

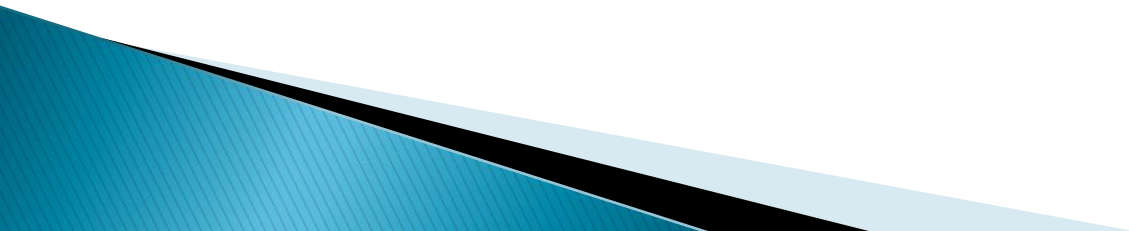
Optoelectronică, structuri și tehnologii

Curs 8
2016/2017

Disciplina 2016/2017

- ▶ 2C/1L Optoelectronică, structuri, tehnologii, circuite, **OSTC**
- ▶ **Minim 7 prezente curs + laborator**
- ▶ Curs – **sl. Radu Damian**
 - Joi 15-18, P5
 - E – 70% din nota
 - **20% test la curs**, saptamana 4-5?
 - probleme + (?1 subiect teorie) + (2p prez. Curs)
 - **2prez=0.5p**
 - toate materialele permise
- ▶ Laborator – **sl. Daniel Matasaru**
 - Joi 8-14 par
 - L – 15% din nota
 - C – 15% din nota

Mini test no. 3



Recapitulare

Curs 7

LED

Dioda electroluminescenta
Capitolul 7

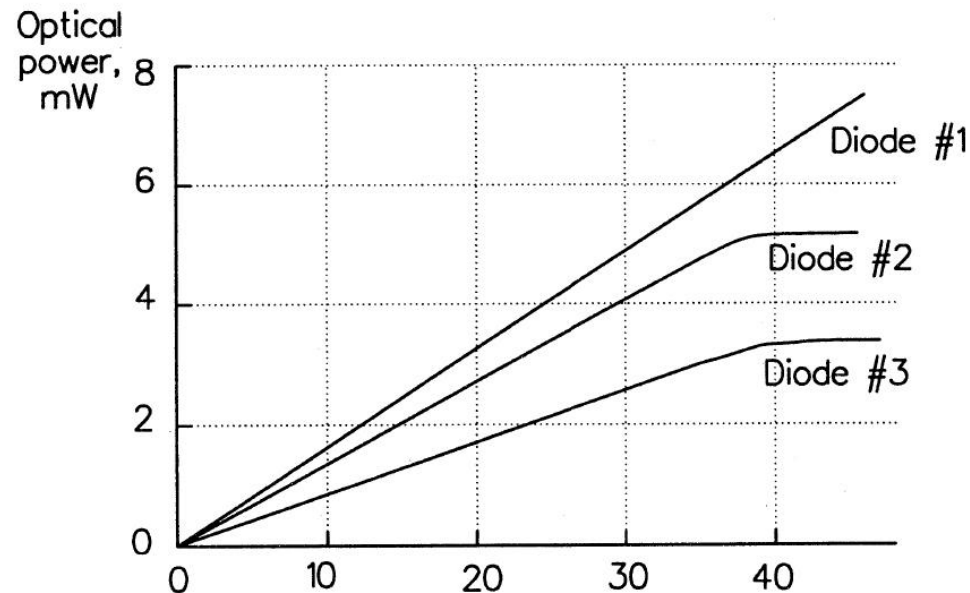
Caracteristica de raspuns a LED-urilor

- ▶ Caracteristica putere optica emisa functie de curentul direct prin LED este liniara la nivele mici ale curentului.
- ▶ Nu exista curent de prag
- ▶ La nivele foarte mari puterea optica se satureaza

- ▶ Responzivitatea

$$r = \frac{P_o}{I} \left[\frac{W}{A} \right]$$

- ▶ Tipic $r = 50 \mu\text{W}/\text{mA}$

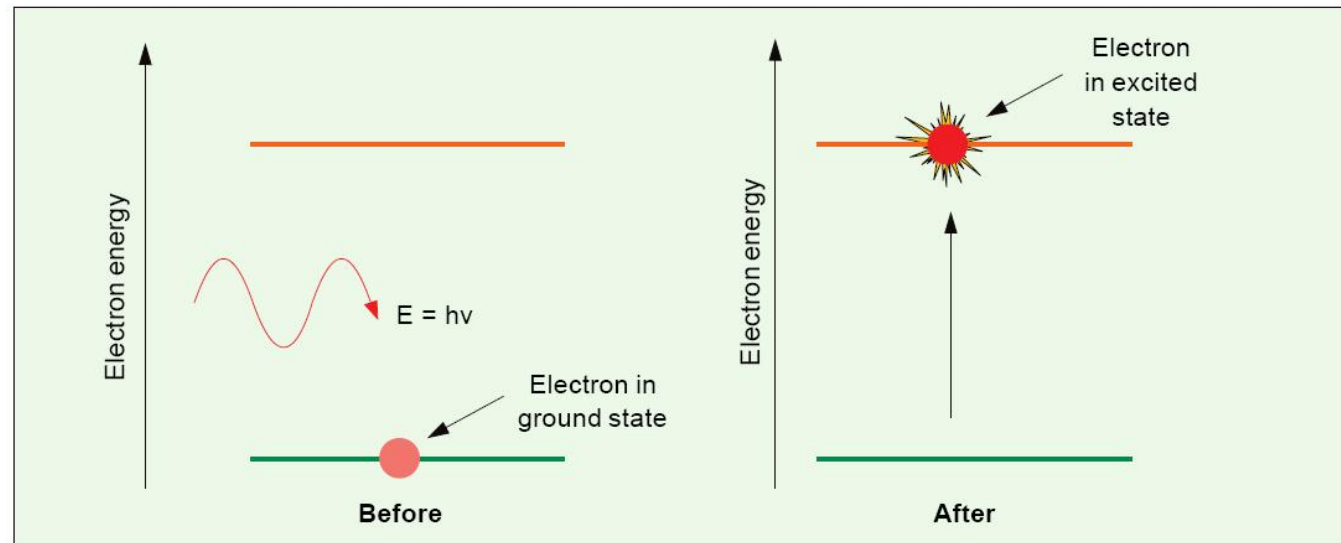


Dioda Laser

Capitolul 8

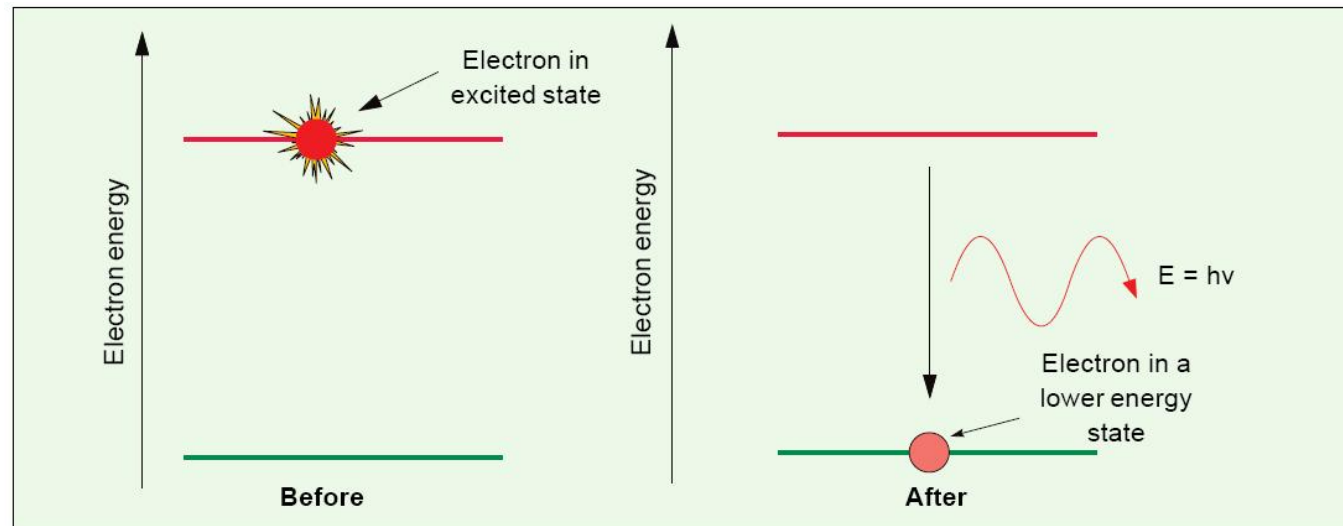
Dioda LASER – Principiu de operare

- ▶ LASER = Light Amplification by the Stimulated Emission of Radiation = Amplificarea Luminiilor prin Emisie Stimulată
- ▶ Un foton incident poate cauza prin absorbție tranziția unui electron pe un nivel energetic superior



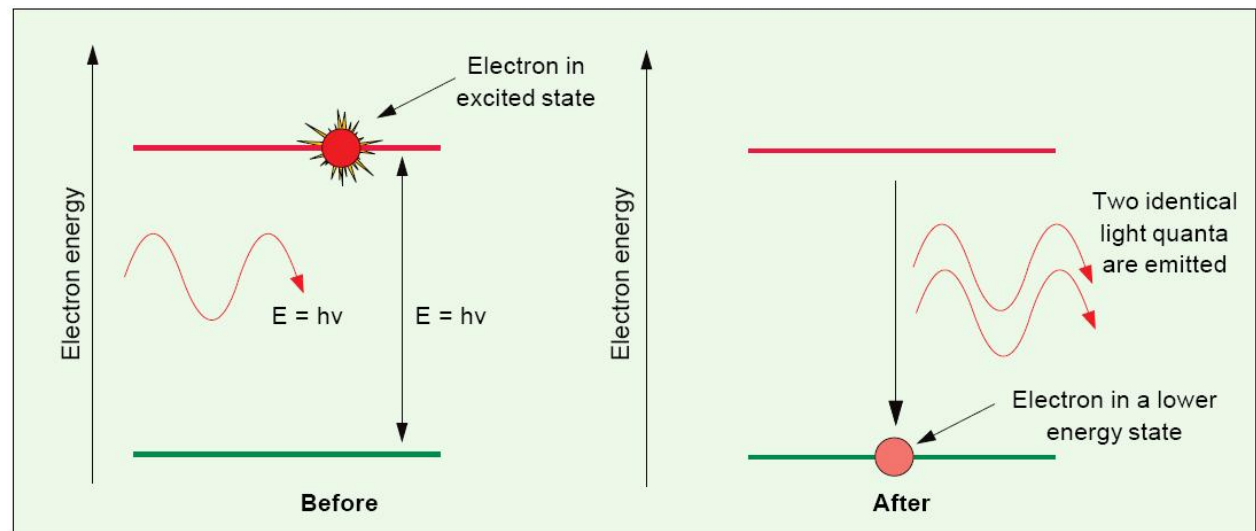
Dioda LASER – Principiu de operare

- ▶ Emisia spontana – electronul trece in starea energetica de echilibru emitand un foton
- ▶ Trecerea se realizeaza prin recombinarea unei perechi electron–gol
- ▶ Directia si faza radiatiei emise sunt aleatoare

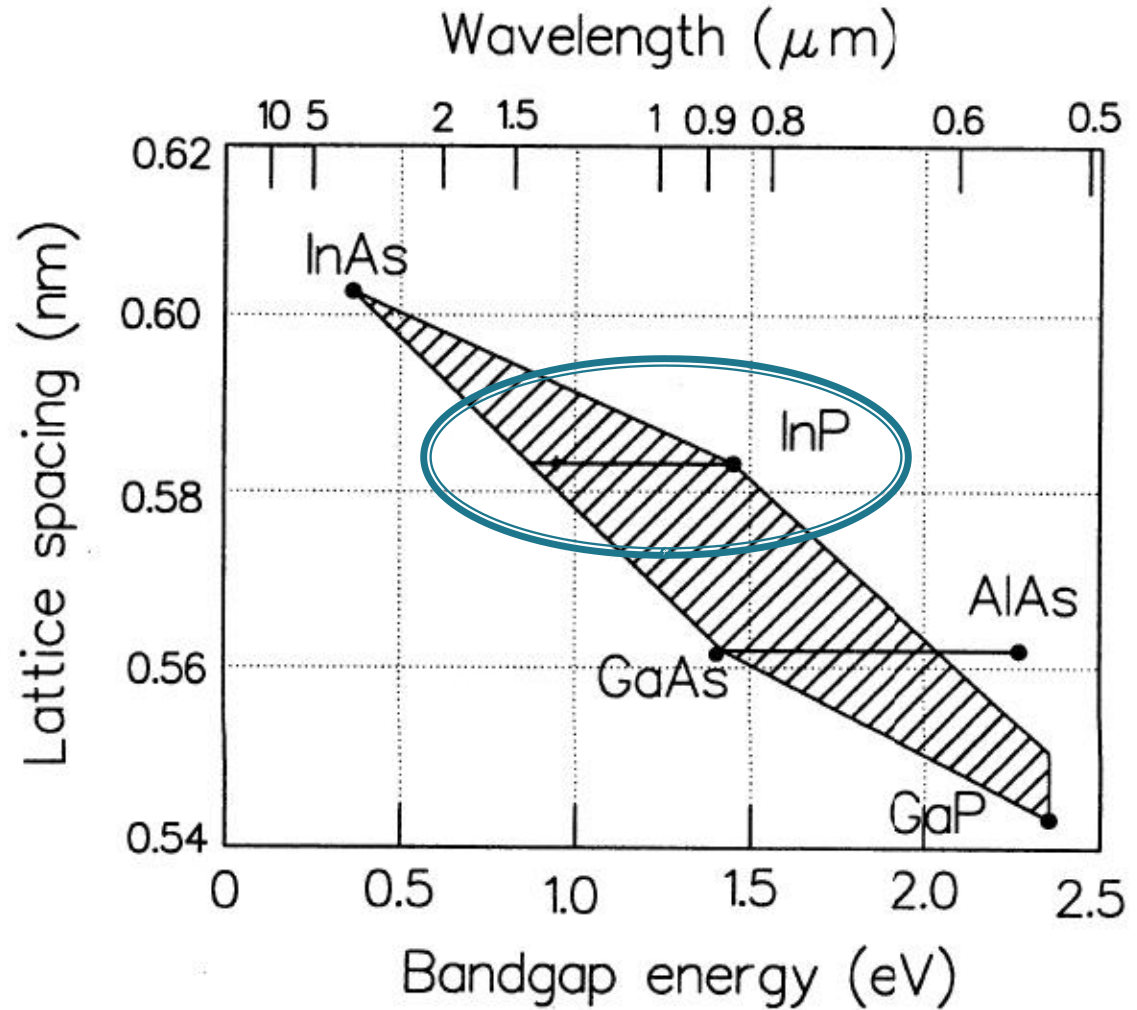
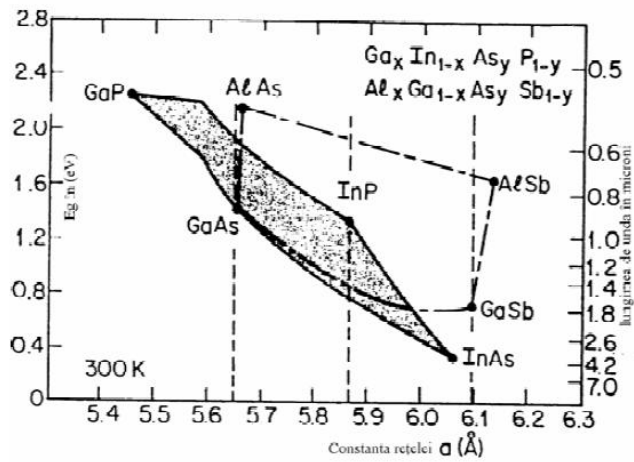


Dioda LASER – Principiu de operare

- ▶ Emisia stimulata – un foton incident cu energie corespunzatoare poate stimula emisia unui al doilea foton **fara a fi absorbit**
- ▶ Noul foton are aceeasi directie si faza cu fotonul incident, Lumina rezultata e coerenta

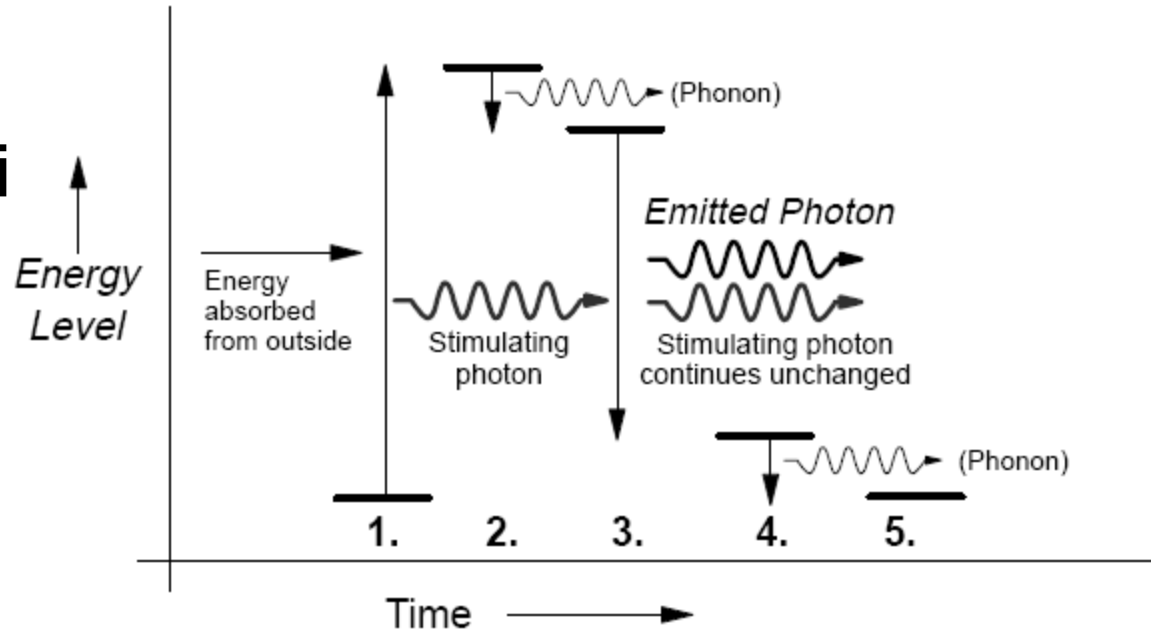


Dependența benzii interzise de constanta rețelei



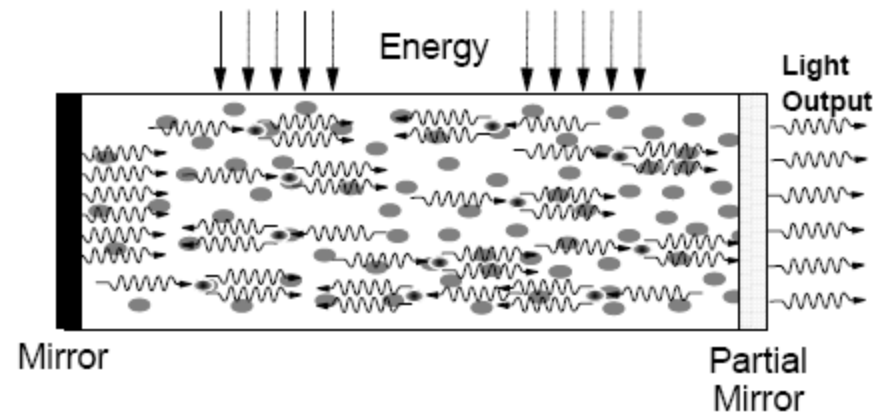
Materialie cu 4 nivele energetice

- ▶ La un material cu 4 nivele energetice tranzitia radianta a electronului (3) se termina intr-o stare instabila, starea de echilibru obtinandu-se prin emisia unui fonon
- ▶ Inversiunea de populatie se obtine mult mai usor datorita electronilor din starea intermediara

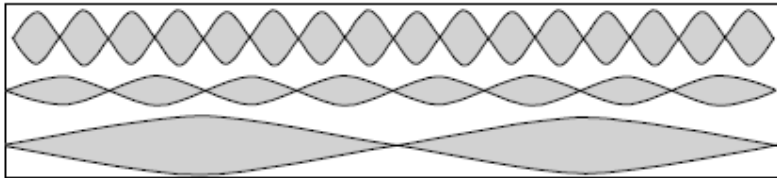


Dioda LASER – Principiu de realizare

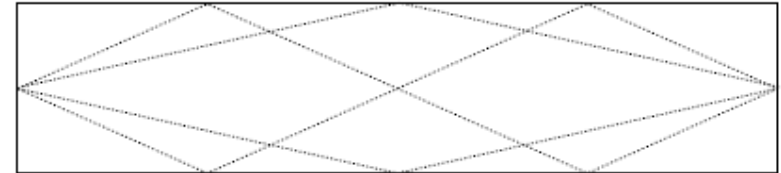
- ▶ Pentru ca emisia stimulata sa apara, fotonii emisi trebuie sa ramana in contact cu materialul o perioada mai mare de timp – 2 oglinzi necesare
- ▶ Pentru a permite extragerea radiatiei e necesar ca una din oglinzi sa fie partial reflectanta



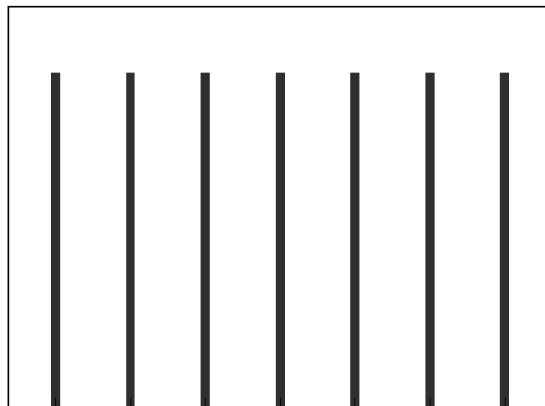
Spectrul diodei LASER



Longitudinal Modes



Lateral Modes



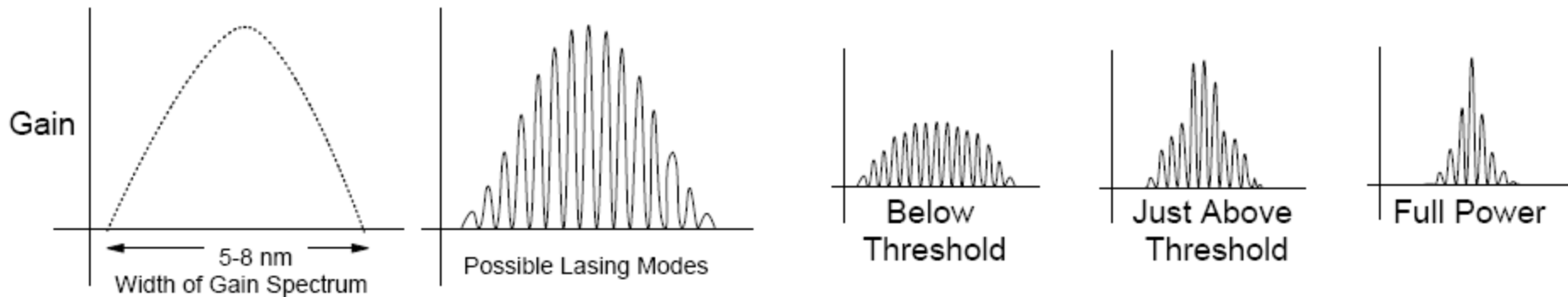
1.490 1.494 1.497 1.5 1.503 1.507 1.510
Wavelength (nm)

$$f_k = k \cdot \frac{c_0}{2 \cdot n \cdot L} \quad \Delta f = \frac{c_0}{2 \cdot n \cdot L}$$

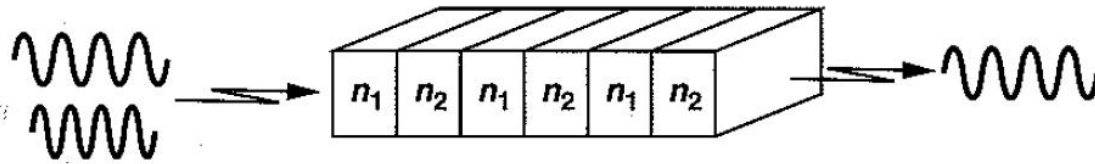
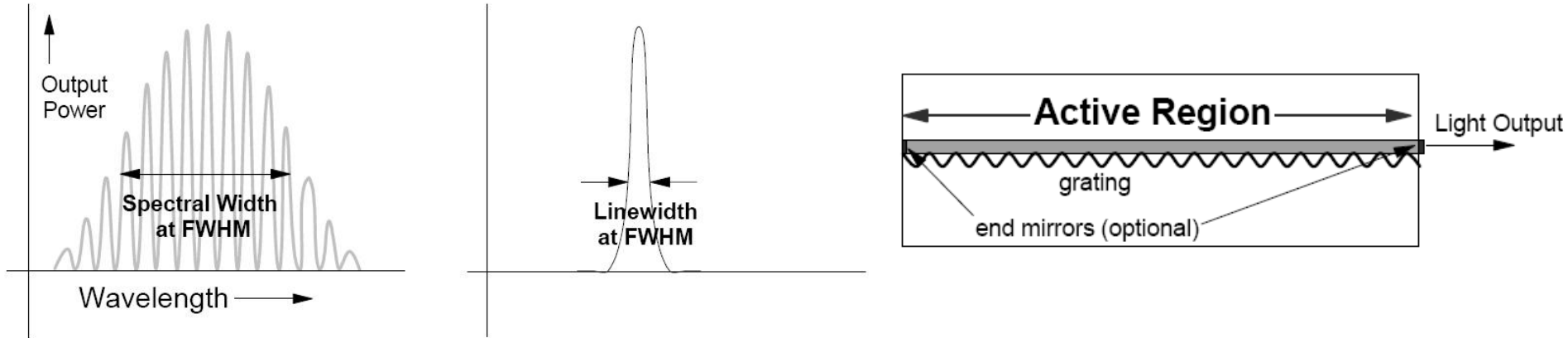
$$\Delta \lambda \cong \frac{\lambda_0^2}{2 \cdot n \cdot L}$$

Spectrul diodei LASER

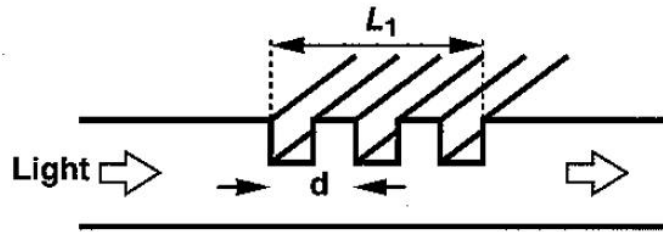
- ▶ Castigul diodei laser (eficacitatea aparitiei emisiei stimulate) depinde
 - de caracteristicile energetice ale materialului din care e realizata dioda
 - de energia pompata din exterior (curentul prin dioda)



Distributed Feedback (DFB) Lasers



(a)

