

- **Fabrication des fibres**
- Types de fibres
- Dispersions dans les fibres
- LED et LASERS
- PIN et APD
- Amplificateurs optiques

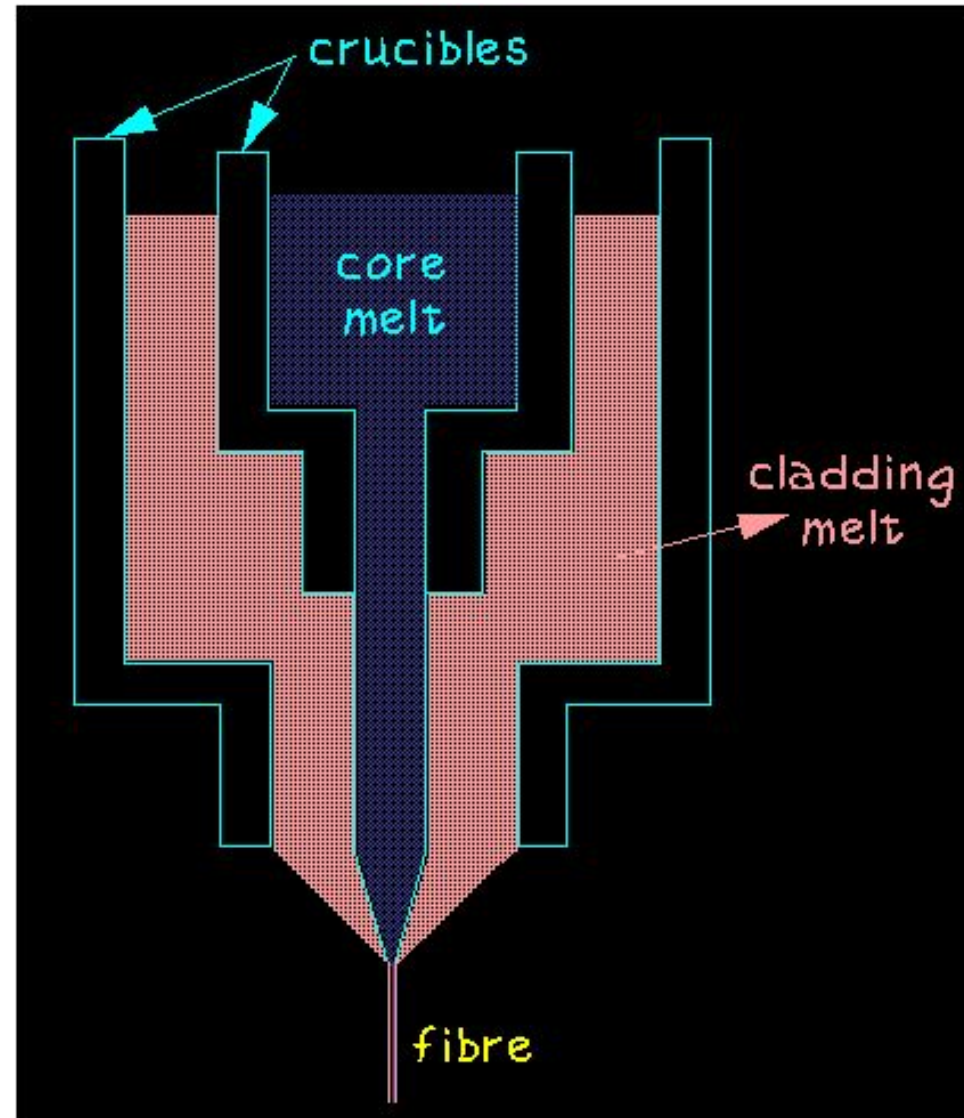


# Making optical fibres

For more information on this, visit  
<http://edweb.photonics.crc.org.au>

## Double crucible method:

- The molten core glass is placed in the inner crucible.
- The molten cladding glass is placed in the outer crucible.
- The two glasses come together at the base of the outer crucible and a fibre is drawn.
- Long fibres can be produced (providing you don't let the content of the crucibles run dry!).
- Step-index fibres and graded-index fibres can be drawn with this method.

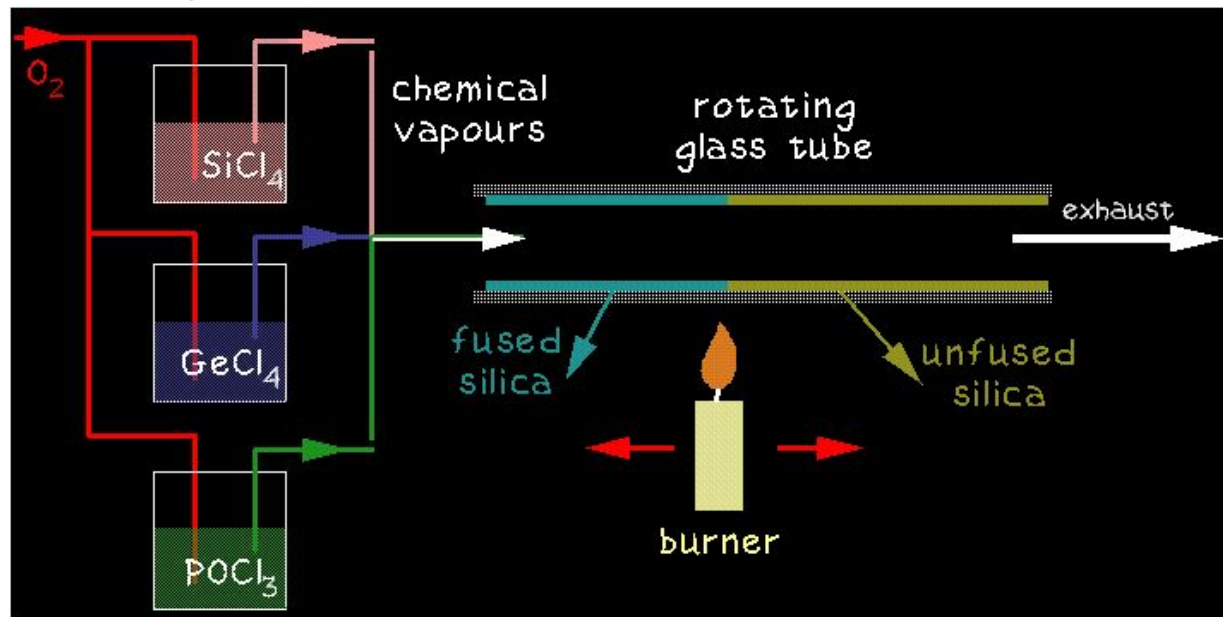




## Making optical fibres

### Modified Chemical Vapour Deposition:

- Chemicals are mixed in vapour phase and react inside a glass tube rotating on a lathe. Fine particles of solid germano or phosphoro silicate glass deposit on the inside of the tube.
- A travelling burner moving along the tube stimulates a chemical reaction and also fuses the particles into glass on the inner wall of the tube.
- Outer cladding layers are deposited first, then core layers further in.
- Next the tube is heated to 2000 C and collapses into a “preform”
- The preform is then put into a furnace and is drawn into fibre.



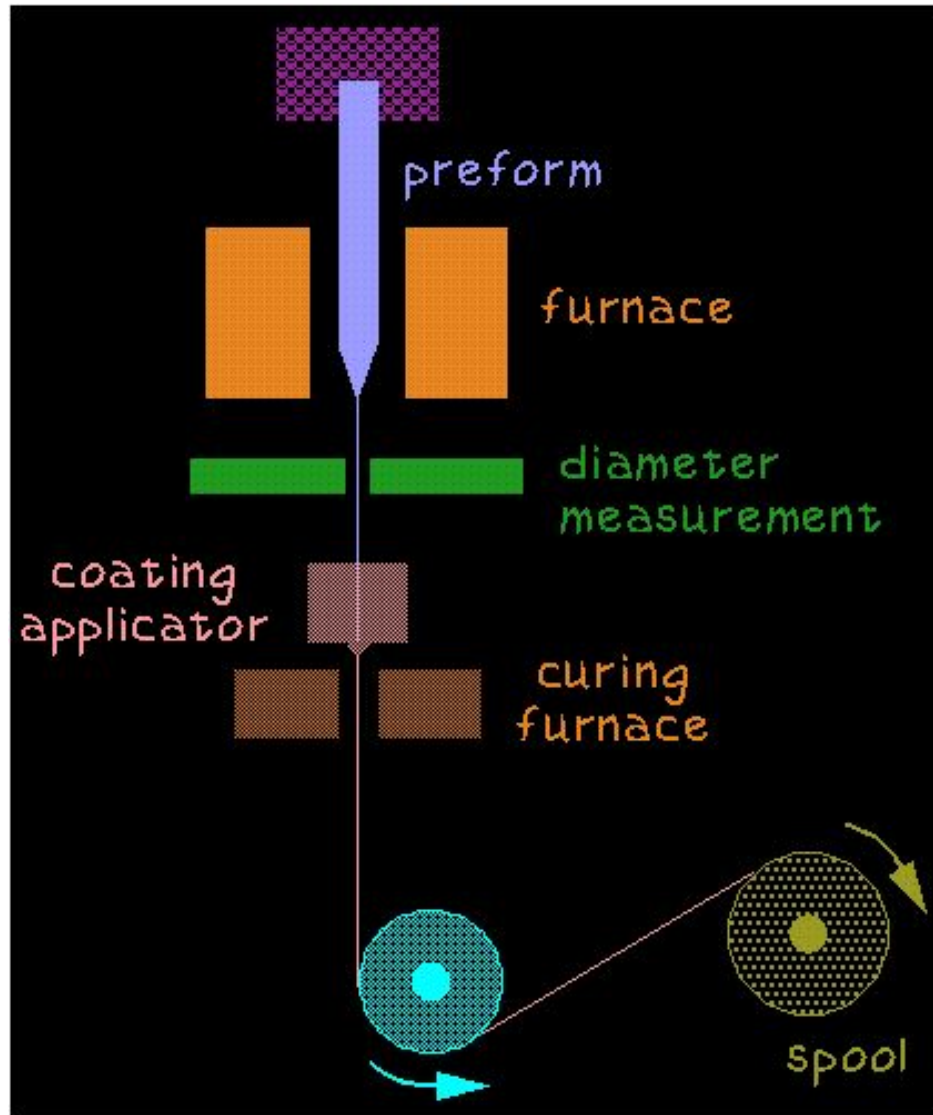
For more information on this, visit <http://edweb.photonics.crc.edu.au>



# Making optical fibres

## Drawing the fibre

- The tip of the preform is heated to about  $2000^{\circ}\text{C}$  in a furnace. As the glass softens, a thin strand of softened glass falls by gravity and cools down.
- The fibre diameter is constantly monitored as it is drawn.
- A plastic coating is then applied to the fibre, before it touches any components. The coating protects the fibre from dust and moisture.
- The fibre is then wrapped around a spool.

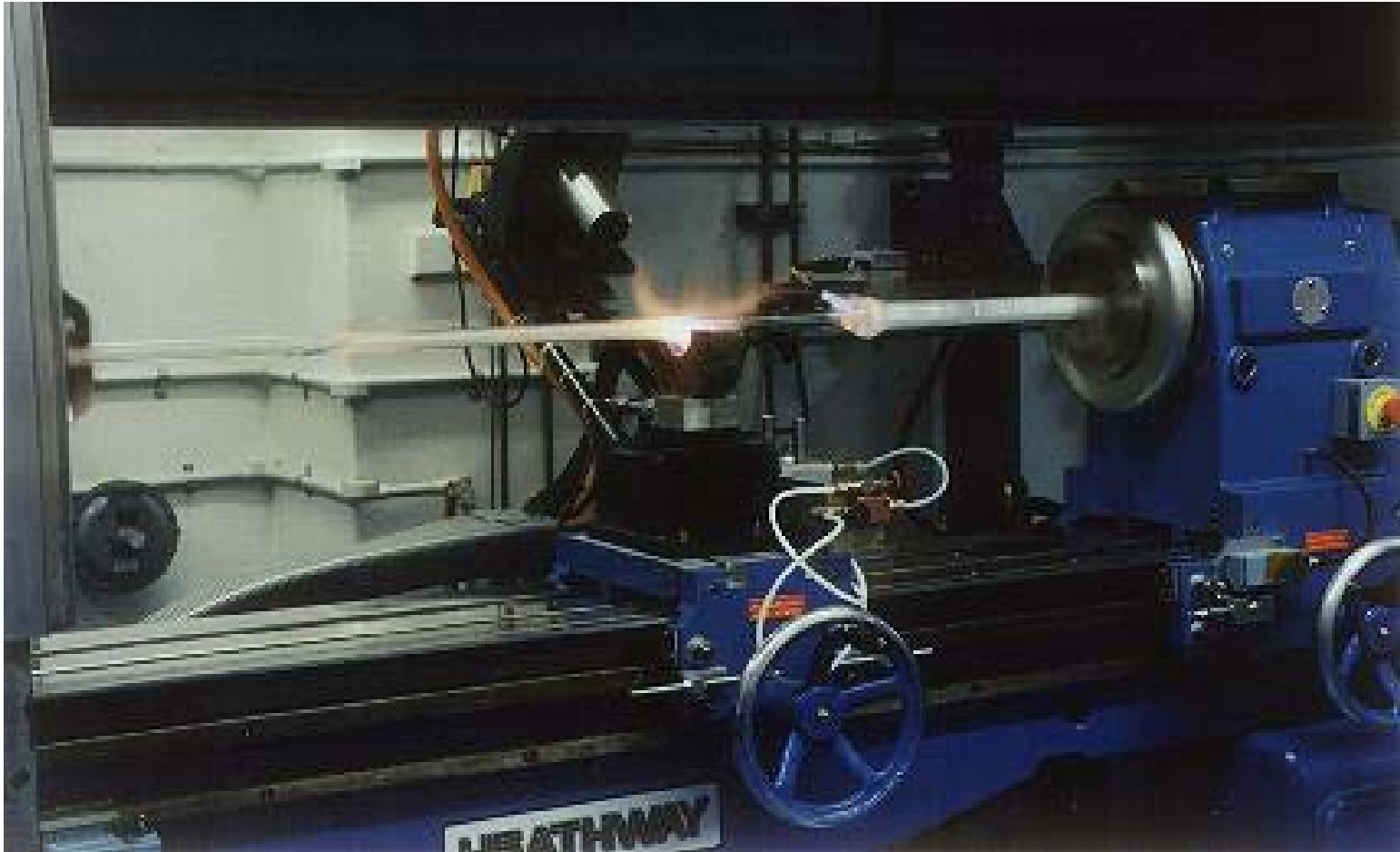


For more information on this, visit  
<http://edweb.photonics.crc.org.au>



## Making optical fibres

### Modified Chemical Vapour Deposition:



For more information on this, visit <http://edweb.photonics.crc.edu.au>

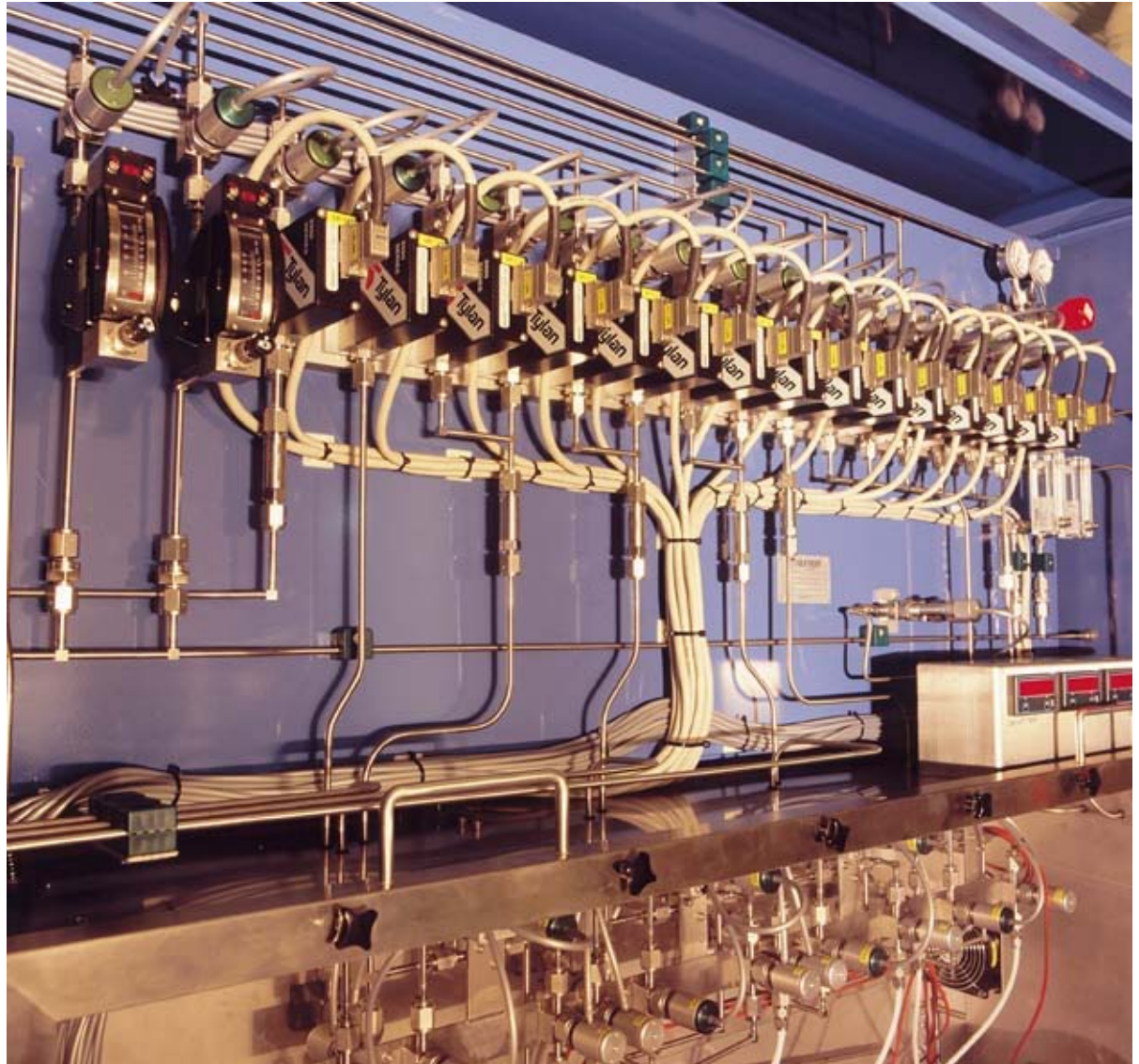




# Making optical fibres

## MCVD

A state-of-the-art array of computer-controlled valves used to adjust the flow of various gas phase reactants used in fabricating preforms for specialised optical fibres at OFTC, Australian Technology Park, Sydney, NSW.



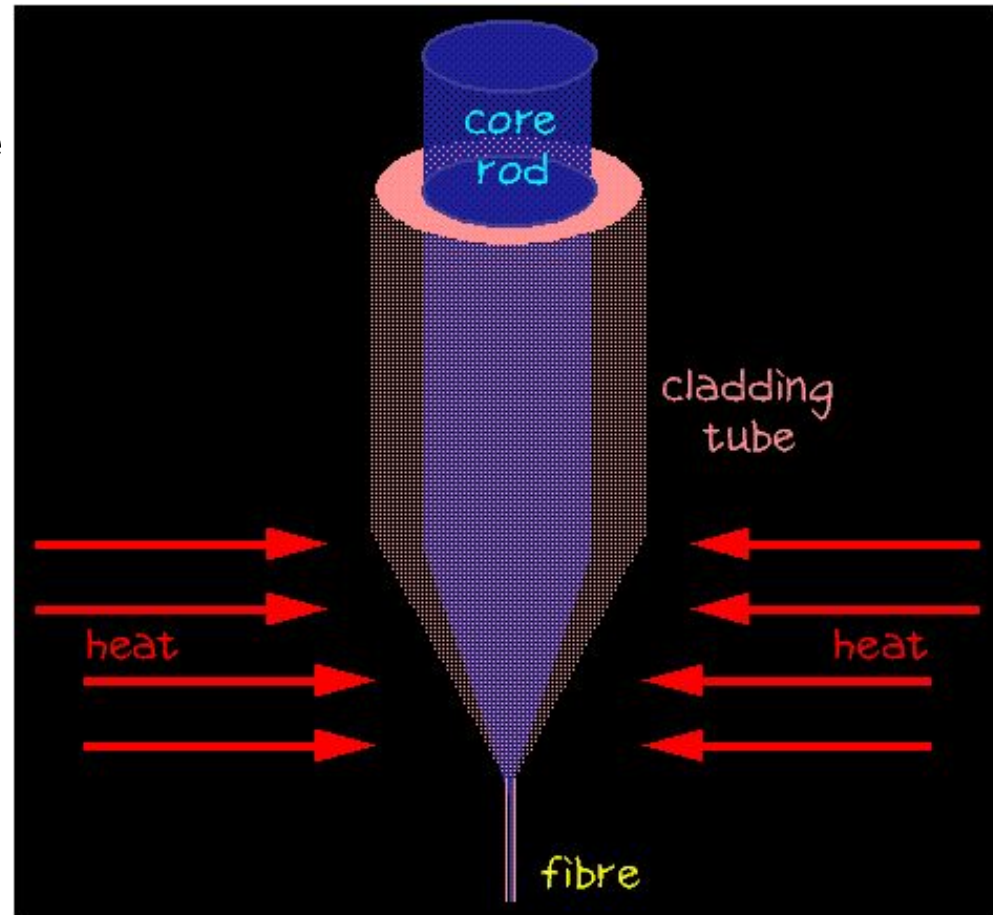


# Making optical fibres

For more information on this, visit <http://edweb.photonics.crc.edu.au>

## Rod-in-Tube method:

- A rod of core glass is placed inside a tube of cladding glass. The end of this assembly is heated; both glass are softened and a fibre is drawn.
- Rod and tube are usually 1 m long. The core rod has typically a 30 mm diameter. The core glass and the cladding glass must have similar softening temperatures.
- However, one must be very careful not to introduce impurities between the core and the cladding.







# Making optical fibres

## Fibre Drawing Tower (OFTC)







# Plan

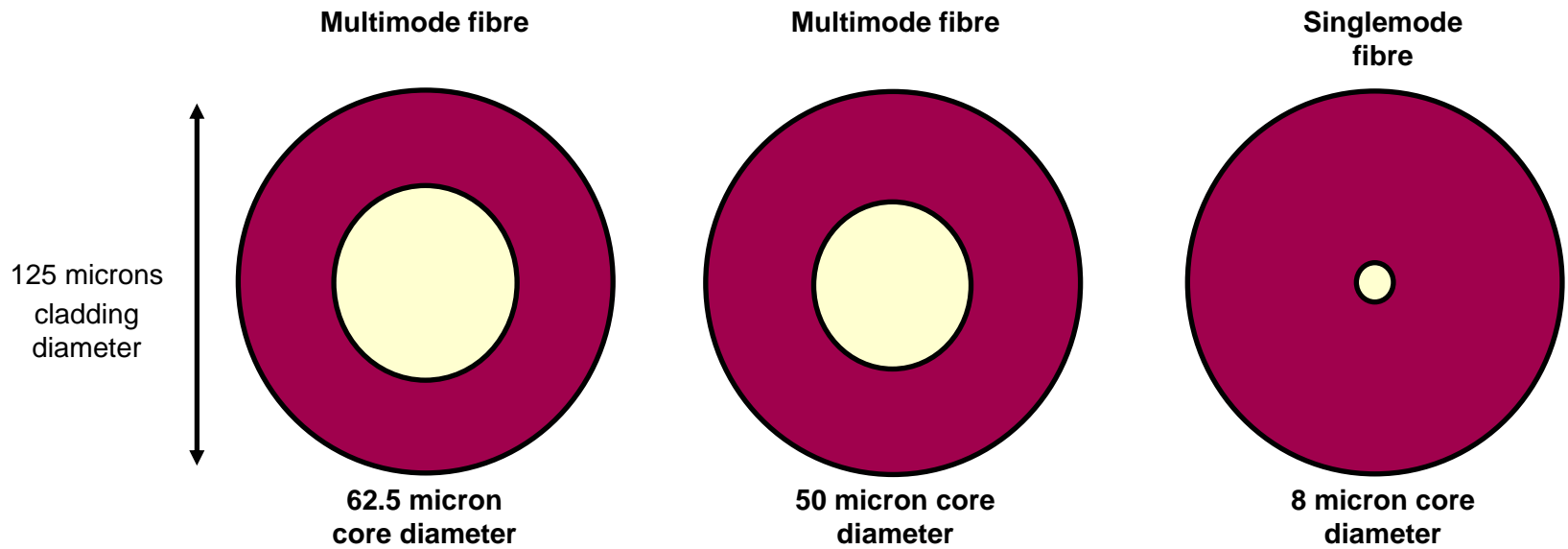
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- Fabrication des fibres
- **Types de fibres**
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# Fibre types

[www.renater.fr/IMG/pdf/2006-11-06\\_Types\\_de\\_fibres.pdf](http://www.renater.fr/IMG/pdf/2006-11-06_Types_de_fibres.pdf)

- Three generic fibre types dominate the building cable market
- Multimode is most popular but singlemode is now being installed more frequently
- Multimode is more tolerant of source and connector types
- Singlemode offers the largest information capacity



# Types de fibres

Tableau. 1 *Exemples de caractéristiques de quelques fibres optiques normalisées*

Norme UIT (Union International des Télécommunications)		G. 652 monomode	G. 653 monomode	G.655 (NZDSF)	G.655 (Téralight)
Propriétés géométriques	Diamètre coeur ( $\mu\text{m}$ )	9	9	9	9
	Diamètre fibre ( $\mu\text{m}$ )	125	125	125	125
Propriétés optiques (à 1550 $\mu\text{m}$ )	Atténuation (dB/km)	0,25	0,25	0,25	0,22
	Dispersion Chromatique (ps/nm/km)	17	0	0,07	8
	Coefficient de non-linéarité ( $\text{W}/\text{m}^2$ )	$2,7 \cdot 10^{-20}$	$2,7 \cdot 10^{-20}$	$2,7 \cdot 10^{-20}$	$2,7 \cdot 10^{-20}$
	Section effective ( $\mu\text{m}^2$ )	80	57	57	65
	PMD ps.km <sup>-1/2</sup>	0,05 à 0,08	0,1 max.	0,1 max.	0,04

Noms constructeurs des NZ-DSF:

- LEAF: Large Effective Area Fiber, Corning.
- TW-RS: True wave reduced slope fiber, Lucent.
- TW-C: Lucent
- SMF-LS: Corning



# Fibres à maintien de polarisation

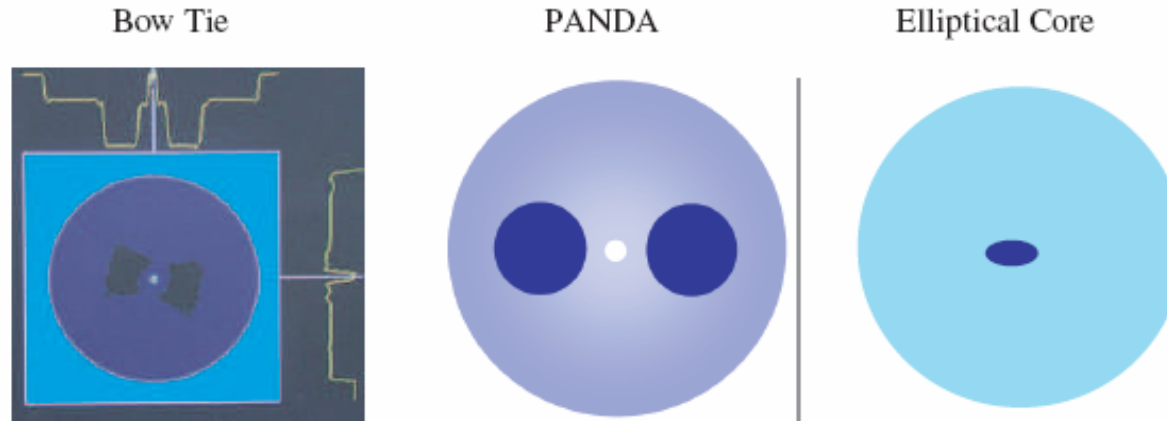


Figure 6: The 3 common methods used to create Polarization Maintaining optical fibers.

Supplier	Fiber Type	Mode Field Diameter ( $\mu m$ )	Beat Length / Birefringence	Loss
Stocker Yale	Bow Tie	10.5	4mm	–
Metrotek	Bow Tie	10.5	2mm	2 dB/km
Fibercore	Bow Tie	10.5	2mm	2 dB/km
KVH	Elliptical core	$2\mu m \times 4\mu m$ core	$B_m = 1.5 \times 10^{-4}$	9 dB/km
Fujikura	Panda	10.5	3-5mm	0.5dB/km

<http://www.ee.byu.edu/class/ee562/notes/mmf625.pdf>

<http://www.ee.byu.edu/class/ee562/notes/smf28.pdf>

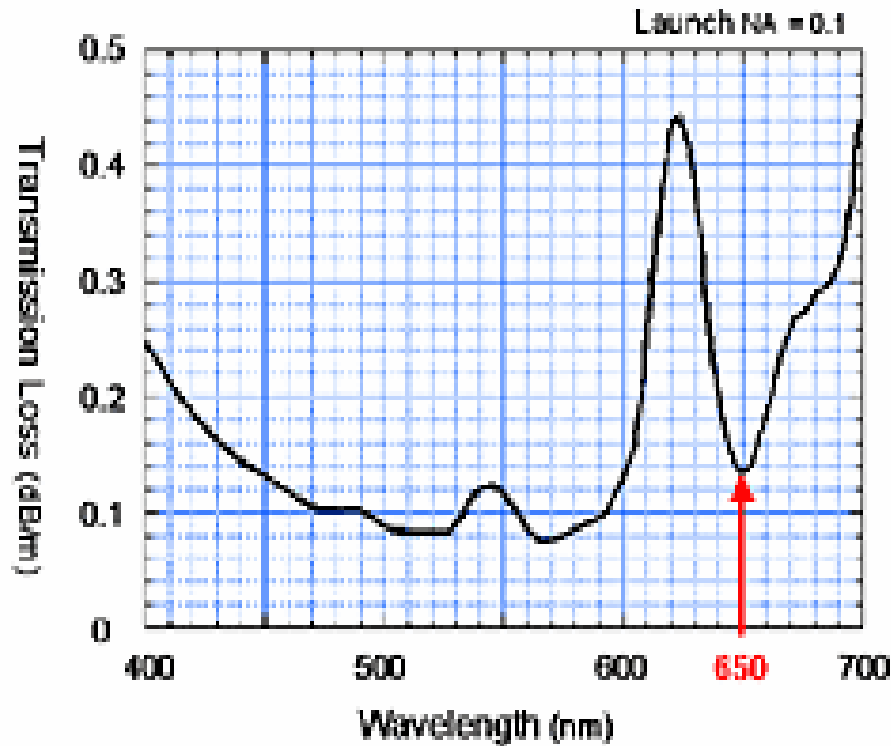
# Representative Fiber Characteristics

SOF Silica Optical Fiber

POF Plastic Optical Fiber

Description	Core Diameter ( $\mu\text{m}$ )	NA	Loss (dB/km)	$\Delta T/L$ $\Delta(\tau/L)$ (ns/km)	$BL$ $f_{3\text{-dB}} \times L$ (MHz $\times$ km)	Source	Wavelength (nm)
Multimode							
Glass							
SI	50	0.24	5	15	33	LED	850
GRIN	50	0.24	5	1	500	LD	850
GRIN	50	0.20	1	0.5	1000	LED, LD	1300
PCS							
SI	200	0.41	8	50	10	LED	800
Plastic							
SI	1000	0.48	200	—	—	LED	580
Single Mode							
Glass	5	0.10	4	<0.5	>1000	LD	850
Glass	10	0.10	0.5	0.006	83000	LD	1300
Glass	10	0.10	0.2	0.006	83000	LD	1550

# fibres plastiques



## PCS

Plastic Clad Silica Fiber

## GI-POF

Graded Index Plastic Optical Fiber

## SI-POF

Step Index Optical Fiber





# Sources

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cnam.probatoire.pdf sur CD

fiber\_types.pdf sur CD

c'est ici qu'il faut dire qq sur les POF

Les prix: voir site [www.thorlabs.com](http://www.thorlabs.com)

Le tableau vient de EE230-4



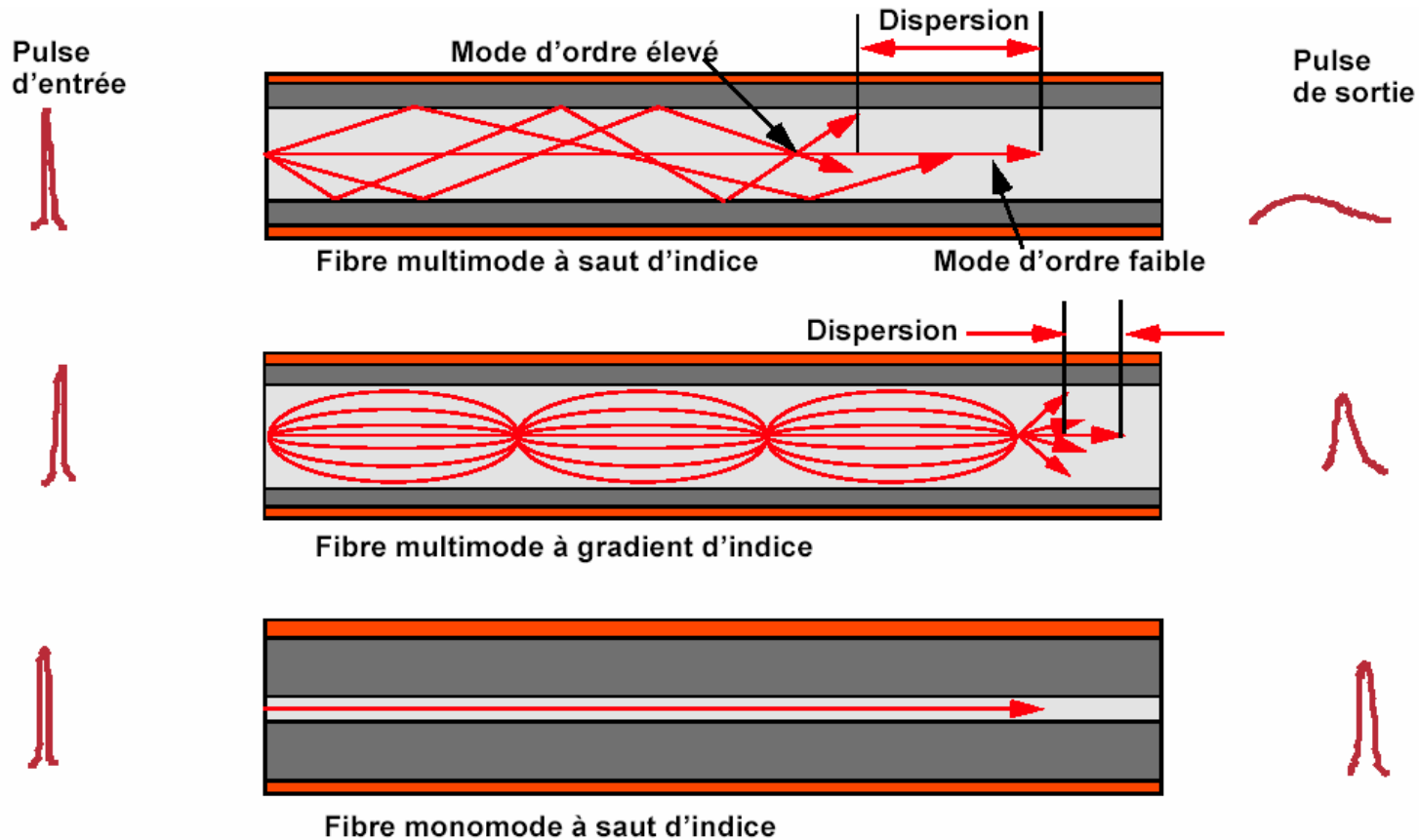
# Plan

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- Fabrication des fibres
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# Dispersion

*On est plus limité par les dispersions que par l'atténuation*



.....les Solitons





# Definitions

Vitesse de groupe

$$v_g = \left( \frac{\partial \beta}{\partial \omega} \right)^{-1}$$

Retard de groupe  
(par unité de longueur)

$$\tau = \frac{\partial \beta}{\partial \omega} = \frac{1}{c} \frac{\partial \beta}{\partial k}$$

Dispersion

$$D = \frac{\partial \tau}{\partial \lambda}$$

## Types of Dispersion

**Modal dispersion:** different modes propagate at different group velocities

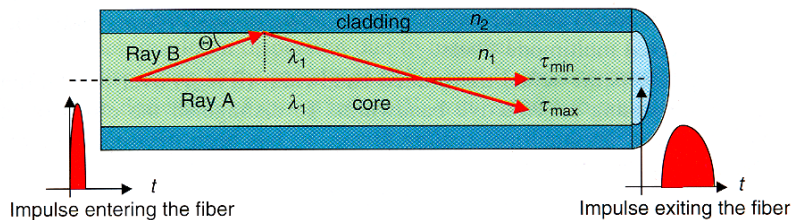
**Chromatic dispersion:** the index of refraction of the medium changes with wavelength (**ps/nm.km**)

