Optoelectronică

Curs 8 (s. 11-12)
2021/2022

Disciplina 2021/2022

- 2C/1L Optoelectronică OPTO
- **Minim 7 prezente curs + laborator**
- Curs – conf. Radu Damian
    - an IV μE
    - Luni 08(:10)–10:00, **P5**, ~~Microsoft Teams~~
    - E – 70% din nota (50+20), P5
        - **20% test (VP) la curs**, saptamana 6?
    - probleme + (2p prez. curs)
    - toate materialele permise
- Laborator – sl. Daniel Matasaru
    - an IV μE
        - Marti 14-18 impar/par
        - Max. 7 prezente
    - L – 30% din nota (+Caiet de laborator)

Orar 2021/2022

- Curs
  - Luni 8-10, P5, 3pz = 0.5p bonus, poate **P2**
  - ~~2C ⇨ 3C~~
    - ~~14*2/3 ≈ 9.33~~
    - ~~9÷10 C ≈ 9C + E~~

LED

Dioda electroluminescenta

Capitolul 7

Cuprins

- **Lumina ca undă electromagnetică** (ecuaţiile lui Maxwell, ecuaţia undelor, parametrii de propagare)
- **Elemente de fotometrie şi radiometrie** (mărimi energetice/luminoase)
- **Fibra optică** (realizare, principiu de funcţionare, atenuare, dispersie, banda de frecvenţă)
- **Cabluri optice** (tehnologie, conectori, lipire – splice)
- **Proiectare sistemică a legăturii pe fibra optică** (bandă de frecvenţă, balanţa puterilor)
- **Emiţătoare optice** (LED şi dioda laser – realizare fizică şi functionare)
- **Receptoare optice** (dioda PIN, dioda cu avalanşă – realizare fizică şi functionare)
- **Amplificatoare transimpedanţă** (parametri, scheme tipice, TIA în buclă deschisă, cu reacţie, diferenţiale, control automat al câştigului)
- **Realizarea circuitelor pentru controlul emiţătoarelor optice (**parametri, scheme tipice, controlul puterii, multiplexoare**)**
- **Dispozitive de captare a energiei solare** (principiu de functionare, utilizare, proiectare)

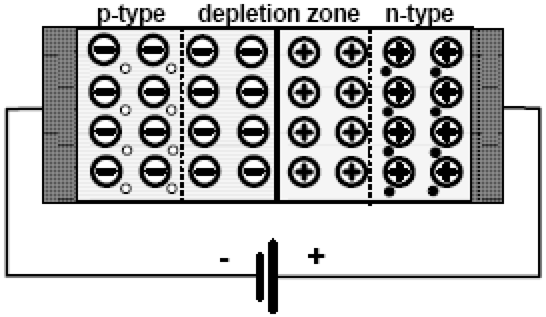
Caracteristici LED

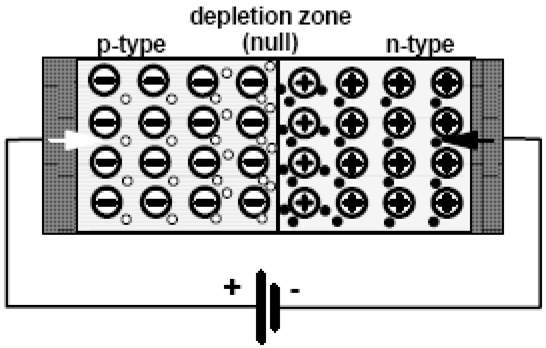
- Dezavantaje (comunicatii)
  - Putere redusa (cuplata in fibra) ~ 100µW
  - Banda (viteza) reduse ~ 150MHz (300Mb/s)
  - Spectru larg ~ 0.05 λ
  - Lumina necoerenta si nedirectiva
- Avantaje
  - Structura interna mult mai simpla (fara suprafete reflective, straturi planare)
  - Cost (dispozitiv si circuit de comanda)
  - Durata de viata
  - Insenzitivitate la temperatura
  - Liniaritate (modulatie analogica)

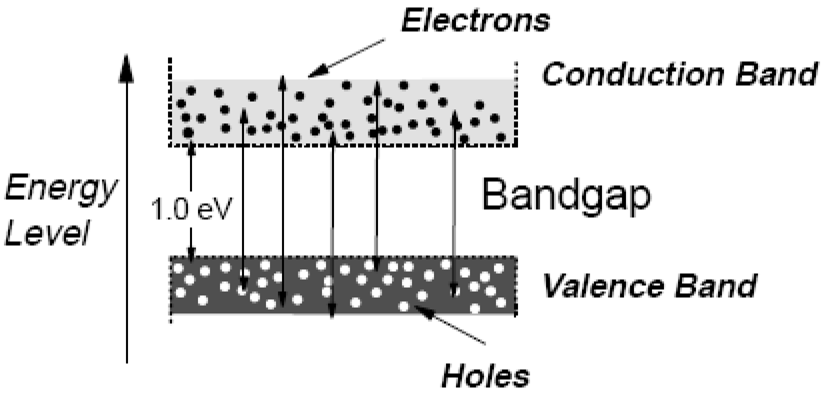
Aplicatii majore LED

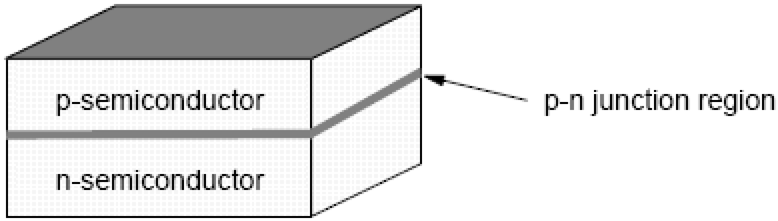
- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- Iluminare
  - Putere ridicata, lumina alba (GaInN)

LED – Principiul de operare





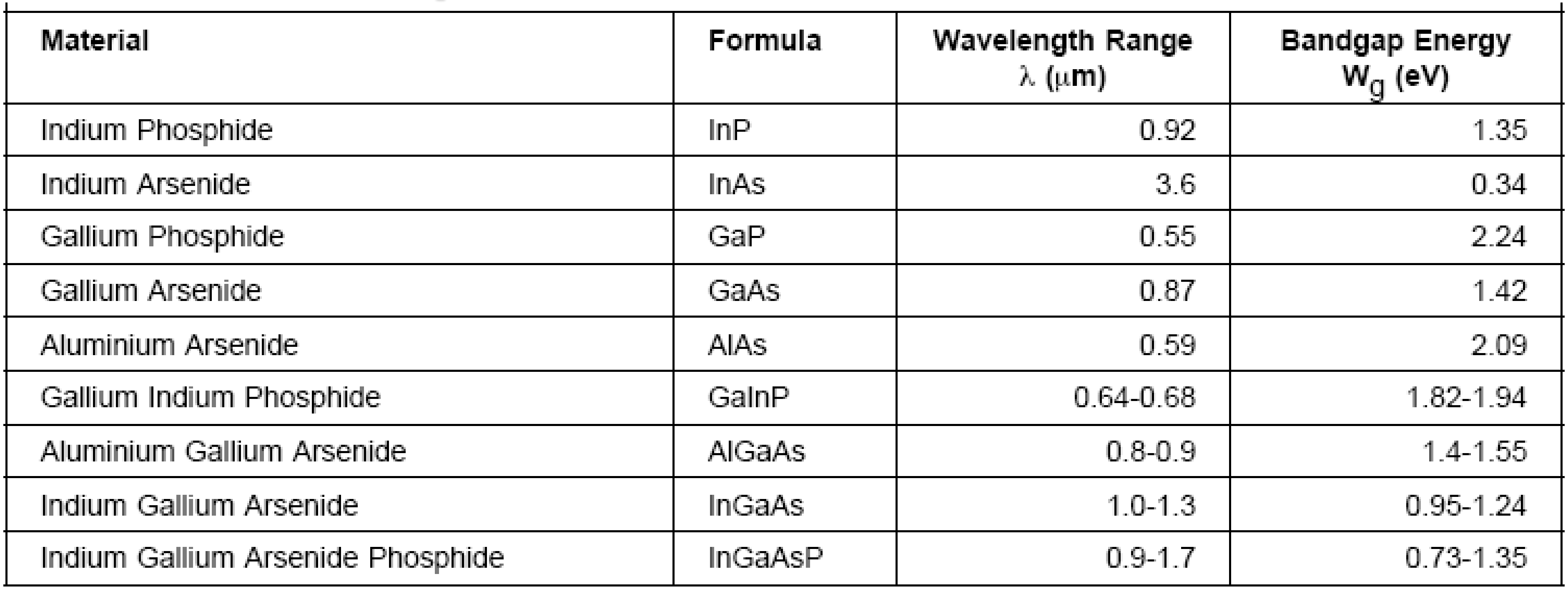




LED – Principiul de operare

- Lumina este generata de o recombinare radiativa dintre un electron si un gol
- Recombinarea neradiativa transforma energia in caldura
- Eficienta cuantica $\eta = \frac{R_r}{R_r + R_{nr}}$
- La recombinarea radiativa $E_g = h\nu; \quad \lambda = \frac{hc}{E_g}$
- Recombinare eficienta:
  - alegerea judicioasa a materialului
  - concentrarea purtatorilor in zona jonctiunii
- Lungimea de unda depinde de temperatura de functionare a dispozitivului: 0.6nm/°C

Lăţimea benzii interzise/lungime de undă pentru materialele uzuale



Material	Formula	Wavelength Range λ (μm)	Bandgap Energy W_g (eV)
Indium Phosphide	InP	0.92	1.35
Indium Arsenide	InAs	3.6	0.34
Gallium Phosphide	GaP	0.55	2.24
Gallium Arsenide	GaAs	0.87	1.42
Aluminium Arsenide	AlAs	0.59	2.09
Gallium Indium Phosphide	GaInP	0.64-0.68	1.82-1.94
Aluminium Gallium Arsenide	AlGaAs	0.8-0.9	1.4-1.55
Indium Gallium Arsenide	InGaAs	1.0-1.3	0.95-1.24
Indium Gallium Arsenide Phosphide	InGaAsP	0.9-1.7	0.73-1.35

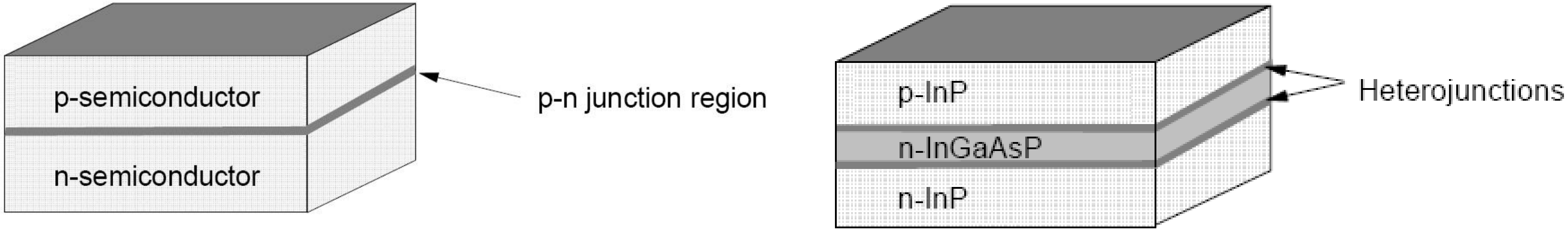
$$E_g = h\nu; \quad \lambda = \frac{hc}{E_g}; \quad \lambda[\mu\mathrm{m}] = \frac{1.240}{E_g[\mathrm{eV}]}$$

- h constanta lui Plank $6.6261 \cdot 10^{-34}$ Ws^2
- c viteza luminii **in vid** $2.998 \cdot 10^{8}$ m/s
- e sarcina electronului $1.6 \cdot 10^{-19}$ C
- benzi energetice: λ_0, **$\Delta\lambda$**

Detalii constructive – 1

- Recombinarea unei perechi electron–gol necesita conservarea "impulsului retelei" (cvasiimpuls)
  - In Si si Ge aceasta conditie presupune aparitia unui fonon intermediar (tranzitie indirecta) a carui energie se transforma in caldura
  - Majoritatea aliajelor de aluminiu Al de asemenea au tranzitie indirecta
- Se utilizeaza aliaje de Ga Al As sau In Ga As P
- Materialele utilizate trebuie sa fie "transparente" la lungimile de unda emise

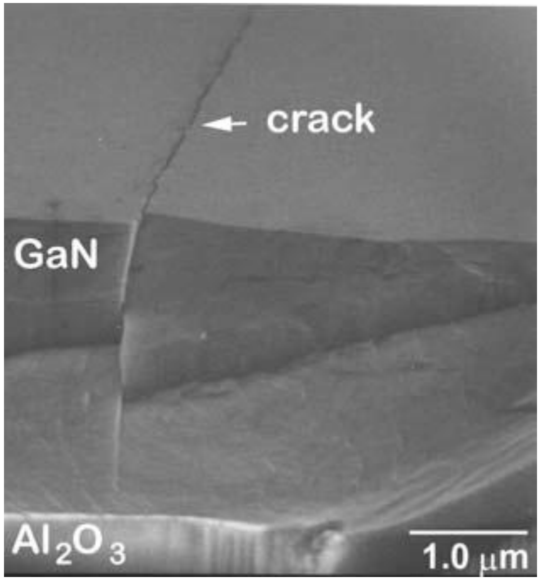
LED cu heterojuncţiuni – principiu



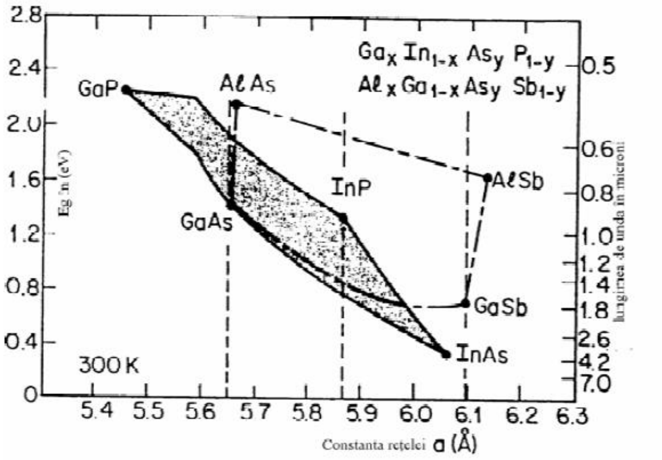
- **Orice** jonctiune p–n emite lumina
- O jonctiune p–n obisnuita este foarte subtire
  - volumul in care apar recombinari este foarte mic
  - eficienta luminoasa, redusa
- lumina este emisa in toate directiile
  - cantitatea de lumina utilizabila (intr–o anumita directie) este redusa

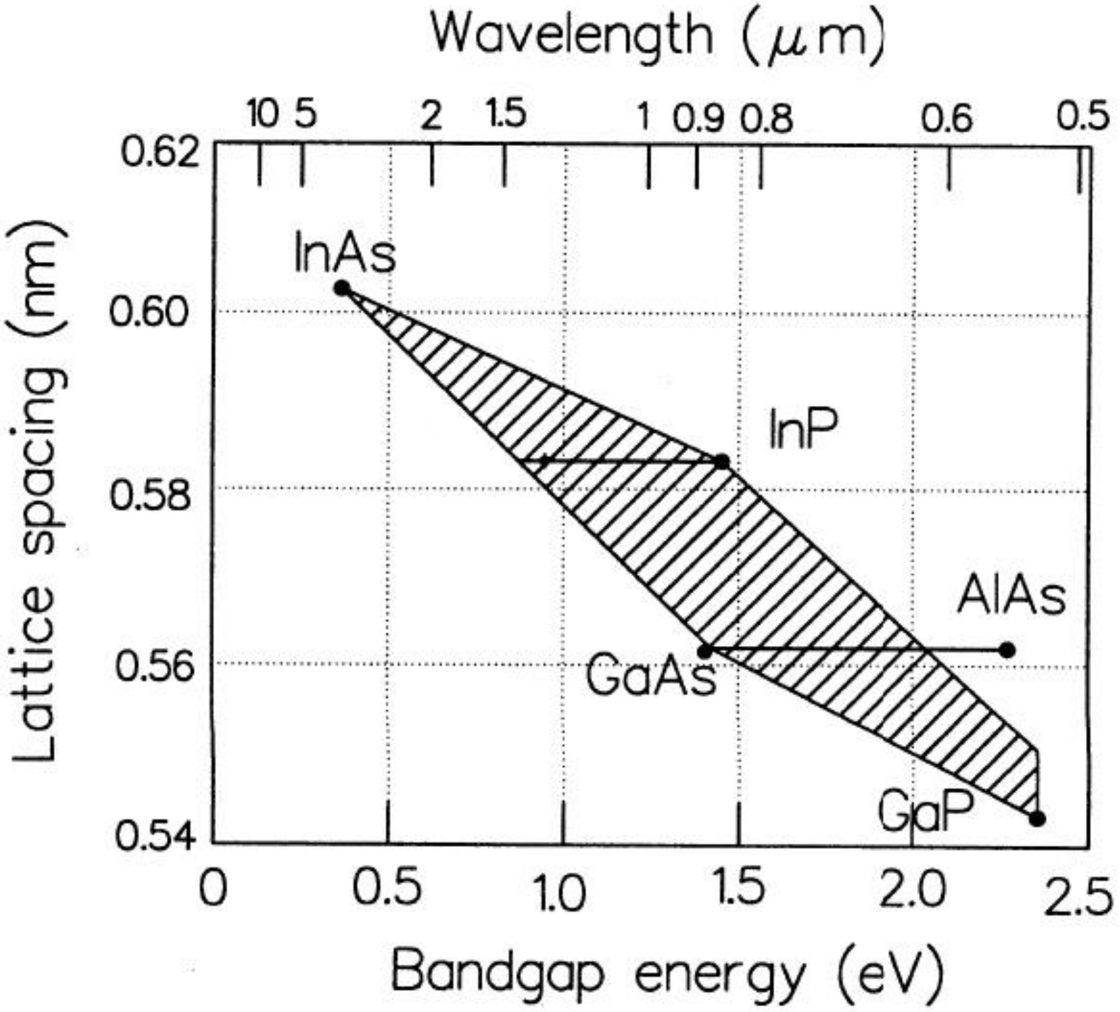
Detalii constructive – 2

- Spatierea atomilor in diferitele straturi trebuie sa fie egala (toleranta 0.1%) pentru a nu se introduce defecte mecanice la jonctiune
  - limitare a aliajelor utilizabile
  - aparitia defectelor
    - creste ineficienta (recombinari neradiative)
    - scade durata de viata a dispozitivului



Dependenţa benzii interzise de constanta reţelei



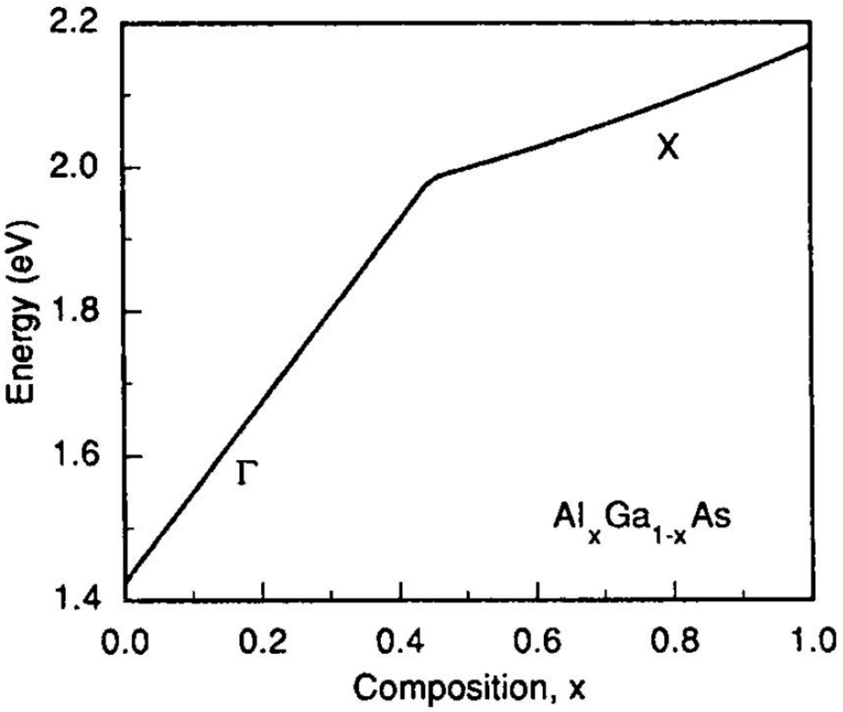


Materiale

- Lungimi de unda mici (spectru vizibil – 1000nm)
  - GaP (665nm), $GaAs_yP_{1-y}$
  - GaAs (900nm), $Ga_{1-x}Al_xAs$ (AlAs – 550nm)
- Lungimi de unda mari (1000÷1700nm)
  - $In_xGa_{1-x}As_yP_{1-y}$
  - x,y concentratii relative in aliaj a materialelor corespunzatoare
  - x,y alese din considerente privind
    - lungimea de unda
    - spatierea atomilor
- Ultraviolet – Albastru: GaInN

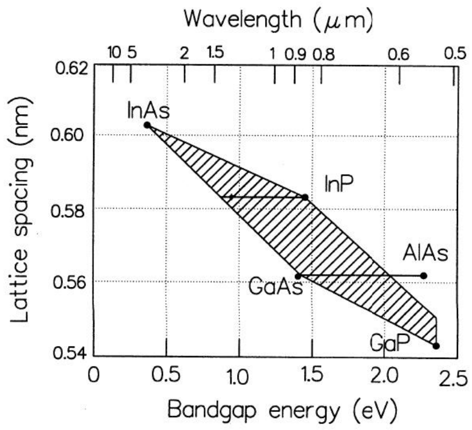
Materiale

- Lungimi de unda mici
  - $Ga_{1-x}Al_xAs$
  - substrat GaAs
  - limitare pentru tranzitie directa, x<0.45
  - E_g (in eV)



$$E_g = 1.424 + 1.247 \cdot x, \quad x < 0.45$$

$$E_g = 1.9 + 0.125 \cdot x + 0.143 \cdot x^2, \quad x > 0.45$$

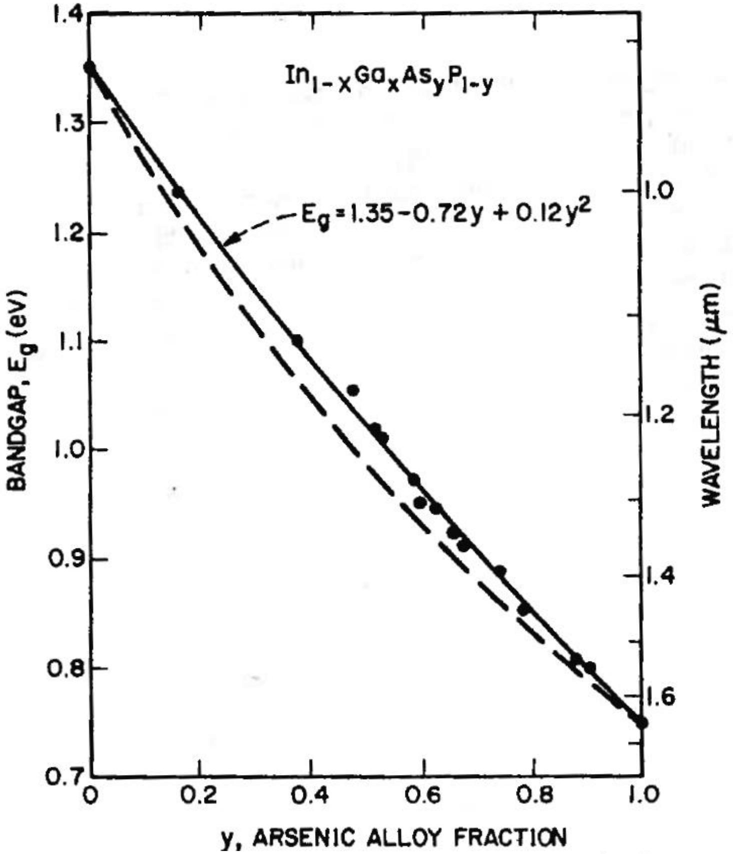


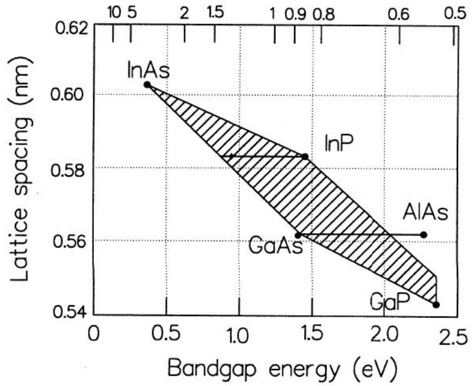
Materiale

- Lungimi de unda mari
  - $In_xGa_{1-x}As_yP_{1-y}$
  - Tipic substratul este InP
    - Spatierea atomilor (lattice spacing) corespunzatoare InP