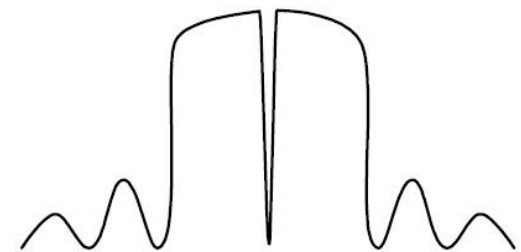
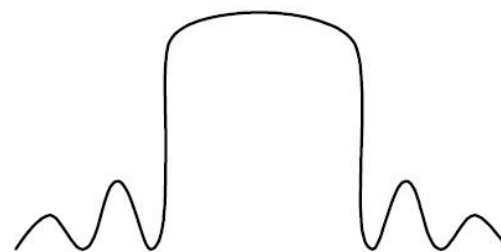
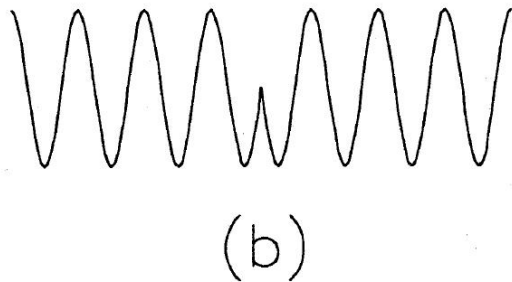
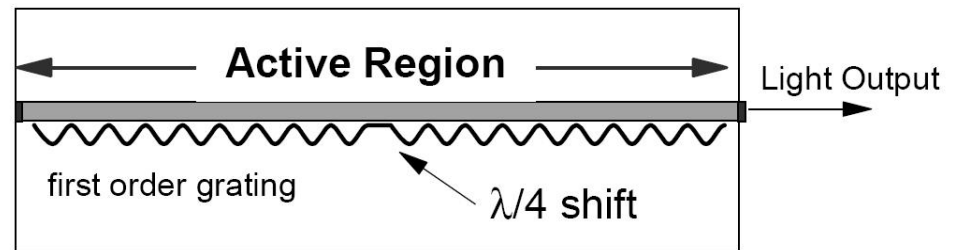
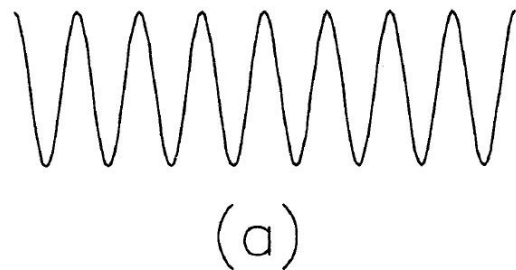


(b)

Filtre spatiale in
regiunea activa

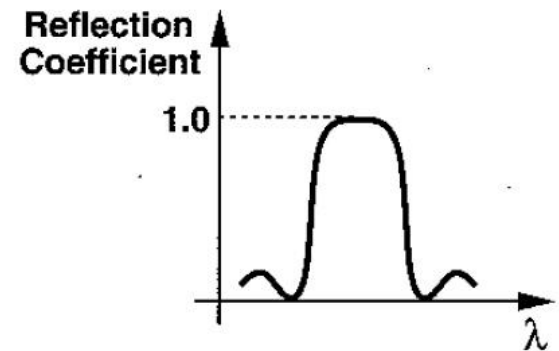
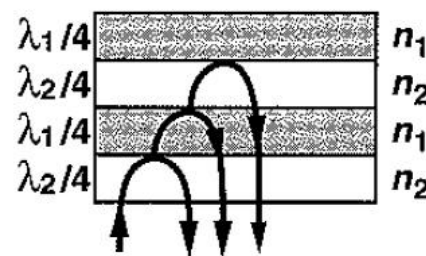
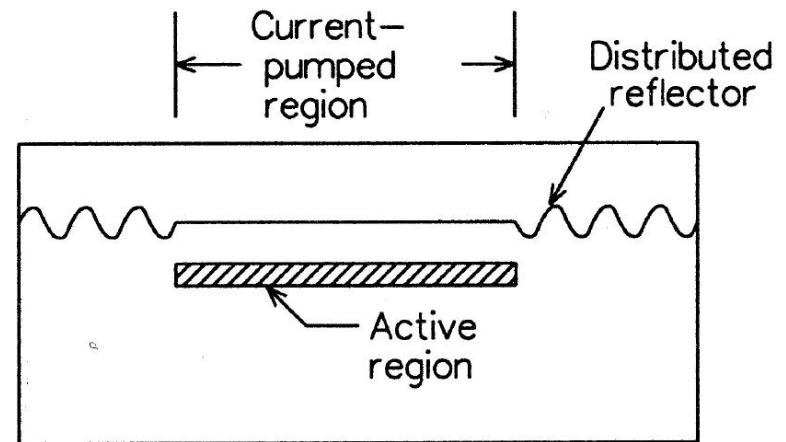
Distributed Feedback (DFB) Lasers

- ▶ Pentru operarea in impulsuri, un salt de $\lambda/4$ ingusteaza suplimentar spectrul diodei laser



Distributed Bragg Reflector (DBR) Lasers

- ▶ Se utilizeaza suprafete reflective selective pentru filtrare optica

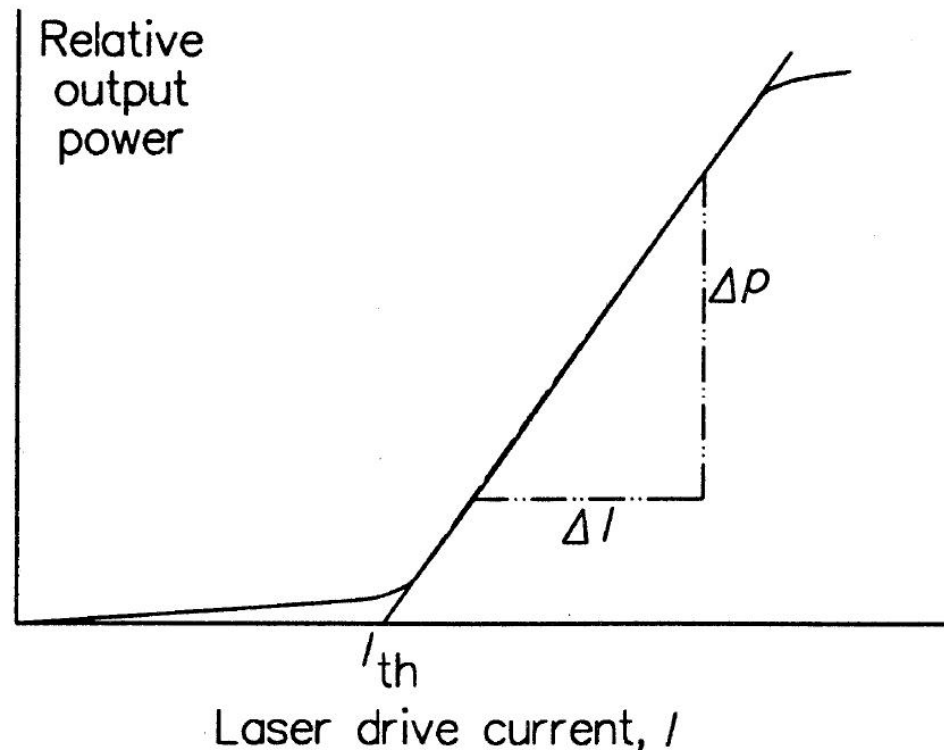


Caracteristici curent tensiune

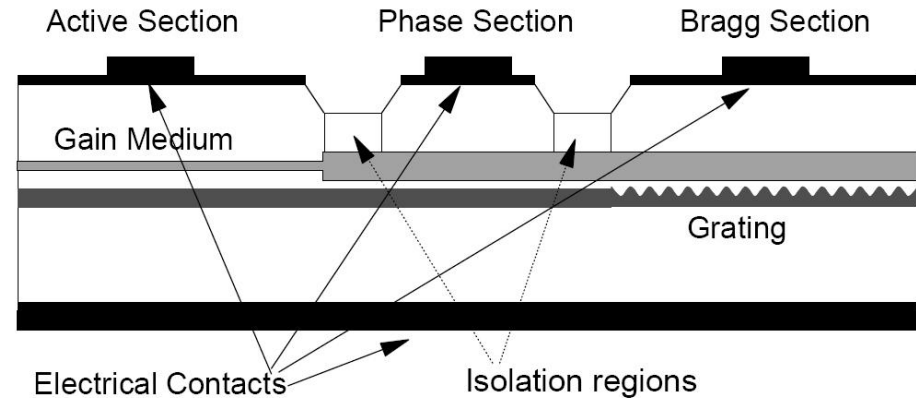
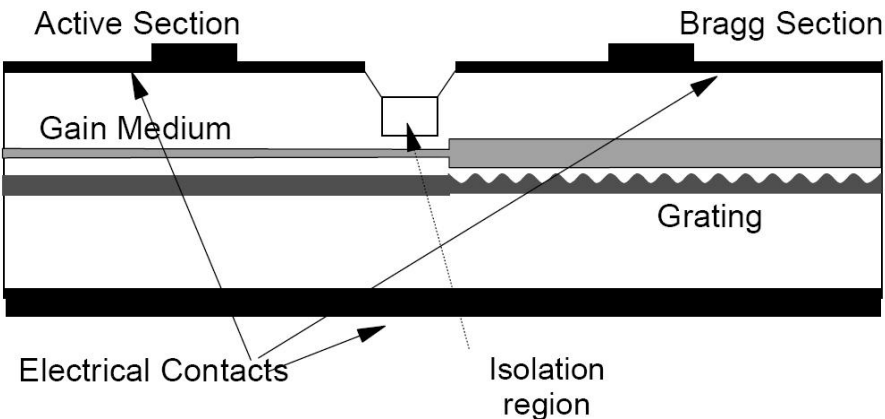
- ▶ Amorsarea emisiei stimulate necesita pomparea unei anumite cantitati de energie – curent de prag

$$I > I_{th}$$

$$r = \frac{\Delta P_o}{\Delta I} \left[\frac{W}{A} \right]$$



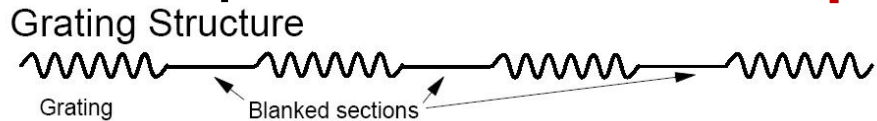
Diode laser reglabile



- ▶ Curentul trece prin zona activa ducand la amplificarea luminii
- ▶ curentul ce parcurge zona corespunzatoare reflectorului Bragg modifica indicele de refractie al acestei zone deci lungimea de unda
- ▶ zona centrala suplimentara permite reglaj fin suplimentar in jurul valorii impuse de reflectorul Bragg

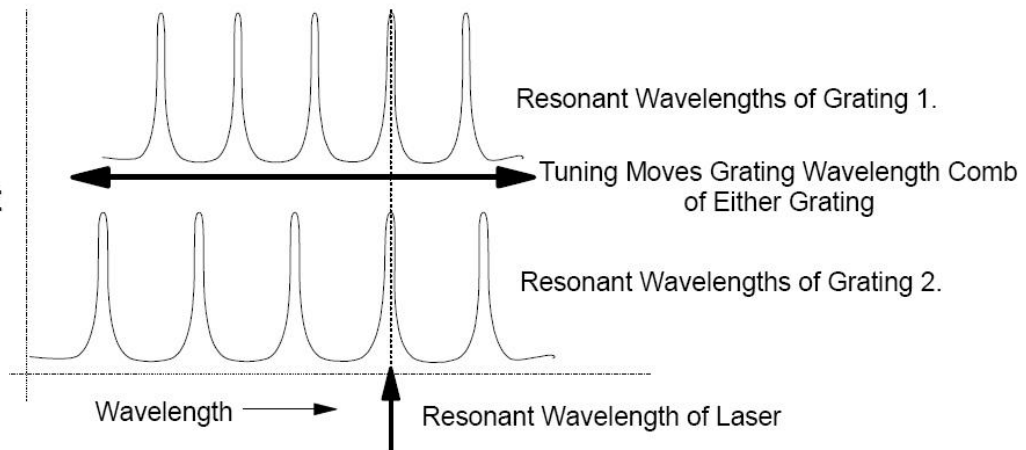
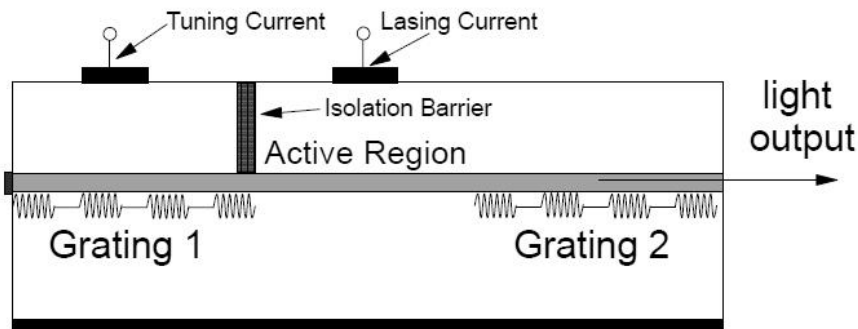
Diode laser reglabile

- ▶ Dezavantajul metodelor anterioare e dat de limita redusa a reglajului (~10nm)
- ▶ Reflectorul Bragg esantionat (periodic) produce spectru de filtrare **periodic**

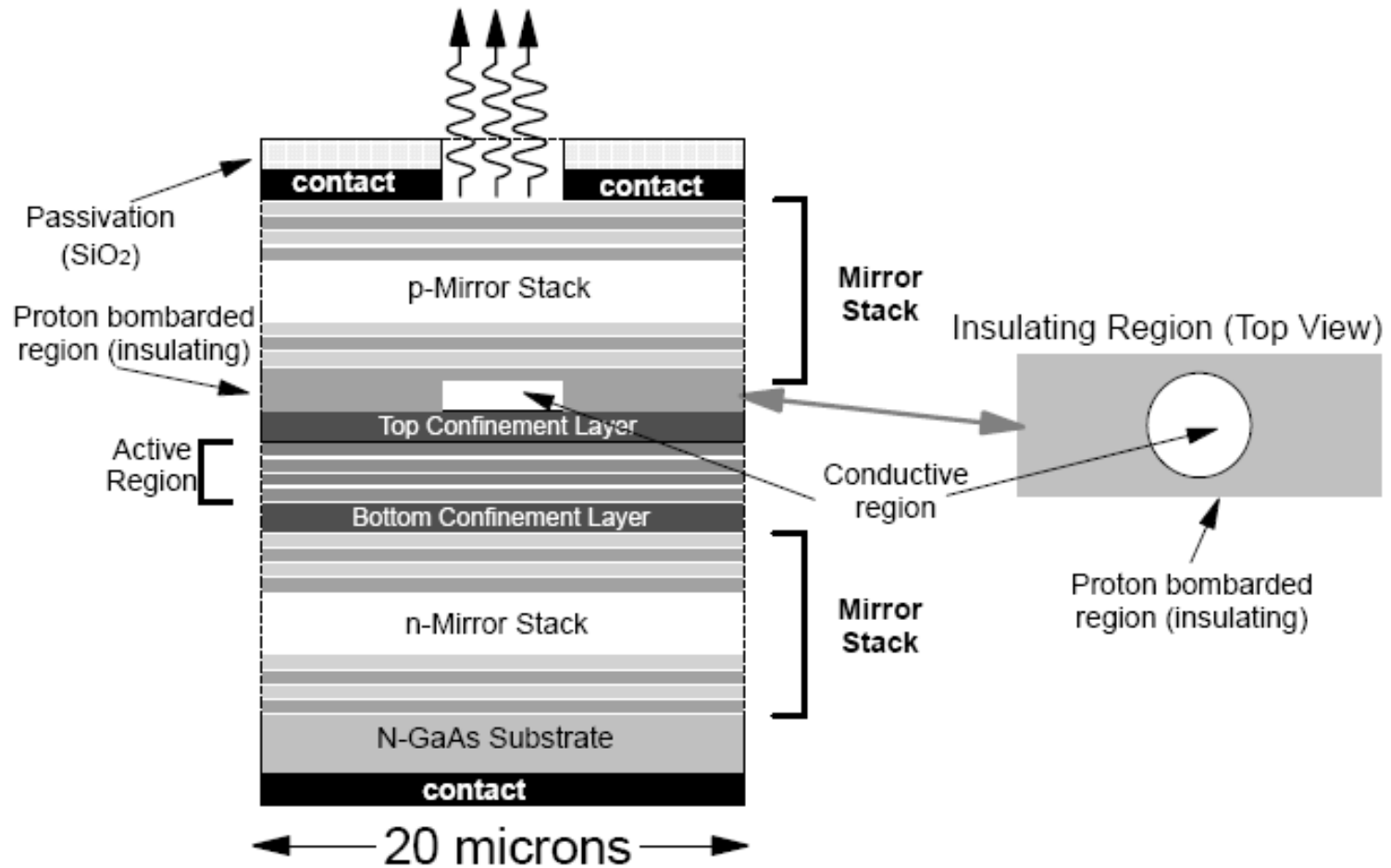


Dezavantaj :
reglajul e discret

- ▶ Regland unul din reflectori se obtine rezonanta la suprapunerea celor doua spectre

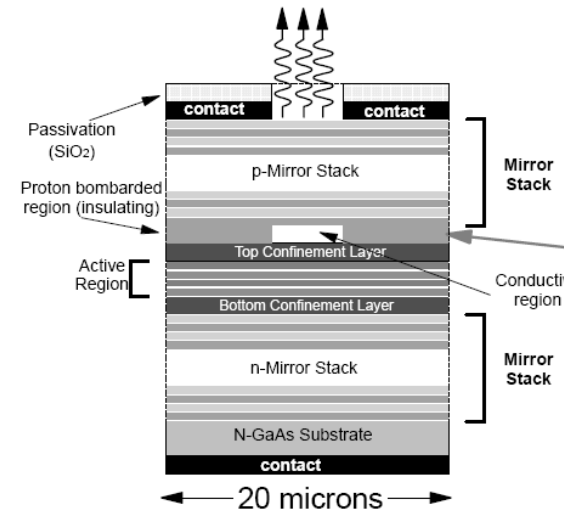


Vertical Cavity Surface Emitting Lasers (VCSEL)



Vertical Cavity Surface Emitting Lasers (VCSEL)

- ▶ Oglinzile pot fi realizate din straturi succesive din semiconductori cu indici de refractie diferiti – reflector Bragg
- ▶ Prelucrarea laterala se rezuma la taierea materialului



- ▶ Caracteristici

- ▶ puteri de ordinul 1mW
- ▶ lungimi de unda 850 si 980 nm
- ▶ radiatie de iesire circulara cu divergenta redusa
- ▶ Curenti de prag foarte mici (5mA) si putere disipata redusa
- ▶ circuite de control speciale nu sunt necesare
- ▶ Banda de modulatie mare (2.4GHz)
- ▶ Stabilitate mare cu temperatura si durata de viata

Continuare



Parametri dioda LASER

Dependenta de temperatura

- ▶ Dependenta de temperatura a curentului de prag este exponentiala

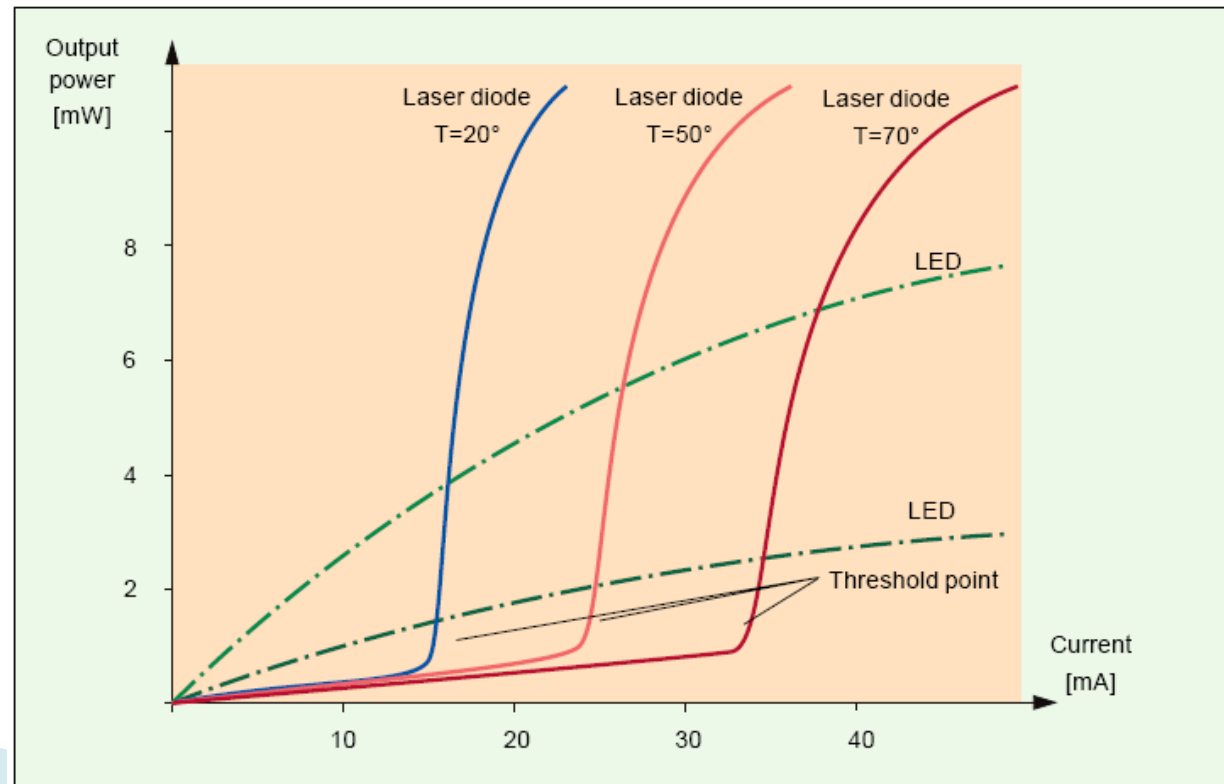
$$I_{th} = I_0 \cdot e^{T/T_0}$$

- ▶ I_0 e o constanta determinata la temperatura de referinta

Material	Lungime de unda	T_0
InGaAsP	1300 nm	60÷70 K
InGaAsP	1500 nm	50÷70 K
GaAlAs	850 nm	110÷140 K

Temperatura si îmbatrânire

- ▶ Curentul de prag variaza cu temperatura si cu timpul
- ▶ Variatia tipica 1–2%/°C



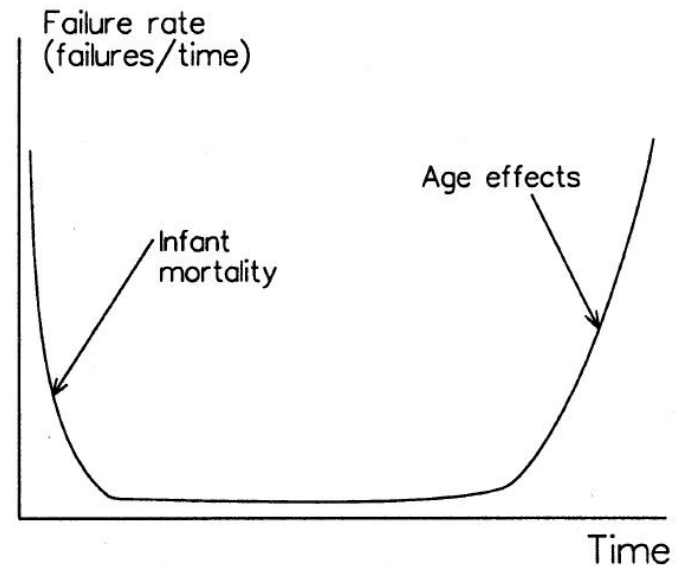
Degradare in timp

- ▶ Puterea scade in timp exponential

$$P(t) = P_0 \cdot e^{-t/\tau_m}$$

- ▶ τ_m – timpul de viata
- ▶ Diodele laser sunt supuse la conditii extreme de lucru
 - densitati de curent in zona activa $2000 \div 5000 \text{ A/cm}^2$
 - densitati de putere optica: $10^5 \div 10^6 \text{ W/cm}^2$
- ▶ Diverse definitii ale timpului de viata fac comparatiile dificile

Degradare in timp



- ▶ Cresterea curentului duce la scaderea duratei de viata

$$\tau_m \sim J^{-n}$$

- $n = 1.5 \div 2$ (empiric)
- dublarea curentului duce la scaderea de 3-4 ori a duratei de viata
- ▶ Cresterea temperaturii duce la scaderea duratei de viata

$$\tau_m \sim e^{E/kT}$$

- $E = 0.3 \div 0.95 \text{ eV}$ (valoarea tipica in teste 0.7eV)
- cresterea temperaturii cu 10 grade injumatateste durata de viata

Parametri

- ▶ Coerenta radiatiei emise
 - LED: $t_c \approx 0.5\text{ps}$, $L_c \approx 15\mu\text{m}$
 - LASER : $t_c \approx 0.5\text{ns}$, $L_c \approx 15\text{cm}$

$$L_c = c \cdot t_c = \frac{\lambda_0^2}{\Delta\lambda}$$

- ▶ Stabilitatea frecventei
 - detectie necoerenta (modulatie in amplitudine)
 - mai ales in sistemele multicanal
- ▶ Timpul de raspuns
- ▶ Viteza, interval de reglaj

Caracteristici curent tensiune

- ▶ Amorsarea emisiei stimulate necesita pomparea unei anumite cantitati de energie - curent de prag

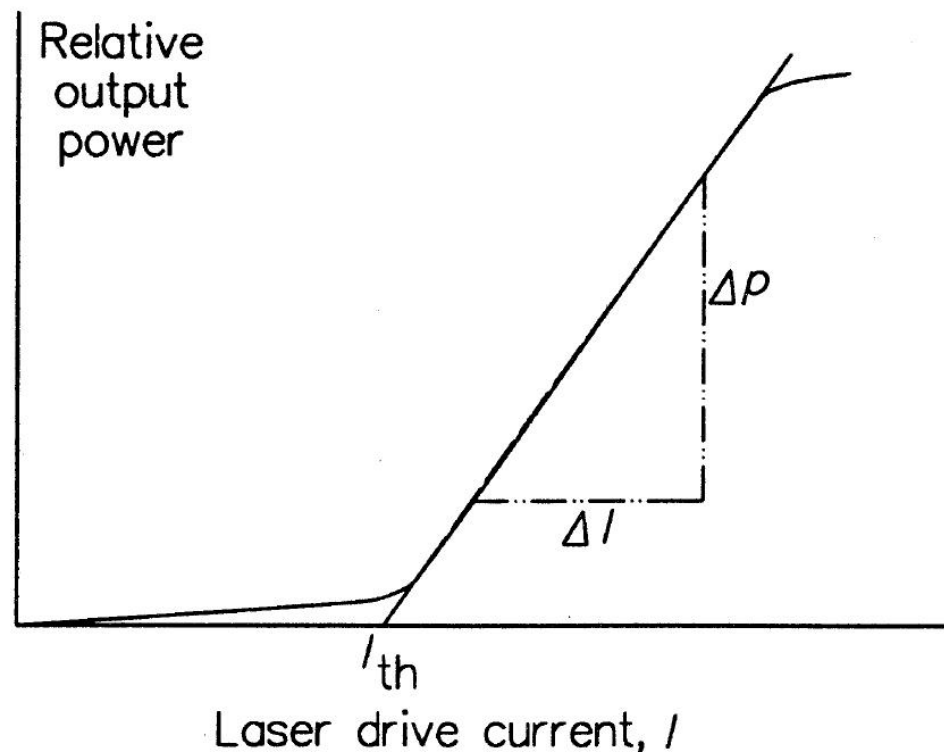
$I < I_{th}$ regim LED
ineficient!, $P_o \cong 0$

$I > I_{th}$ regim LASER

$$r = \frac{\Delta P_o}{\Delta I} \left[\frac{W}{A} \right]$$

$$P_o = r \cdot (I - I_{th})$$

Apare saturare la nivele mari de curent



Eficienta

- ▶ eficienta de conversie electro-optic (randament)

$$\eta = \frac{P_{out}(optic)}{P_{in}(electric)} = \frac{P_o}{V_f \cdot I_f} \approx \frac{r \cdot (I_f - I_{th})}{V_f \cdot I_f}$$

