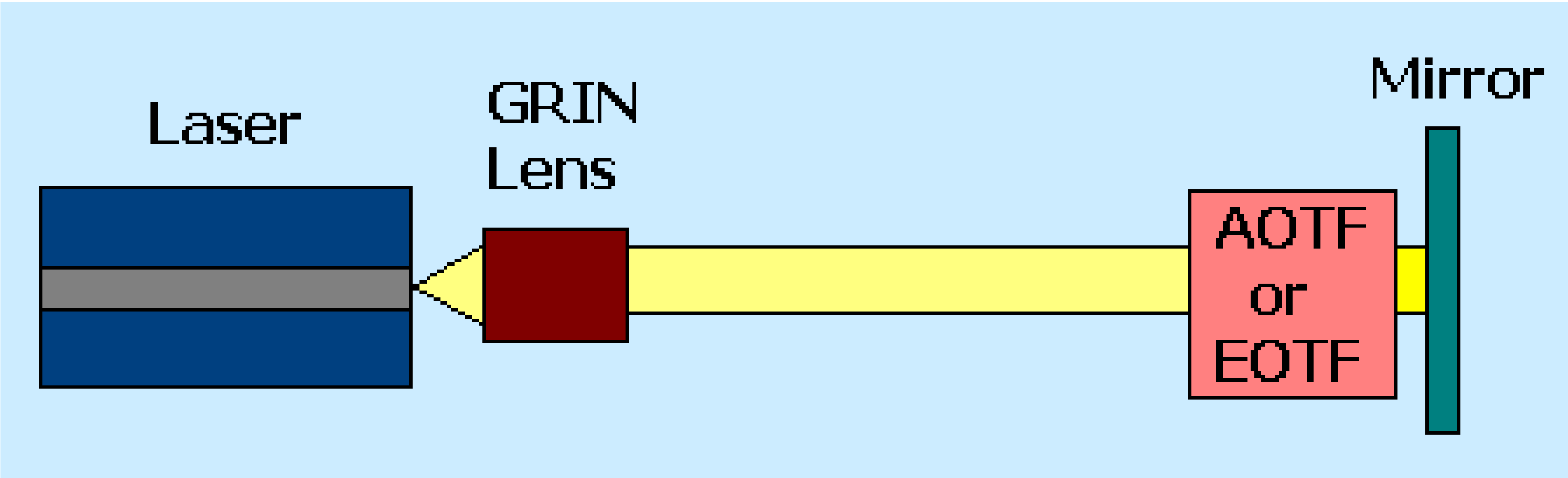
1-Micro-Electro-Mechanical Systems: MEMS

Wavelength tuning is achieved by applying a voltage to the MEMS actuator, which rotates the mirror to allow a particular diffracted wavelength to couple back into the laser diode.

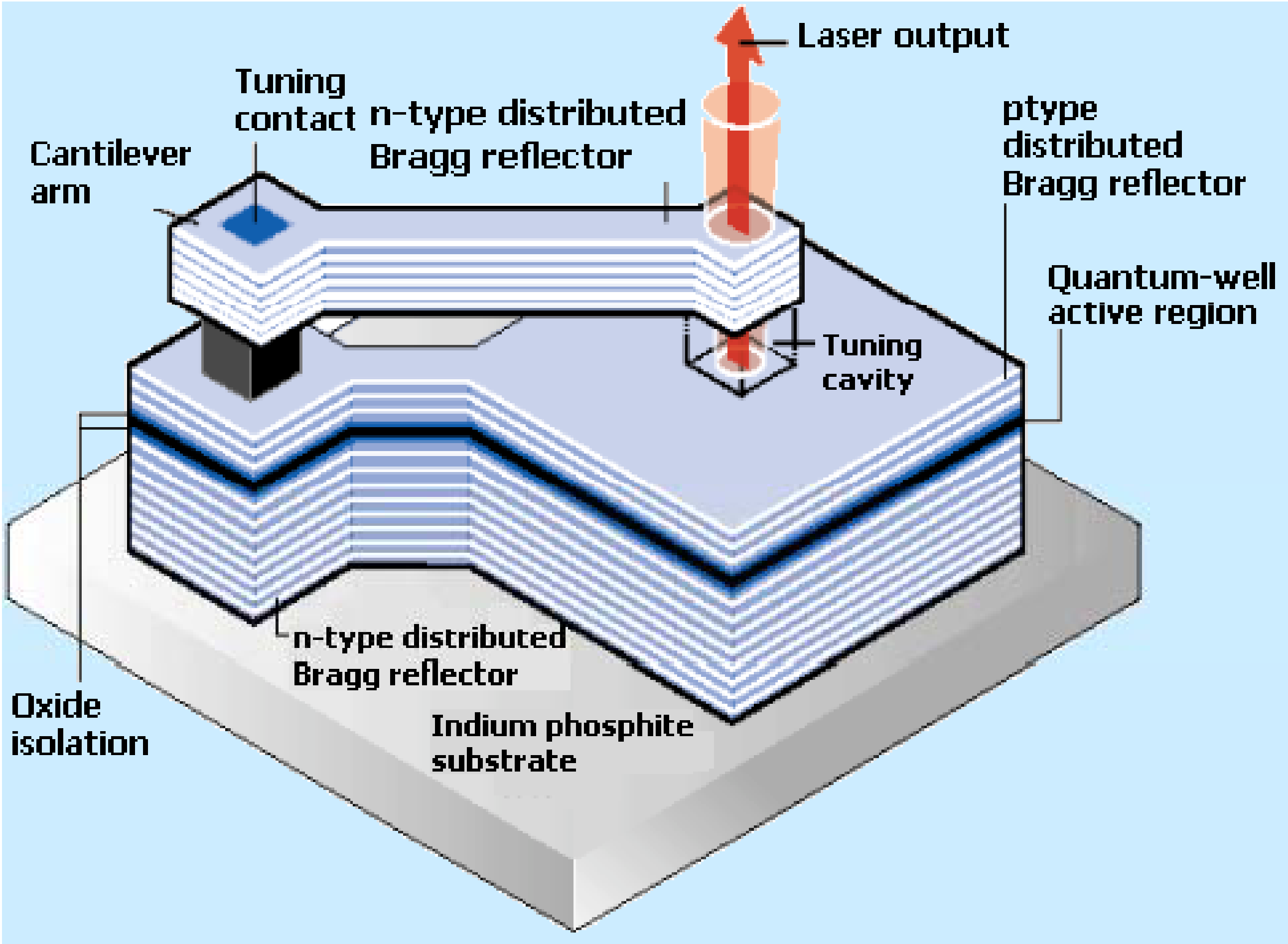


2-Acousto-Optically(AO) and Electro-optically (EO) tunable laser

the tunable filter (AO or EO) determines the wavelength that is reflected back to laser diode

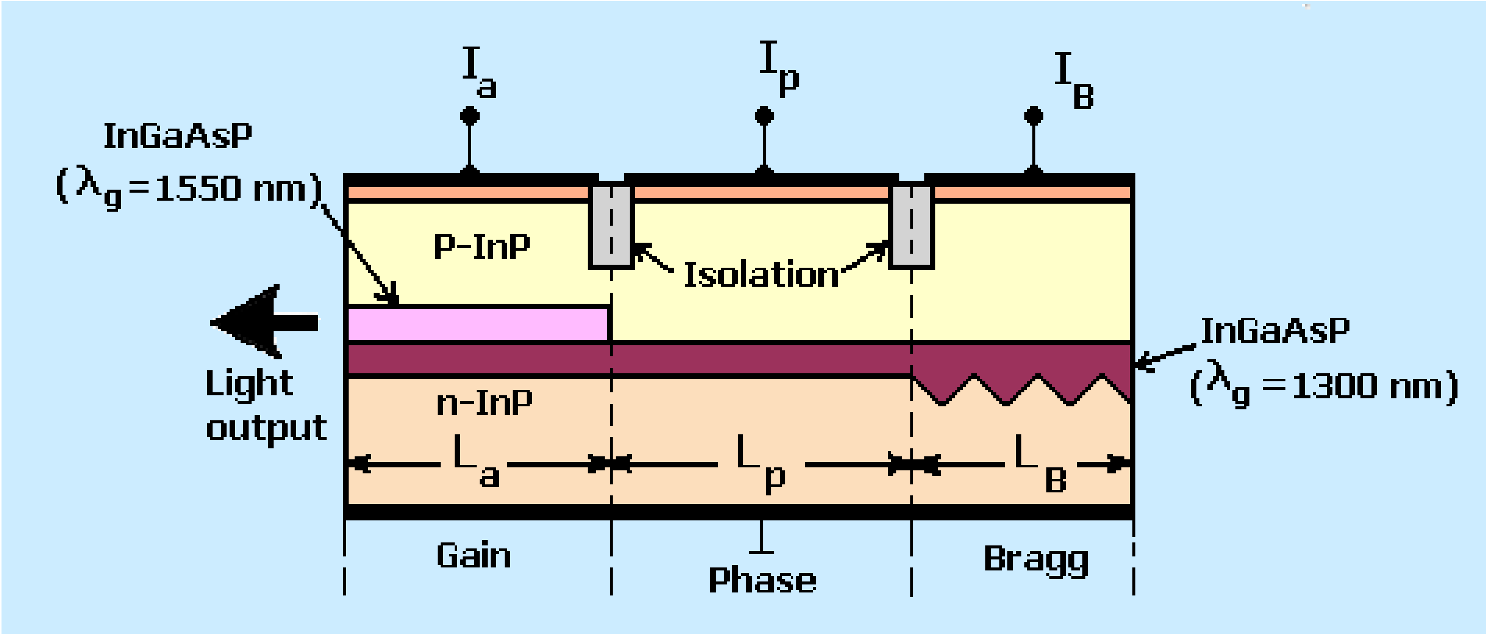


3- Vertical Cavity Surface Emitting Laser (VCSEL)



- Monolithic Integrated Tunable Lasers

1-three-section DBR laser

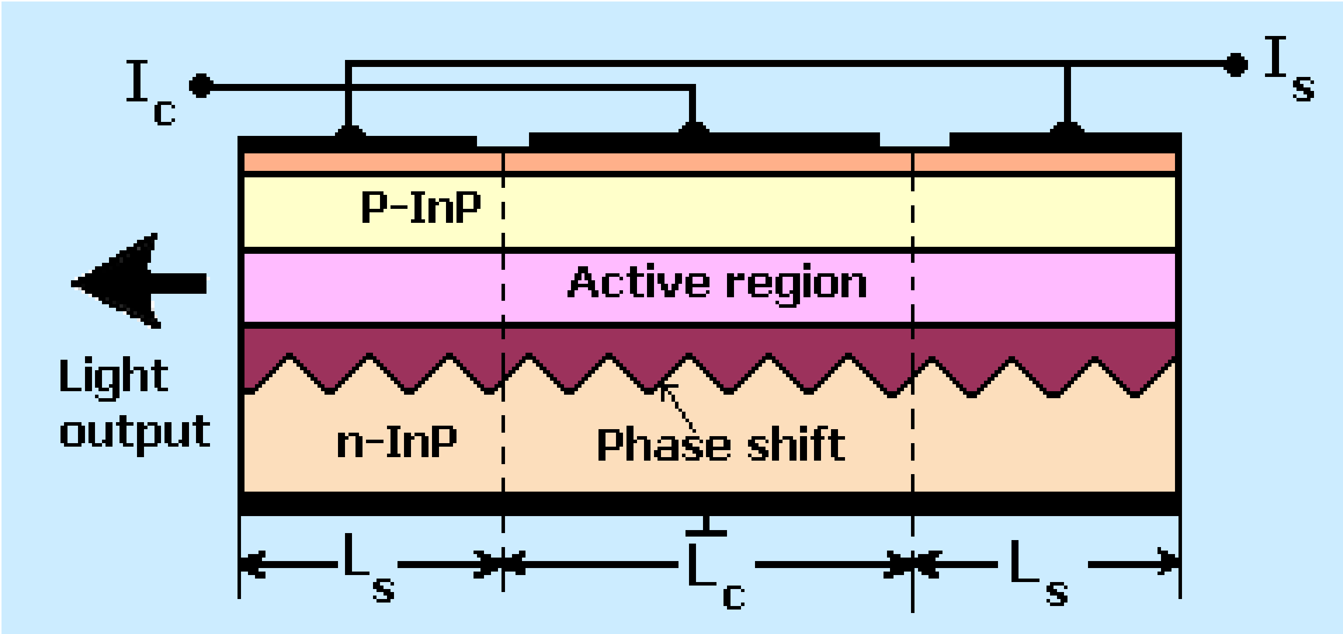


I_a , optical gain

I_p , location of comb-mode spectrum

I_B, Cavity gain peak wavelength(Bragg wavelength)

2-three-section DFB Lasers



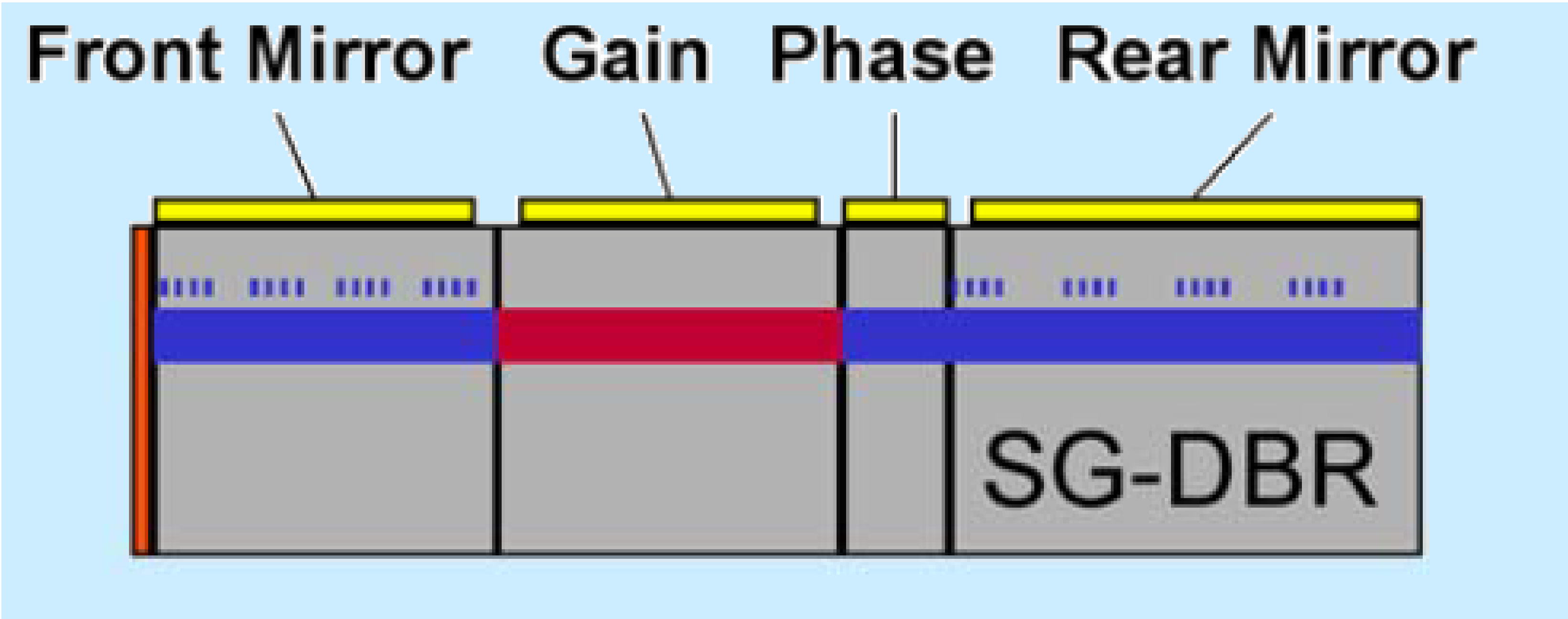
I_s , optical gain (higher than threshold current)