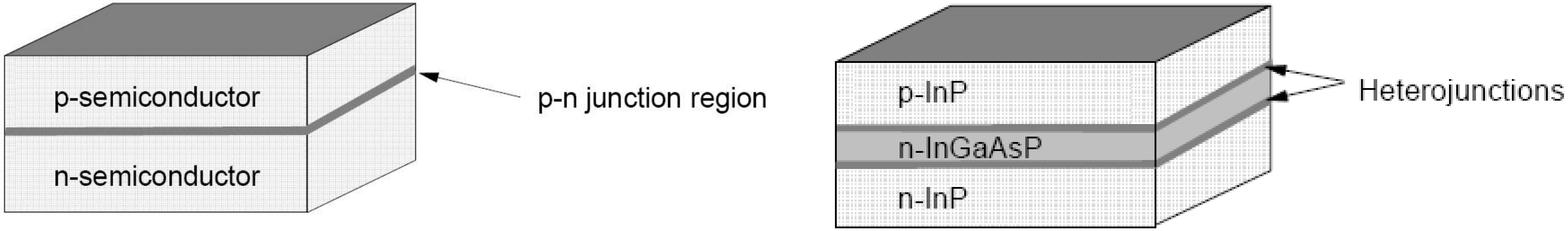
      $$x=\frac{0.4526\cdot y}{1-0.031\cdot y}$$
  - E_g (in eV)

    $$E_g = 1.35-0.72\cdot y+0.12\cdot y^2$$
  - Exemplu: 1300nm se obtine cu y=0.611 si x=0.282,
    - $In_{0.282}Ga_{0.718}As_{0.611}P_{0.389}$





LED cu heterojuncţiuni – principiu



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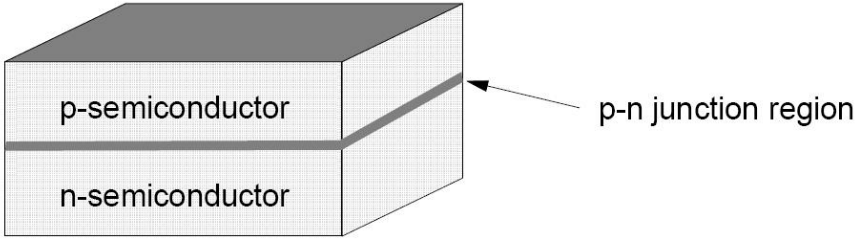
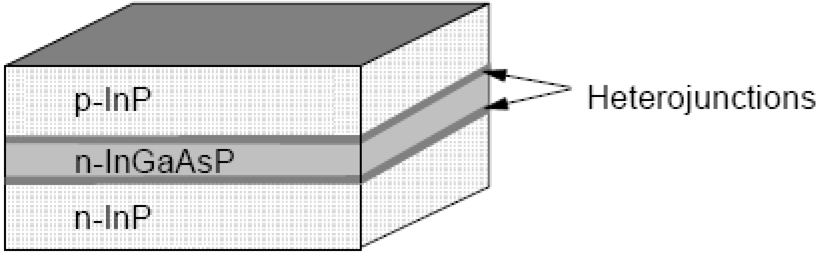
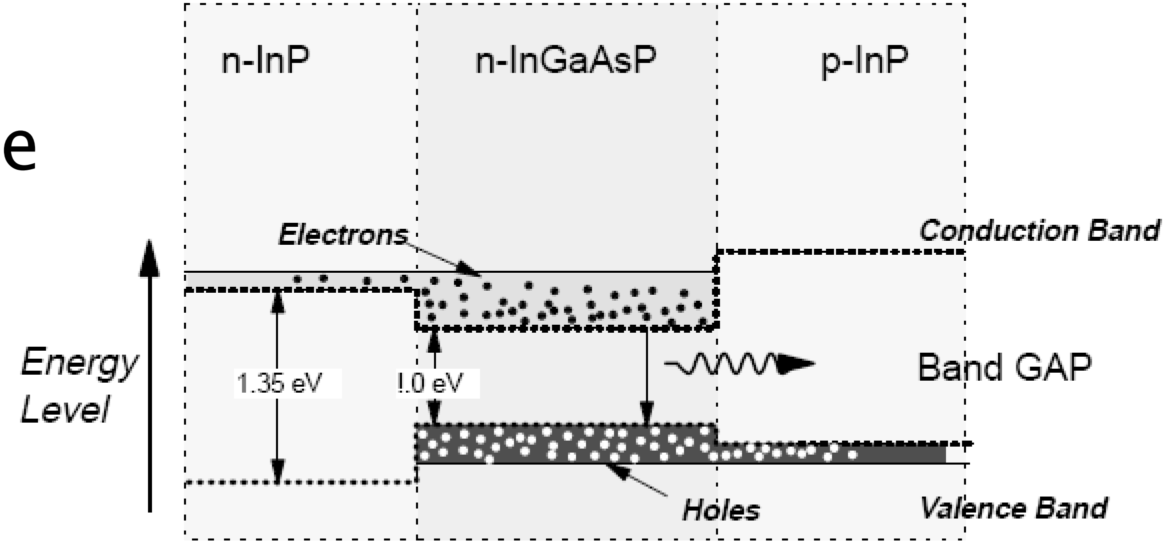
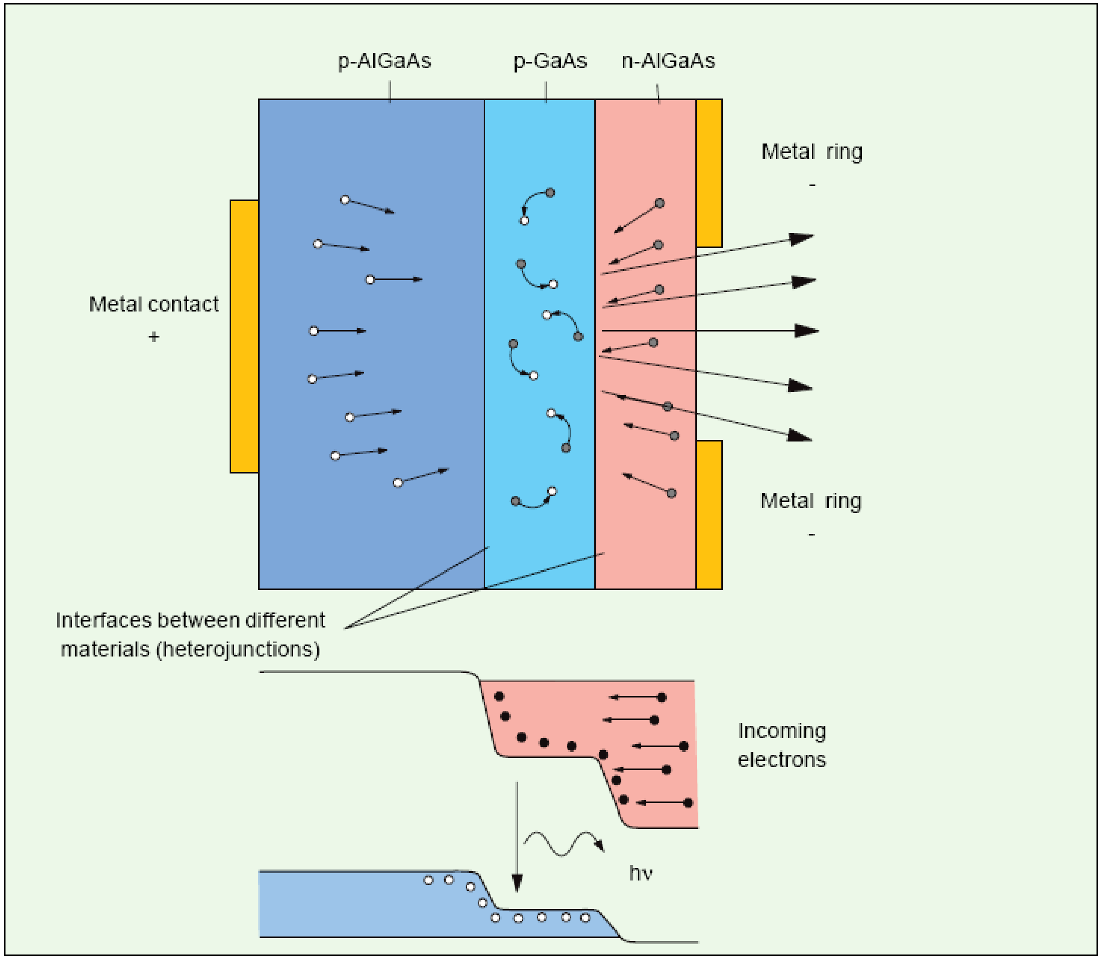




- Structura de nivele energetice permite capturarea purtatorilor intre cele doua heterojonctiuni

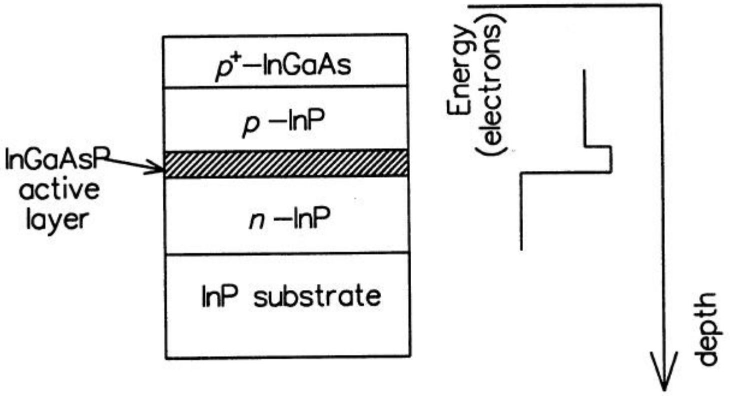


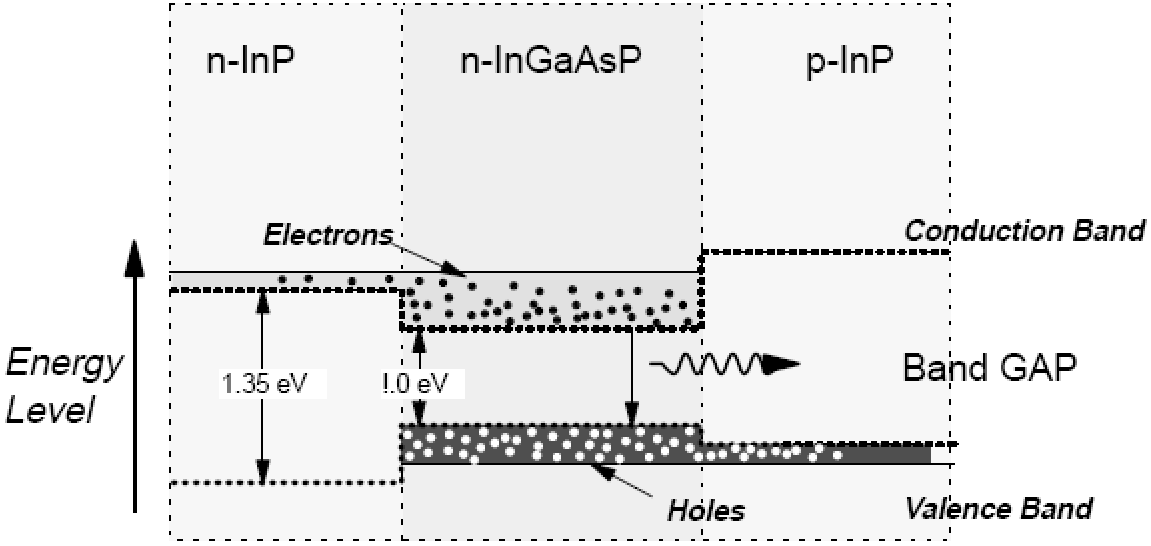
LED cu heterojuncţiuni – principiu



LED cu heterojuncţiuni – principiu

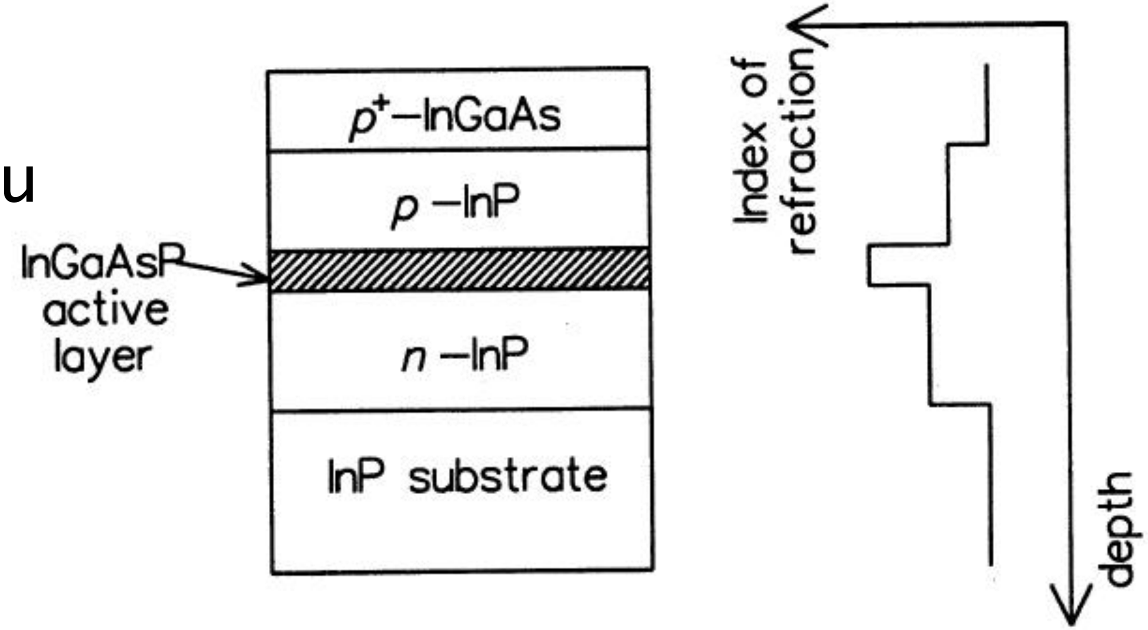
- Concentrare verticala a purtatorilor
  - Electronii sunt atrasi din zona n in zona activa
  - O bariera energetica existenta intre zona activa si zona n concentreaza electronii in zona activa
  - Situatie similara corespunzatoare golurilor
  - Purtatorii sunt concentrati in zona activa, crescand eficienta





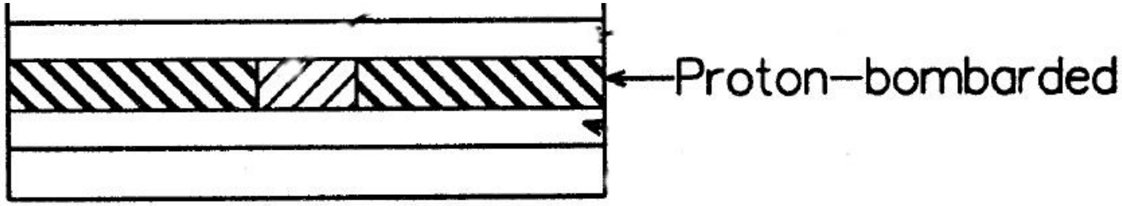
LED cu heterojuncţiuni – principiu

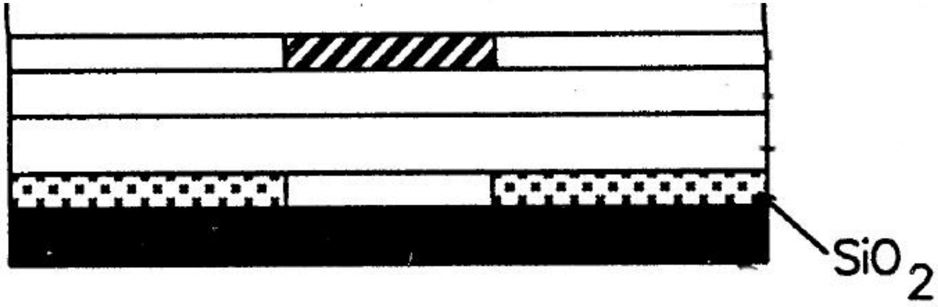
- Concentrare verticala a luminii
  - in general la diode laser (eficienta procesului LASER depinde de intensitatea luminoasa)
  - prezenta si la LED pentru cresterea eficientei luminoase: dirijarea luminii spre exterior si evitarea absorbtiei interne
- Straturile din materiale diferite au indici de refractie diferiti formand un ghid dielectric



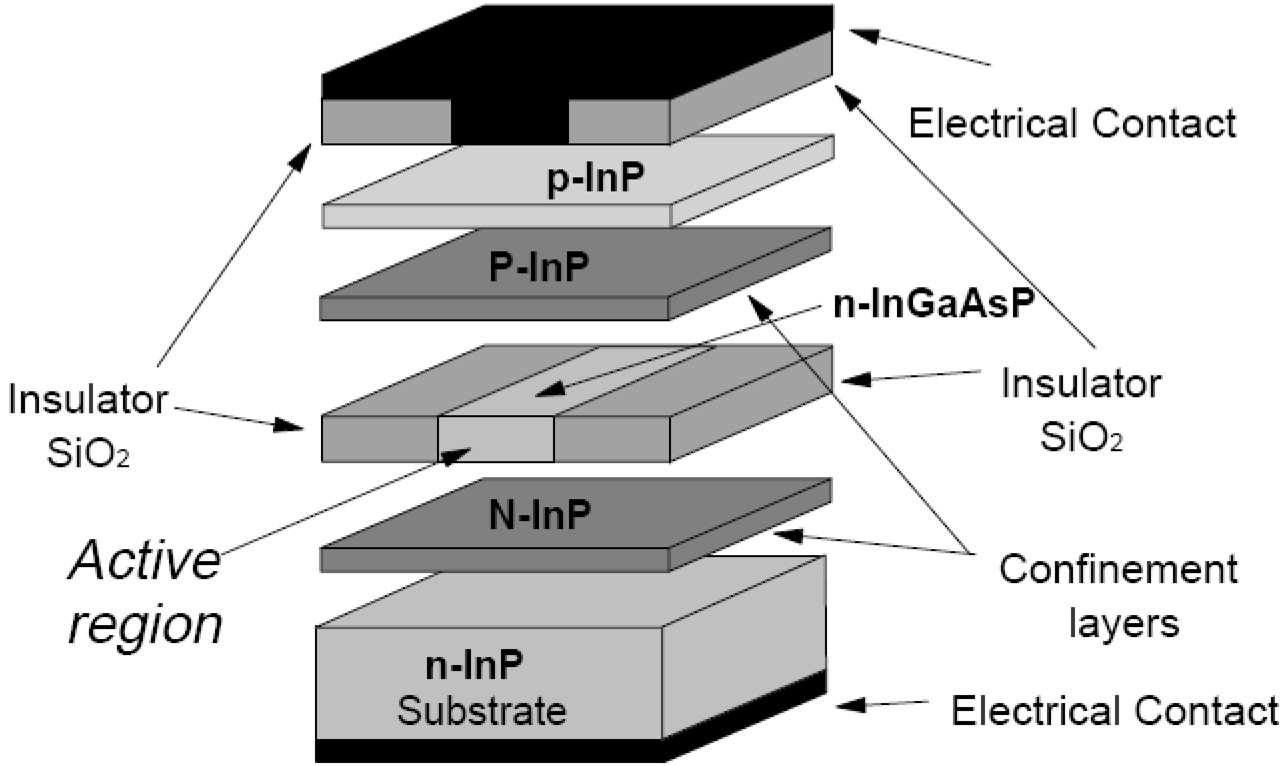
LED cu heterojuncţiuni – principiu

- Concentrare orizontala a curentului
  - Eficienta conversiei depinde de concentratia de purtatori, deci e necesara cresterea densitatii de curent in zona activa (20–50µm)
  - Se utilizeaza:
    - strat izolator (tipic SiO_2) cu o deschidere in dreptul zonei active
    - Bombardarea cu protoni a regiunii din jurul zonei active
    - Alte metode:
      - eliminarea materialului in jurul zonei active (mesa structure)
      - difuzie de Zn in zona centrala