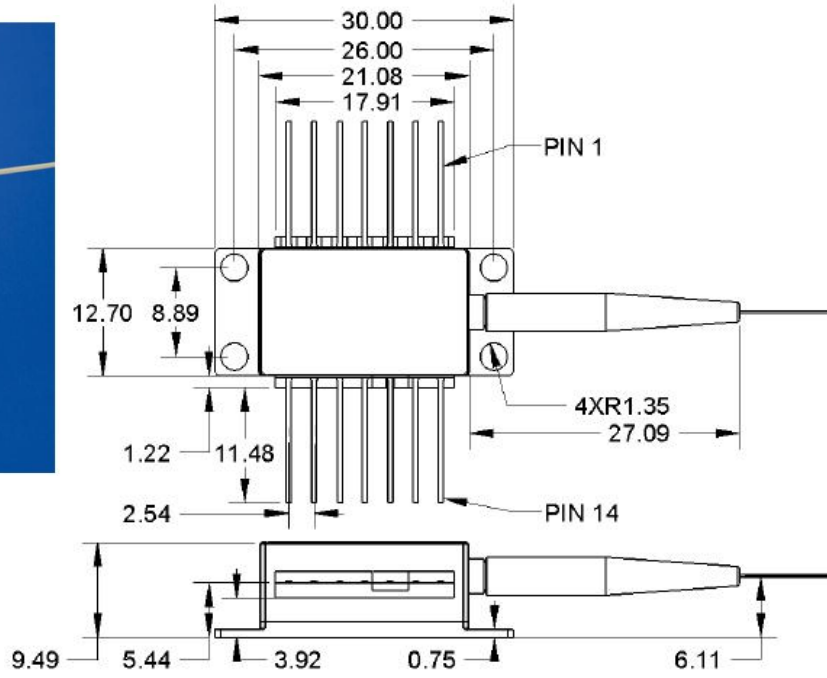
- ▶ tipic, randamente sub 10% sunt intalnite
- ▶ eficienta cuantica
 - interna
 - externa

$$\eta = \frac{n_f}{n_e} \quad \eta = \frac{\Delta P / h\nu}{\Delta I / e} = r \cdot \frac{e}{h\nu}$$

1550nm DFB Laser

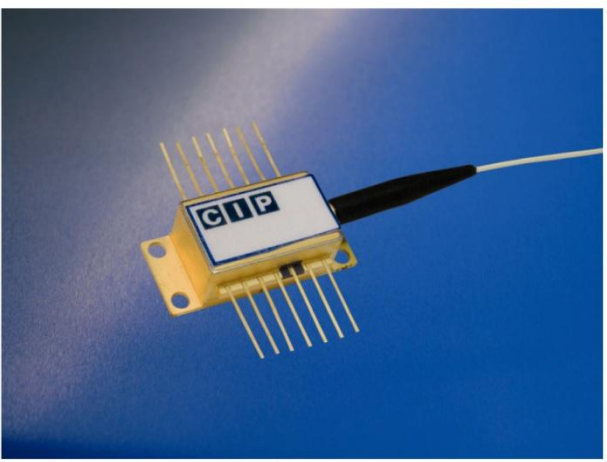
Mechanical Drawing

All units in mm

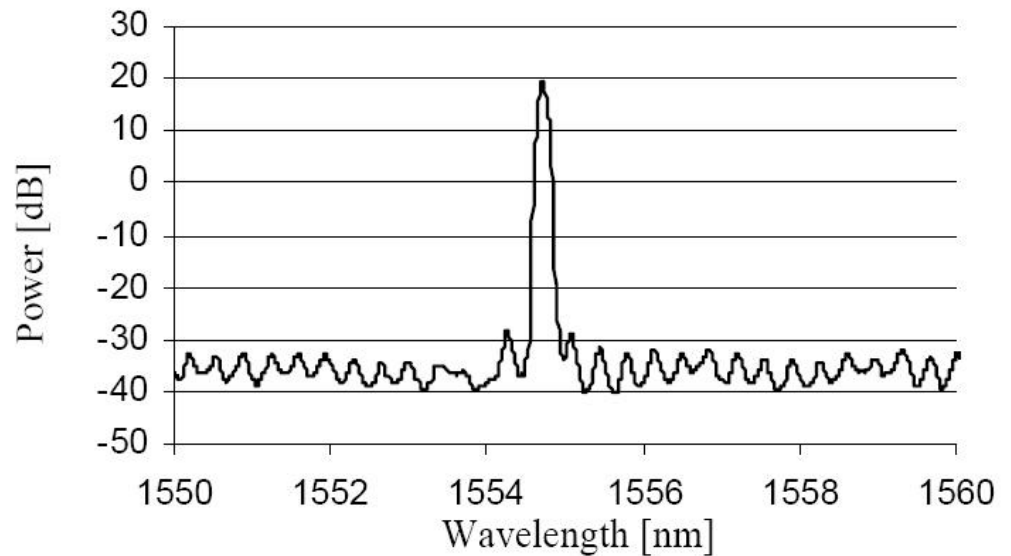
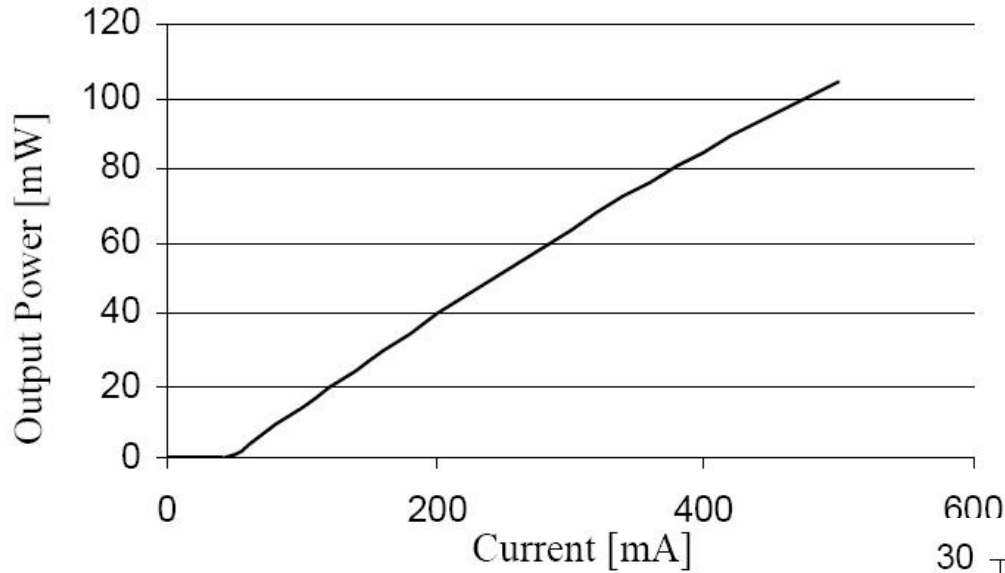


Pin out

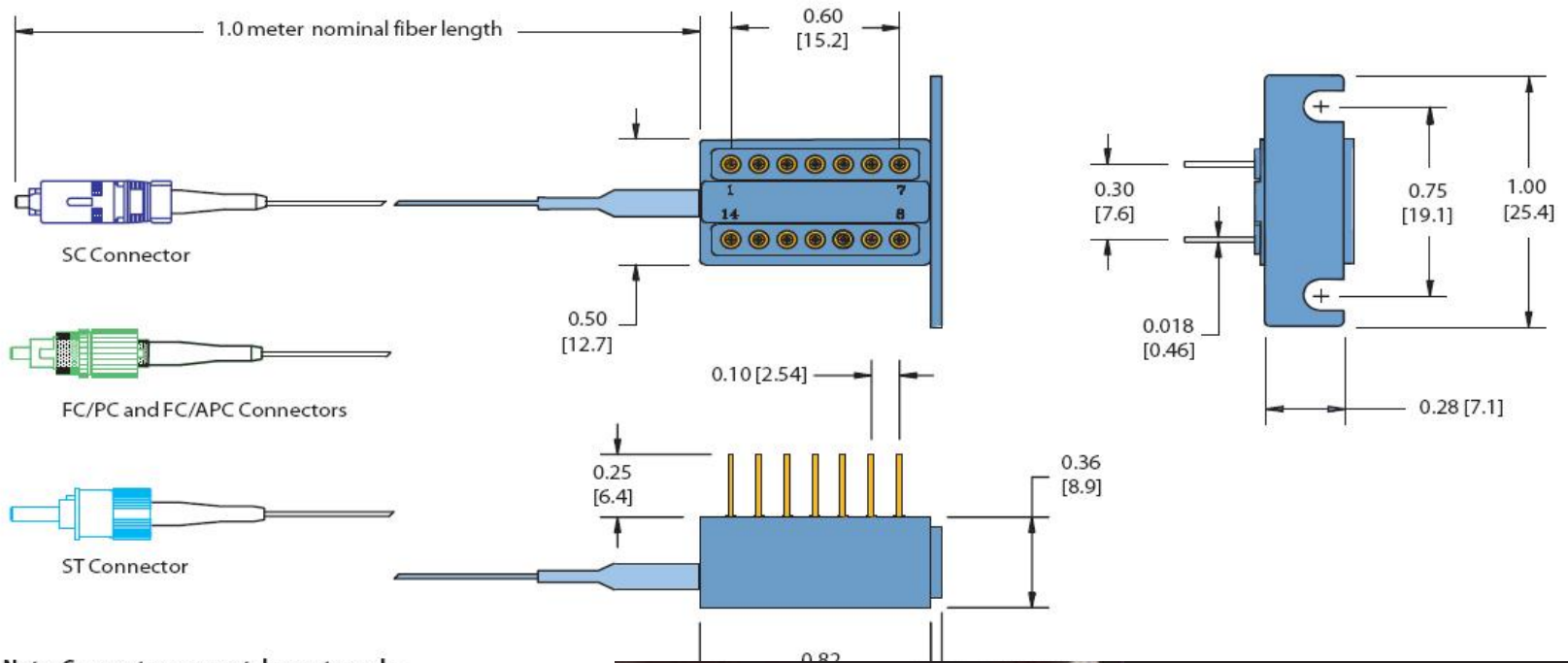
Pin	Description
1	Thermistor
2	Thermistor
3	Laser Cathode (Bias)
4	Monitor PD Anode
5	Monitor PD Cathode
6	TEC +
7	TEC -
8	Case GND, Laser Anode
9	Case GND, Laser Anode
10	Case GND, Laser Anode
11	Case GND, Laser Anode
12	Laser Cathode (modulation)
13	Case GND, Laser Anode
14	Case GND, Laser Anode



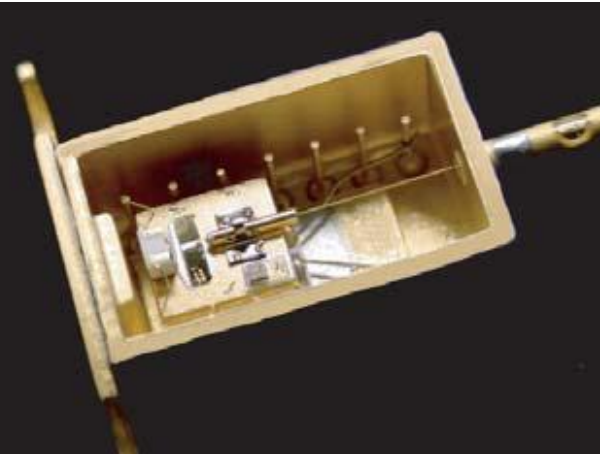
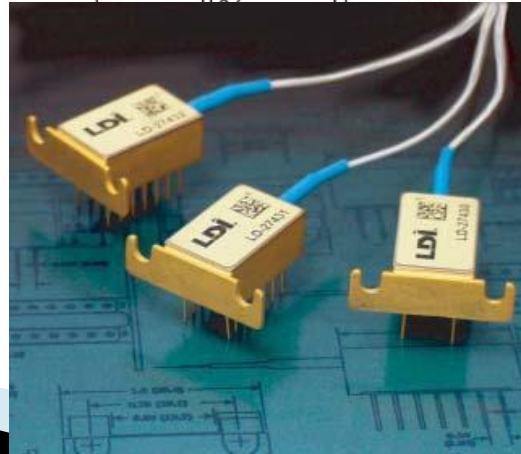
1550nm DFB Laser



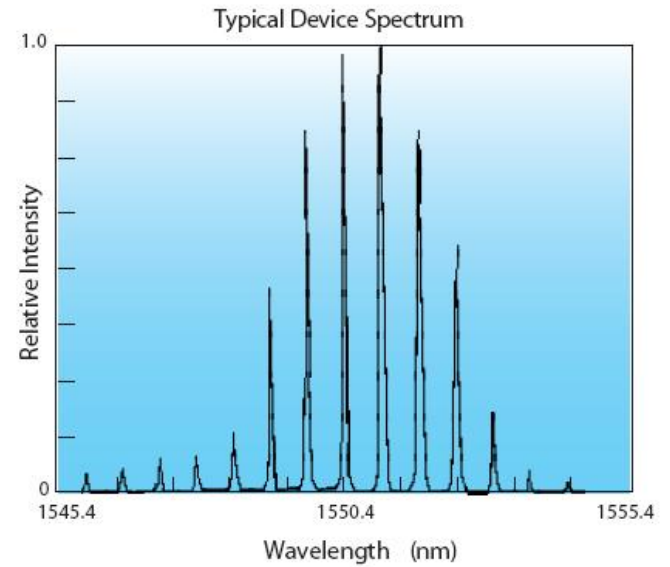
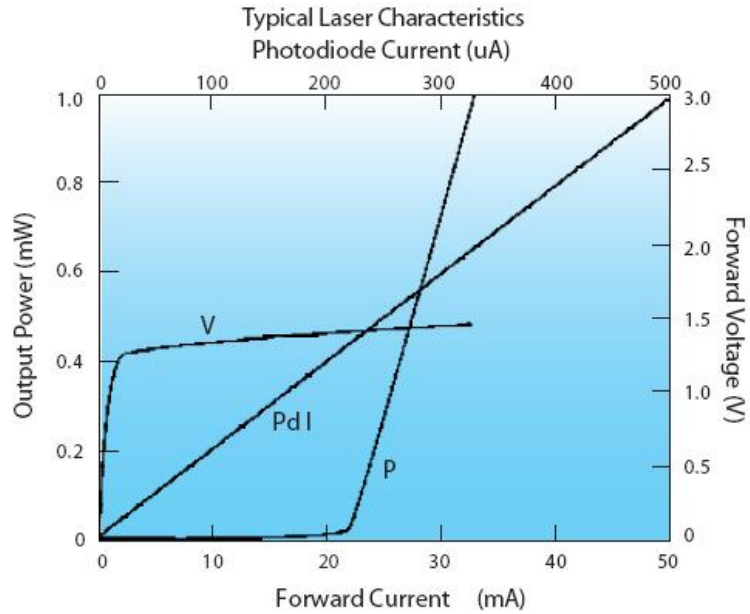
1550nm MQW Laser



Note: Connectors are not drawn to scale.

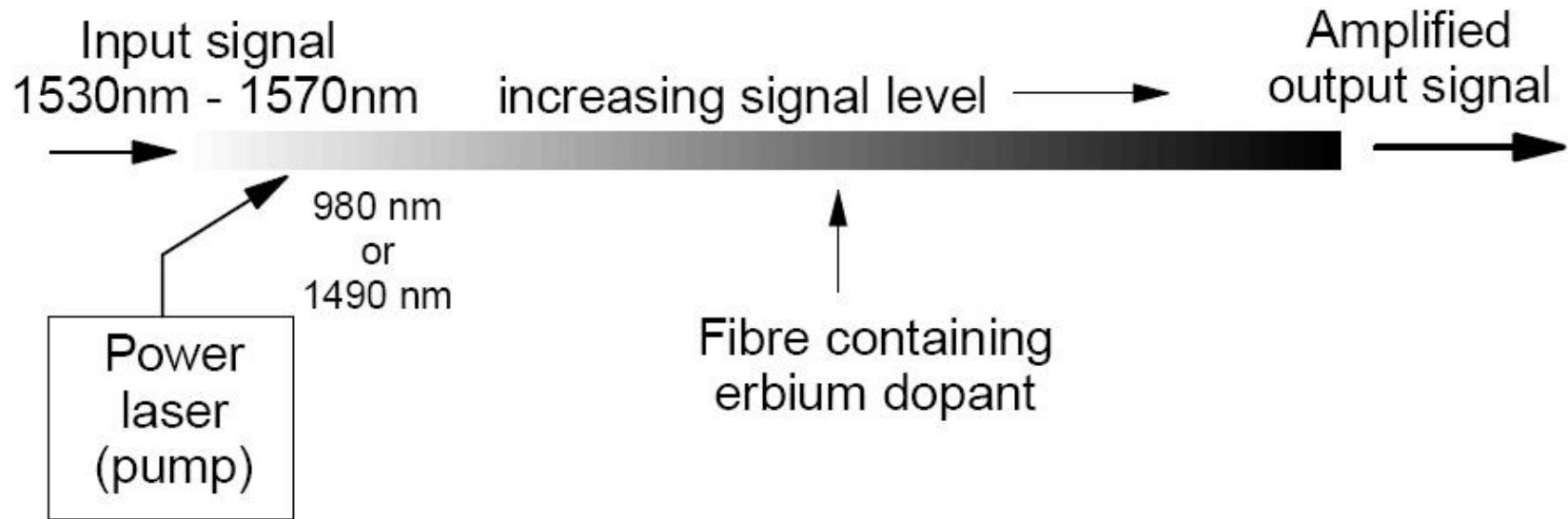


1550nm MQW Laser

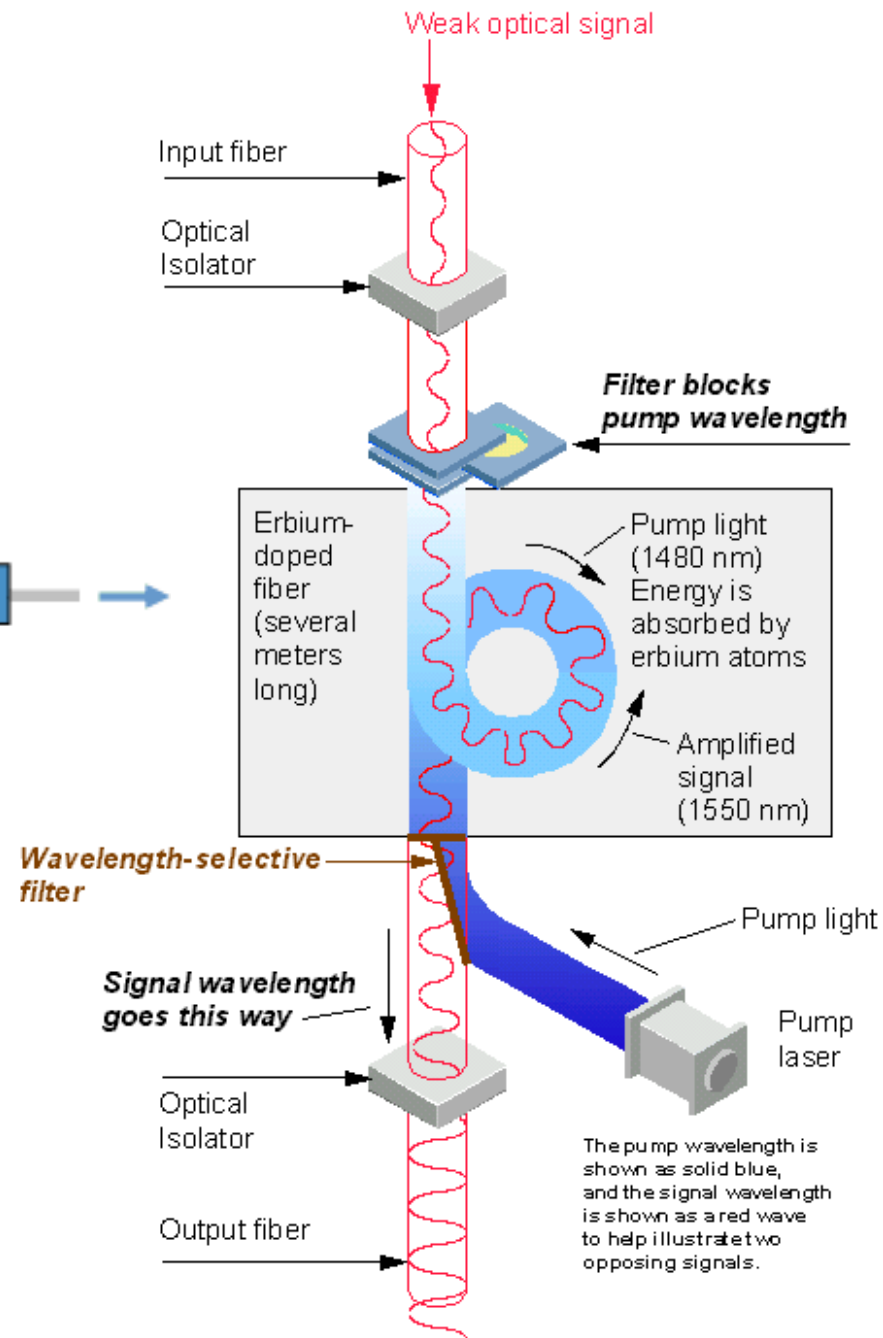
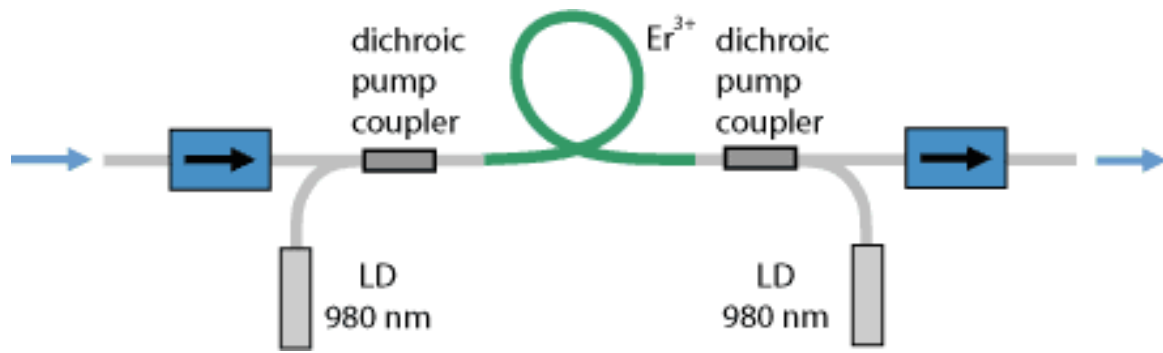