**Waveguide dispersion:** index change across waveguide means that different wavelengths have different delays

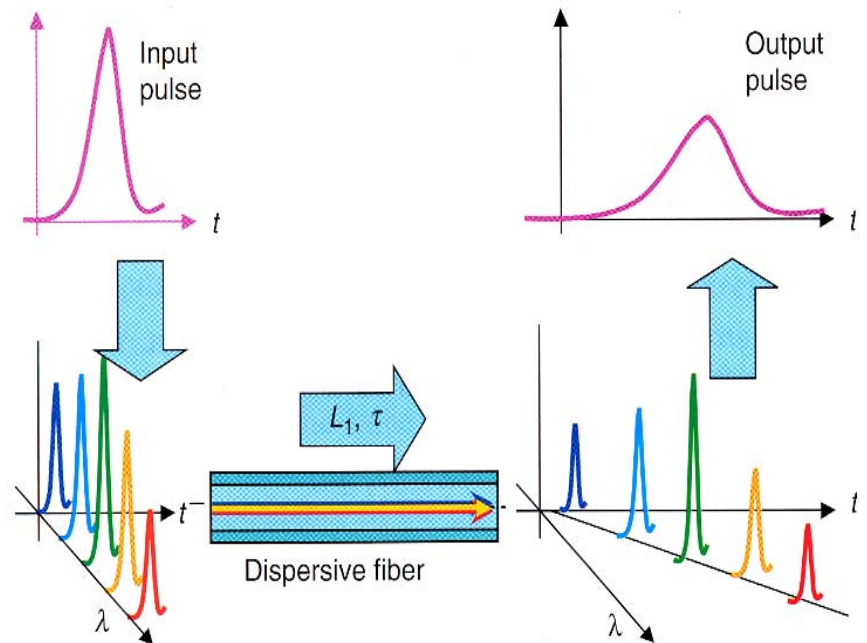
**Polarization mode dispersion:** if waveguide is birefringent

# Dispersions

## *Modal Dispersion*



## *Chromatic dispersion*



***Modal Dispersion is zero in Single Mode Fiber***

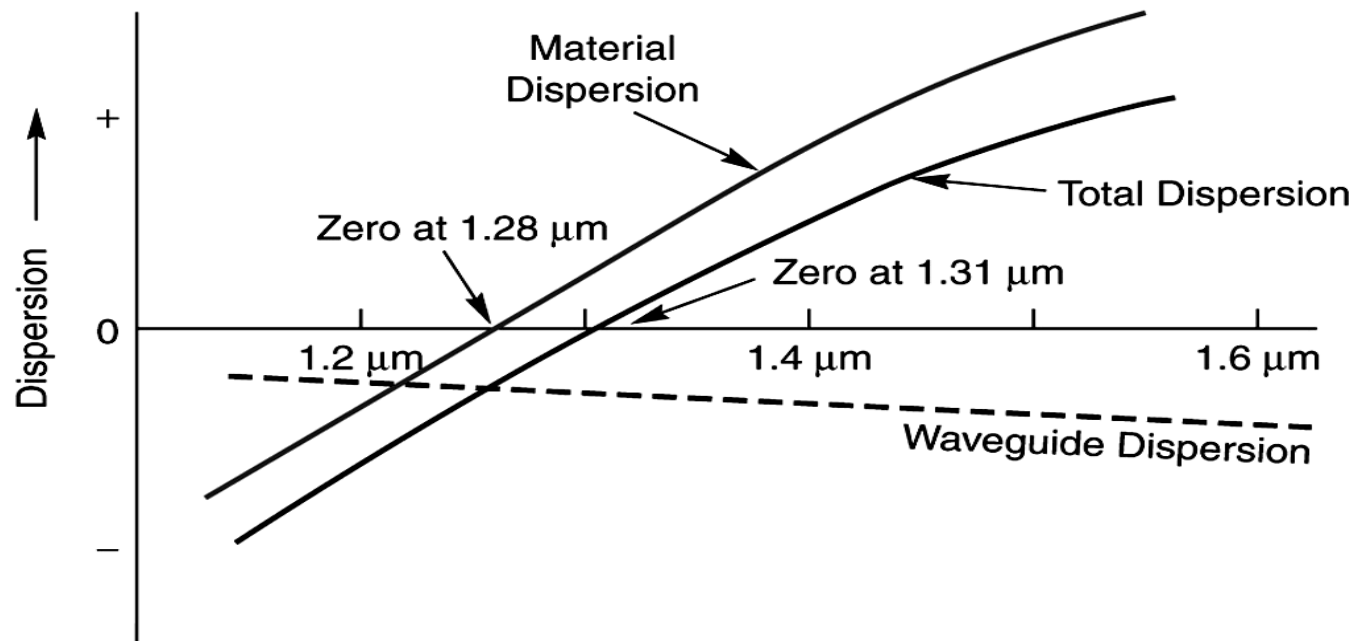
# Non-Dispersion-Shifted Fiber (NDSF) G.652

*...or standard single-mode,*

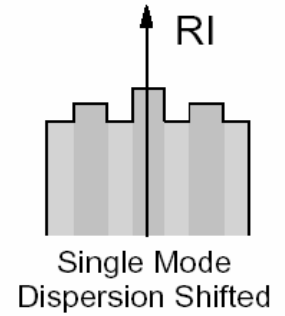
**zero chromatic dispersion at 1310 nm**

**Lasers and Detectors at 1310 nm are inexpensive.**

Doc IBM p87



# Dispersion-Shifted Fiber (DSF), G.653

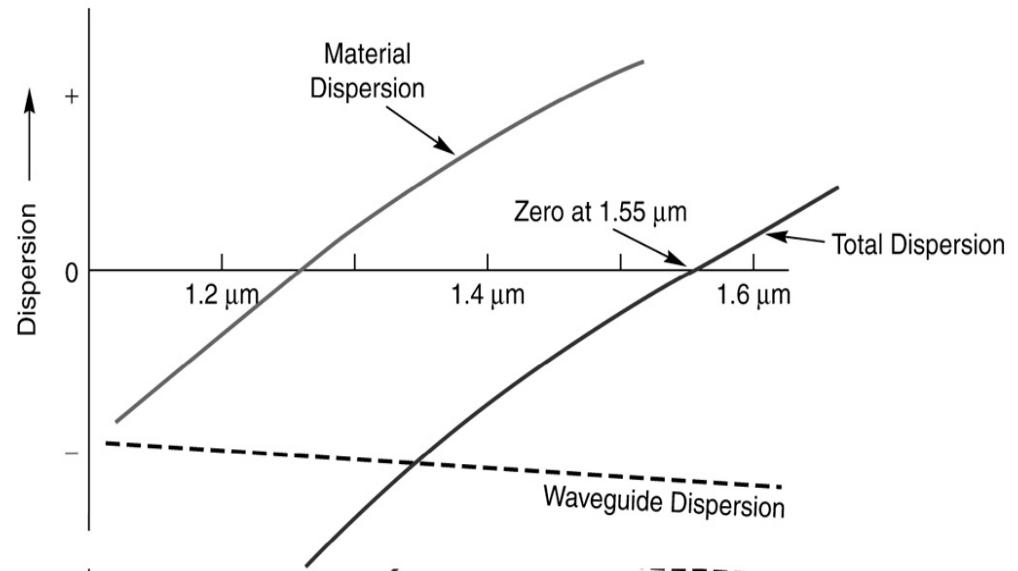


*for C and L bands :*

- lower attenuation
- operating wavelength is the same as that of EDFA 's
- but dispersion characteristics are severely limiting

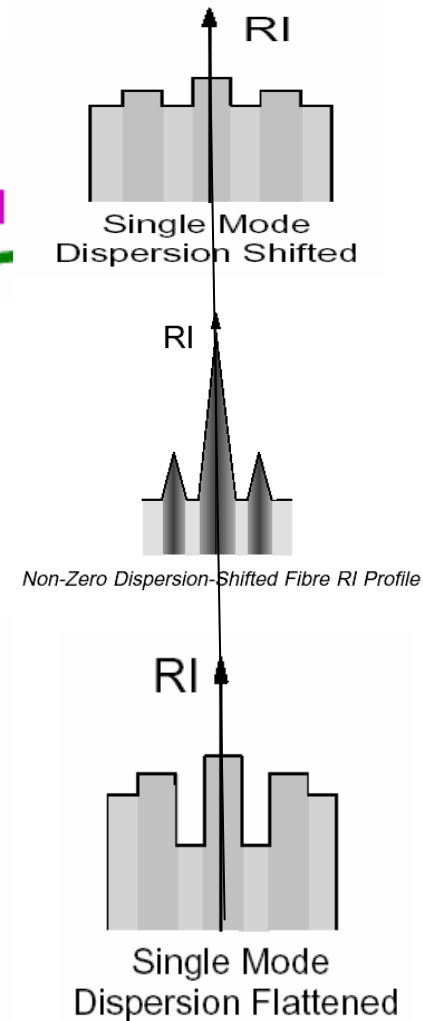
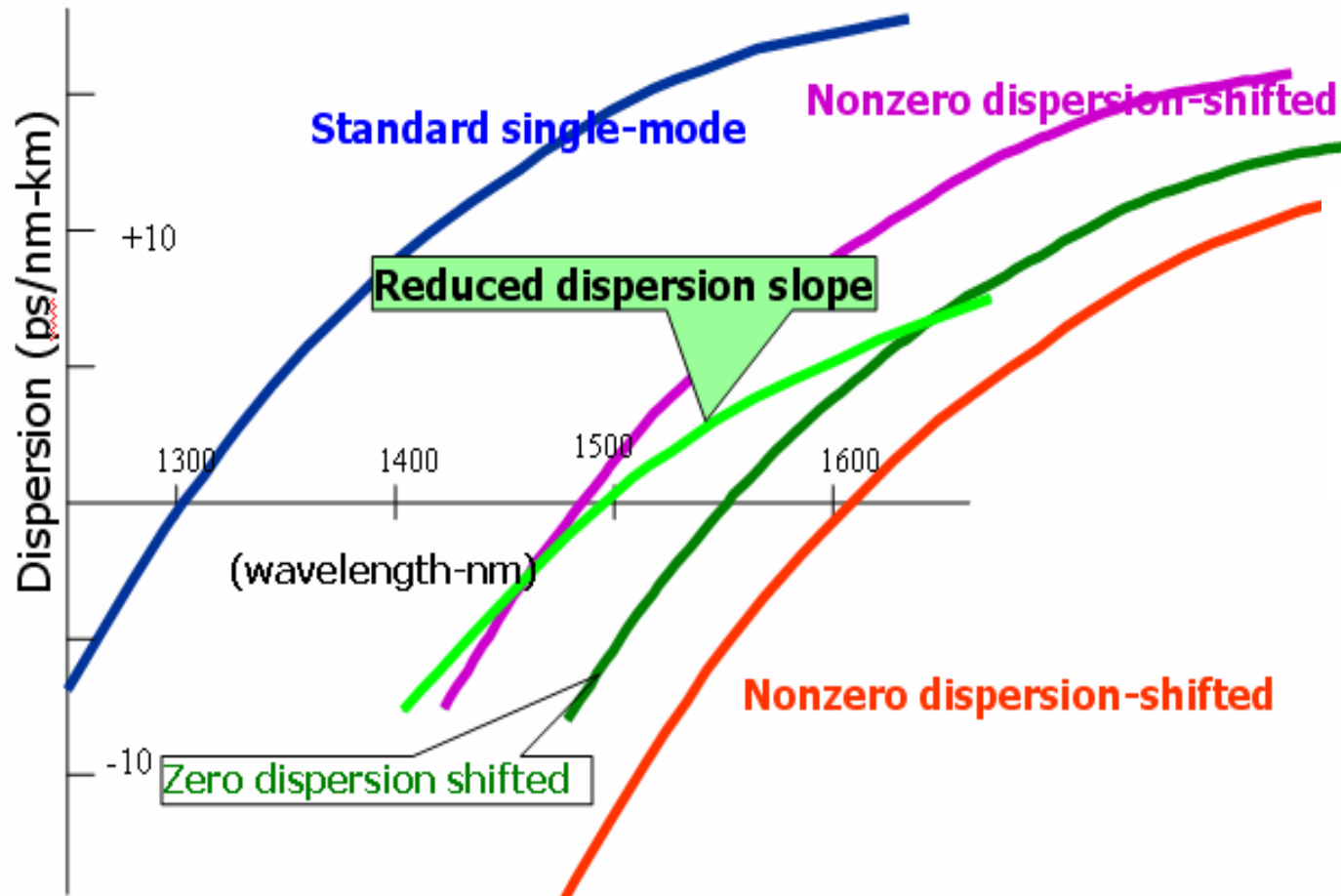
- Material and waveguide dispersion cancel at about 1310 nm
- This can be moved to 1550 nm by using a layered core design

- zero-dispersion point at 1550 nm



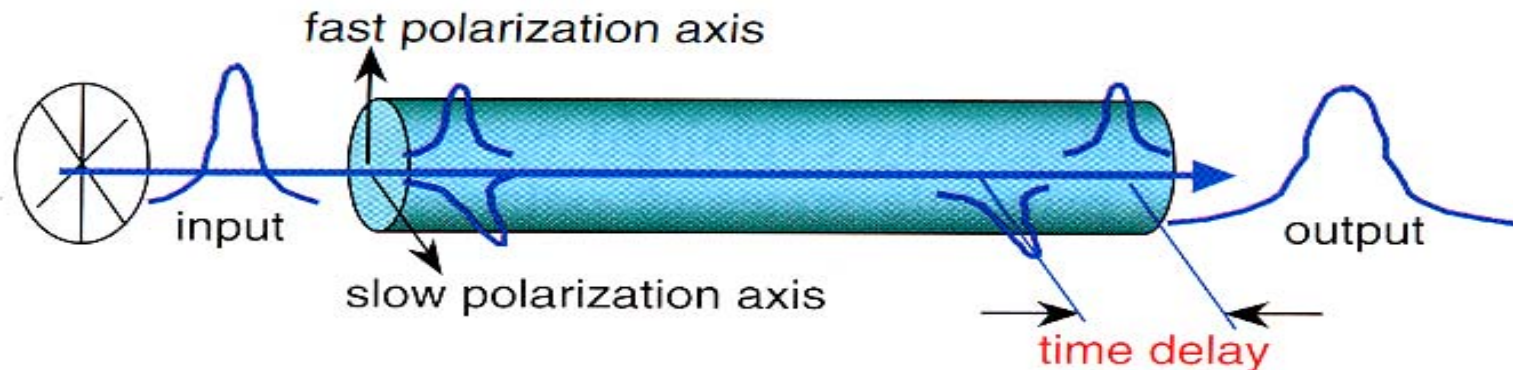
# Résumé

## Chromatic dispersion in single-mode fibers



# Polarization Mode Dispersion (PMD)

- caused by asymmetry and stress in the fiber core that results in birefringence
- An arbitrarily polarized pulse of light entering the fiber can be resolved into two components. These polarization modes will travel at different speeds through the fiber. It leads to pulse broadening
- PMD is measured in  $\text{ps}/(\text{Km}^{1/2})$



*PMD is important over 40 Gbps*  
[eri.ict.gov.ir/video/seminar84\\_10\\_28.ppt](http://eri.ict.gov.ir/video/seminar84_10_28.ppt)





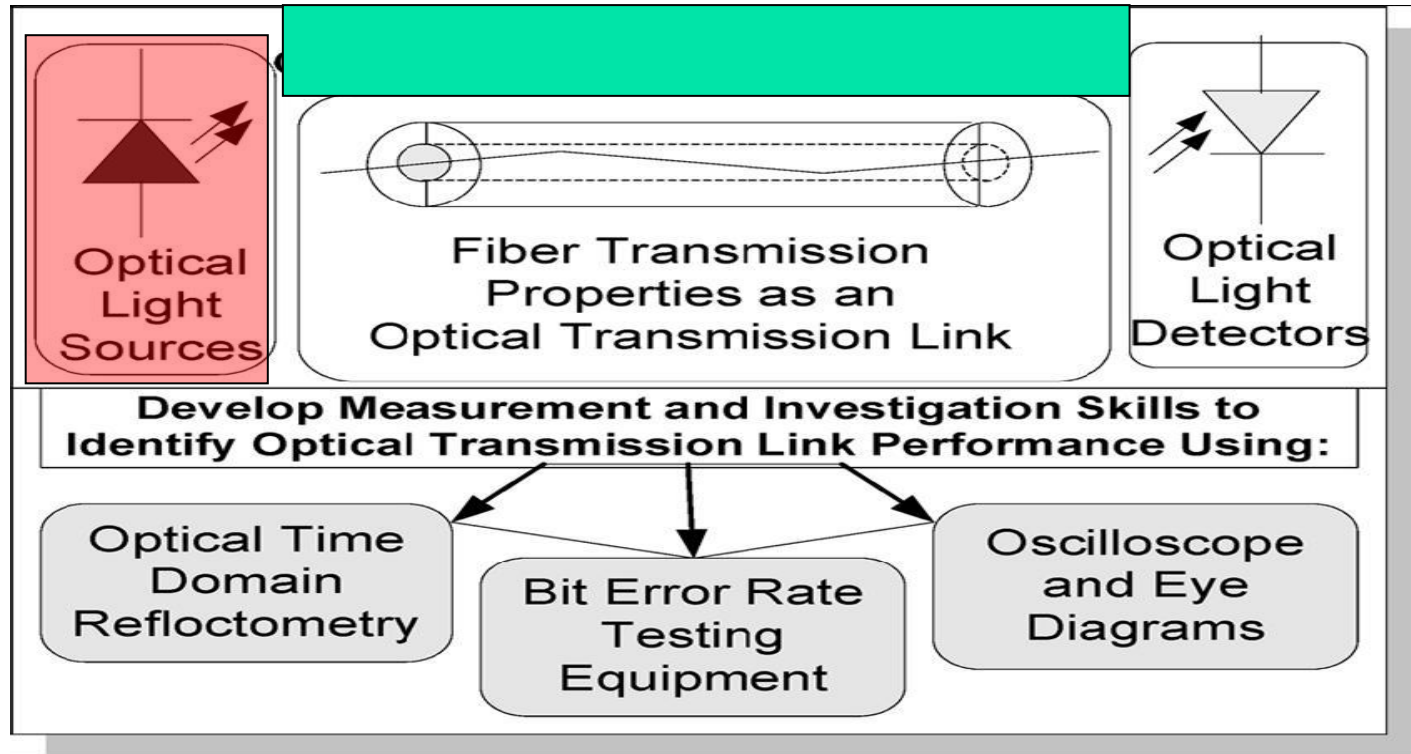
# Plan

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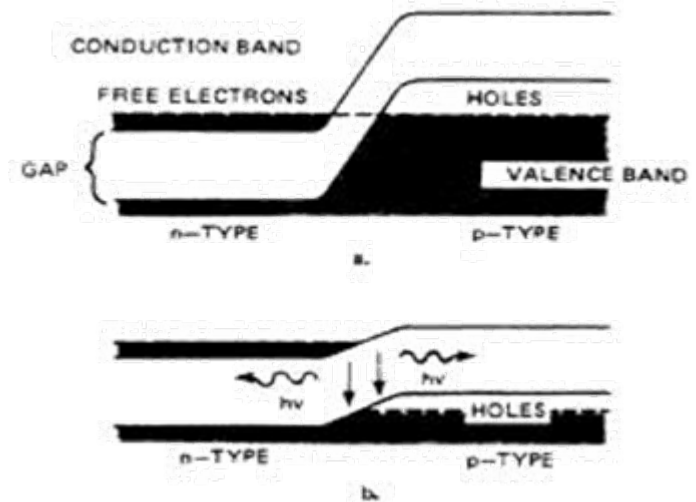
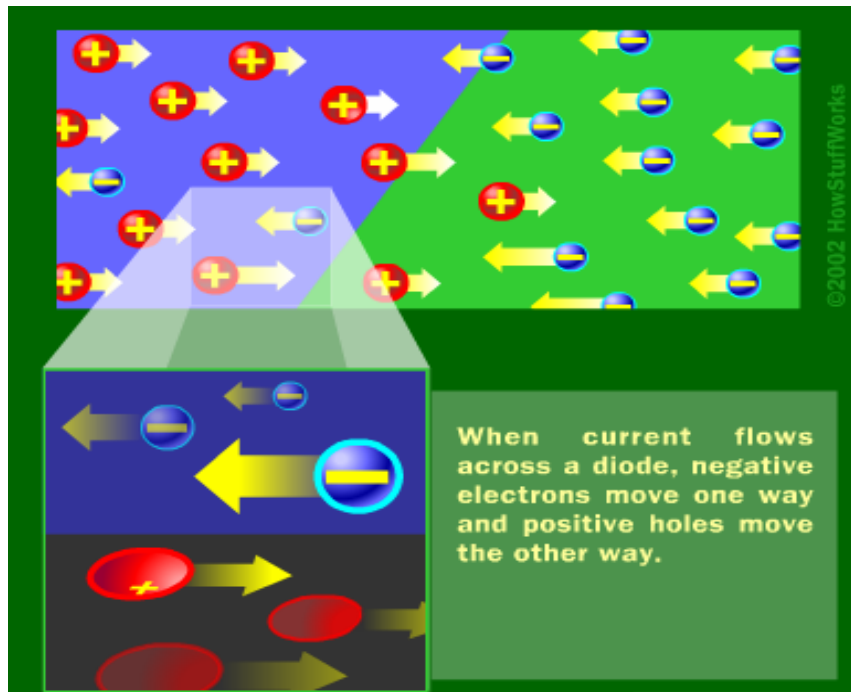
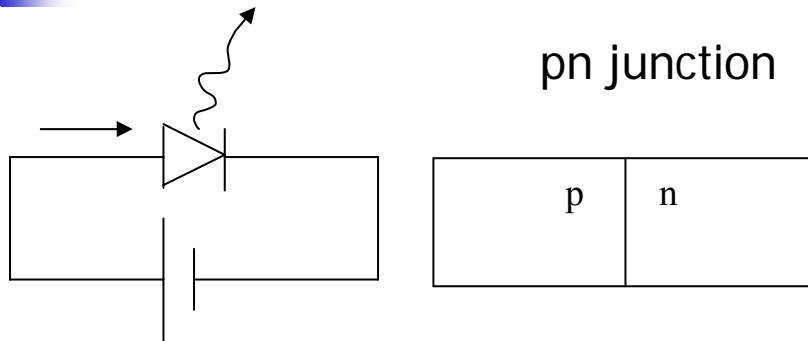
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# Diodes Electroluminescentes Diodes laser

## LED LD

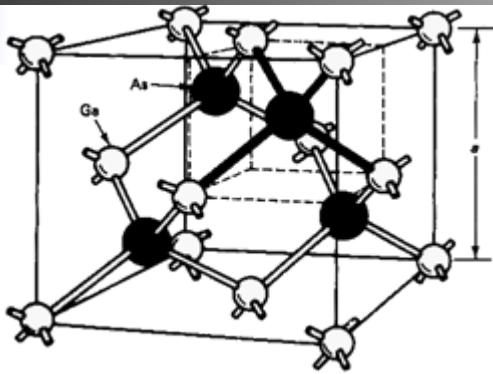


# Light emitting diode LED

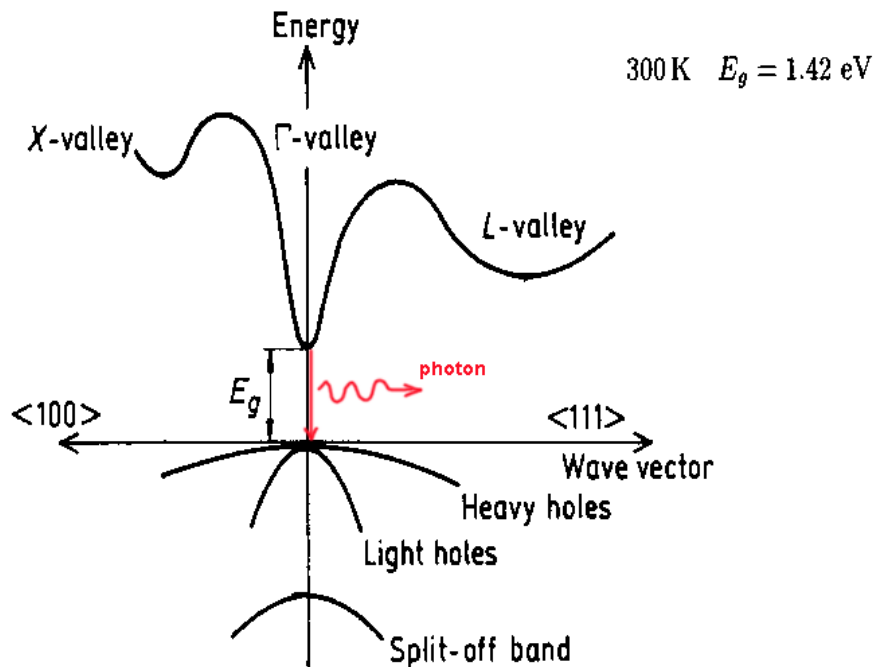


For the LED, all of the light is created by **spontaneous emission** to electron and hole recombination.

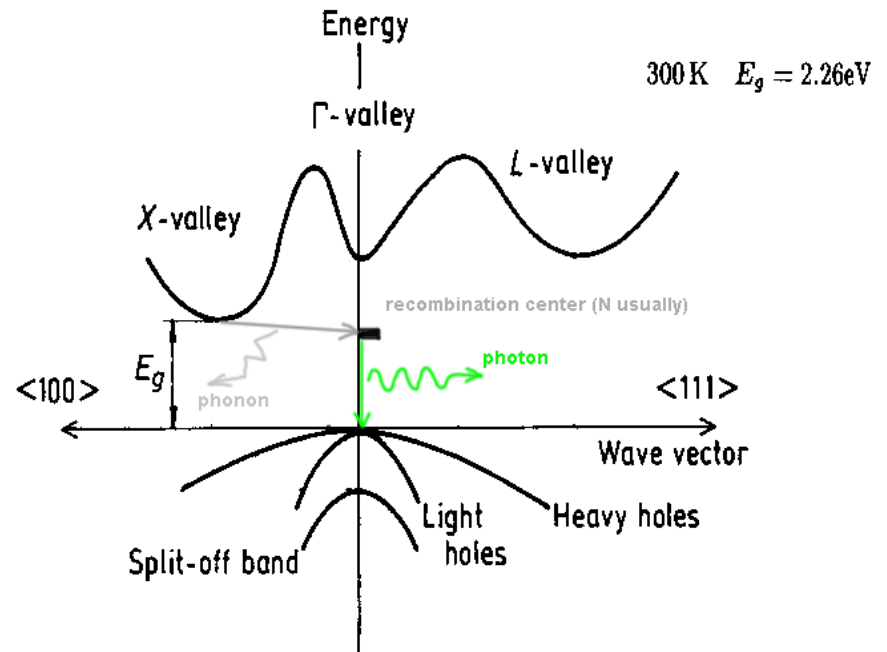
# III-Vs. Band structure



Direct bandgap semiconductor  
→ high emission efficiency!  
→ sharp absorption.



GaAs - direct



GaP - indirect

# Light Source Material

## Periodic table and semiconductors

IIB	IIIB	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg	Tl	Pb	Bi	Po

**IV (Si, Ge)**

**III-V (GaAs, GaN, InP, InSb)**

**II-VI (CdS, CdTe, ZnS, ZnSe)**

**I-VII (CuCl, CuI)**

**I-III-VI<sub>2</sub> (CuAlS<sub>2</sub>, CuInSe<sub>2</sub>)**

**II-IV-V<sub>2</sub> (CdGeAs<sub>2</sub>, ZnSiP<sub>2</sub>)**

Most of the light sources contain III-V ternary & quaternary compounds.

$\text{Ga}_{1-x}\text{Al}_x\text{As}$  by varying  $x$  it is possible to control the band-gap energy and thereby the emission wavelength over the range of 800 nm to 900 nm. The spectral width is around 20 to 40 nm.

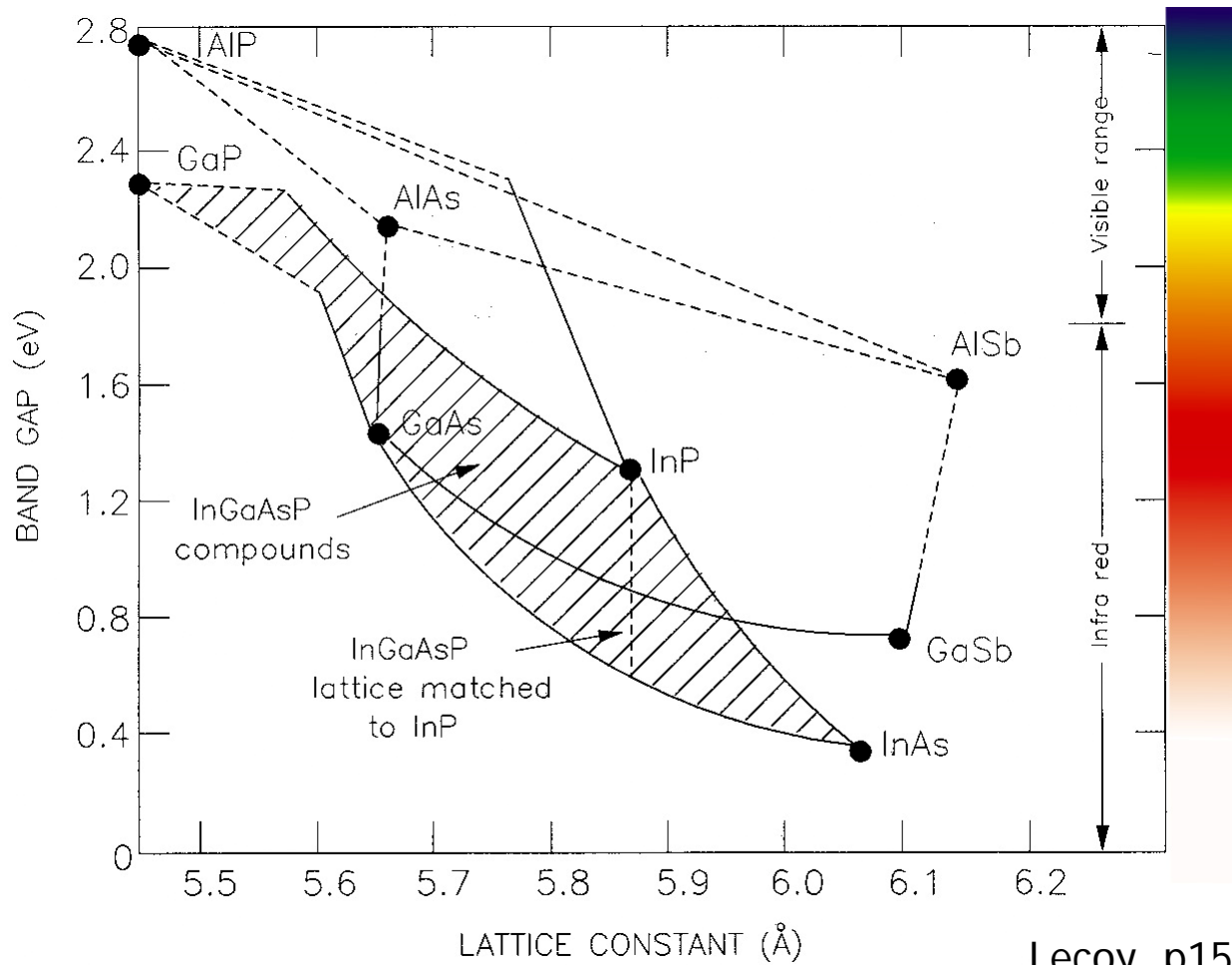
$\text{In}_{1-x}\text{Ga}_x\text{AsP}_{1-y}$  By changing  $0 < x < 0.47$ ;  $y$  is approximately  $2.2x$ , the emission wavelength can be controlled over the range of 920 nm to 1600 nm. The spectral width varies from 70 nm to 180 nm when the wavelength changes from 1300 nm to 1600 nm. These materials are lattice matched.

# III-Vs for Optoelectronics

Materials	Type	Substrate	Devices	$\eta$ -extern, %	$\lambda$ , nm
GaP	III-V	GaP	Detectors, Green LEDs	<1	150-550
InGaN	III-V	GaN, SiC	Blue LEDs, lasers	2	405-460
InGaN	III-V	Sapphire	Green LEDs	3	500-530
AlGaAs	III-V	GaAs	LEDs, lasers, Imagers	5-20	640-870
GaAs	III-V	GaAs	LEDs, Lasers, Solar Cells, Intensifiers, Imagers	10	870-900
InGaP	III-V	GaP	Visible Lasers, LEDs Solar Cells		500-700
InAlGaP	III-V	GaAs	High-brightness LEDs	1-10	500-630
GaAsP	III-V	GaP	Visible LEDs	<1	560-700
GaAsP	III-V	GaAs	Red-IR LEDs	<1	630-870
InGaAs	III-V	InP	Detectors		940-1680
InGaAsP	III-V	InP	Telecom Lasers, LEDs	>10	1000-1600
InAlAs	III-V	InP	Lasers, Detectors		1000-2500
InAlGaAs	III-V	InP	Lasers, Detectors		1000-2500
GaSb/GaAlSb	III-V	GaSb	Lasers, Detectors		2000-3500



# III-Vs. Solid Solution. Bandgap Engineering



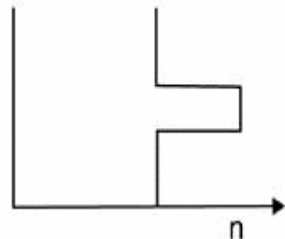
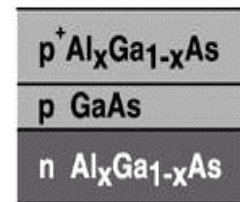
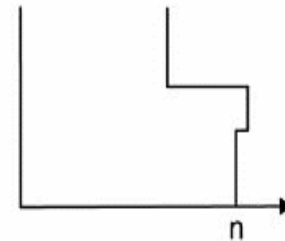
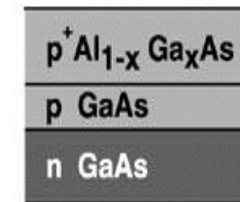
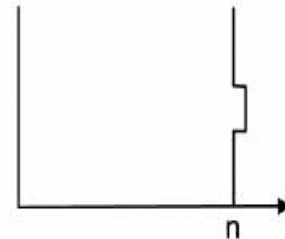
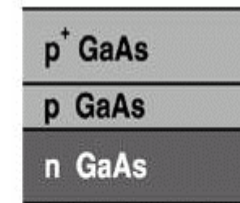
# Light emitting structure

$$\lambda(nm) = \frac{hc}{E(eV)}$$

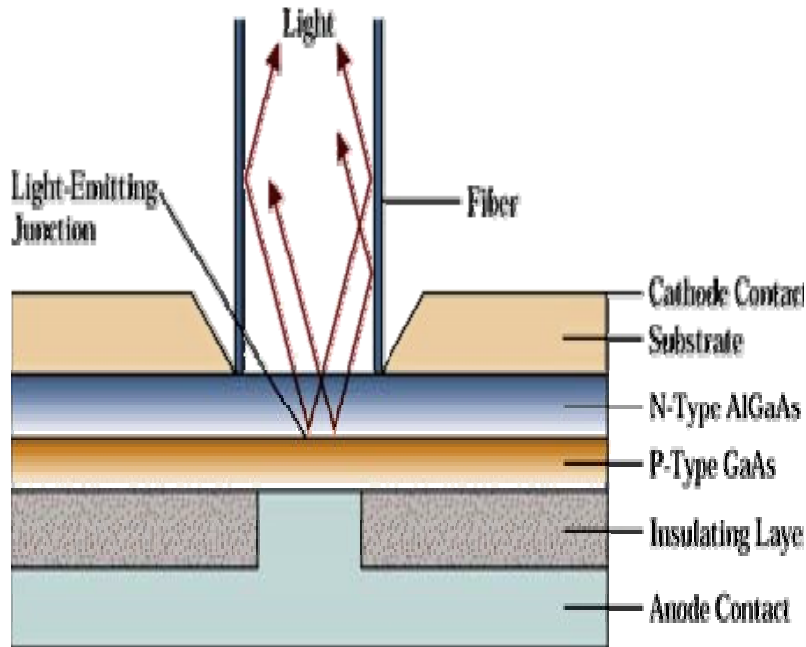
$$\lambda(nm) = \frac{1242}{E(eV)}$$

Material	Wavelength Range ( $\mu m$ )	Bandgap Energy (eV)
GaInP	0.64 - 0.68	1.82 - 1.94
GaAs	0.9	1.4
<b>AlGaAs</b>	<b>0.8 - 0.9</b>	<b>1.4 - 1.55</b>
InGaAs	1.0 - 1.3	0.95 - 1.24
<b>InGaAsP</b>	<b>0.9 - 1.7</b>	<b>0.73 - 1.35</b>

homojunction  
double heterojunction  
triple heterojunction



# Structures



Surface emitting

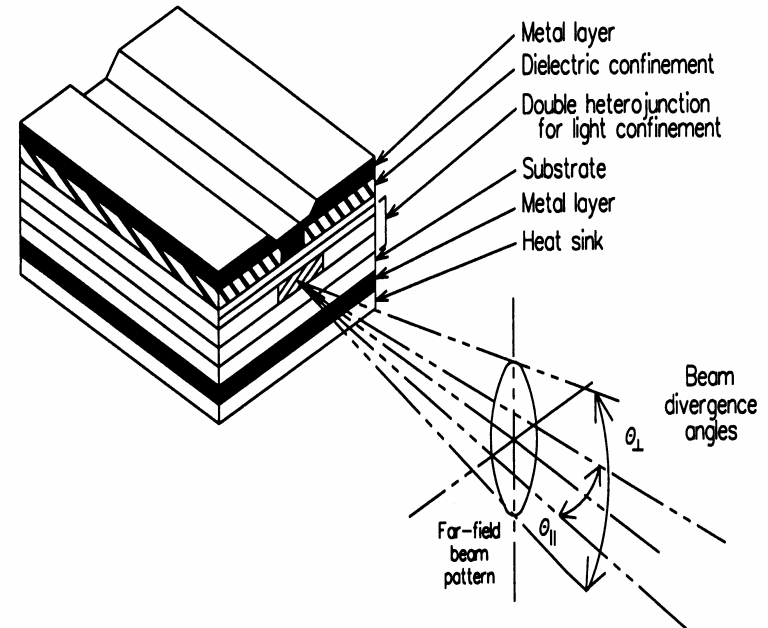
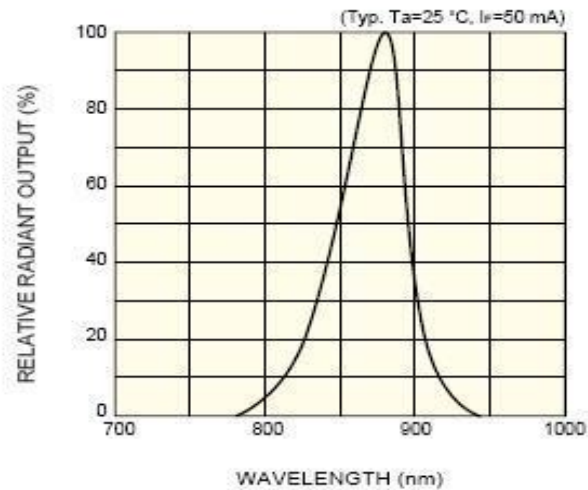


Figure 5.6 Representative edge emitter and far-field beam pattern.