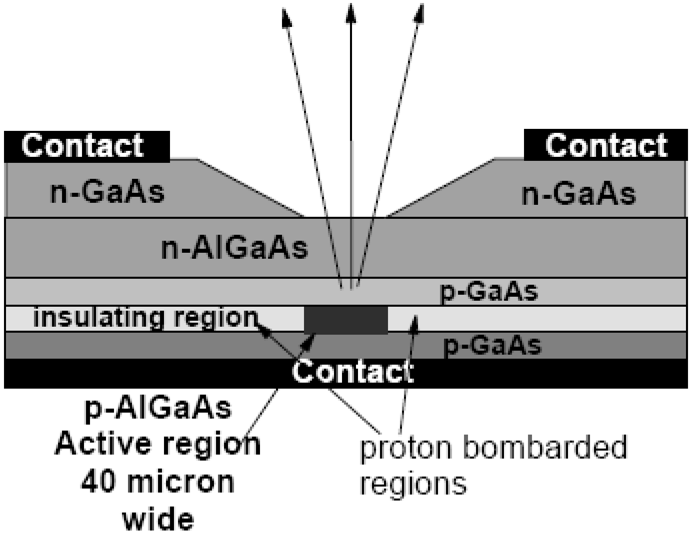




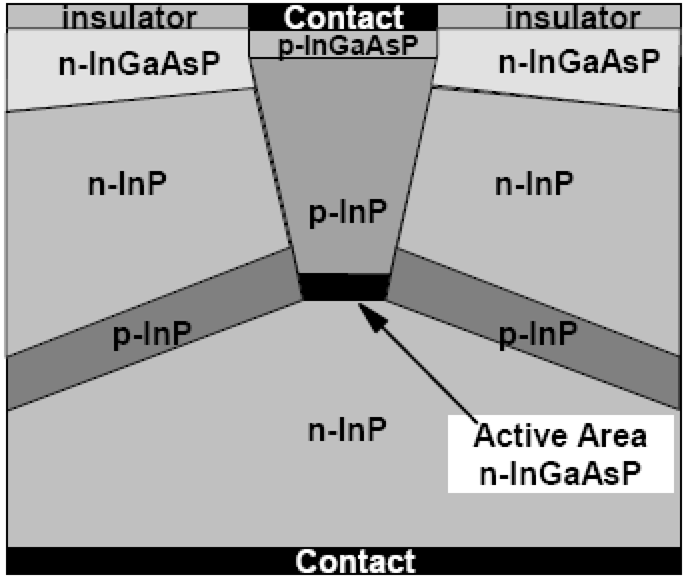
LED cu heterojuncţiuni – detalii



Structuri constructive pentru LED

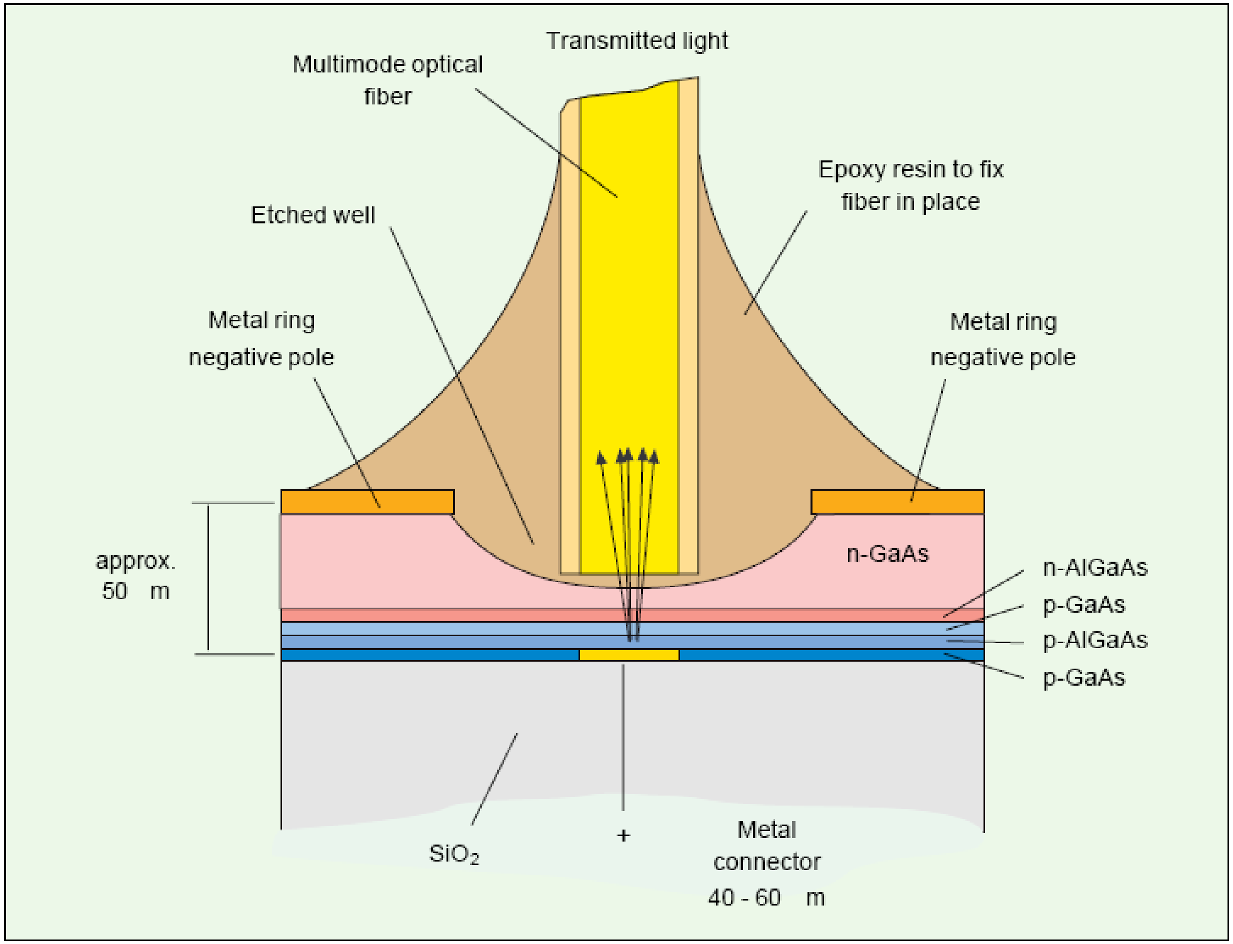


Burrus Surface Emitting LED (SLED)



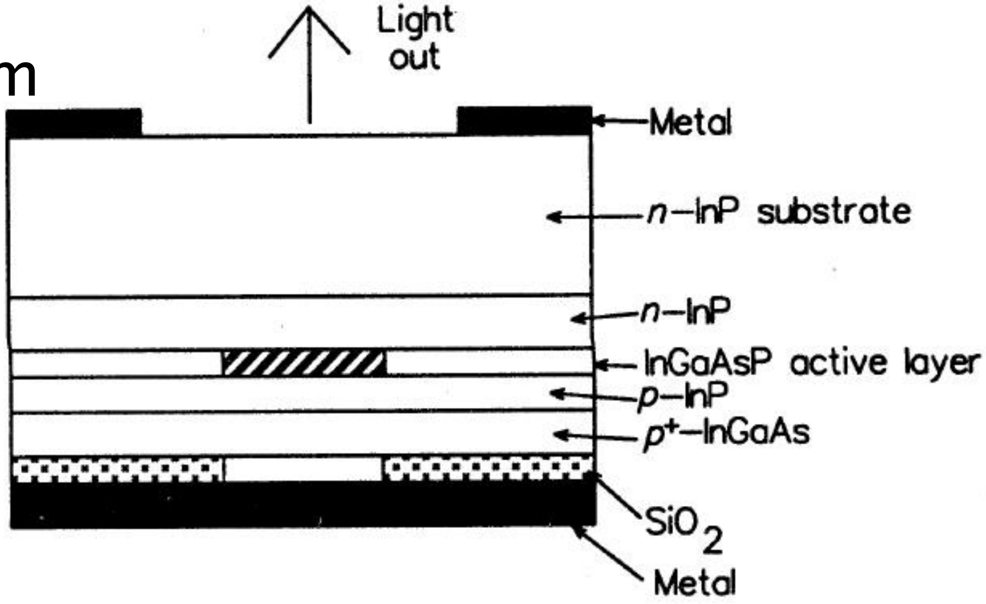
Edge Emitting LED (ELED)

LED cu emisie de suprafaţă



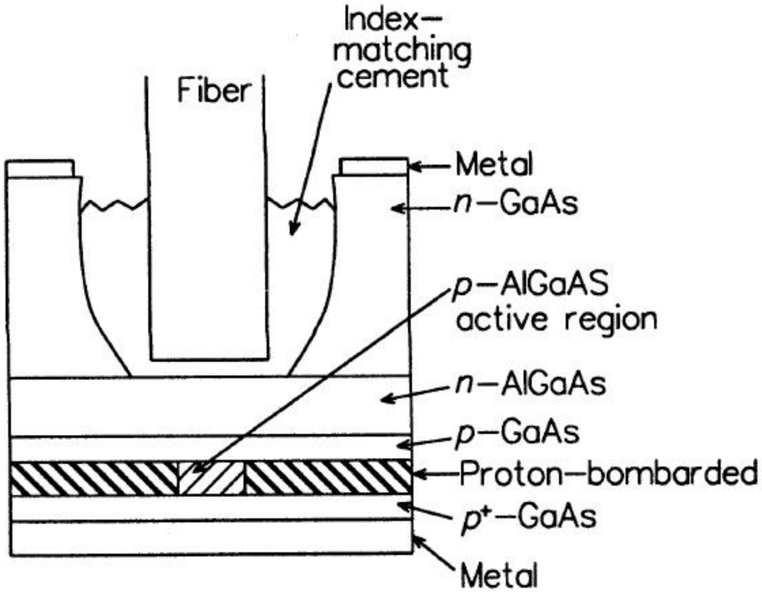
SLED InGaAsP – constructie

- InGaAsP
- 4 straturi
  - n InP ~2÷5μm
  - p InGaAsP ~0.4÷1.5μm
  - p InP ~1÷2μm
  - p^+ InGaAs ~0.2μm
- Latimea zonei active
  - ~20÷50μm diametru

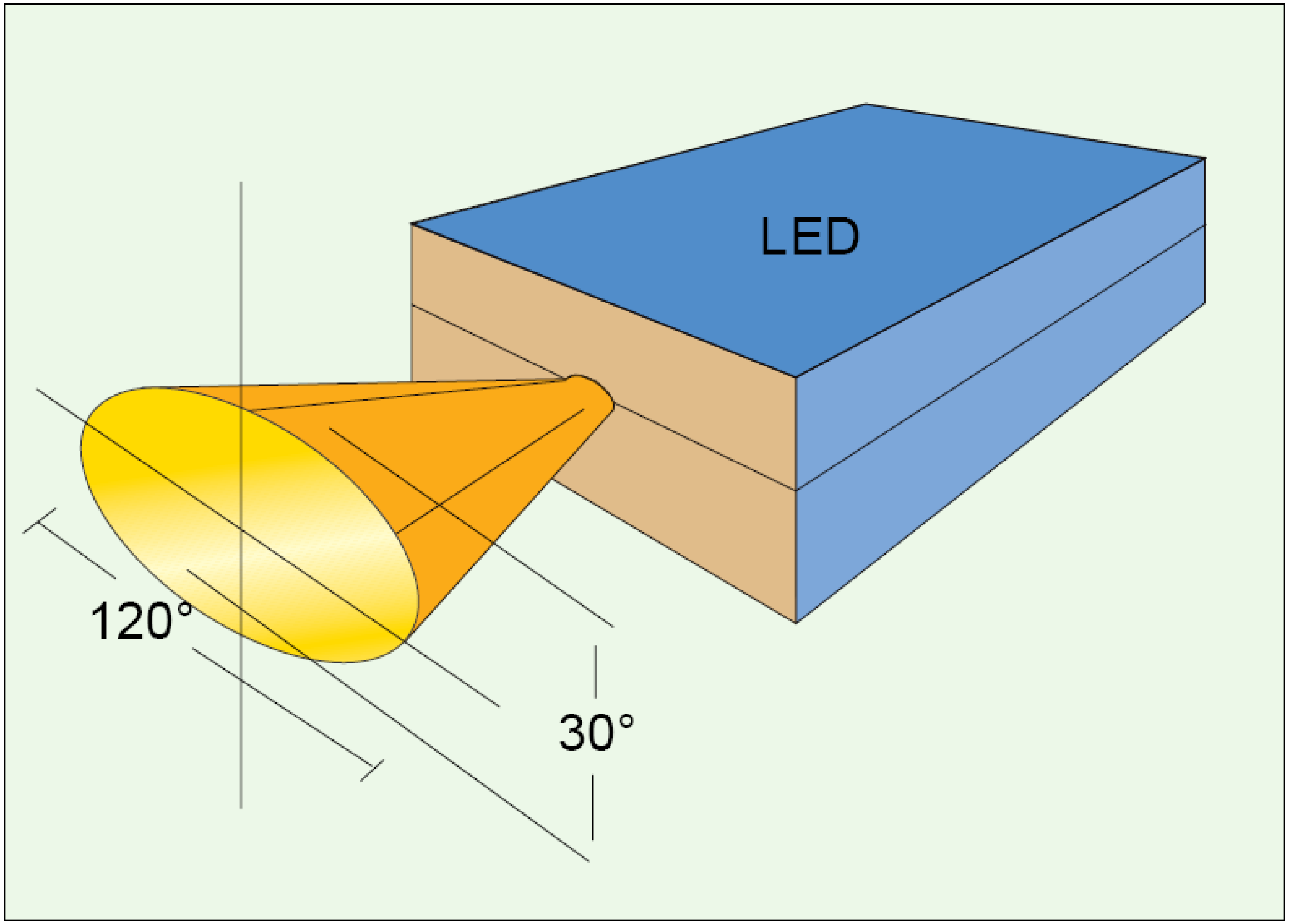


SLED GaAlAs – constructie

- GaAlAs
- diferenta principala e data de absorbtia crescuta a substratului GaAs, care este eliminat partial pentru a permite accesul luminii spre exterior



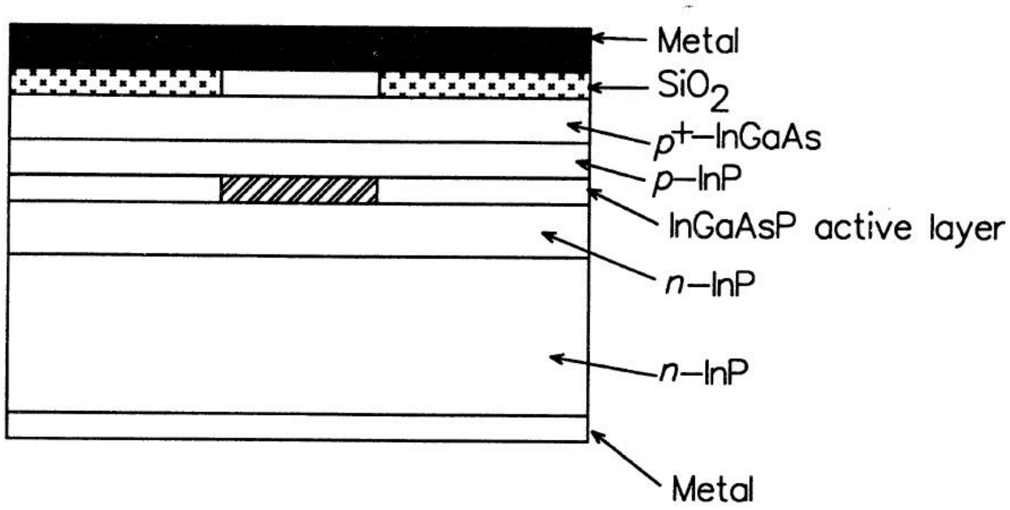
LED cu emisie laterală



ELED – constructie

- InGaAsP
- strict pentru comunicatii
- Cele patru straturi sunt in general similare
- Stratul activ este mult mai subtire decat la SLED ~0.05÷0.25µm

- Regiunea activa
  - latime 50÷70µm
  - lungime 100÷150µm
  - p InP ~1÷2µm
  - p^+ InGaAs ~0.2µm
- Apare concentrarea verticala a luminii



Emisia luminii spre exterior

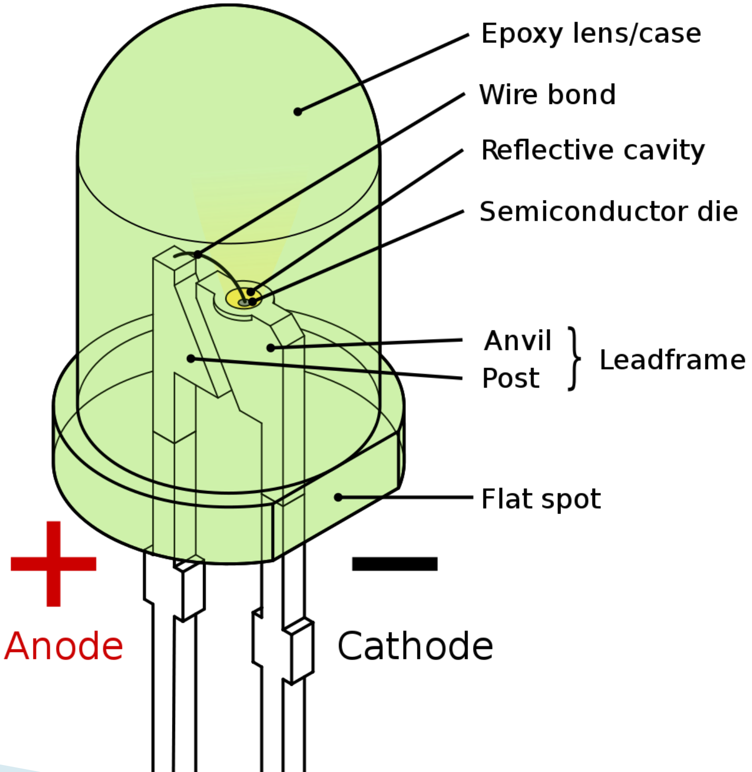
- Indici de refractie ridicati
  - InP n=3.4
  - GaAs n=3.6
- Doua probleme generate
  - pierderi prin reflexie ridicate
  - unghi critic de numai 15°

Emisia luminii spre exterior

- Solutii
  - utilizarea unui material intermediar pentru adaptarea indicelui de refractie (rasina epoxidica)
  - adaptarea formei de iesire din dispozitiv – forma de dom
    - eficienta de cuplaj

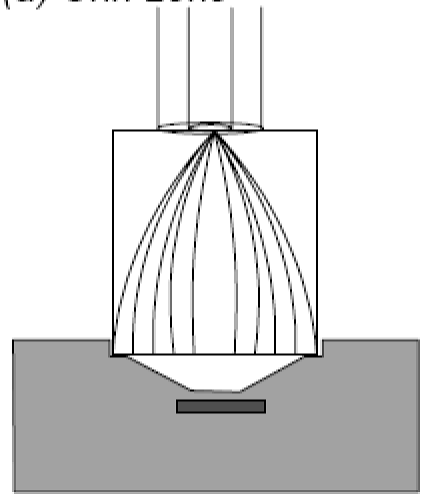
interfata plana semiconductor aer $\dfrac{1}{n\cdot(n+1)^2}$

dom $\dfrac{2n}{(n+1)^2}$

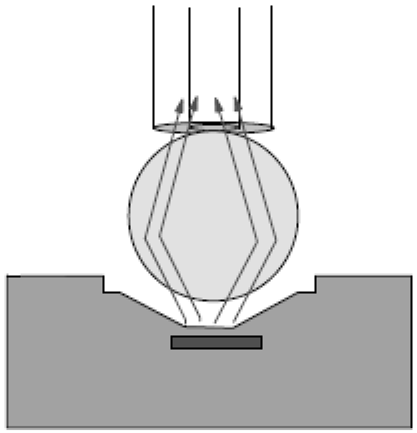


Cuplarea luminii în fibră

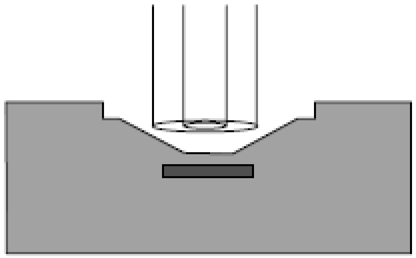
(a) Grin Lens



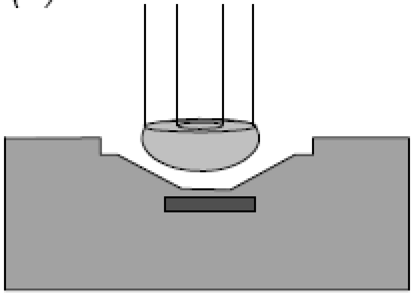
(b) Ball Lens



(c) Direct coupling



(d) Lensed fibre end



numai pentru fibre multimod cu salt de indice

Directivitatea radiatiei exterioare

- Sursa lambertiana

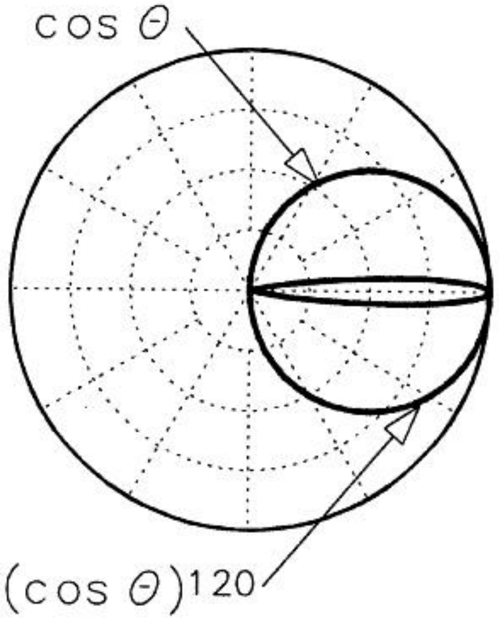
$$P(\theta) = P_0 \cdot \cos\theta$$

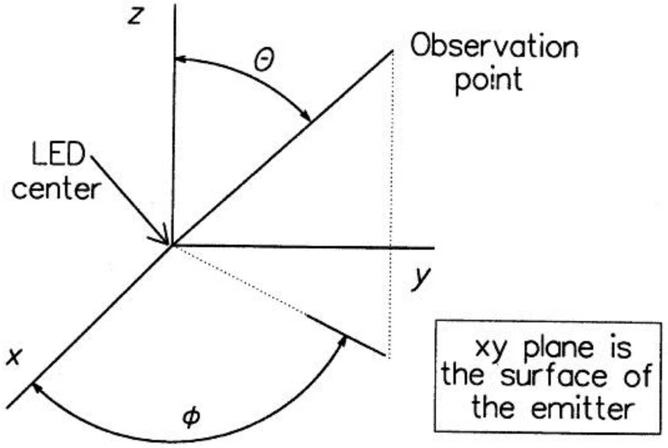
- Aproximatie Lambertiana pentru surse cu directivitate crescuta

$$P(\theta) = P_0 \cdot \cos^n \theta$$

- Surse cu emisie asimetrica

$$P(\theta) = \frac{P_0}{\dfrac{\sin^2\phi}{\cos^T\theta} + \dfrac{\cos^2\phi}{\cos^L\theta}}$$





Directivitatea radiatiei exterioare

- SLED
  - radiatia este emisa cu simetrie circulara, in interiorul unui con cu unghi la varf tipic de 60°
  - Viewing Half Angle ~ 10÷15°
- ELED
  - radiatia emisa nesimetric in forma de con eliptic
    - perpendicular pe jonctiune ~60°
    - paralel cu jonctiunea ~30°