EDFA

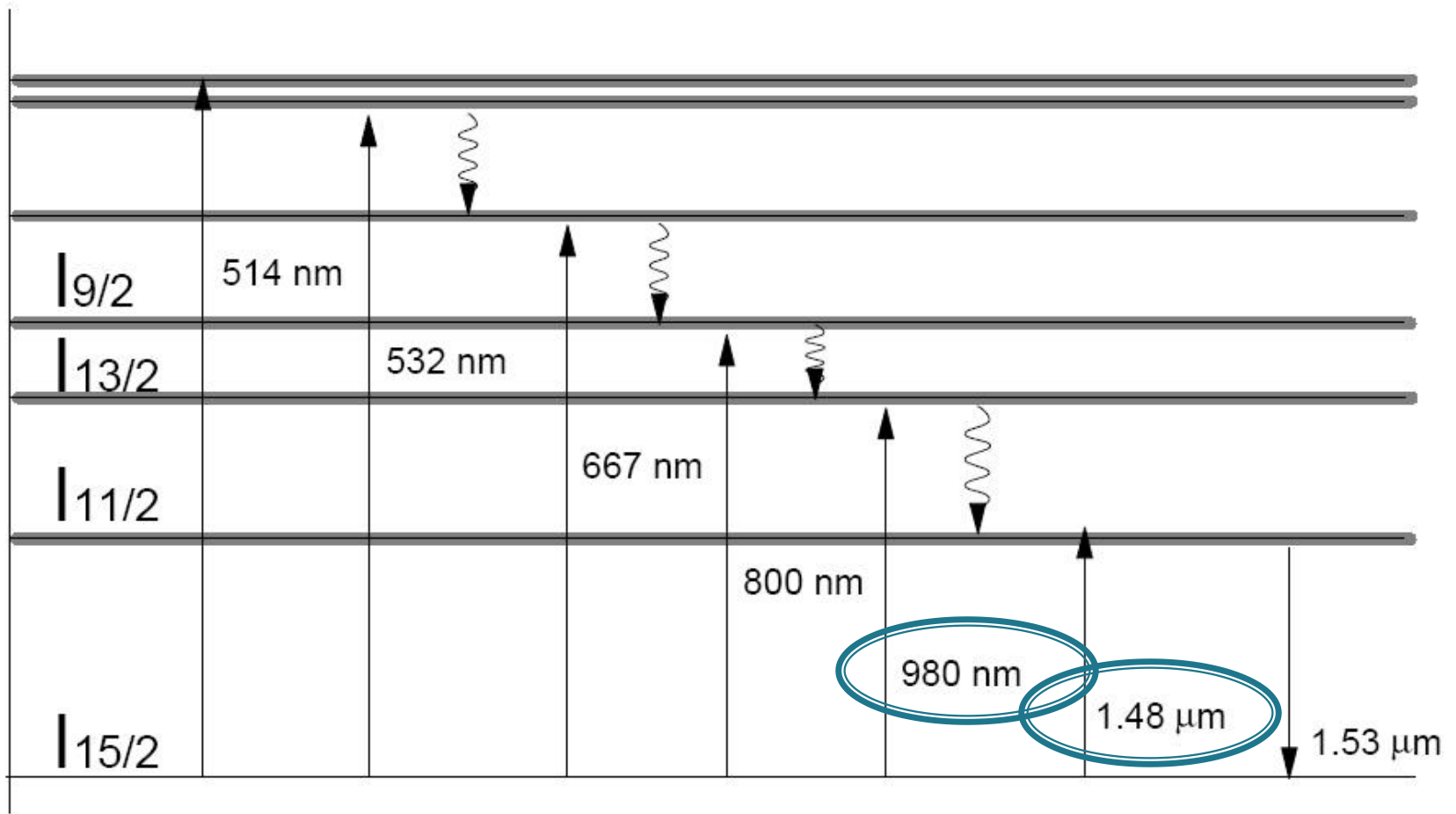
▶ Erbium Doped Fiber Amplifier



EDFA

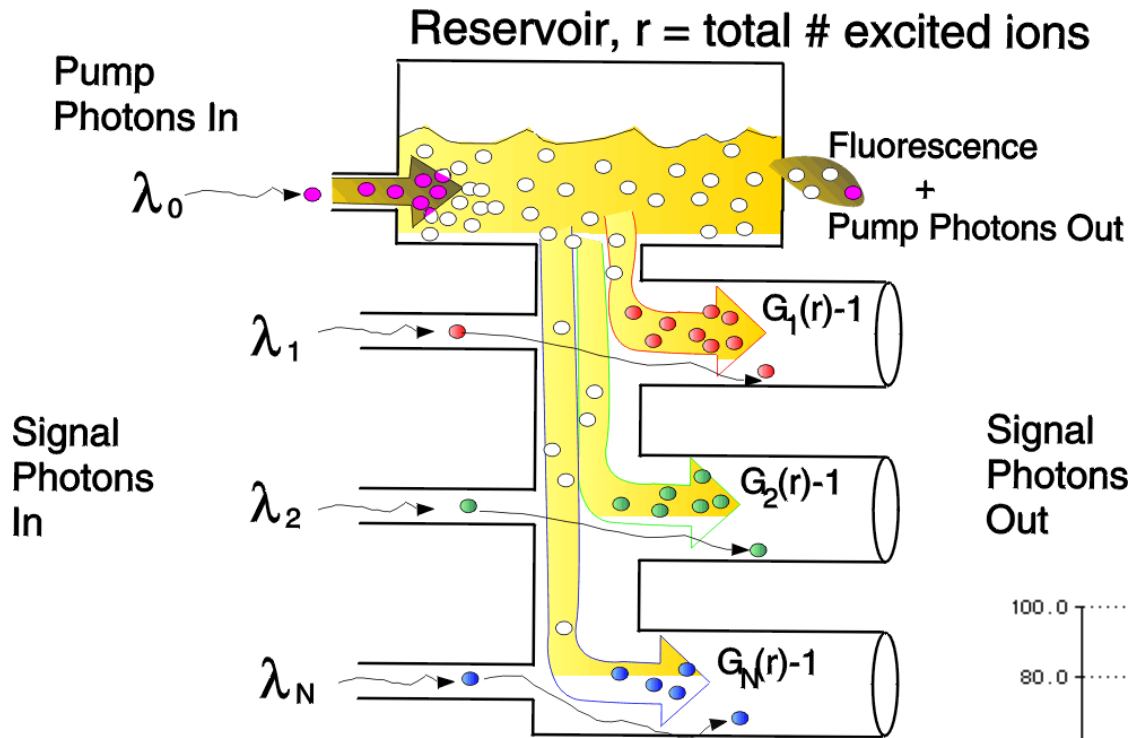


EDFA

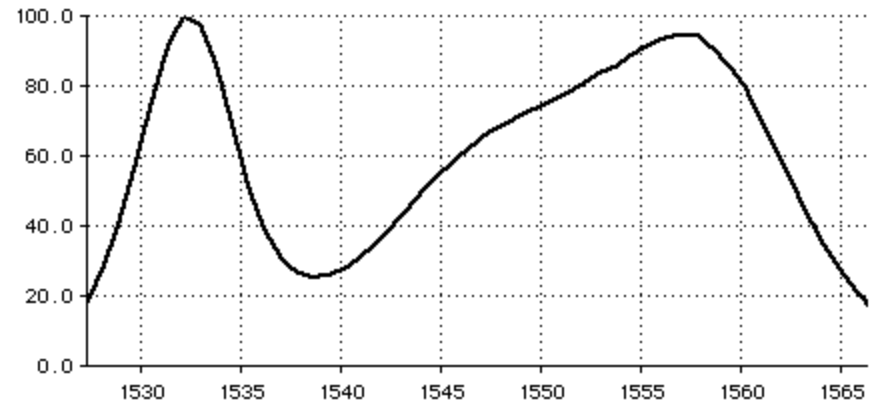


EDFA

How to think of an EDFA

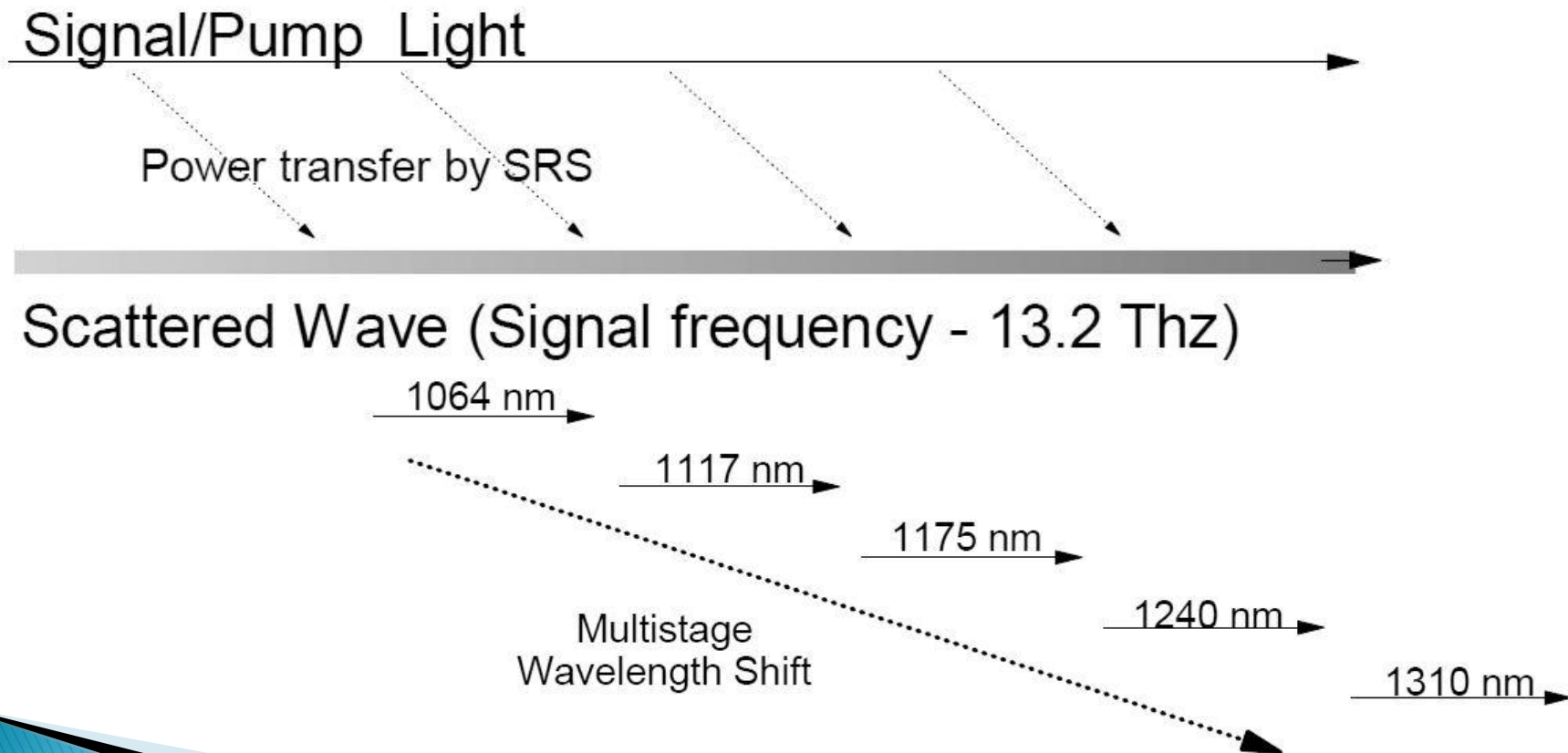


Signal Photons Out

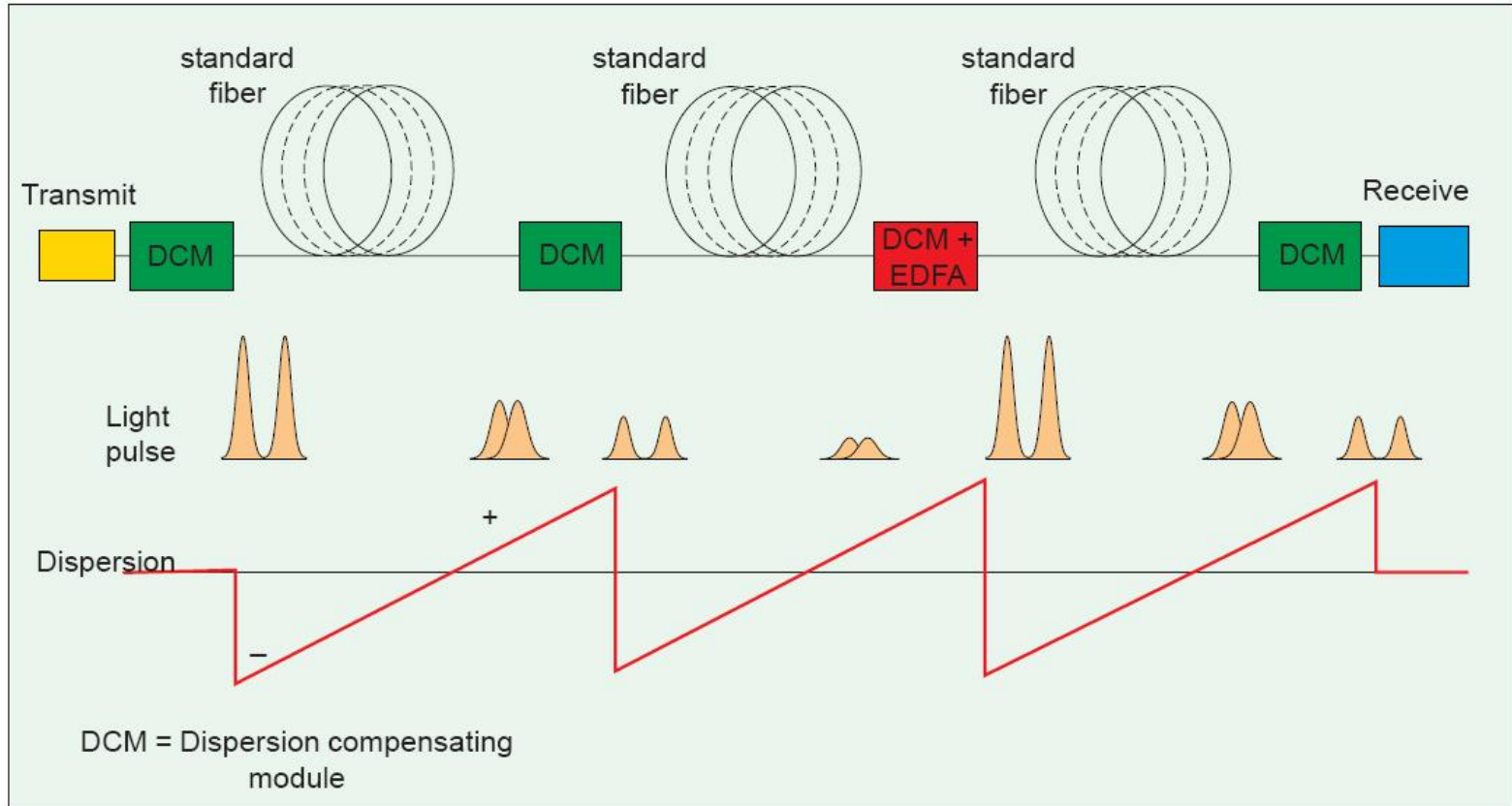


Amplificator cu efect Raman

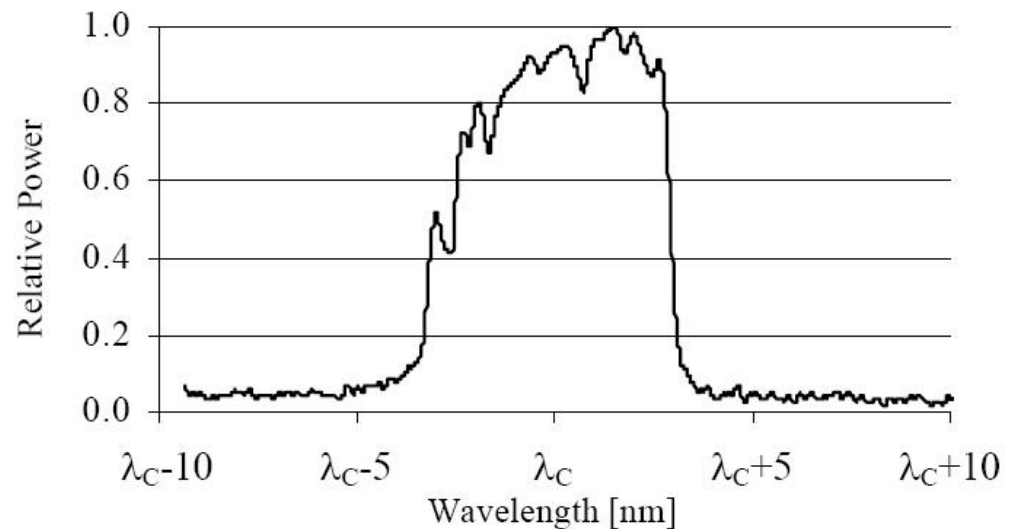
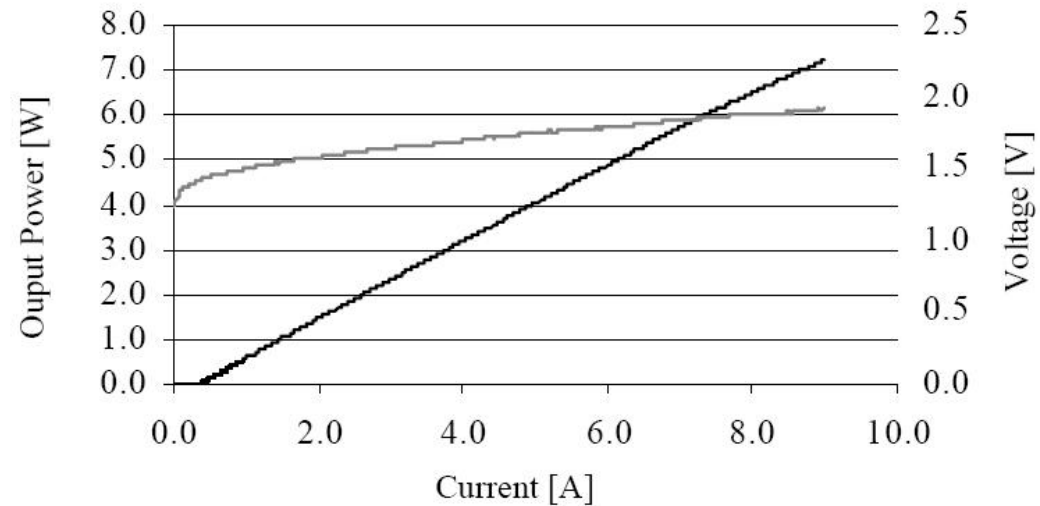
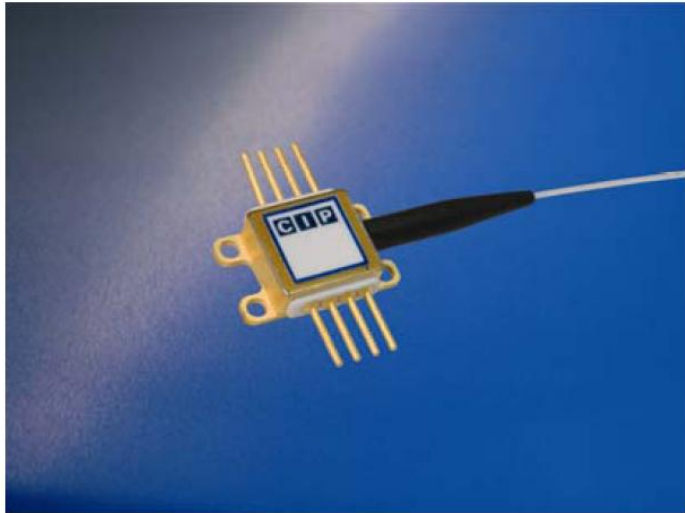
- ▶ Bazat pe efect Raman



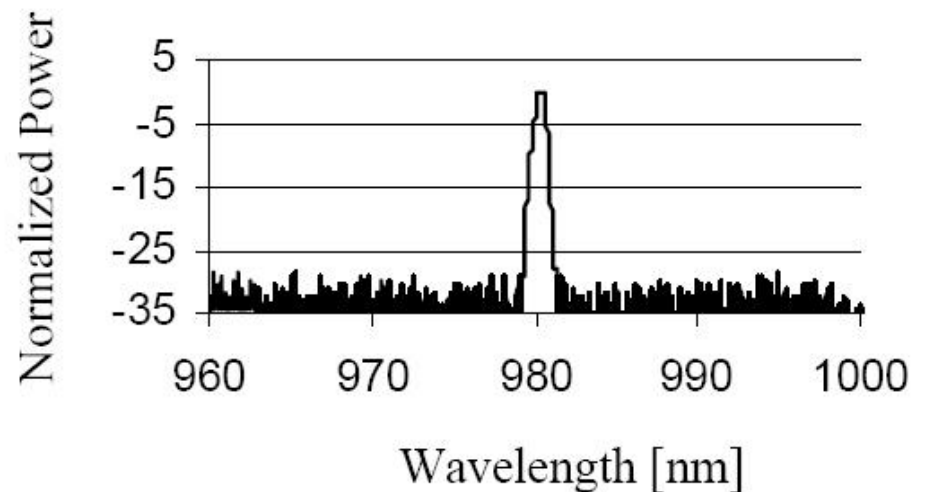
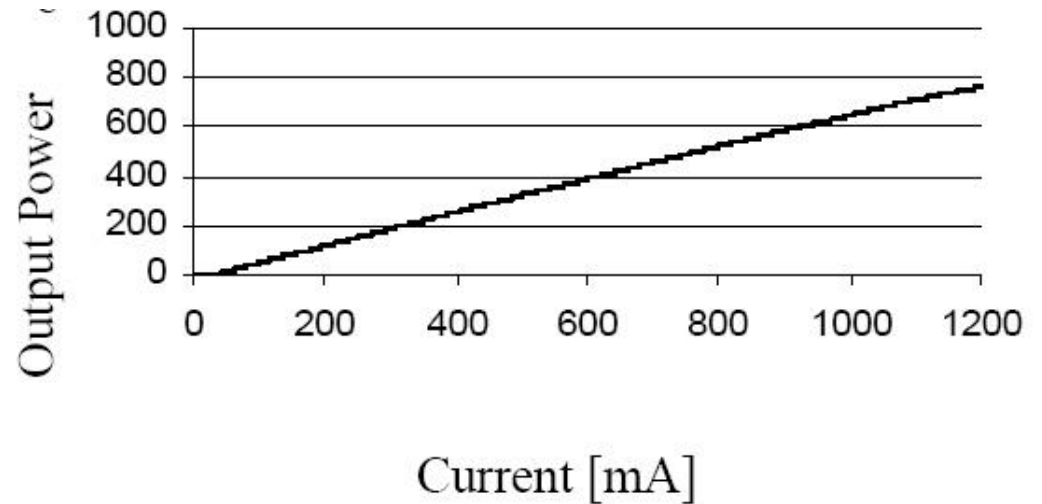
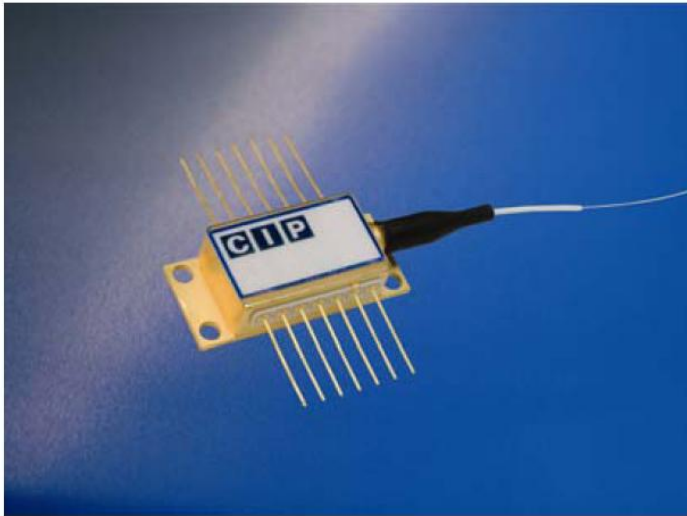
Utilizare amplificatoare optice



7W 980 nm Multimode Pump Laser

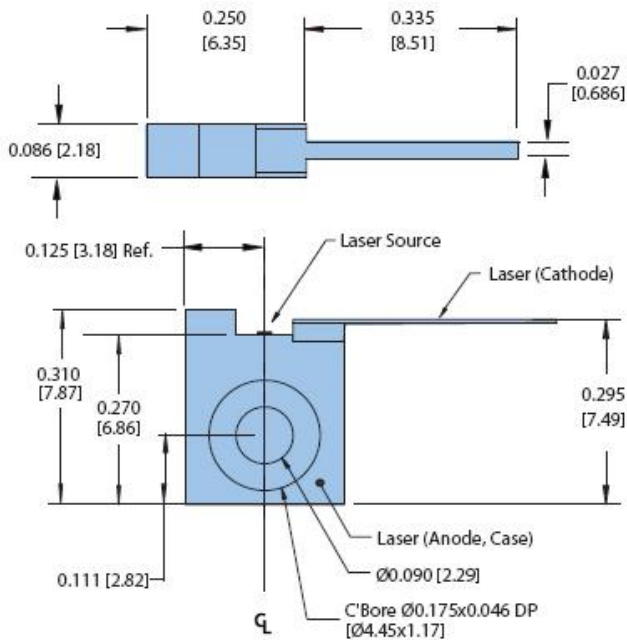


600mW 980 nm Singlemode Pump Laser

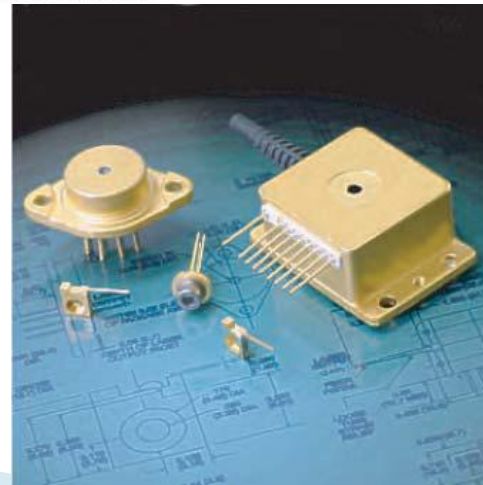
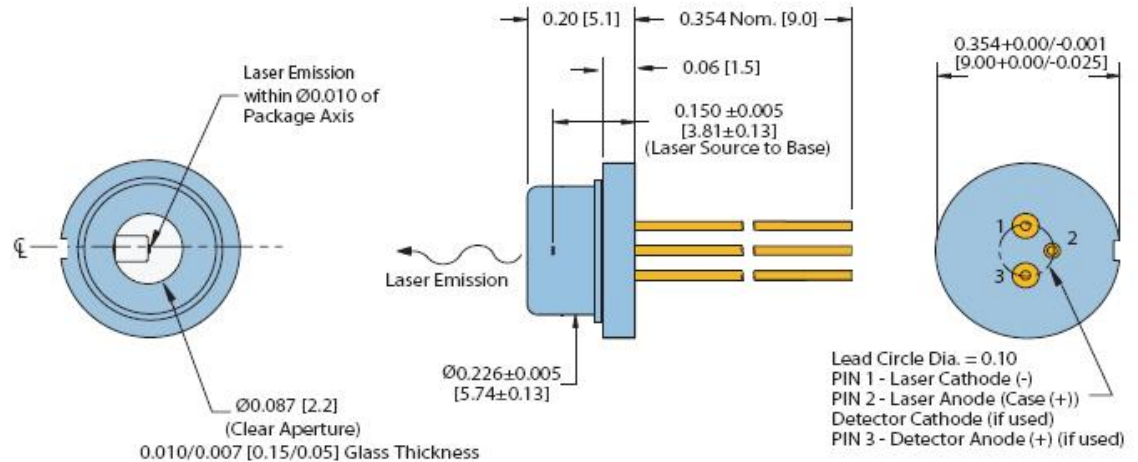


6 W, CW, 800nm

C-Mount Package

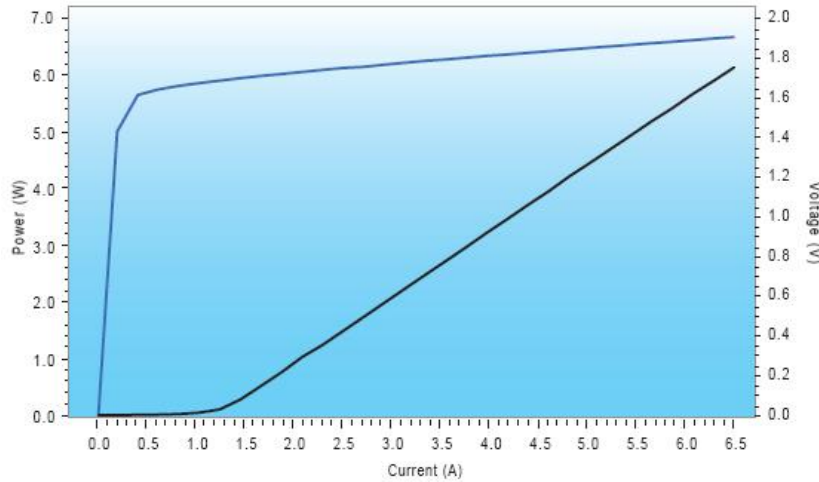


9mm Package

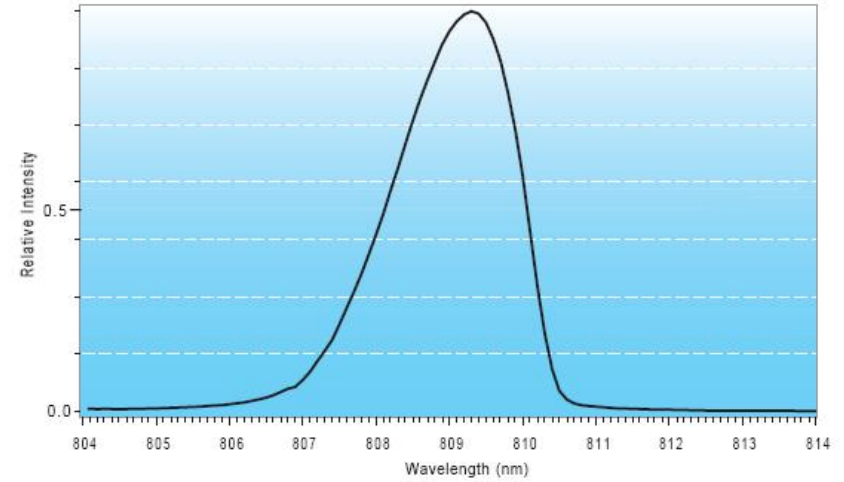


6 W, CW, 800nm

Typical L/I, V/I Graph

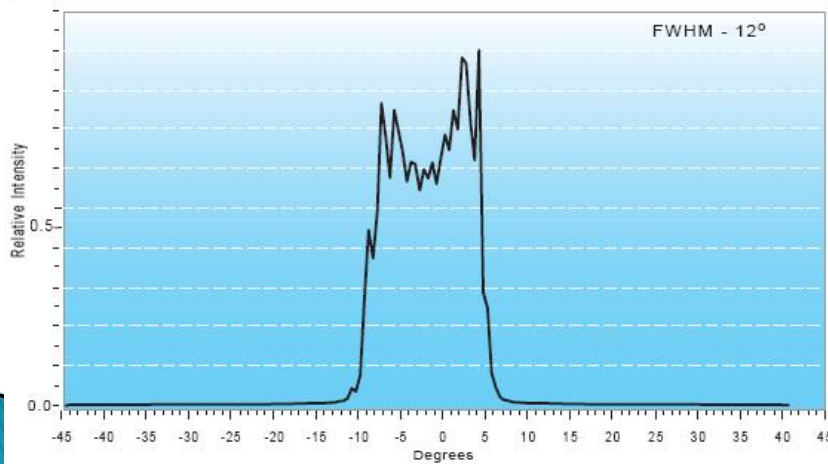


Wavelength Distribution



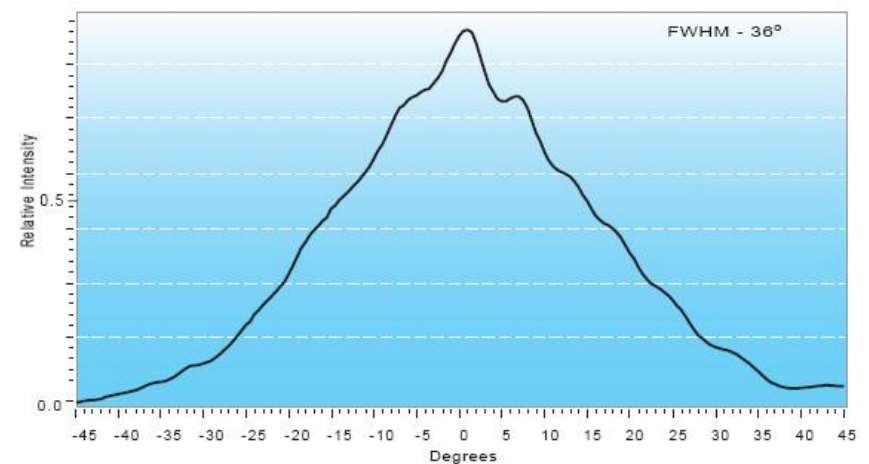
Typical Beam Divergence

Parallel

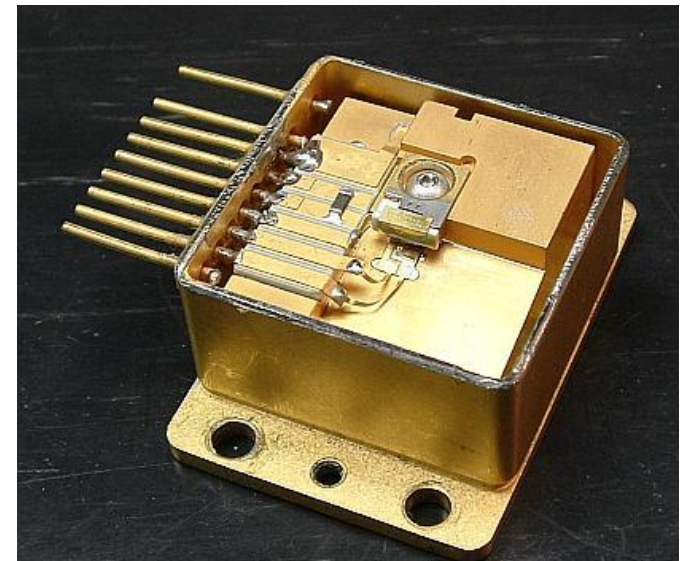
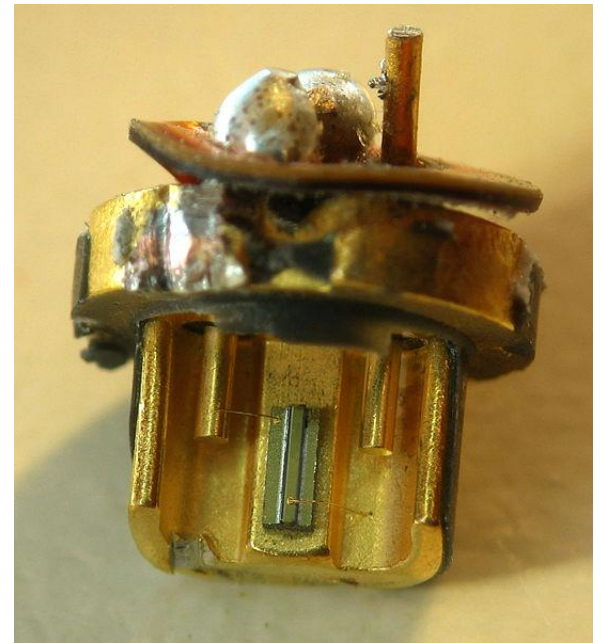
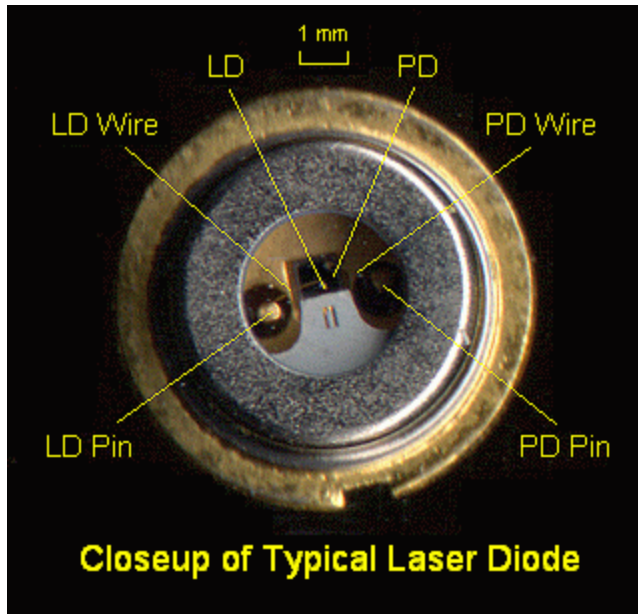