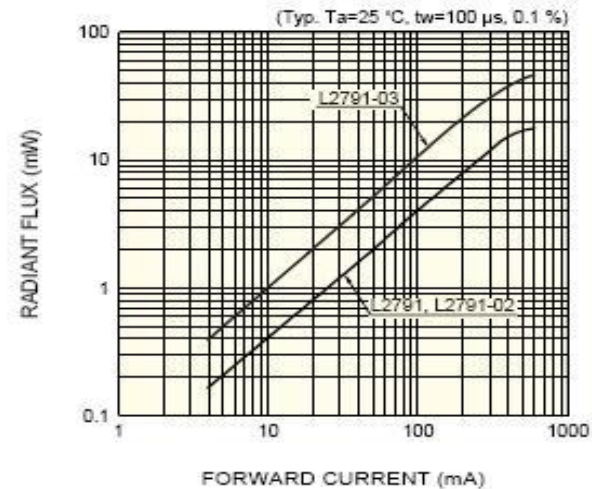
Edge emitting

# LED datasheet

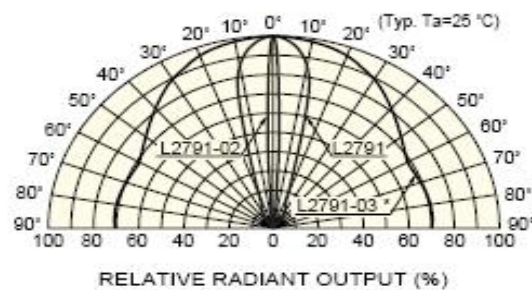
## ■ Emission spectrum



## ■ Radiant flux vs. forward current

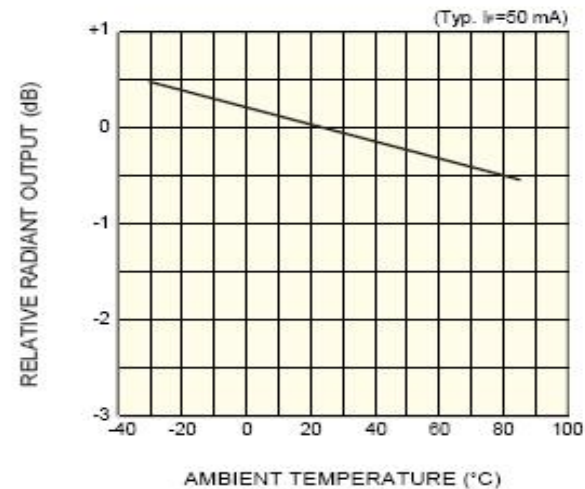


## ■ Directivity



\* L2791-03: Except for reflection ingredient of the base.

## ■ Radiant output vs. ambient temperature

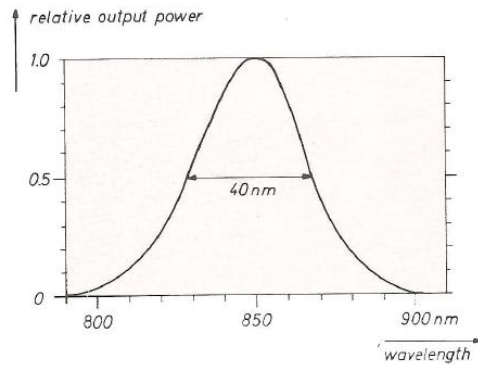




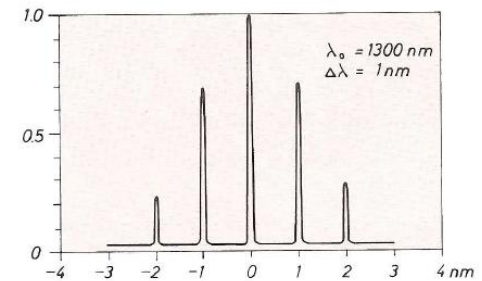
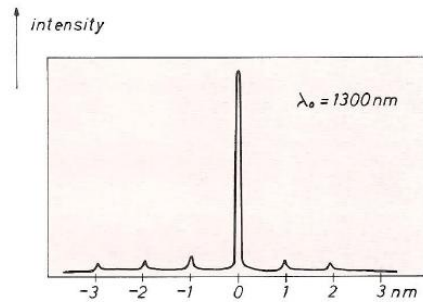
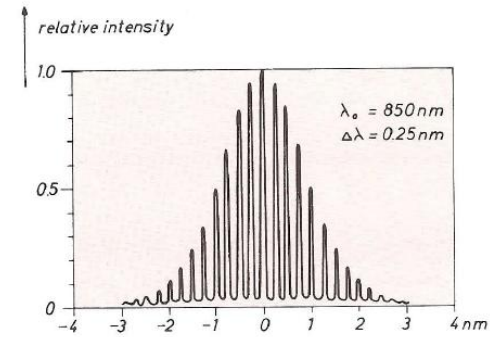
# Principales caractéristiques

- NA de 0.9 à 0.2
- Densité d'énergie faible / DL (diode laser)
- Difficile à coupler fibre grad ind et monomode (POF)
- Moins rapides /DL
- Commandées en courant, très linéaire, pas de seuil
- Coef de temp 1 à 2%/°C
- Pas de modal noise ni de partitionning noise
- Puissance-courant : 10uW/mA
- Diagramme d'émission en loi de Lambert
- Durée de vie > DL > 10 ans

# Spectre d'émission

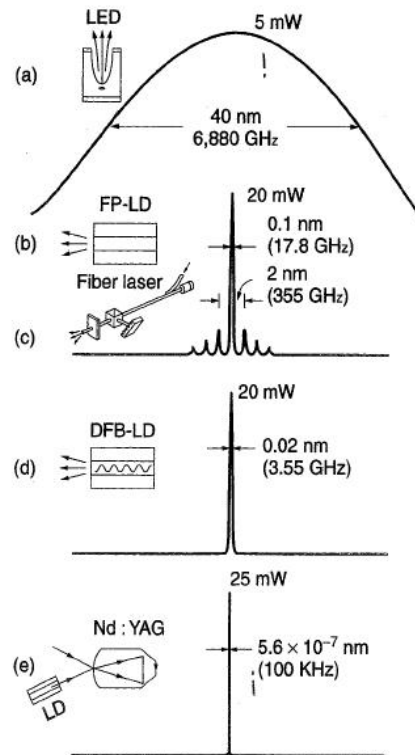


SPECTRUM OF AN 850NM LED





# Largeurs des spectres

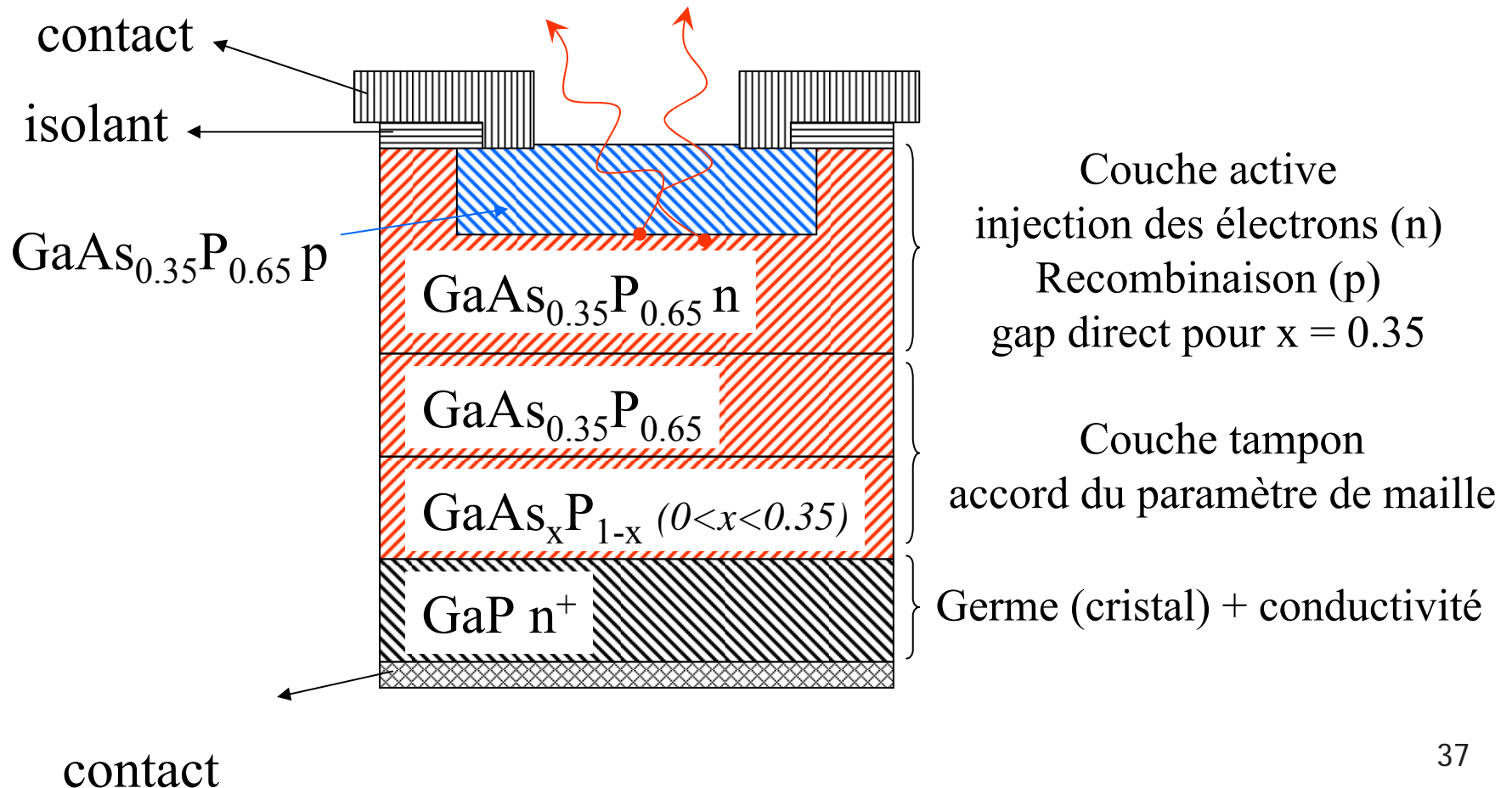


Comparison of the spectra of sources. (a) Light-emitting diode (LED). (b) Fabry-perot laser diode (FP-LD). (c) Erbium-doped fiber laser. (d) Distributed feedback laser diode (DFB-LD). (e) Laser diode driven Nd:YAG solid-state laser.

# Photoémetteurs

## Diode électroluminescente LED

Structure des LEDs usuelles :  $\text{GaAs}_{0.35}\text{P}_{0.65}$  (orange)





# Photoémetteurs

## *Diode électroluminescente LED*

### *Spectre d'émission*

Matériau	Pic (nm)	Couleur	Rendement (%)
GaAs (Si)	1000	IR	10
GaAs (Zn)	900	IR	0.1
GaP (Zn, O)	699	Rouge	4
GaAs <sub>0.6</sub> P <sub>0.4</sub> (Te)	644	Rouge	0.2
GaAs <sub>0.35</sub> P <sub>0.35</sub> (S, N)	632	Orange	0.2
GaP (N)	690	Jaune	0.1
GaAs <sub>0.15</sub> P <sub>0.85</sub> (S, N)	589	Jaune	0.05
GaP (N)	570	Vert	0.1

Gap

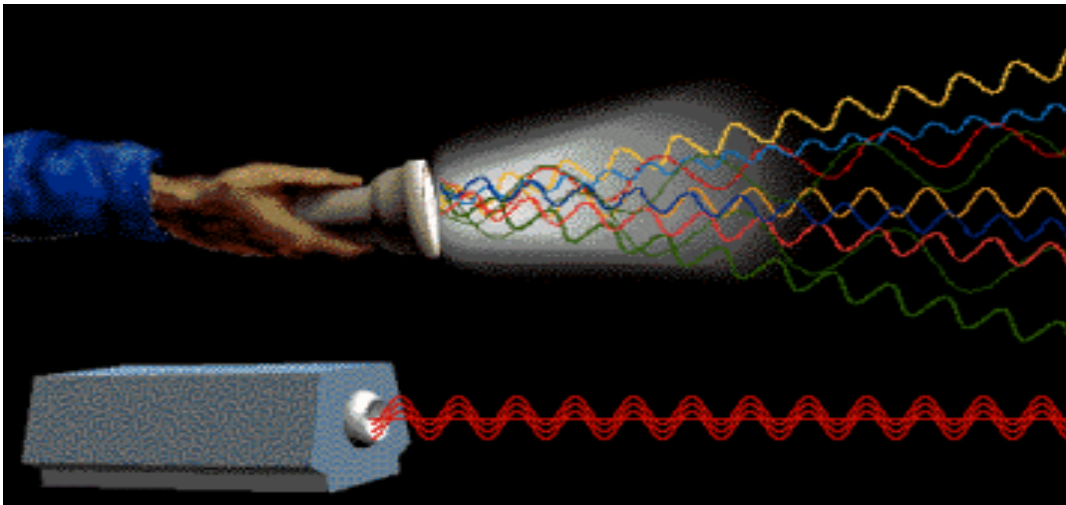
indirect



# Les Lasers

## ■ Caractéristiques

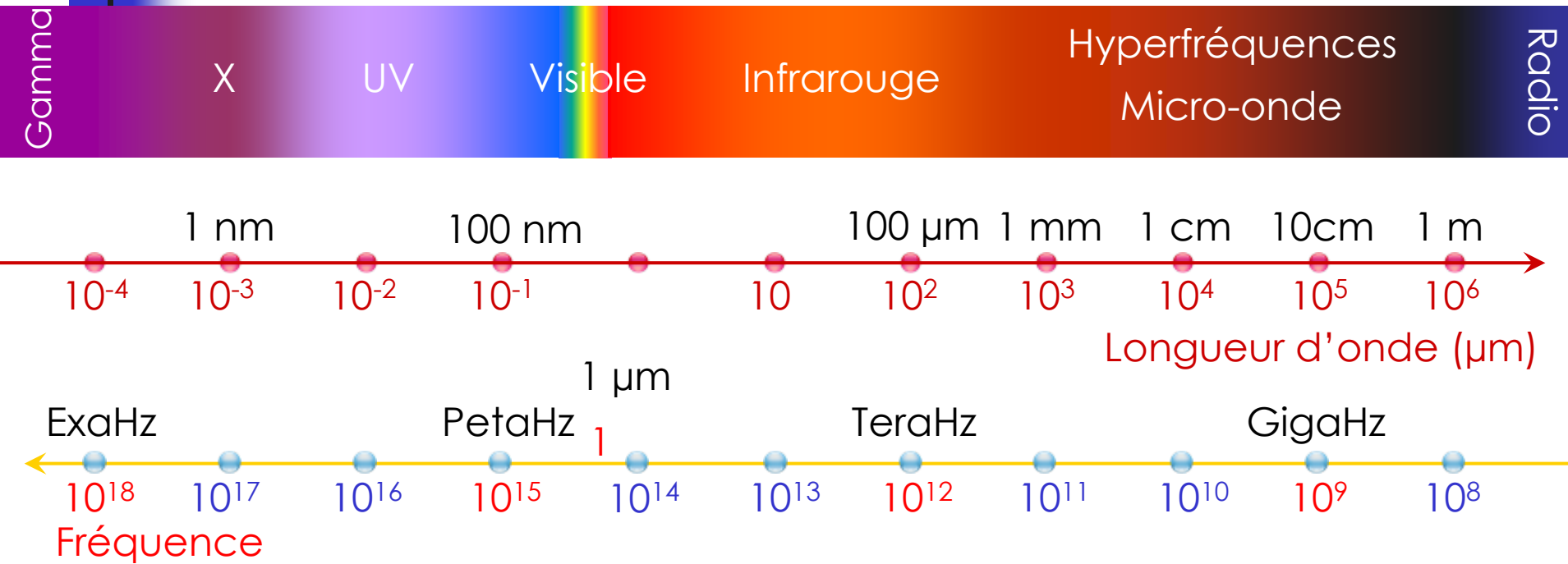
- Emission directionnelle
- Emission cohérente (relation de phase)
- Emission quasi – monochromatique



Light **A**mplification by **S**timulated **E**mission of **R**adiation

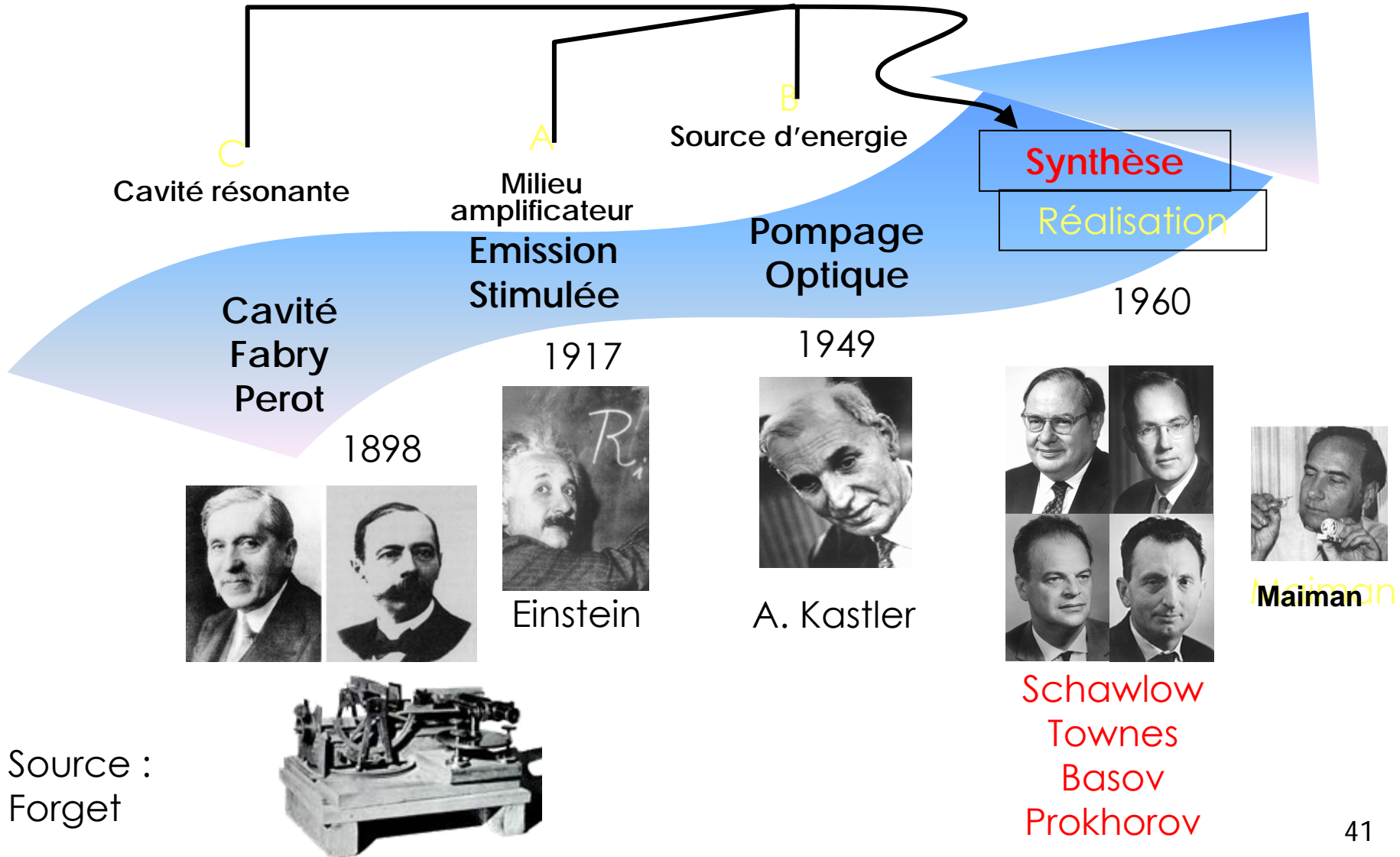
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# Lasers



# Un peu d'Histoire

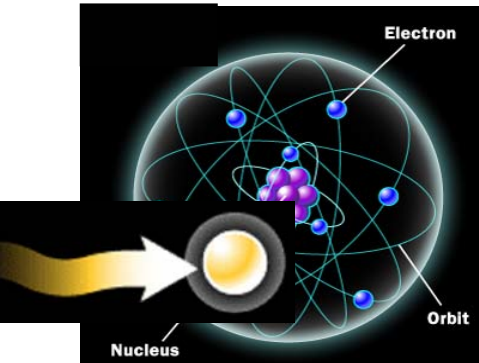
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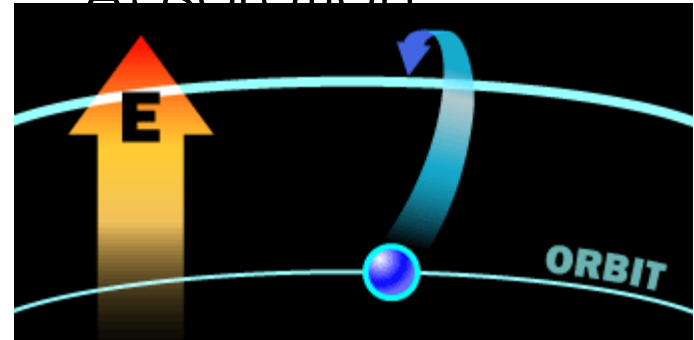


# Absorption-Emission spontanée

[www-lpl.univ-paris13.fr:8088/lumen/documents/Lpro/seance1.ppt](http://www-lpl.univ-paris13.fr:8088/lumen/documents/Lpro/seance1.ppt)

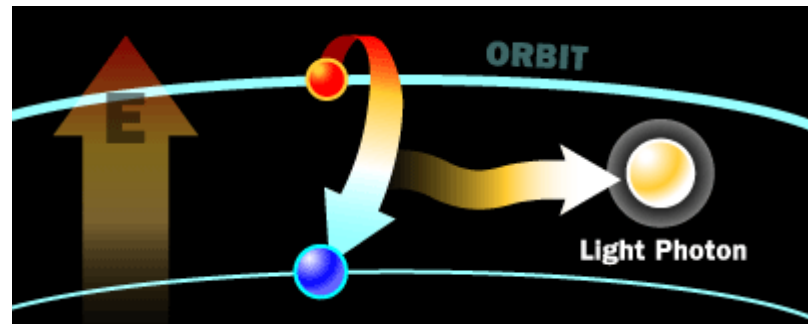


## Absorption



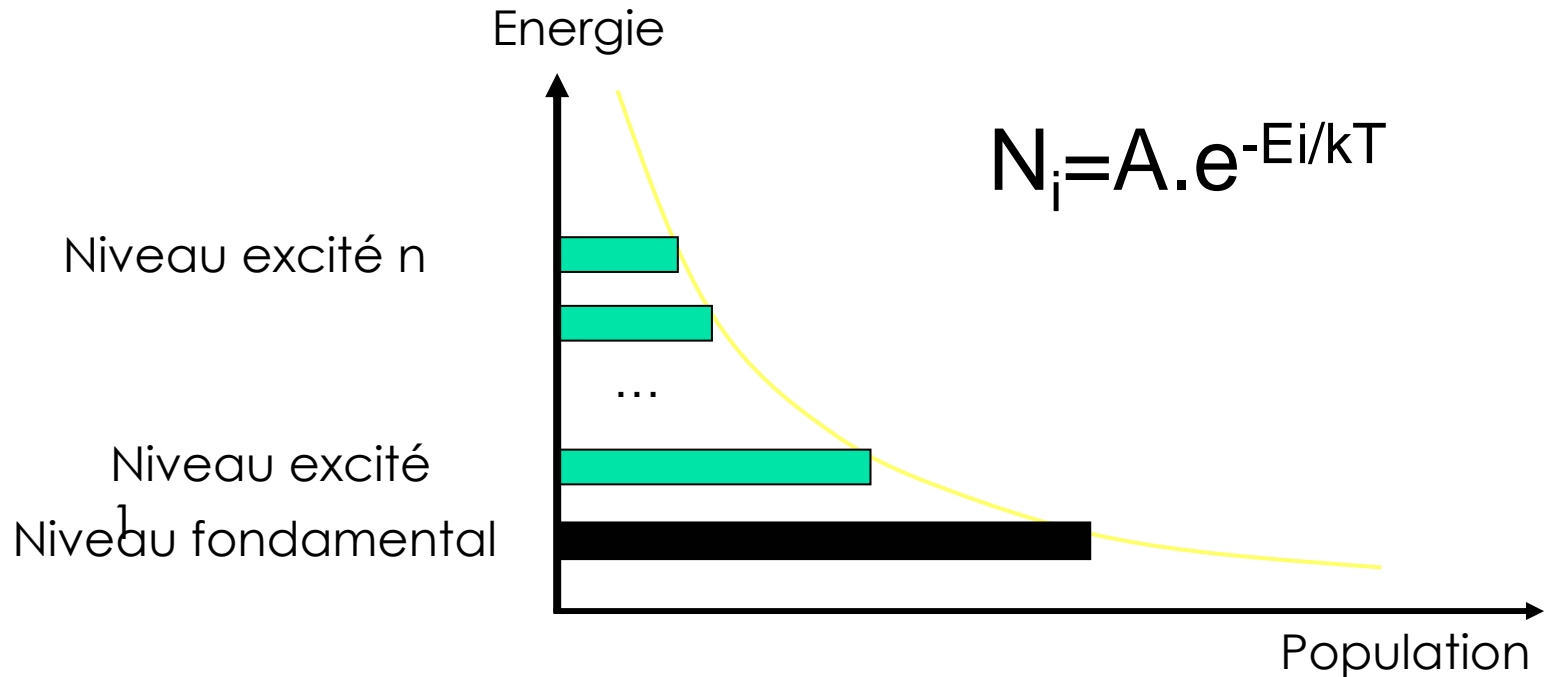
Mécanismes  
“classiques”

Emission spontanée (temps  $\tau$ )



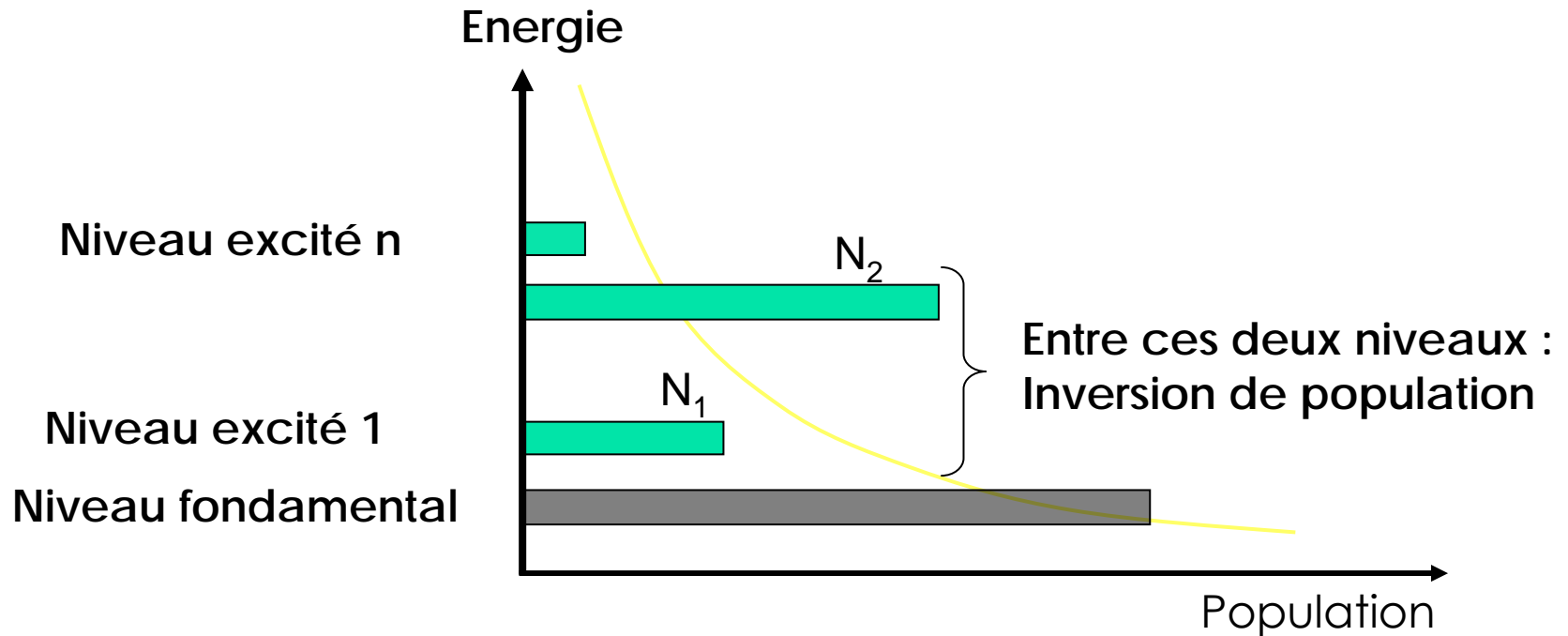
# L'inversion de population

- Etat stable : populations régies par la statistique de Boltzmann



Il faut **FORCER** l'inversion de Population en **POMPANT** le milieu

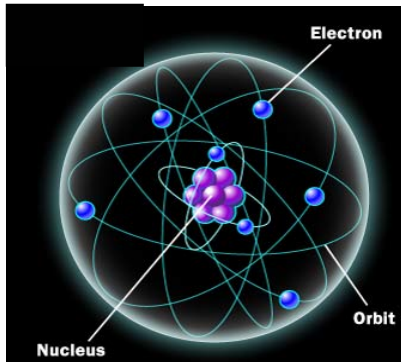
# L'inversion de population



# L'émission stimulée

[www-lpl.univ-paris13.fr:8088/lumen/documents/Lpro/seance1.ppt](http://www-lpl.univ-paris13.fr:8088/lumen/documents/Lpro/seance1.ppt)

Emission stimulée ➡ Amplification



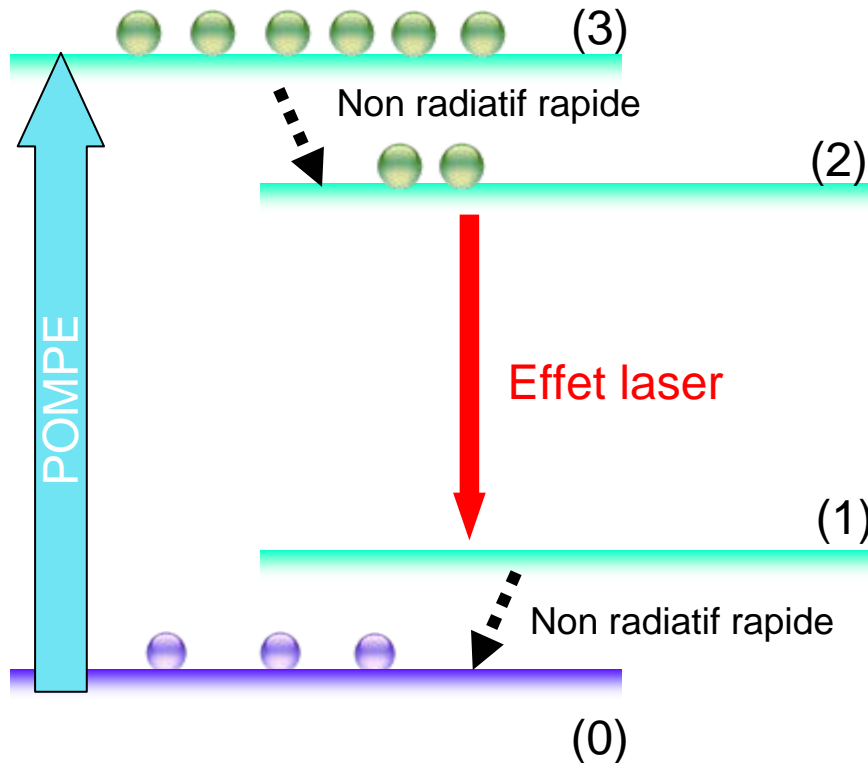
## Conditions :

- Même direction de propagation
- 2 ondes en phase
- Même état de polarisation
- Energie du photon incident ( $h\nu$ ) = Energie du niveau haut – énergie du niveau bas ( $\Delta E$ )
- $N_{\text{atomes excités}} > N_{\text{atomes dans le niveau fondamental}}$



“Inversion de population” indispensable

# Systeme à 4 niveaux



Inversion de Population facile !

Il faut peupler (2) → OK

Il faut vider (1) → OK (vite dépeuplé vers (0))

*Rq : Dès que le pompage est actif ( $N_2 \neq 0$ )  
l'inversion de population est atteinte ( $N_1 = 0$ )*

Fonctionnement en continu possible

Pas de seuil de transparence

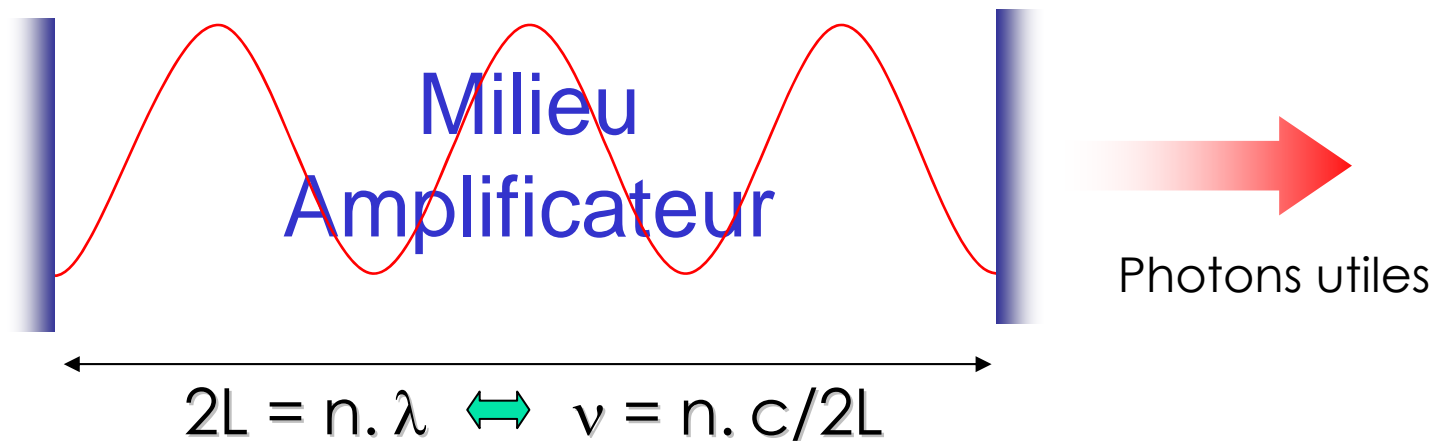
Source:Forget

Le système à 2 niveaux ne 'lase' pas.

Le système à 3 niveaux 'lase' plus difficilement.