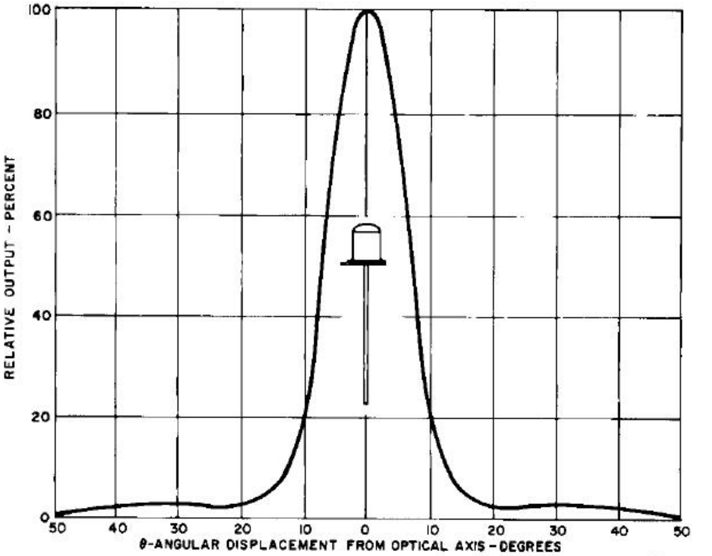
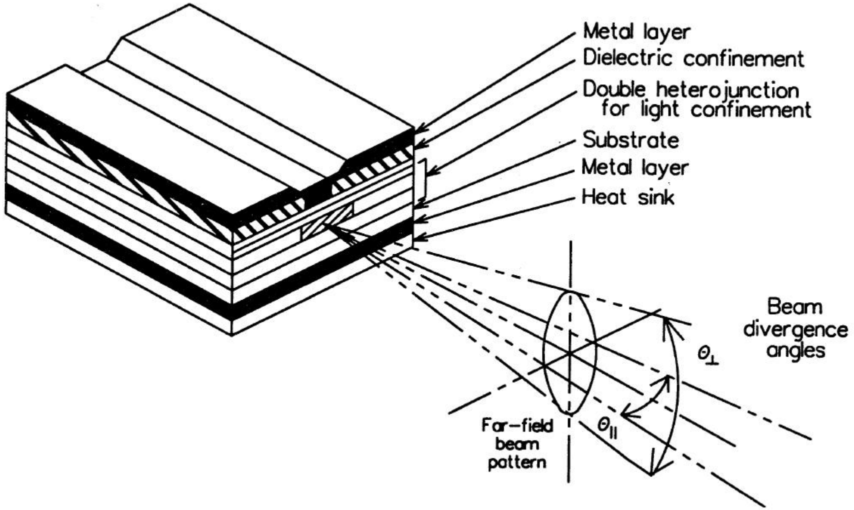
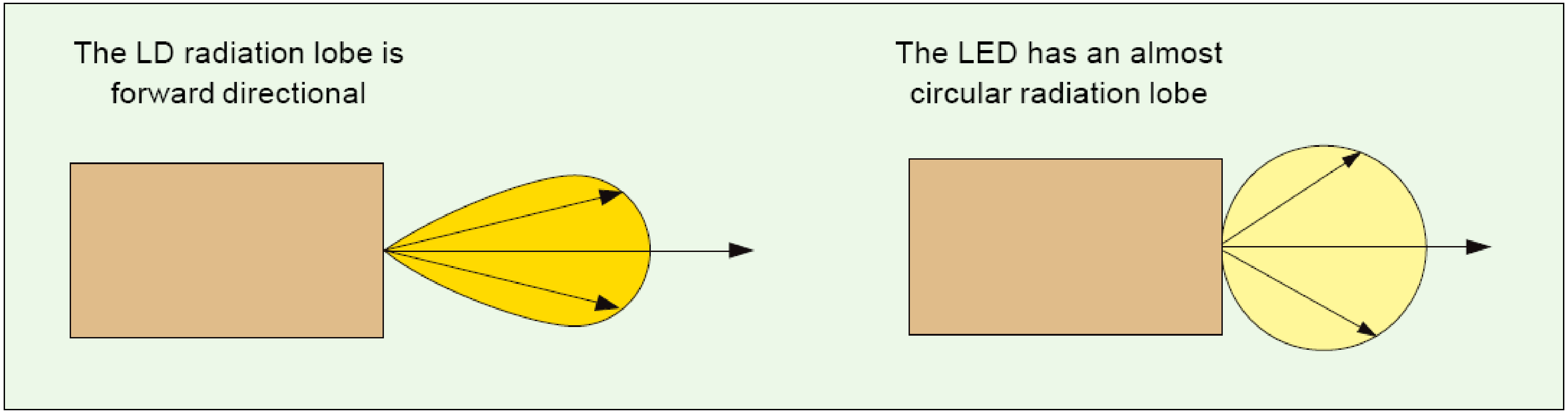


Fig. 5. Typical Radiation Pattern

ST1054

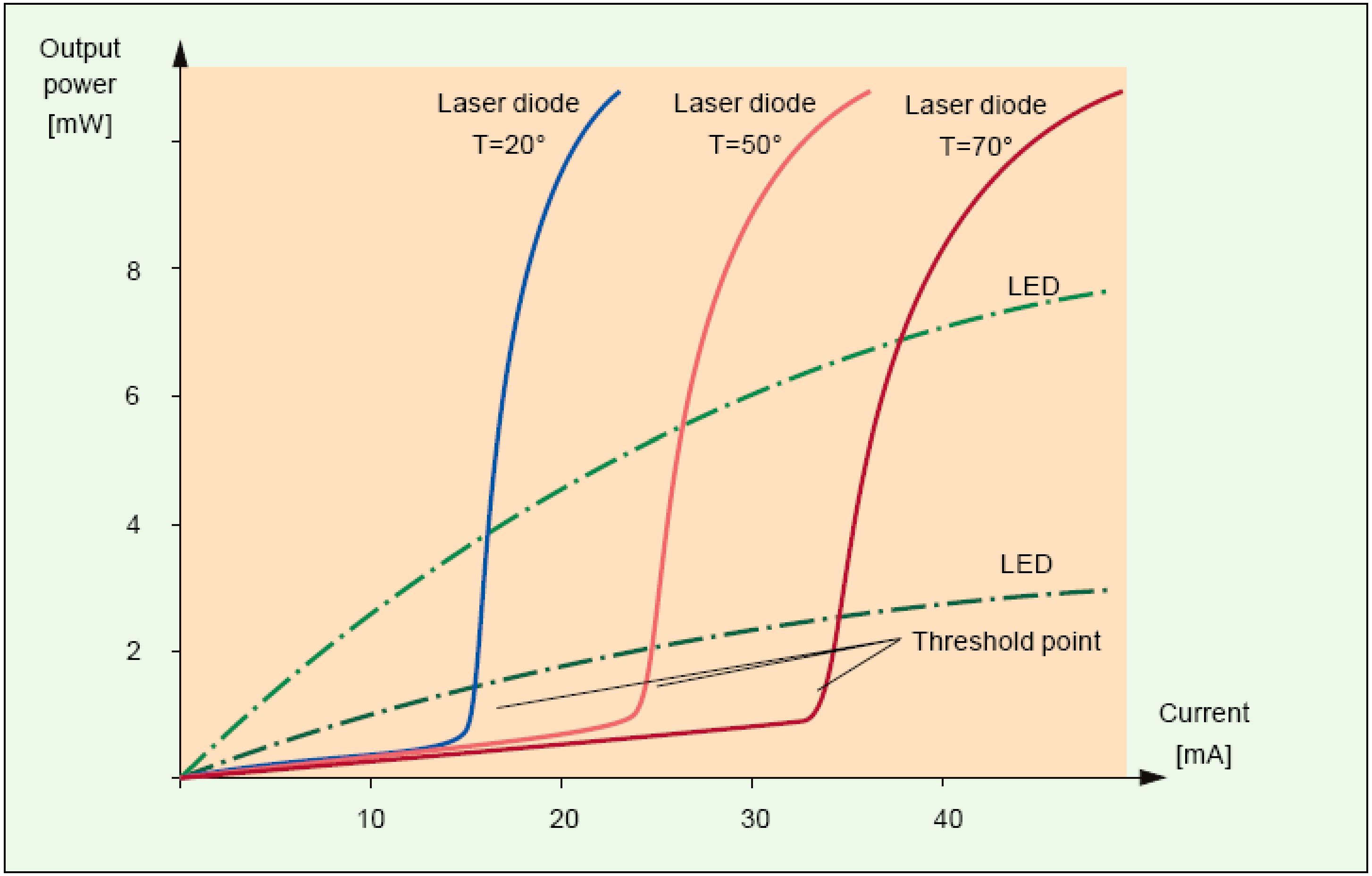


Profil de radiaţie a emiţătorilor optici



- Apertura numerică poate varia de la 0.9 pentru un LED de unghi foarte larg, la 0.2 pentru un LED prevăzut cu lentilă.
- Chiar şi pentru un NA de 0.2, aria emisivă este mare comparativ cu a unui laser. În consecinţă, densitatea de putere emisă este mică astfel încît se reduce drastic puterea care poate fi cuplată într-o fibră cu indice gradat, şi devine practic imposibilă cuplarea cu o fibră monomod.

Caracteristici putere optică/curent a emiţătorilor optici

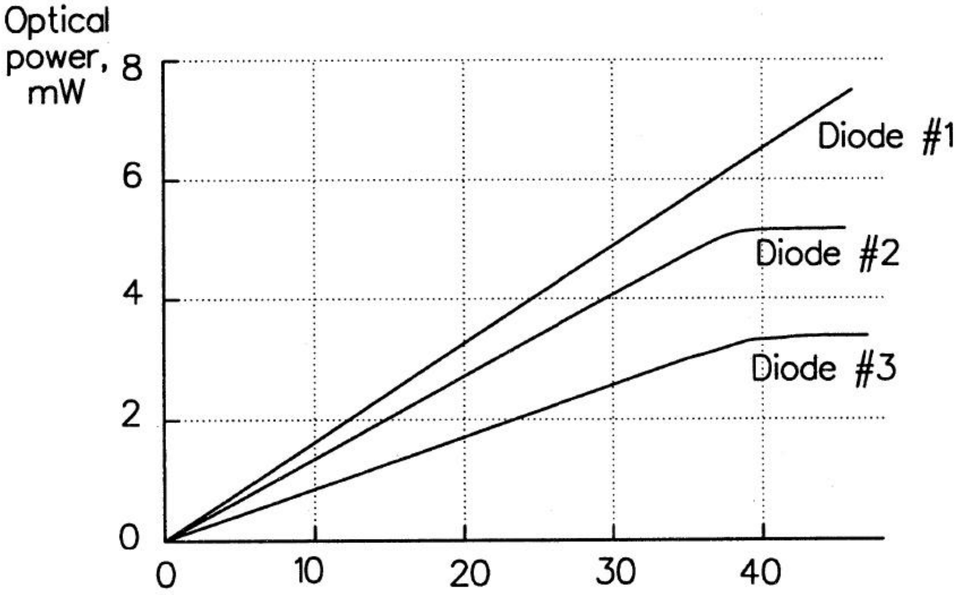


Caracteristica de raspuns a LED-urilor

- 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

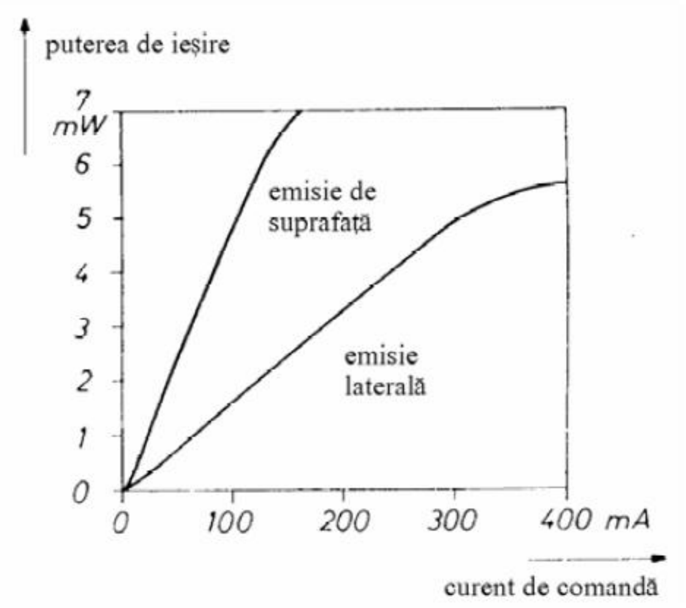
$$r = \frac{P_o}{I} \quad \left[\frac{W}{A}\right]$$

- Tipic r=50µW/mA



Caracteristica de raspuns a LED-urilor

- Tipic SLED au eficienta mai buna decat ELED



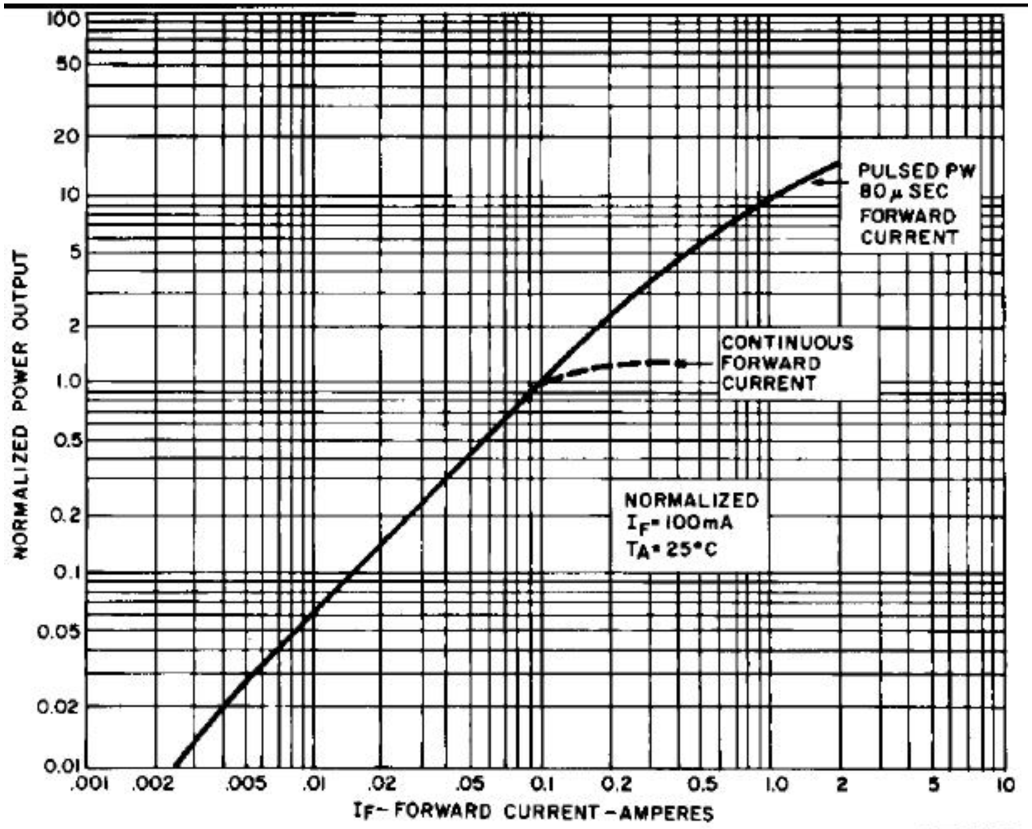


Fig. 1. Power Output vs. Input Current

ST1052

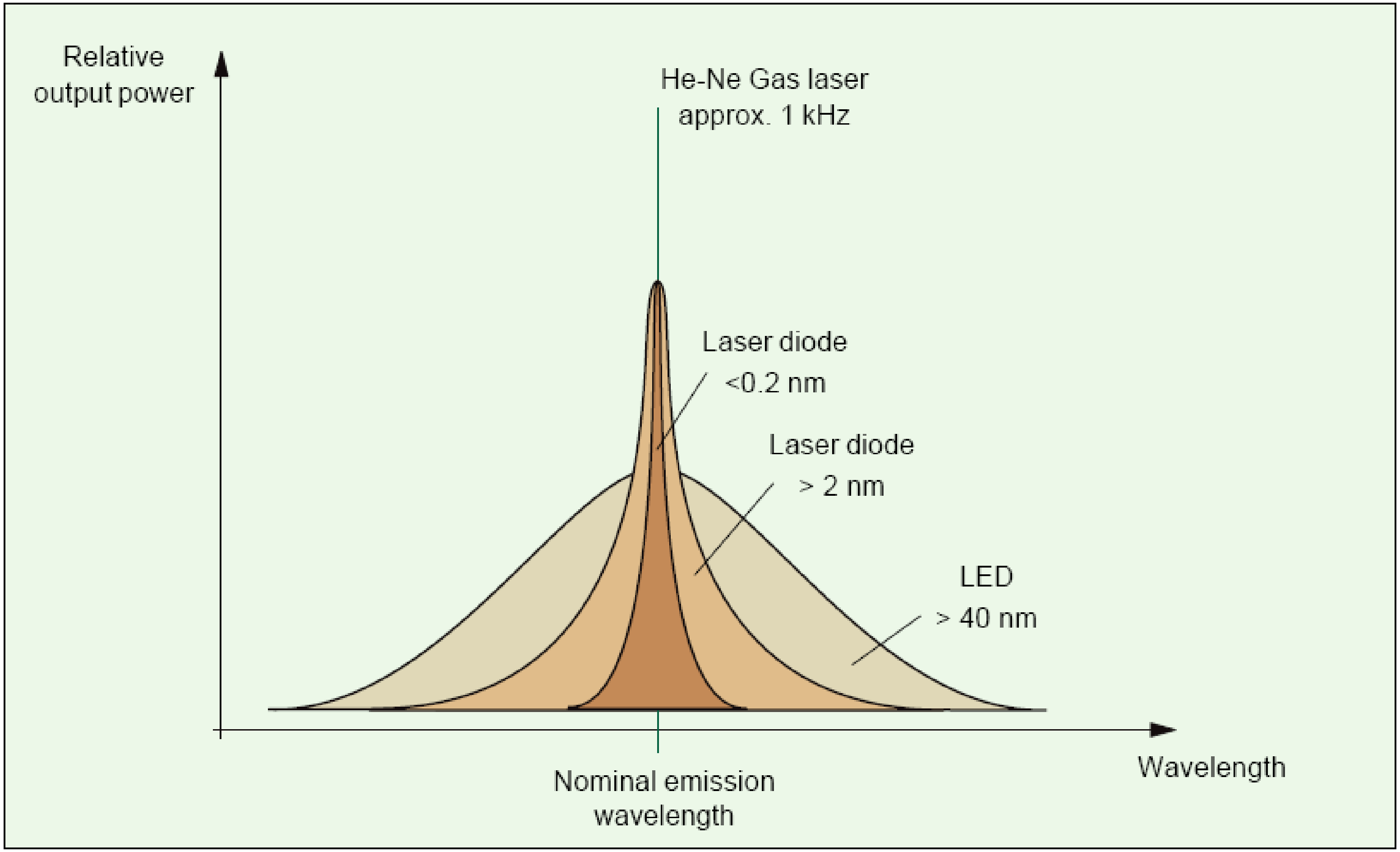
Probleme

- Un dispozitiv de semnalizare e realizat cu 100 LED-uri care emit lungimea de undă dominantă $\lambda_0 = 590\text{nm}$ sub un con cu unghi la vârf de 5.2° (emisie presupusă **uniformă** în acest con). O diodă are responzivitatea de 90µW/mA şi este parcursă de un curent de 85mA.
- a) Estimaţi intensitatea luminoasă a dispozitivului pe direcţie normală.
- Dacă se consideră emisia **uniformă** în interiorul conului de emisie, fluxul optic energetic este constant în interiorul acestui con şi va fi egal cu puterea optică emisă (ambele mărimi reprezintă viteze ale energiei, măsurate în W, cu diferenţa că puterea optică reprezintă o mediere a fluxurilor emise după diferite direcţii, valoarea medie a unei mărimi constante fiind egală cu acea mărime)

Aplicatii majore LED

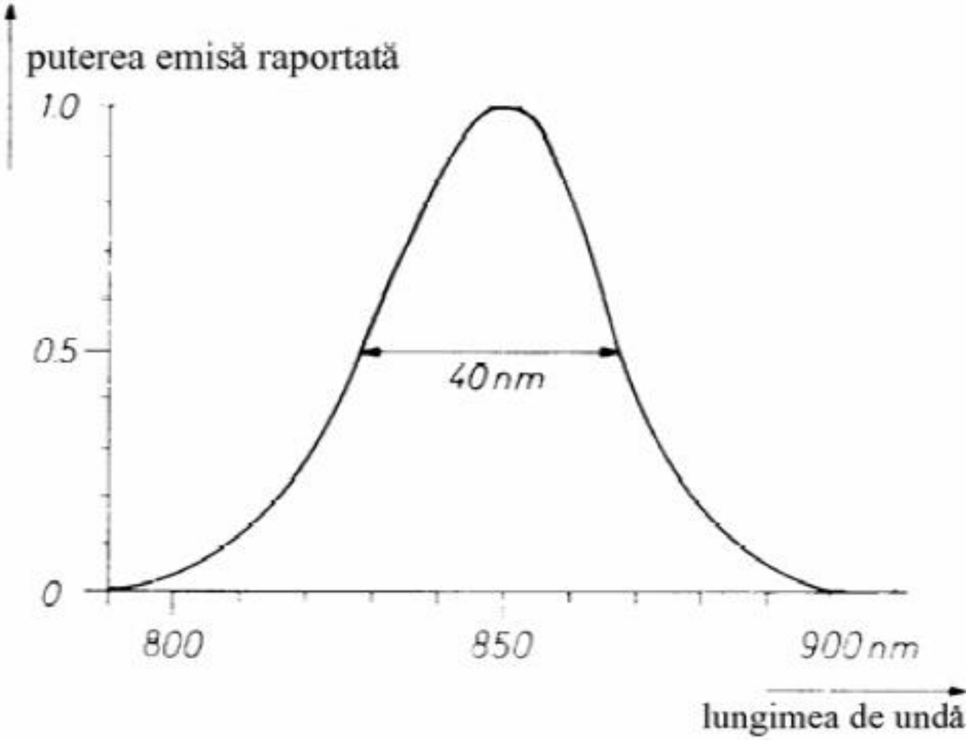
- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- Iluminare
  - Putere ridicata, lumina alba (GaInN)

Calitatea spectrală a emiţătorilor optici



Latimea spectrala a LED-urilor

- Aproximativ $\Delta\lambda \approx 0.05\lambda$
- Relatie empirica $\Delta\lambda[\mu m] \approx 1.45\lambda^2[\mu m]\cdot(kT)[eV]$
- Tipic
  - GaAlAs – 20-40 nm
  - InGaAsP
    - SLED – 100 nm
    - ELED – 60-80 nm
  - GaInN – 30-40 nm (10%)



Comportare dinamica a LED

- Puterea de iesire la modulatia cu un semnal sinusoidal cu ω

$$P_{out} = \frac{P_o}{1+\omega^2\tau_{lf}^2}$$

  - Puterea electrica variaza proportional cu patratul curentului
  - Puterea optica variaza proportional cu curentul
- Banda la 3 dB electrica

$$\frac{P_{out}^2}{P_o^2} = \frac{1}{2} \qquad f_{3dB-el} = \frac{1}{2\cdot\pi\cdot\tau_{lf}}$$

  - Banda la 3 dB optic

$$\frac{P_{out}}{P_o} = \frac{1}{2}$$

Comportare dinamica a LED

- Cand curentul care trece prin dispozitiv e mic timpul de viata al purtatorilor e independent de curent si este dependent liniar de nivelul de dopare in regiunea activa
- Cand curentul este mare timpul de viata al purtatorilor este proportional cu $\sqrt{d}$ si invers proportional cu $\sqrt{J}$
- Banda poate fi crescuta
  - Crescand nivelul de dopare
  - Reducand inaltimea zonei active
  - Crescand densitatea de curent

Comportare dinamica a LED

- In domeniul timp
- Timpul de crestere (rise time)

$$t_r = 2.20 \cdot \left(\frac{2 \cdot k \cdot T \cdot C_s}{e \cdot I_p} + \tau_{lf} \right)$$

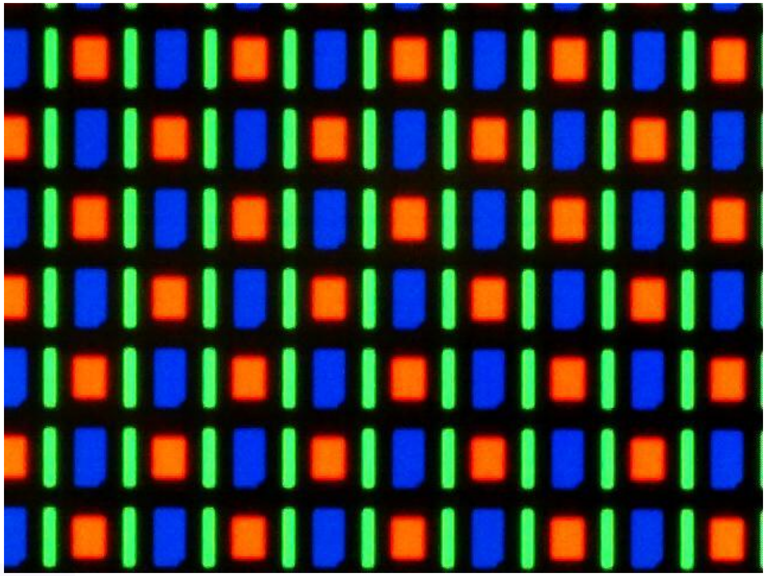
- Capacitatea asociata sarcinilor in regiunea activa: 350÷1000pF
- Produs Putere × Banda