I_c , tuning current that is a little less than or equal to threshold current)

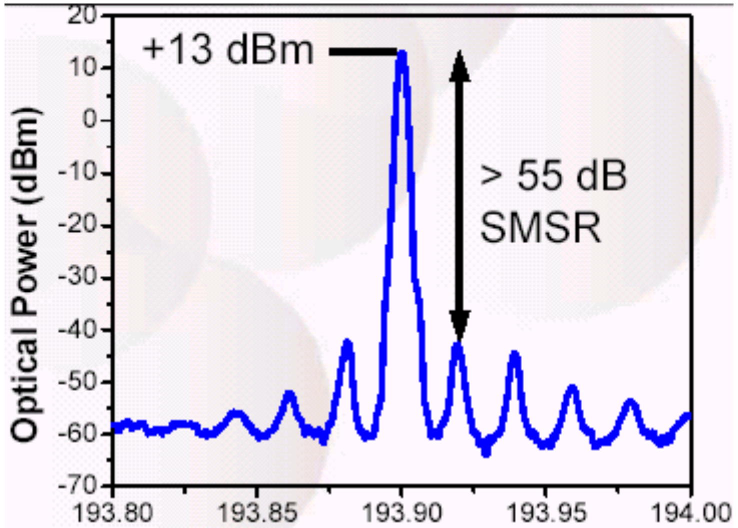
By: Dr. Jabbari

3- Sampled Grating-DBR (SG-DBR)

- In the gain section, current injection controls output power.
- In the front and rear mirror sections, injected carriers induce a change in refractive index which tunes the lasing wavelength through shifts in DBR reflectance spectra.
- phase section tunes cavity modes



important characteristics



Fixed wavelength lasers

- Operating wavelength
- Linewidth
- Output power
- Side Mode Suppression Ratio (SMSR)

Tunable lasers

- Tuning range
- Tuning speed

Start

Phenomenal
Rate Equation with gain

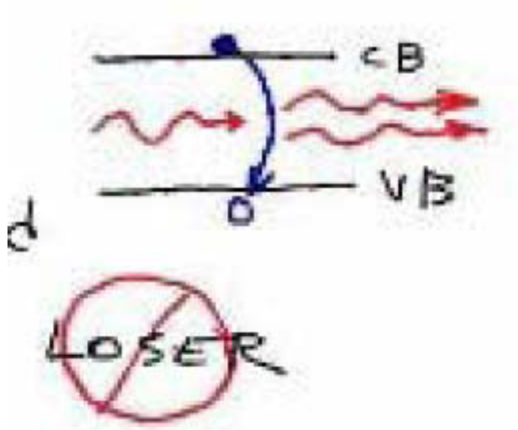
Fundamentals of the
Quantum Theory and the Solid State(QM)

Quantum Mechanics
described the gain media

Quantum Mechanics
Described Electromagnetic Equations

Applications such as LED Laser and so on

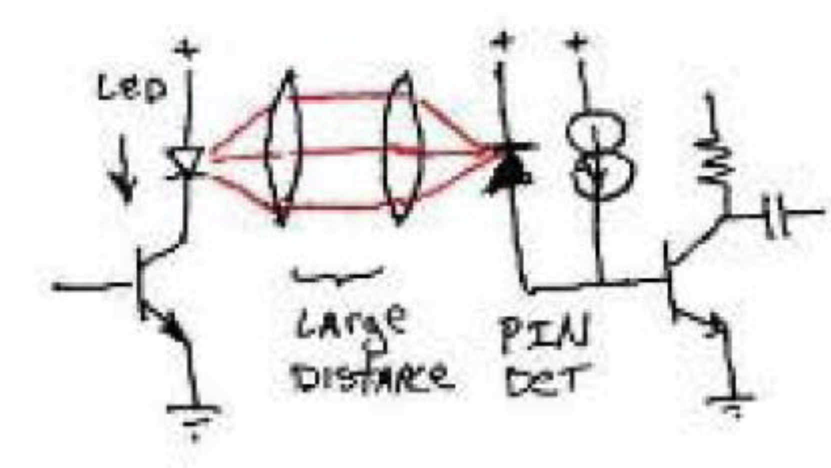
Laser: **light amplification by stimulated emission of radiation**



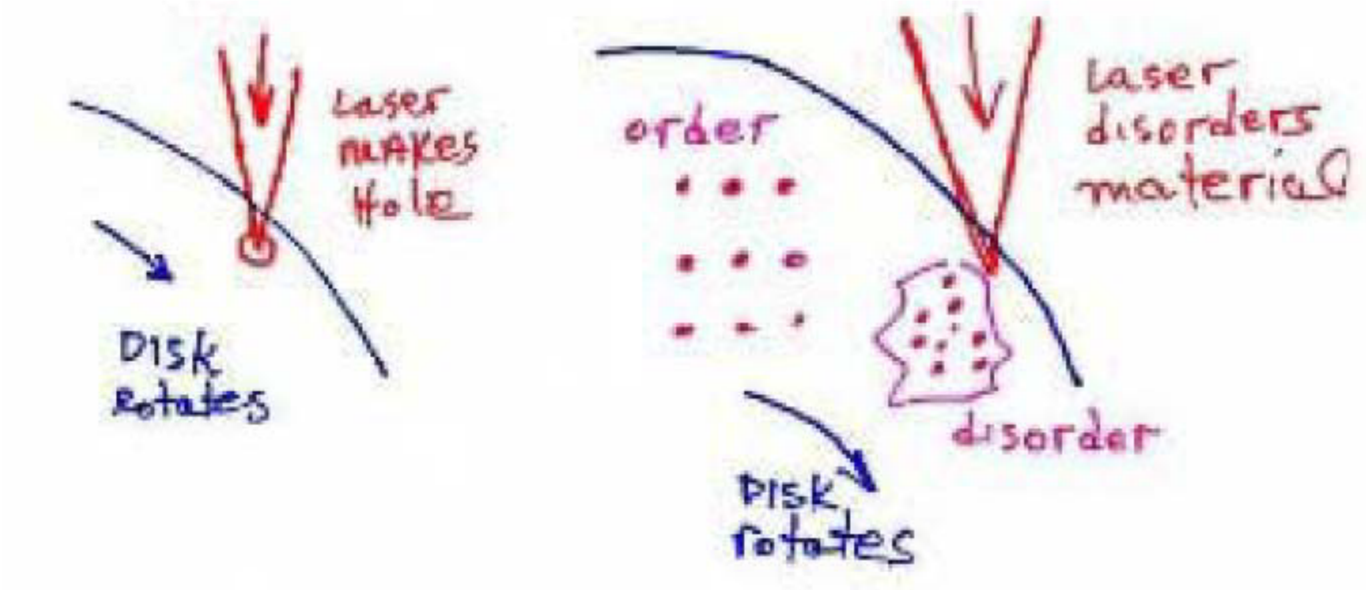
A name briefly considered light oscillator
By stimulated emission of radiation

Application:

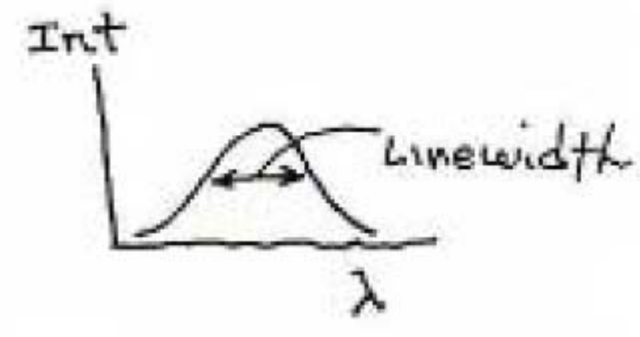
Communication Internet

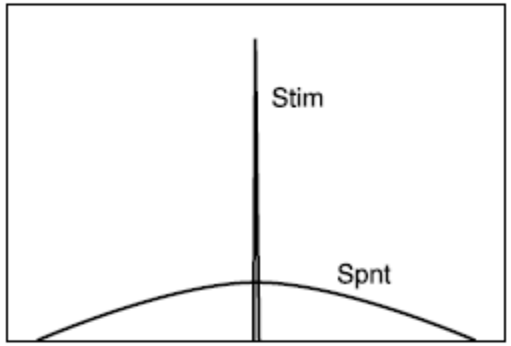


Memory



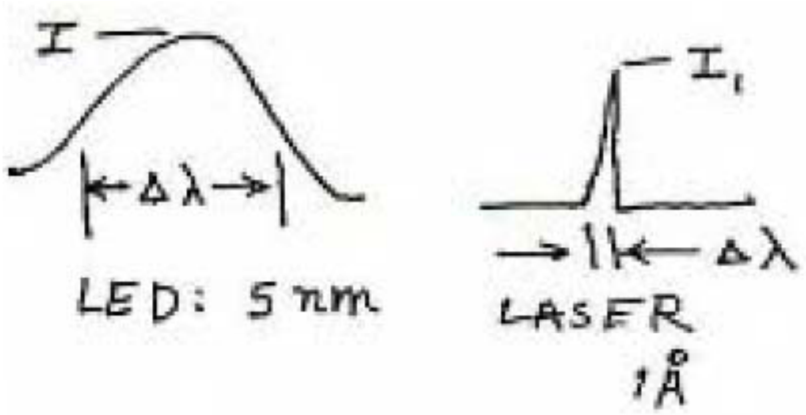
Nice Properties: Lasers have larger bandwidth than other sources

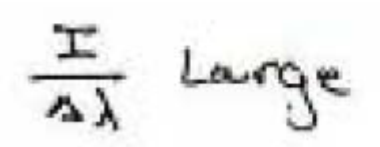




High speed

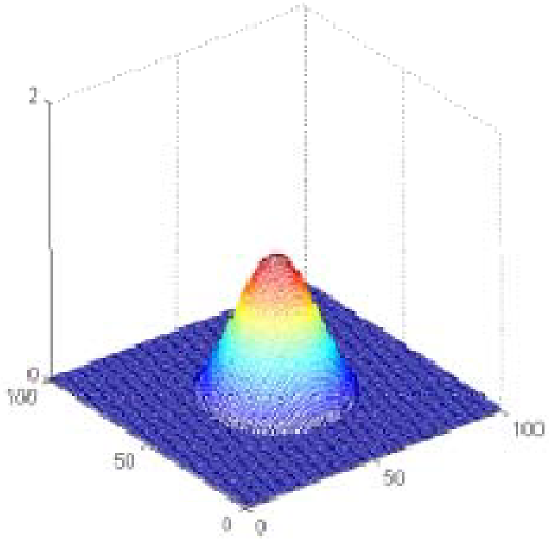
Bright coherent sources



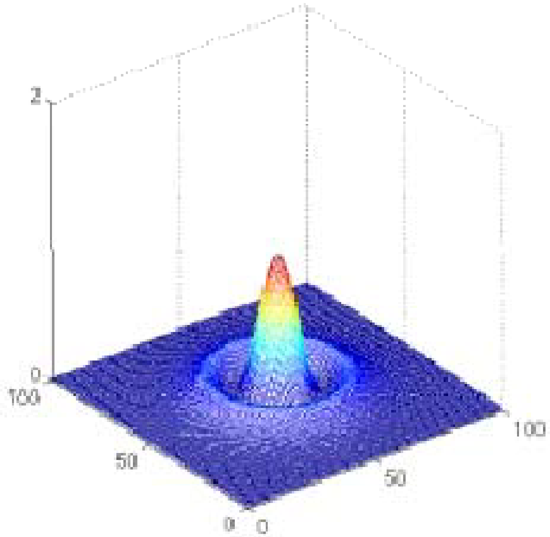


2-mode fibers

LP01 mode

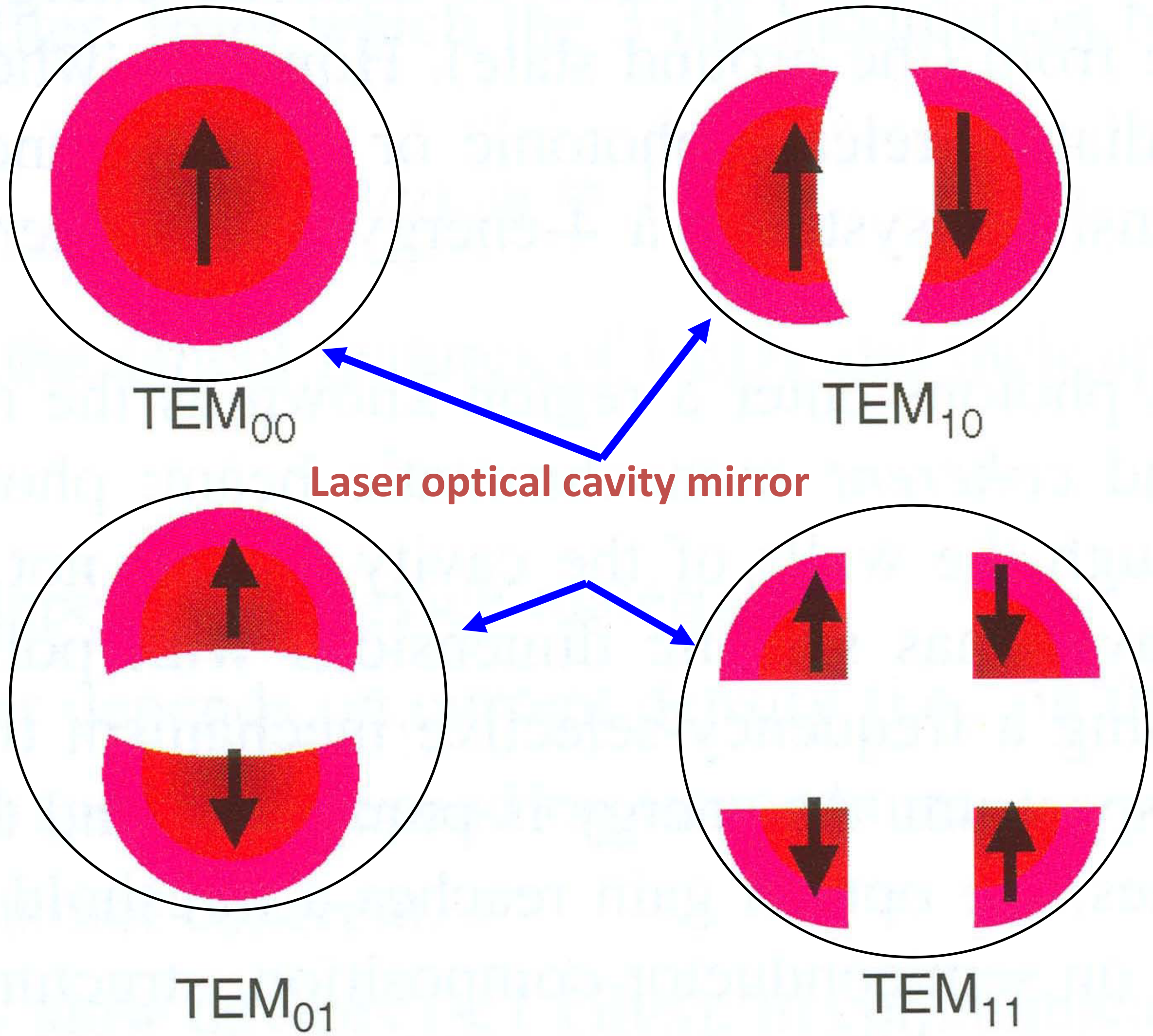


LP02 mode



LP modes intensity pattern

The lower order transvers modes of laser



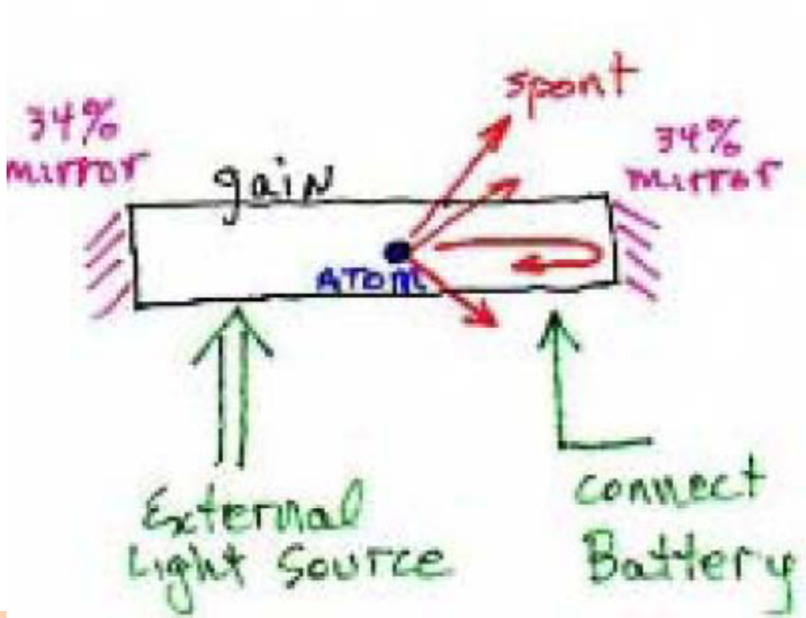
Basic component of laser:

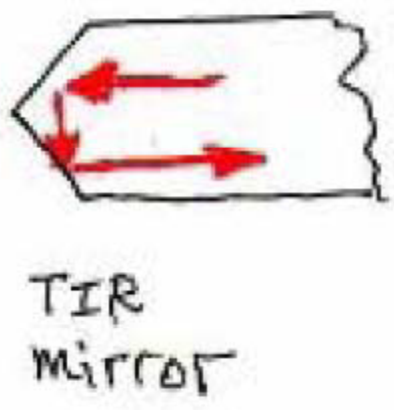
Gain medium: amplifier light

Pump: add energy to medium

Positive feedback: oscillator

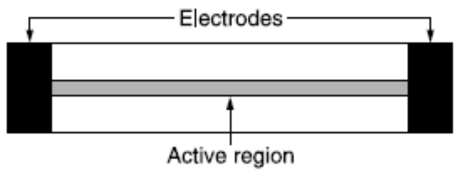
Output coupler: extract a sifnal

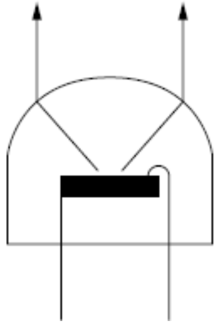




Laser could have been invented in the 1920-1930

Engineers----------→ Oscillation and feed back
Physicists-----→ Matter – light interaction





Gain: Semiconductor , GaAS prototype can have other

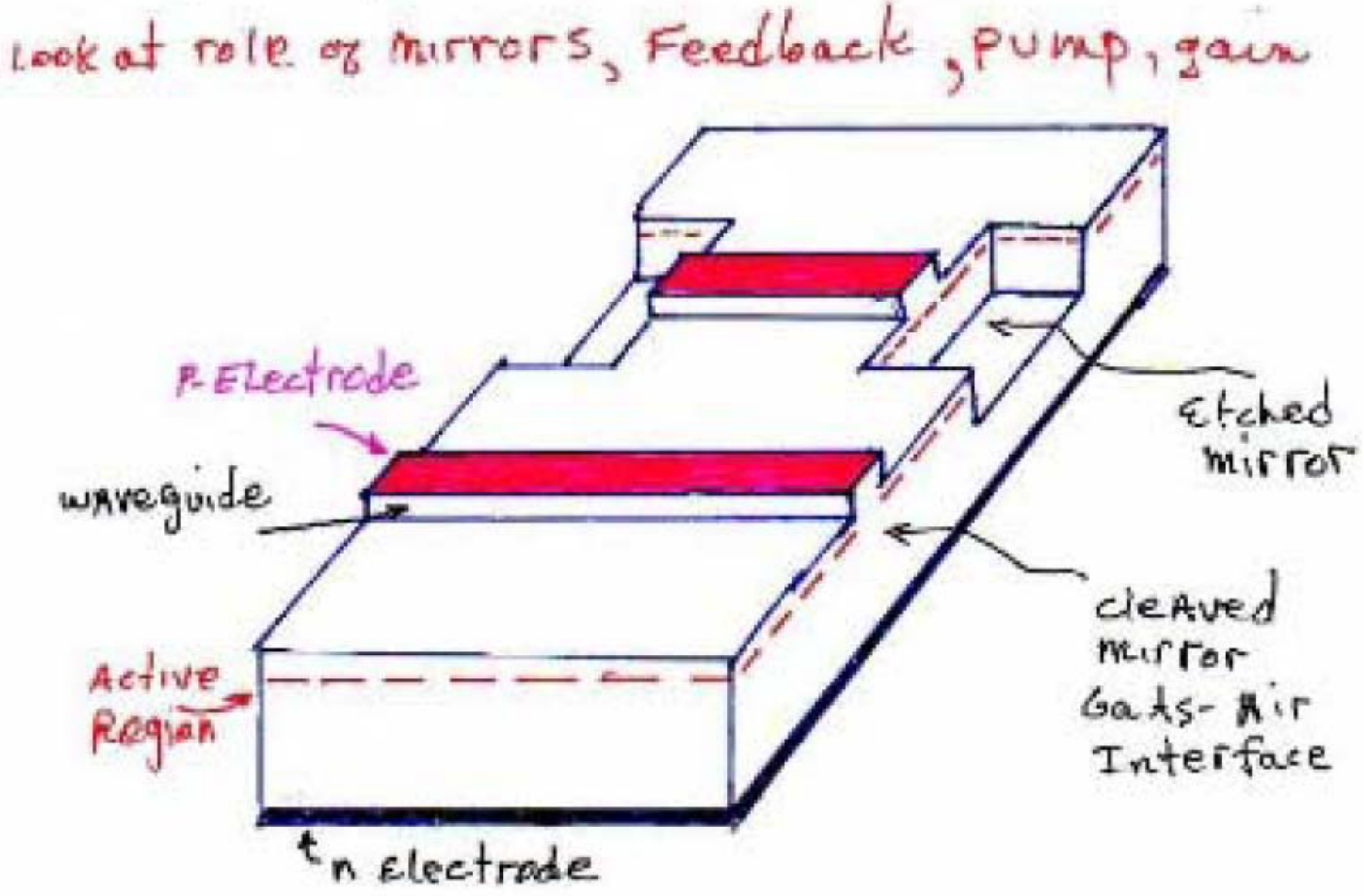
Gas: HeNe Argon Co2

Solid state: Ruby, Doped glass (Fiber)

Typical construction of semiconductors lasers :

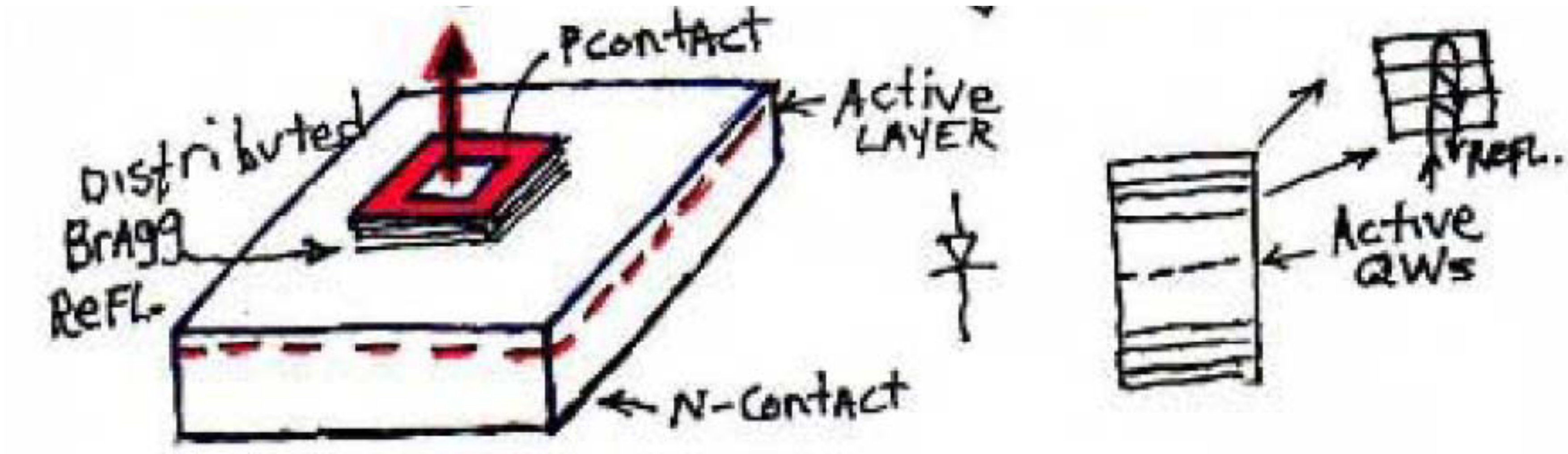
IPL= Inplane Laser,, Edge emitting

Cleaved and etched mirrors

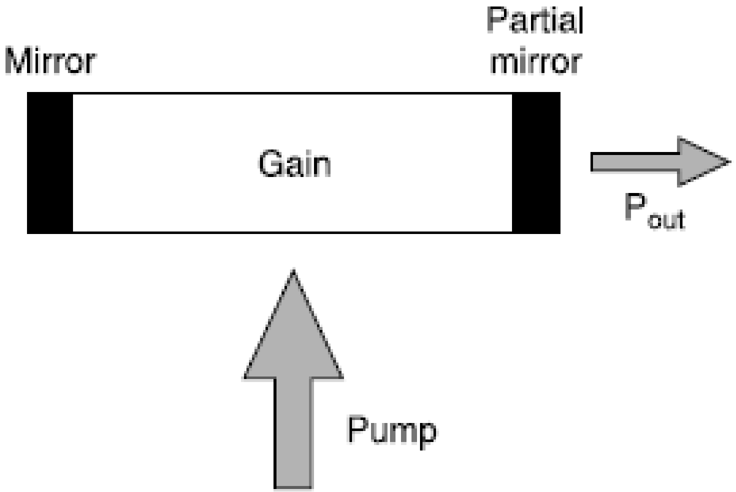


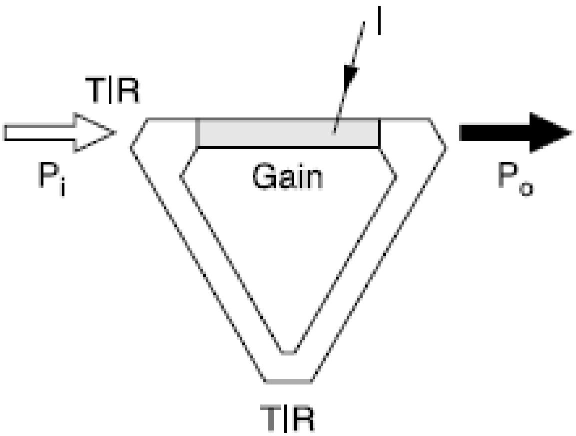
Vertical cavity surface emitting laser

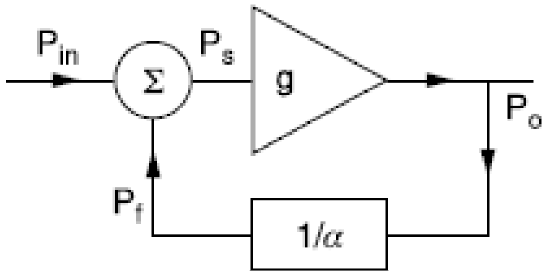
VCSEL



Basic Components and the Role of Feedback





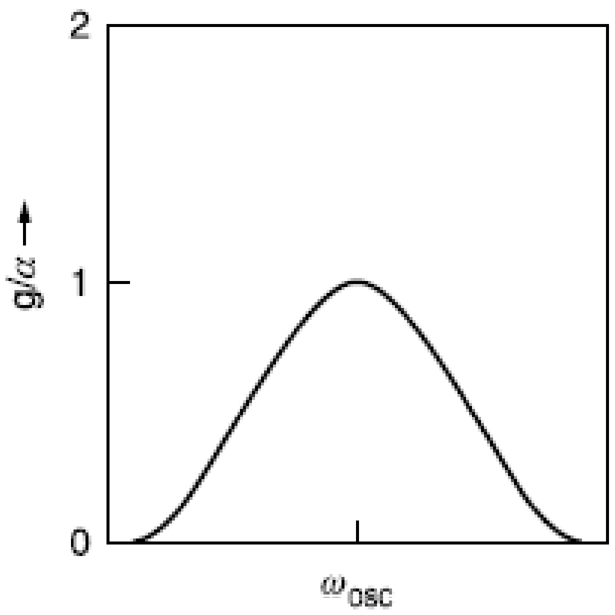


$$\begin{cases} P_o = gP_s \\ P_s = P_{in} + P_f \\ P_f = \dfrac{1}{\alpha} P_o \end{cases} \rightarrow \quad P_o = \frac{gP_{in}}{1 - (g/\alpha)}$$

Unlike Op-Amp laser has g=g(constant)

+ FREQ Dependent Gain

$$G = G(\omega)$$



oscillates at Frequency ω_0 Since $g(\omega_0) \approx \beta$

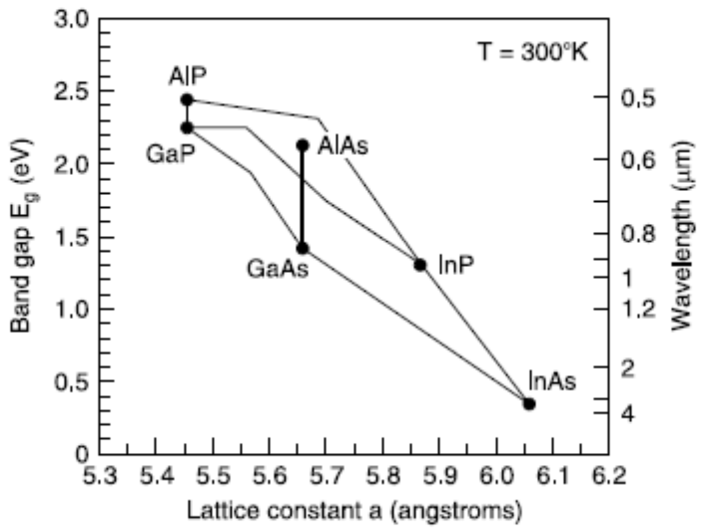
Basic Properties of Lasers

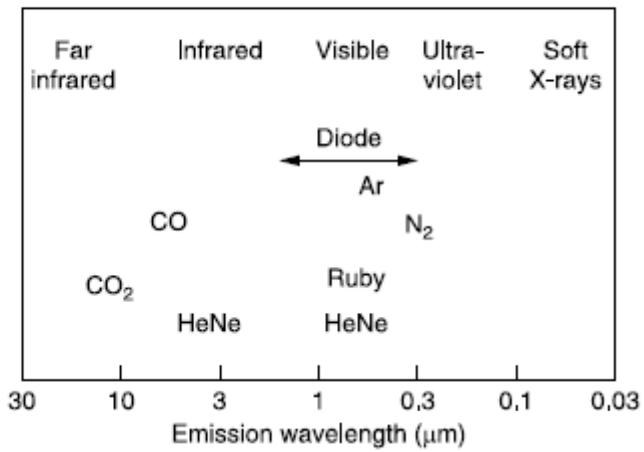
The "brightness," defined as the amount of output power per unit frequency, determines the spectral purity of the source.