Typical Beam Divergence

Perpendicular



CW Laser, 650 nm



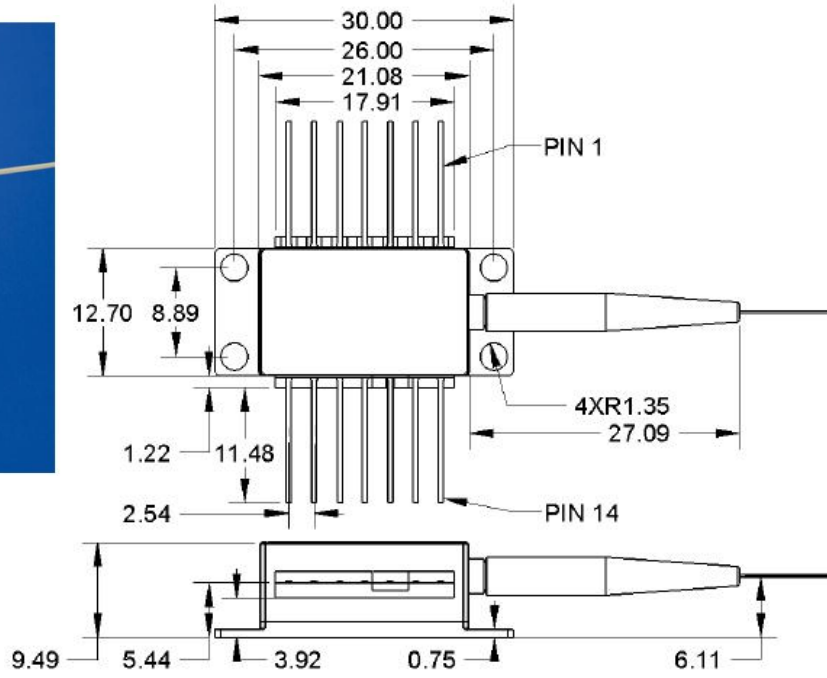
Lungimi de unda

- ▶ **405 nm** – InGaN blue-violet laser, in Blu-ray Disc and HD DVD drives
- ▶ **445–465 nm** – InGaN blue laser multimode diode recently introduced (2010) for use in mercury-free high-brightness data projectors
- ▶ **510–525 nm** – Green diodes recently (2010) developed by Nichia and OSRAM for laser projectors.
- ▶ **635 nm** – AlGaInP better red laser pointers, same power subjectively twice as bright as 650 nm
- ▶ **650–660 nm** – GaInP/AlGaInP CDDVD, cheap red laser pointers
- ▶ **670 nm** – AlGaInP bar code readers, first diode laser pointers (now obsolete, replaced by brighter 650 nm and 671 nm DPSS)
- ▶ **760 nm** – AlGaInP gas sensing: O₂
- ▶ **785 nm** – GaAlAs Compact Disc drives
- ▶ **808 nm** – GaAlAs pumps in DPSS Nd:YAG lasers (e.g., in green laser pointers or as arrays in higher-powered lasers)
- ▶ **848 nm** – laser mice
- ▶ **980 nm** – InGaAs pump for optical amplifiers, for Yb:YAG DPSS lasers
- ▶ **1,064 nm** – AlGaAs fiber-optic communication, DPSS laser pump frequency
- ▶ **1,310 nm** – InGaAsP, InGaAsN fiber-optic communication
- ▶ **1,480 nm** – InGaAsP pump for optical amplifiers
- ▶ **1,512 nm** – InGaAsP gas sensing: NH₃
- ▶ **1,550 nm** – InGaAsP, InGaAsNSb fiber-optic communication
- ▶ **1,625 nm** – InGaAsP fiber-optic communication, service channel
- ▶ **1,654 nm** – InGaAsP gas sensing: CH₄
- ▶ **1,877 nm** – GaInAsSb gas sensing: H₂O
- ▶ **2,004 nm** – GaInAsSb gas sensing: CO₂
- ▶ **2,330 nm** – GaInAsSb gas sensing: CO
- ▶ **2,680 nm** – GaInAsSb gas sensing: CO₂
- ▶ **3,030 nm** – GaInAsSb gas sensing: C₂H₂
- ▶ **3,330 nm** – GaInAsSb gas sensing: CH₄

1550nm DFB Laser

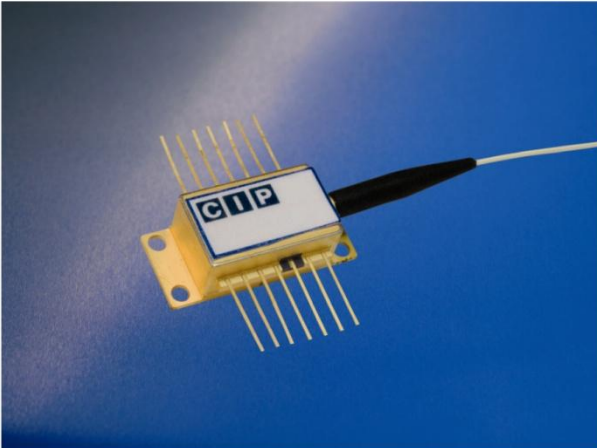
Mechanical Drawing

All units in mm

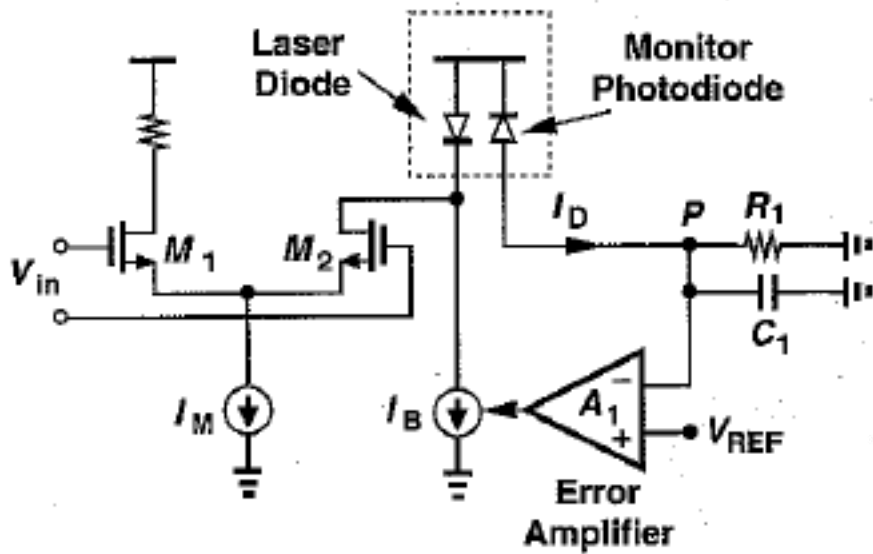


Pin out

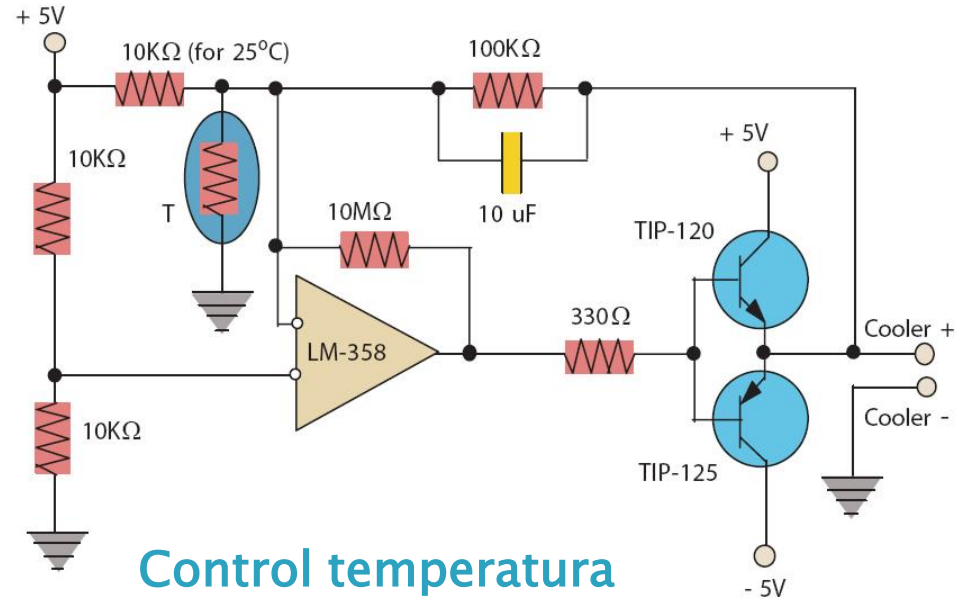
Pin	Description
1	Thermistor
2	Thermistor
3	Laser Cathode (Bias)
4	Monitor PD Anode
5	Monitor PD Cathode
6	TEC +
7	TEC -
8	Case GND, Laser Anode
9	Case GND, Laser Anode
10	Case GND, Laser Anode
11	Case GND, Laser Anode
12	Laser Cathode (modulation)
13	Case GND, Laser Anode
14	Case GND, Laser Anode



Control dioda LASER



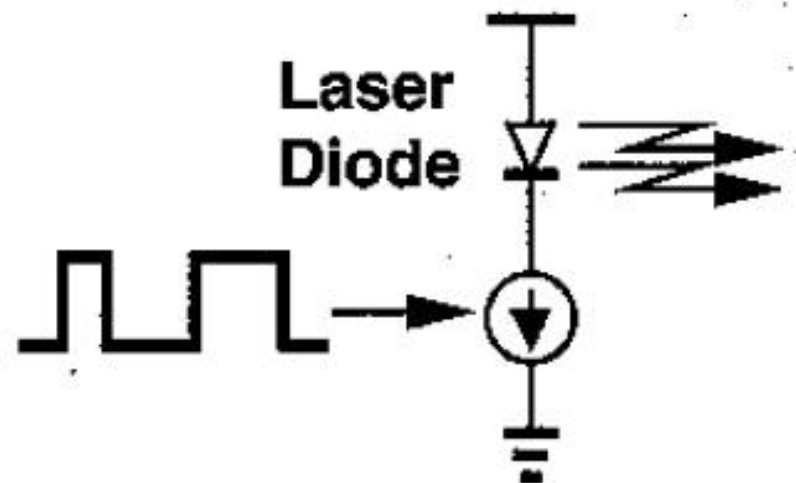
Control putere optica



Control temperatura

Dioda LASER

- ▶ Ca și în cazul LED, pentru DL intensitatea luminoasă emisă este o funcție de curentul prin dioda
 - aproape exclusiv, DL sunt controlate în curent
 - controlul în curent are avantajul unei viteze mai mari de lucru



Dioda LASER

- ▶ Cerinte pentru driver-ele de diode laser
 - viteza mare de basculare pentru minimizarea interferentei intersimbol
 - curent mare de iesire
 - capacitatea de a rezista la variatiile de tensiune pe dioda Laser
- ▶ Cerintele sunt dificil de respectat deoarece sunt contradictorii
 - viteza mare presupune micșorarea dimensiunii componentelor
 - micșorarea dimensiunii
 - scade tensiunea de strapungere
 - scade capabilitatea de curent/putere disipata

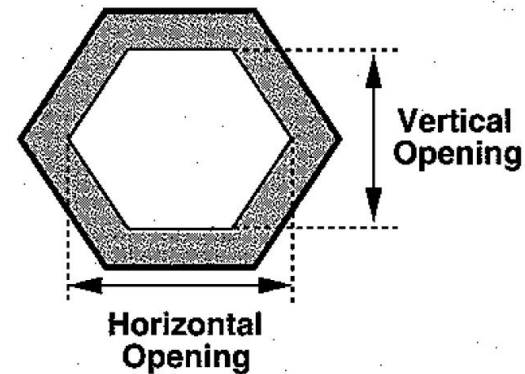
Caracteristici driver-e DL

▶ Viteza

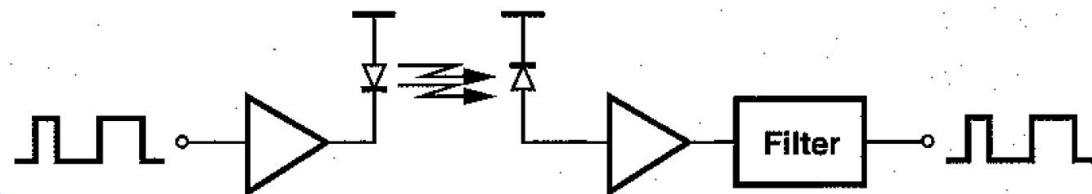
- caracterizata de timpii de crestere si de cadere
- suma acestora trebuie sa fie mult mai mica decat perioada de bit la viteza nominala de lucru

▶ Testarea vitezei de lucru

- standardizata
- “eye diagram”



(a)

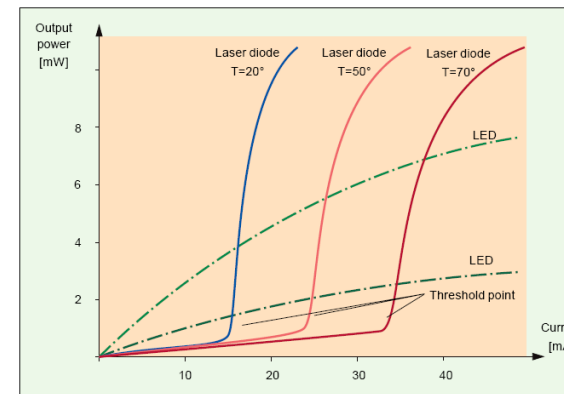


(b)

Caracteristici driver-e DL

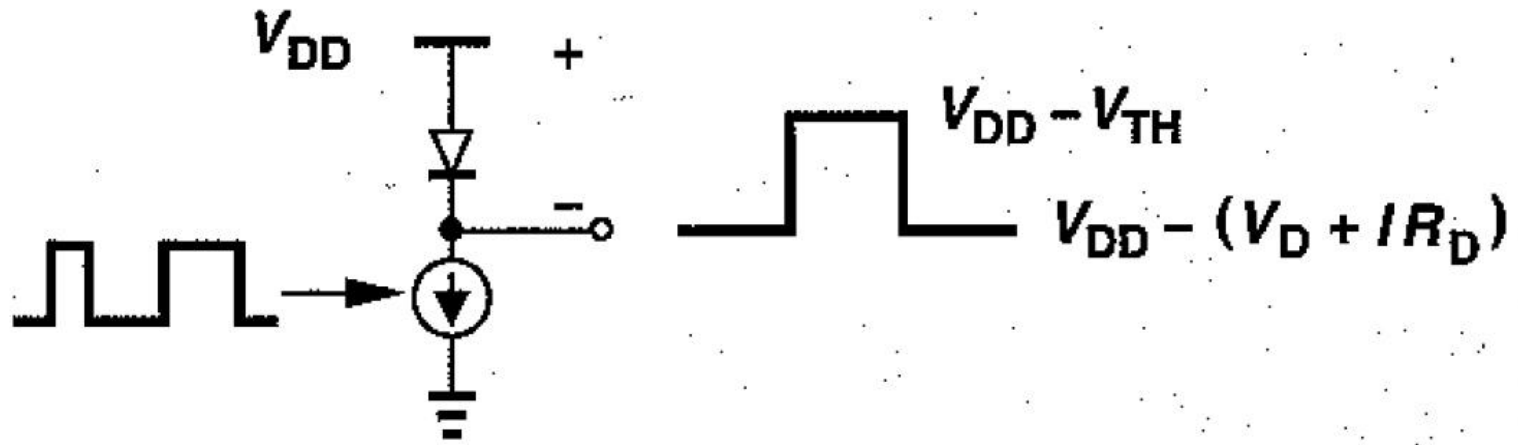
▶ Curent de iesire

- laserele trebuie polarizate in vecinatatea pragului, astfel incat o mica variatie de curent sa poata deschide dioda
- driver-ele de DL trebuie sa poata furniza:
 - un curent de “polarizare”
 - un curent de “modulatie”
- Curentul de “polarizare” (~ de prag) variaza cu temperatura si varsta diodei extrem de mult
- Curentul de “modulatie” (semnal) nu depinde de aceste elemente deoarece pentru DL
 - pragul depinde de temperatura si varsta
 - panta este aproximativ constanta



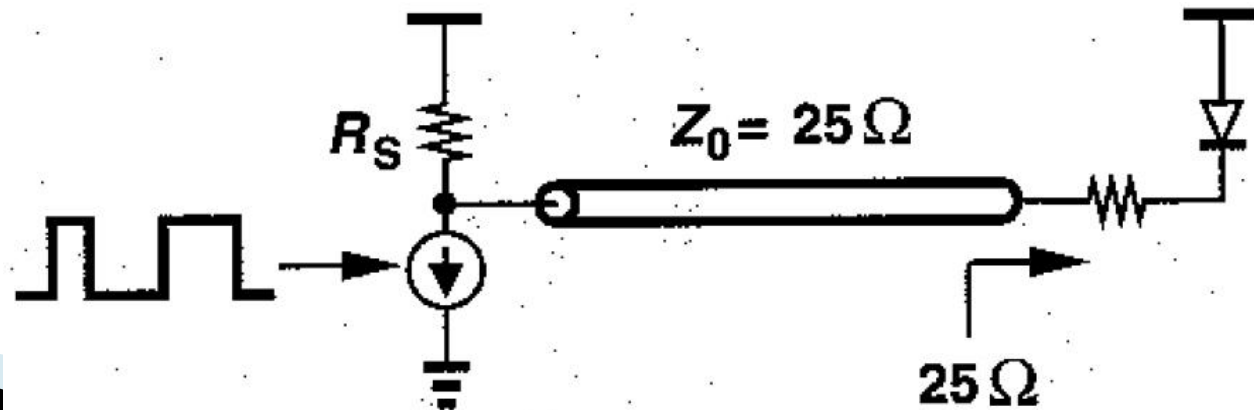
Caracteristici driver-e DL

- ▶ Variatii de tensiune pe dioda LASER
 - generate de variatiile mari de curent si rezistenta interna a diodei



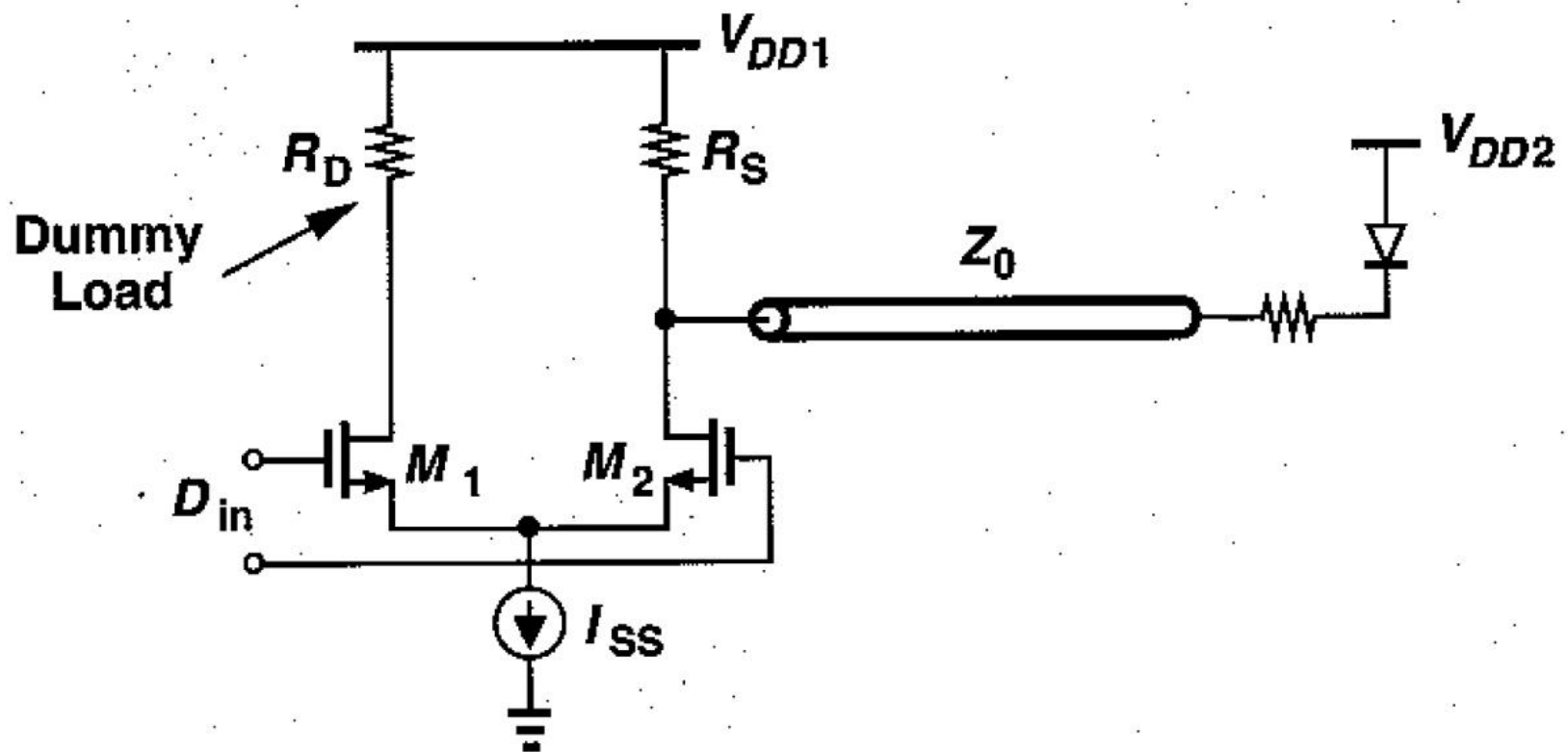
Caracteristici driver-e DL

- ▶ Impedante de intrare si iesire
- ▶ Se lucreaza la viteze mari (1 Gb/s, 10 GB/s)
 - se aplica considerente de proiectare a circuitelor de microunde
 - Intrarea in amplificator are tipic o impedanta de 50Ω
 - Iesirea trebuie adaptata la impedanta diodei Laser
 - daca aceasta impedanta e prea mica, se creste la valori adecvate ($\sim 25\Omega$) prin introducerea unui rezistor in serie