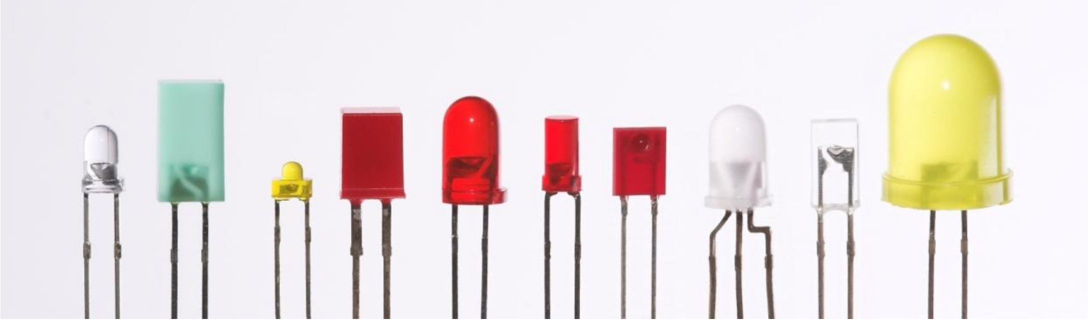
$$P \times \Delta f = \frac{h \cdot c}{2 \cdot \pi \cdot e \cdot \lambda} \cdot \frac{J}{\tau_{lf}}$$

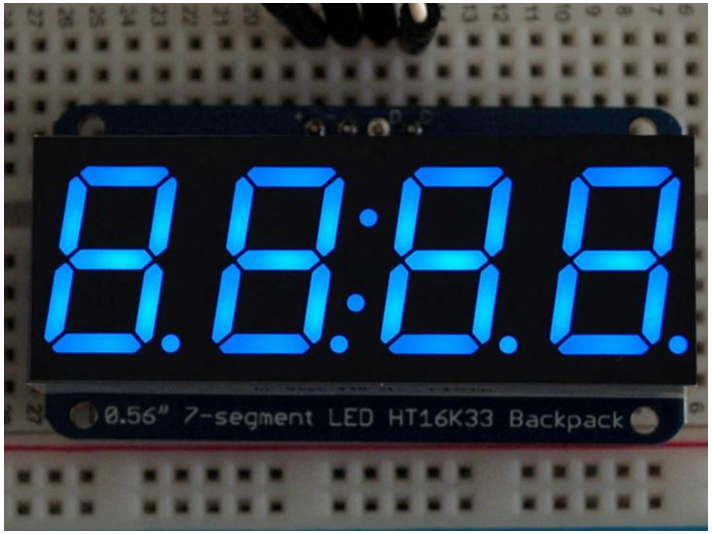
Aplicatii majore LED

- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- Iluminare
  - Putere ridicata, lumina alba (GaInN)

Aplicatii in spectru vizibil

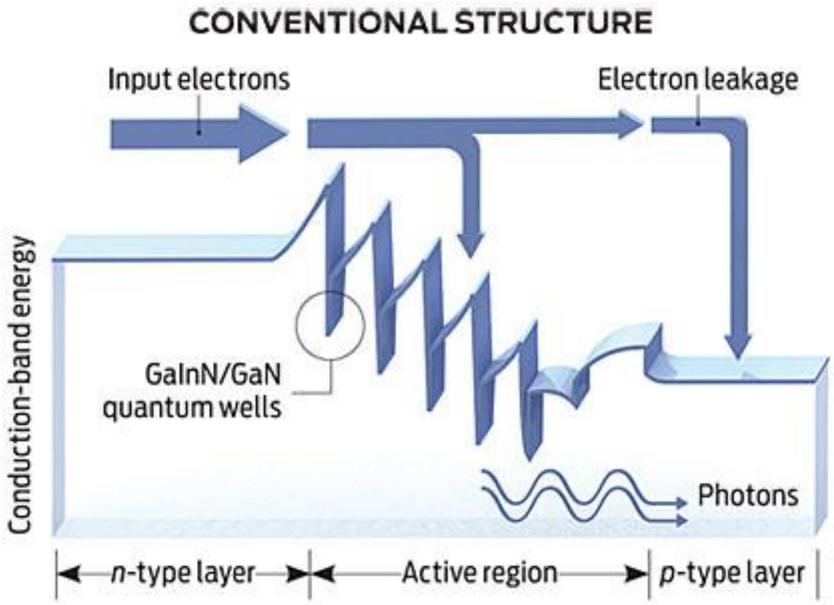


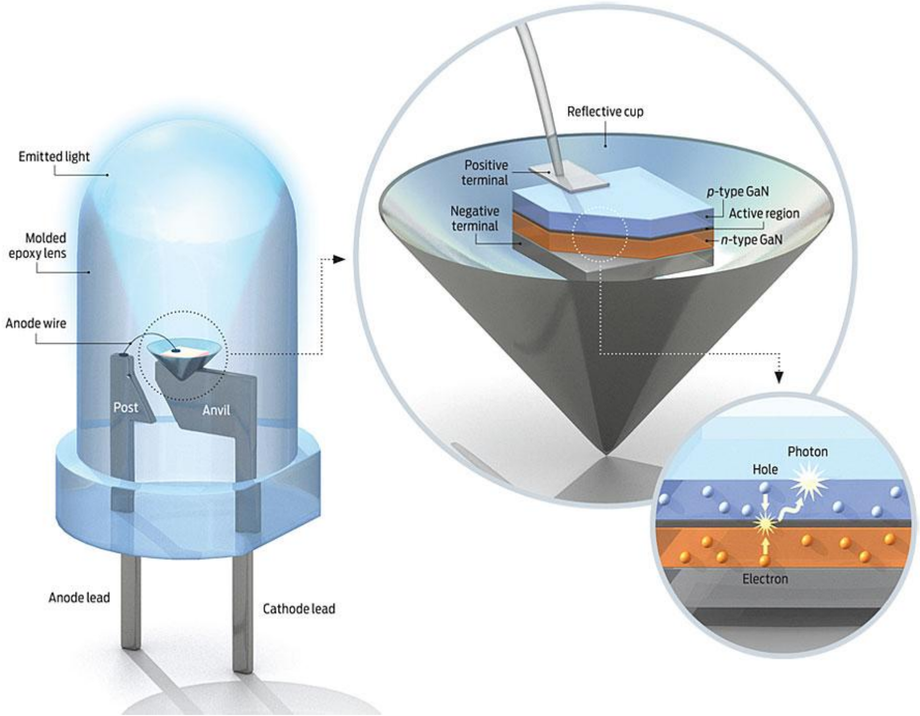




LED albastru

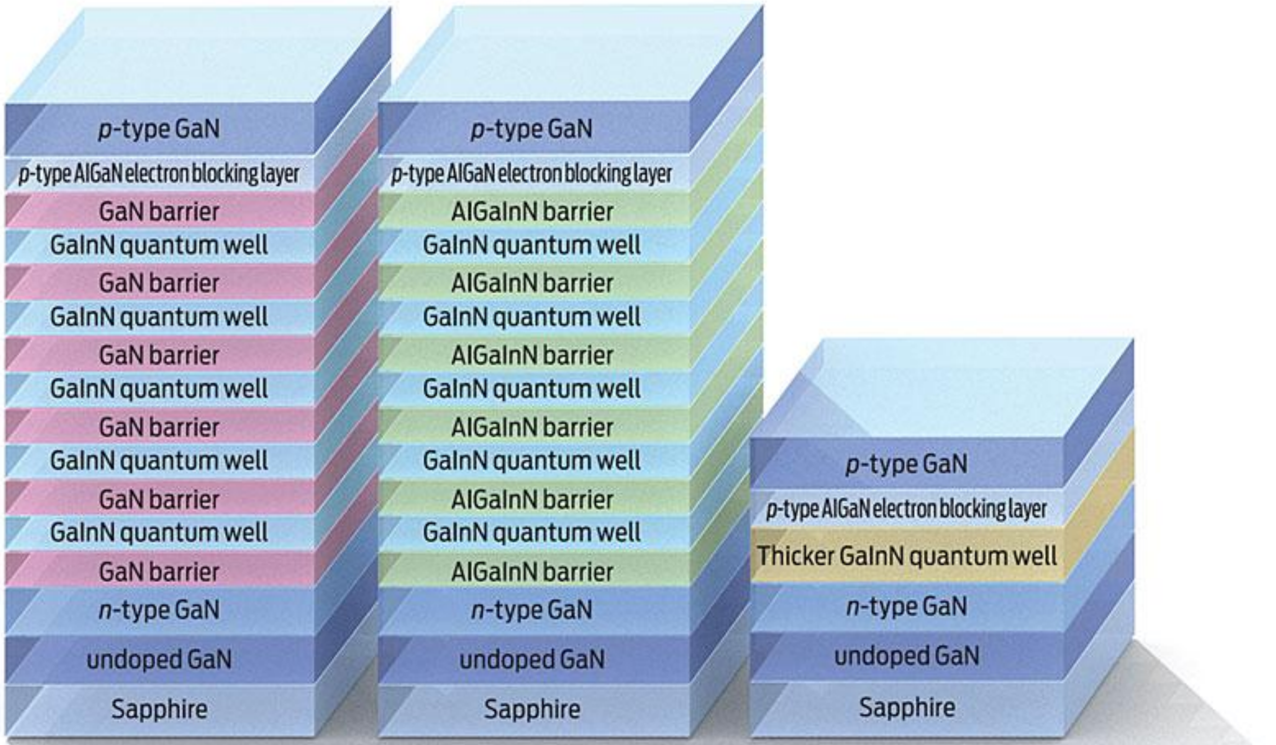
- bazat pe GaInN
- dezvoltare tardiva (GaN)





LED albastru

- realizare: GaInN Quantum Well/GaN



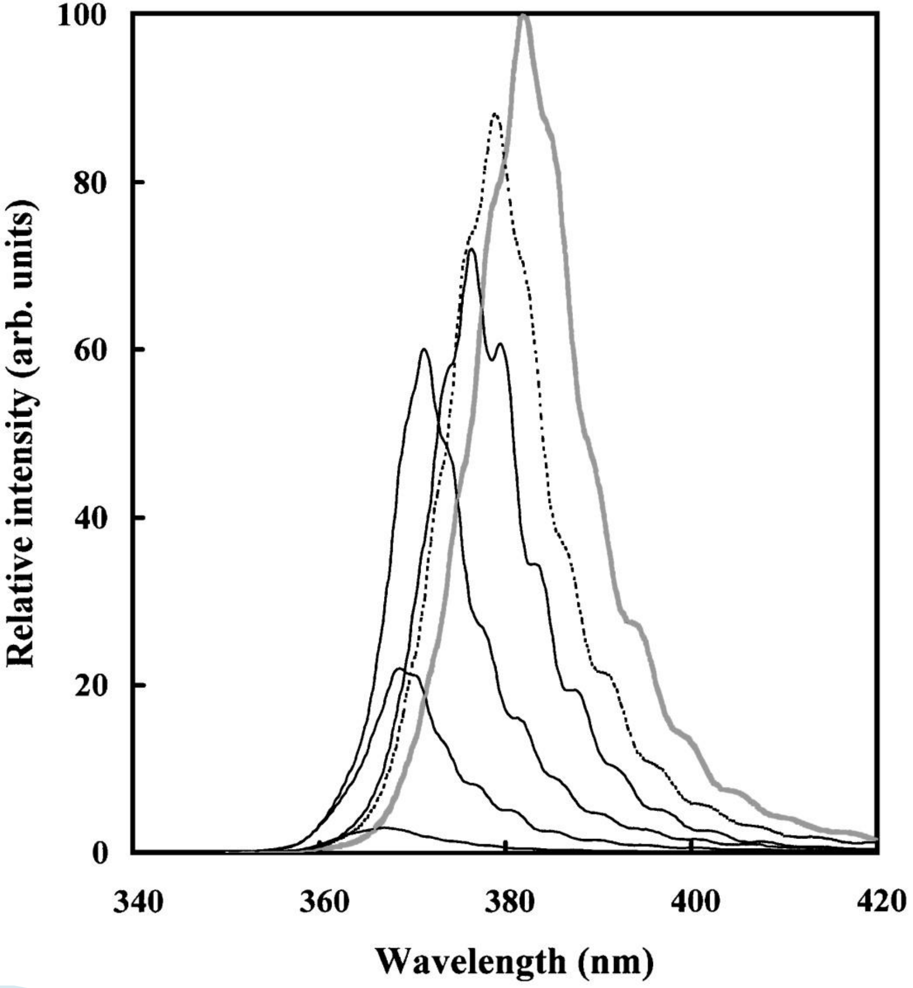
Conventional structure

Rensselaer Polytechnic Institute's polarization-matched structure

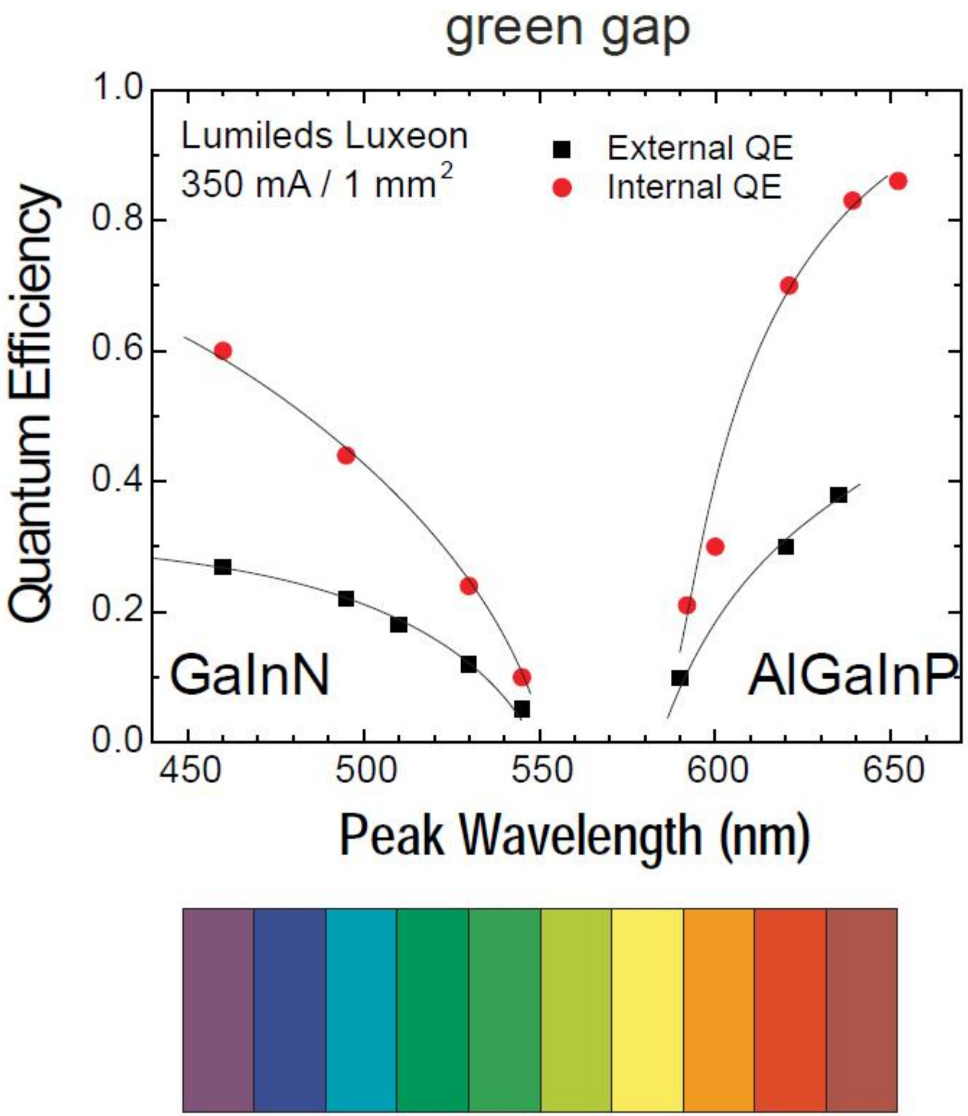
Lumileds' double heterostructure

Spectru LED albastru

- Δλ relativ la λ mai mare



Eficienta cuantica



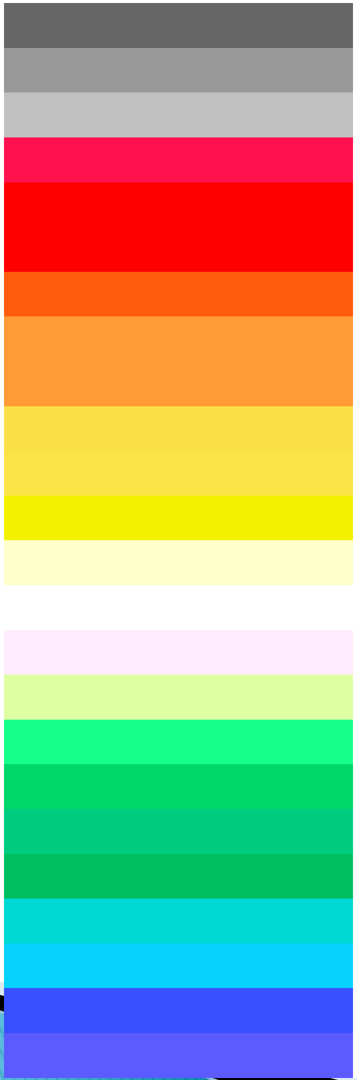
Culori/materiale – 1

	Color	Wavelength (nm)	Voltage (V)	Semiconductor Material
⬛	Infrared	$\boldsymbol{\lambda} > 760$	$\Delta V < 1.9$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
🟥	Red	$610 < \lambda < 760$	$1.63 < \Delta V < 2.03$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟧	Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟨	Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟩	Green	$500 < \lambda < 570$	$1.9 < \Delta V < 4.0$	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)

Culori/materiale – 2

	Color	Wavelength (nm)	Voltage (V)	Semiconductor Material
🟦	Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)
🟪	Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	Indium gallium nitride (InGaN)
🟪	Purple	multiple types	$2.48 < \Delta V < 3.7$	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
⬛	Ultraviolet	$\lambda < 400$	$3.1 < \Delta V < 4.4$	Diamond (235 nm) Boron nitride (215 nm) Aluminium nitride (AlN) (210 nm) Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN) — (down to 210 nm)
	White	Broad spectrum	$\Delta V = 3.5$	Blue/UV diode with yellow phosphor

Denumiri tipice – LED



Wavelength (nm)	Color Name
940	Infrared
880	Infrared
850	Infrared
660	Ultra Red
635	High Eff. Red
633	Super Red
620	Super Orange
612	Super Orange
605	Orange
595	Super Yellow
592	Super Pure Yellow
585	Yellow
4500K	"Incandescent" White
6500K	Pale White
8000K	Cool White
574	Super Lime Yellow
570	Super Lime Green
565	High Efficiency Green
560	Super Pure Green
555	Pure Green
525	Aqua Green
505	Blue Green
470	Super Blue
430	Ultra Blue

Aplicatii majore LED

- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- Iluminare
  - Putere ridicata, lumina alba (GaInN)

Premiul Nobel, Fizica, 2014

Nobelpriset i fysik 2014

The Nobel Prize in Physics 2014

Nobelpriset i fysik 2014

KUNGL.
VETENSKAPS
AKADEMIEN

Isamu Akasaki
Meijo University, Nagoya, Japan
Nagoya University, Japan

Hiroshi Amano
Nagoya University, Japan

Shuji Nakamura
University of California,
Santa Barbara, CA, USA

"för uppfinningen av effektiva blå lysdioder vilka möjliggjort ljusstarka och energisnåla vita ljuskällor"

"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"