Wavelength and Energy

$$E = \hbar\omega = h\nu \quad \lambda = 2\pi/k \quad c = \nu\lambda = \omega/k$$

$$E \hat{=} 1240/\lambda.$$

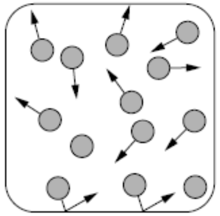




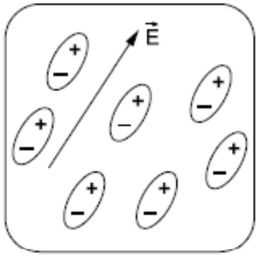
Introduction to Matter and Bonds

Classification of Matter

- Gases



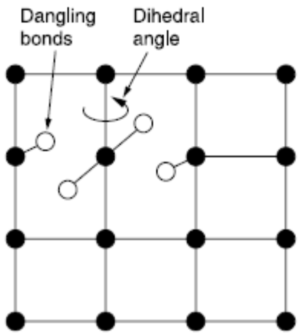
- Liquids and Liquid Crystals



- **Solids**

By: Dr. Jabbari

Bonding and the Periodic Table



Periods	I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	0
1	1,0079 H[1]																1,0079 H[1]	4,00260 He[2]
2	6,941 Li[3]	9,01218 Be[4]											10,81 B[5]	12,011 C[6]	14,0067 N[7]	15,9994 O[8]	18,9984 F[9]	20,179 Ne[10]
3	22,9898 Na[11]	24,305 Mg[12]											26,9815 Al[13]	23,086 Si[14]	30,9738 P[15]	32,06 S[16]	35,453 Cl[17]	39,948 Ar[18]
4	39,098 K[19]	40,08 Ca[20]	44,9559 Sc[21]	47,90 Ti[22]	50,9414 V[23]	51,996 Cr[24]	54,9380 Mn[25]	55,847 Fe[26]	58,9332 Co[27]	58,71 Ni[28]	63,546 Cu[29]	65,38 Zn[30]	69,72 Ca[31]	72,59 Ge[32]	74,9216 As[33]	78,96 Se[34]	79,904 Br[35]	83,80 Kr[36]
5	85,4678 Rb[37]	87,62 Sr[38]	88,9059 Y[39]	91,22 Zr[40]	92,9064 Nb[41]	95,94 Mo[42]	98,9062 Tc[43]	101,07 Ru[44]	102,9055 Rh[45]	106,4 Pd[46]	107,868 Ag[47]	112,40 Cd[48]	114,82 In[49]	118,69 Sn[50]	121,75 Sb[51]	127,60 Te[52]	126,9045 I[53]	131,30 Xe[54]
6	132.9054 Cs[55]	137.34 Ba[56]	[57-71]	178.49 Hf[72]	180.9479 Ta[73]	183.85 W[74]	186.2 Re[75]	190.2 Os[76]	192.22 Ir[77]	195.09 Pt[78]	196.9665 Au[79]	200.59 Hg[80]	204.37 Tl[81]	207.2 Pb[82]	208.9804 Bi[83]	(210) Po[84]	(210) At[85]	(222) Rn[86]
7	(223) Fr[87]	226.0254 Ra[88]	[89-103]	[104]	[105]	[106]	[107]	[109]										

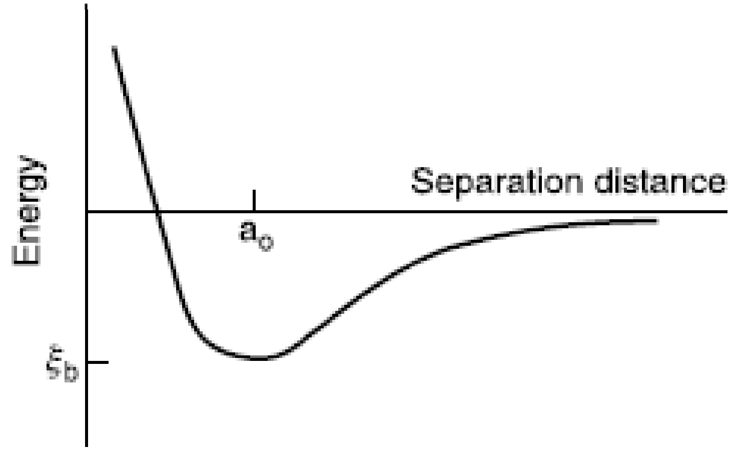
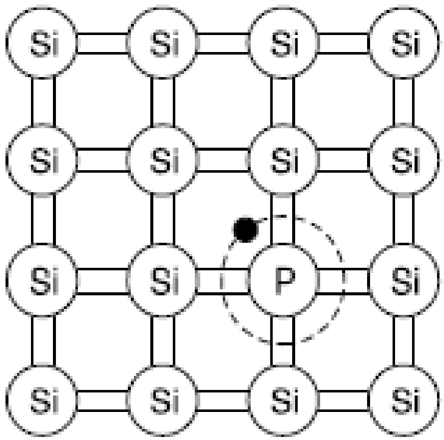


FIGURE 1.4.7
Total energy of two atoms as a function of their separation distance.



An *n*-type dopant atom embedded in a silicon host crystal.

Introduction to Bands and Transitions

Intuitive Origin of Bands

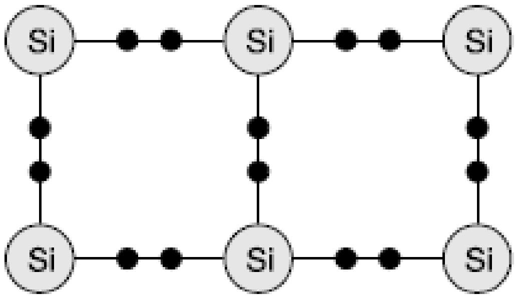


FIGURE 1.5.1
Cartoon representation of silicon crystal at 0 K.

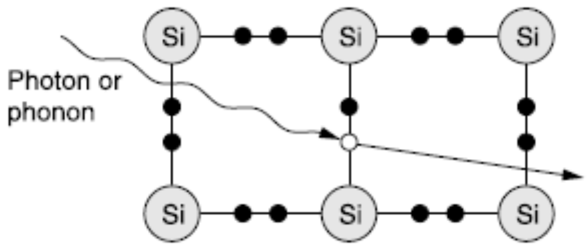


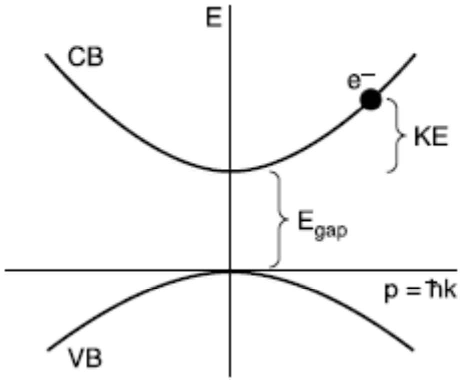
FIGURE 1.5.2
Cartoon representation of transition from VB to CB.

The total energy of a conduction electron can be written as

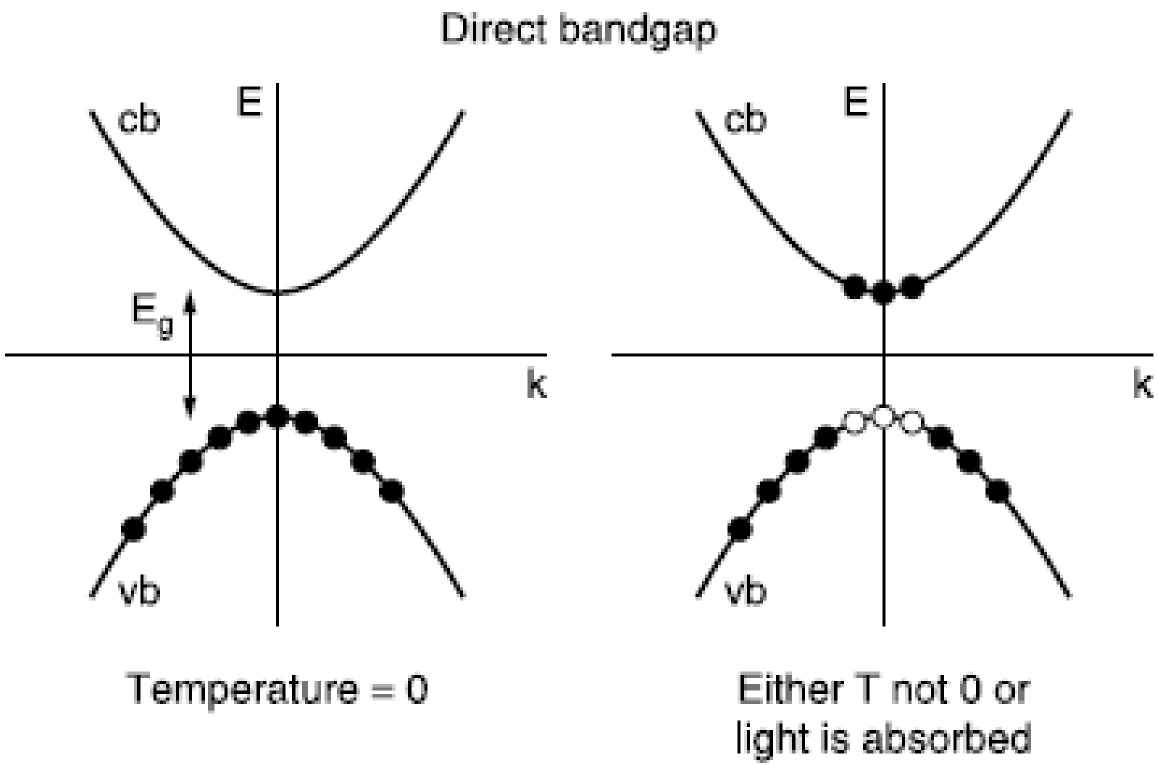
$$E = \mathrm{PE} + \mathrm{KE} = E_g + \tfrac{1}{2} m_e v^2$$

$$p = m_e v$$

$$E = E_g + \frac{p^2}{2m_e}$$



$$E = \frac{p^2}{2m_h}$$



An elementary band diagram for gallium arsenide

Indirect Bands, Light and Heavy Hole Bands

$$p = \hbar k = m_e v.$$

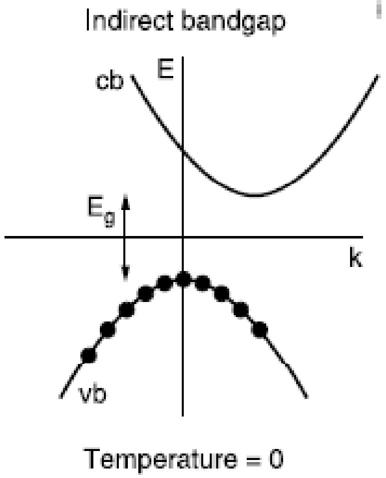


FIGURE 1.5.5
A semiconductor at zero degrees Kelvin with an indirect bandgap.

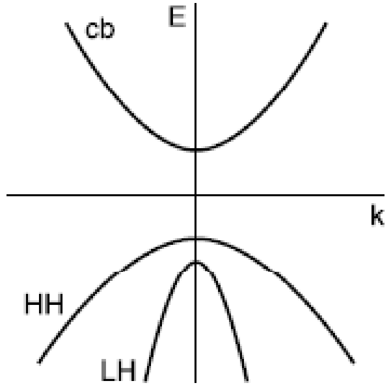
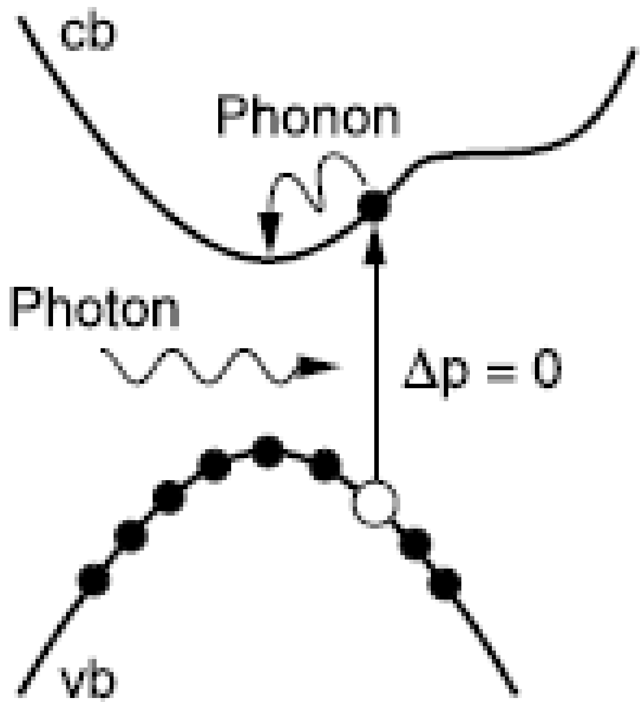
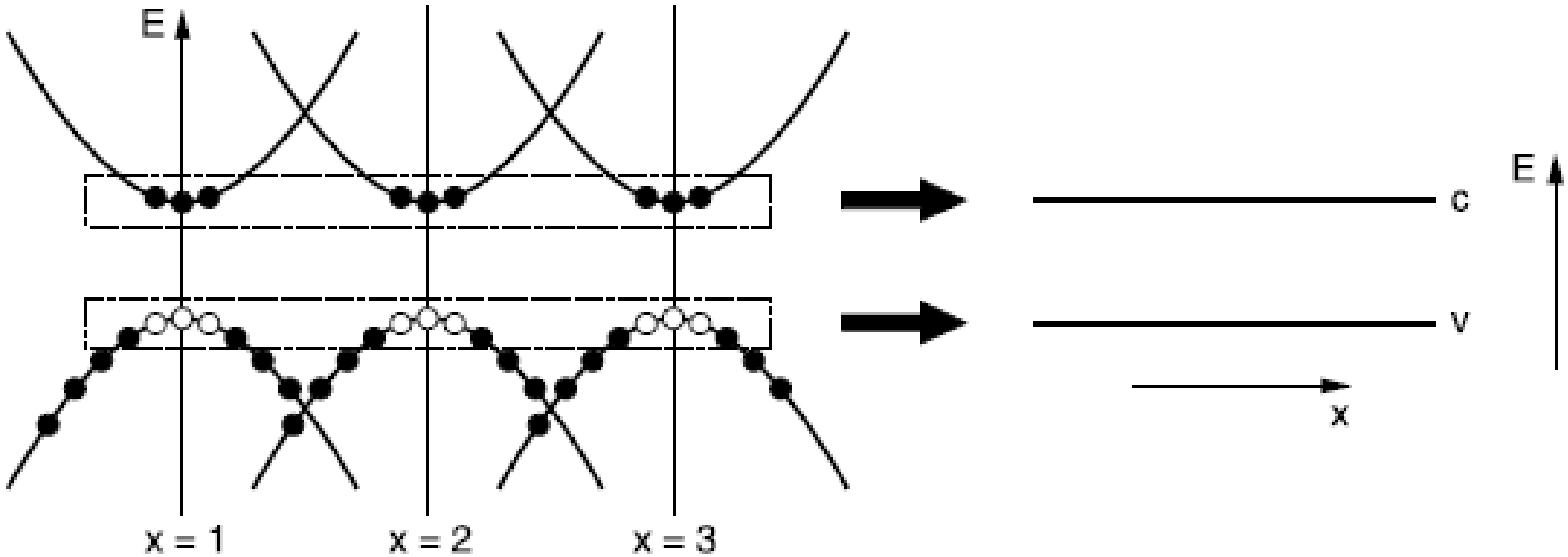