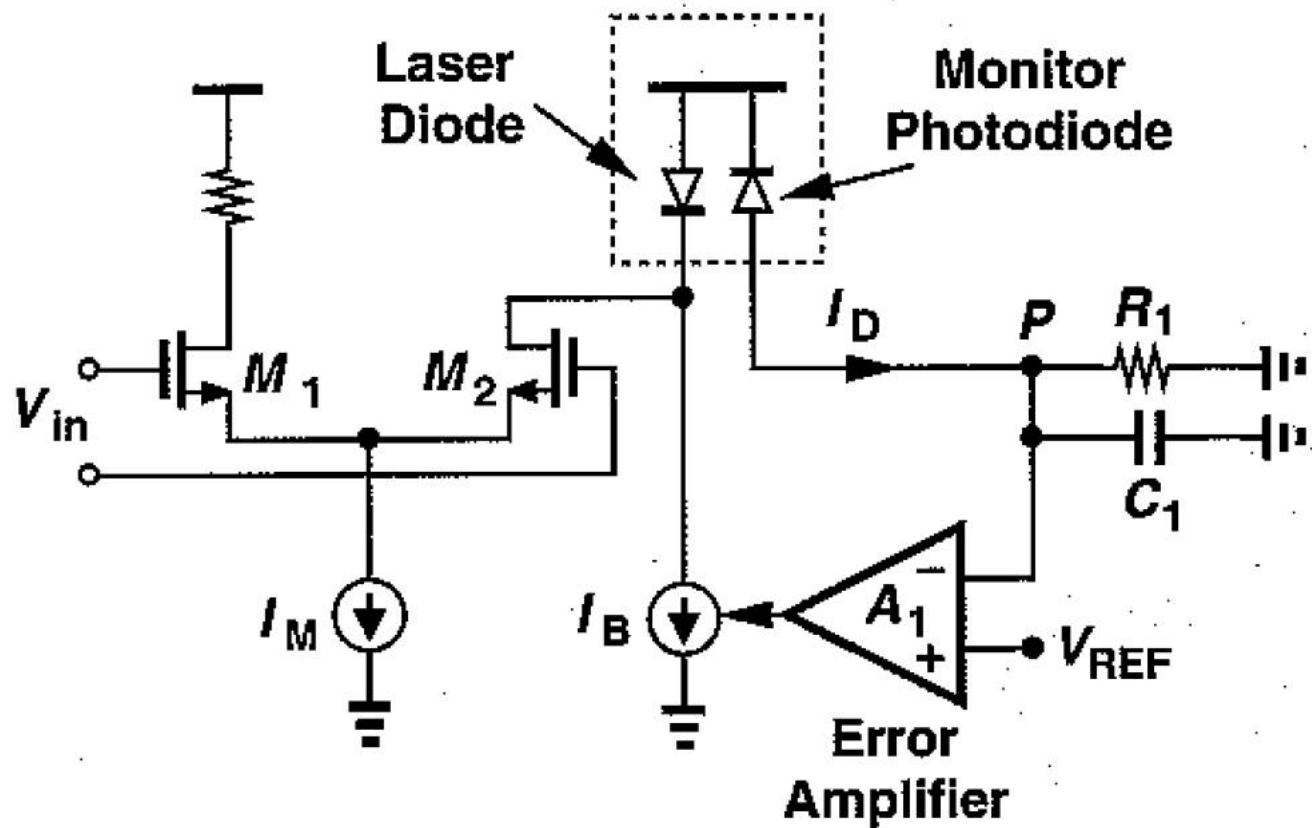
Principii de proiectare

- ▶ Tipic etajul de iesire se realizeaza diferential



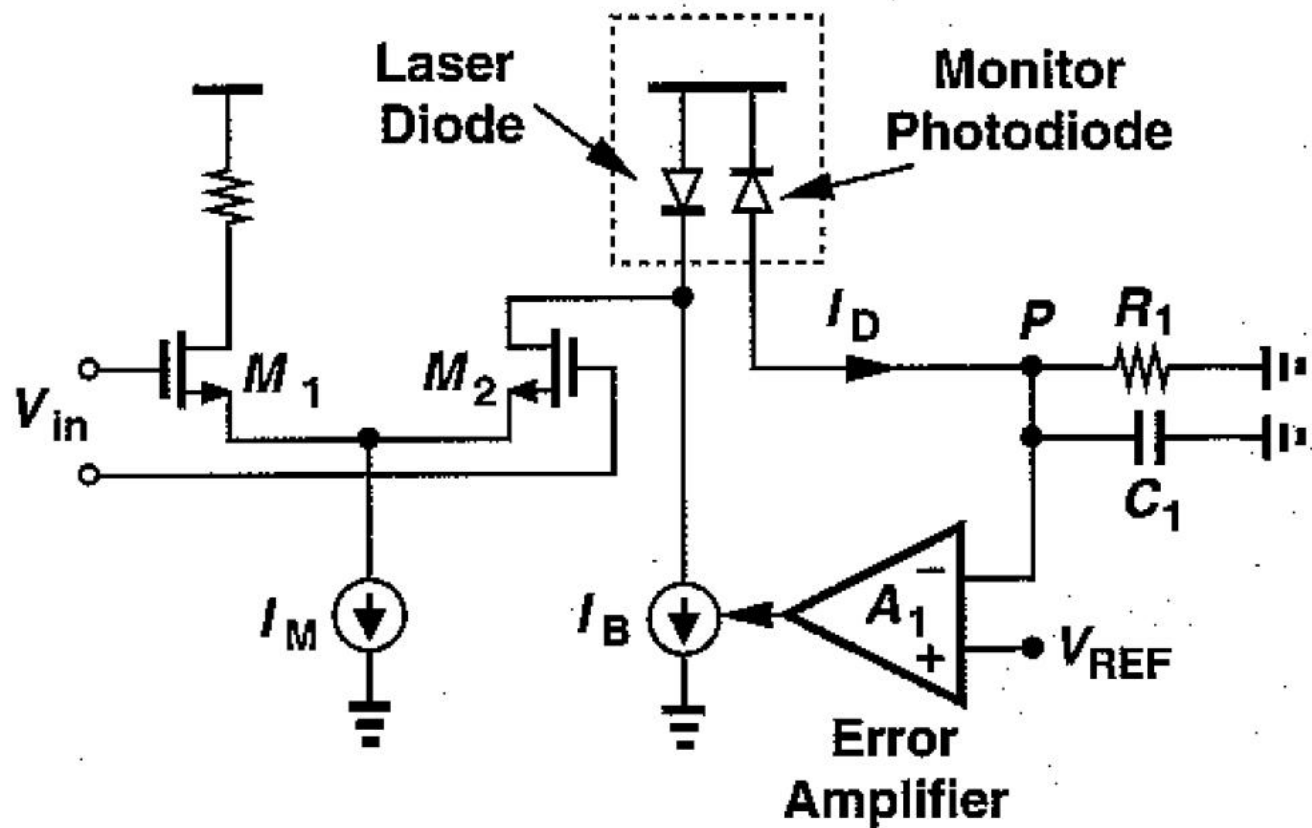
Controlul puterii in DL

- ▶ Necesara datorita variatiei curentului de “polarizare”



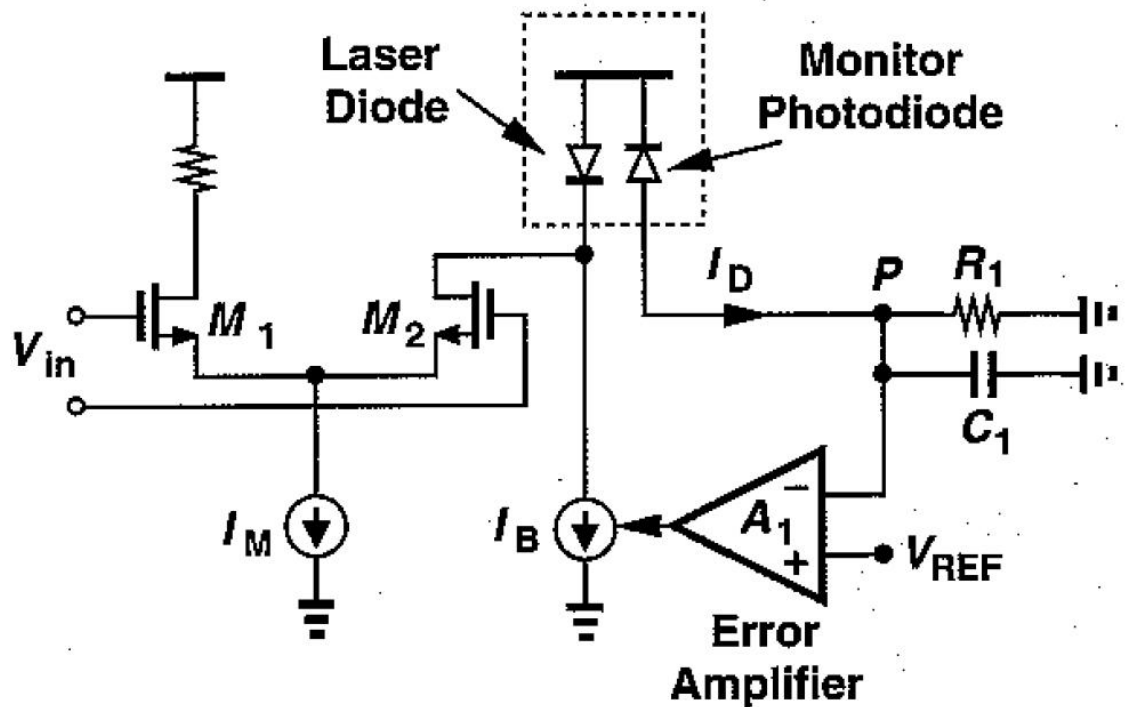
Controlul puterii in DL

- ▶ circuitul RC din schema de reglaj a curentului de polarizare realizeaza o filtrare trece sus a semnalului



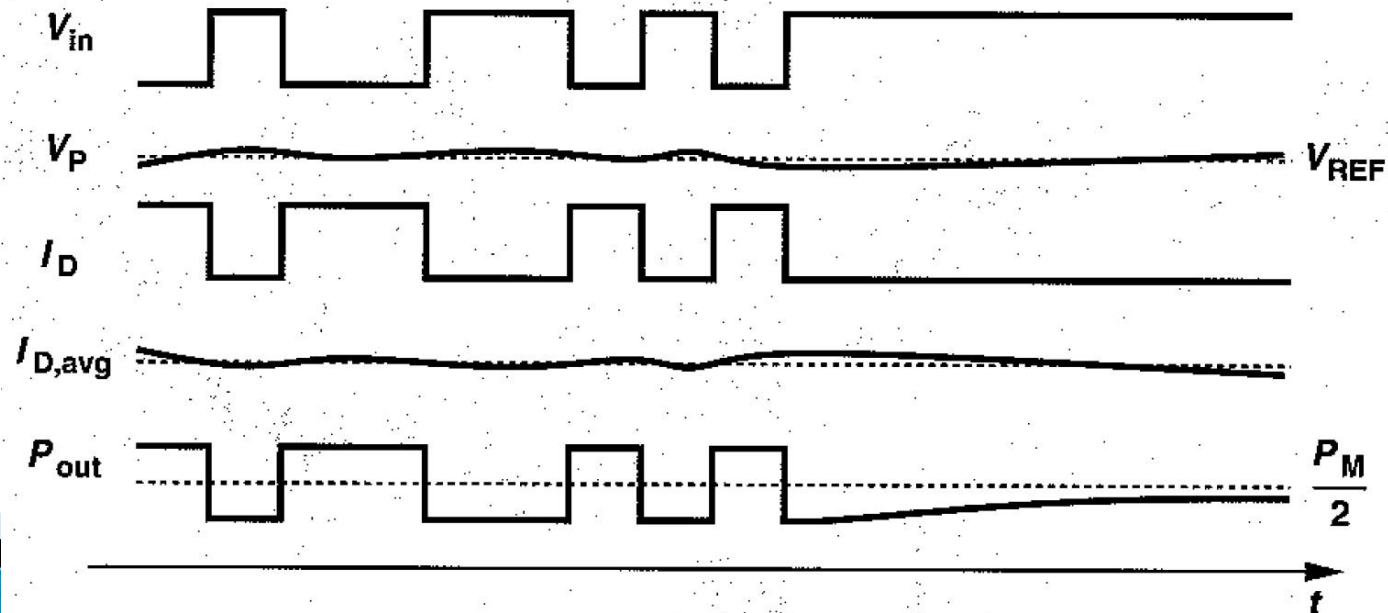
Controlul puterii in DL

- ▶ La frecvente prea mici de lucru bucla de reatie e suficient de rapida pentru a urmari si anula curentul de semnal



Controlul puterii in DL

- ▶ Bucla de reactie are efect si in cazul unei suite lungi de biti 1 transmisi
 - In acest caz, la limita curentul emis de dioda laser in starea OFF ajunge jumătate din curentul corespunzator starii ON
 - Capacitatea de filtrare din bucla trebuie aleasa mare pentru a minimiza acest efect
 - daca valoarea e prea ridicata e necesara o capacitate externa circuitului integrat



Fotodioda

Capitolul 9

Detectori optici

▶ Cerinte

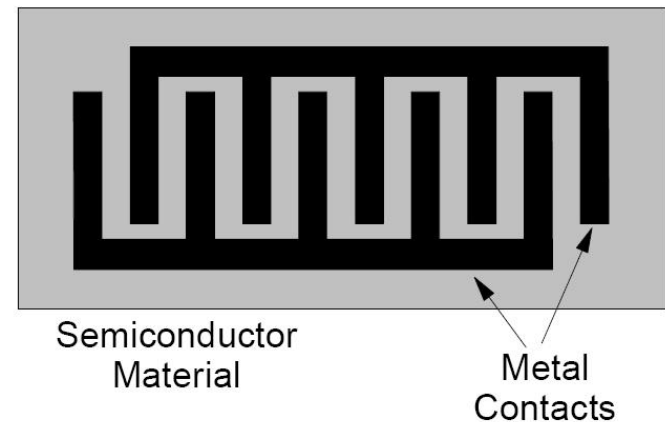
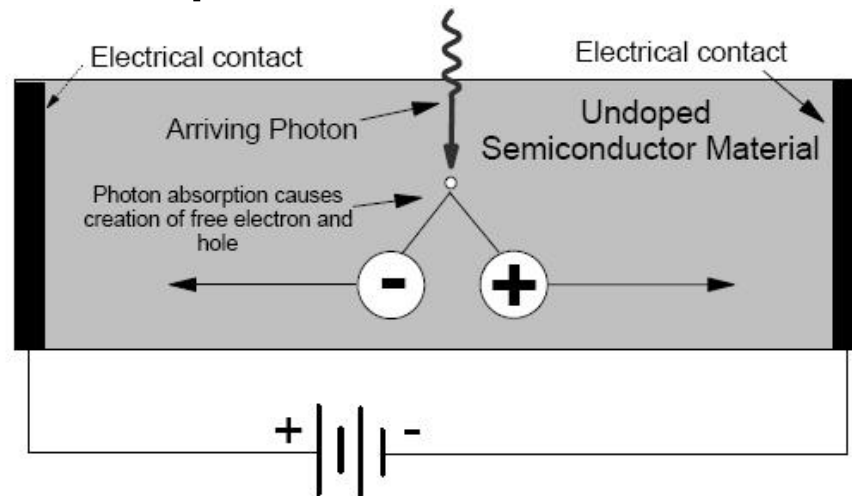
- eficienta crescuta a conversiei optic/electric
- zgomot redus
- raspuns uniform la diferite lungimi de unda
- viteza de raspuns ridicata
- liniaritate

▶ Principii de operare

- fotoconductori $R = R(P_o)$
- fototranzistori $I_B = I_B(P_o)$
- fotodiode $I = I(P_o)$
 - pn
 - pin
 - pin cu multiplicare in avalansa
 - Schottky

Fotoconductor

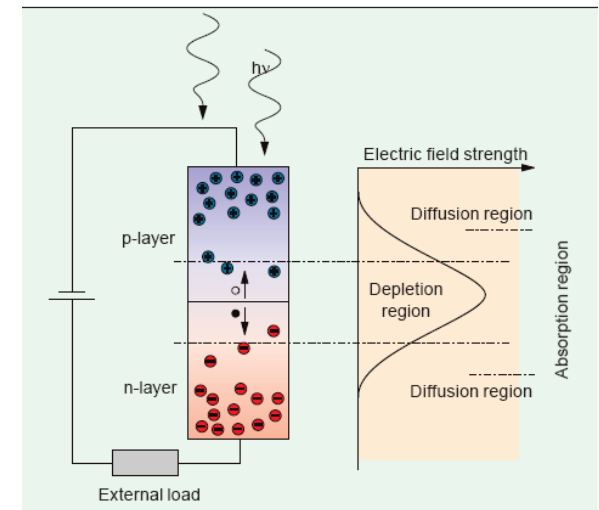
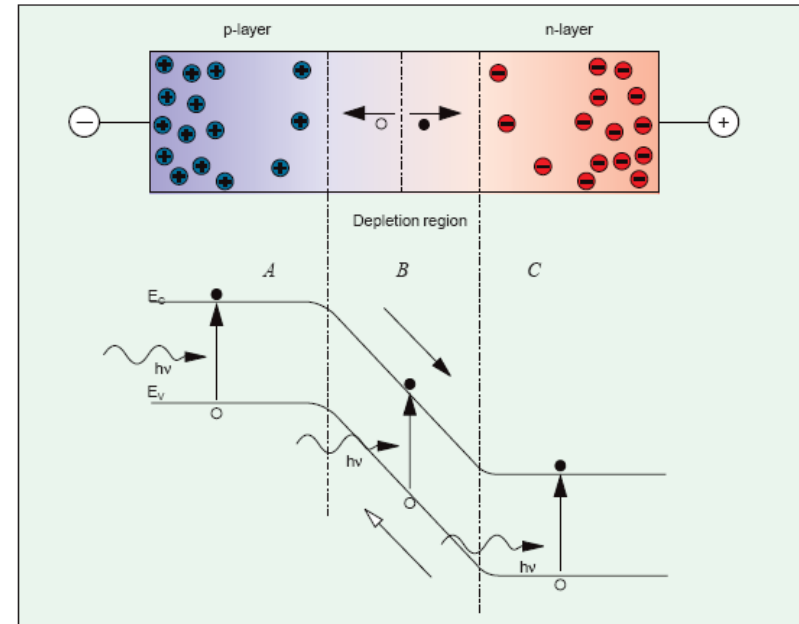
▶ Principiu



- ▶ Recent dispozitive Metal Semiconductor Metal (filtru interdigital) au inceput sa fie utilizate pentru usurinta de fabricare si integrare in aplicatii mai putin pretentioase

Fotodioda – Principiul de operare

- ▶ Jonctiunea pn este polarizata invers
- ▶ Lumina este absorbita in regiunea golita de purtatori, un foton absorbit generand o pereche electron-gol
- ▶ Sarcinile sunt separate de campul electric existent in regiunea golita si genereaza un curent in circuitul exterior



Fotodioda – Principiul de operare

- ▶ Energia necesara pentru eliberarea unei perechi electron gol

$$h\nu = \frac{hc}{\lambda} \geq E_g$$

- ▶ Lungime de unda de taiere

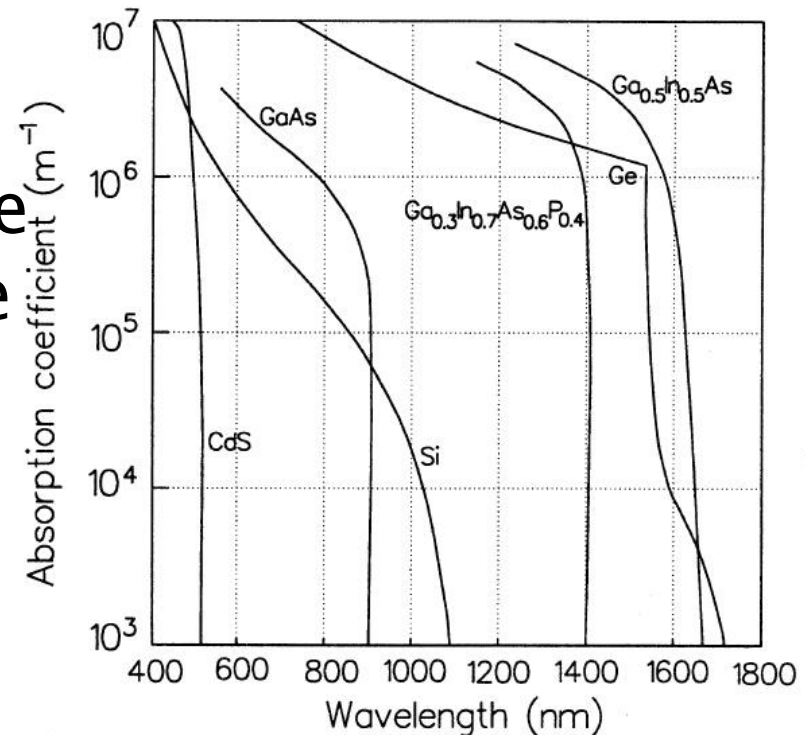
$$\lambda_{\max} = \frac{hc}{E_g}$$

- ▶ Puterea optica absorbita in zona golita de purtatori (w) aflata la o adincime d in interiorul dispozitivului

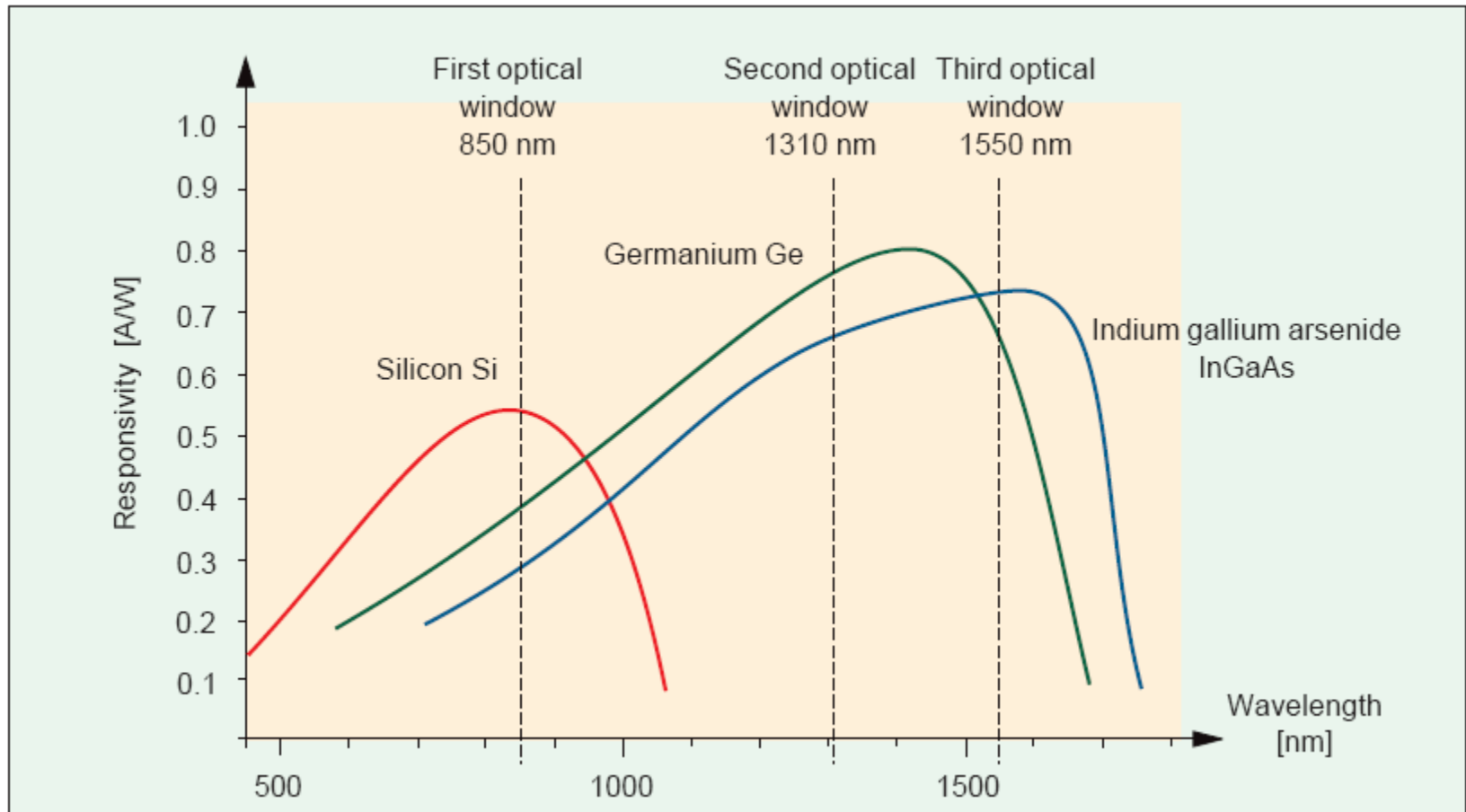
$$P(w) = P_i \cdot e^{-\alpha \cdot d} \cdot (1 - e^{-\alpha \cdot w}) \cdot (1 - R_f)$$

Fotodioda – Principiul de operare

- ▶ Coeficientul de absorbtie pentru materialele uzuale
- ▶ Valoarea mare a coeficientului de absorbtie la lungimi de unda reduse implica scaderea rezponzivitatii
- ▶ Ca urmare comportarea **tuturor** materialelor este de tip trece banda



Materiale utilizate pentru fotodiode



Fotodioda – Marimi caracteristice

- ▶ Eficienta cuantica – raportul dintre numărul de perechi electron–gol generate și numărul de fotoni incidenti

$$\eta = \frac{n_e}{n_f}$$

- ▶ In unitatea de timp numarul de fotoni depinde de puterea optica, iar numarul de electroni impune curentul generat

$$\eta = \frac{I/e}{P/h\nu}$$

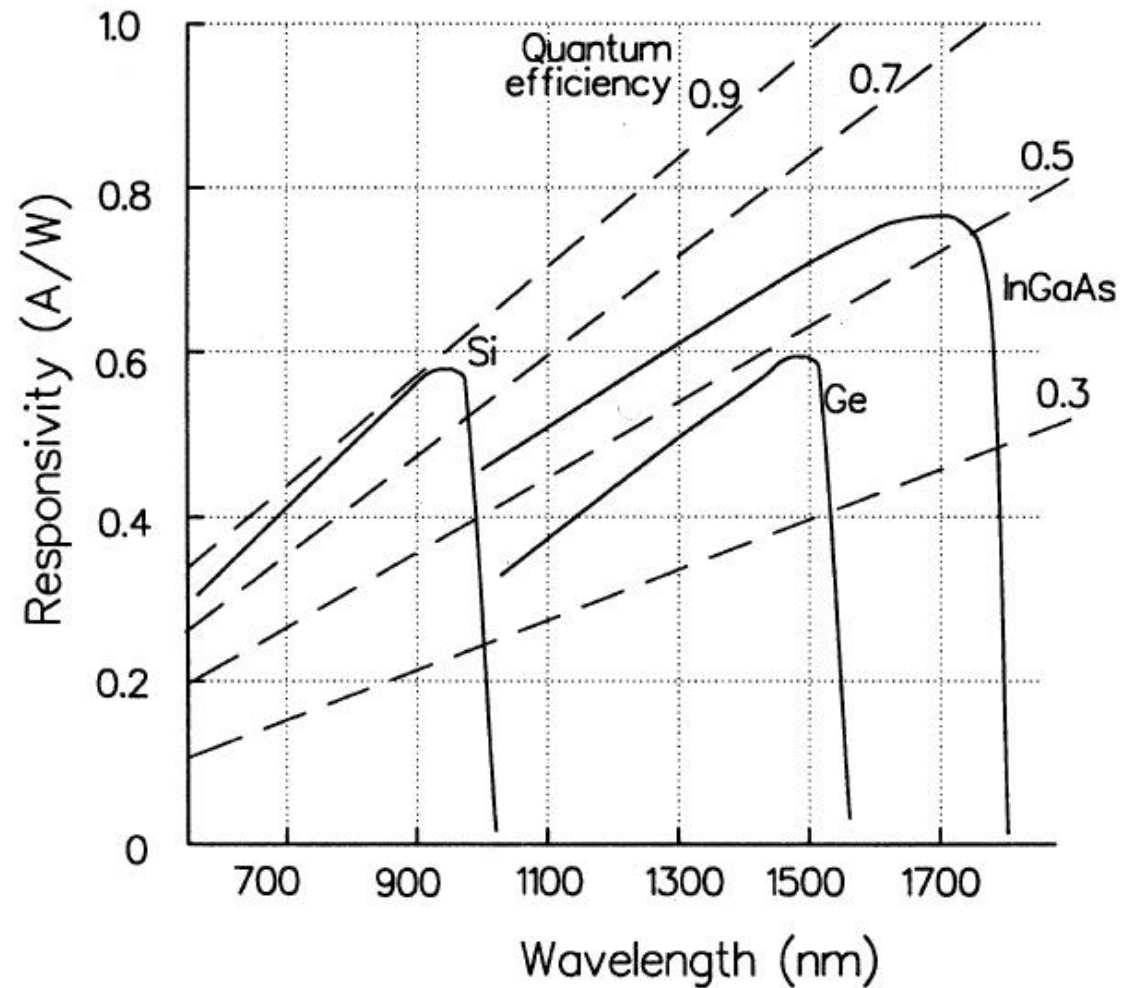
- ▶ Responzivitatea

$$R = \frac{I}{P_o} = \frac{\eta \cdot e \cdot \lambda}{hc}$$

$$R = 0.8 \cdot \eta \cdot \lambda [\mu m] \left[\frac{A}{W} \right]$$

Fotodiode - marimi karakteristik

$$R = \frac{I}{P_o} = \eta \cdot \frac{e}{hc} \cdot \lambda$$



Material utilizate pentru fotodiode

Material	λ [μm]	Responsivitate [A/W]	Viteza [ns]	Curent de intuneric
Si	0.85	0.55	3	1
Si	0.65	0.4	3	1
InGaAs	1.3–1.6	0.95	0.2	3
Ge	1.55	0.9	3	66