2014-10-07

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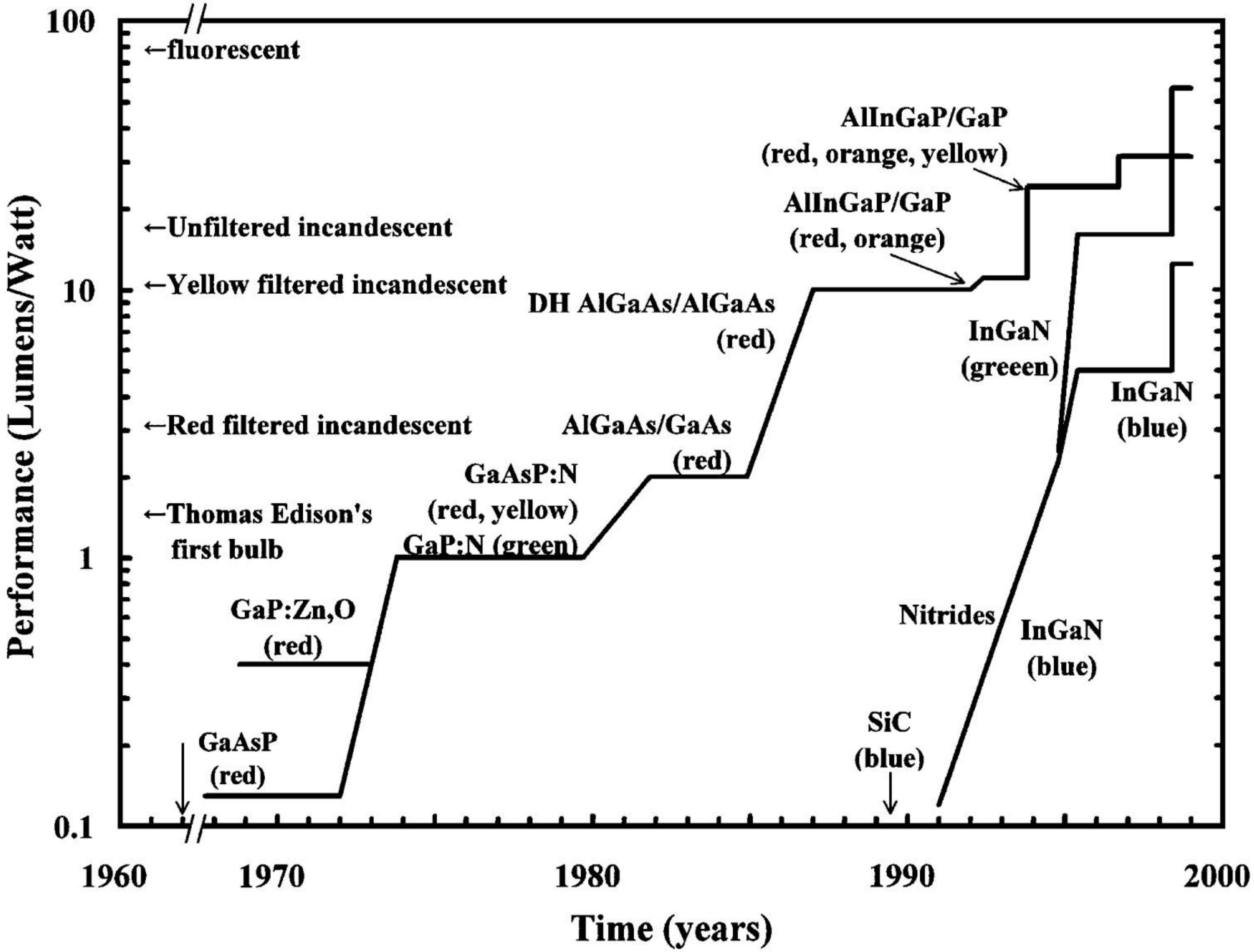
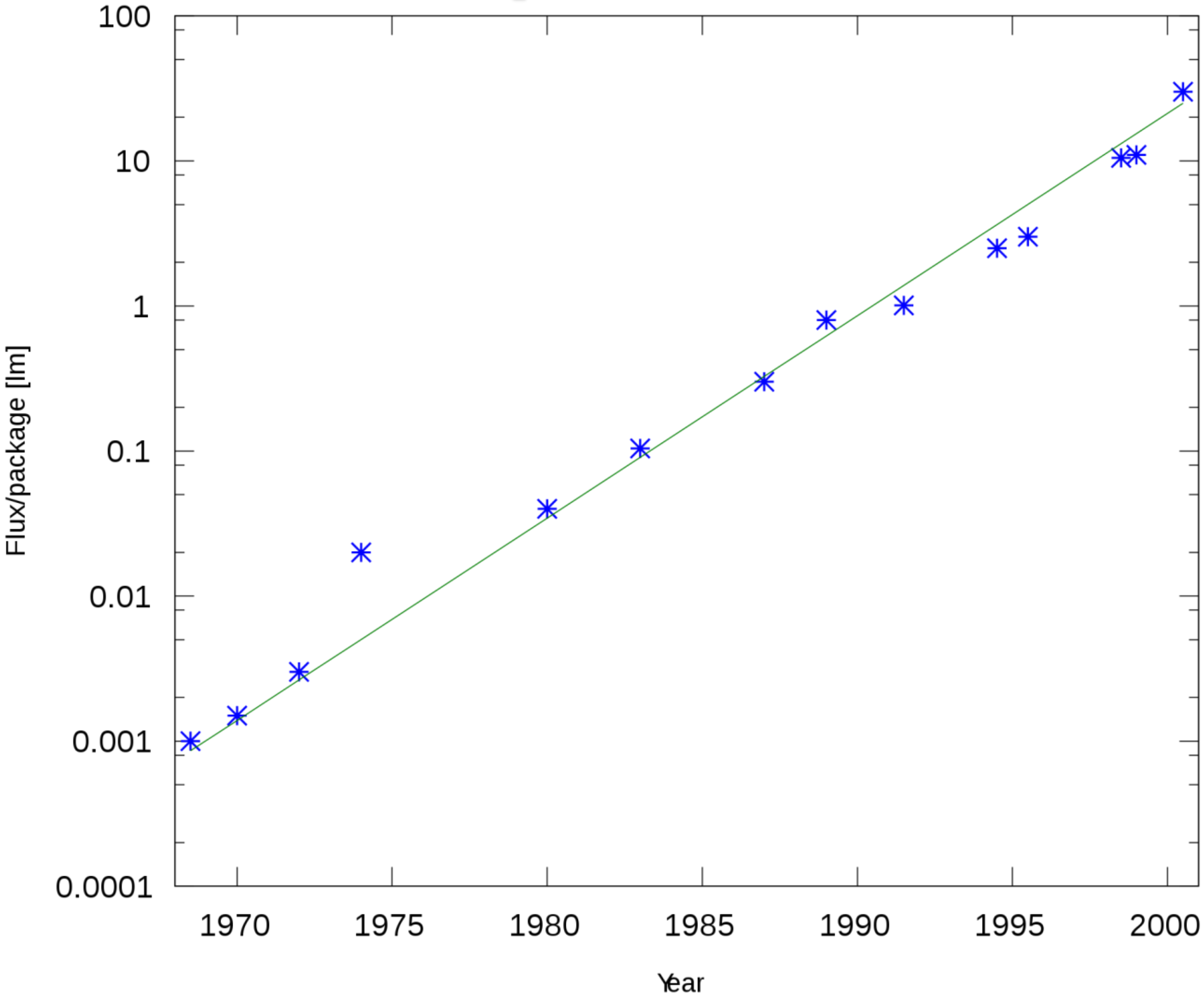
Eficienta

- Bec cu incadescenta
  - 16 lm/W
- Tub fluorescent
  - 100 lm/W
- LED
  - curent: 250 lm/W
  - curand: 300 lm/W