# La Cavité

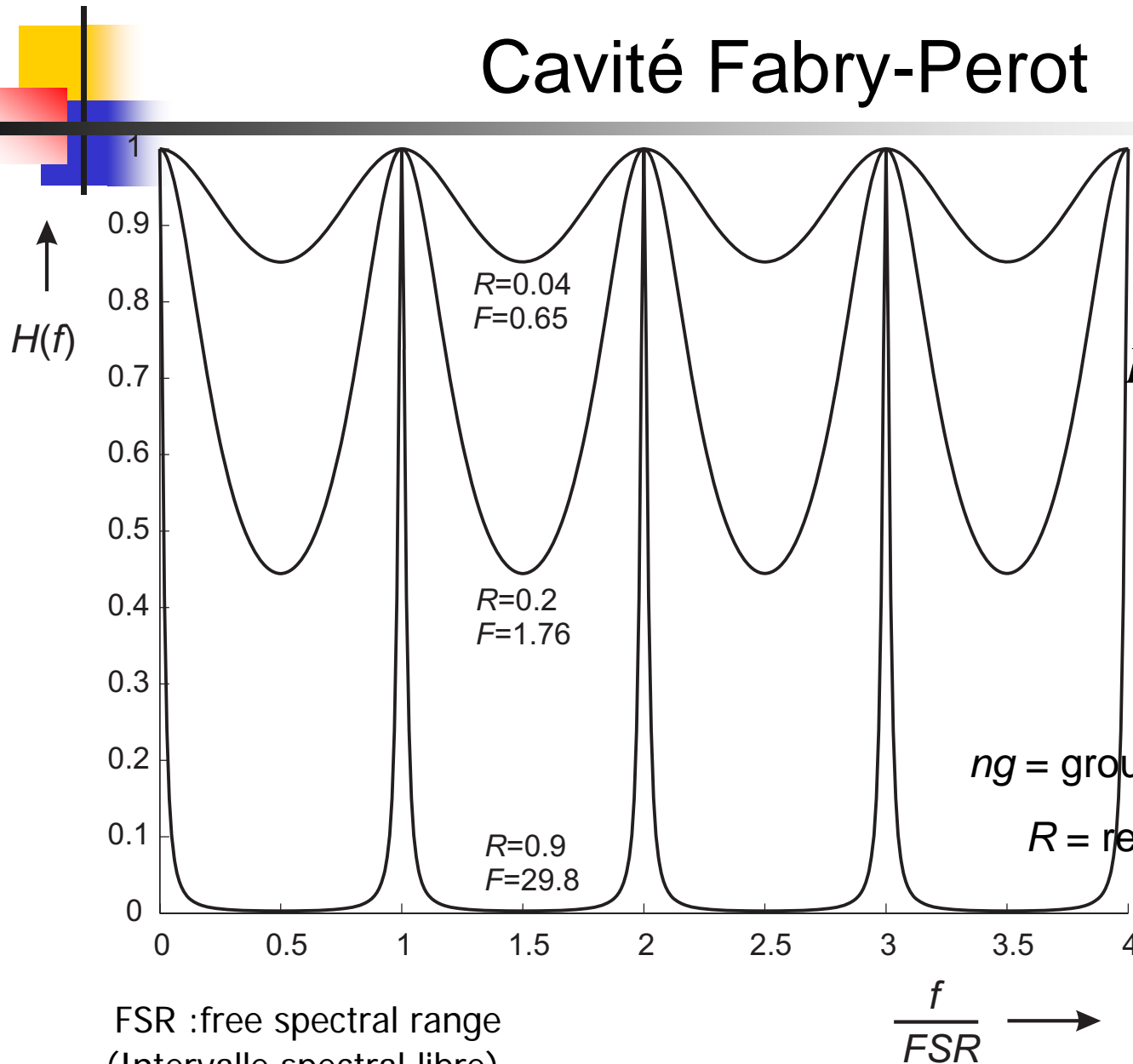
- Permet de **recycler les photons** et d'obtenir un effet en cascade
- Longueur **multiple de  $\lambda$**  : ondes stationnaires
- La plus simple : 2 miroirs dont **un partiellement réfléchissant** pour extraire les photons utiles



Source: Forget

Condition de "Rebouclage en phase" sur un aller-retour

# Cavité Fabry-Perot



Finesse

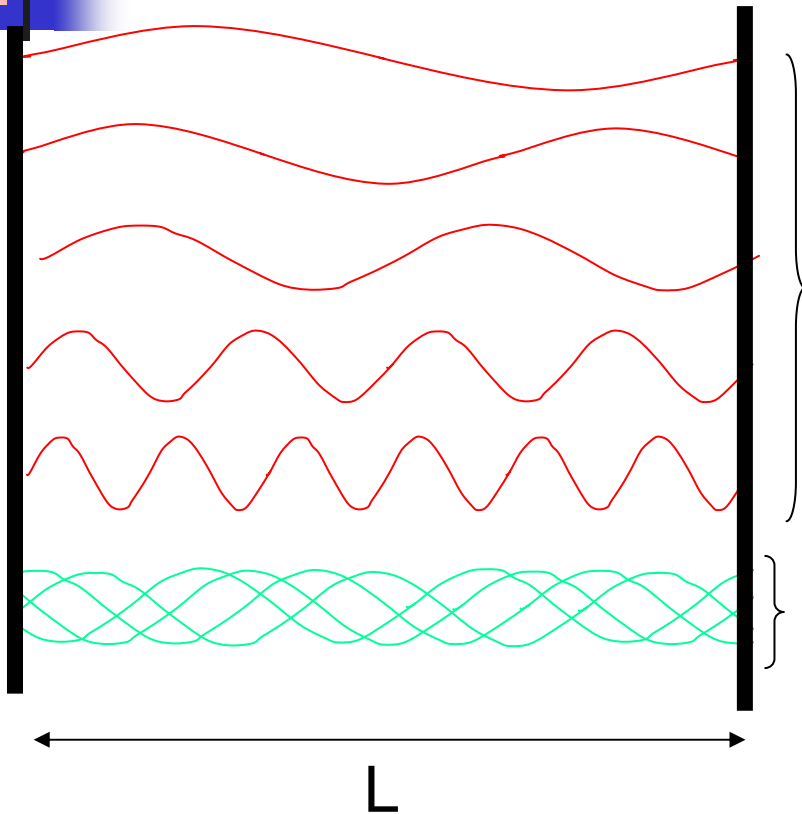
$$F = \frac{FSR}{BW_{FWHM}} = \frac{\pi\sqrt{R}}{1-R}$$

$$FSR = \Delta f = \frac{c}{n_g L}$$

$n_g$  = group index of the material

$R$  = reflectivity of the mirrors

# Les modes d'une cavité



Modes  
propres

$$2L = n \cdot \lambda$$

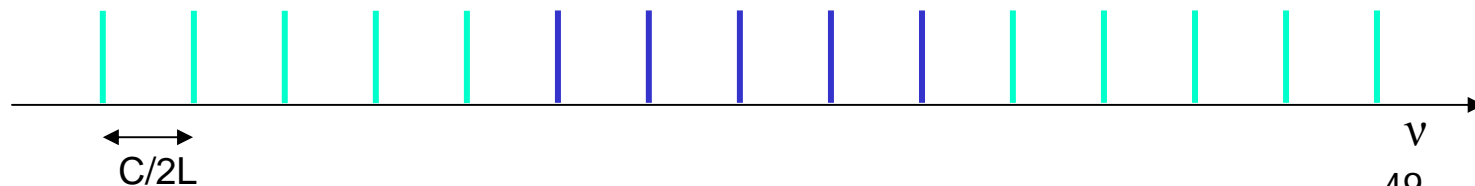


$$\nu_n = n \cdot c / 2L$$

Condition de  
"Rebouclage  
en phase" sur  
un aller-retour

Au bout de quelques  
AR tout mode *non*  
*résonnant* a une  
intensité nulle

Dans l'espace des fréquences :



Source:  
Forget

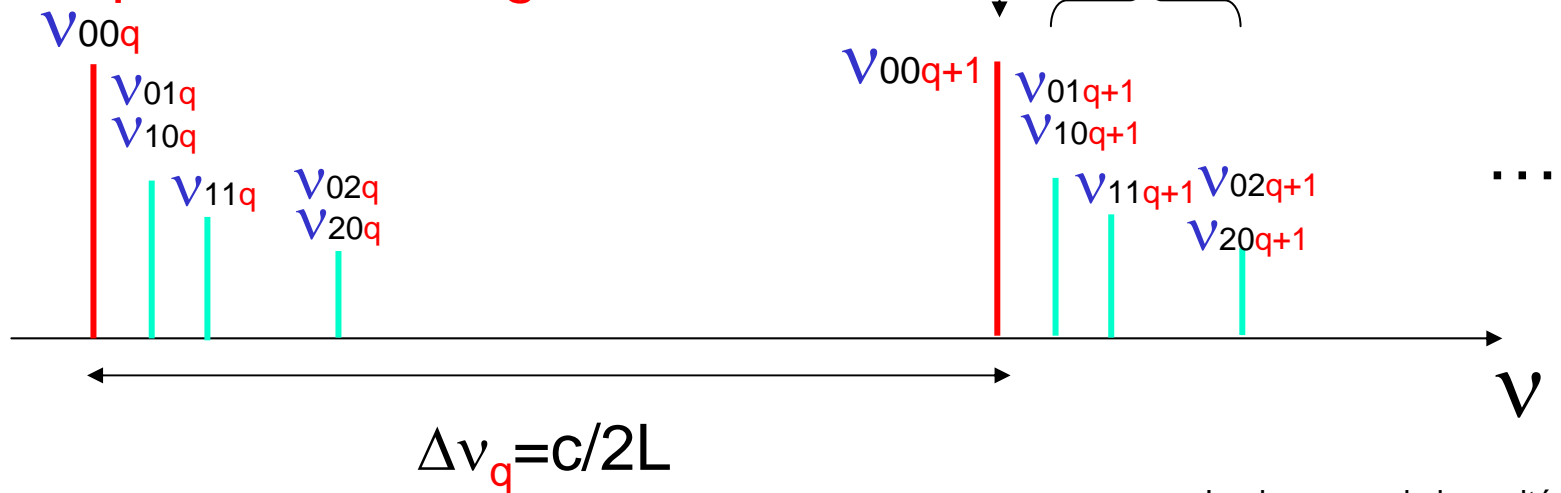


# Répartition spectrale des modes

- Un mode  $V_{mpq}$  = un triplet  $m, p, q$

- $m, p$  = modes transverses

- $q$  = modes longitudinaux



Écart entre 2 modes longitudinaux consécutifs

$L$  = longueur de la cavité

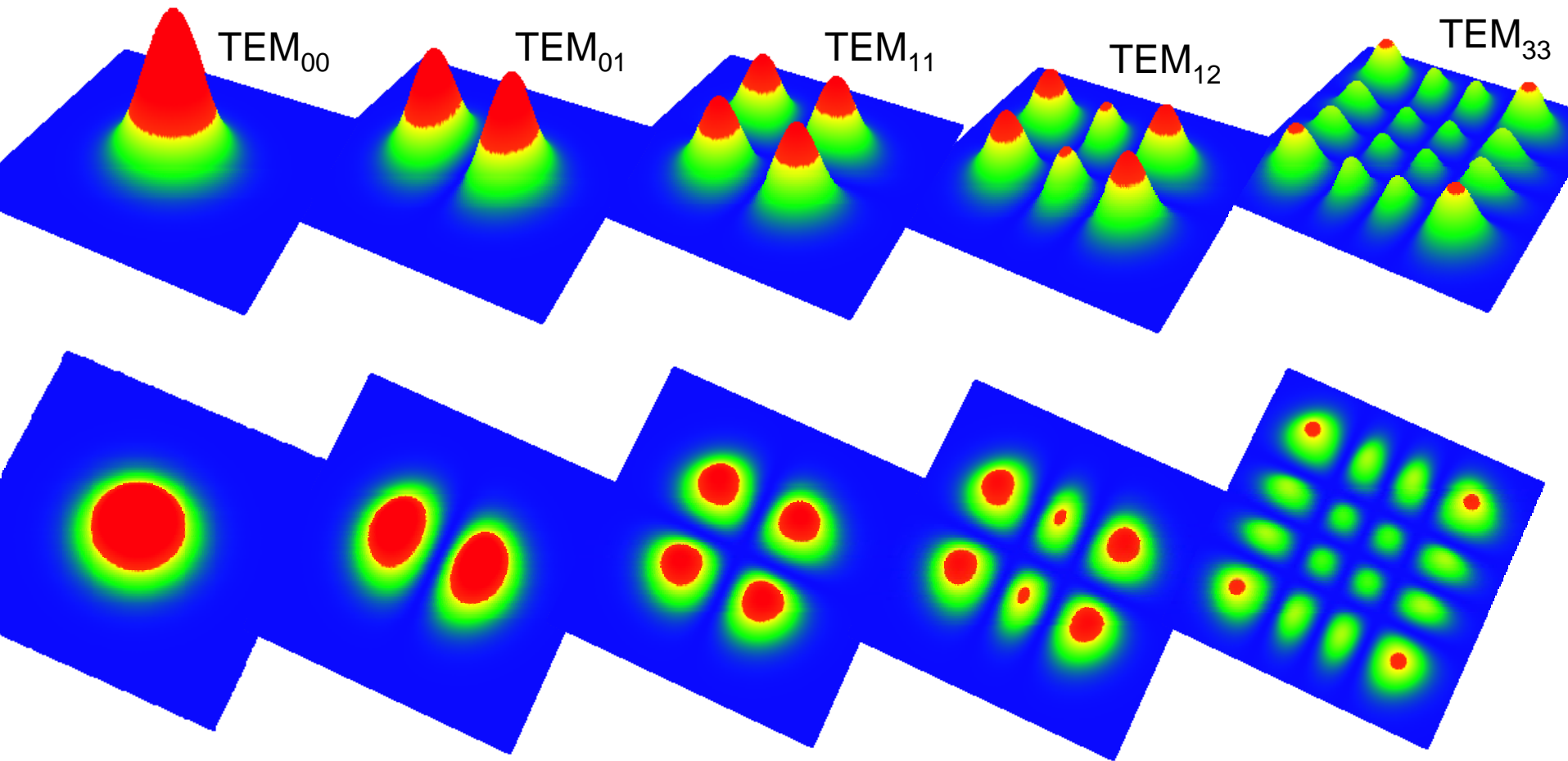
$c$  = vitesse de la lumière

Source: Forget

Un laser est **monomode longitudinal** si **seuls les** modes  $TEM_{mpq}$  lasent ( $q$  fixé)

Un laser est **monomode transverse** si **seuls les** modes  $TEM_{00q}$  lasent

# Répartition spatiale des modes



[www-lpl.univ-paris13.fr:8088/lumen/documents/Lpro/seance1.ppt](http://www-lpl.univ-paris13.fr:8088/lumen/documents/Lpro/seance1.ppt)



# Laser types

## gas lasers:

- He-Ne: red, low power (often only mW)
- CO<sub>2</sub>(-N<sub>2</sub>): high efficiency (30%), high power infrared, welding and cutting
- Ar: green, high power, up to 100 W, used as a pump laser

## solid state lasers:

Ruby: first laser

Nd-YAG: extremely high power, pulsed

semiconductor lasers, laser diodes: low power, cheap, industry standard

## Molecular lasers:

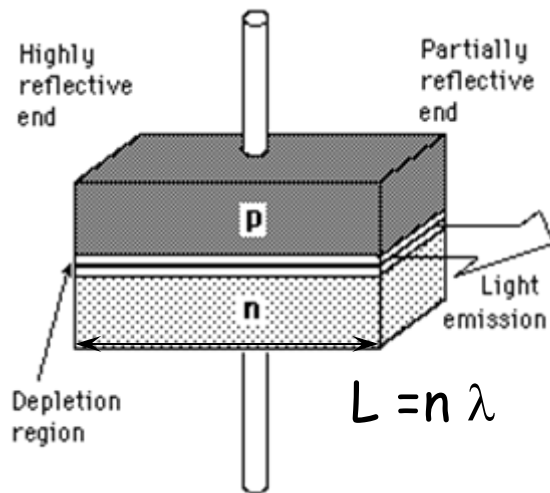
Excimer

Free electron laser: IR - X-ray, continuous wavelength

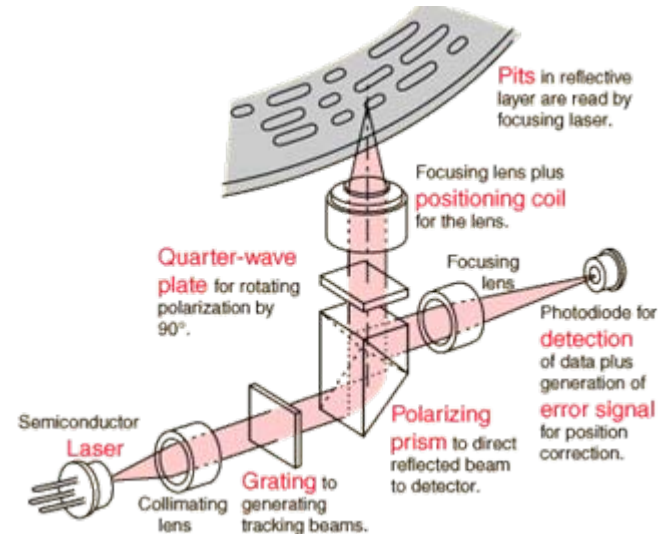
Dye lasers: tunable

# semiconductor lasers

- photon production by electron **hole pair recombination** as in LED
- above a **threshold current**, stimulated emission occurs -> lasing



CD player: GaAs, 5mW, 840 nm

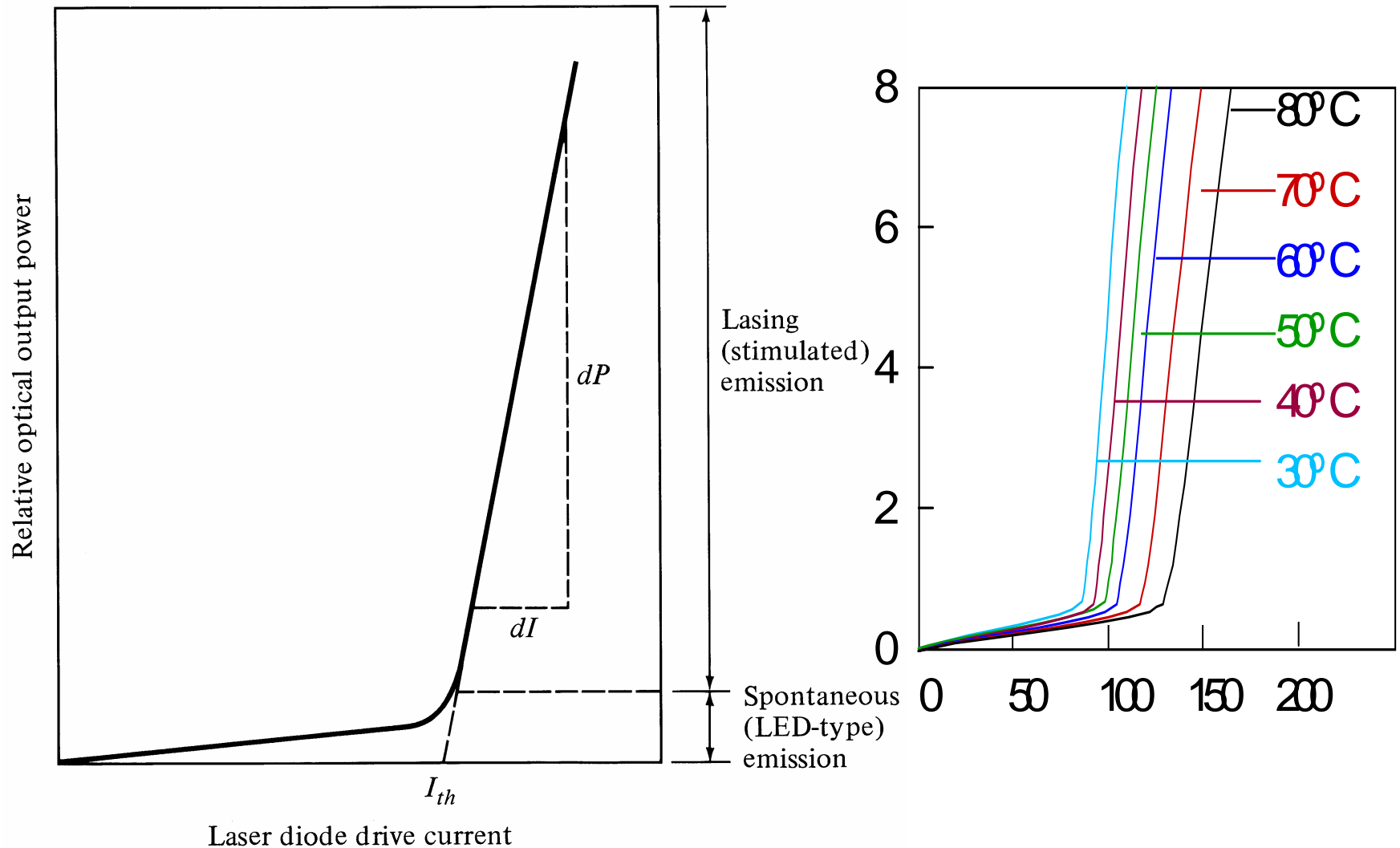


Laser printer: AlGaAs, 50mW, 760 nm

Telecom: GaInAlP, 20 mW, 1300 nm

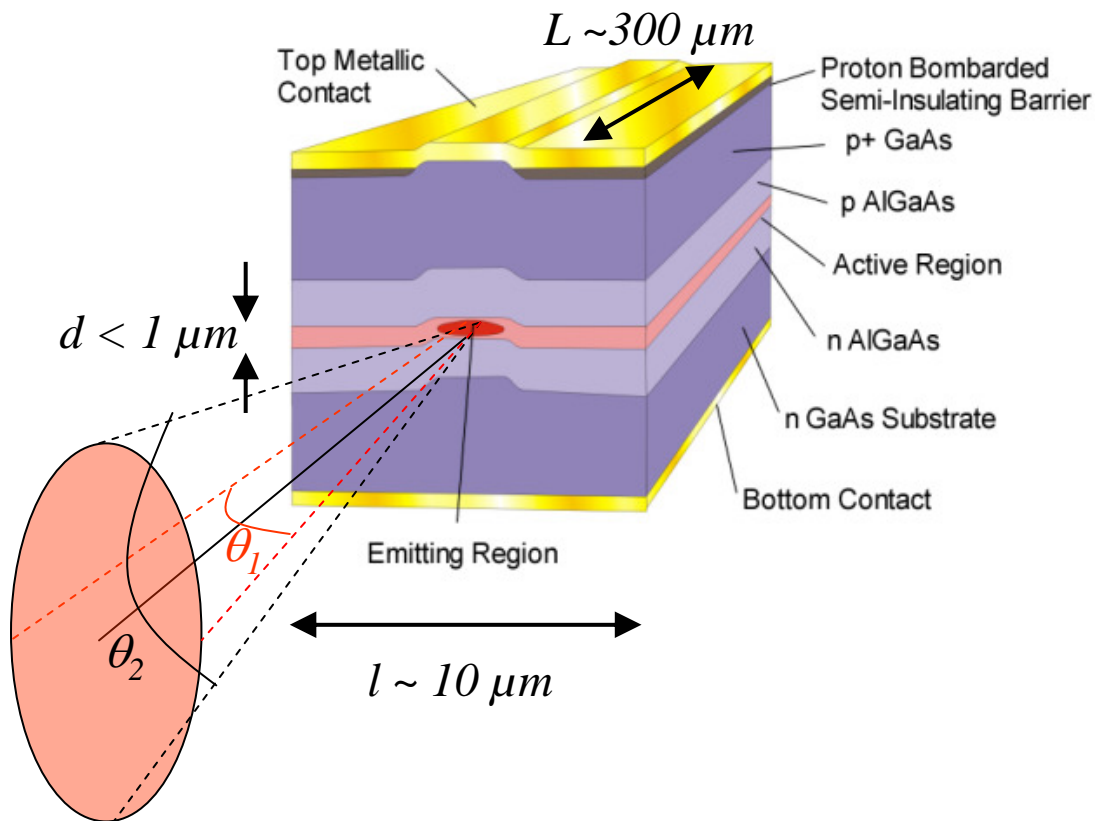
compact, cheap, variable wavelength

# Optical output vs. drive current



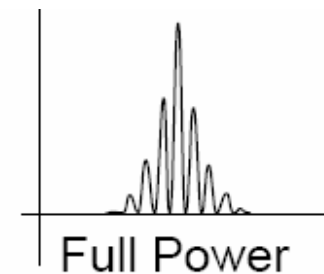
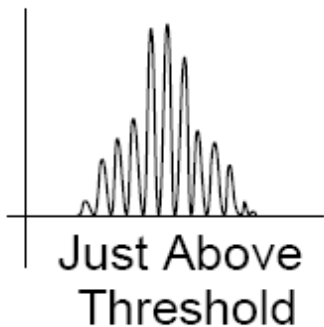
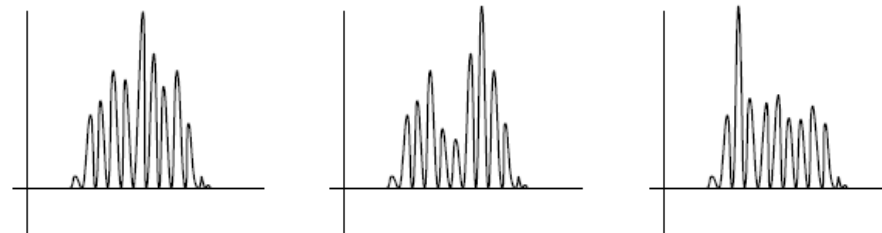
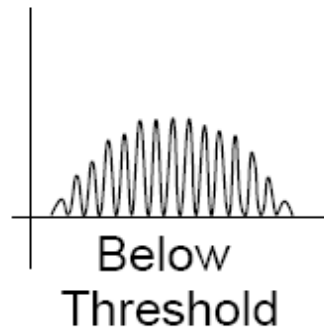
# Laser à semiconducteur

$$\lambda(\mu m) = \frac{1.24}{E_g (eV)}$$

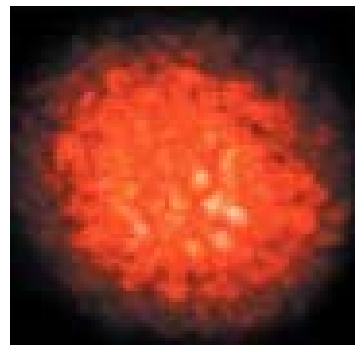


Material	Wavelength Range $\lambda (\mu m)$
InP	0.92
InAs	3.6
GaP	0.56
GaAs	0.87
AlAs	0.59
GaInP	0.64-0.68
AlGaAs	0.8-0.9
InGaAs	1.0-1.3
InGaAsP	0.9-1.7

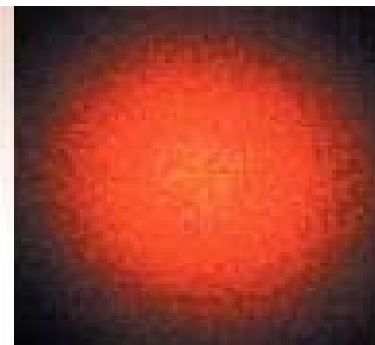
# Spectrum from a laser diode (FP laser)



**Fabry-Perot**



**Multimode Beam**

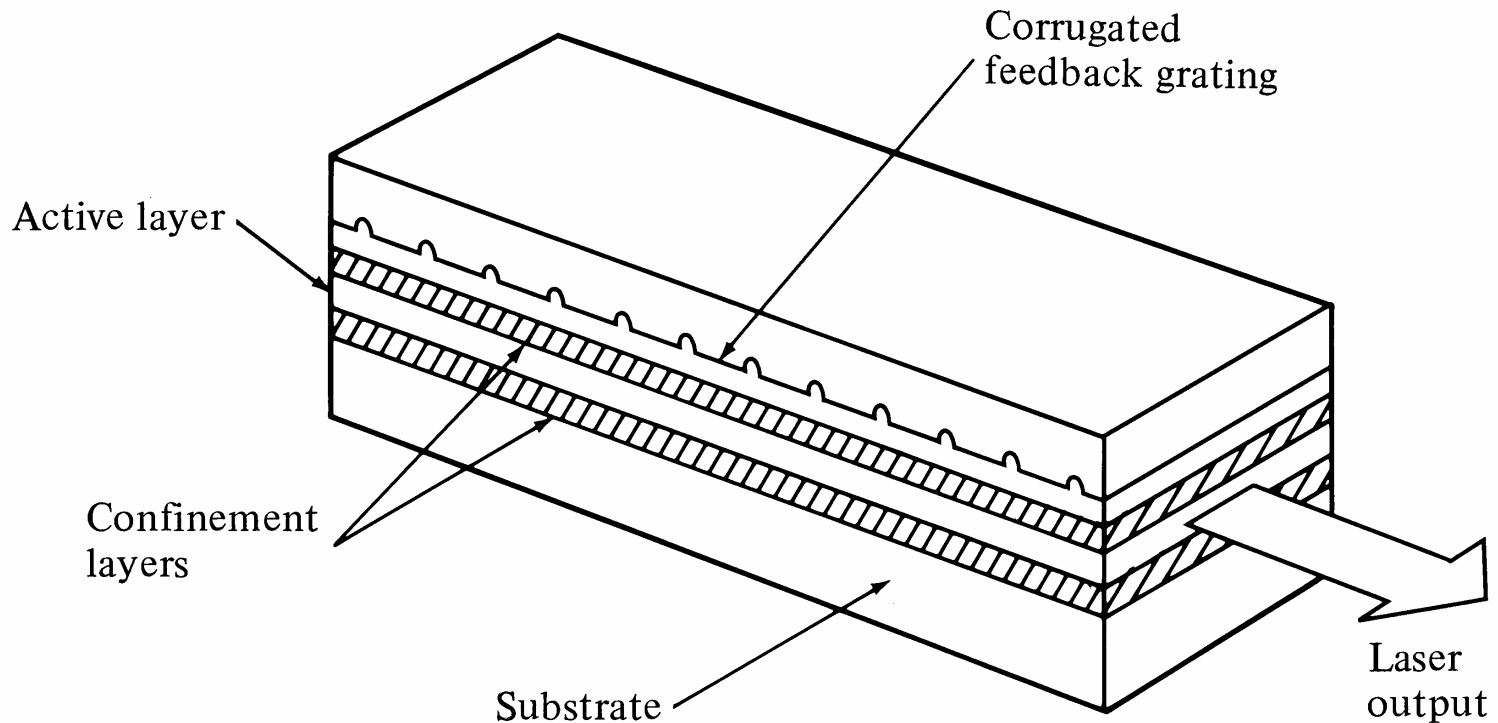


**Single Mode Beam**

**DFB**

# DFB(Distributed FeedBack) Lasers

In DFB lasers, the optical resonator structure is due to the incorporation of Bragg grating or periodic variations of the refractive index into multilayer structure along the length of the diode.

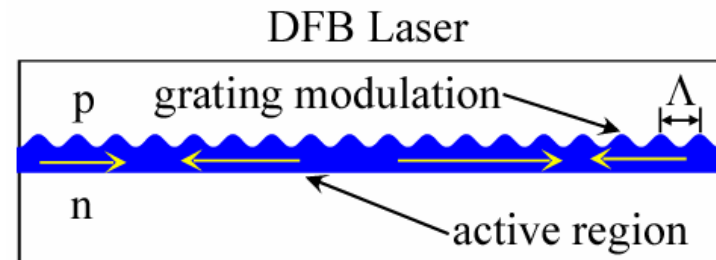




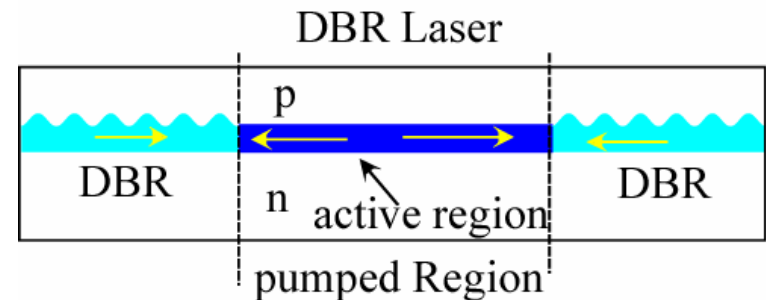
# Periodic Reflector Lasers: DFB DBR

- Periodic structure (grating) couples between forward and backward propagating waves

$$\Lambda = \frac{\lambda}{2n}$$



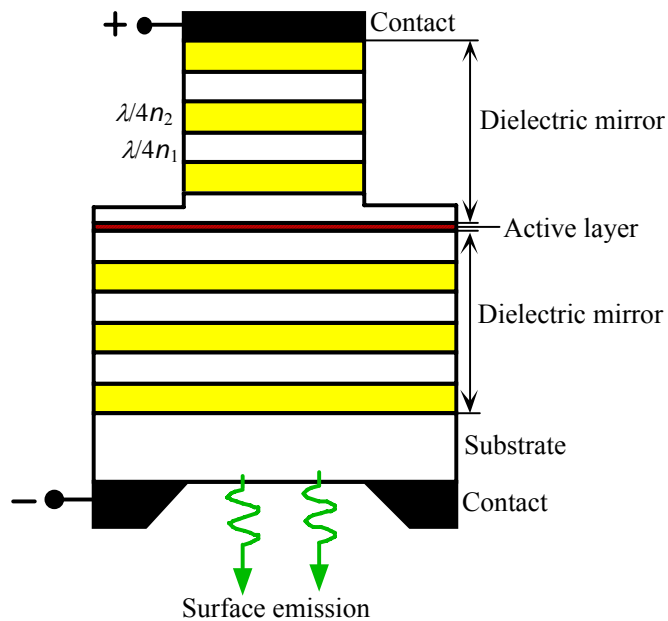
- Distributed feedback (DFB) laser
  - Grating distributed over entire active region
- Distributed Bragg reflector (DBR) laser
  - Grating replaces mirror at end face



# VCSEL

## Vertical Cavity Surface Emitting Laser

<http://britneyspears.ac/physics/vcsels/vcsels.htm>



A simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL).

© 1999 S.O. Kasap, *Optoelectronics* (Prentice Hall)

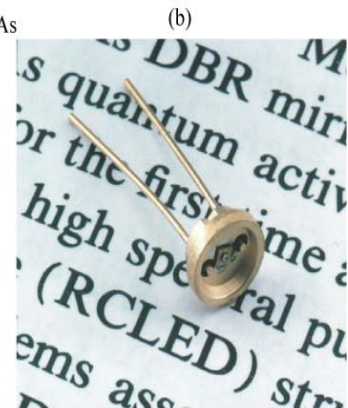
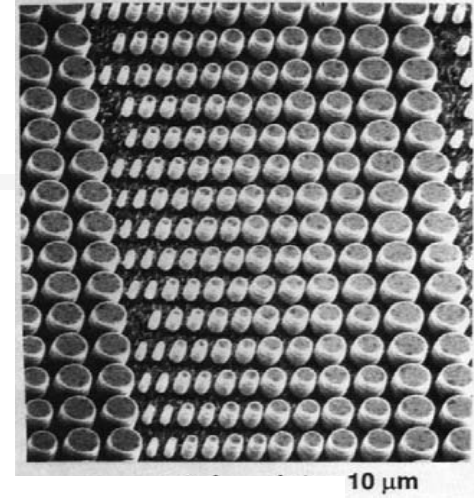
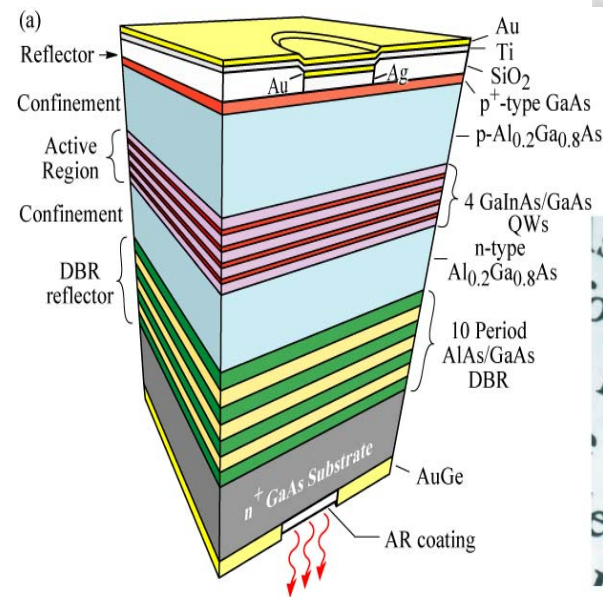
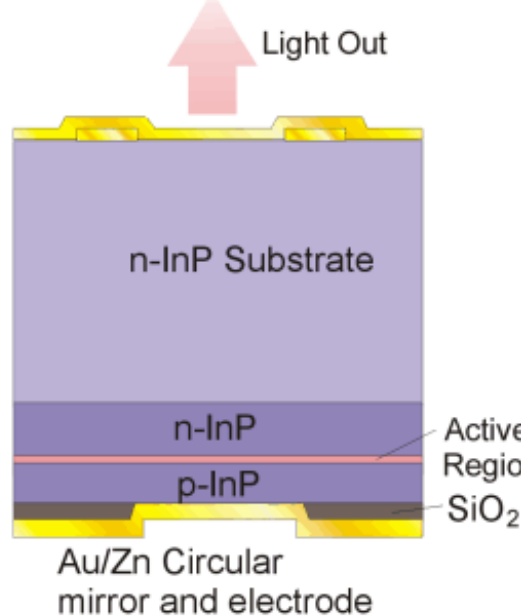


Fig. 15.4. (a) Schematic structure of a substrate-emitting GaInAs/GaAs RCLED consisting of a metal top reflector and a bottom distributed Bragg reflector (DBR). The RCLED emits at 930 nm. The reflectors are an AlAs/GaAs DBR and a Ag top reflector. (b) Picture of the first RCLED (after Schubert *et al.*, 1994).

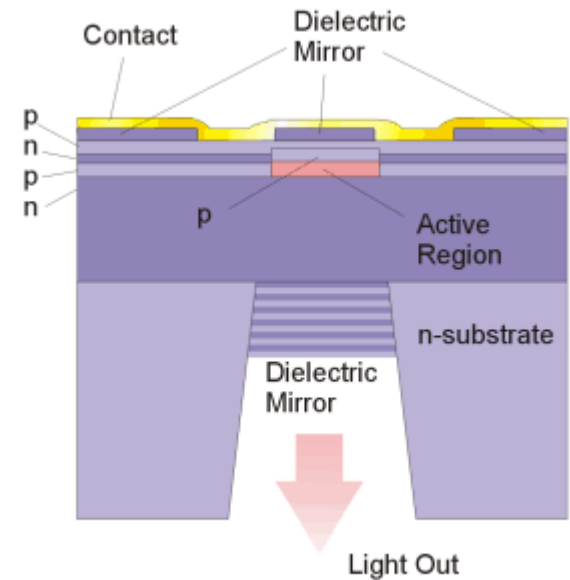
E. F. Schubert  
Light-Emitting Diodes (Cambridge Univ. Press)  
[www.LightEmittingDiodes.org](http://www.LightEmittingDiodes.org)

# Examples of VCSELs:

VCSELs have been constructed that emit energy at 850 and 1300 nanometers, which is in the near infrared portion of the electromagnetic spectrum.