- ▶ Dezavantajul major pentru Ge este curentul de intuneric mare

Material	E_g (eV)
GaAs	1.43
GaSb	0.73
$\text{GaAs}_{0.88}\text{Sb}_{0.12}$	1.15
Ge	0.67
InAs	0.35
InP	1.35
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	0.75
$\text{In}_{0.14}\text{Ga}_{0.86}\text{As}$	1.15
Si	1.14

Curent de intuneric

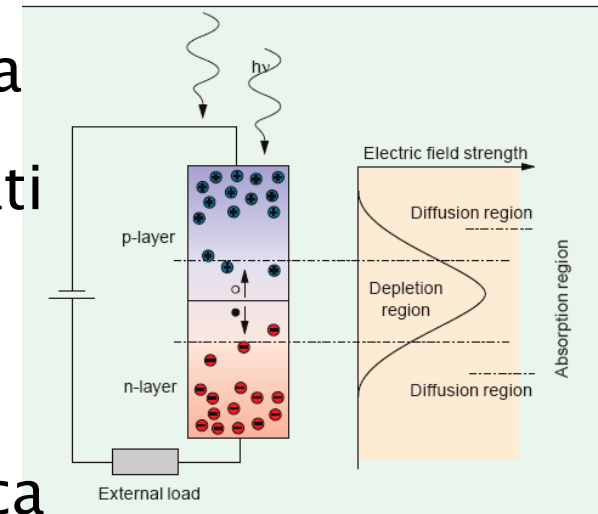
- ▶ Curentul invers al jonctiunii p-n, datorat agitatiei termice, prezent in absenta iluminarii
- ▶ Constitutie o importanta sursa de zgomot (limiteaza aplicatiile Ge)

$$I_D = I_S \approx \frac{\beta \cdot kT}{eR_0}$$

- β – coeficient de idealitate $\beta = 1 \div 2$
- R_0 – rezistenta la intuneric a diodei (invers proportionala cu aria diodei)

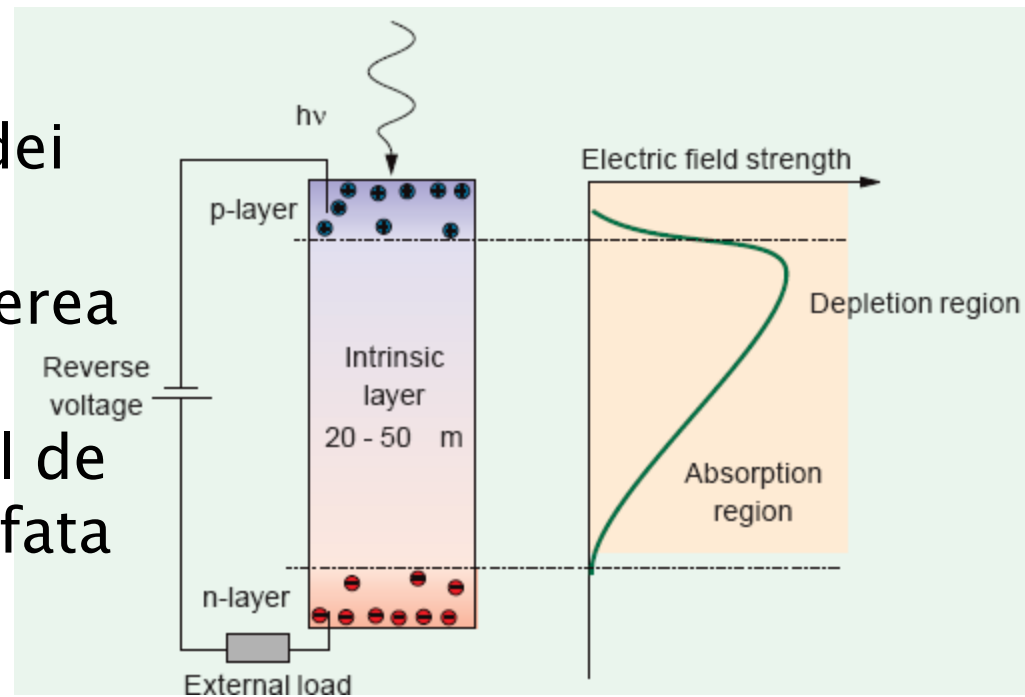
Fotodioda PIN

- ▶ Existenta campului electric in regiunea golita de purtatori face ca eventualii purtatori generati optic sa fie accelerati spre terminale pentru constituirea fotocurentului
- ▶ Problemele utilizarii diodei pn polarizate invers ca fotodetector sunt generate de adancimea extrem de mica a zonei golite (w)
- ▶ Puterea optica absorbita in interiorul acestei zone e in consecinta redusa
- ▶ Purtatorii generati inafara zonei de golire ajung eventual in zona golita si vor fi accelerati spre terminale, dar viteza fenomenului este prea redusa pentru aplicatii in comunicatii



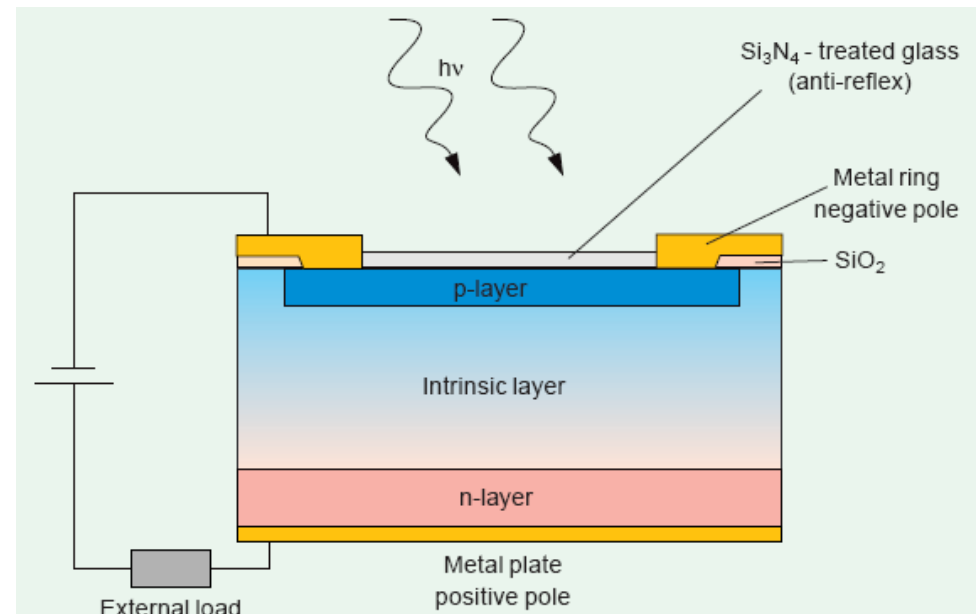
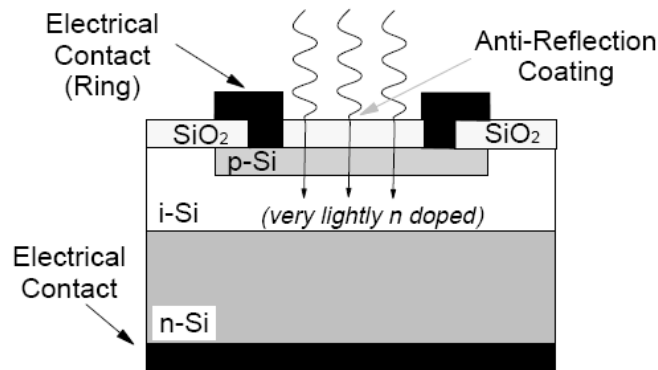
Fotodioda PIN

- ▶ Solutia consta in introducerea unui strat foarte slab dopat (intrinsec) intre cele doua zone ale diodei
 - creste volumul de absorbtie deci creste sensibilitatea fotodiodei
 - capacitatea jonctiunii scade ducand la cresterea vitezei
 - este favorizat curentul de conductie (mai rapid) fata de cel de difuzie



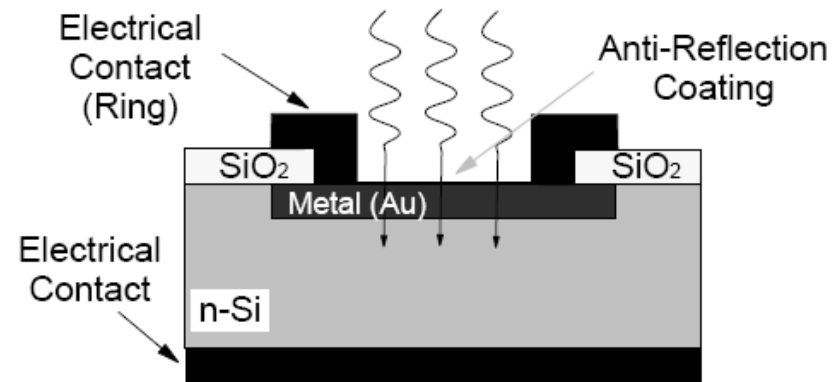
Structura fotodiodei PIN

- ▶ tipic, adancimea stratului intrinsec este de 20–50 μm
- ▶ cresterea suplimentara a adancimii ar duce la cresterea timpului de tranzit
 - $w=20\mu\text{m} \rightarrow T_{tr} \cong 0.2\text{ns}$



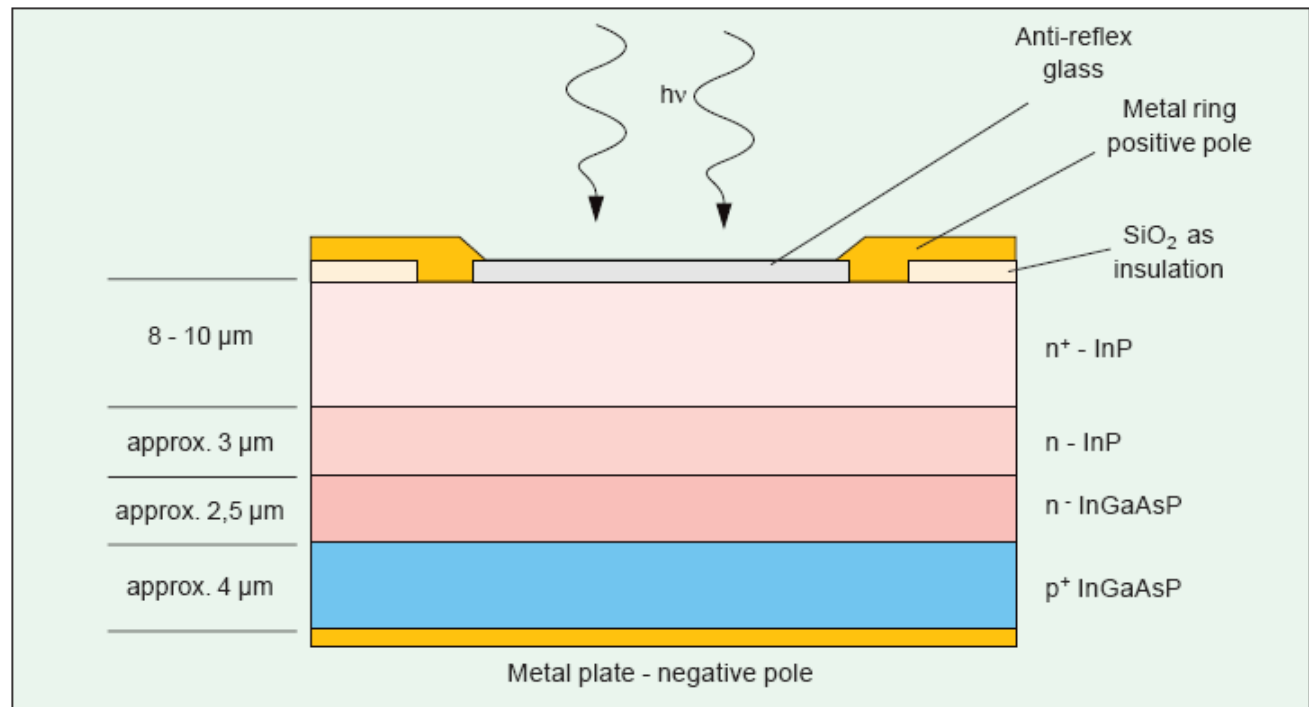
Structura fotodiodelor Schottky

- ▶ se bazeaza pe jonctiunea metal semiconductor
- ▶ vitezele de lucru sunt mult mai mari, metalul fiind un bun conductor realizeaza evacuarea mult mai rapida a purtatorilor din jonctiune
- ▶ permite utilizarea unor materiale cu eficienta mai mare dar care nu pot fi dopate simultan p si n pentru utilizare in PIN
- ▶ modulatie cu 100GHz posibila



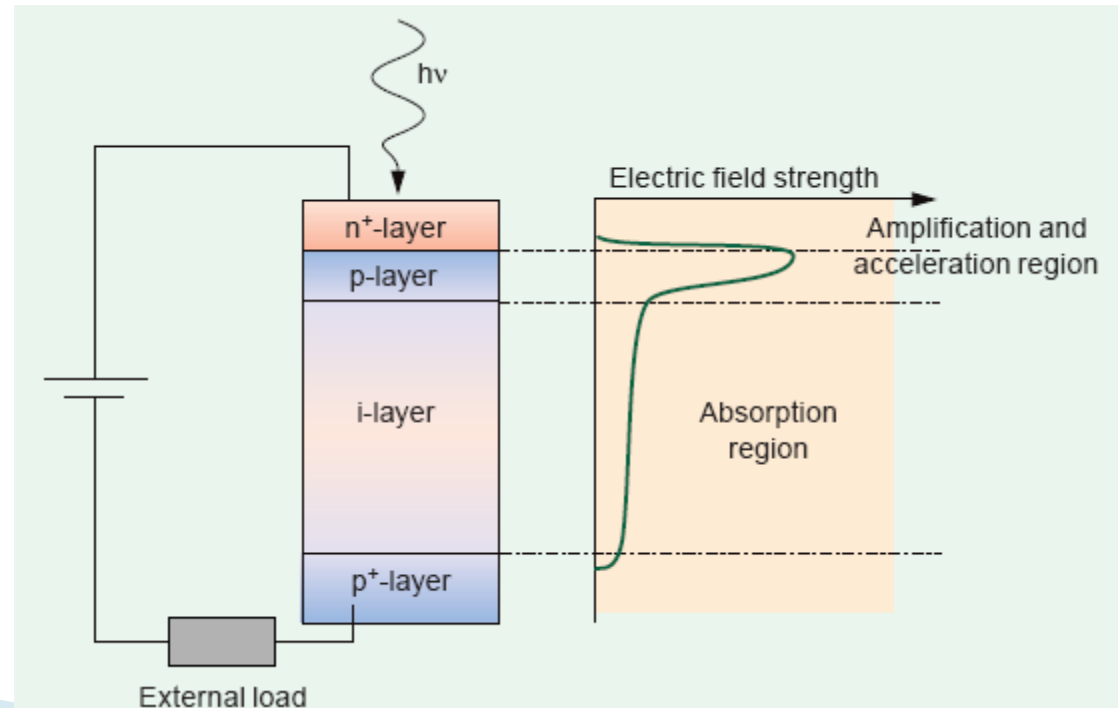
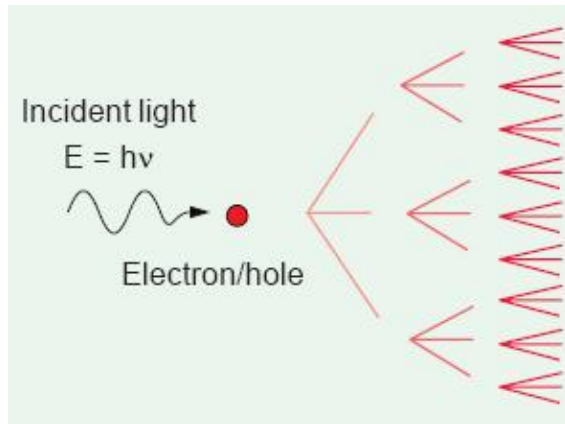
Fotodioda PIN pentru lungimi de unda crescute (1550nm)

- ▶ se utilizeaza tipic
 - InGaAsP pe substrat InP
 - GaAlAsSb pe substrat GaSb



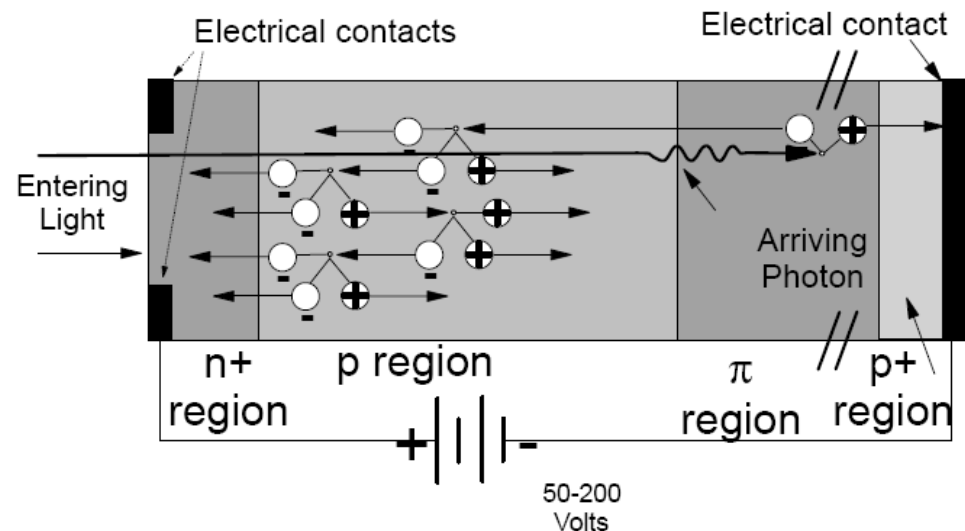
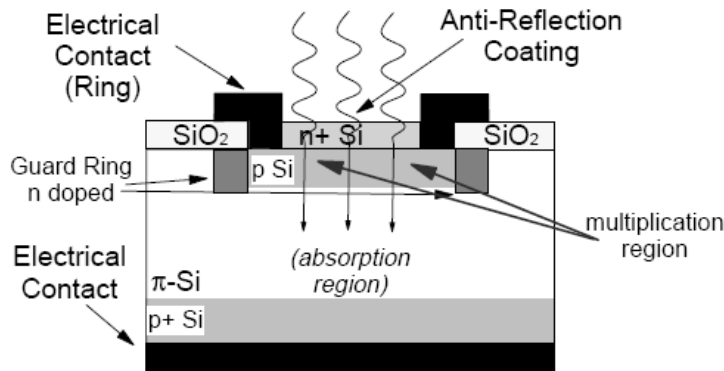
Fotodioda PIN cu multiplicare in avalansa

- ▶ daca viteza purtatorilor este suficient de mare genereaza noi perechi electron/gol prin ionizare de impact
- ▶ amplificarea are loc in acelasi timp cu detectia

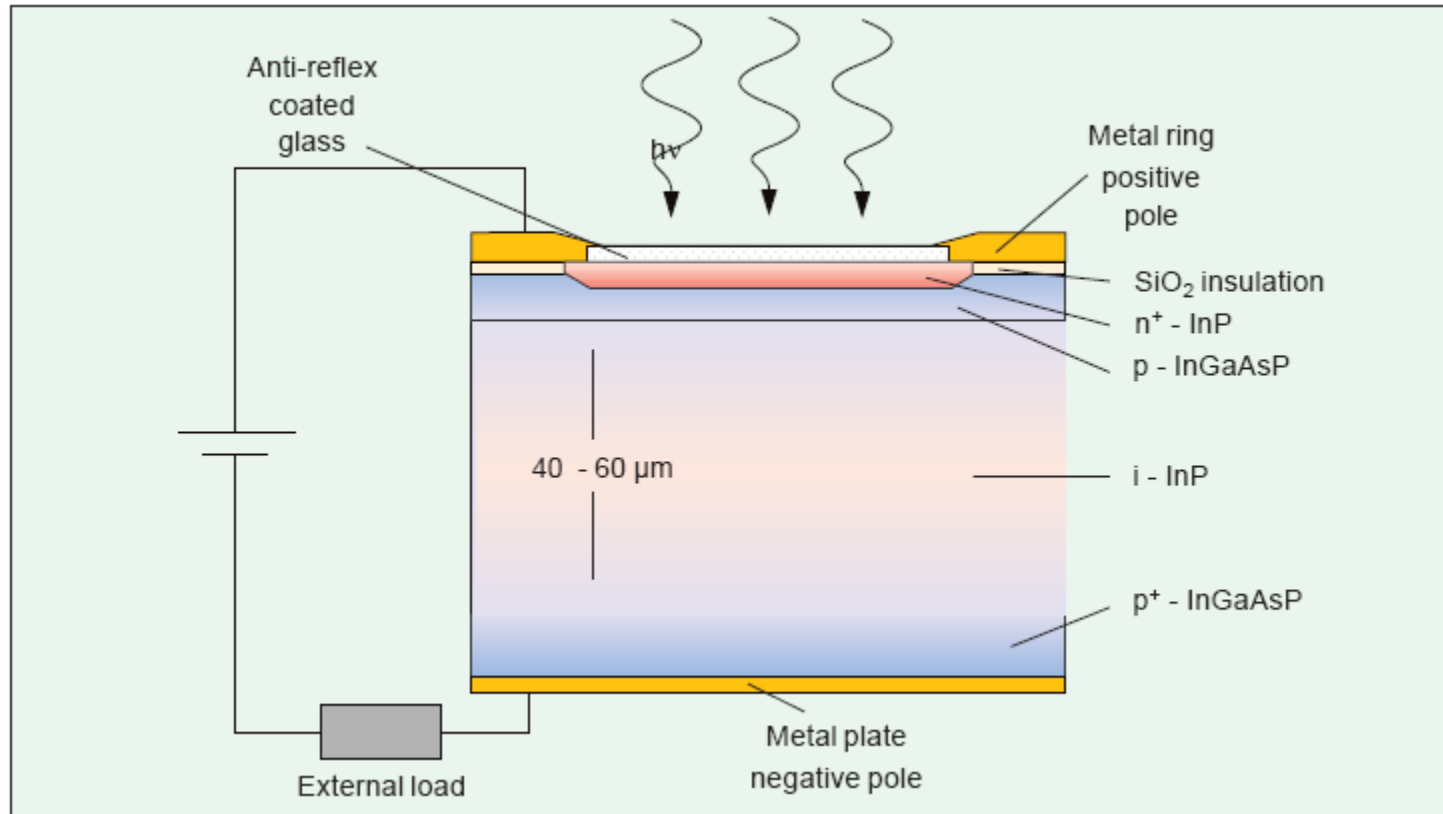


Functionarea fotodiodei cu multiplicare in avalansa

- ▶ campuri electrice de ordinul minim: 3×10^5 V/m, tipic: 10^6 V/m sunt necesare
- ▶ aceste campuri sunt generate de tensiuni inverse de polarizare de ordinul 50–300V
- ▶ structura este modificata pentru concentrarea campului in zona de accelerare



Structura fotodiodei cu multiplicare in avalansa



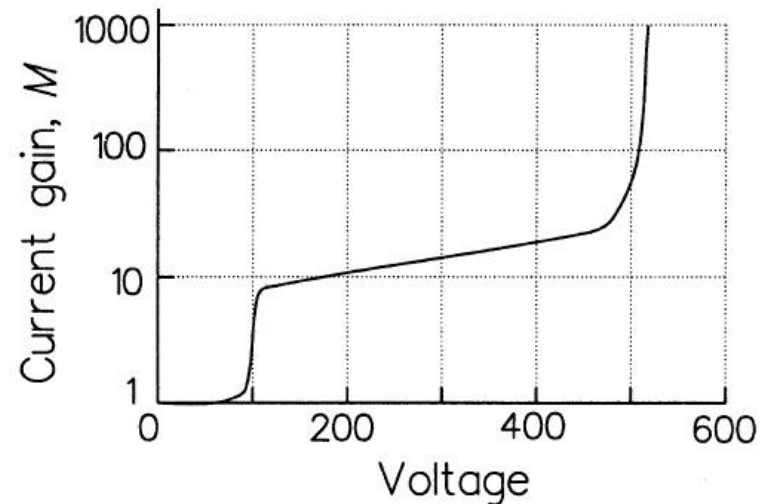
Caracteristicile fotodiodei cu multiplicare in avalansa

- ▶ factorul de multiplicare caracterizeaza amplificarea fotocurentului generat

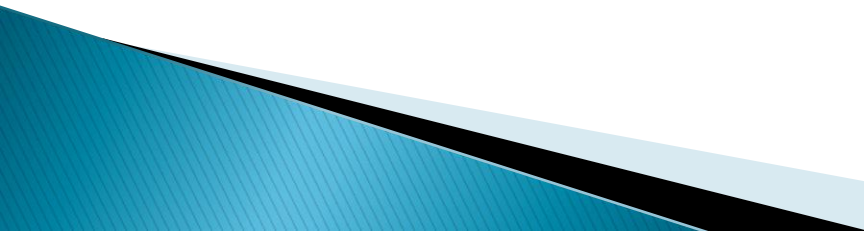
$$M = \frac{I_M}{I}$$

- ▶ Responzivitatea

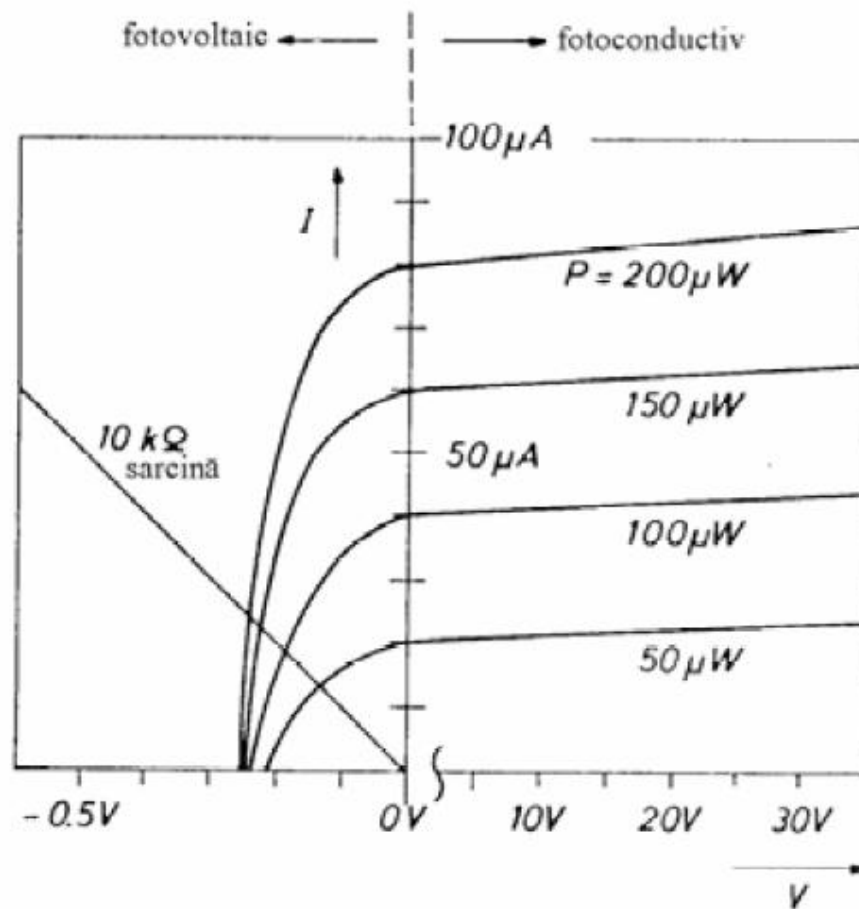
$$R = \frac{I}{P_o} = \frac{\eta \cdot e \cdot \lambda}{hc} \cdot M$$