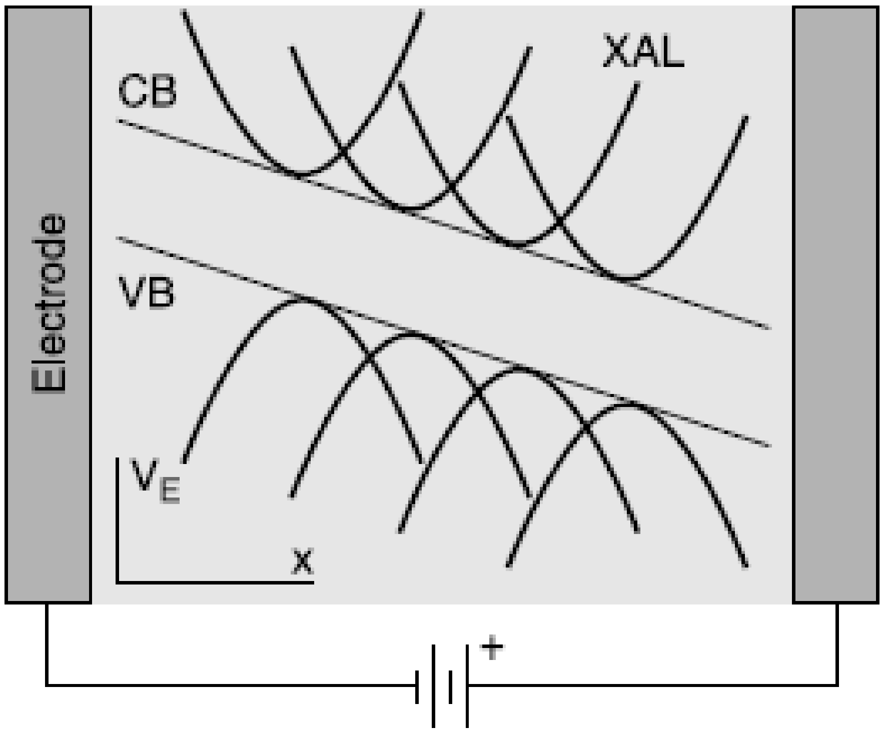
FIGURE 1.5.6
GaAs has a light LH and heavy HH hole valence band.

$$\frac{1}{m_{\text{eff}}} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k^2}$$

Introduction to Band Edge Diagrams




E
x = 1
x = 2
x = 3
E
c
v
x


CB
XAL
VB
Electrode
V_E
x
+

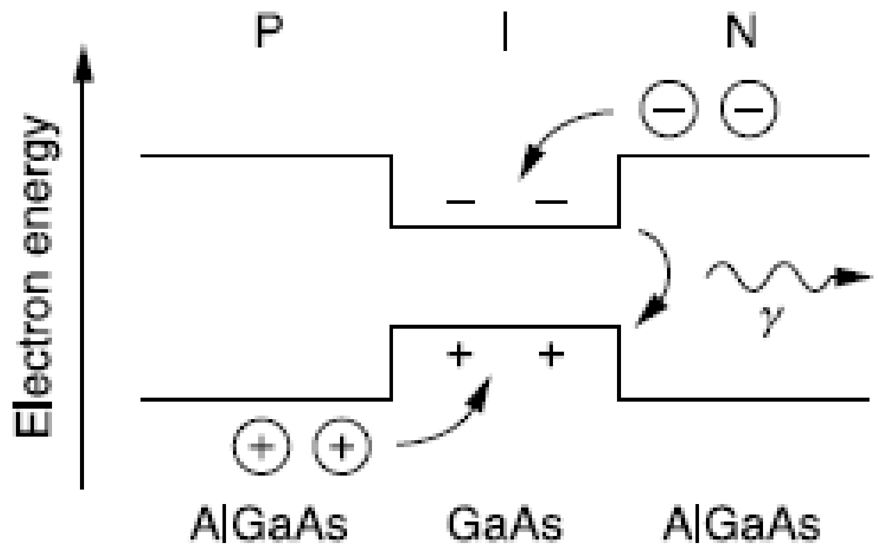


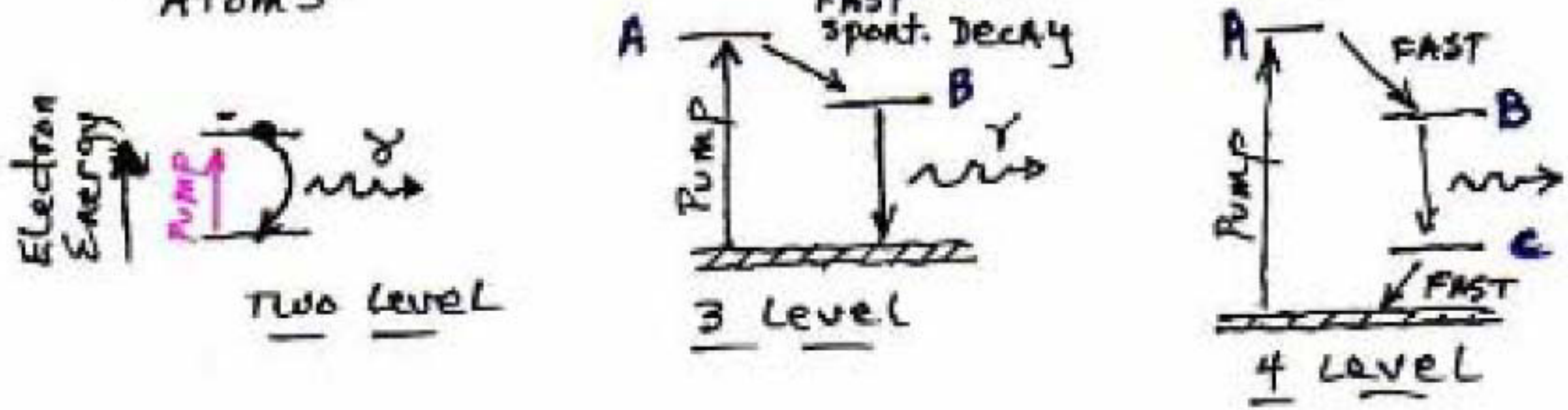
FIGURE 1.5.10
Band-edge diagram for heterostructure with a single quantum well.

(1.9)

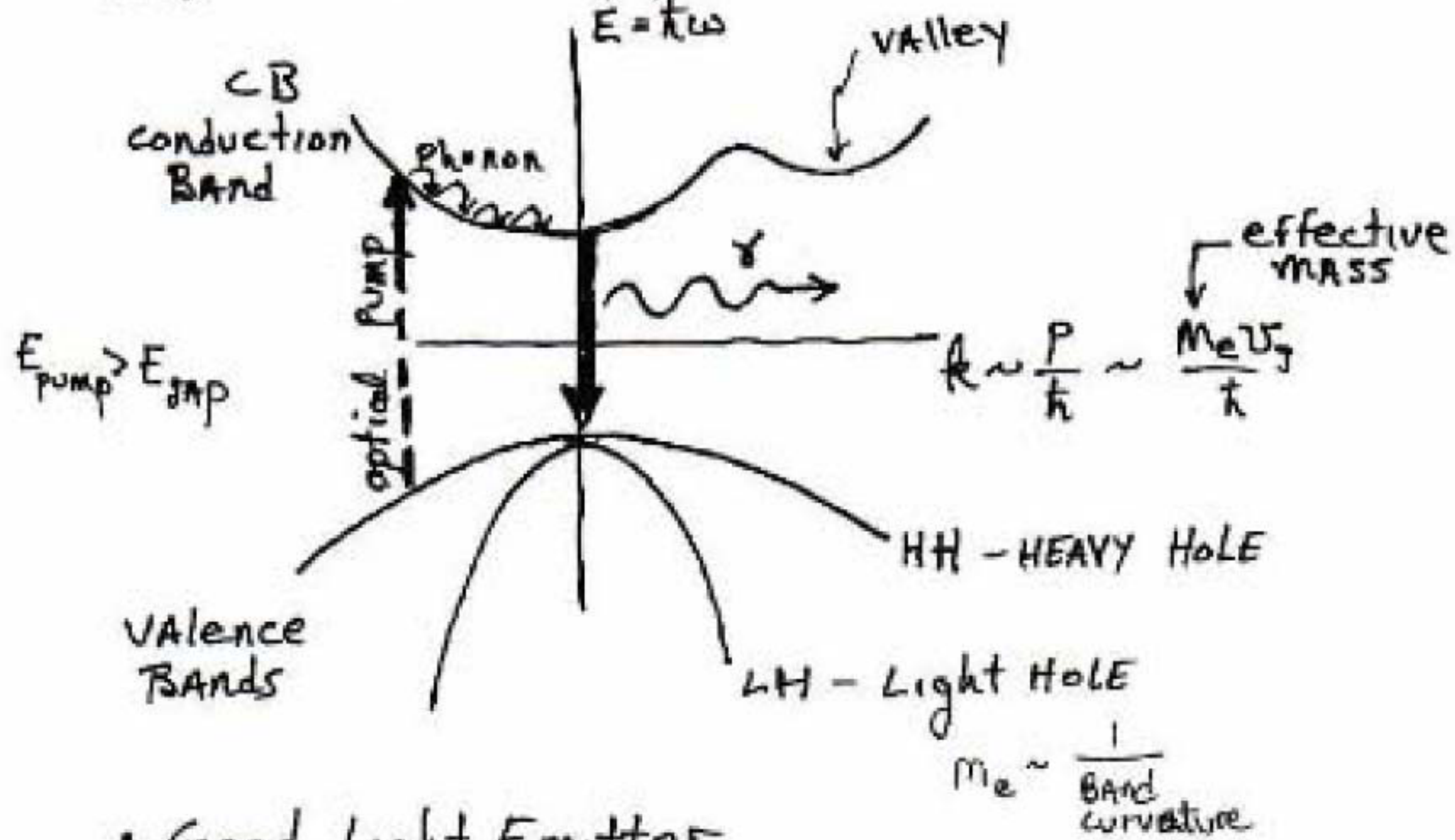
+ Semiconductors Produce Gain

- Need Direct Band Gap
  - Some Reports of Stimulated Emission From indirect bandgap material
  - can also use intra-band transitions

- initially we work with two-level "Atoms"



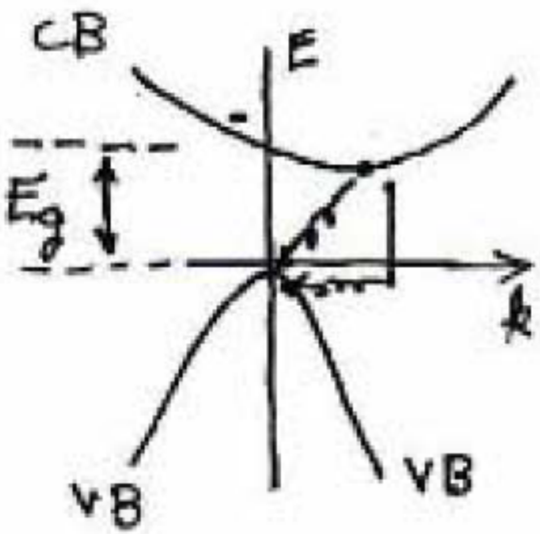
+ GaAs – Direct Bandgap



• Good Light Emitter

+ INDIRECT Band gaps : Silicon

- poor Light Emitter



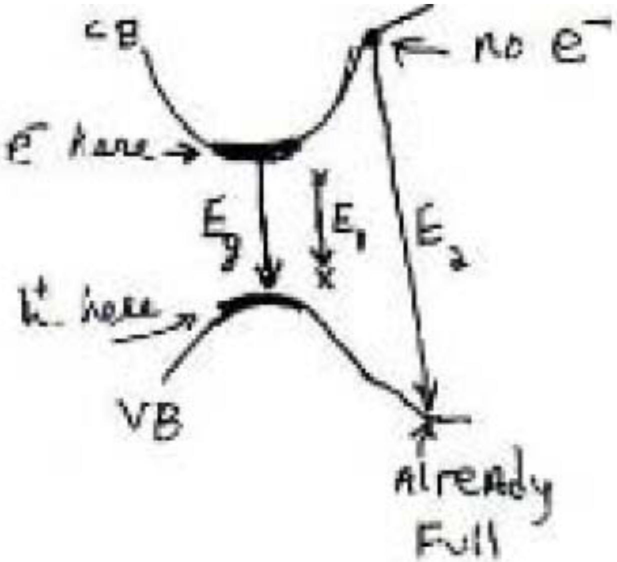
- TRANSition FROM CB → VB involves phonons
- phonons : Sound waves, motion of XAl Atoms
- phonons have Large Momentum, Small energy.
  Photons Large Energy
  Small momentum

CB → VB Requires
LARge Δk ≡ Large momentum ⟹
Phonons

Consider again the op. Amp case where $g = g(\omega)$. Can now see same for semiconductor gain.

→ LASER GAIN Depends on Frequency

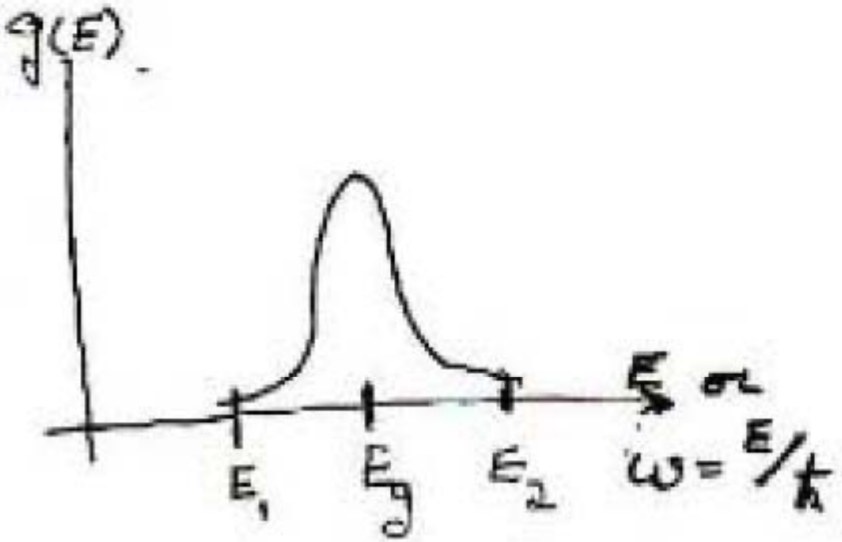
- $E = \hbar\omega$ ω = Angular Frequency



The transition across E_g can occur... e^- drops into a hole. There is gain for photons with frequency $\omega_g = E_g/\hbar$