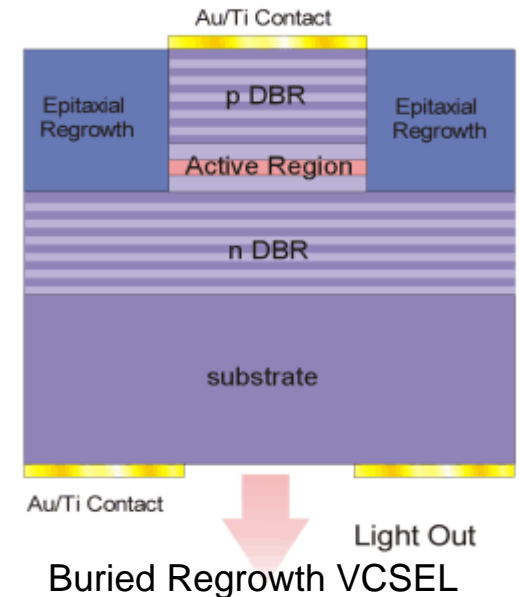
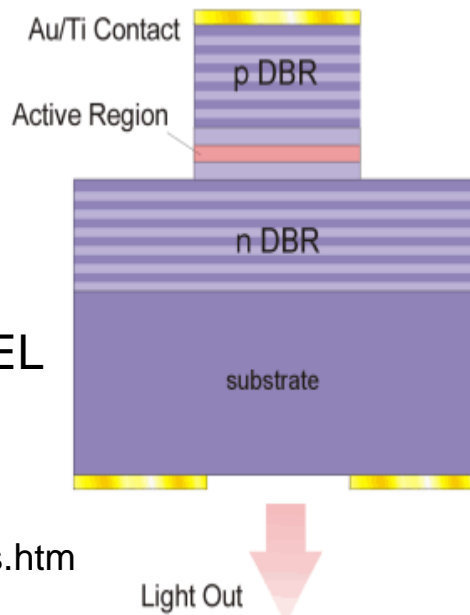


Metallic Reflector VCSEL



Etched Well VCSEL

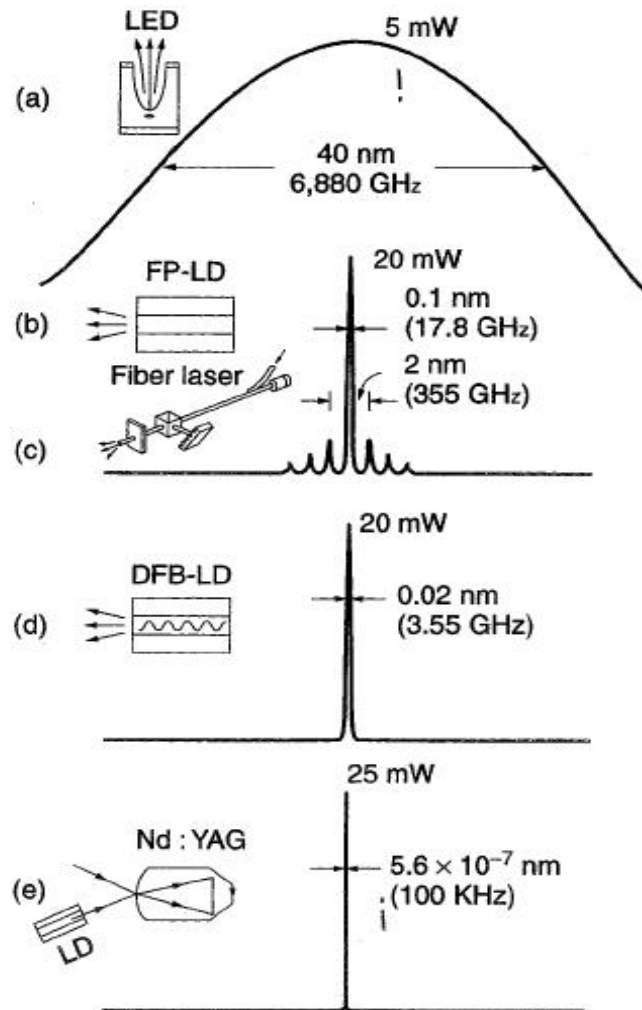
Air Post VCSEL



Buried Regrowth VCSEL

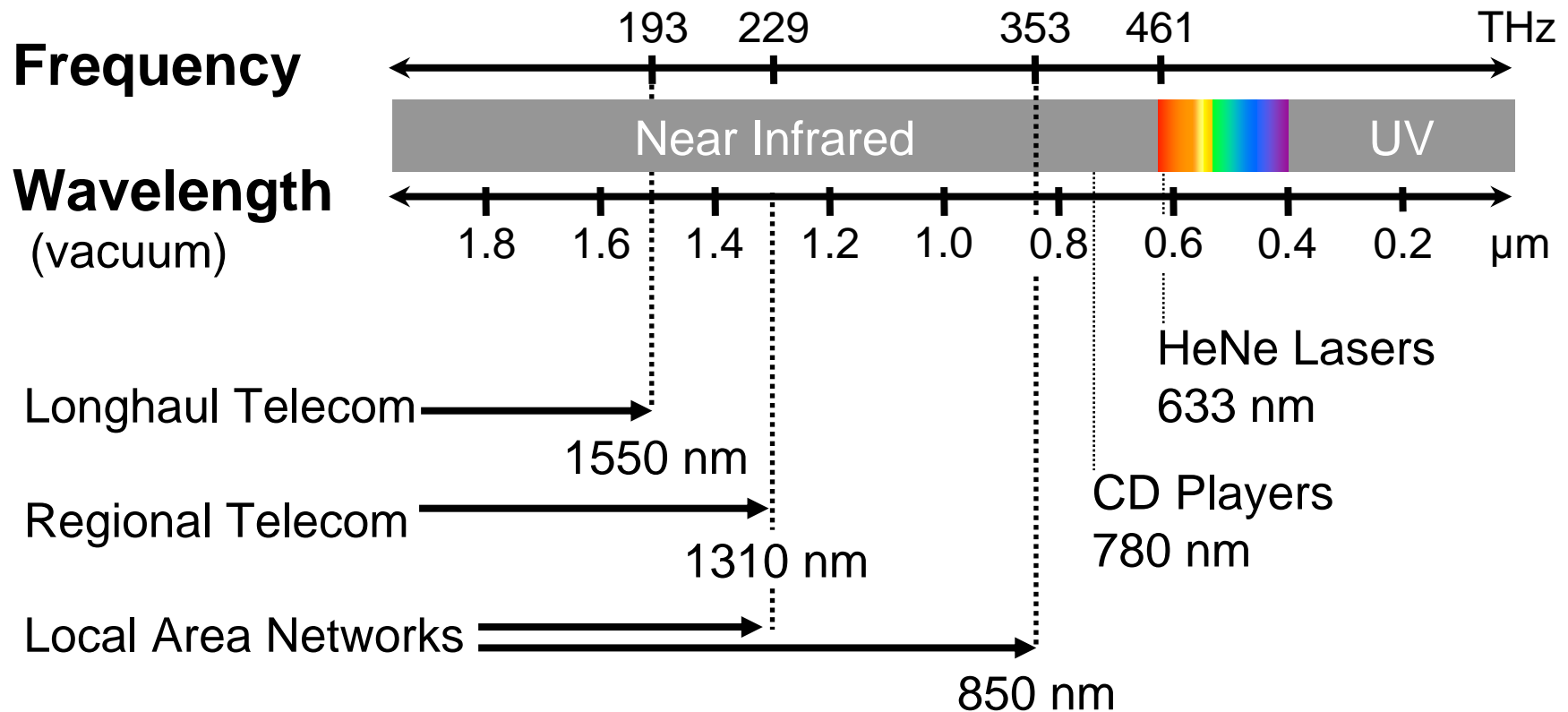
<http://britneyspears.ac/physics/vcsels/vcsels.htm>

# FB versus DFB



Comparison of the spectra of sources. (a) Light-emitting diode (LED). (b) Fabry-perot laser diode (FP-LD). (c) Erbium-doped fiber laser. (d) Distributed feedback laser diode (DFB-LD). (e) Laser diode driven Nd:YAG solid-state laser.

# LW Transmission Bands



Source: Agilent

# DFB laser specs



Laser/TEC Drivers  
Benchtop

Laser/TEC Drivers  
Platforms

Laser/TEC  
OEM Drivers

Laser Mounts

Laser Diodes

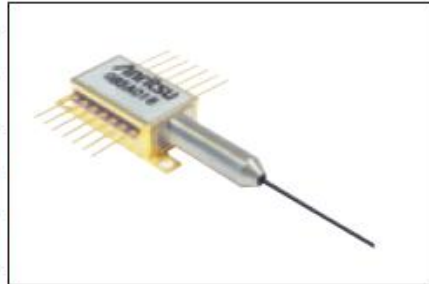
Pigtailed Lasers

Laser Modules

Accessories

## Laser Diode Technologies

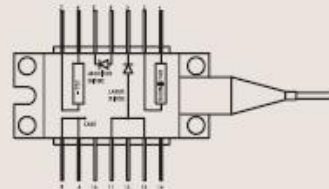
### DFB Laser C-Band and L-Band P = 20mW



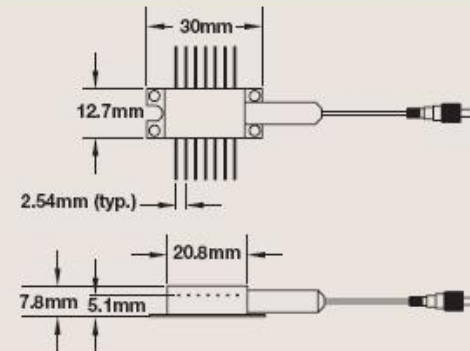
- Wavelength: ITU grid, 100GHz steps
- Single Longitudinal Mode
- Accurate Peak Wavelength ( $\pm 0.5\text{nm}$ )
- Built-in Optical Isolator (30dB)
- Built-in Monitor Photodiode
- Built-in Cooler and Thermistor
- PMF Pigtail Type
- FC/APC Connector, Slow Axis Aligned to Connector Key



Pin Connection (Top View)



COMPATIBLE WITH LM14S2  
BUTTERFLY MOUNT USING  
TYPE 2 ADAPTER CARD  
SEE PAGE 432



<http://www.thorlabs.com/>

# FP Laser specs

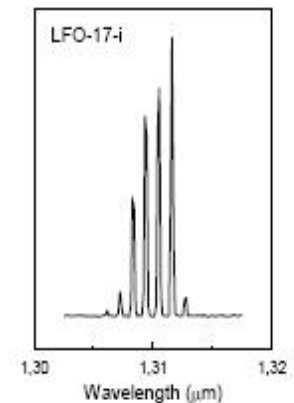
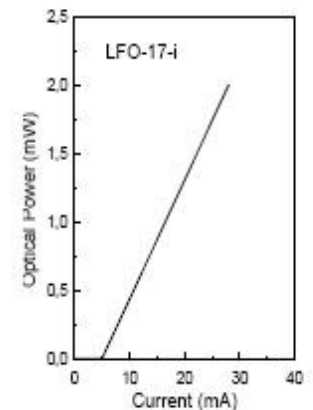
1.29 + 1.33  
μm

CW output power  
> 2.0 mW

**LFO-17-i**

Optical and electrical characteristics (T=25°C):

Characteristics	Symbol	Test condition	Min	Typ.	Max	Units
<b>Laser diode</b>						
Output power from fiber end	P <sub>OP</sub>	I <sub>OP</sub>	1.8	2.0		mW
Wavelength	λ <sub>OP</sub>	P <sub>OP</sub>	1290	1310	1330	nm
Spectral width (FWHM)	Δλ	P <sub>OP</sub>		1.0	2.0	nm
Threshold current	I <sub>TH</sub>	CW		5.0	15	mA
Forward current	I <sub>F</sub>	P <sub>OP</sub>		30	40	mA
Forward voltage	U <sub>OP</sub>	P <sub>OP</sub>		1.1	1.5	V
Rise time/fall time	t <sub>R</sub> /t <sub>F</sub>	P <sub>OP</sub>		0.3	0.7	ns
<b>Monitor photodiode</b>						
Monitor current	I <sub>FD</sub>	U <sub>REV</sub> =5.0 V, P <sub>OP</sub>	100	500		μA
Dark current	I <sub>D</sub>	U <sub>REV</sub> =5.0 V		0.01	0.1	μA
Capacitance	C <sub>FD</sub>	U <sub>REV</sub> =5.0 V, f=1 MHz		10	20	pF
<b>Thermistor</b>						
Resistance	R <sub>T</sub>	T=T <sub>OP</sub>		10		kΩ
<b>Thermocooler</b>						
Forward current	I <sub>C</sub>	P <sub>OP</sub>			0.35	A
Forward voltage	U <sub>C</sub>	P <sub>OP</sub>			6.5	V
<b>Optical fiber</b>						
Fiber core/cladding diameter	D <sub>C</sub> /D <sub>CL</sub>			50/125		μm
Fiber length	L			400..1500		mm
Optical connector type				«FC»		



[http://www.roithner-laser.com/All\\_Datasheets/Laserdiodes/LFO-17-i.pdf](http://www.roithner-laser.com/All_Datasheets/Laserdiodes/LFO-17-i.pdf)



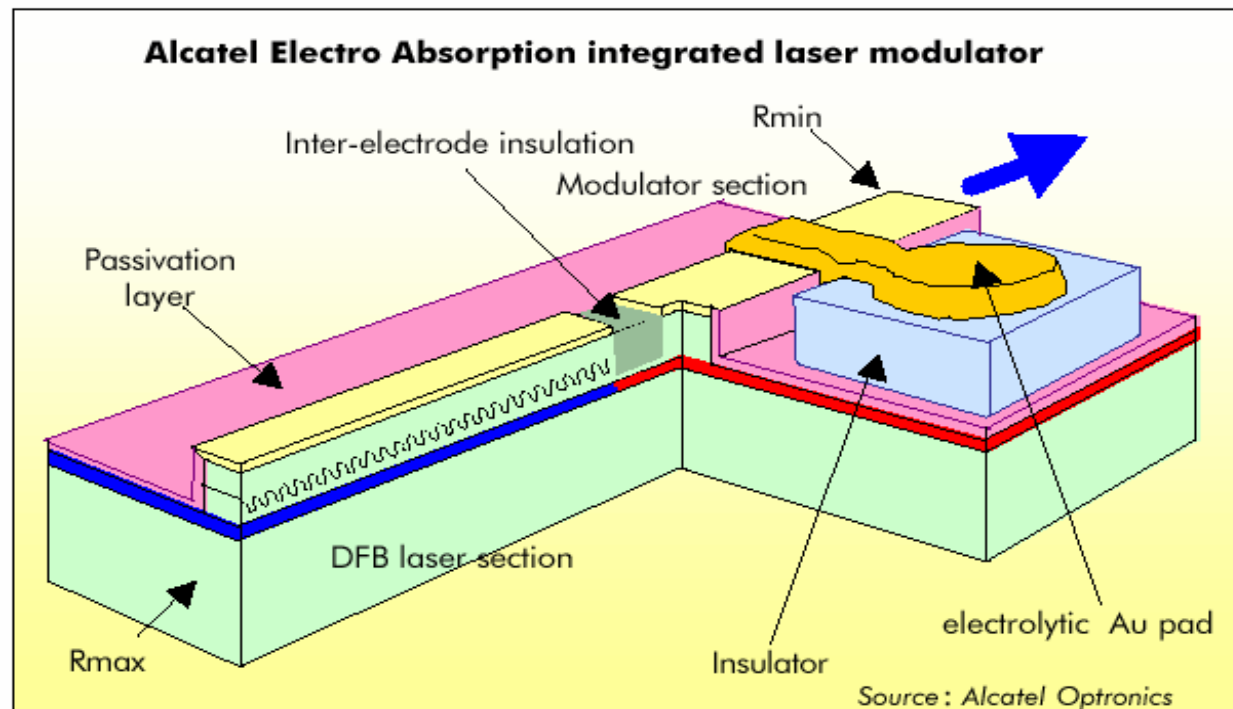
# Modulation des diodes laser

modulation Interne : par courant



## Integrated DFB-EA Transmitter

modulation externe:



- 10Gb/s module,  $I_{th} = 20\text{mA}$ ,  $P_{max} = 4\text{mW}$ .
- @80mA , extinction ratio = 15dB for -2.5V.





# Bruit dans les LED et Lasers

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Bruit schottky  
Bruit RIN

- Site <http://www.thorlabs.com/> pour avoir une idée des prix (Laser, modulateur, etc )
- COVEGA catalogue pour des datasheet
- <http://www.covega.com/pdfs/COVEGA%20Catalog%202007.pdf>

## ■ Sécurité Laser

[phys.strath.ac.uk/information/safety/LaserSafety/071012lecture\\_beginner.PPT](http://phys.strath.ac.uk/information/safety/LaserSafety/071012lecture_beginner.PPT)

Color	Wavelength interval	Frequency interval
red	~ 625 to 740 nm	~ 480 to 405 THz
orange	~ 590 to 625 nm	~ 510 to 480 THz
yellow	~ 565 to 590 nm	~ 530 to 510 THz
green	~ 520 to 565 nm	~ 580 to 530 THz
cyan	~ 500 to 520 nm	~ 600 to 580 THz
blue	~ 430 to 500 nm	~ 700 to 600 THz
violet	~ 380 to 430 nm	~ 790 to 700 THz

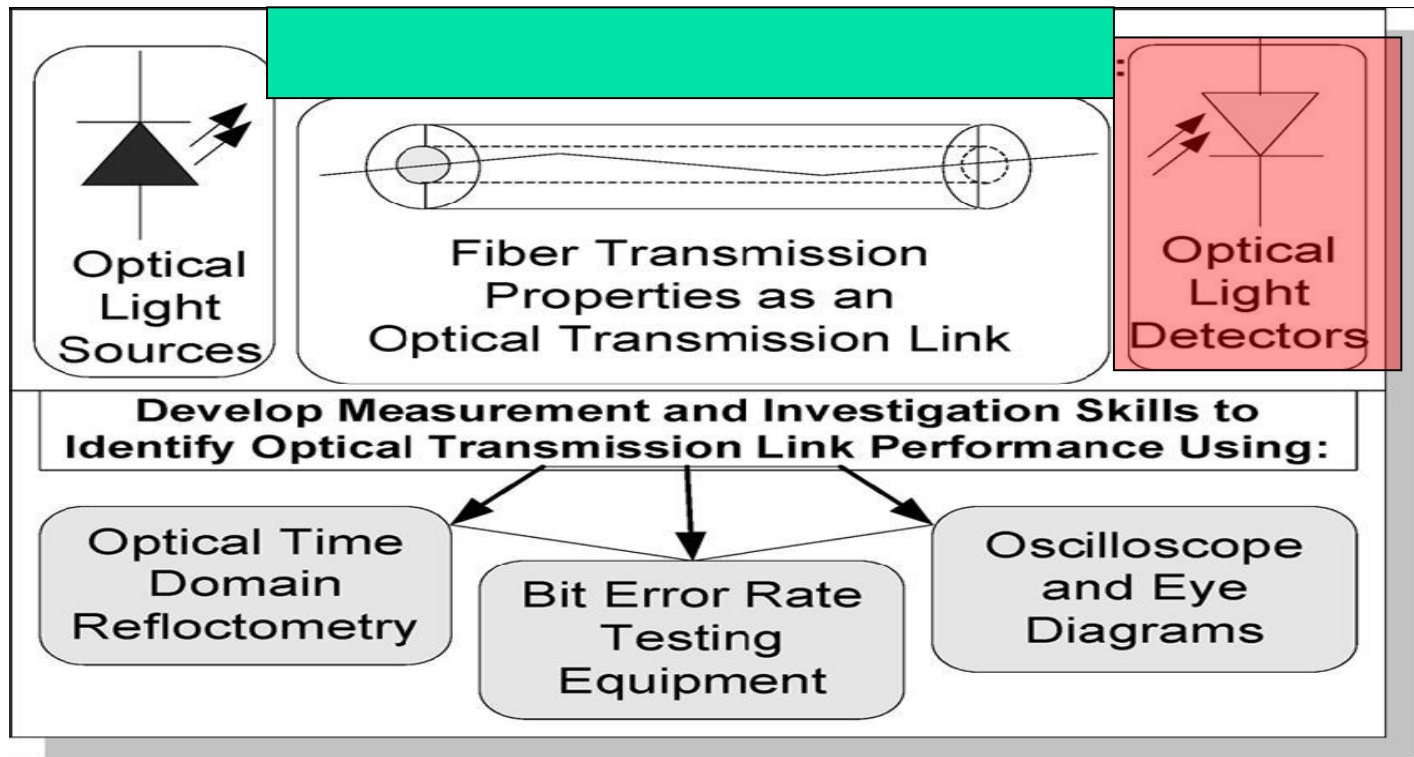


# Plan

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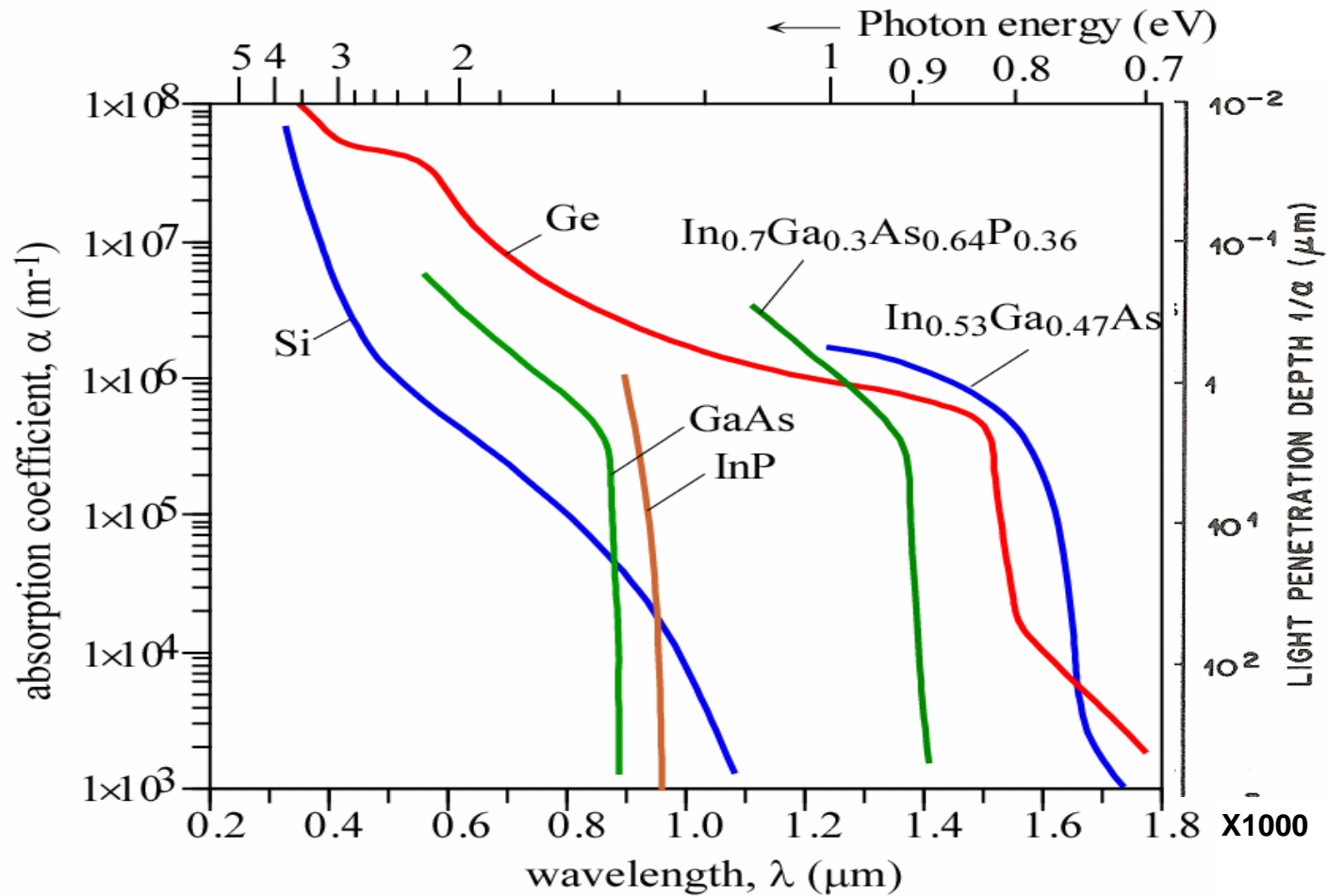
- Fabrication des fibres
- Types de fibres
- Dispersions dans les fibres
- LED et LASERS
- **PIN et APD**
- Amplificateurs optiques

# Détecteurs PIN et APD

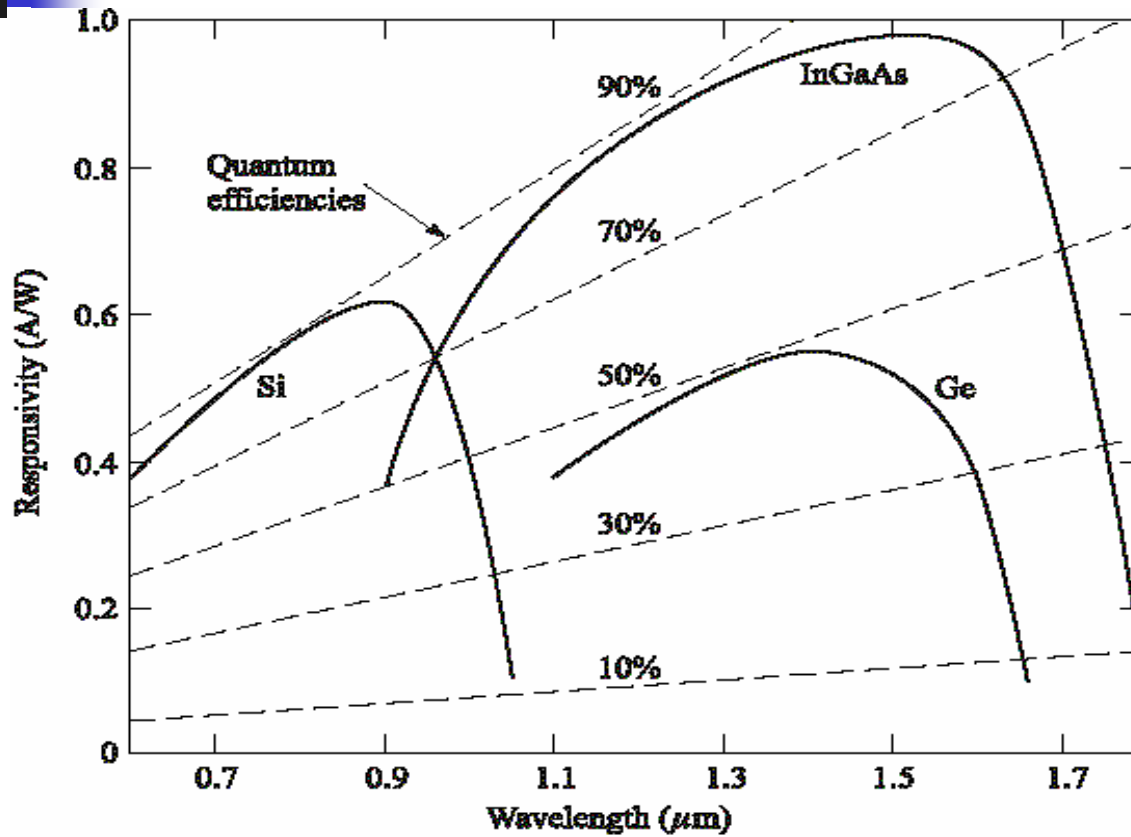


- Semiconducteur
- PIN
- APD
- Ampli
- Data sheet module de réception

# Coefficient d'absorption



# Sensibilité spectrale $R$



$$R = \frac{e\eta}{h\nu} = \frac{e\eta}{hc} \lambda$$

$$\lambda_{th} = \frac{hc}{E_g}$$

$$\lambda_{th} = \frac{1.24}{E_g} \quad [\mu\text{m}]$$

$\eta =$

$$\eta = \text{Efficacité quantique} = \frac{\text{nombre de paires e-h créées}}{\text{nombre de photons incidents}}$$

# Characteristics of Photodetectors

- **Internal Quantum Efficiency**

$$\eta_i = \frac{\text{Number of Collected electrons}}{\text{Number of Photons *Entering* detector}} = [1 - e^{-\alpha W}]$$

- **External Quantum efficiency**

$$\eta_e = \frac{\text{Number of Collected electrons}}{\text{Number of Photons *Incident* on detector}} = \frac{i_{ph}/q}{P_o/h\nu} = (1 - R_p)[1 - e^{-\alpha W}]$$

- **Responsivity**

$$R = \frac{\text{Photo Current (Amps)}}{\text{Incident Optical Power (Watts)}} = \frac{i_{ph}}{P_o} = \frac{q}{h\nu}(1 - R_p)[1 - e^{-\alpha W}]$$

- **Photocurrent**

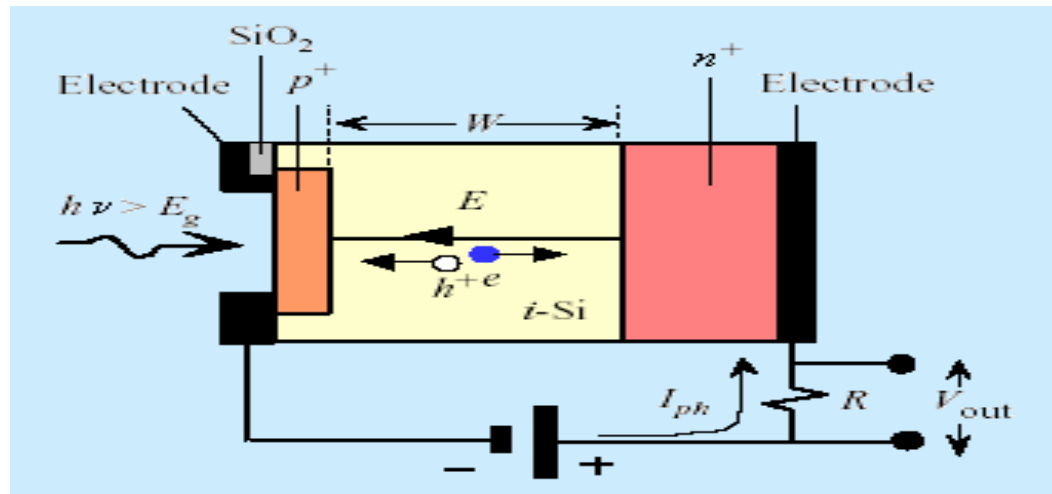
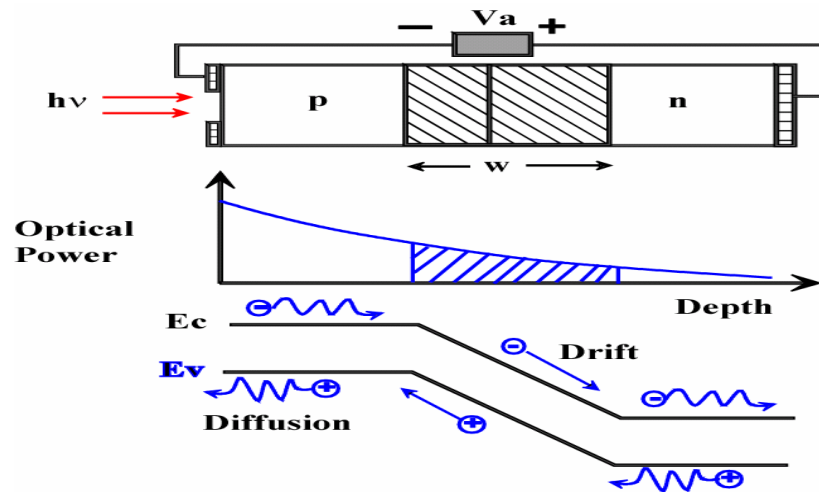
$$i_{ph} = q \left[ \frac{P_o}{h\nu} \right] (1 - R_p) [1 - e^{-\alpha W}] = R P_o$$

↓  
Fraction Transmitted  
into Detector

↑  
Incident Photon Flux  
(#/sec)

↑  
Fraction absorbed in  
detection region

# Structure de diode PIN

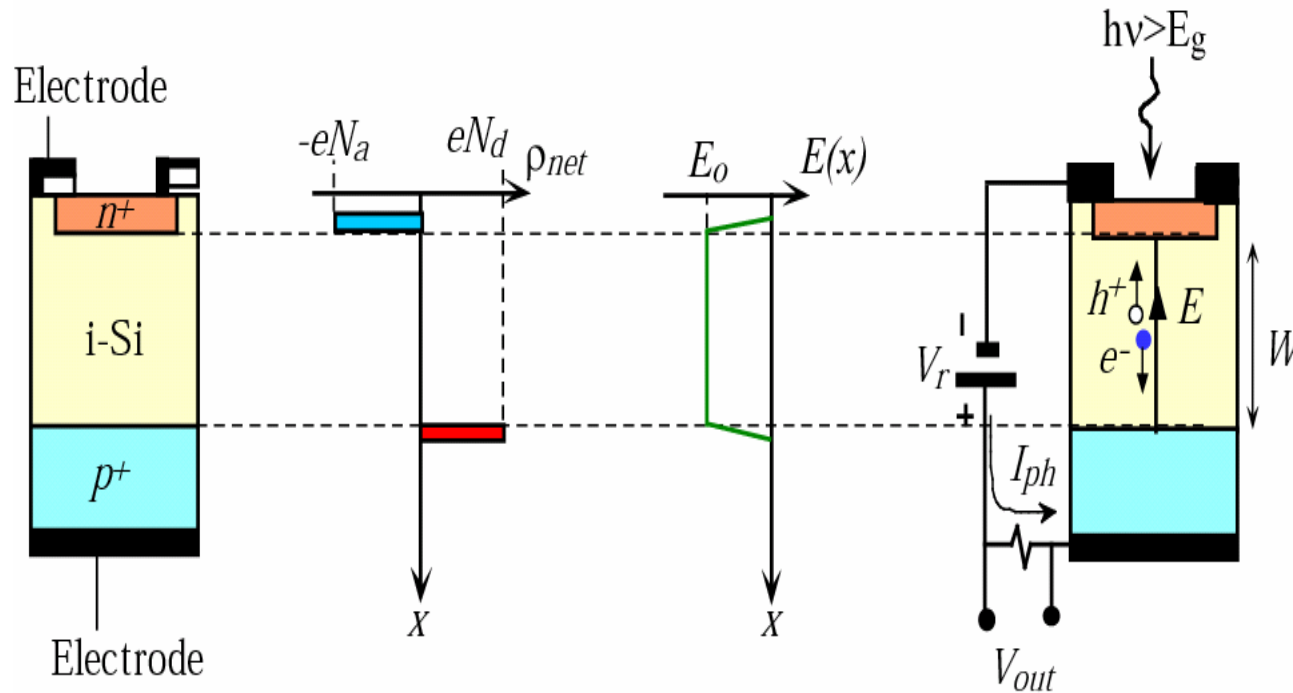
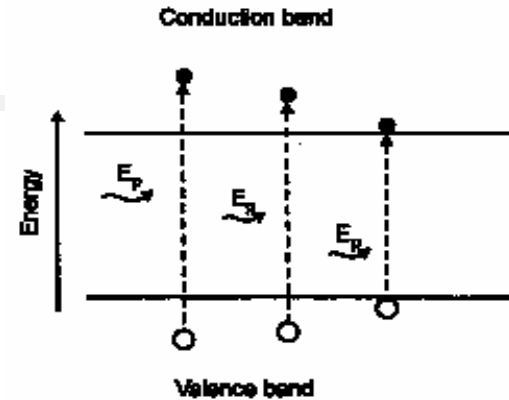




# Diode PIN

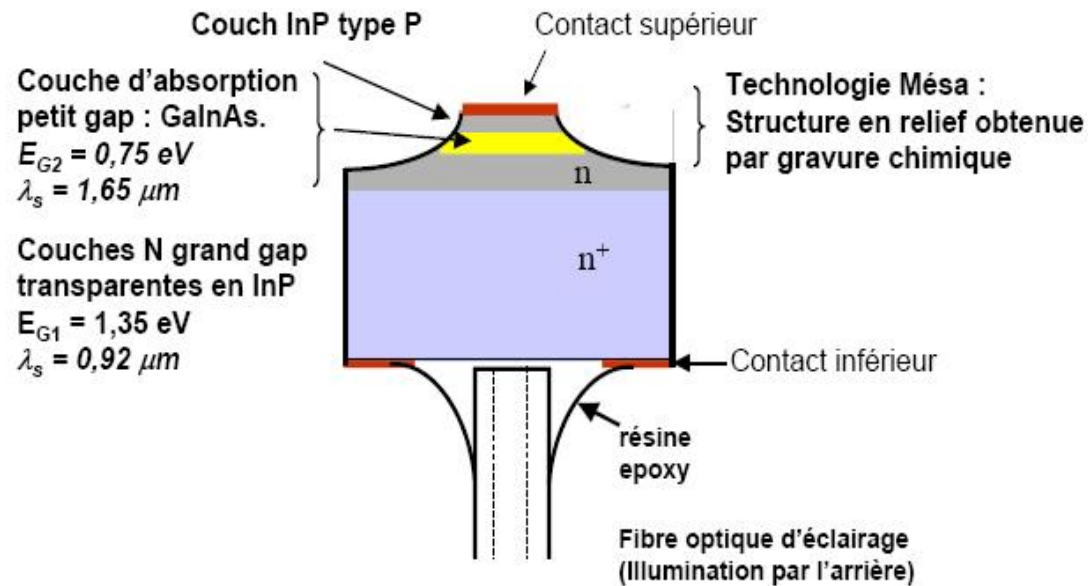
■ Intrinsic layer is introduced

- Increase the space charge region
- Minimize the diffusion current



# Diode PIN fibrée

## PIN A HETEROJONCTION POUR TRANSMISSIONS A 1,55 $\mu\text{m}$



Utilisable dans le domaine  $0,92 \mu\text{m} < \lambda < 1,65 \mu\text{m}$

# PIN

## PHOTODIODE

### InGaAs PIN photodiode **G9801 series**

Receptacle type, 1.3/1.55  $\mu\text{m}$ , 2 GHz



G9801 series are high-speed receivers specifically developed for 1.3/1.55  $\mu\text{m}$  band optical fiber communications. These devices incorporate a high-speed, high-sensitivity InGaAs PIN photodiode integrated in a receptacle module. Packages are available with various connectors and mounting styles.

#### Features

- High-speed response: 2 GHz Typ.
- Low dark current: 20 pA Typ.
- High sensitivity: 0.9 A/W Typ. ( $\lambda=1.31 \mu\text{m}$ )
- Low terminal capacitance: 1 pF Typ.

#### Applications

- Optical fiber communications

#### ■ Absolute maximum ratings ( $T_a=25^\circ\text{C}$ )

Parameter	Symbol	Value	Unit
Reverse voltage	$V_R$ Max.	20	V
Operating temperature	$T_{opr}$	-20 to +70	$^\circ\text{C}$
Storage temperature	$T_{stg}$	-40 to +85	$^\circ\text{C}$

#### ■ Electrical and optical characteristics ( $T_a=25^\circ\text{C}$ )

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Spectral response range	$\lambda$		-	0.9 to 1.7	-	$\mu\text{m}$
Peak sensitivity wavelength	$\lambda_p$		-	1.55	-	$\mu\text{m}$
Photo sensitivity	$S^*1$	$\lambda=1.3 \mu\text{m}$	0.75	0.9	-	A/W
		$\lambda=1.55 \mu\text{m}$	0.8	0.95	-	A/W
Dark current	$I_D$	$V_R=5 \text{ V}$	-	0.02	0.4	nA
Cut-off frequency	$f_c$	$V_R=5 \text{ V}$ , $R_L=50 \Omega$ $\lambda=1.3 \mu\text{m}$ , -3 dB	-	2	-	GHz
Terminal capacitance	$C_t$	$V_R=5 \text{ V}$ , $f=1 \text{ MHz}$	-	1	1.5	pF
Noise equivalent power	NEP	$V_R=5 \text{ V}$ , $\lambda=1.55 \mu\text{m}$	-	$3 \times 10^{-15}$	-	$\text{W/Hz}^{1/2}$

\*1: Using a single mode optical fiber with a master plug.