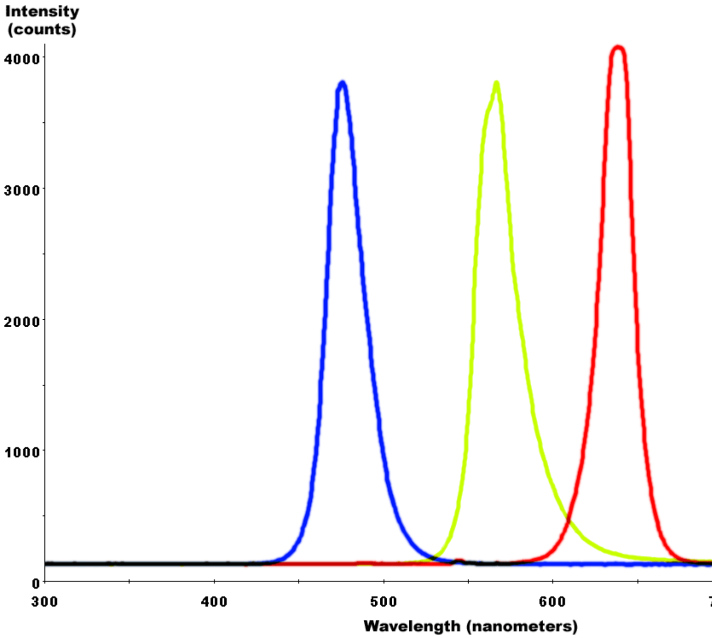
Eficienta in timp

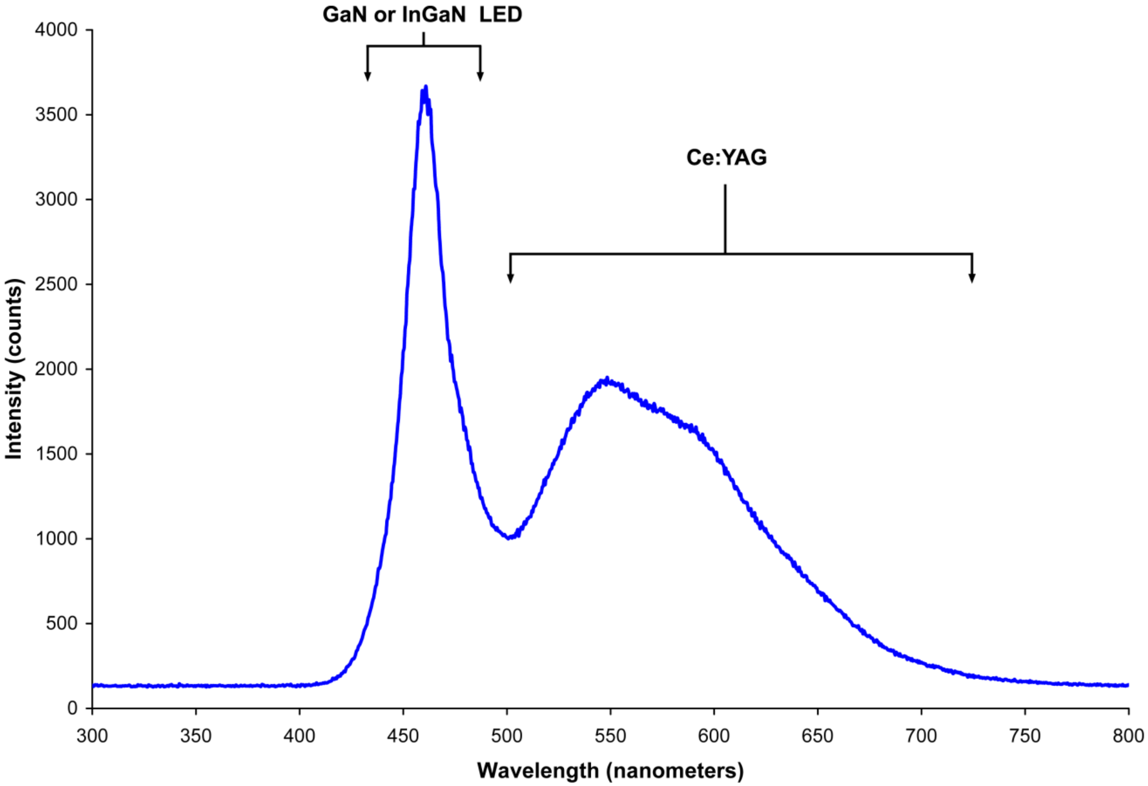


Eficienta in timp

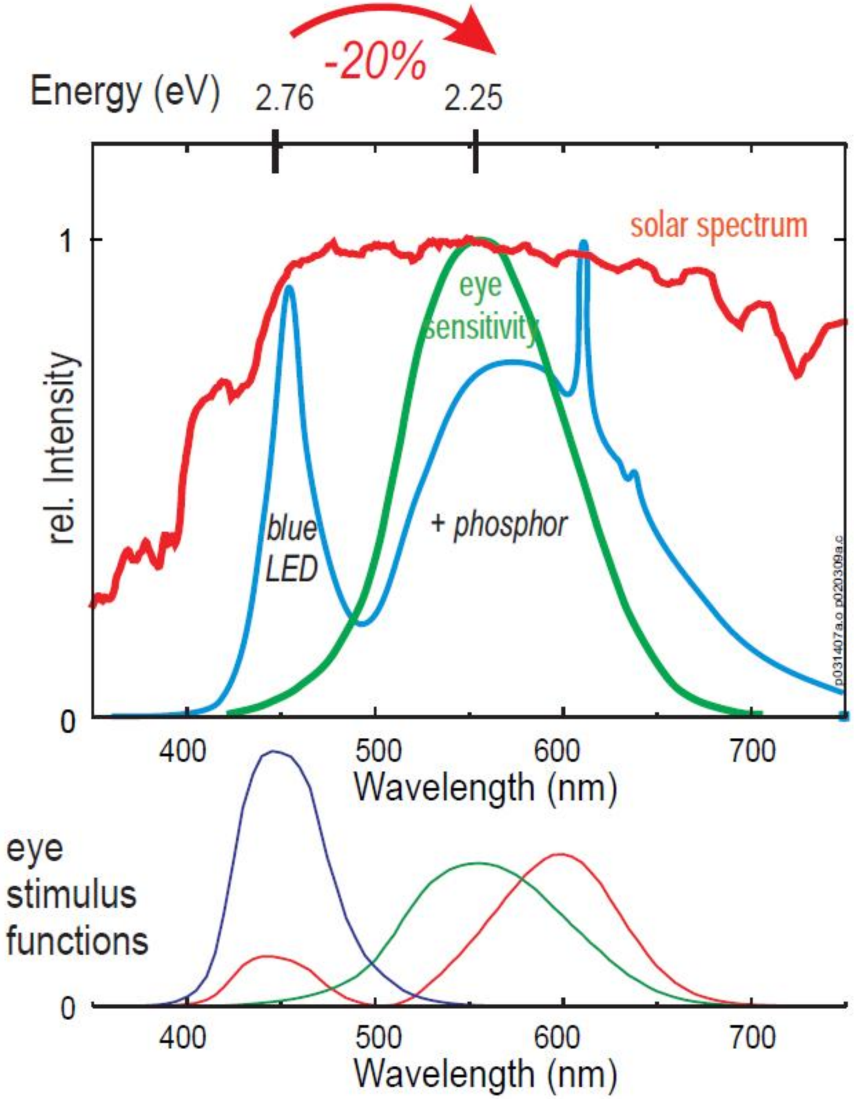


Culoare alba

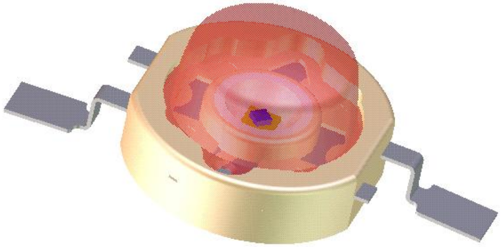


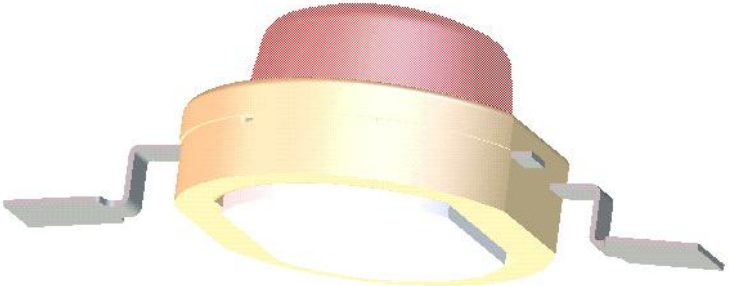


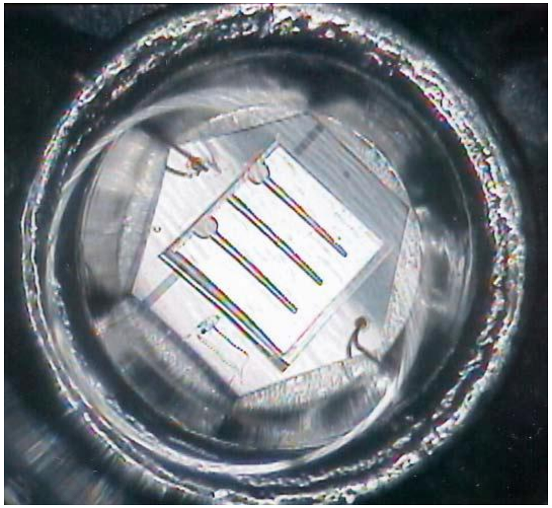
Fosfor activat de LED albastru/UV



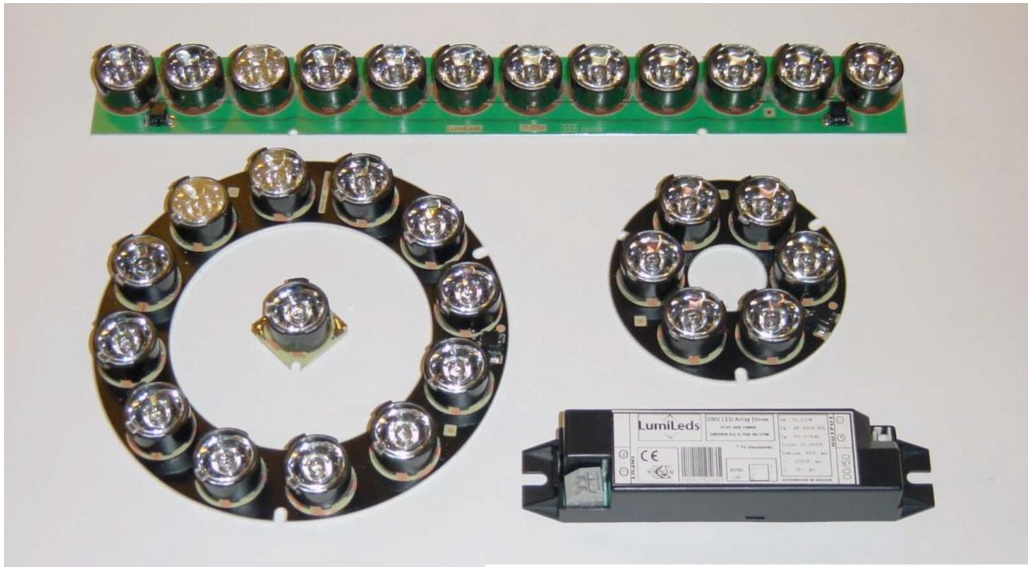
Realizare LED de putere

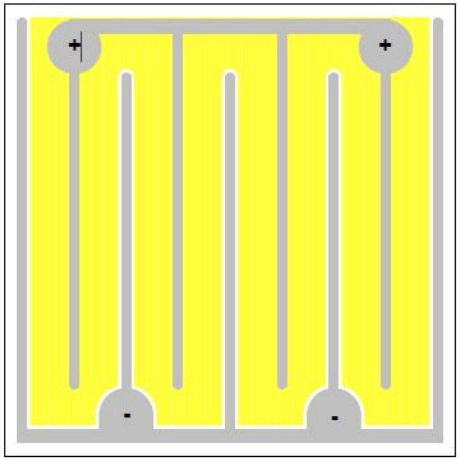




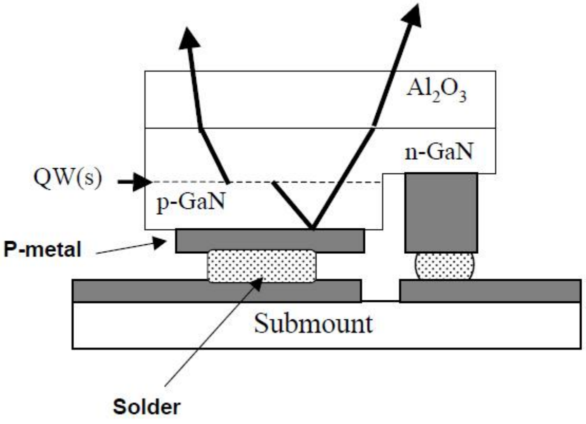


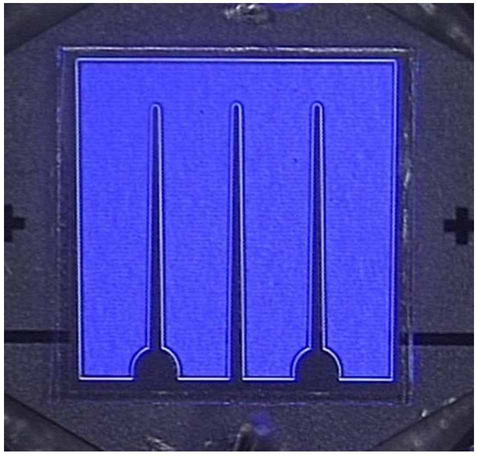
Realizare LED de putere



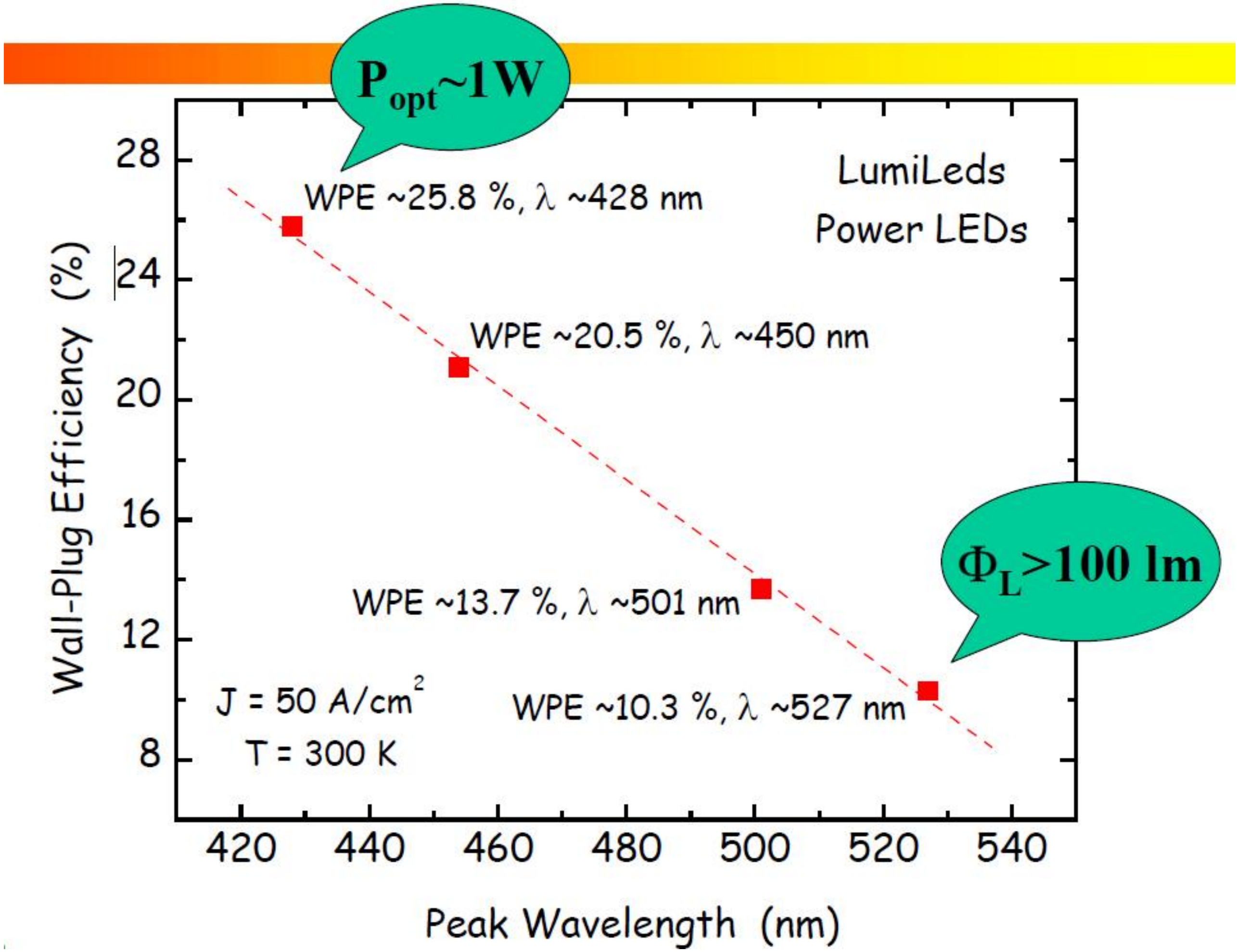


$A_{chip} \sim 1 \times 1\ \mathrm{mm}^2;\ N = 4$



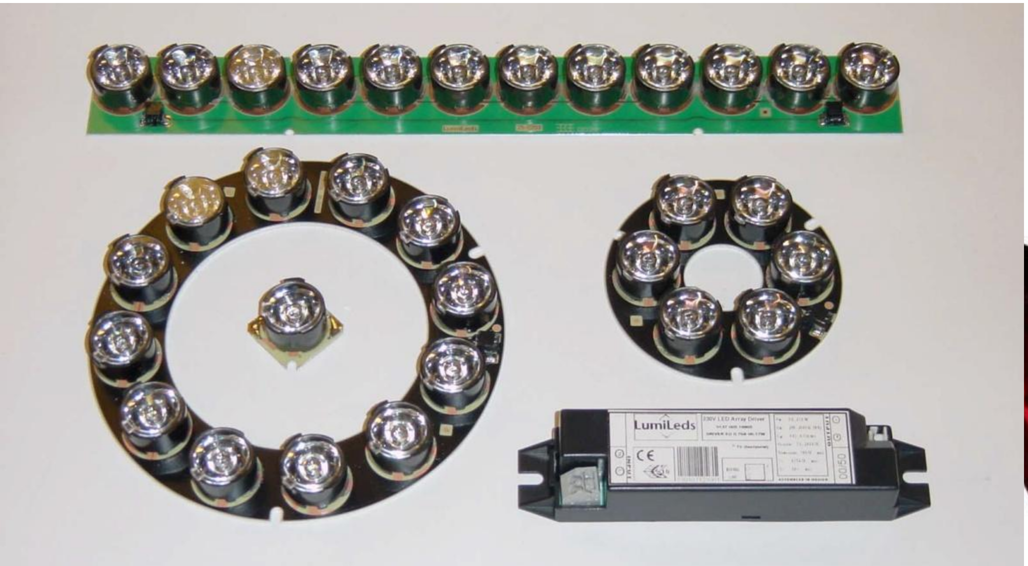


Performanta



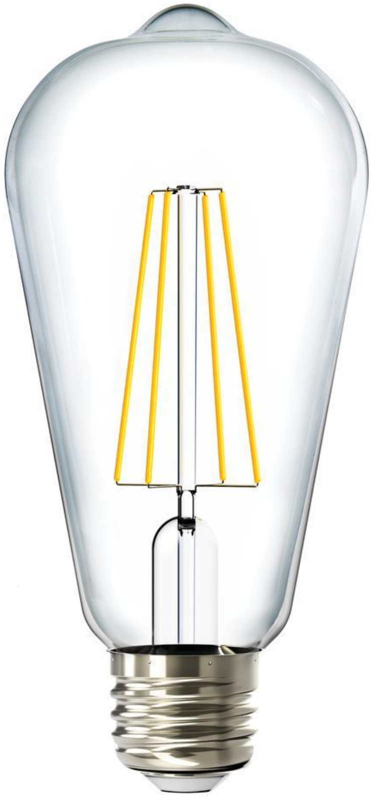
Aplicatii

- auto



Aplicatii

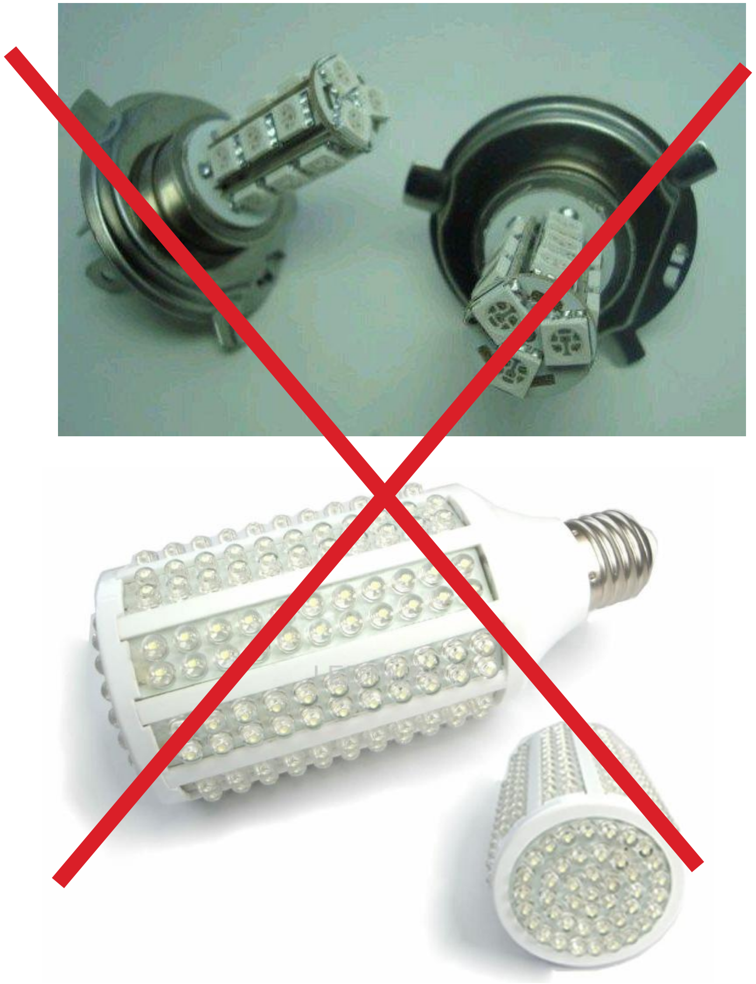
- casnic

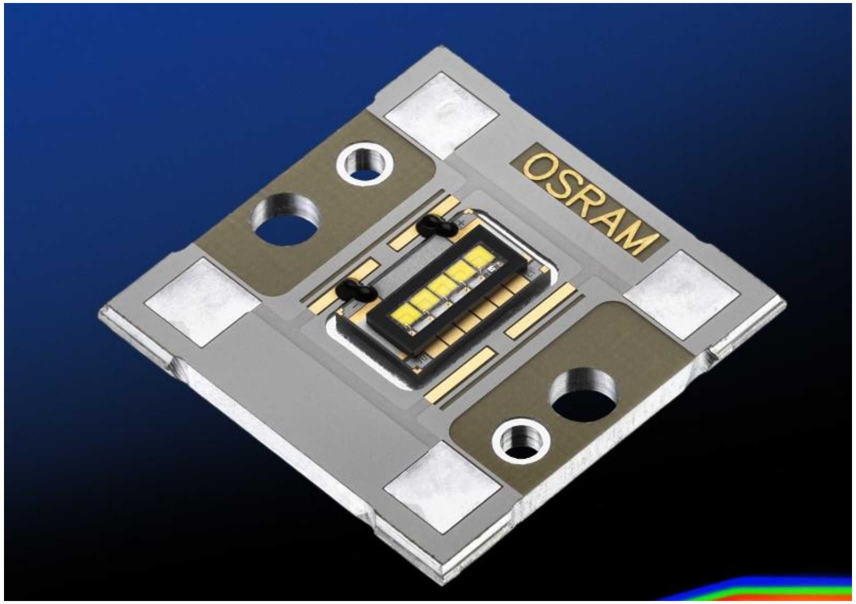


Aplicatii

- iluminat public

Aplicatii





Avantaje

- Eficienta
- Culoare usor de implementat (nativ)
- Dimensiune
- Timp de raspuns
- Reglaj al intensitatii luminoase
- Radiatie de caldura (IR) redusa
- Timp de viata
- Rezistenta la socuri
- Directivitatea luminii (nativ)

Dezavantaje

- Pret
- Dependenta de temperatura
- Sensibilitate la tensiune (prag)
- Calitatea luminii (corp negru)
- Directivitate (sursa de suprafata/punctuala)

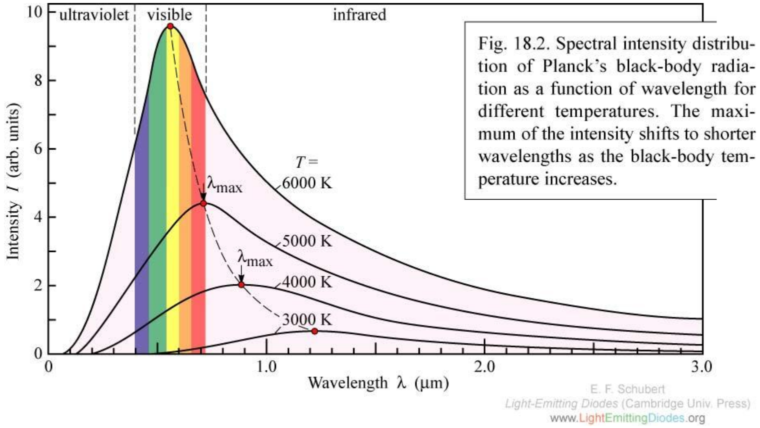
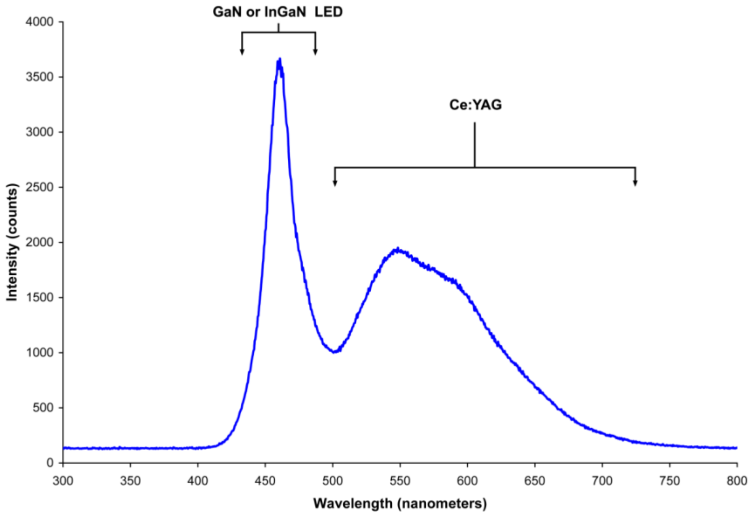
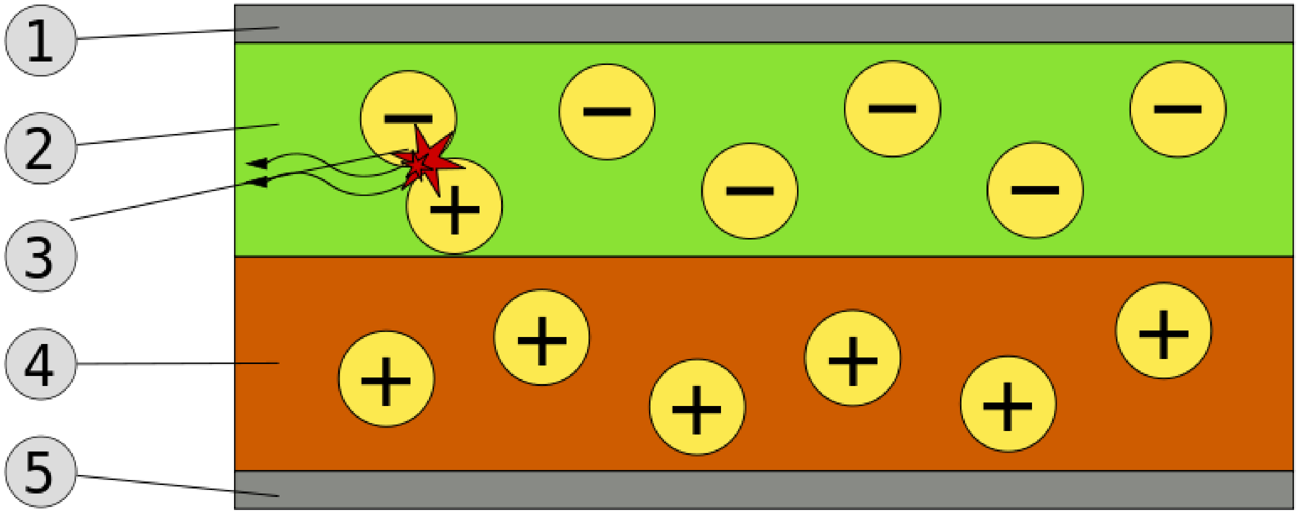


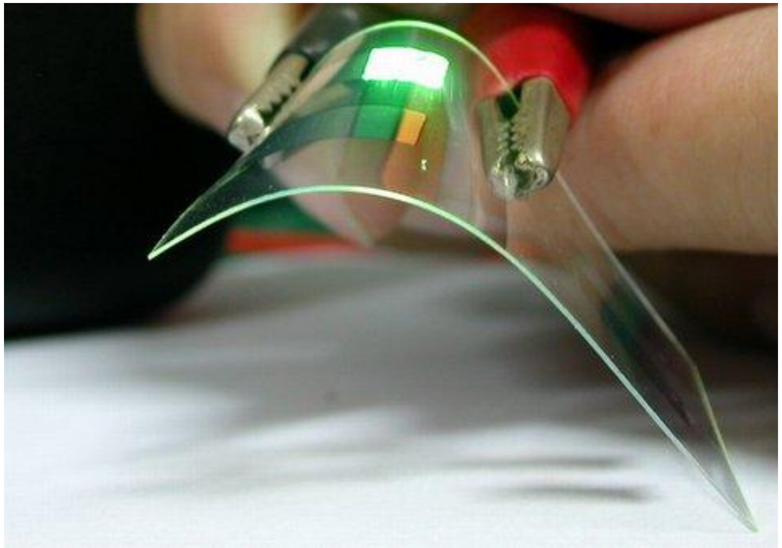
Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

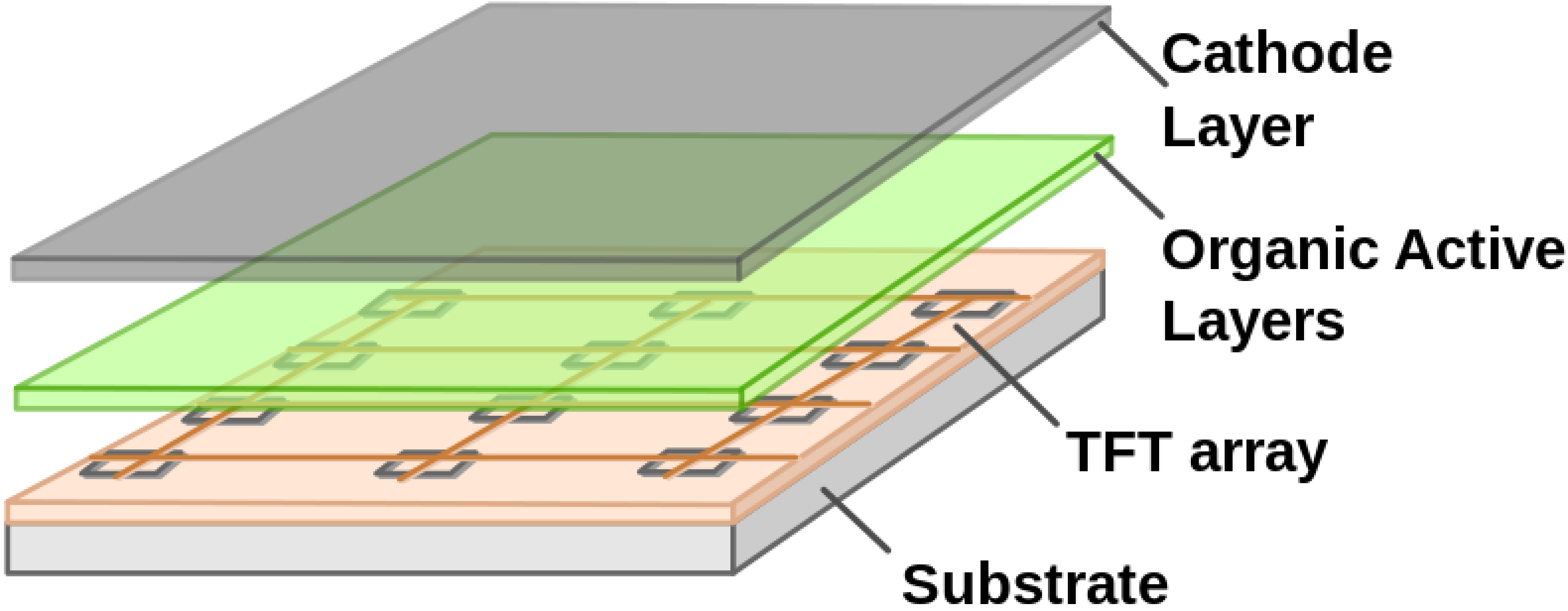


OLED





AMOLED

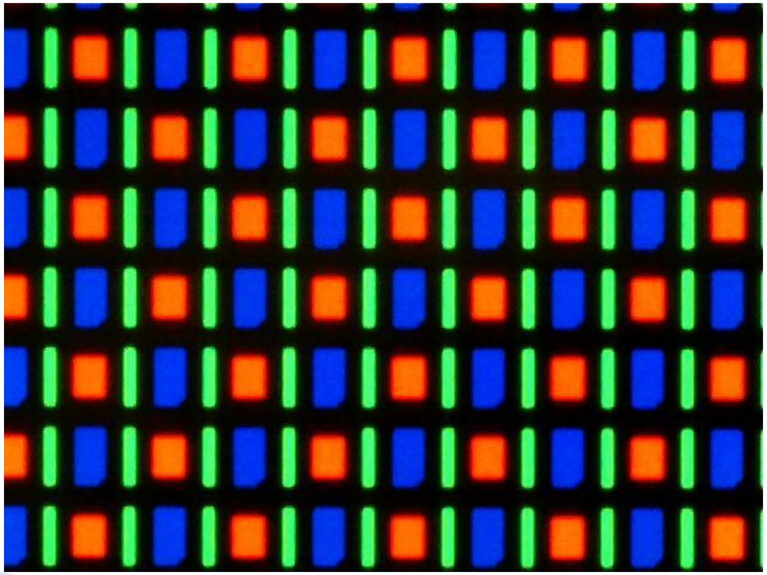


Cathode Layer

Organic Active Layers

TFT array

Substrate



Caracteristica de raspuns a LED-urilor

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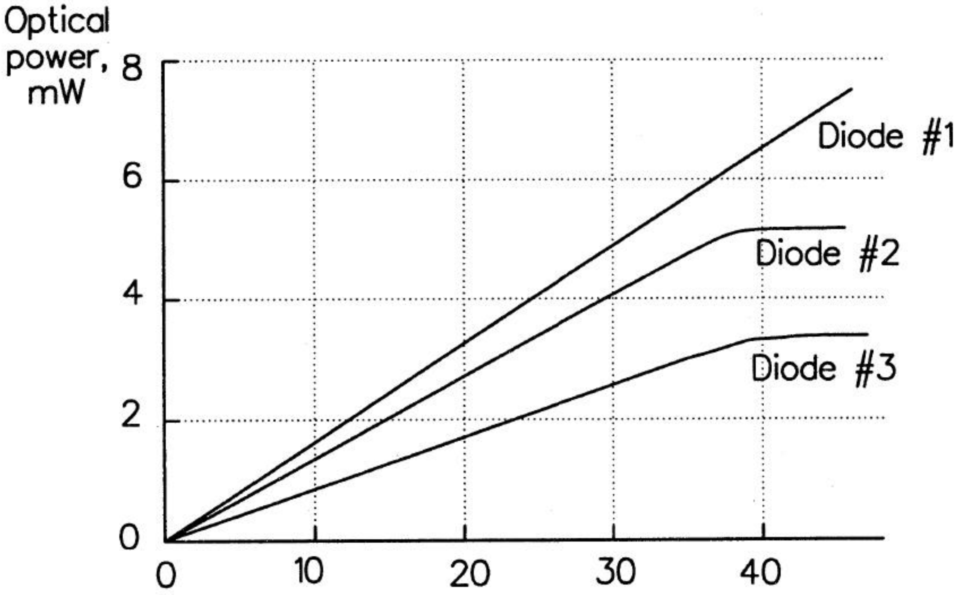
- Nu exista curent de prag
- La nivele foarte mari puterea optica se satureaza
- Responzivitatea

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

- Tipic r=50μW/mA

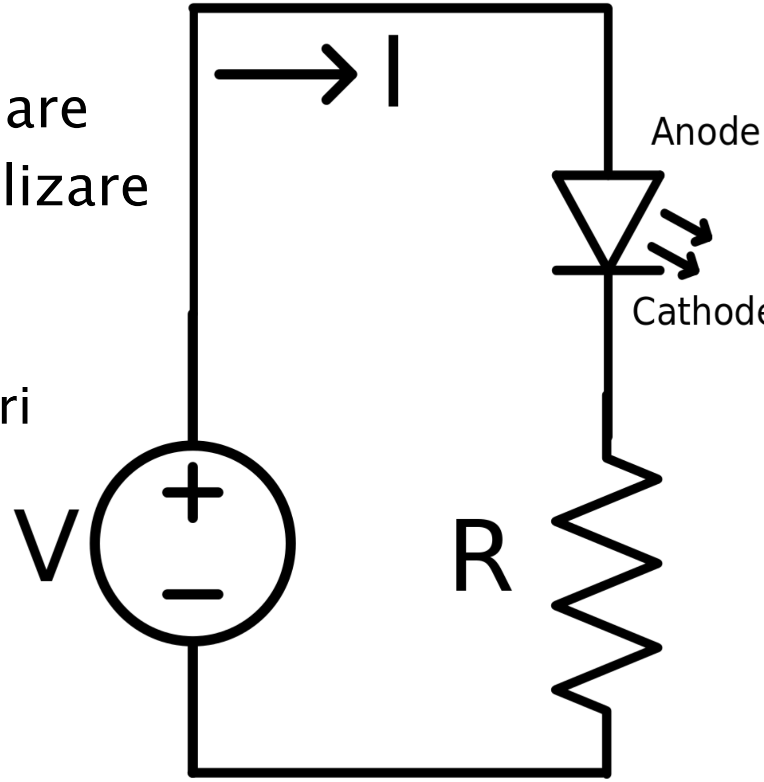


Control static LED

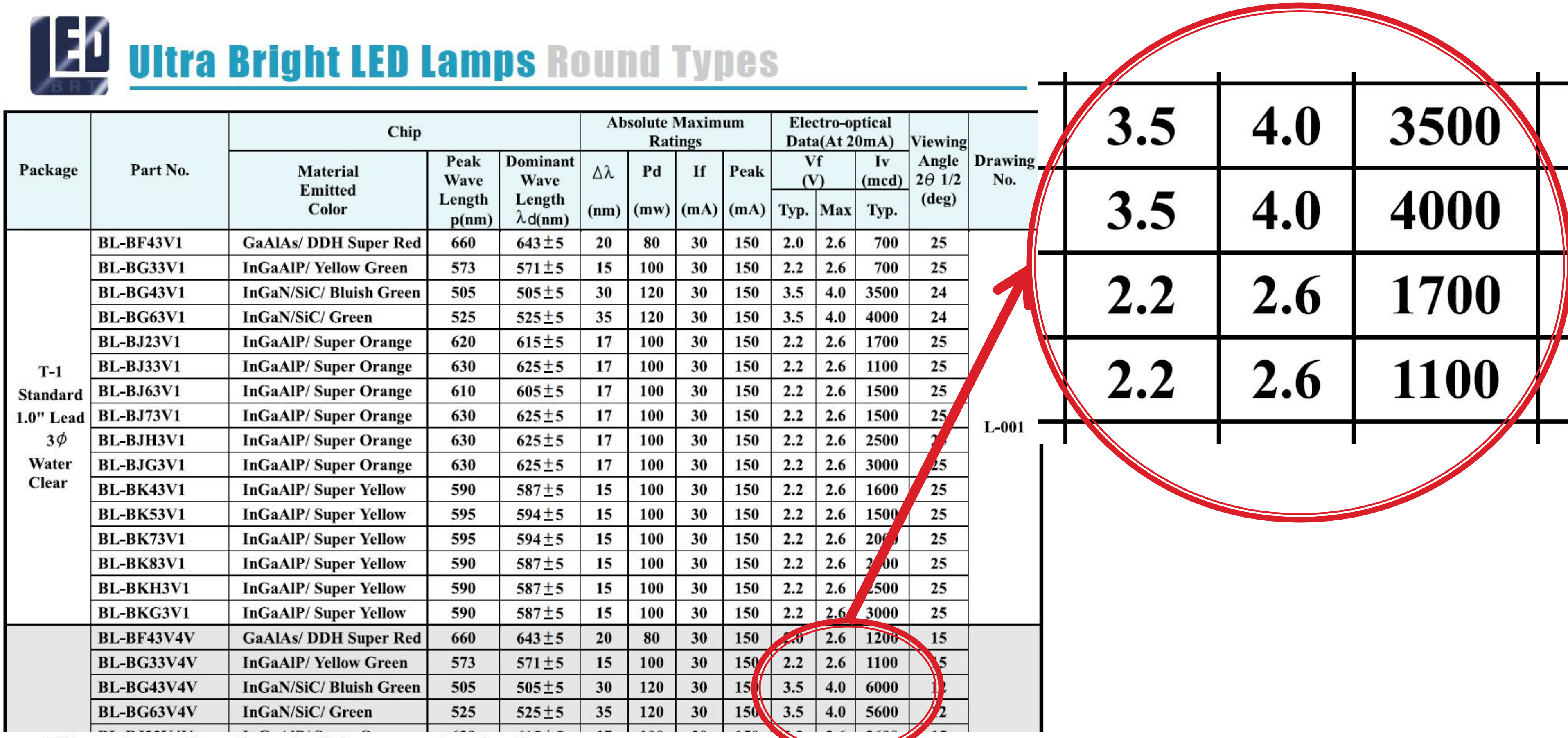
- Cea mai simpla schema de control: un rezistor in serie cu LED
  - **Atentie!** Tensiunea directa poate varia semnificativ (>>0.7V) si trebuie preluata din catalog
    - mai ales la intensitate luminoasa mare
    - datorita materialelor diferite de realizare a LED-urilor
    - dependenta de lungimea de unda
      - mai mica la lungimi de unda mai mari