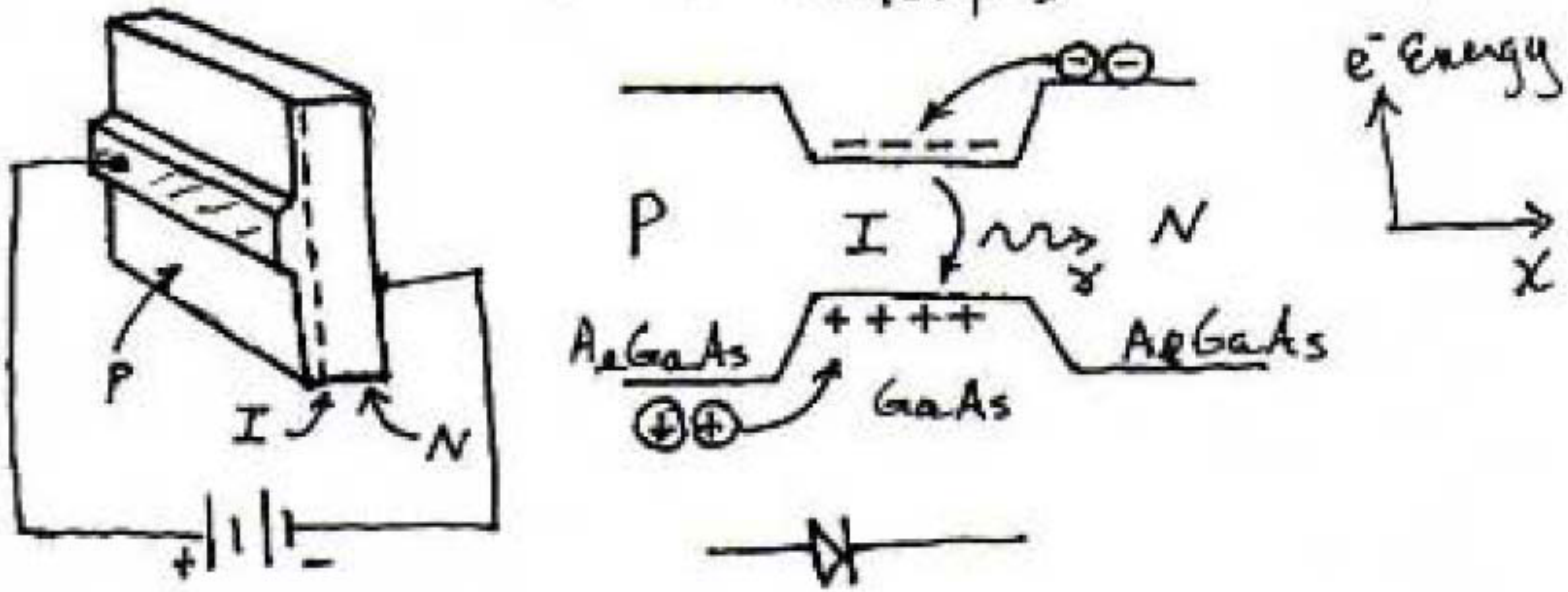
For E_1 transition: no e^- or holes for recombination ... therefore no gain to produce photons

- Same for E_2: no e^- at CB and no empty state available in VB



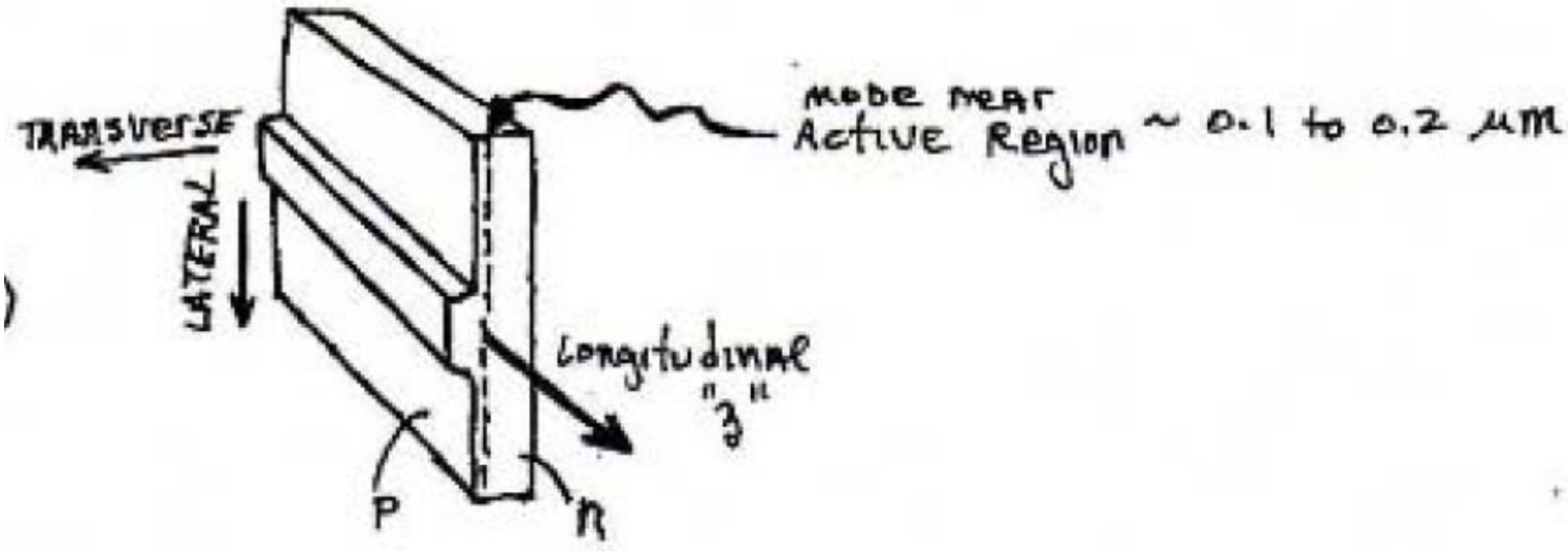
HETERO Junctions : Double Heterostruct.

- PIN : P = P-doped I = Intrinsic -UNDOPED N = N-doped

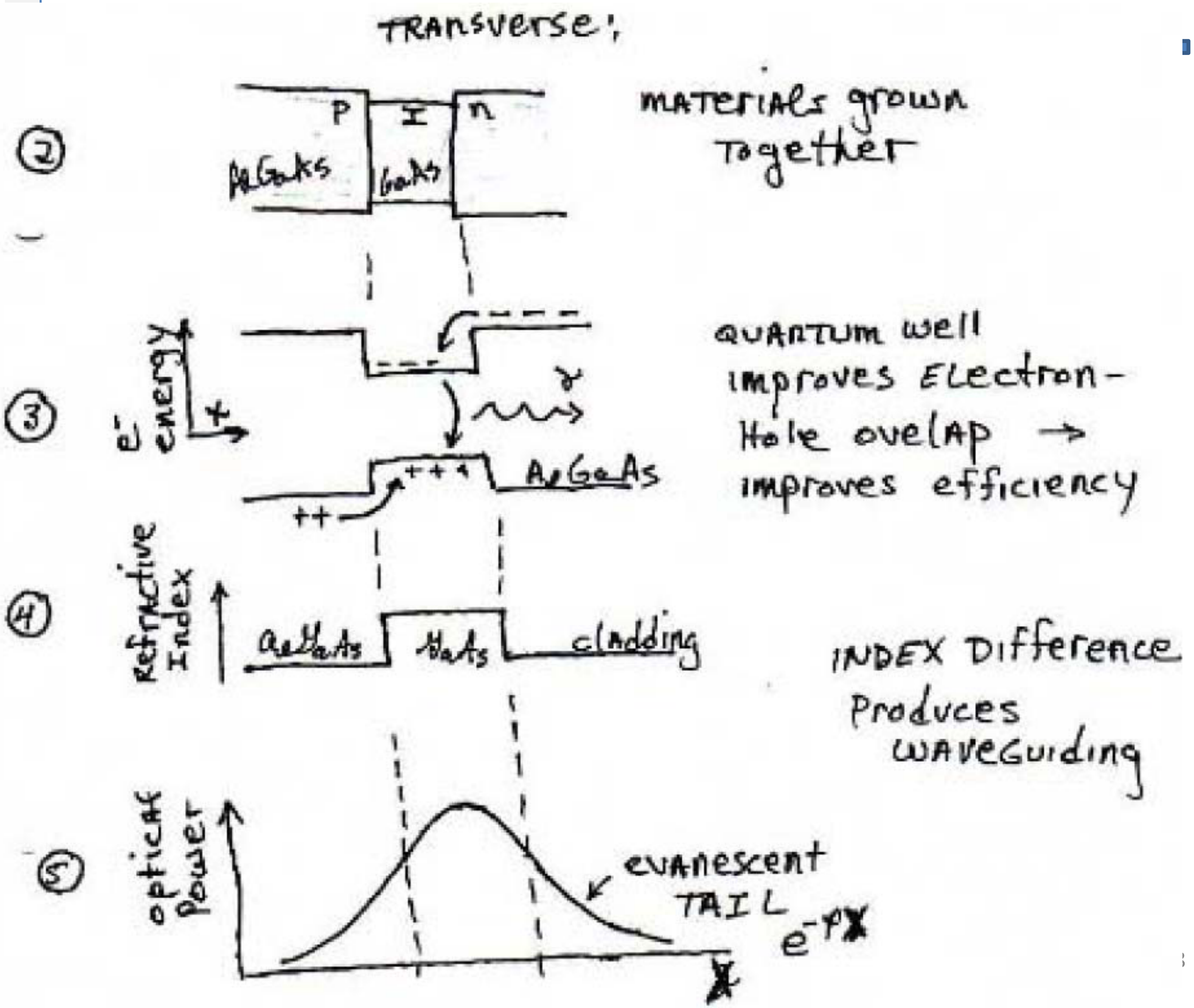


- HETERO means DIFFERENT

Basic Waveguiding in a SEMiConductor Laser

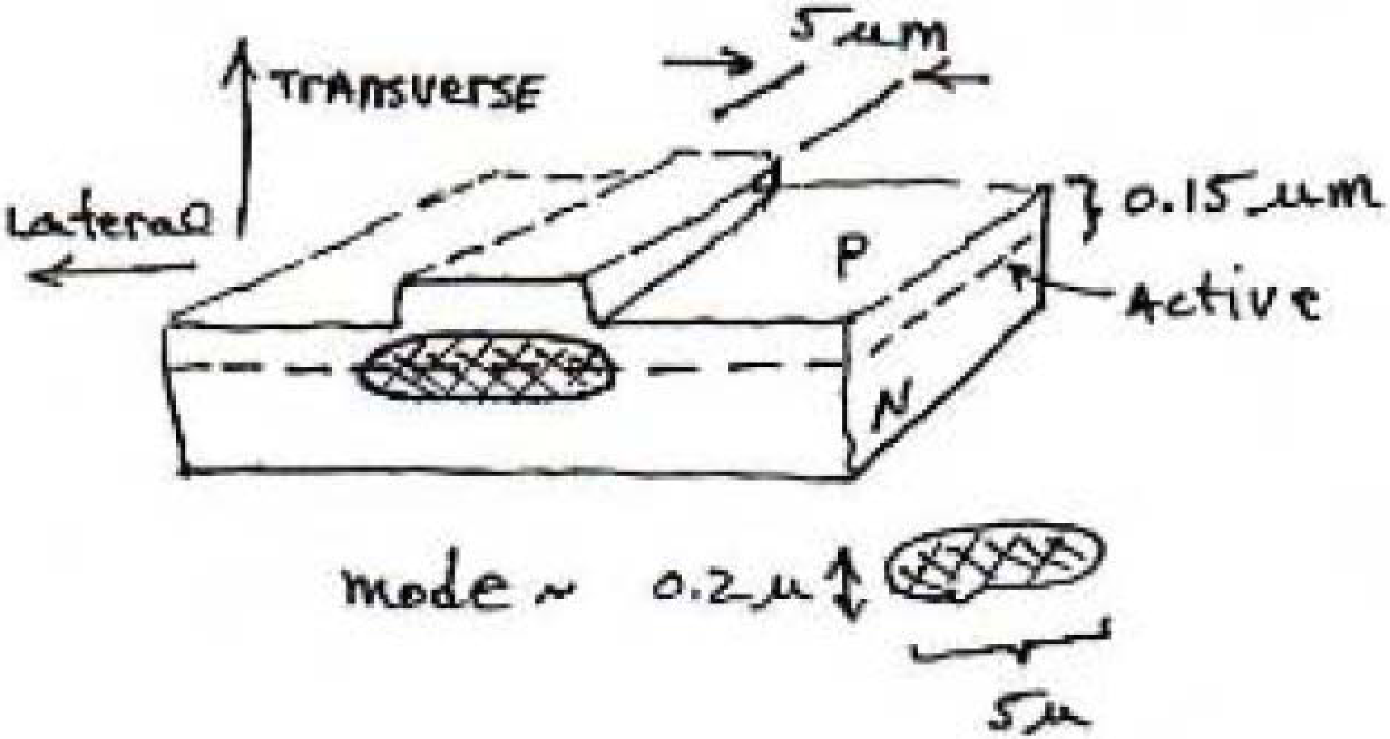


دانشگاه آزاد مرودشت



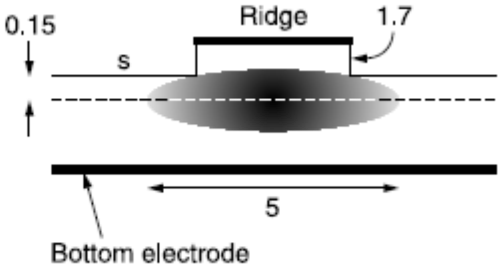
By: Dr. J

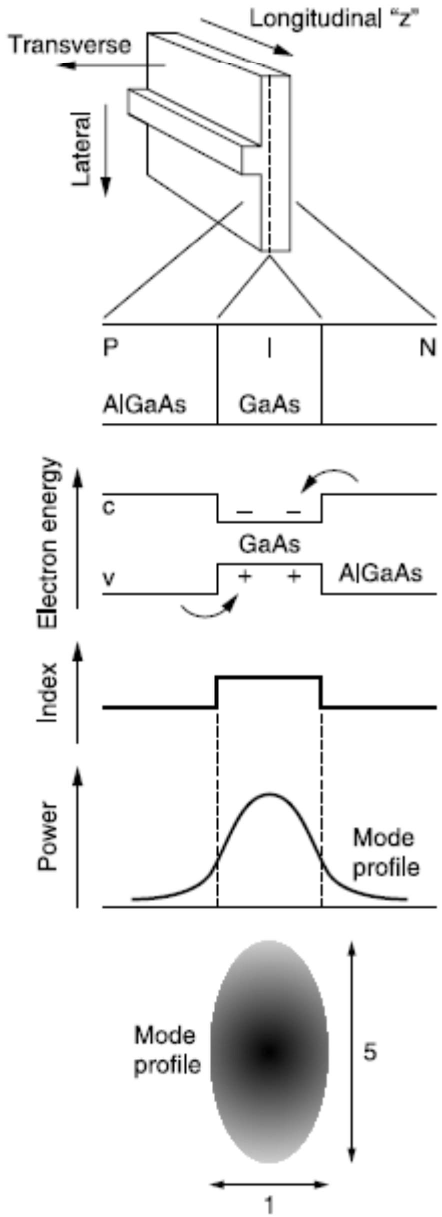
End view of waveguiding : Ridge waveguide

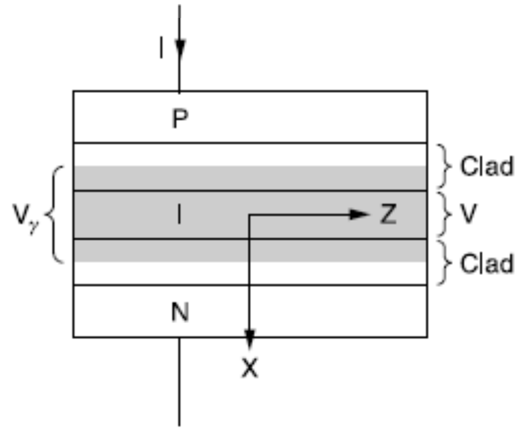


+ Transverse waveguiding due to Epitaxially grown layers with various refractive indices

+ Lateral waveguiding
P surface close enough to Active Region so that the ~~most~~ optical Energy "Feels" it --- Evanescent tail touches it ⇒ air lowers Effective INDEX of Region occupied by the Energy ⇒ waveguiding


0.15
Ridge
1.7
s
5
Bottom electrode


Longitudinal "z"
Transverse
Lateral
P
I
N
AlGaAs
GaAs
Electron energy
c
GaAs
v
AlGaAs
Index
Power
Mode profile
Mode profile
5
1


I
P
Clad
I
Z
V
Clad
N
X

Introduction to Laser Dynamics

معادلات ماکسول به کمک مکانیک کوانتم اندر کنش بین فوتون و الکترون را تعیین می کند
به کمک این معادلات می توان معادلات نرخ رسید

The rate equations describe how the gain, pump, feedback, and output couplermechanisms affect the carrier and photon concentration in a device.