#### ■ Package lineup

Parameter	G9801		
	-21	-22	-32
Mounting style	Board		Panel
Connector	SC	FC	FC
Dimensional outline	①	②	③

# PIN avec préampli

## InGaAs PIN photodiode with preamp **G9821 series**

Receptacle type, 1.3/1.55  $\mu\text{m}$ , 2.5 Gbps



G9821 series is a family of high-speed receivers specifically developed for 1.3/1.55  $\mu\text{m}$  band optical fiber communications. These devices incorporate a high-speed, high-sensitivity InGaAs PIN photodiode and a high-speed preamp integrated in a receptacle module. Packages are available with various connectors and mounting styles.

### Features

- High-speed response
- High gain with AGC (Auto Gain Control)
- Low power supply voltage: 3.3 V
- Differential output
- Sensitivity: -25.5 to +1 dBm

### Applications

- Optical fiber communications
- Fiber channel
- Gigabit Ethernet
- HDTV
- SDH/SONET (STM-16/OC-48)

### ■ Absolute maximum ratings

Parameter	Symbol	Value	Unit
Supply voltage	Vcc	-0.5, +5.0	V
Operation temperature *1	Topr	-40 to +85	°C
Storage temperature *1	Tstg	-40 to +85	°C

\*1: No condensation

### ■ Electrical and optical characteristics

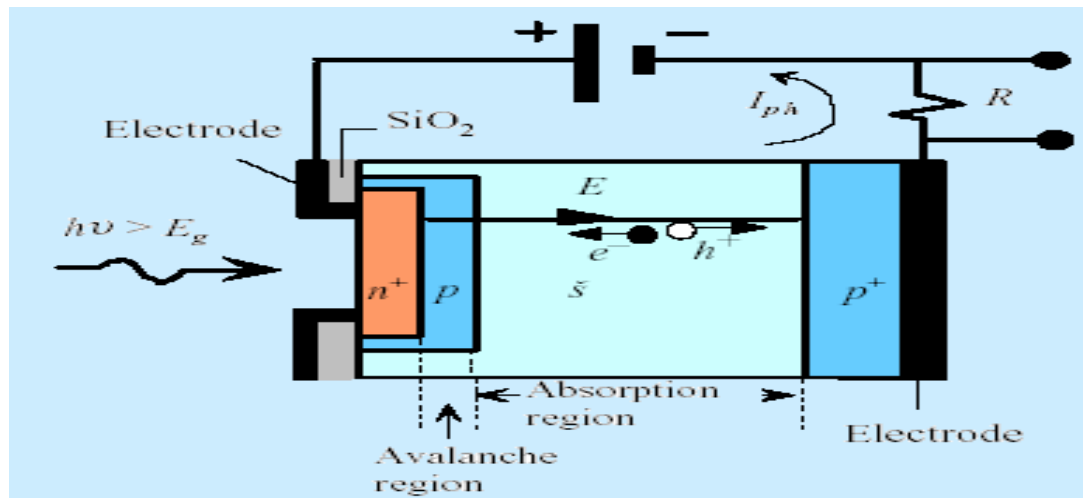
(Ta=25 °C, Vcc=3.3 V, Vee=0 V, RL=50  $\Omega$  \*2,  $\lambda$ =1.31  $\mu\text{m}$ , unless otherwise noted)

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Photo sensitivity	S	Pin= -22 dBm *2, *3	1.0	1.5	-	V/mW
Supply current	Icc	Dark state, RL=∞	-	45	60	mA
Output bias voltage	Vo	Dark state, RL=∞	-	3.0	-	V
Cut-off frequency	fc	Pin= -22 dBm, -3 dB *2	1.7	2.1	-	GHz
Low cut-off frequency	fc-L	Pin= -22 dBm, -3 dB	-	3.0	-	kHz
Noise equivalent power	NEP	Dark state, to 1875 MHz, *2, *3	-	310	500	nWrms
Minimum receivable sensitivity	Pmin	2.5 Gbps, PRBS=2 <sup>23</sup> -1 BER=10 <sup>-10</sup>	-	-25.5	-23.5	dBm
Maximum receivable sensitivity	Pmax	Extinction ratio=10 dB	+1	-	-	
Output impedance	Rout		40	50	60	$\Omega$
Optical return loss	ORL	1.3/1.55 $\mu\text{m}$	12	14	-	dB

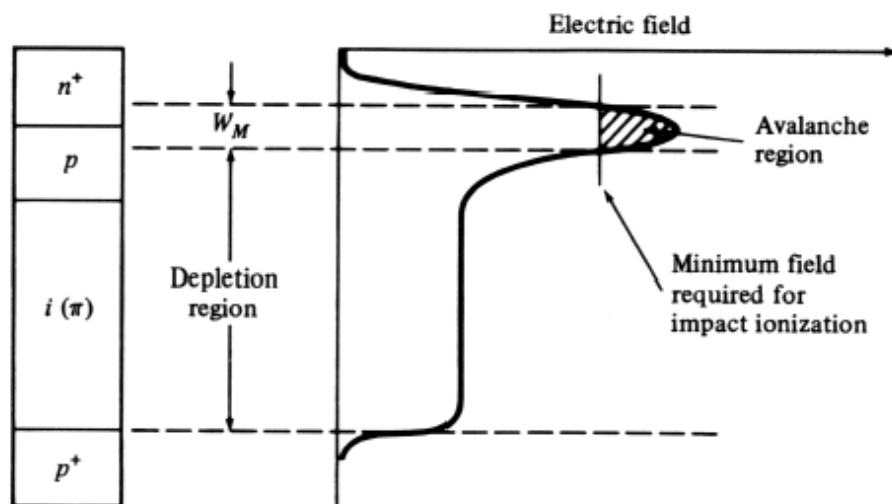
\*2: Output: capacitive coupling

\*3: Single-ended (Vout+) measurement

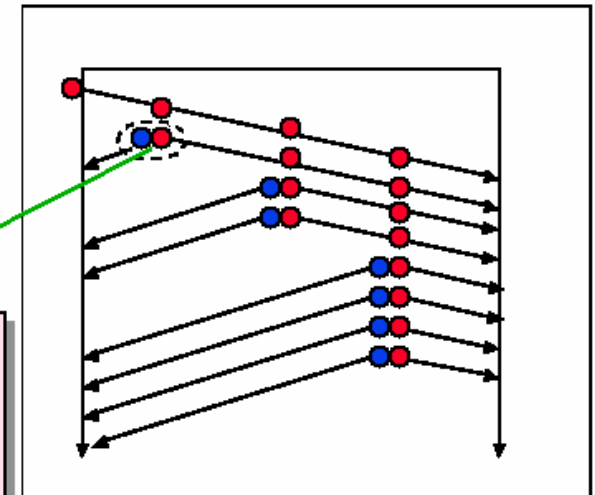
# APD (Avalanche PhotoDiode)



The free electrons are accelerated by the high electric field. More free electrons are created through impact ionization.



E-h pair generation  
By impact from an  
accelerated electron



# Avalanche Photodiodes (APDs)

- High resistivity p-doped layer increases electric field across absorbing region
- High-energy electron-hole pairs ionize other sites to multiply the current
- Leads to greater sensitivity

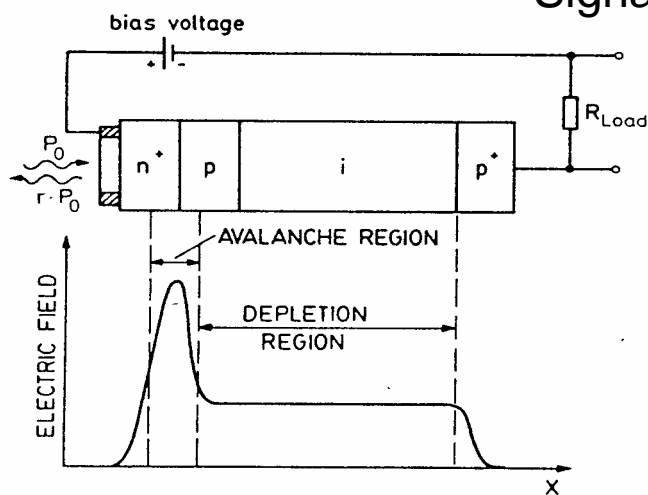
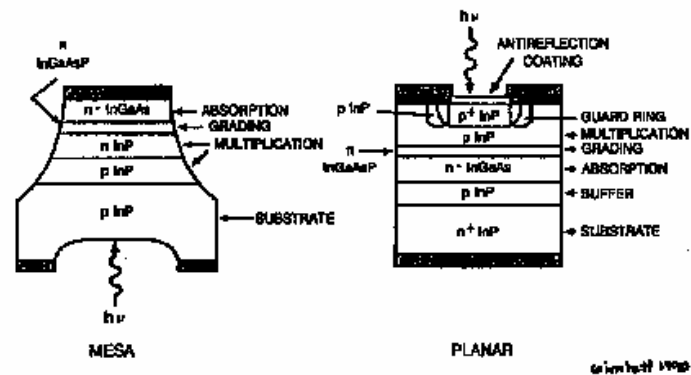
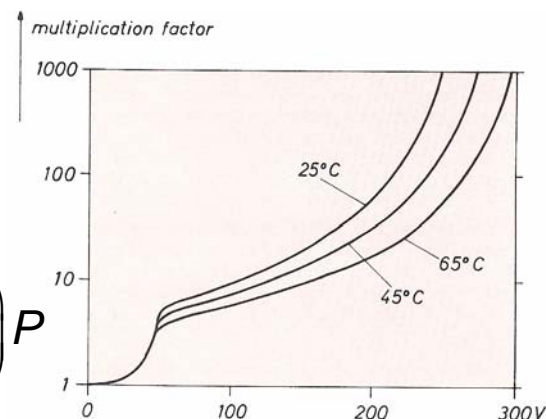


FIGURE 4. Structure of an APD and the electric field distribution in the avalanche and depletion region.

$$\text{Signal Current } i_s = M \left( \frac{\eta q}{h\nu} \right) P$$





# APD

## PHOTODIODE

### InGaAs APD G8931-04

Time response characteristics compatible with SONET and G/GE-PON

G8931-04 is an InGaAs APD that delivers a high-speed response of 2.5 Gbps required for trunk line optical fiber communications such as SONET (Synchronous Optical Network), G-PON (Gigabit-capable Passive Optical Network) and GE-PON (Gigabit Ethernet-Passive Optical Network).



#### Features

- High-speed response: 2.5 Gbps
- Low dark current
- Low capacitance
- Active area:  $\phi 0.04$  mm
- High sensitivity

#### Applications

- Optical fiber communications
- High-speed data links

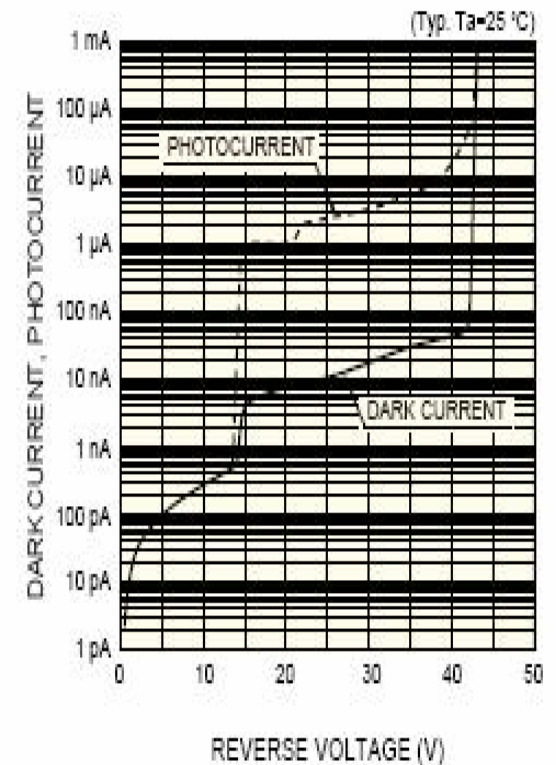
#### General ratings

Parameter	Symbol	Value	Unit
Active area	-	$\phi 0.04$	mm
Parameter	Symbol	Value	Unit
Forward current	$I_F$	2	mA
Reverse current	$I_R$	500	$\mu A$
Operating temperature	$T_{opr}$	-40 to +85	$^{\circ}C$
Storage temperature	$T_{stg}$	-55 to +125	$^{\circ}C$

#### Electrical and optical characteristics (Ta=25 $^{\circ}C$ )

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Spectral response range	$\lambda$		-	0.9 to 1.7	-	$\mu m$
Peak sensitivity wavelength	$\lambda_p$		-	1.55	-	$\mu m$
Photo sensitivity	S	$\lambda=1.55 \mu m, M=1$	0.8	0.9	-	A/W
Breakdown voltage	$V_{BR}$	$I_D=100 \mu A$	40	-	60	V
Temperature coefficient of $V_{BR}$	$\Gamma$	-40 to +85 $^{\circ}C$	-	0.11	0.16	$V/^{\circ}C$
Dark current	$I_D$	$V_R=V_{BR} \times 0.9$	-	40	65	nA
Cut-off frequency	$f_c$	$M=10$	3	4	-	GHz
Terminal capacitance	$C_t$	$V_R=V_{BR} \times 0.9$ $f=1$ MHz	-	0.35	0.45	pF

#### Dark current vs. reverse voltage



# Typical Characteristics of PIN and APD

Parameter	Symbol	Unit	Type	Material		
				Si	Ge	InGaAs
Wavelength	$\lambda$	nm		0.4–1.1	0.8–1.8	1.0–1.7
Responsivity	$R$	A/W	<i>p-i-n</i>	0.4–0.45	0.8–0.87	0.5–0.95
Quantum efficiency	$\eta$	%	<i>p-i-n</i>	75–90	50–55	60–70
APD gain	$M$	—	APD	—	50–200	10–40
Dark current	$I_d$	nA	<i>p-i-n</i>	1–10	50–500	1–20
			APD	0.1–1	50–500	1–5
Bandwidth	BW	GHz	<i>p-i-n</i>	0.125–1.4	0–0.0015	0.0025–40
			APD	—	1.5	1.5–3.5
Bit rate	BR	Gbit/s	<i>p-i-n</i>	0.01	—	0.1555–53
			APD	—	—	2.5–4
Reverse voltage*	$V$	V	<i>p-i-n</i>	50–100	6–10	5–6
			APD	200–250	20–40	20–30
<i>k</i> -factor	$k_A$	—	APD	0.02–0.05	0.7–1.0	0.5–0.7



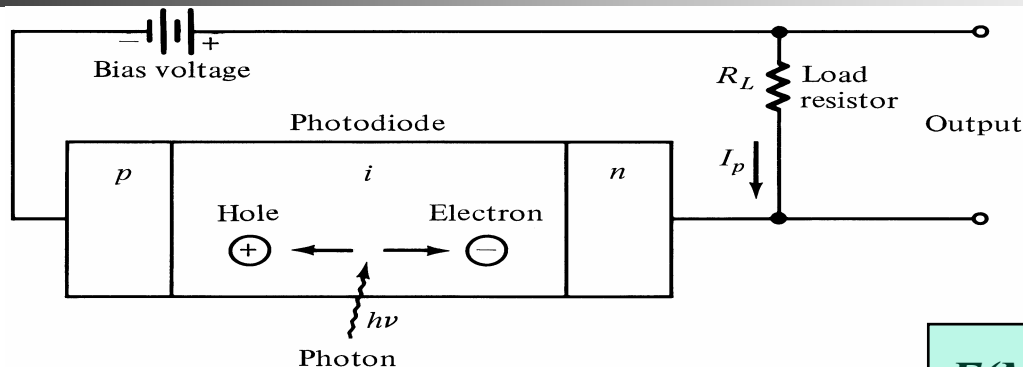


# APD vs PIN

- PIN gives higher bandwidth and bit rate
- APD gives higher sensitivity
- Si works only up to 1100 nm; InGaAs up to 1700, Ge up to 1800
- InGaAs has higher  $\eta$  for PIN, but Ge has higher M for APD
- InGaAs has lower dark current

	PIN	APD
Advantages	<ul style="list-style-type: none"><li>■ Low Voltage</li><li>■ Low Noise</li><li>■ Low dark Current</li><li>■ Easy to use</li><li>■ Low cost</li></ul>	<ul style="list-style-type: none"><li>■ Current Gain</li><li>■ Sensitivity more than PIN</li></ul>
Disadvantages	<ul style="list-style-type: none"><li>■ Low Sensitivity</li><li>■ Without Current Gain</li></ul>	<ul style="list-style-type: none"><li>■ High Noise</li><li>■ High dark Current</li><li>■ More Sensitivity to Temperature</li><li>■ High operating Voltage</li></ul>

# SNR signal to noise ratio



$$\langle i_Q^2 \rangle = 2 q I_p B M^2 F(M)$$

**$F(M)$ : APD Noise Figure**

**$F(M) \sim M^x$  ( $0 \leq x \leq 1$ )**

**$I_p$ : Mean Detected Current**

**$B$  = Bandwidth**

$$\langle i_{DB}^2 \rangle = 2 q I_D B M^2 F(M)$$

**Bulk Dark Current Noise**

$$\langle i_{DS}^2 \rangle = 2 q I_L B$$

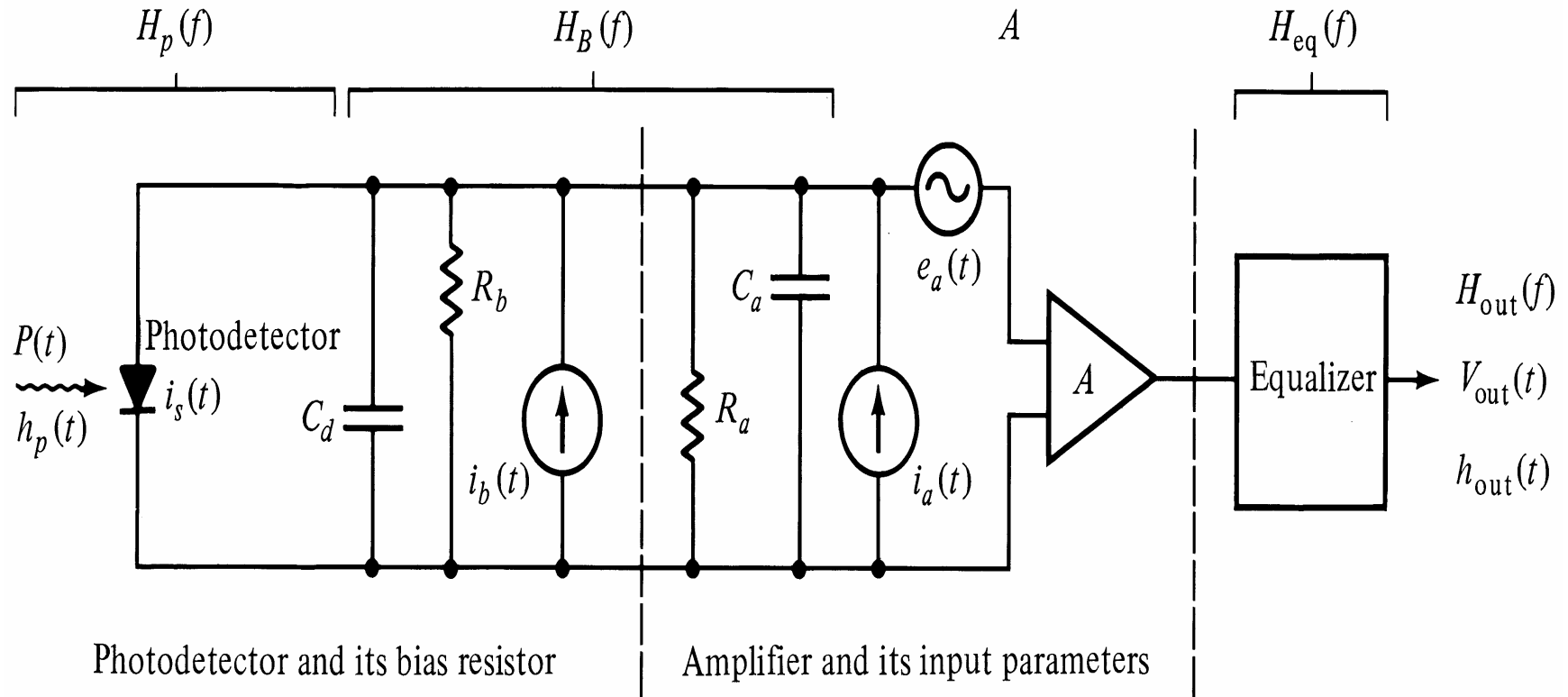
**Surface leakage current noise**

$$\langle i_T^2 \rangle = 4 K_B T B / R_L$$

**$R_L$  thermal (Johnson) noise current**

$$SNR = \frac{\langle i_p^2 \rangle M^2}{2q(I_p + I_D)M^2 F(M)B + 2qI_L B + 4k_B T B / R_L}$$

# Optical receiver schematic



dBm  
NEP  
Personick


[cc.ee.ntu.edu.tw/~wujsh/9602ON/Chapter%204.ppt](http://cc.ee.ntu.edu.tw/~wujsh/9602ON/Chapter%204.ppt)

## 10Gb/s surface mount coplanar PIN preamp receiver with integrated MEMS VOA PTV10GC

The PTV10GC receiver consists of a PIN photodetector, a low-noise preamplifier, a MEMS variable optical attenuator (VOA) and a precision NTC thermistor in a hermetic coplanar package with a connectorized single-mode fiber pigtail. Differential outputs are provided to improve noise rejection for enhanced sensitivity. It has been optimised for use in 10Gb/s metro or long haul applications, either as a discrete device or within a transponder, using NRZ modulation, with or without FEC, at data rates up to 10.709Gb/s.



### Features:

- High sensitivity, -18.5dBm typical
- Integrated MEMS VOA extends overload beyond +10dBm
- Low capacitance high speed InGaAs PIN photodetector
- Supports FEC rates up to 10.709Gb/s
- Best in class power consumption, only 350mW
- Designed to exceed the environmental requirements of Telcordia GR-468-CORE
- RoHS 5/6 compliant 

### Applications:

- Client or line side links
- DWDM TDM transponder applications

# PIN+ampli 2/3

## Operating Characteristics

PTV10GC

Case temperature = 25°C unless otherwise specified

Parameter	Symbol	Measurement Conditions	Min	Typ	Max	Unit
Optical sensitivity BOL [1] [2]	Sens	$2^{31-1}$ PRBS BER<10 <sup>-12</sup>		-18.5	-17.0	dBm
Sensitivity penalty EOL over temperature [1] [2]		$2^{31-1}$ PRBS BER<10 <sup>-12</sup> T=-5 to +75°C		0.75	1.0	dB
Deviation from linear phase		DC – 6GHz	-10		+10	°
High frequency -3dB corner	f <sub>H</sub>	Small signal	8	9.5		GHz
Low frequency -3dB corner	f <sub>L</sub>				40	kHz
Transimpedance gain [3] [4] [5]	T <sub>Z</sub>	Small signal	1.1	1.6	2.3	kΩ
Maximum output voltage [6]	V <sub>OUT</sub>	Peak-to-peak		600	700	mV
Return loss	S <sub>22</sub>	DC to 7.0GHz			-8	dB
Optical overload [2]	P <sub>SAT</sub>	0dB Attenuation BER<10 <sup>-12</sup>	+1			dBm
Optical overload extension		With VOA actuated	+9			dBm
PIN bias voltage	V <sub>pd</sub>			5		V
PIN responsivity [1]	R		0.7	0.8		A/W
Dark current	I <sub>d</sub>				10	nA
Amplifier bias current	I <sub>oc</sub>			75	95	mA

# PIN+ampli 3/3

## Operating Characteristics

suite

PTV10GC

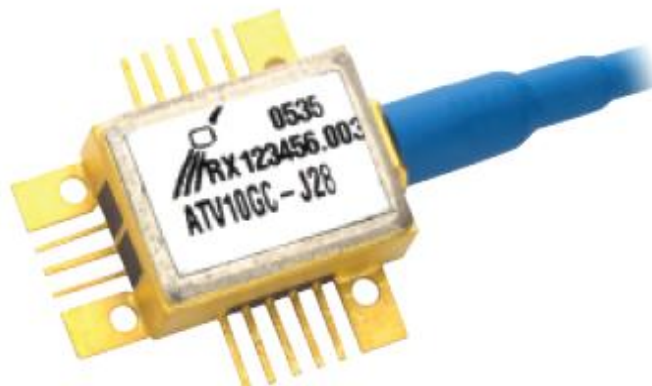
Case temperature = 25°C unless otherwise specified

Parameter	Symbol	Measurement Conditions	Min	Typ	Max	Unit
PIN bias voltage	$V_{pd}$			5		V
PIN responsivity [1]	R		0.7	0.8		A/W
Dark current	$I_d$				10	nA
Amplifier bias current	$I_{oc}$			75	95	mA
Input current for output limiting	$I_{in\_lim}$	Peak-to-peak		0.5		mA
VOA maximum attenuation	Att		20	30		dB
VOA control voltage [7]	$V_{Att}$	Attenuation = 20dB		5.5	9	V
VOA current	$I_{Att}$	Attenuation = 20dB		6	7.2	mA
VOA power dissipation (continuous)	$P_{Att}$	Attenuation = 20dB		33	65	mW
VOA response time [8]		From attenuation = 1dB to 20dB		5	10	ms
Polarisation dependent loss	PDL	VOA unbiased			0.15	dB
Polarisation dependent loss	PDL	VOA biased			0.4	dB
Thermistor resistance	$R_{TH}$			10		k $\Omega$


# APD + ampli 1/2

## 10Gb/s surface mount coplanar APD preamp receiver with integrated MEMS VOA ATV10GC

The ATV10GC receiver consists of an avalanche photodiode, a low-noise preamplifier, a MEMS variable optical attenuator (VOA), and a precision NTC thermistor in a hermetic coplanar package with a connectorized single-mode fiber pigtail. Differential outputs are provided to improve noise rejection for enhanced sensitivity. It has been optimised for use in 10Gb/s metro or long-haul applications, either as a discrete device or within a transponder, using NRZ modulation, with or without FEC, at data rates up to 10.709Gb/s.



### Features:

- High sensitivity, -26.5dBm typical
- Integrated MEMS VOA extends overload beyond +10dBm
- Low capacitance high speed InGaAs APD photodetector
- Supports FEC rates up to 10.709Gb/s
- Best in class power consumption, only 350mW
- Designed to exceed the environmental requirements of Telcordia GR-468-CORE
- RoHS 5/6 compliant 

### Applications:

- Client or line side links
- DWDM TDM transponder applications



# APD + ampli 2/2

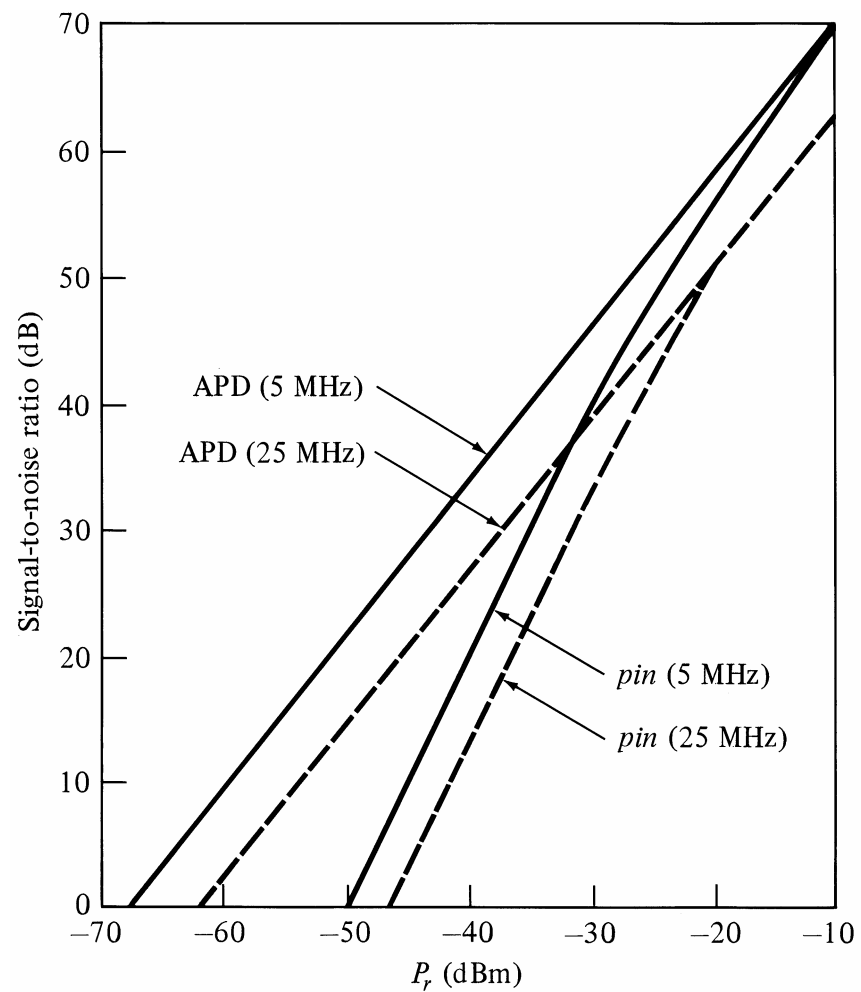
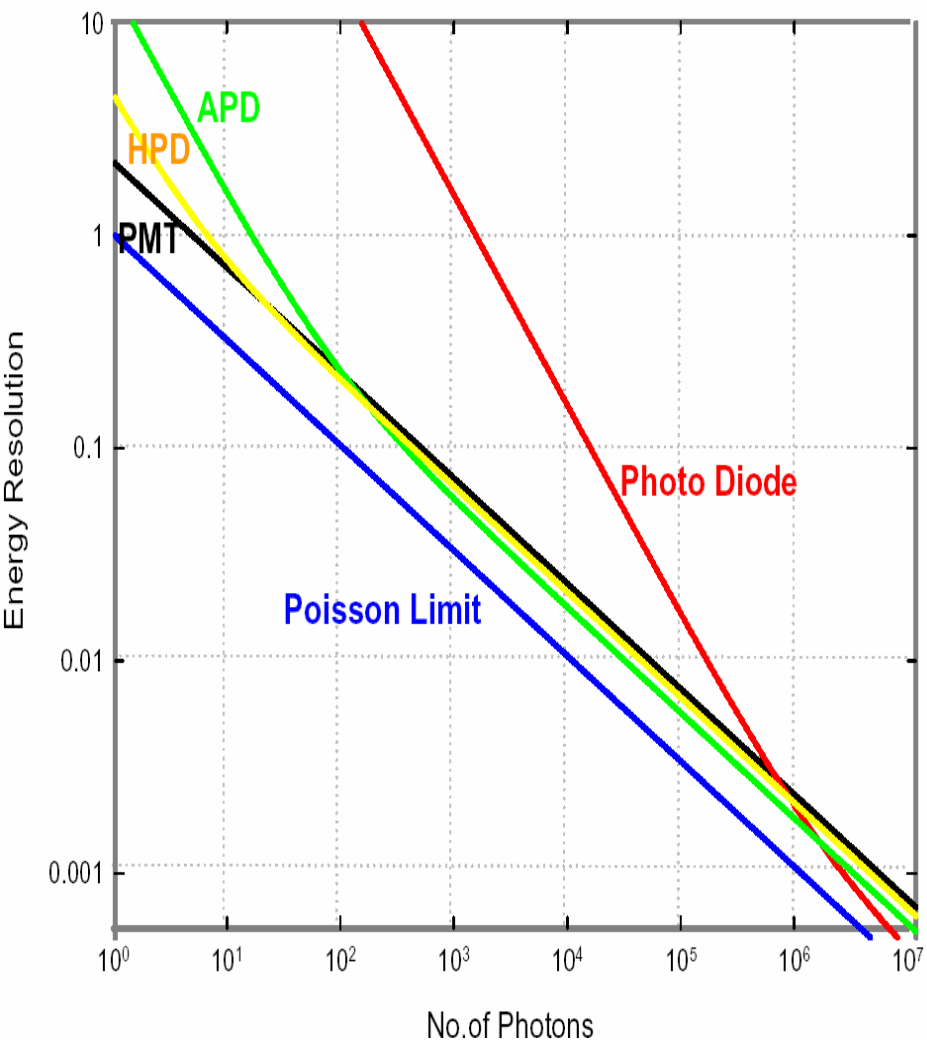
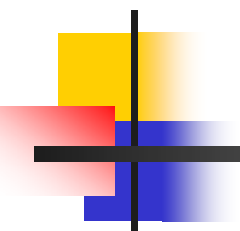
## Operating Characteristics

## ATV10GC

Case Temperature = 25°C unless otherwise specified

Parameter	Symbol	Measurement Conditions	Min	Typ	Max	Unit
Optical sensitivity BOL [1] [2]	Sens	2 <sup>31</sup> -1 PRBS BER<10 <sup>-12</sup> V <sub>APD</sub> =V <sub>M10</sub>		-26.5	-25.0	dBm
Sensitivity penalty EOL over temperature [1] [2]		2 <sup>31</sup> -1 PRBS BER<10 <sup>-12</sup> V <sub>APD</sub> =V <sub>M10</sub> T=-5 to +75°C		0.75	1.0	dB
Deviation from linear phase		DC - 6GHz	-10		+10	°
High frequency -3dB corner	f <sub>H</sub>	V <sub>APD</sub> =V <sub>M10</sub> Small signal	7	7.5		GHz
Low frequency -3dB corner	f <sub>L</sub>				40	kHz
Transimpedance gain [3] [4] [5]	T <sub>Z</sub>	Small signal	1.1	1.6	2.3	kΩ
Maximum output voltage <sup>6</sup>	V <sub>OUT</sub>	Peak-to-peak		600	700	mV
Return loss	S <sub>22</sub>	DC to 7.0GHz			-8	dB
Optical overload [2]	P <sub>SAT</sub>	0dB Attenuation V <sub>APD</sub> =V <sub>M3</sub> BER<10 <sup>-12</sup>	-3	-1		dBm
Optical overload extension		With VOA actuated	+13			dBm
APD breakdown voltage	V <sub>br</sub>	T=25°C I <sub>APD</sub> =10mA	25		40	V
APD breakdown voltage temperature coefficient	T <sub>vbr</sub>		0.030	0.045	0.061	V/°C
Dark current	I <sub>d</sub>	At 90% of V <sub>br</sub>			100	nA
Amplifier bias current	I <sub>oc</sub>			75	95	mA







# Plan

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- Fabrication des fibres
- Types de fibres
- Dispersions dans les fibres
- LED et LASERS
- PIN et APD
- **Amplificateurs optiques**



# Amplificateurs optiques

*Pour compenser l'atténuation des fibres on amplifie directement le signal optique sans passer par une conversion O/E, une amplification-régénération et enfin une conversion E/O (cas des **répéteurs**)*

Il existe 3 types d'amplificateurs optiques:

**AMPLIFICATEUR OPTIQUE A SEMICONDUCTEUR (AOS)**

Semiconductor Optical Amplifier (**SOA**)

**AMPLIFICATEUR A FIBRE OPTIQUE DOPEE ERBIUM (EDFA)**

Erbium Doped Fibre Amplifier (**EDFA**)

**AMPLIFICATEUR RAMAN**

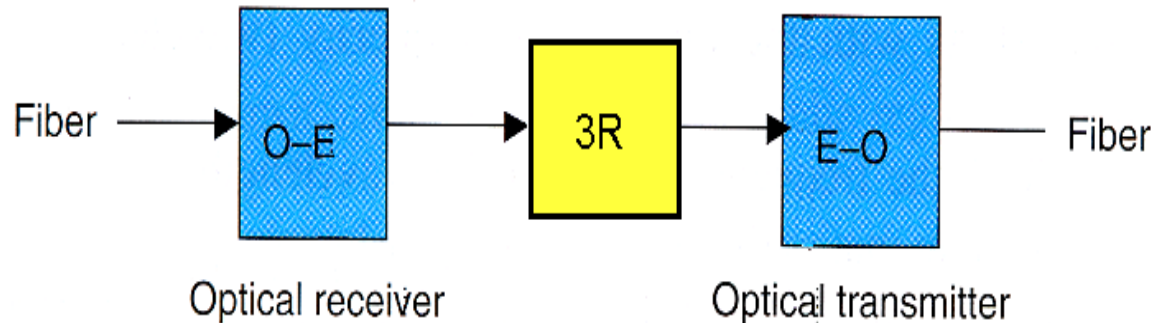
RAMAN Amplifier

[http://www.cnam.fr/elau/publi/hincelin/images/4.fibre\\_optique.pdf](http://www.cnam.fr/elau/publi/hincelin/images/4.fibre_optique.pdf)

[http://www.electronics.dit.ie/staff/tfreir/optical\\_2/](http://www.electronics.dit.ie/staff/tfreir/optical_2/) (unit\_5.ppt)

<http://www.redbooks.ibm.com/redbooks/pdfs/sg245230.pdf> pp181-207

# 3R regeneration



**Amplification of optical signals :**

**1- Optical- Electrical-Optical (O-E-O)**

- Converting the optical signal to an electronic signal
- Retiming, Reshaping, and Reamplification (**3R**) of the electronic signal
- Converting the signal back to an optical signal.

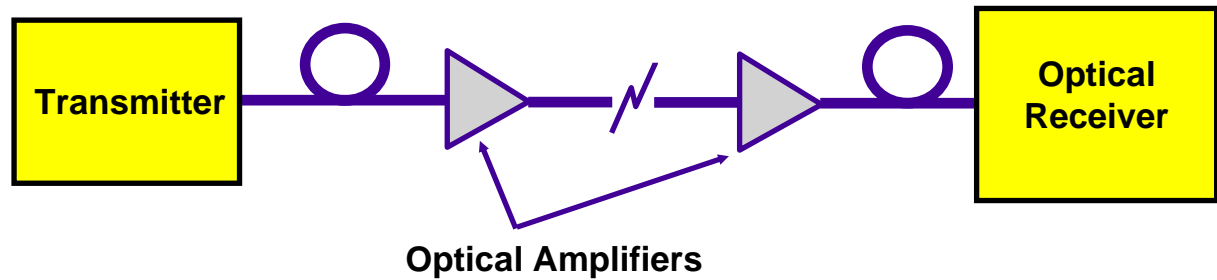
This function is known as **regeneration**.