Dezavantaje

- ▶ tensiuni inverse de polarizare mari cresc complexitatea circuitului
 - ▶ diodele cu multiplicare in avalansa sunt intrinsec mai zgomotoase (curentul de zgomot este amplificat de asemenea)
 - ▶ factorul de multiplicatie are o componenta aleatorie (zgomot suplimentar)
 - ▶ viteza mai redusa (timp de generare al avalansei)
- 

Caracteristici curenț/tensiune Fotodioda

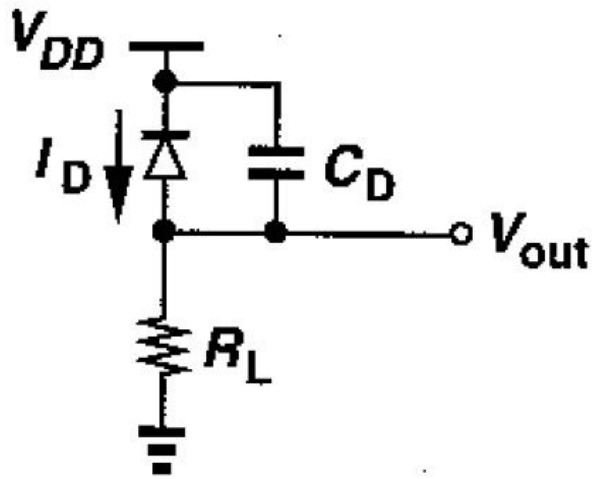


Amplificatoare transimpedanta

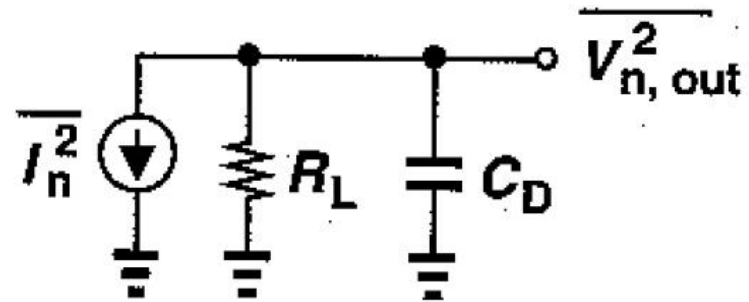
- ▶ Fotodiodele genereaza un curent proportional cu puterea optica receptionata
- ▶ Primul pas necesar este conversia acestui curent la o tensiune
- ▶ Amplificatoarele transimpedanta sunt amplificatoarele atacate in curent si care ofera la iesire o tensiune proportionala cu acesta
- ▶ Amplificarea este masurata in Ω ($k\Omega$)

Amplificatoare transimpedanta

- ▶ Cel mai simplu amplificator transimpedanta este un rezistor



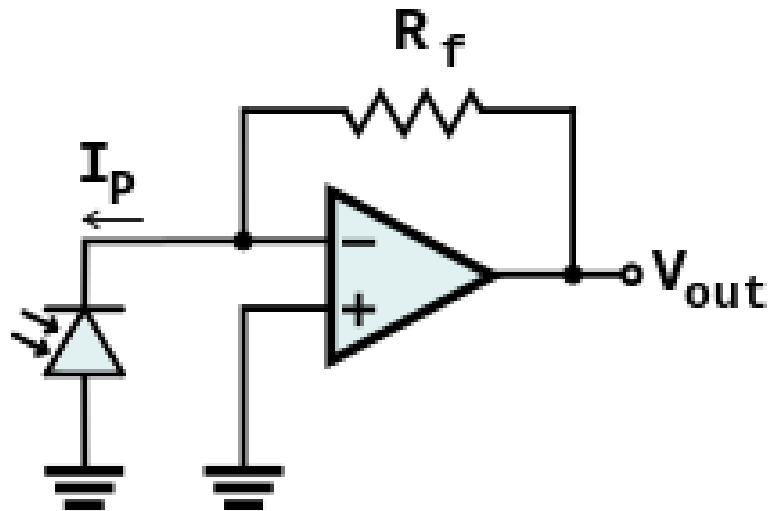
(a)



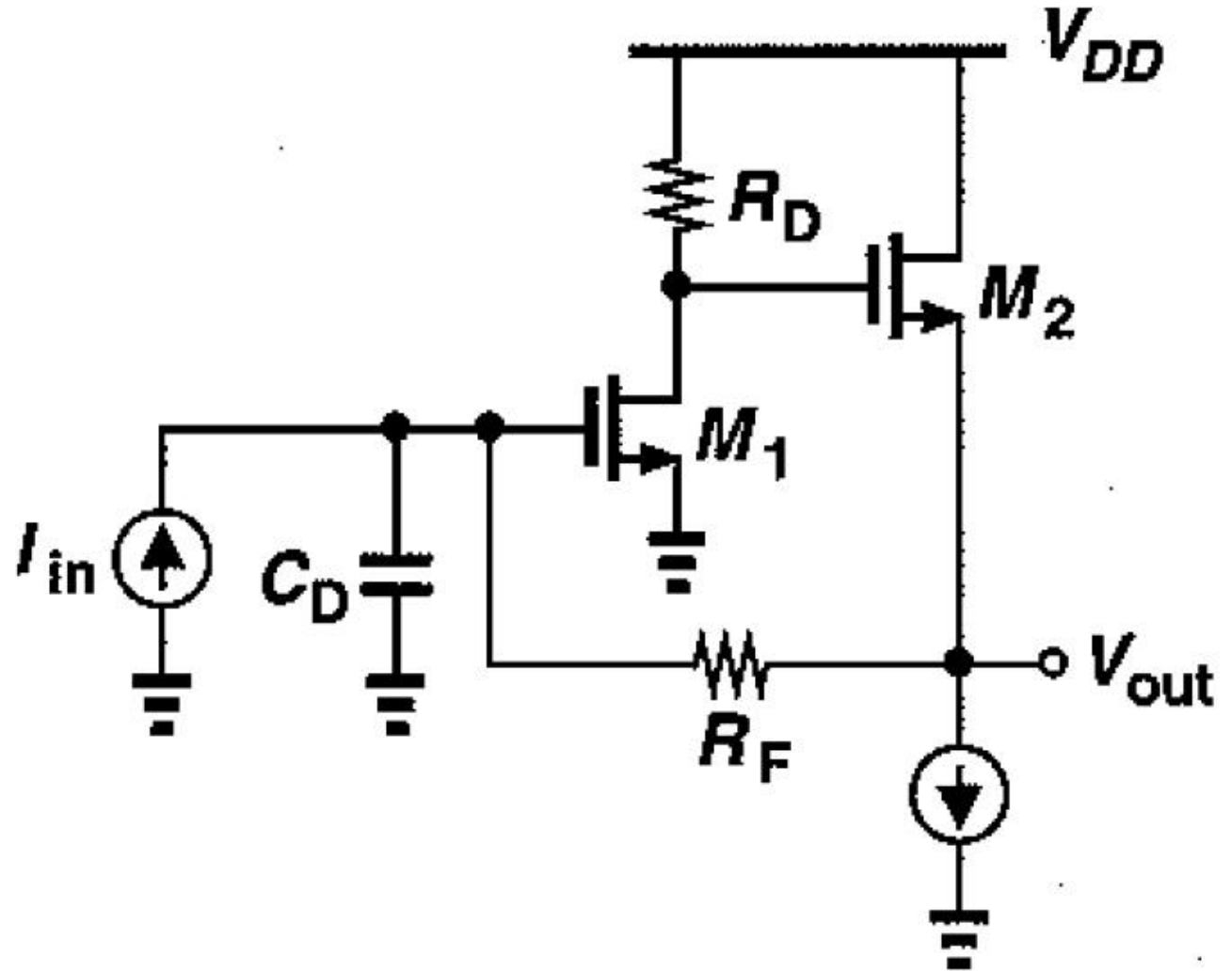
(b)

Amplificatoare transimpedanta

- ▶ Trebuie realizat un compromis intre
 - zgomot
 - castig
 - viteza
- ▶ De obicei sunt realizate cu reactie



Amplificatoare transimpedanta



Zgomotul traductorilor electro-optici

Zgomotul emitatorilor optici

▶ LED

- este considerat o sursa lipsita de zgomot
- nu contamineaza semnalul cu zgomot suplimentar

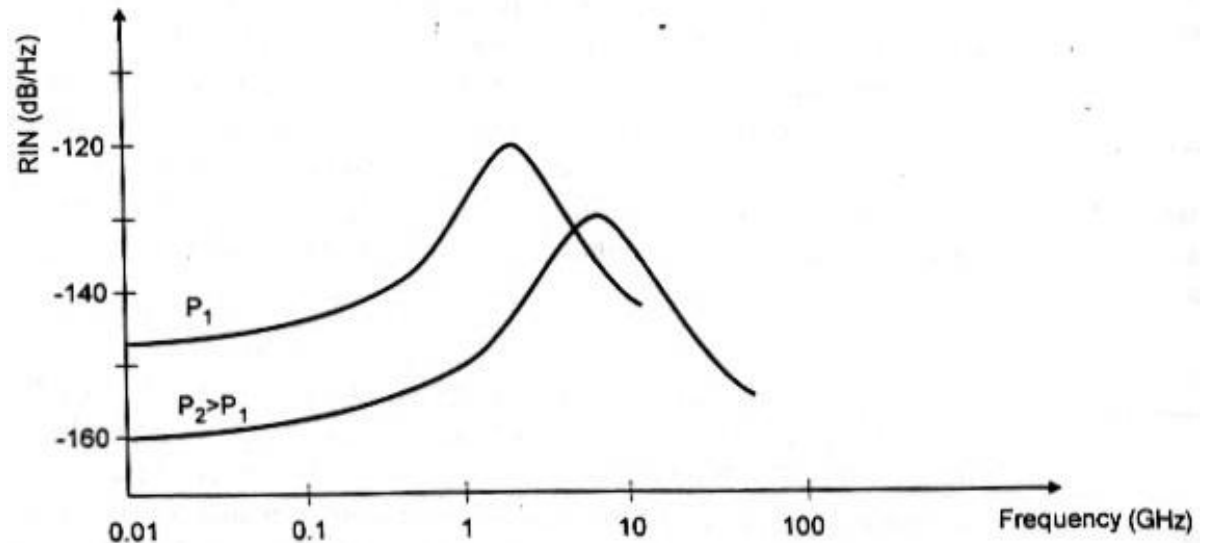
▶ Dioda LASER

- fluctuatii de faza, determina o largire a spectrului emis
- fluctuatii de intensitate, determina zgomotul de intensitate introdus de dioda
- RIN – Relative Intensity Noise

$$RIN[1/Hz] = \frac{\langle P_n^2 \rangle}{\langle P^2 \rangle \cdot BW}$$

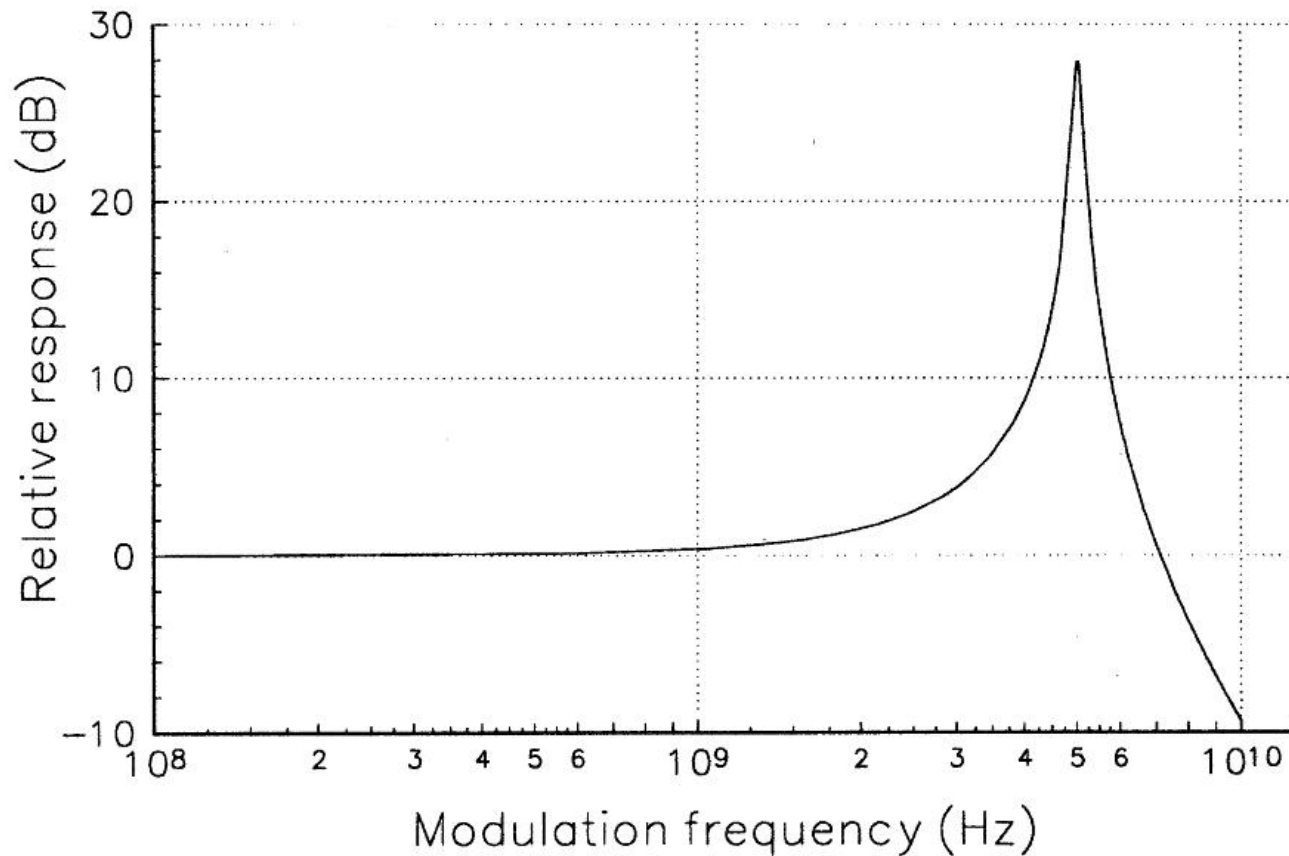
RIN

- ▶ reprezinta o densitate spectrala de zgomot
 - puterea de zgomot depinde de RIN si de banda semnalului
- ▶ Depinde de puterea semnalului
 - P^{-3} la puteri mici, P^{-1} la puteri mari



Raspunsul unei diode laser

- ▶ oscilatii de relaxare - x GHz



EIN

▶ Equivalent Input Noise

- R_i – rezistenta de intrare in circuitul de modulare a diodei
- Variatiile de putere (zgomot) echivalente unor variatii de curent (zgomot) prin dioda

$$\langle P_n^2 \rangle = r \cdot \langle I_n^2 \rangle$$

$$EIN[W] = R_i \cdot \langle I_n^2 \rangle \quad 1 \text{ Hz banda}$$

$$EIN[W / Hz] = RIN \cdot (I_0 - I_{th})^2 \cdot R_i$$

Zgomotul fotodiodei

▶ NEP

- Noise Equivalent Power
- r – rezonvizitatea diodei

$$NEP[W] = \frac{\int \sqrt{\langle i_n^2 \rangle} df}{r}$$

- r depinde de λ , implica NEP depinde de λ
- In cataloage apare de obicei densitatea spectrala

$$NEP[W / \sqrt{Hz}] = \frac{\sqrt{\langle i_n^2 \rangle}}{r} = \frac{NEP}{\sqrt{BW_{PD}}}$$

Zgomotul fotodiodei

▶ NEP

- cea mai mica putere detectabila

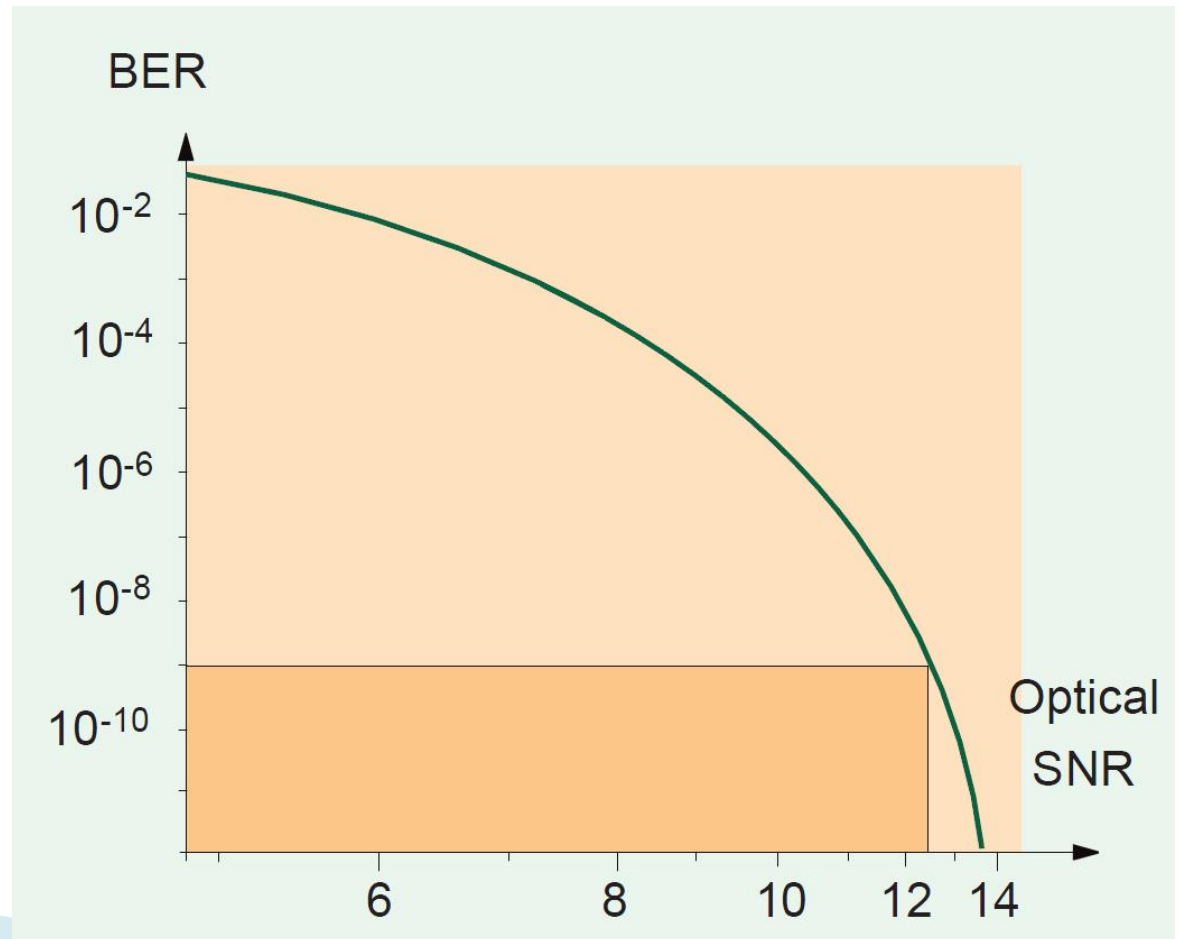
$$\langle i_n^2 \rangle = 2 \cdot e \cdot I \cdot BW_{PD} = 2 \cdot e \cdot (I_S + I_{dark}) \cdot BW_{PD}$$

$$P_{\min} = \frac{\sqrt{\langle i_n^2 \rangle_{\min}}}{r} = \frac{1}{r} \cdot \sqrt{2 \cdot e \cdot I_{dark} \cdot BW_{PD}}$$

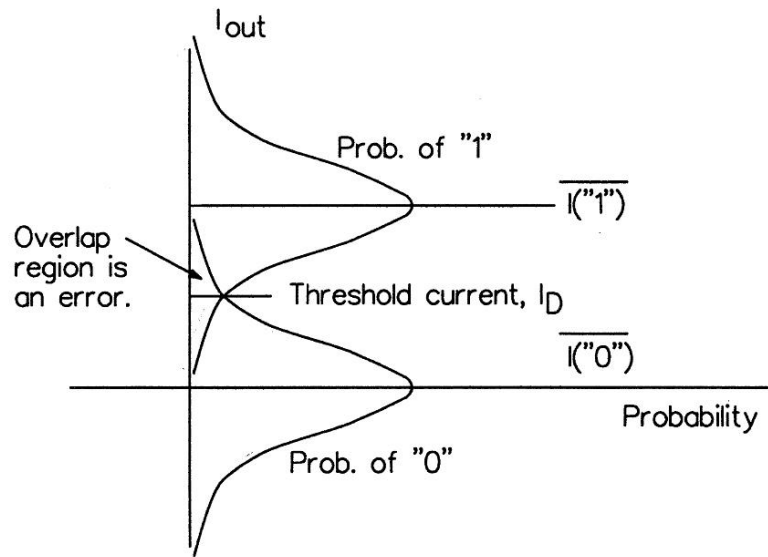
$$NEP [W / \sqrt{Hz}] = \frac{1}{r} \cdot \sqrt{2 \cdot e \cdot I_{dark}}$$

BER

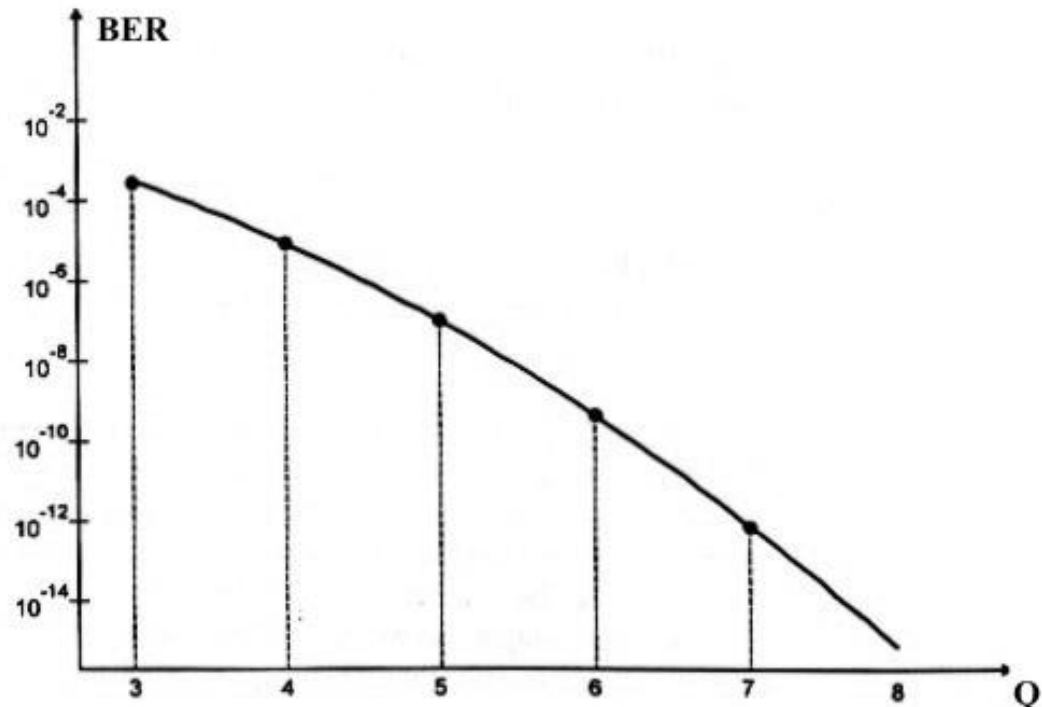
▶ Bit Error Rate



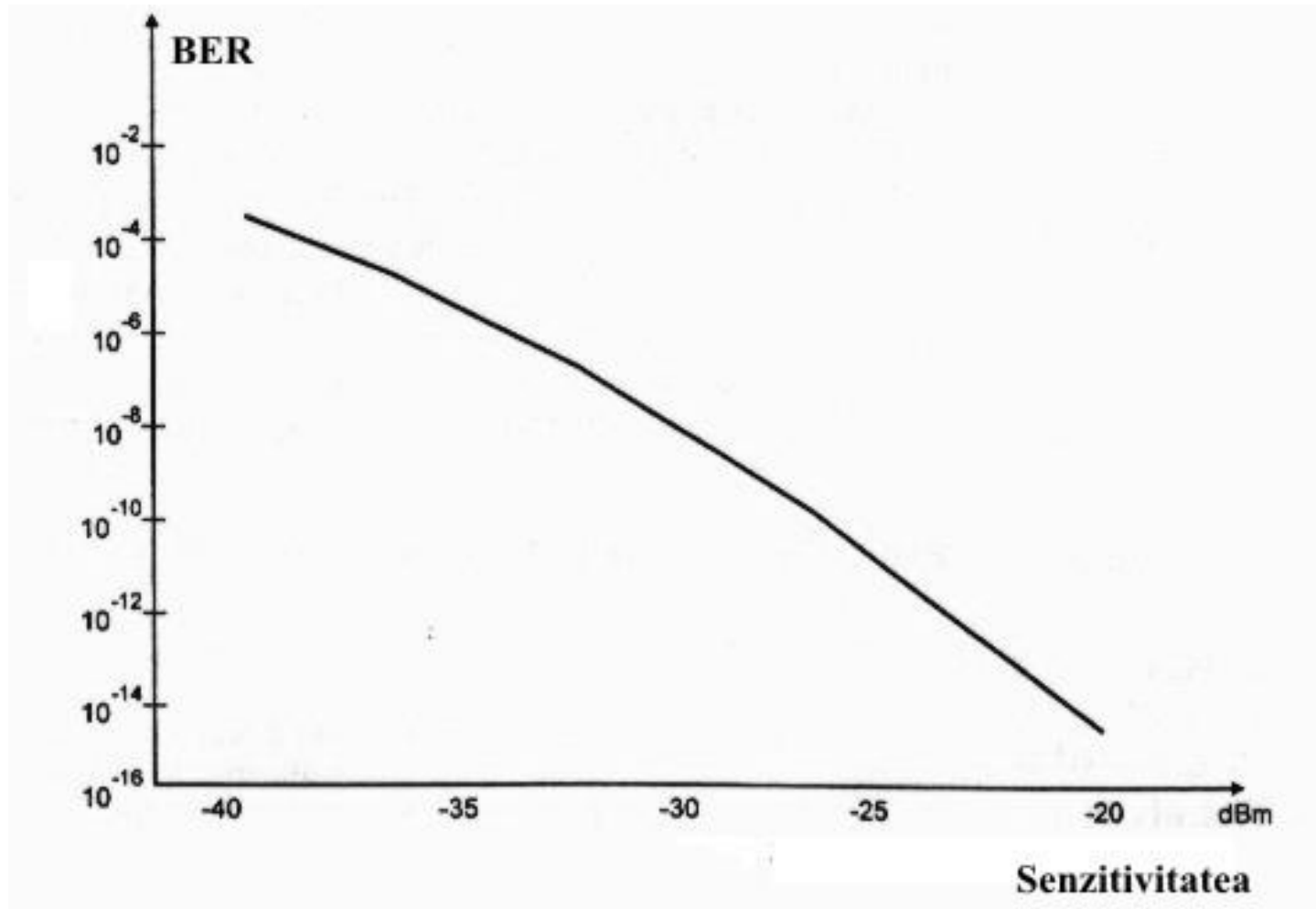
Probabilitate de eroare



$$Q = \frac{\overline{i(1)} - I_D}{\sigma_1} = \frac{I_D - \overline{i(0)}}{\sigma_0}$$



Senzitivitatea unei diode



Contact

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- ▶ rdamian@etti.tuiasi.ro