معادلات نرخ معین کننده اندرکنش بین فوتون و الکترون در یک محیط با بهره می باشد

The **photon rate equation** describes the effects of the output coupler and feedback mechanism through a relaxation term incorporating the cavity lifetime.

Introduction to the Rate Equations

اندر کنش نور و ماده سبب ایجاد پدیده های متعددی از قبیل گسیل و جذب فوتون و غیره می گردد

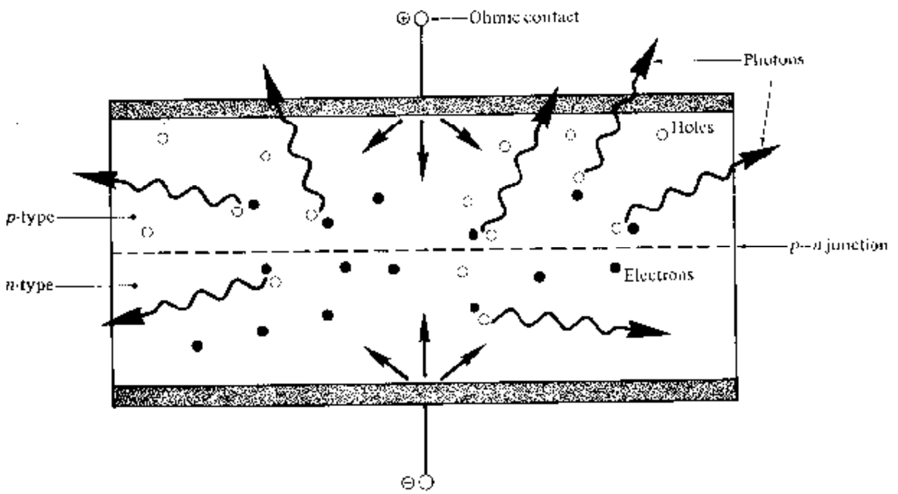


Fig. 6.12 An illustration of carrier recombination giving spontaneous emission of light in a p–n junction diode.

تعدادی از پارامترهایی مورد نیاز:

Density of photons (the number of photons per cm3), γ

the density of electrons $n\ (\#/\mathrm{cm}^3)$

pump-current number density $\mathcal{J}\ (\#\mathrm{carriers/s/cm}^3)$.

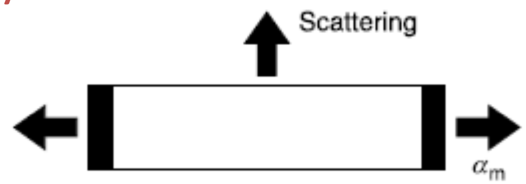
A second set of equations uses variables describing the optical power P (W) and current I (A).

+ SEVERAL SETS of PARAMETERS

$\gamma = \frac{\#\text{photons}}{cm^3}$	P = WATTS	$\vec{E}$ = Electric Field
	I = currents	ϕ = phase
$n = \frac{\#e^-}{cm^3}$, J	Q = charge	$n = \frac{\#e^-}{Vol}$

Basic principle: Rapid change of state of an electron

- Must go from high energy state to lower energy state
- Loss of energy must appear somewhere
  - Emitted in form of light
  - Lattice vibrations
- Electron can be bound to a particular atom or molecule or be free (part of electron "gas"), as in most conductors



Two types of emission of light

- Spontaneous
- Stimulated

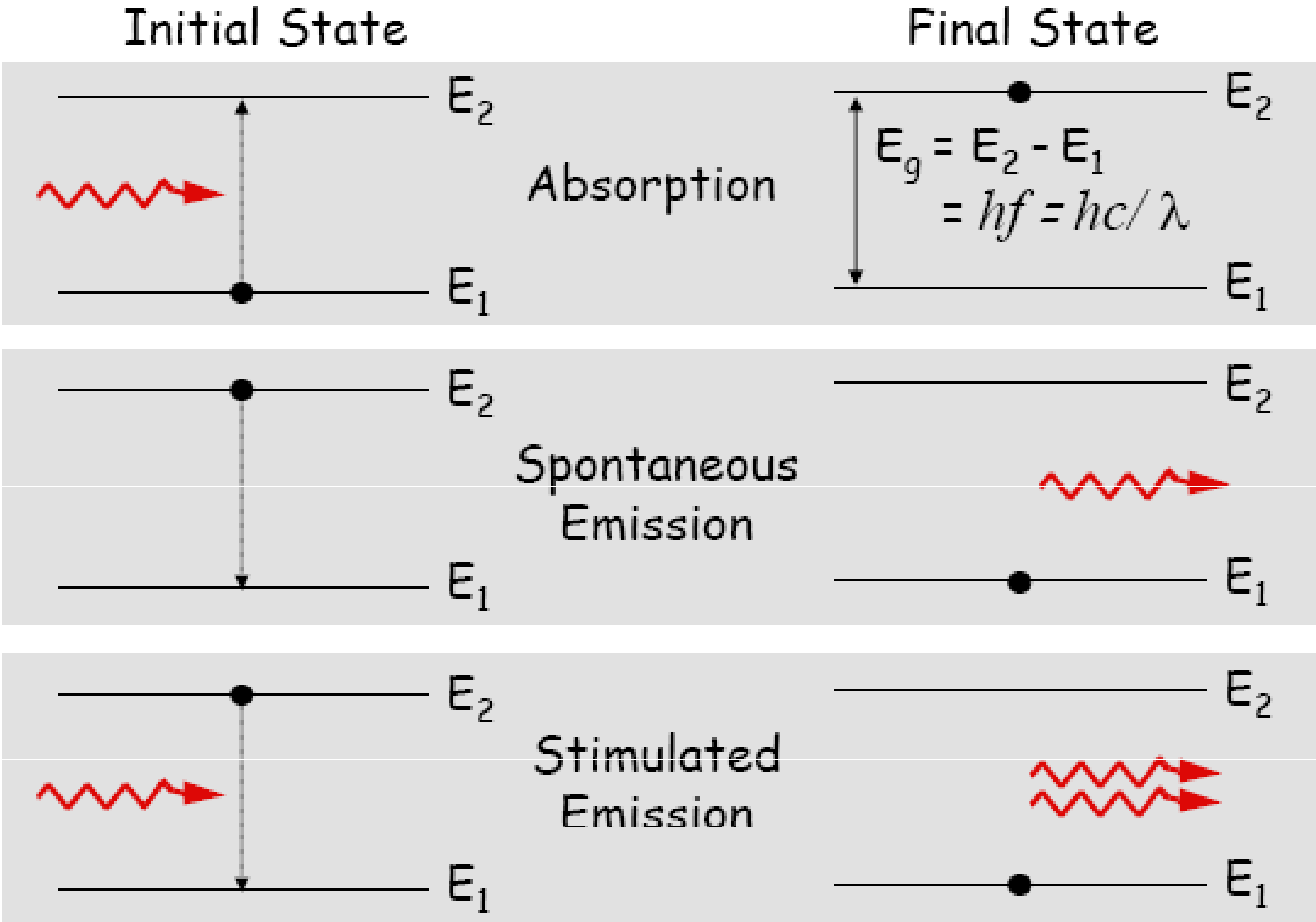
Light production: spontaneous

- Normal case
- Electron in high energy state is unstable
  - Spontaneously returns to lower state
  - Occurs in a few picoseconds
  - Photon emitted in process
  - Direction, phase random
  - Energy of photon determined by transition undergone by electron

Light production: stimulated

- Electron in high energy metastable state
  - Can remain there for a “long” time (~microseconds)
  - Can fall back spontaneously, or be “stimulated” to emit its energy by another photon
    - Incident photon must have correct energy
    - Newly emitted photon will have same wavelength, phase, and direction as incident (stimulating) photon

ABSORPTION & EMISSION



By: Dr. Jabbari

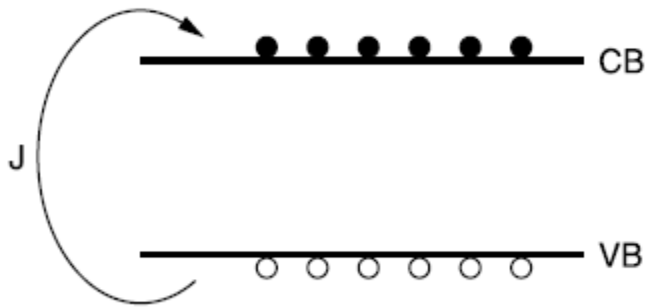
The Simplest Rate Equations

مشخص کننده تغییر زوج حاملها در درون ناحیه فعال یک لیزر

$$\frac{dN}{dt} = \text{Generation} - \text{Recombination}$$

$$N = nV$$

We assume
- intrinsic semiconductor (n=p)
- two levels



Generation
- pumping
- absorption

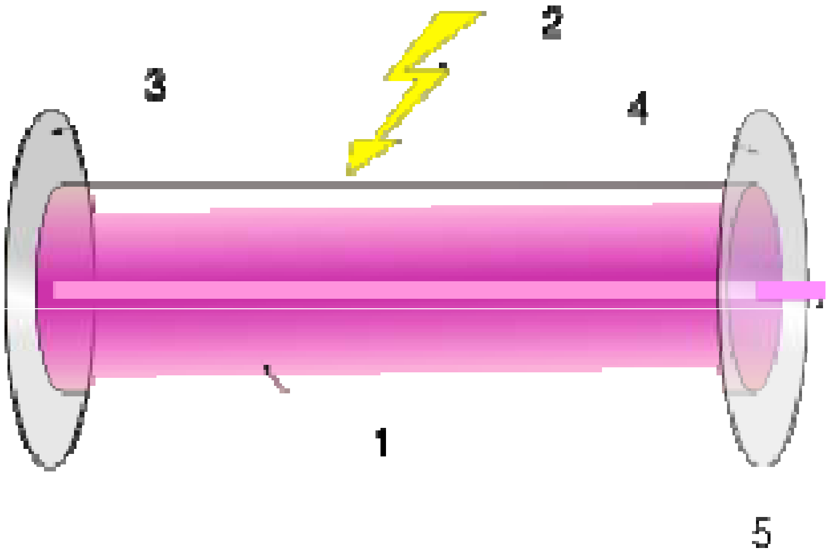
Recombination
- stimulated
- spontaneous

By: Dr. Jabbari

$$\frac{dN}{dt} = -\begin{pmatrix}\text{Stimulated}\\ \text{Emission}\end{pmatrix} + \begin{pmatrix}\text{Stimulated}\\ \text{Absorption}\end{pmatrix} + \text{Pump} - \begin{pmatrix}\text{Non-Radiative}\\ \text{Recombination}\end{pmatrix} - \begin{pmatrix}\text{Spontaneous}\\ \text{Recombination}\end{pmatrix}$$

پمپ توسط جریانی که از بالایی لیزر به آن تزریق می شود و یا از طریق یک شدت نور ایجاد می گردد

$$\text{Pump} = \mathscr{J}V$$

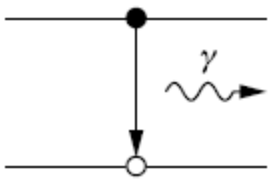


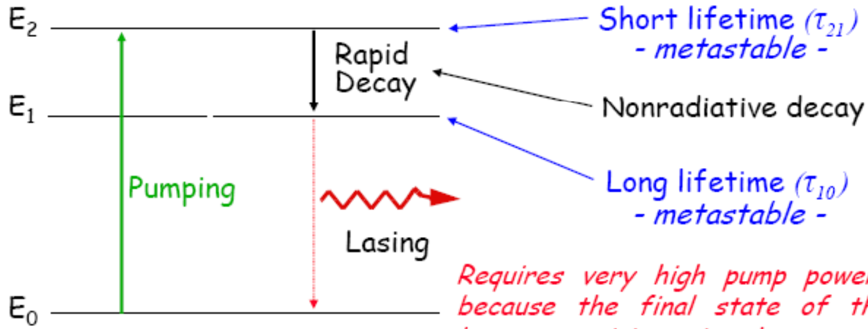
افزایش یا کاهش الکترونها نسبت عکس با تعداد فوتونها دارد

ENERGY LEVEL DIAGRAM

- Three Level System -

Spontaneous absorption

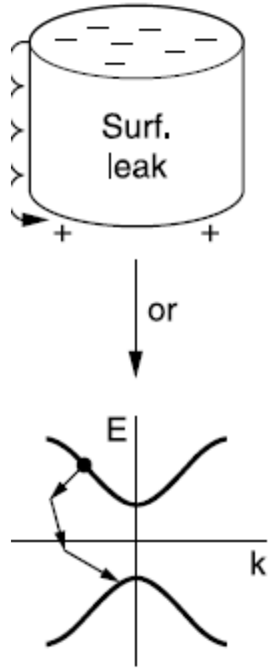




Three Level System
Ruby Laser (crystal)

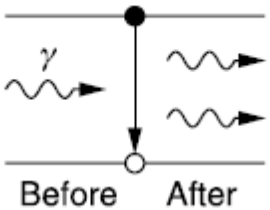
Requires very high pump powers because the final state of the laser transitions is the ground state. Thus, over half of the ground state atoms must be pumped into the metastable state to achieve population inversion

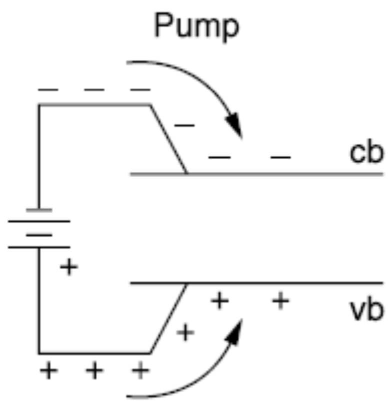
Non-radiative recombination



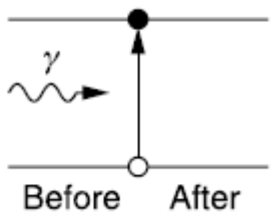
$$\frac{d\Upsilon}{dt} = +\begin{pmatrix}\text{Stimulated}\\ \text{Emission}\end{pmatrix} - \begin{pmatrix}\text{Stimulated}\\ \text{Absorption}\end{pmatrix} - \begin{pmatrix}\text{Optical}\\ \text{Loss}\end{pmatrix} + \begin{pmatrix}\text{Fraction of}\\ \text{Spont. Emiss.}\end{pmatrix}$$

Stimulated recombination





Stimulated absorption



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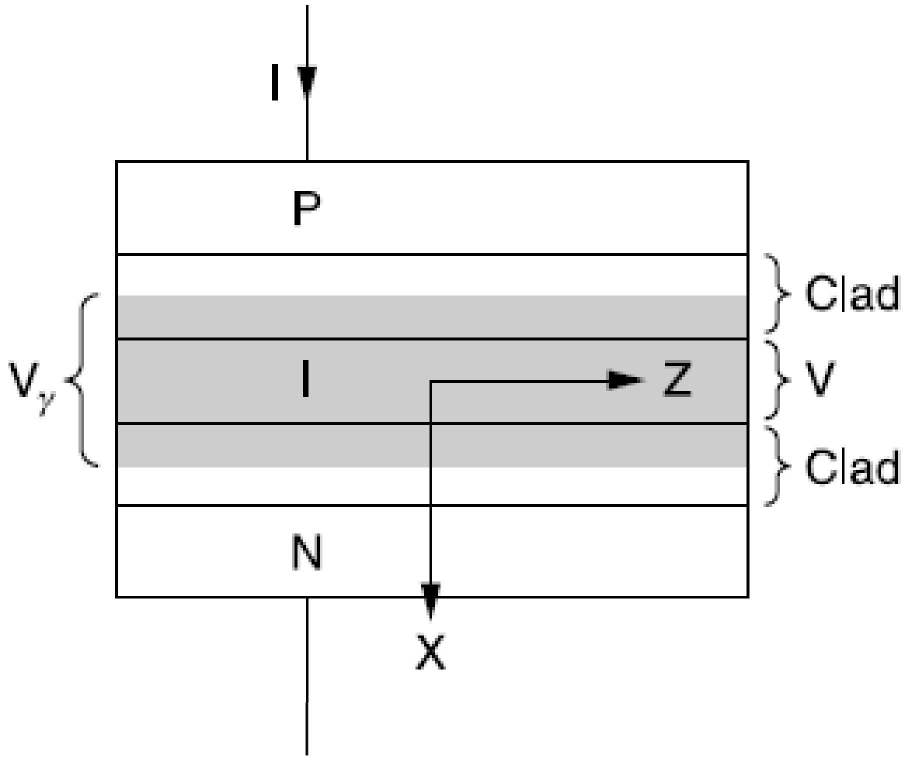
Optical Confinement Factor



$$\Gamma = V / V_{\gamma}$$

The Pump Term and the Internal Quantum Efficiency

The number of electron–hole pairs that contribute to the **photon emission** process in each unit of volume (cm3) of the active region in **each second** can be related to the **bias current** I by

Internal Quantum Efficiency → **represents the fraction of terminal current I that generates carriers in the active region**

$$\mathscr{I} = \frac{\eta_i I}{qV}$$

where $\mathscr{I}$ represent the "pump-current number density,

$\eta_i I$ → **provides the actual current absorbed in the active region**

Pumping (whether optical or electrical) initiates laser action when the carrier population reaches the ‘‘threshold’’ density (to be discussed later).