Typically, a regenerator consists of three major functional blocks:

- optical receiver
- electronic amplifier
- optical transmitter

# Optical Amplifier Applications

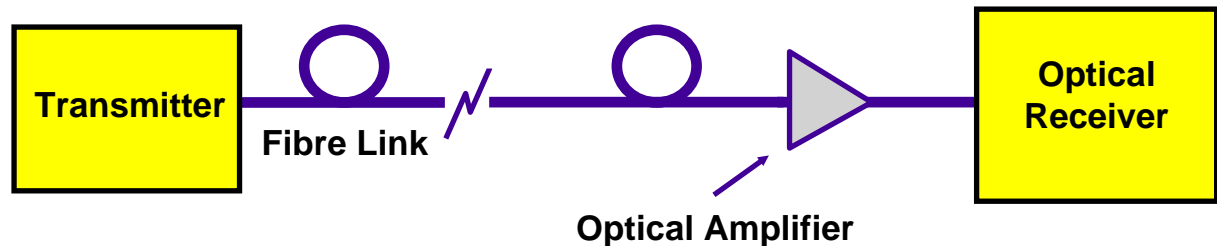
**In-line  
Amplifier**



**Power  
Amplifier**



**Preamplifier**





# Amplifier types

- **Semiconductor Optical Amplifiers (SOA)**

- conventional SOA
- GC-SOA (Gain-Clamped SOA)
- LOA (Linear Optical Amplifier)

- **Fiber Optical amplifiers (FOA)**

- Rare earth-Doped Fiber Amplifiers**

- *Erbium-Doped Fiber Amplifiers (EDFA)* : C, L-Band
- Thulium-Doped Fiber Amplifiers (TDFA) : S-Band
- Praseodymium-Doped Fiber Amplifiers (PDFA) : O-Band

- **Not based on stimulated emission but on nonlinear effects**

- Fiber Raman Amplifiers**

- Discrete Raman Amplifiers

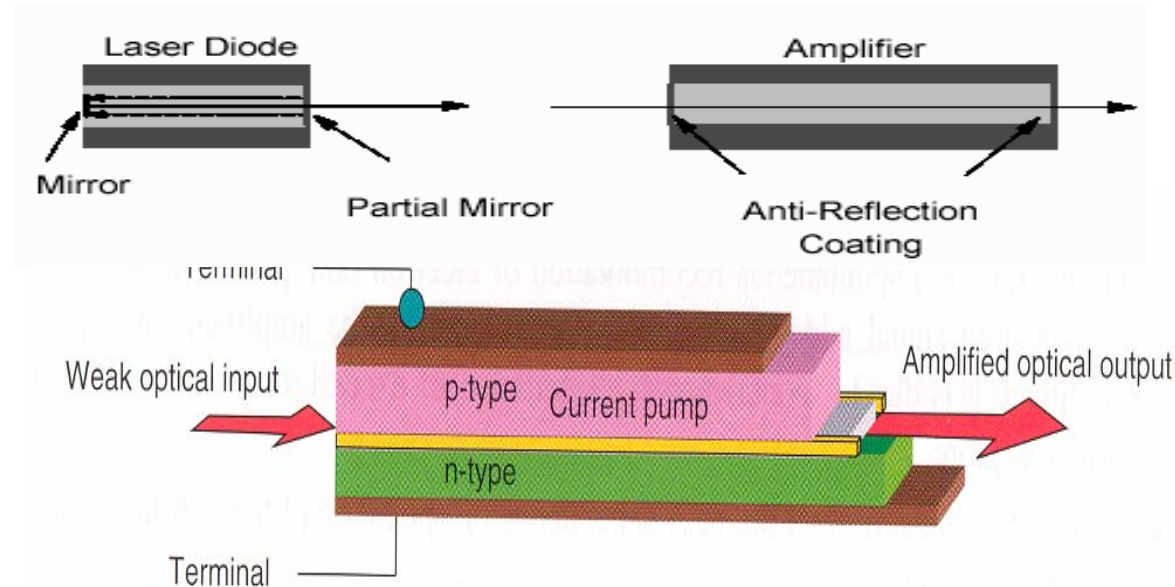
- Distributed Raman Amplifiers (DRA)*

- **Hybrid EDFA/Raman Amplifier**

# SOA

## Semiconductor Optical/Laser Amplifiers (SOA/SLA)

Similar to FP lasers, but with non-reflecting ends and broad wavelength emission.



## SOA Characteristics

Working in 1310 and 1550 nm windows (1280-1340 and 1530-1570)

Application in Booster and Pre-Amplifier

# SOA

## Semiconductor Optical Amplifier

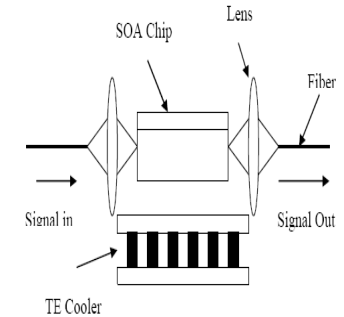
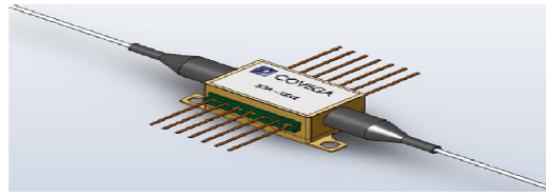
### SOA 1013: 1550nm C-band Semiconductor Optical Amplifier

7.1.2.SP.1013 Rev D

#### Description

COVEGA's 1013 SOA is a polarization insensitive optical amplifier housed in a standard 14-pin butterfly package. Advanced epitaxial wafer growth and opto-electronic packaging techniques enable high output saturation power, low noise figure, and large gain across a broad spectral bandwidth.

Packaging options include input and output isolators, SMF and PMF fiber tails and choice of connectors.



#### Applications

- ✓ Optical Booster and In-line Amplification in WDM Metro Network Systems
- ✓ Optical Loss Compensator
  - Channel Launch (Modulator)
  - Mid-Stage (Add/Drop)
- ✓ Pre-Amplifier
- ✓ High Speed optical on/off switch

#### Features

- High Fiber-to-Fiber Gain
- Broad Spectral Bandwidth
- High Fiber-to-Fiber Gain

#### Specifications

CW; T (Chip) = 25°C, T (Case) = 0 - 70°C

Parameter		Min	Typ	Max	
Operating Current	$I_{OP}$		500	600	mA
Operating Wavelength Range: C-band	$\Lambda$	1528		1562	nm
Peak Wavelength	$\lambda_C$	1480	1500	1520	nm
Optical 3 dB Bandwidth	BW	70	74		nm
Saturation Output Power @ -3 dB	$P_{SAT}$	12	14		dBm
Small Signal Gain over C-band $\Lambda$ @ Pin = -20 dBm	G	10	13		dB
Gain Flatness over C-band $\Lambda$ @ Pin = -20 dBm	$\Delta G$		5	7	dB
Gain Ripple (p-p) @ $I_{OP}, \lambda_C$	$\delta G$		0.1	0.5	dB
Polarization Dependent Gain	PDG		1.0	1.5	dB
Noise Figure	NF		8	9.5	dB
Forward Voltage	$V_F$		1.6	1.8	V
TEC Operation (typ / max @ T <sub>CASE</sub> = 25°C / 70°C)					
- TEC Current	$I_{TEC}$		0.23	1.5	A
- TEC Voltage	$V_{TEC}$		0.5	3.5	V
- Thermistor Resistance	$R_{TH}$		10K		$\Omega$

SPECIFICATIONS ARE SUBJECT TO CHANGE WITHOUT NOTICE

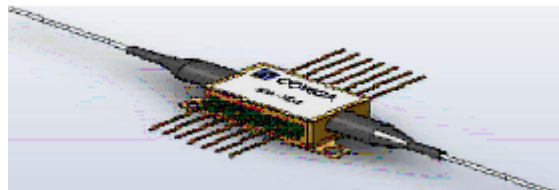
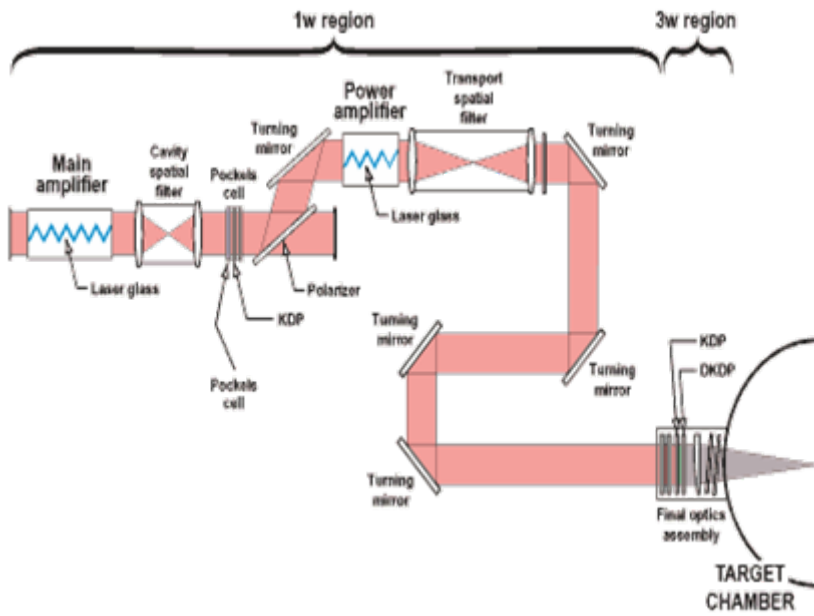
The picture is a representation. The actual part may vary from the one shown.

*C'est une diode laser sans cavité*

doc COVEGA

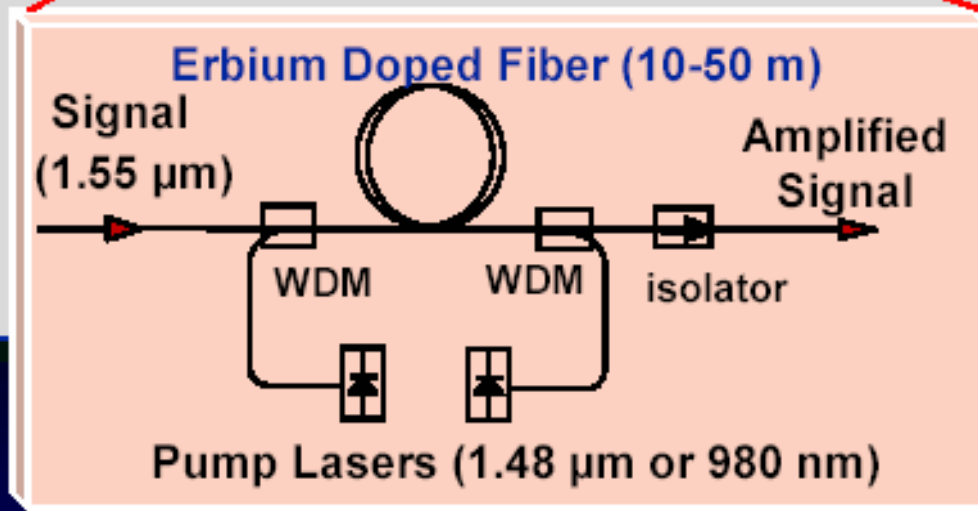
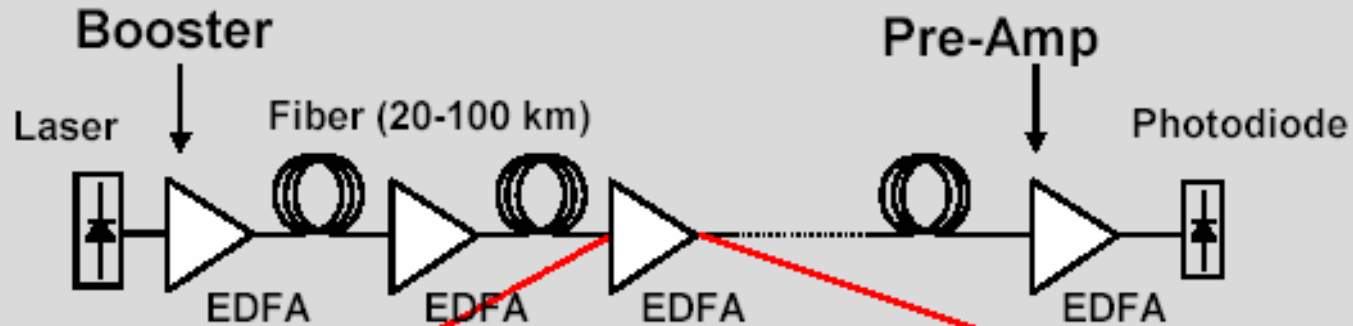


# Laser Amplifiers



# EDFA

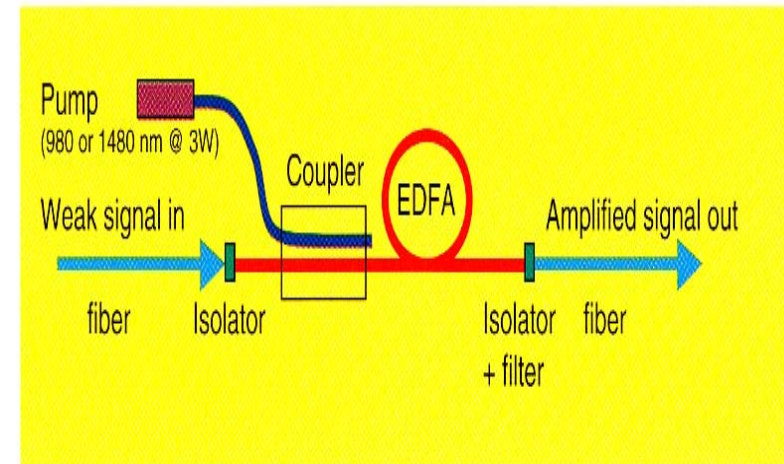
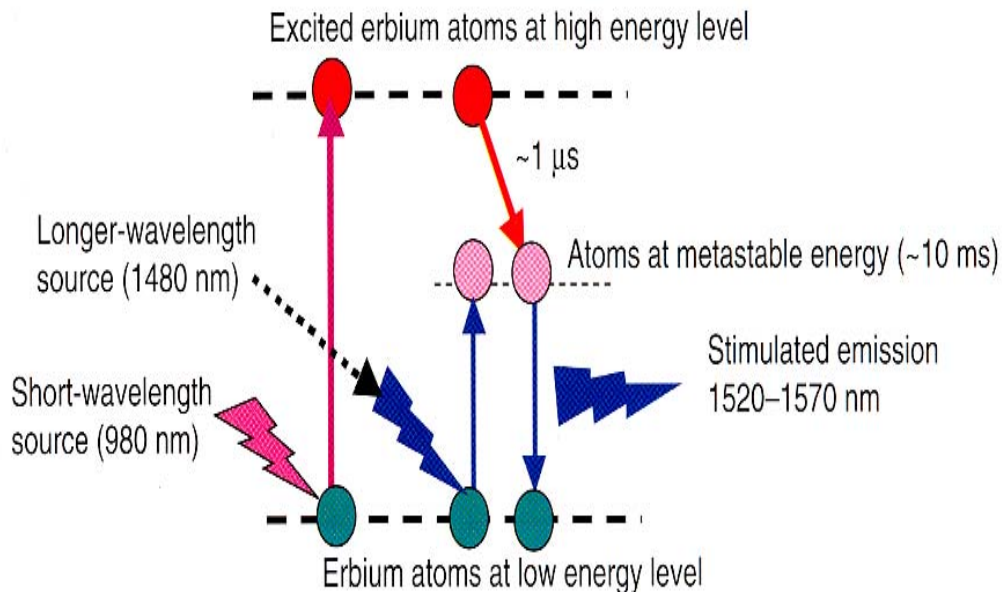
## *Erbium Doped Fibre Amplifier*



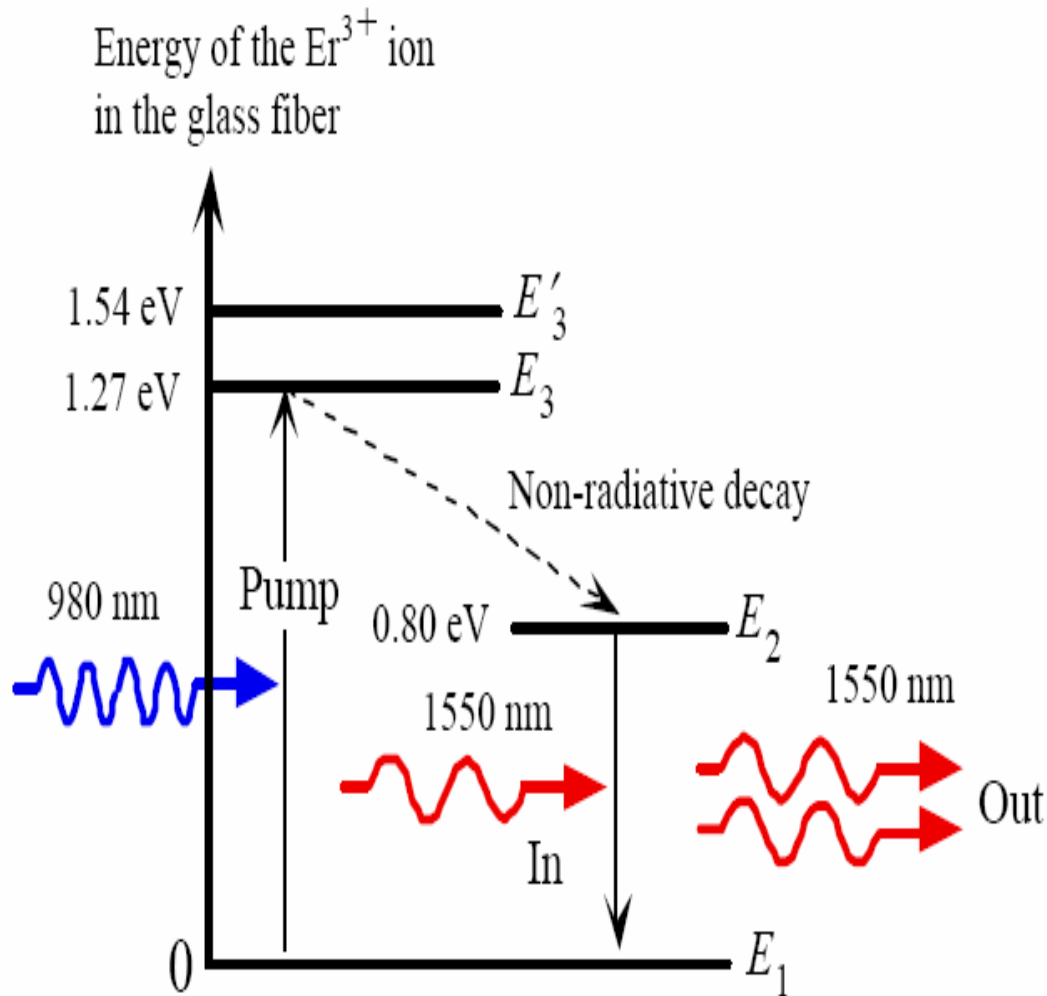
Bits continue in photonic format

# EDFA (*Erbium Doped Fibre Amplifier*)

An EDFA amplifier consists of an erbium-doped silica fiber, an optical pump, a coupler and isolators at both ends.



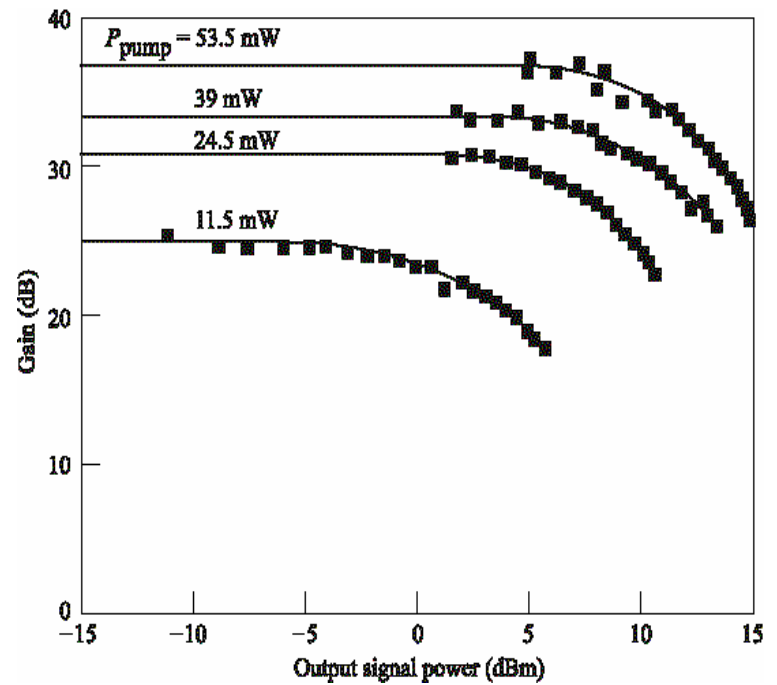
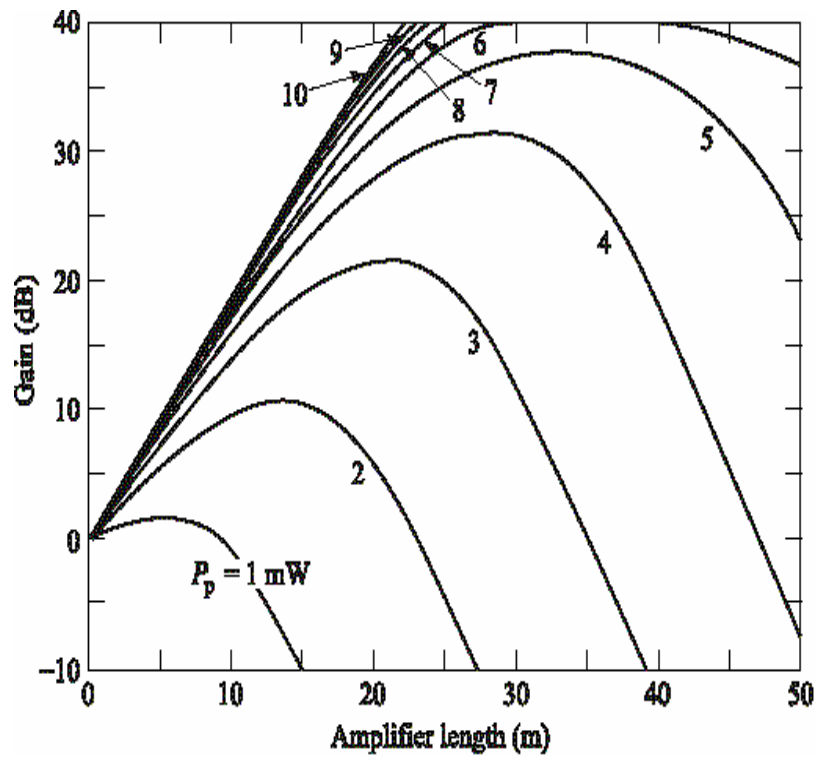
# erbium



			13	27,0	14	28,1	15	31,0	16	32,1	17	35,5	18	39,9	
			Al	Aluminium	Si	Silicium	P	Phosphore	S	Soufre	Cl	Chlore	Ar	Argon	
29	63,5	30	65,4	31	69,7	32	72,6	33	74,9	34	79,0	35	79,9	36	83,8
Cu	Cuivre	Zn	Zinc	Ga	Gallium	Ge	Germanium	As	Arsenic	Se	Sélénium	Br	Brome	Kr	Krypton
47	107,9	48	112,4	49	114,8	50	118,7	51	121,8	52	127,6	53	126,9	54	131,3
Ag	Argent	Cd	Cadmium	In	Indium	Sn	Étain	Sb	Antimoine	Te	Tellure	I	Iode	Xe	Xénon
79	197,0	80	200,6	81	204,4	82	207,2	83	209,0	84	(209)	85	(210)	86	(222)
Au	Or	Hg	Mercre	Tl	Thallium	Pb	Plomb	Bi	Bismuth	Po	Polonium	At	Astafe	Rn	Radon
111	(272)	112	(277)			114				116				118	
Uuu	Ununium	Uub	Unubium			Uuq	Ununquadium			Uuh	Ununhexium			Uuo	Ununoctium
64	157,4	65	158,9	66	162,5	67	164,9	68	167,3	69	168,9	70	173,0	71	175,0
Gd	Gadolinium	Tb	Terbium	Dy	Dysprosium	Ho	Holmium	Er	Erbium	Tm	Thulium	Yb	Ytterbium	Lu	Lutétium
96	(247)	97	(247)	98	(251)	99	(254)	100	(257)	101	(258)	102	(259)	103	(260)
Cm	Curium	Bk	Berkélium	Cf	Californium	Es	Einsteinium	Fm	Fermium	Md	Mendélévium	No	Nobélium	Lw	Lawrencium

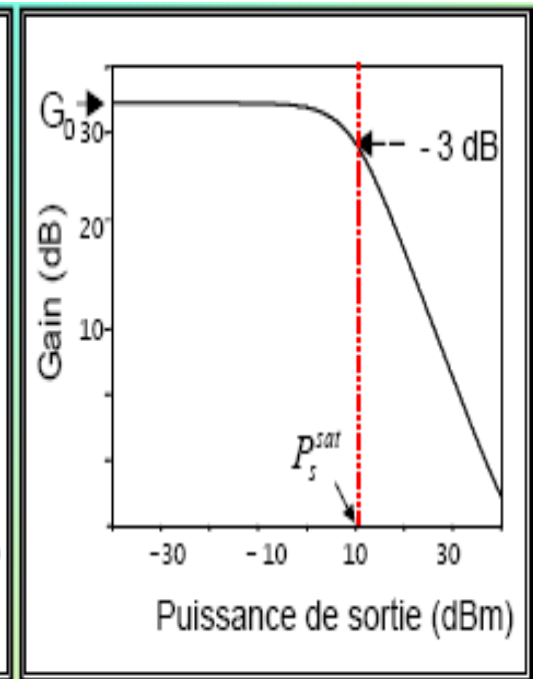
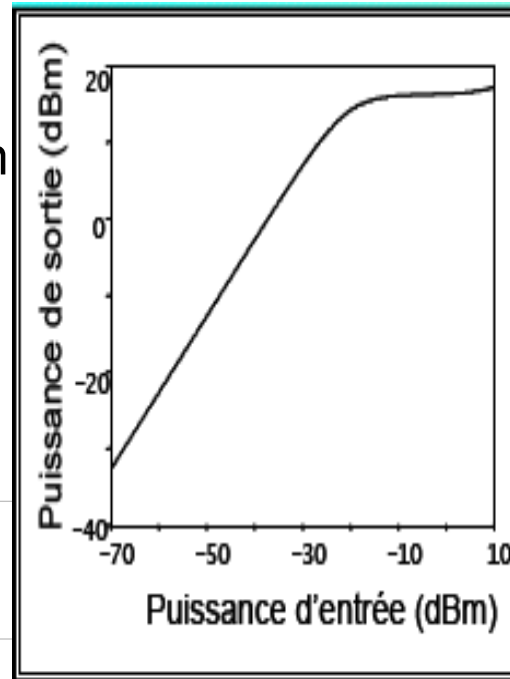
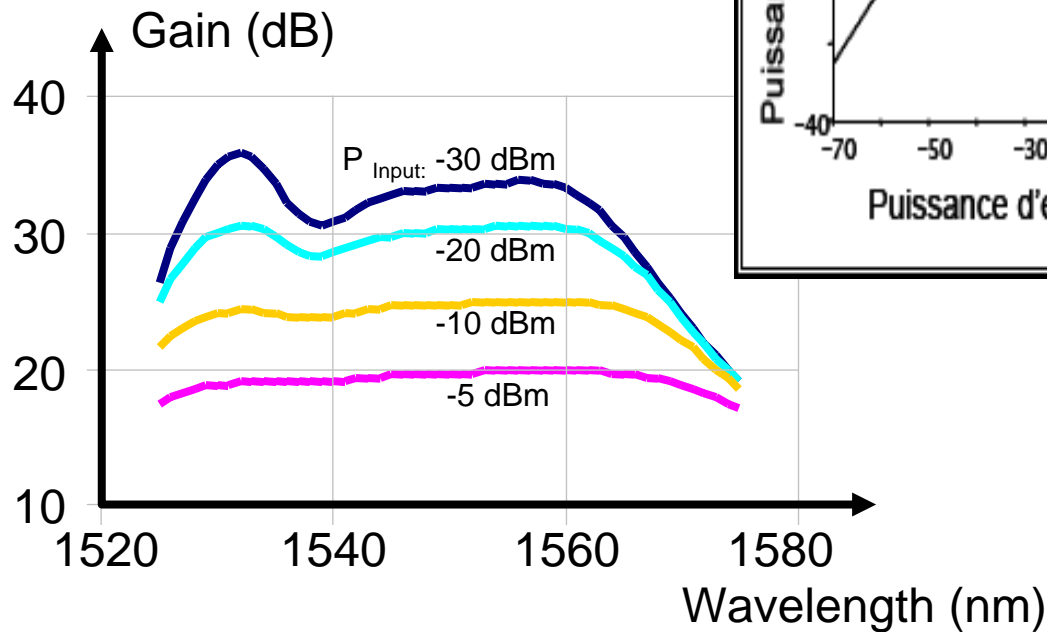
1842 Ytterby( Suède)  
Gadolinite:  
erbium  
terbium  
yttrium  
ytterbium

# gain EDFA



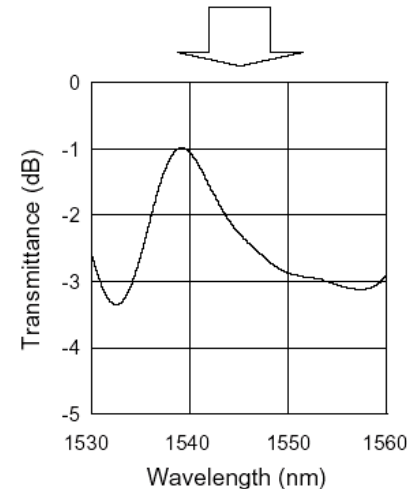
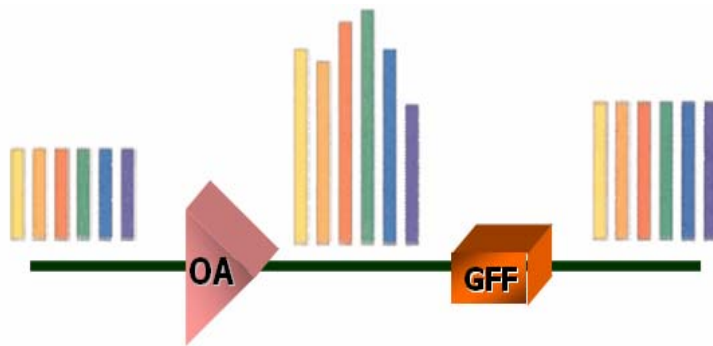
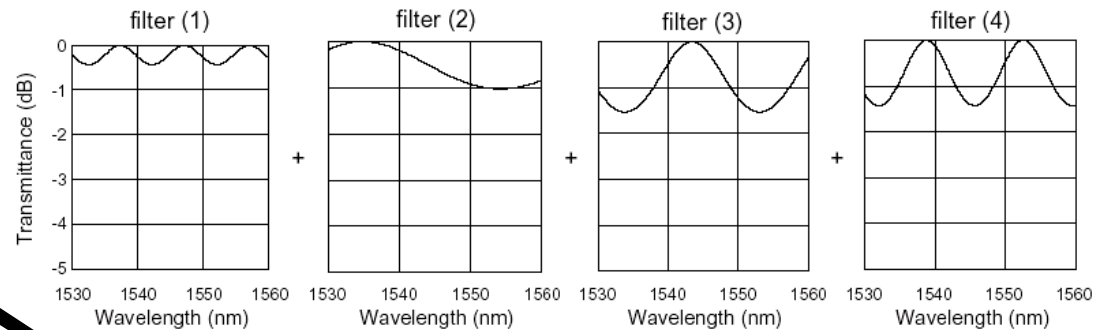
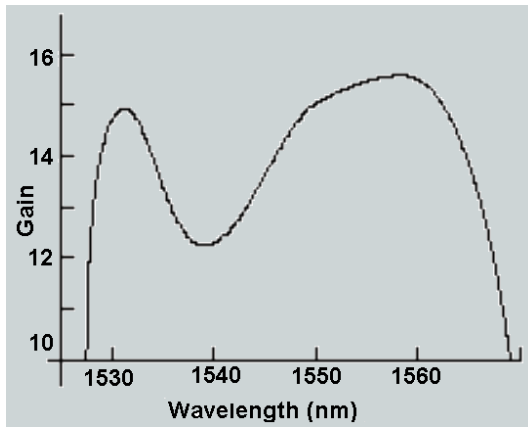
# optical gain

EDFA gain strongly depends on power and wavelength of incoming signal



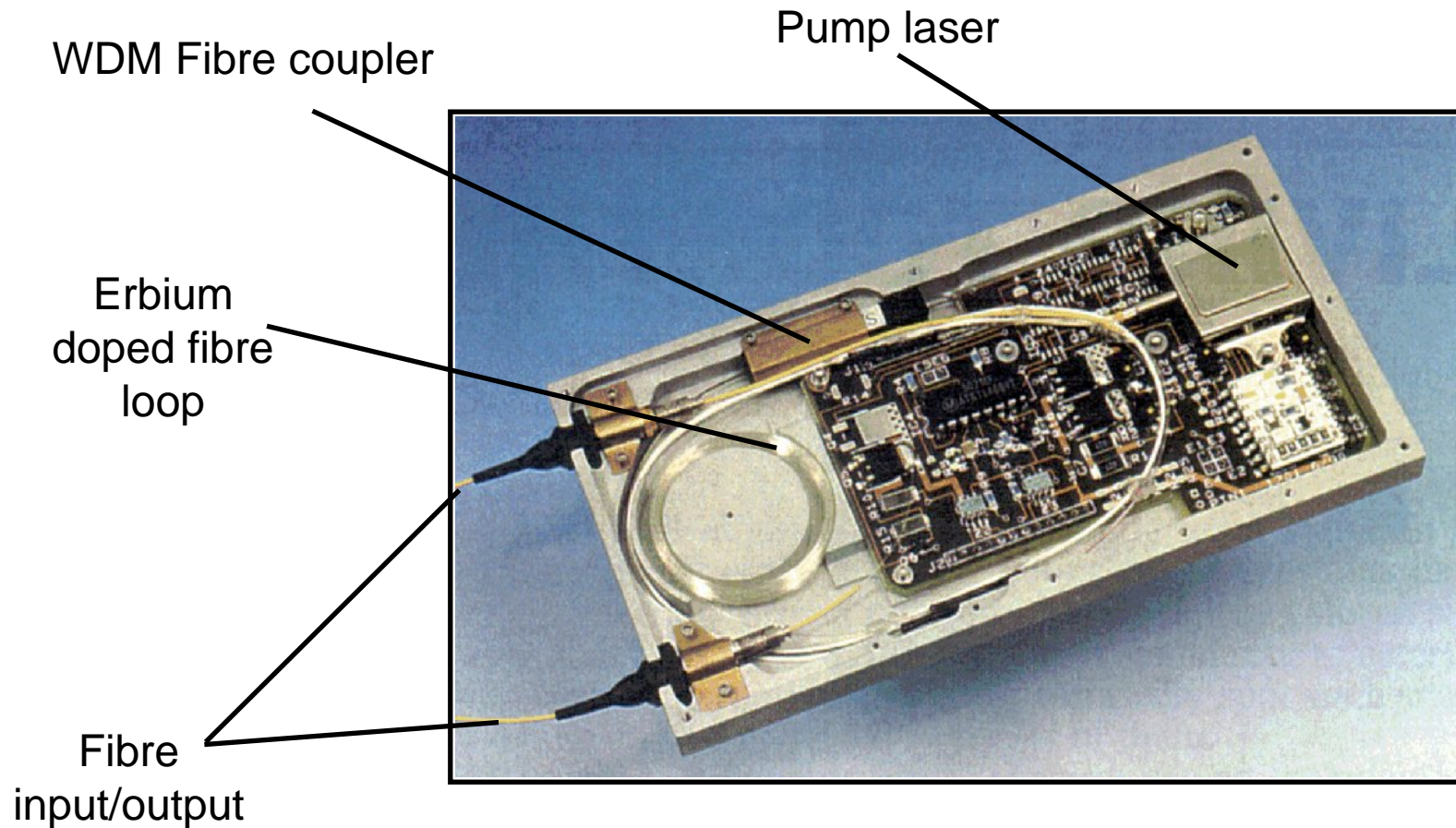
# EDFA gain equalization

Since the EDFA gain spectrum is not flat, GFF (Gain Flattening Filter) or GEQ (Gain Equalizer) is used for flattening.





# Interior of an Erbium Doped Fibre Amplifier (EDFA)

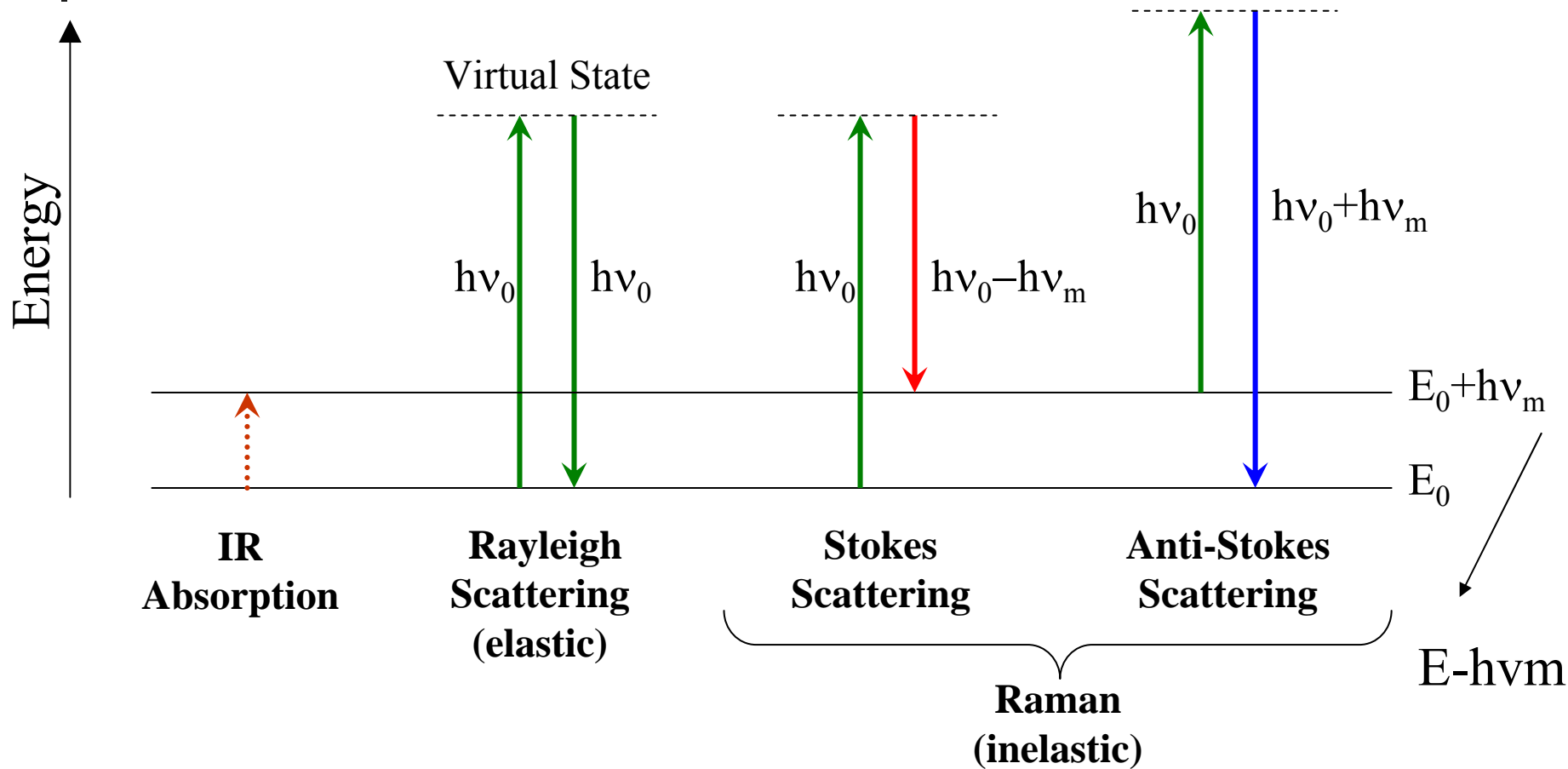




# SOA *versus* EDFA

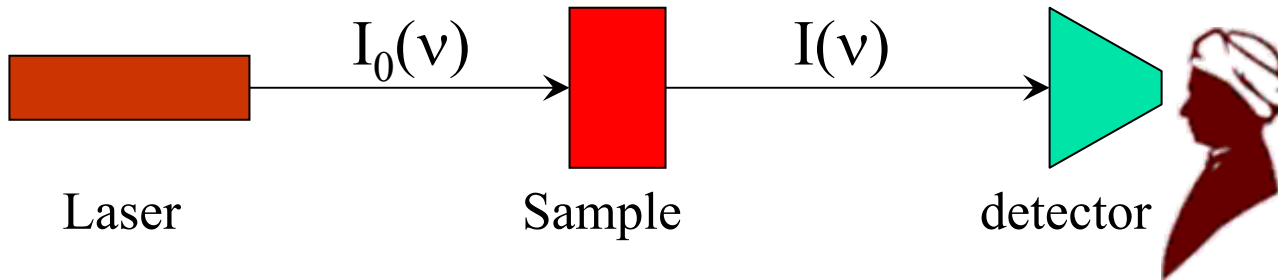
Properties of amplifier	EDFA	SOA
<i>Active medium</i>	Er <sup>3+</sup> ions in silica	electrons & holes in semic.
<i>typical length</i>	few meters	500 μm
<i>pumping scheme</i>	optical	electrical
<i>gain spectrum</i>	λ = 1500-1600 nm	λ = 1300-1500 nm
<i>gain bandwidth</i>	25-35 nm	100 nm
<i>relaxation time</i>	0.1-1 ms (metastable)	< 10-100 ps
<i>maximum gain</i>	30-50 dB	25-30 dB
<i>saturation power</i>	> 10 dBm	0-10 dBm
<i>crosstalk</i>	NO	for bite rate < 10 GHz
<i>polarization</i>	insensitive	sensitive
<i>noise figure</i>	3-4 dB	6-8 dB
<i>insertion loss</i>	< 1 dB	4-6 dB
<i>optics</i>	pump LD couplers, splice	AR coating, WG coupling
<i>optoelectronic integration</i>	NO	YES

# RAMAN Energy Scheme for Photon Scattering

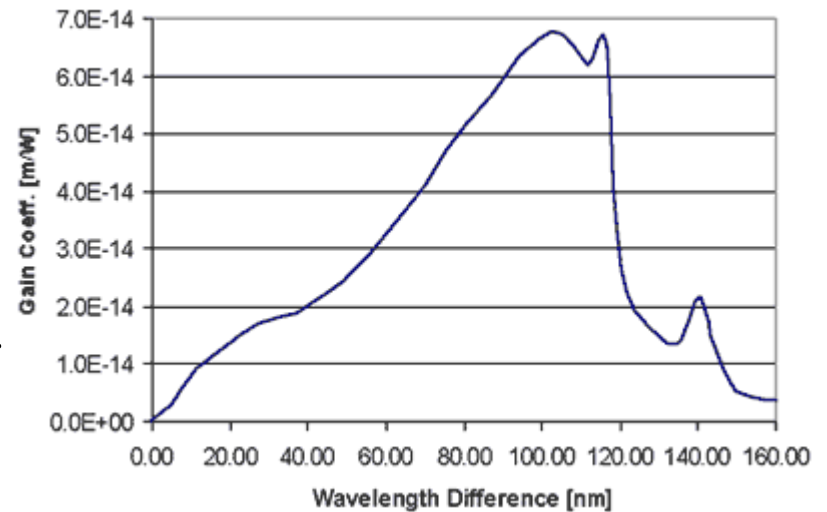
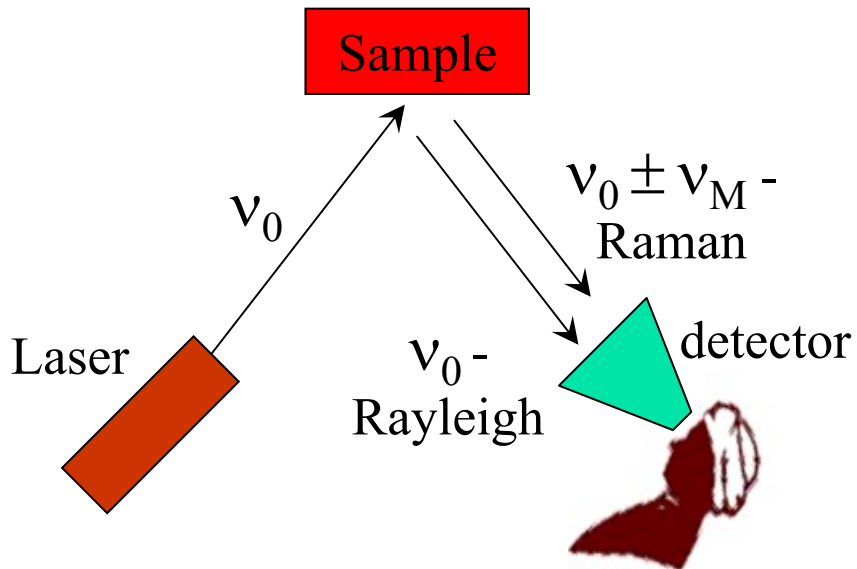


The Raman effect comprises a very small fraction,  
about 1 in  $10^7$  of the incident photons.

# IR Spectrography - Absorption

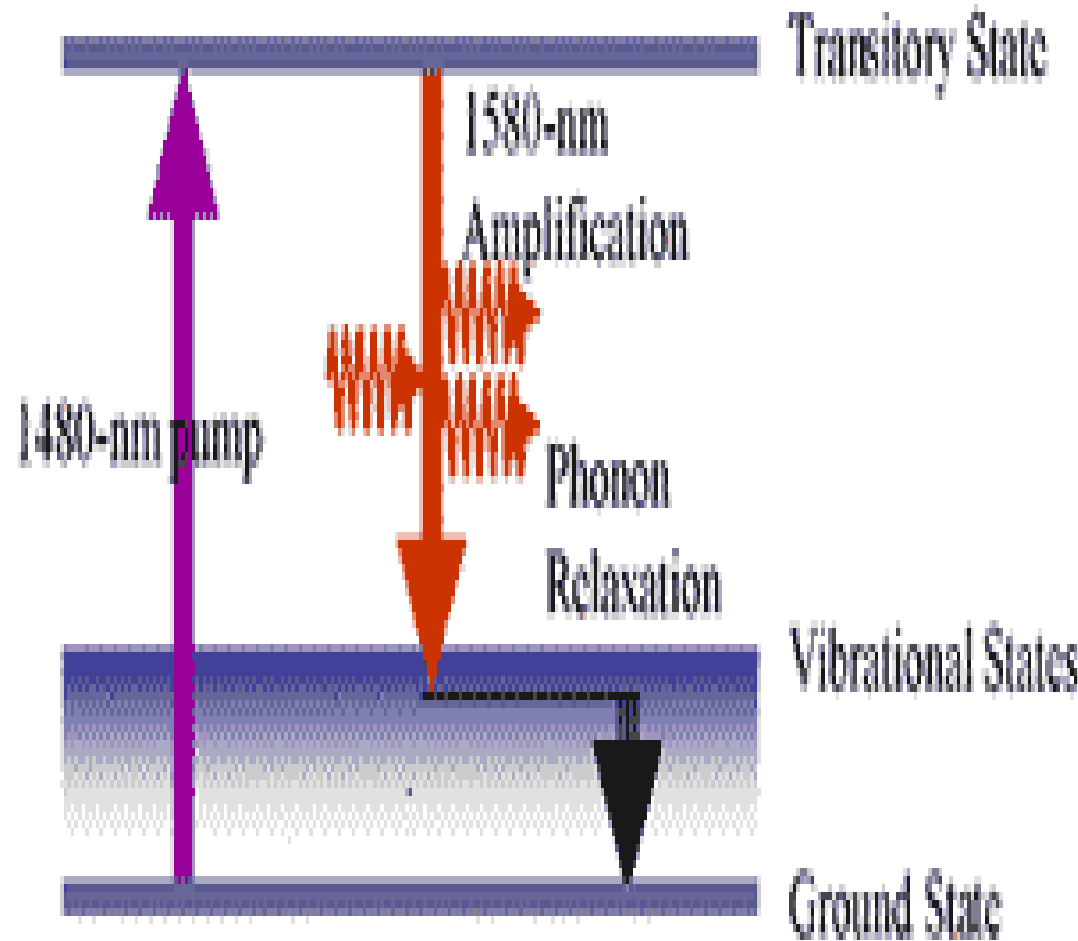


## Raman Spectrography - Scattering



# Distributed Raman Amplifier (DRA)

- DRA is based on Raman Scattering.
- A large pump is co-launched at a lower wavelength than the signal to be amplified





## DFA vs DRA

Characteristic	Doped-Fiber Amplifier	Raman Amplifier
Amplification Band	depends on dopant	depends on availability of pump wavelengths
Amplification Bandwidth	20 nm, more for multiple dopants/fibers	48 nm, more for multiple pump waves
Gain	20 dB or more, depending on ion concentration, fiber length, and pump configuration	4–11 dB, proportional to pump intensity and effective fiber length
Saturation Power	depends on gain and material constants	equals about power of pump waves
Pump Wavelength	980 nm or 1480 nm for EDFAs	100 nm lower than signal wavelength at peak gain

# Amplifier Comparison

	SOA	EDFA	RAMAN	
<b>Gain</b>	>30	>40	>25	dB
<b>Wavelength</b>	1280-1650	1530-1560+	1280-1650	nm
<b>Bandwidth (3dB)</b>	60	30-60	<i>pump dependent</i>	nm
<b>Psat</b>	15	20	$0.5 * Pump$	dBm
<b>Sat.Power max</b>	18	22	$0.75 * Pump$	dBm
<b>Polarisation</b>	<0.5	0	0	dB
<b>Noise Figure</b>	8	5	5	dB
<b>Pump Power</b>	<400 mA	25 dBm	>30 dBm	
<b>Time constant</b>	0.2 ns	10 ms	fs	
<b>Size</b>	<i>compact</i>	<i>rack module</i>	<i>bulk module</i>	
<b>Switchable</b>	yes	no	no	
<b>Cost Factor</b>	<i>competitive</i>	<i>medium</i>	<i>high</i>	



# Amplifier Comparison

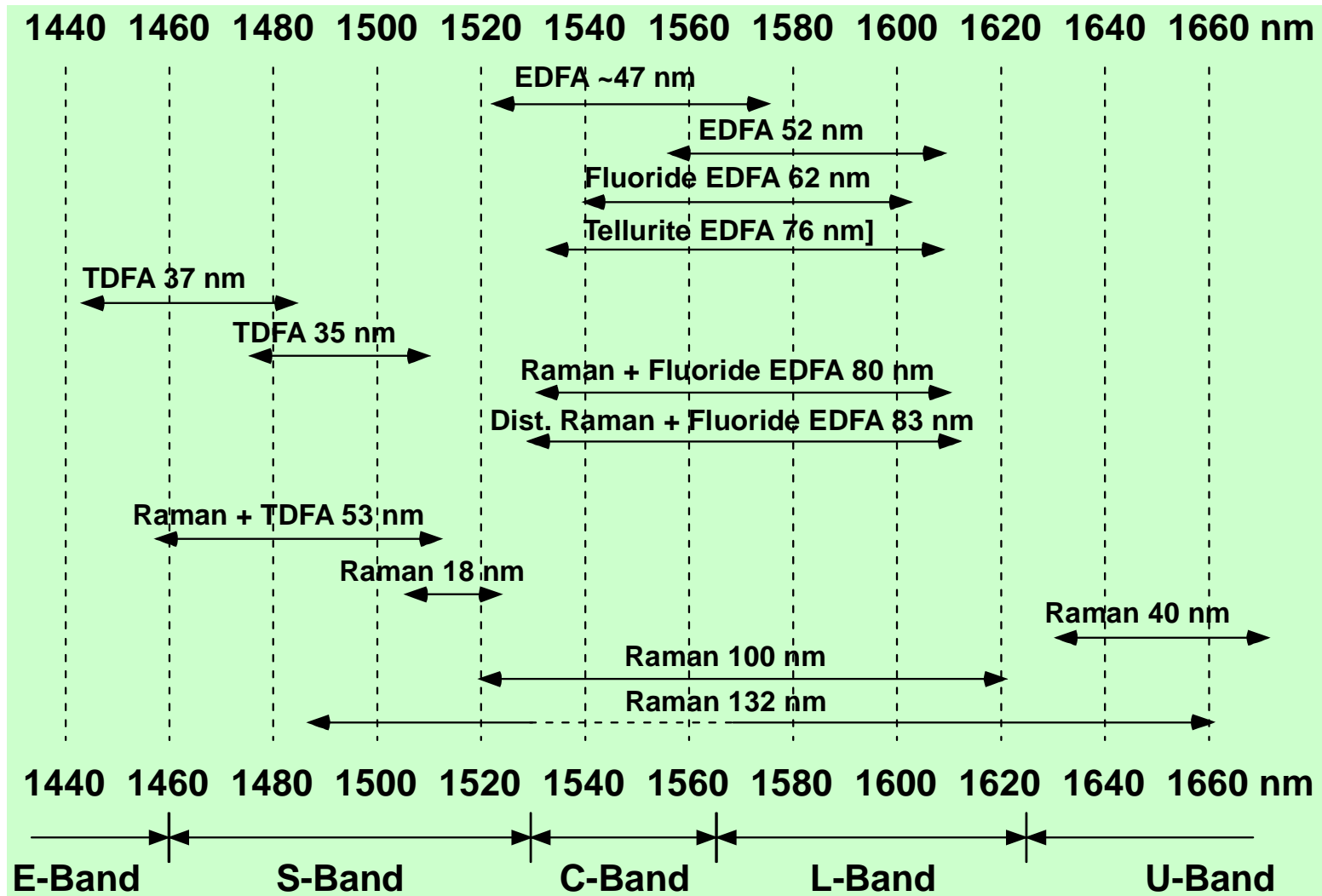
## “Performance Analysis of Optical Amplifiers in Optical Communication Systems”

Table 1.1 Comparison of Optical Amplifiers (NA: not applicable)

Property	SOA	EDFA	Raman Amplifiers	Brillouin Amplifier
Unsaturated device gain	>20dB	>20dB	5 - 15dB	>25dB
Optical pump power	NA	20 – 50mW	100 – 200mW	<10mW
Optical pump Wavelength	NA	820nm, 980nm 1400 – 1500nm	Stokes shift below signal	
Electrical bias current	50mA	>100mA	>500mA	<50mA
Wavelength of operation	any	1525 – 1565nm	Any, but subject to pump	
Bandwidth	20 – 50nm	10 – 40nm	20 – 40nm	0.001nm
Coupling loss	5 – 6dB	<1dB	<1dB	<1dB
Polarization sensitivity	> few dB	0dB	0dB	0dB
Saturated output	> few mW	few mW	Limited only by pump power	
Directions	bidirectional	bidirectional	bidirectional	unidirectional
Noise	low	low	Very low	Very low

<http://dsp.space.tiet.ac.in:8080/dspace/bitstream/123456789/181/1/8044102.pdf>

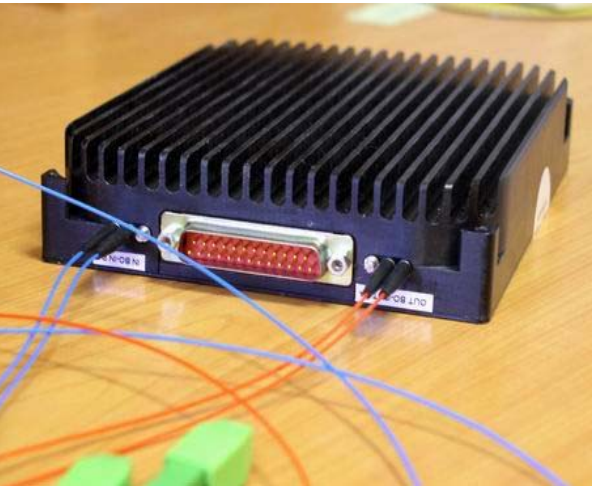
# Gain bandwidth of optical amplifiers



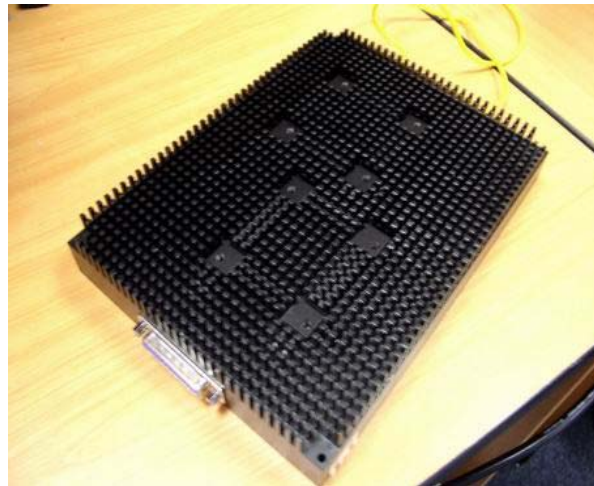


# Amplifier Examples

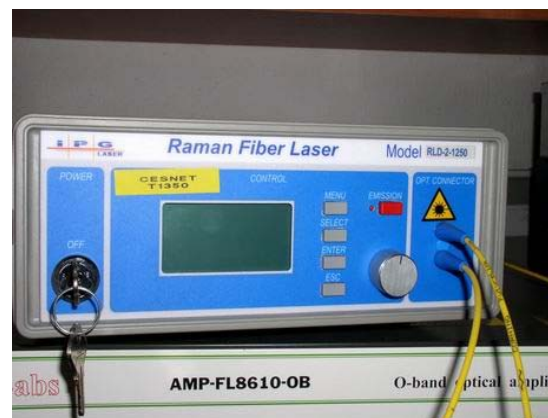
EDFA



Raman



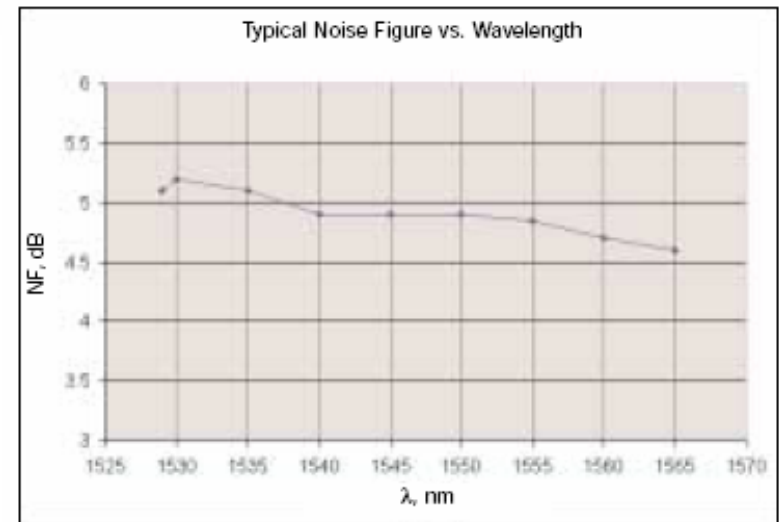
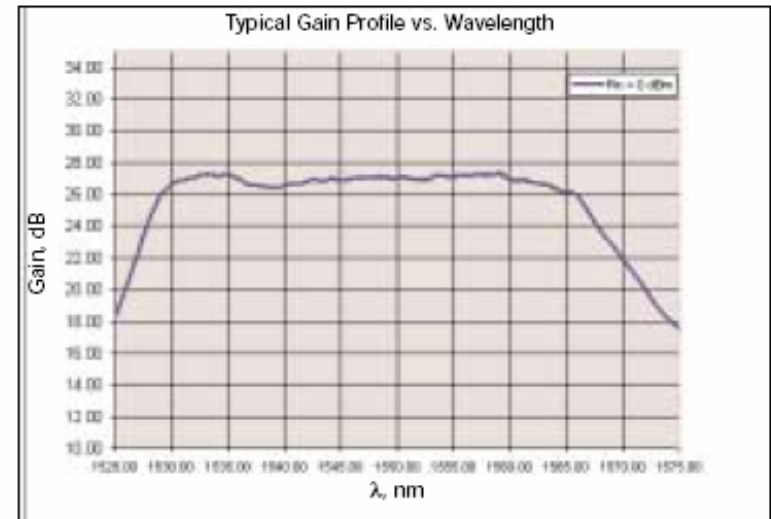
SOA



# Telecom EDFA

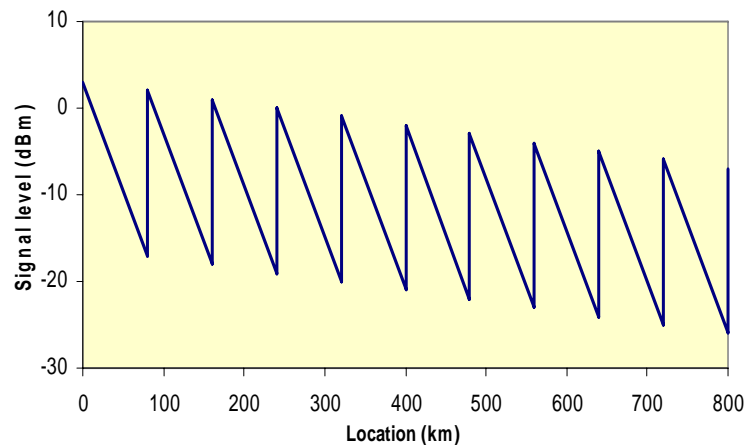


Bandwidth: 1529-1564 nm  
Output Power 100mW-2W  
Gain >25dB



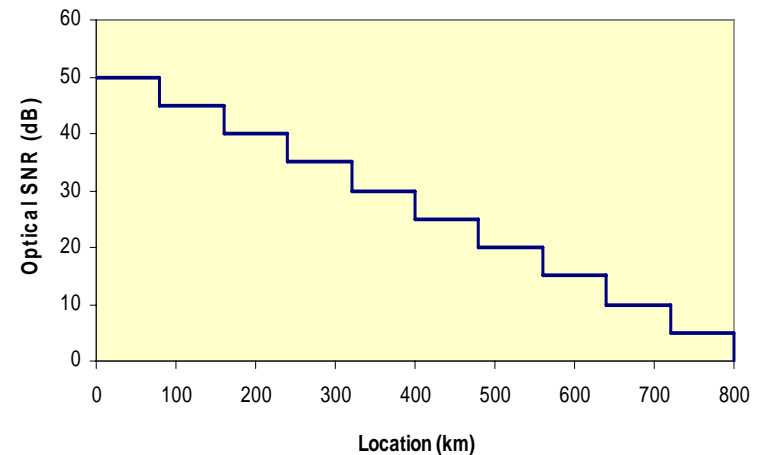
# Chaîne d'amplis

Sample system uses 0.25 atten fibre,  
80 km fibre sections, 19 dB amplifiers  
with a noise figure of 5 dB



Each amplifier restores the signal level to a value almost equivalent to the level at the start of the section – in principle reach is extended to 700 km +

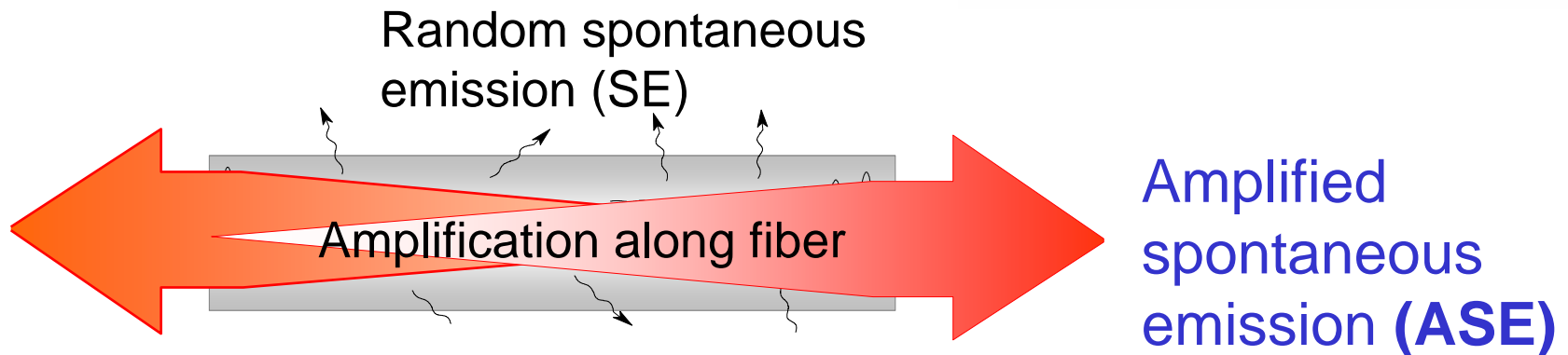
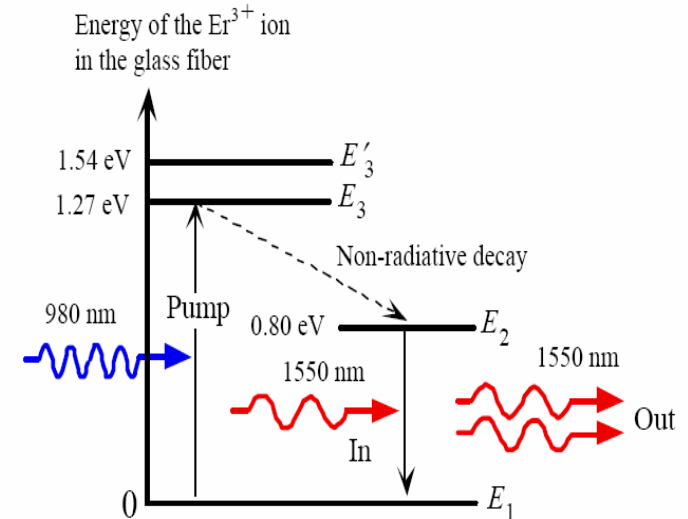
Same sample system: Transmitter SNR is 50 dB, amplifier noise figure of 5 dB,



30 dB as a reasonable limit, the max distance between T/X and R/X is only 300 km

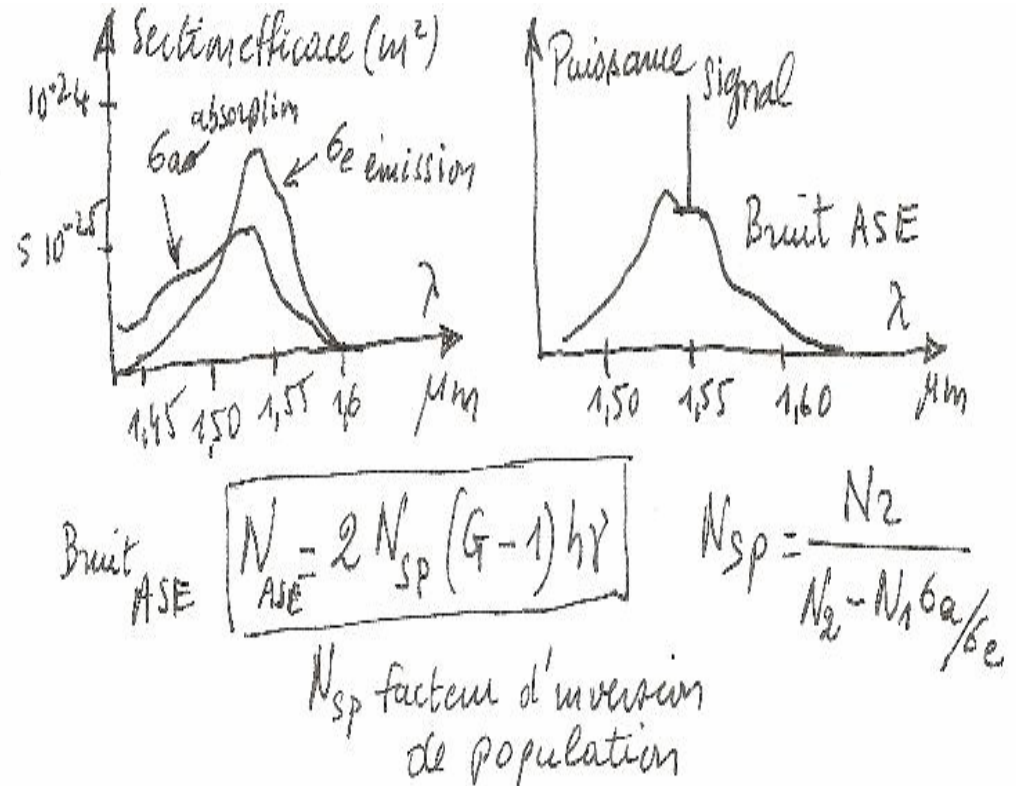
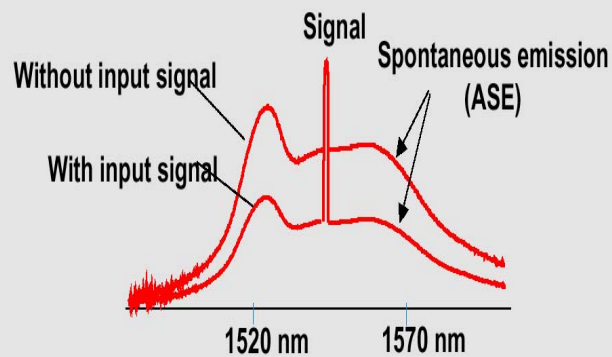
# Bruit ASE

- Erbium randomly emits photons between 1520 and 1570 nm
  - Spontaneous emission (SE) is not polarized or coherent
  - Like any photon, SE stimulates emission of other photons
  - With no input signal, eventually all optical energy is consumed into amplified spontaneous emission
  - Input signal(s) consume metastable electrons  $\rightarrow$  much less ASE



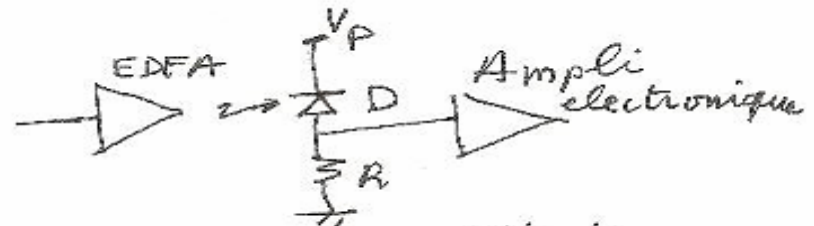
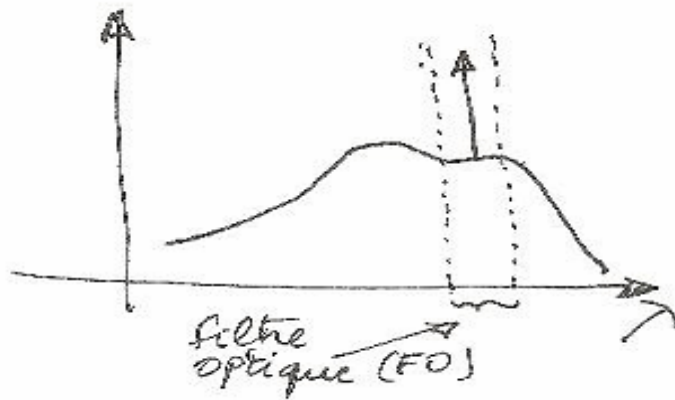
# Bruit ASE

## ASE Depends on Signal Power





# Facteur de bruit des EDFA



D est un détecteur quadratique (sensible à  $E^2$ )

$$(E_1 \cos \omega_1 t + E_2 \cos \omega_2 t)^2$$

On détectera les battements  $|\omega_2 - \omega_1|$  qui sont dans la bande passante de D

$\omega_1$  et  $\omega_2$  doivent être dans FO et  $|\omega_2 - \omega_1|$  dans la bande passante de D.

Bruits de l'EDFA

Bruit Shot de D

Bruit thermique de R

Bruit Shot du signal

Bruit de battement Signal-ASE

Bruit de battement ASE-ASE

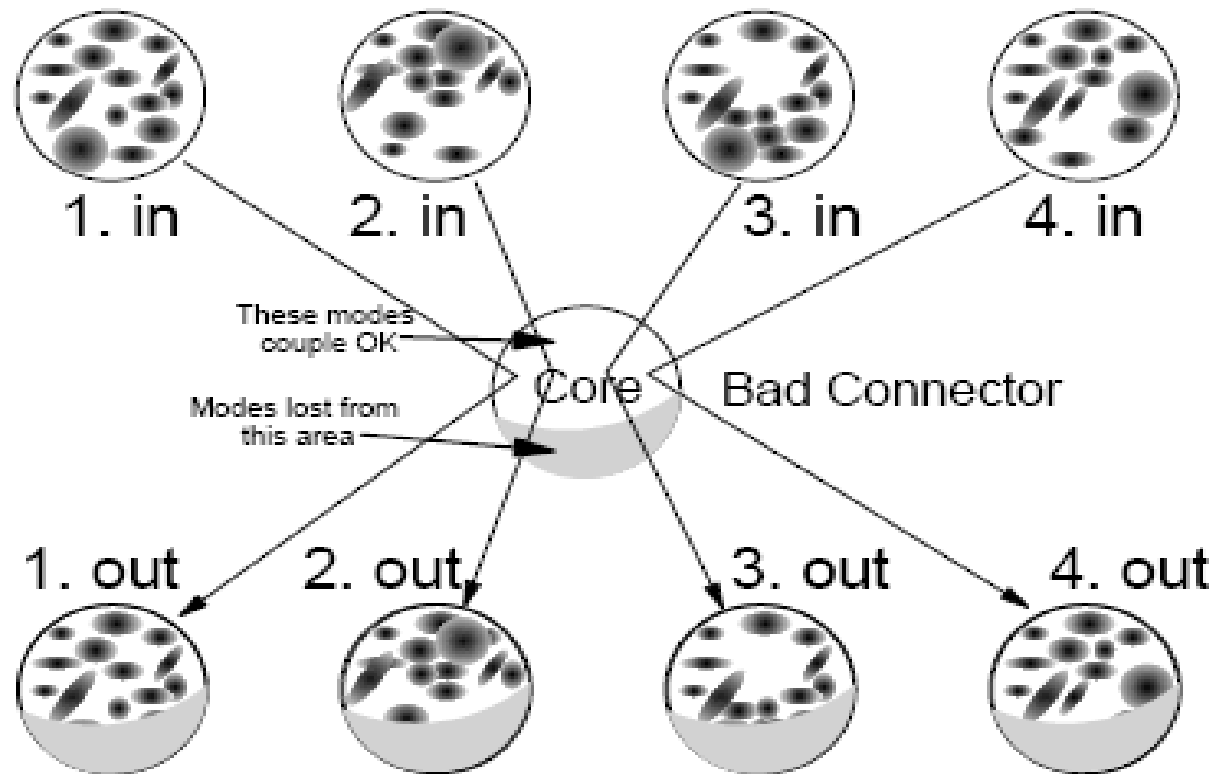
Quand G grand on montre alors

$$N_{sp} = \frac{N_2}{N_2 - N_1} \frac{h\nu}{e}$$

$$NF \approx 2 N_{sp}$$

$$N_{sp \downarrow SOA} > N_{sp \downarrow EDFA}$$

## Bruit .... Modal Noise



*Figure 33. Origin of Modal Noise. The speckle pattern changes rapidly over time, however, energy is conserved and all the power is conserved. When the signal meets a lossy connector, power is lost from some modes and other modes may be unaffected. Since the amount of power in the lost modes changes randomly, the amount of power passing the connector varies randomly.*