Without carrier recombination, the pump would continuously increase the carrier population according to

$$dn/dt = \mathcal{J} \text{ (recall } n = p).$$

جهت جلوگیری از پراکندگی بحث هدف این است که روابط زیر را بدست آوریم
(معادلات نرخ حاملها و موج)

$$V\frac{dn}{dt} = -\begin{pmatrix}\text{Stimulated}\\ \text{Emission}\end{pmatrix} + \begin{pmatrix}\text{Stimulated}\\ \text{Absorption}\end{pmatrix} + JV - \begin{pmatrix}\text{Non-Radiative}\\ \text{Recombination}\end{pmatrix} - \begin{pmatrix}\text{Spontaneous}\\ \text{Recombination}\end{pmatrix}$$

$$V\frac{dn}{dt} = -V\,v_g g\,\gamma + JV - \frac{n}{\tau_e}V$$

$$\frac{1}{\tau_e} = A + Bn + Cn^2 \qquad \text{and} \qquad A = 1/\tau_n$$

For good material, $A = C = 0$

$$\frac{dn}{dt} = -\,v_g g\,\gamma + J - Bn^2$$

$$V_\gamma \frac{d\gamma}{dt} = +\begin{pmatrix}\text{Stimulated}\\ \text{Emission}\end{pmatrix} - \begin{pmatrix}\text{Stimulated}\\ \text{Absorptions}\end{pmatrix} - \begin{pmatrix}\text{Optical}\\ \text{Loss}\end{pmatrix} + \begin{pmatrix}\text{Fraction of}\\ \text{Spont. Emiss.}\end{pmatrix}$$

$$V_\gamma \frac{d\gamma}{dt} = +V\, v_g\, g(n)\, \gamma - V_\gamma \frac{\gamma}{\tau_\gamma} + \beta B n^2 V_\gamma$$

$$\frac{d\gamma}{dt} = +\Gamma\, v_g\, g(n)\, \gamma - \frac{\gamma}{\tau_\gamma} + \beta B n^2$$

$$\frac{dn}{dt} = -v_g\, g(n)\, \gamma + J - Bn^2$$

$$\frac{d\gamma}{dt} = +\Gamma v_g\, g(n)\, \gamma - \frac{\gamma}{\tau_\gamma} + \beta B n^2$$

که حال
همگی این
پارامترها
توضیح
داده
خواهد شد

Recombination Terms
- radiative
- nonradiative

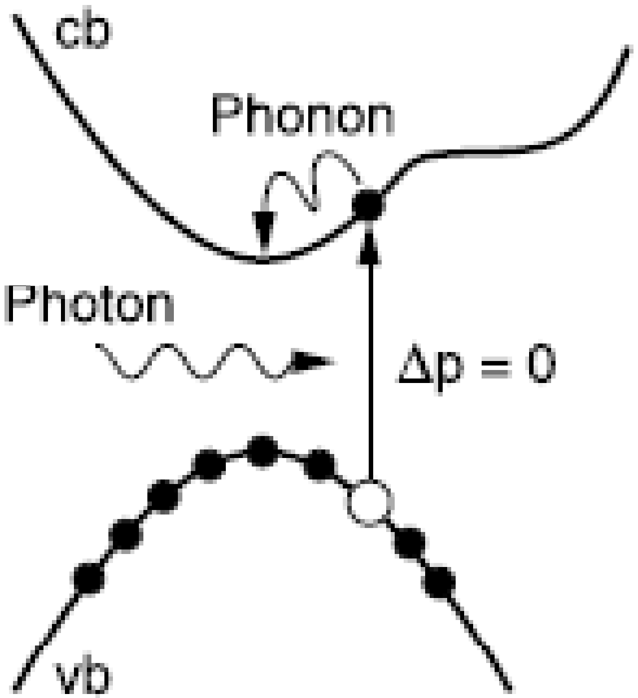
radiative

produces photons usually as spontaneous emission

Nonradiative recombination

occurs primarily through **phonon p**rocesses by material with **indirect bandgap**

The result is heat



Main process in the Laser

Monomolecular (nonradiative) $\frac{dn}{dt} = -\frac{n}{\tau_n} = -An$ $R_{mono}V = AnV$

bimolecular (radiative) $R_{sp}V = Bn^2V$

produces spontaneous emission

Auger recombination (nonradiative)

occurs when carriers transfer their energy to other carriers, which interact with phonons to return to an equilibrium condition

Auger recombination **is important** for lasers (such as InGaAsP) with emission wavelengths **larger than 1 mm (small bandgap)**

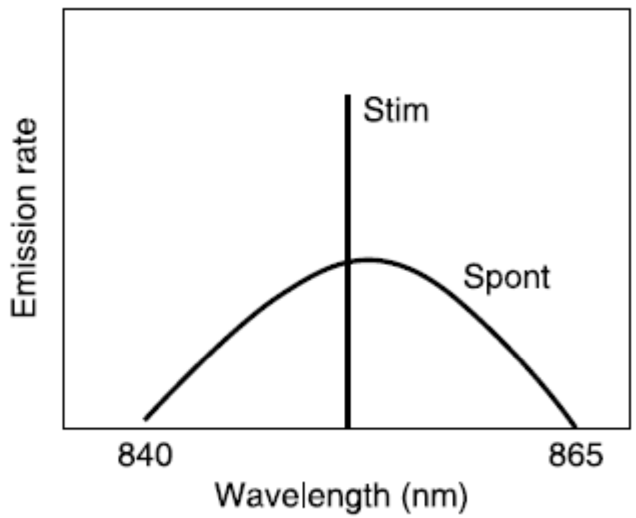
$$R_{aug}V = Cn^3V$$

$$R_r = R_{\text{radiative}} + R_{\text{nonradiative}} = An + Bn^2 + Cn^3$$

$$\frac{1}{\tau_e} = A + Bn + Cn^2$$

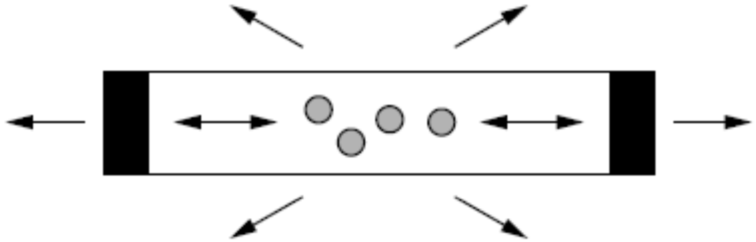
Spontaneous Emission Term

Of those photons that enter the waveguide, a fraction of them have exactly the right frequency to match that of the lasing mode



$$V_\gamma R_{sp} = V_\gamma \beta B n^2$$

The Optical Loss Term



All of the optical losses contribute to an overall relaxation time τ_γ

called the cavity lifetime

$$V_\gamma \frac{d\gamma}{dt} = -\frac{V_\gamma \gamma}{\tau_\gamma}$$

$$\gamma(t) = \gamma_o \exp\left(-\frac{t}{\tau_\gamma}\right)$$

which shows that the initial photon density decays exponentially as the carriers are lost

Absorption and Gain

$$\alpha = \tau_\gamma^{-1} / v_g$$

$$\frac{1}{\tau_\gamma} = \alpha v_g$$

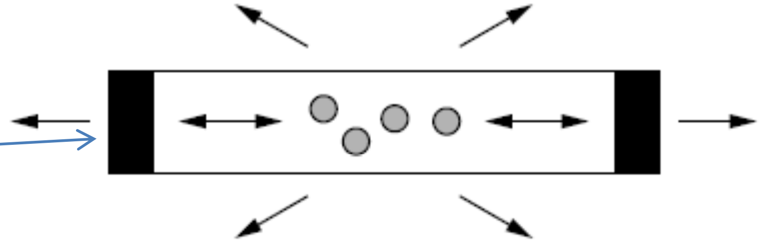
v_g represents the group velocity of the wave.

mirror loss α_m

as distributed along the length of the cavity

a partial differential equation with **boundary conditions** at the mirrors must be solved

result ➡ $\frac{1}{\tau_m} = v_g \alpha_m = \frac{v_g}{L} Ln(1/R)$



both mirrors have the same power reflectivity R (0.34 for GaAs).

The loss per mirror must be ➡ $\alpha_m/2.$

reciprocal of the cavity lifetime becomes $$\frac{1}{\tau_\gamma} = \frac{1}{\tau_{\text{int}}} + \frac{1}{\tau_m} = v_g \alpha = v_g(\alpha_{\text{int}} + \alpha_m)$$

Stimulated Emission—Absorption and Gain

types of gain
- Temporal Gain
- Single Pass Gain
- Material Gain
- Material Transparency
- Introduction to the Energy Dependence of Gain

Temporal Gain

The CB electrons and VB holes produce "gain" in the sense that incident photons with the proper wavelength can stimulate **carrier recombination** and thereby produce **more photons** with the same characteristics as the incident ones.

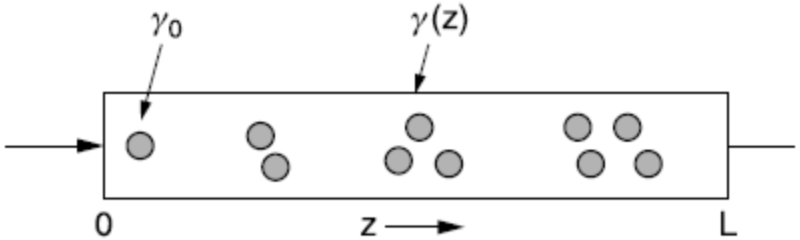
The word ''stimulated'' means that a photon must be incident on the material before either stimulated emission or absorption can proceed

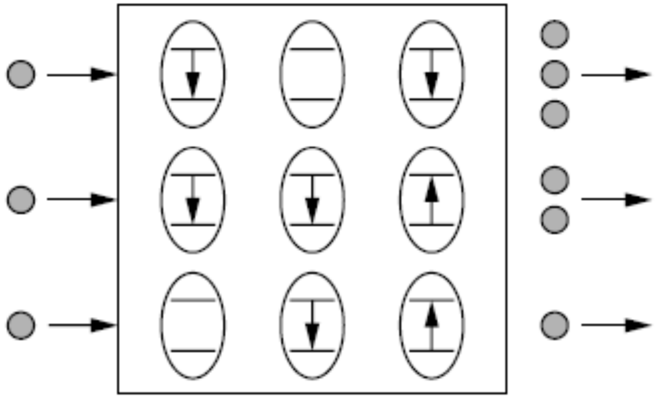
$$R_{\text{stim}} V_\gamma = V_\gamma \frac{d\gamma}{dt}\bigg|_{\text{stim}} \sim \gamma$$

$$R_{\text{stim}} V_\gamma = V_\gamma \frac{d\gamma}{dt}\bigg|_{\text{stim}} = V g_t \gamma$$

$$R_{\text{stim}} = \frac{d\gamma}{dt}\bigg|_{\text{stim}} = \frac{V}{V_\gamma} g_t \gamma = \Gamma g_t \gamma$$

Single Pass Gain





$$\frac{d\gamma}{dz} = \Gamma g \gamma \quad \rightarrow \quad \gamma(z) = \gamma(0)\, e^{\Gamma g z}$$

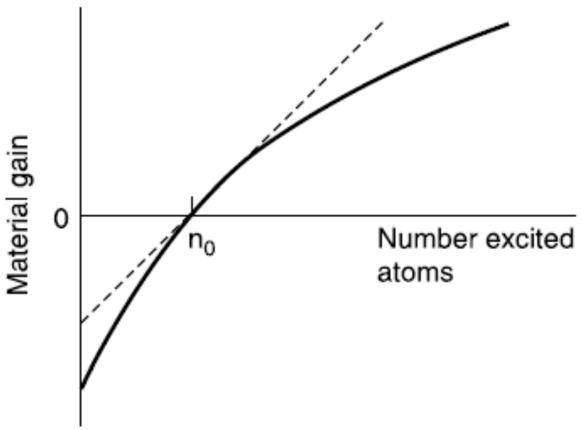
$$G = e^{\Gamma g z}$$

Material Gain

$$g \sim \frac{1}{\text{Length}} \sim \frac{1}{\text{Sec}} \frac{\text{Sec}}{\text{Length}} \sim g_t \frac{t}{L} \sim \frac{g_t}{v_g}$$

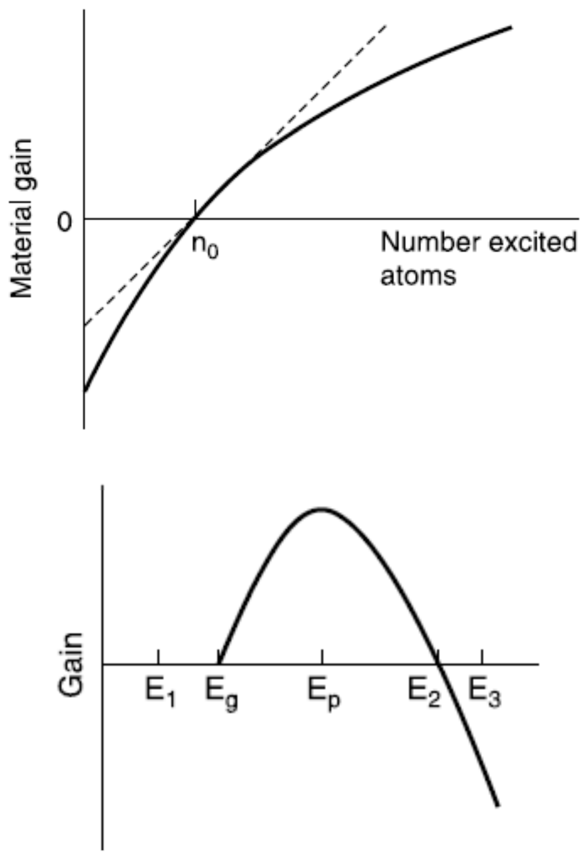
$$g(n) = g_o \operatorname{Ln}\left(\frac{n - n_\infty}{n_o - n_\infty}\right)$$

$$g_o(n) = \frac{dg(n)}{dn}$$



Material Transparency

G=1. The material gain in this case is g=0



Introduction to the Energy Dependence of Gain