$I_v = f\left(I_F[\text{mA}]\right) \quad [\text{cd/mcd}]$

$$I_F = \frac{V_{cc} - V_F}{R}$$



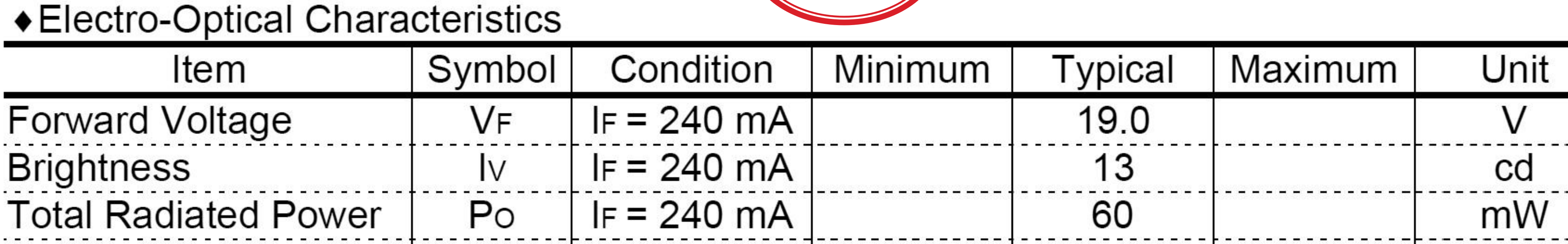
Control static LED



Ultra Bright LED Lamps Round Types

Package	Part No.	Chip			Absolute Maximum Ratings				Electro-optical Data(At 20mA)			Viewing Angle 2θ 1/2 (deg)	Drawing No.
		Material Emitted Color	Peak Wave Length p(nm)	Dominant Wave Length λd(nm)	Δλ (nm)	Pd (mw)	If (mA)	Peak (mA)	Vf (V) Typ.	Vf (V) Max	Iv (mcd) Typ.		
T-1 Standard 1.0" Lead 3φ Water Clear	BL-BF43V1	GaAlAs/ DDH Super Red	660	643±5	20	80	30	150	2.0	2.6	700	25	L-001
	BL-BG33V1	InGaAlP/ Yellow Green	573	571±5	15	100	30	150	2.2	2.6	700	25	
	BL-BG43V1	InGaN/SiC/ Bluish Green	505	505±5	30	120	30	150	3.5	4.0	3500	24	
	BL-BG63V1	InGaN/SiC/ Green	525	525±5	35	120	30	150	3.5	4.0	4000	24	
	BL-BJ23V1	InGaAlP/ Super Orange	620	615±5	17	100	30	150	2.2	2.6	1700	25	
	BL-BJ33V1	InGaAlP/ Super Orange	630	625±5	17	100	30	150	2.2	2.6	1100	25	
	BL-BJ63V1	InGaAlP/ Super Orange	610	605±5	17	100	30	150	2.2	2.6	1500	25	
	BL-BJ73V1	InGaAlP/ Super Orange	630	625±5	17	100	30	150	2.2	2.6	1500	25	
	BL-BJH3V1	InGaAlP/ Super Orange	630	625±5	17	100	30	150	2.2	2.6	2500	2[illegible]	
	BL-BJG3V1	InGaAlP/ Super Orange	630	625±5	17	100	30	150	2.2	2.6	3000	25	
	BL-BK43V1	InGaAlP/ Super Yellow	590	587±5	15	100	30	150	2.2	2.6	1600	25	
	BL-BK53V1	InGaAlP/ Super Yellow	595	594±5	15	100	30	150	2.2	2.6	1500	25	
	BL-BK73V1	InGaAlP/ Super Yellow	595	594±5	15	100	30	150	2.2	2.6	20[illegible]	25	
	BL-BK83V1	InGaAlP/ Super Yellow	590	587±5	15	100	30	150	2.2	2.6	2[illegible]00	25	
	BL-BKH3V1	InGaAlP/ Super Yellow	590	587±5	15	100	30	150	2.2	2.6	[illegible]500	25	
	BL-BKG3V1	InGaAlP/ Super Yellow	590	587±5	15	100	30	150	2.2	2.6	3000	25	
	BL-BF43V4V	GaAlAs/ DDH Super Red	660	643±5	20	80	30	150	[illegible]	2.6	1200	15	
	BL-BG33V4V	InGaAlP/ Yellow Green	573	571±5	15	100	30	150	2.2	2.6	1100	15	
	BL-BG43V4V	InGaN/SiC/ Bluish Green	505	505±5	30	120	30	150	3.5	4.0	6000	12	
	BL-BG63V4V	InGaN/SiC/ Green	525	525±5	35	120	30	150	3.5	4.0	5600	12	

3.5	4.0	3500
3.5	4.0	4000
2.2	2.6	1700
2.2	2.6	1100



♦Electro-Optical Characteristics

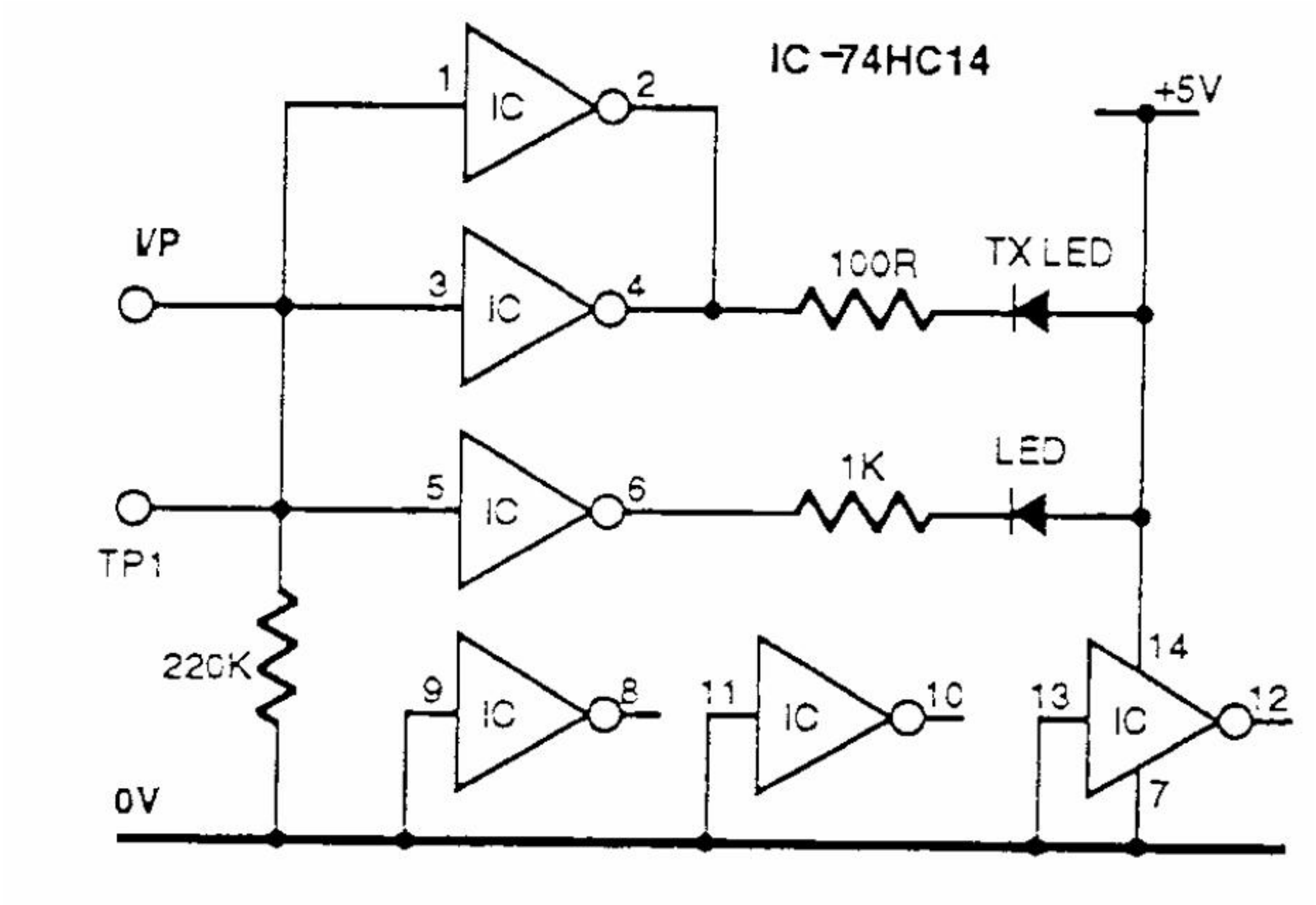
Item	Symbol	Condition	Minimum	Typical	Maximum	Unit
Forward Voltage	V_F	I_F = 240 mA		19.0		V
Brightness	I_V	I_F = 240 mA		13		cd
Total Radiated Power	P_O	I_F = 240 mA		60		mW

Control dinamic LED

- Variatii mici ale tensiunii (mai ales in jurul tensiunii de deschidere) pot duce la variatii mari ale curentului
- Se prefera de multe ori controlul in curent al LED-ului

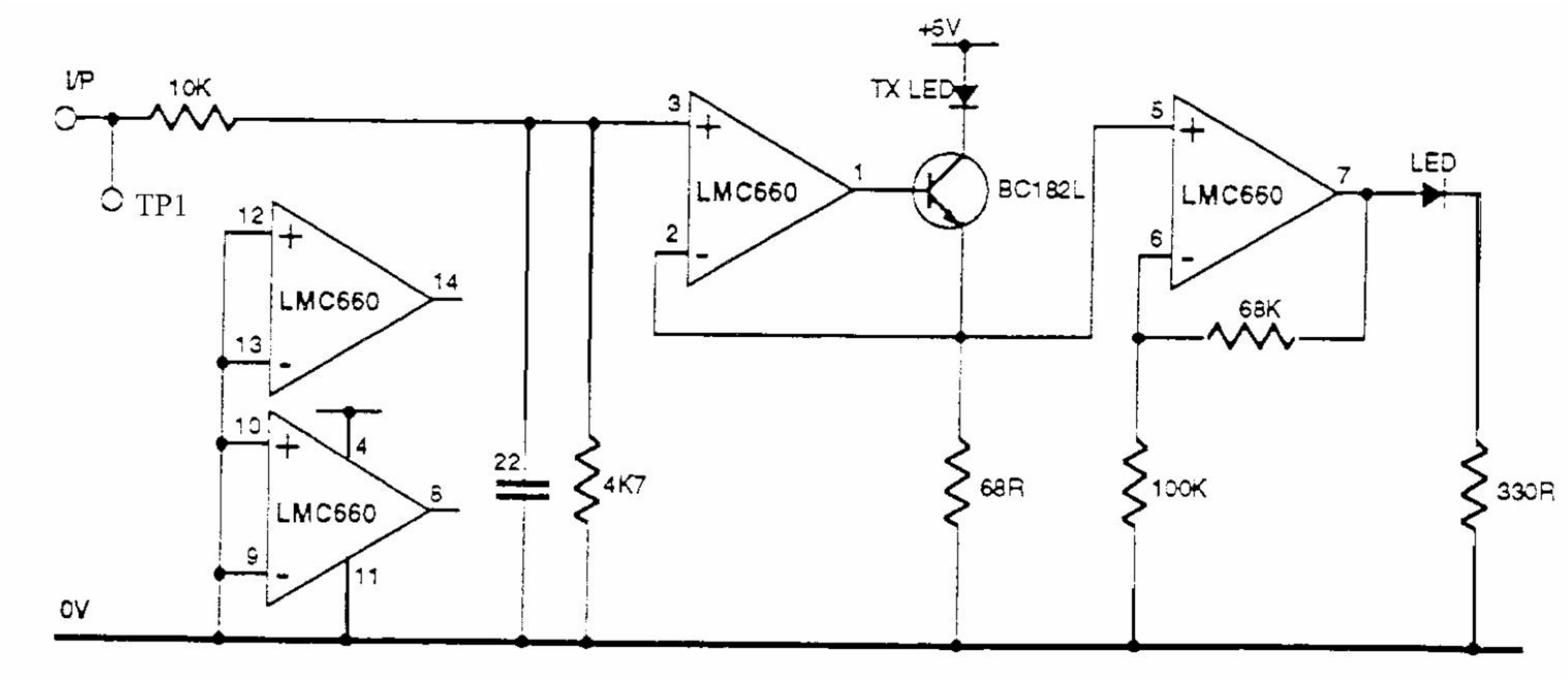
Control dinamic LED, Lab 1

- Control in tensiune
  - Schema electrică a emiţătorului în impuls



Control dinamic LED, Lab 1

- Control in curent
  - Schema electrică a emiţătorului optic analogic



Dioda Laser

Capitolul 8

Cuprins

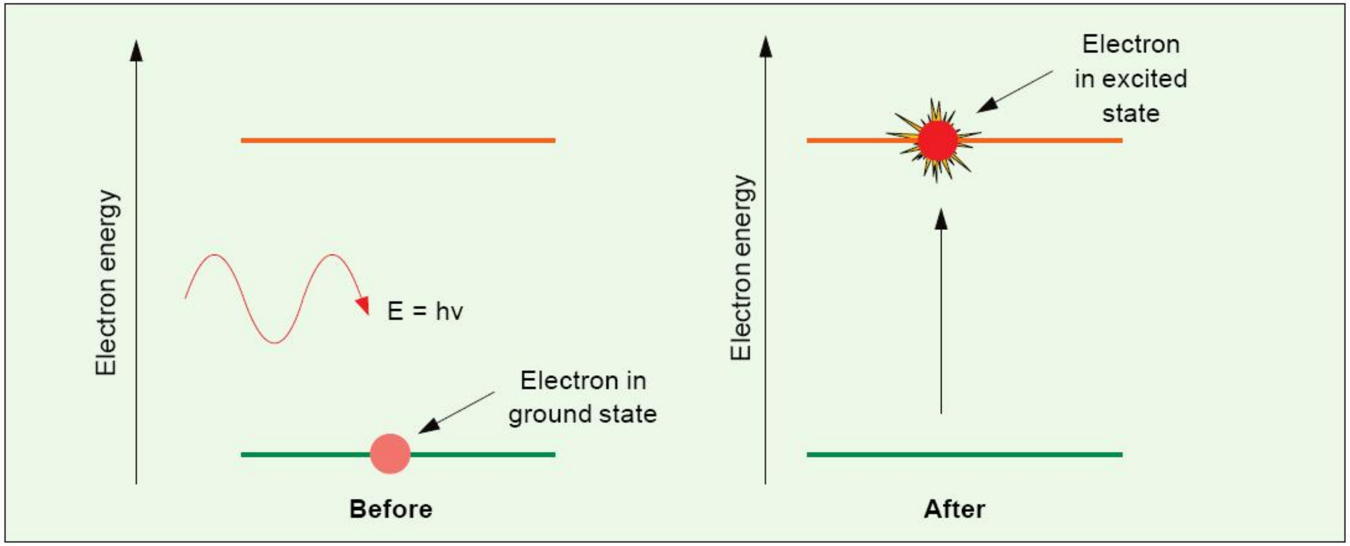
- **Lumina ca undă electromagnetică** (ecuaţiile lui Maxwell, ecuaţia undelor, parametrii de propagare)
- **Elemente de fotometrie şi radiometrie** (mărimi energetice/luminoase)
- **Fibra optică** (realizare, principiu de funcţionare, atenuare, dispersie, banda de frecvenţă)
- **Cabluri optice** (tehnologie, conectori, lipire - splice)
- **Proiectare sistemică a legăturii pe fibra optică** (bandă de frecvenţă, balanţa puterilor)
- **Emiţătoare optice** (LED şi dioda laser - realizare fizică şi functionare)
- **Receptoare optice** (dioda PIN, dioda cu avalanşă - realizare fizică şi functionare)
- **Amplificatoare transimpedanţă** (parametri, scheme tipice, TIA în buclă deschisă, cu reacţie, diferenţiale, control automat al câştigului)
- **Realizarea circuitelor pentru controlul emiţătoarelor optice (**parametri, scheme tipice, controlul puterii, multiplexoare**)**
- **Dispozitive de captare a energiei solare** (principiu de functionare, utilizare, proiectare)

Caracteristici dioda laser

- Avantaje
  - Putere optica ridicata (50mW functionare continua, 4W functionare in impulsuri)
  - Precizie ridicata a controlului (impulsuri cu latimea de ordinul fs – femptosecunde) – viteza mare de lucru
  - Spectru ingust, teoretic LASER ofera o singura linie spectrala
  - Lumina coerenta si directiva (~80% poate fi cuplata in fibra)
- Dezavantaje
  - Cost (dispozitiv si circuit de comanda: controlul puterii si al temperaturii)
  - Durata de viata
  - Senzitivitate crescuta cu temperatura
  - Modulatie analogica dificila (de obicei cu dispozitive externe)
  - Lungime de unda fixa

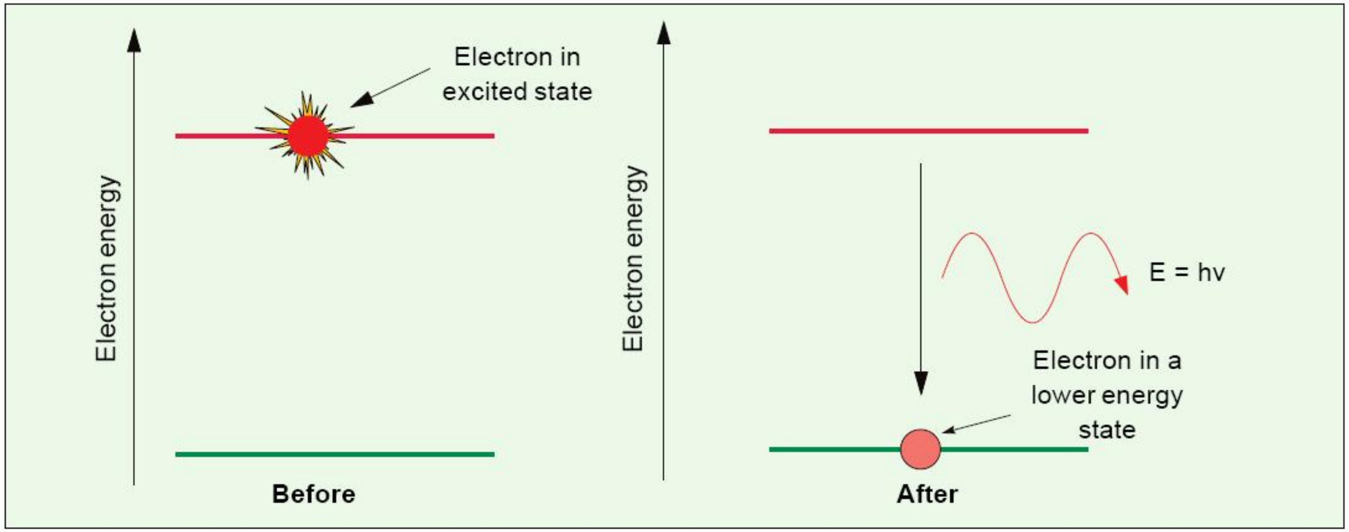
Dioda LASER – Principiu de operare

- LASER = Light Amplification by the Stimulated Emission of Radiation = Amplificarea Luminii prin Emisie Stimulata
- Un foton incident poate cauza prin absorbtie tranzitia unui electron pe un nivel energetic superior



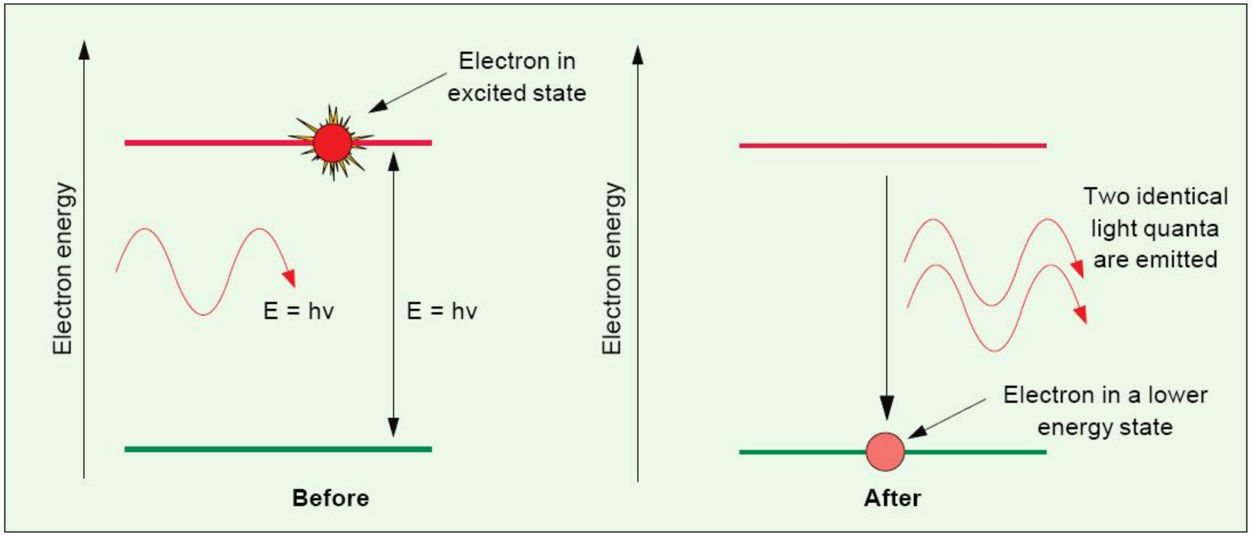
Dioda LASER – Principiu de operare

- 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



Detalii constructive

- Recombinarea unei perechi electron-gol necesita conservarea impulsului
- In Si si Ge aceasta conditie presupune aparitia unui foton intermediar (tranzitie indirecta) a carui energie se transforma in caldura
- Se utilizeaza aliaje de Ga Al As sau In Ga As P
- Spatierea atomilor in diferitele straturi trebuie sa fie egala (toleranta 0.1%) pentru a nu se introduce defecte mecanice la jonctiune
  - limitare a aliajelor utilizabile
  - aparitia defectelor
    - creste ineficienta (recombinari neradiative)
    - scade durata de viata a dispozitivului

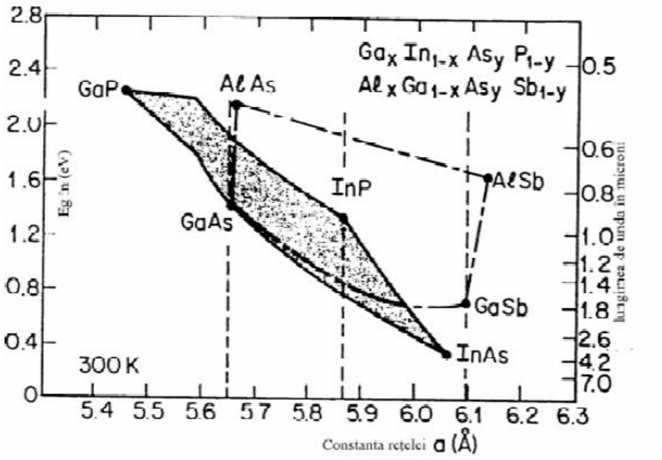
Lăţimea benzii interzise/lungime de undă pentru materialele uzuale

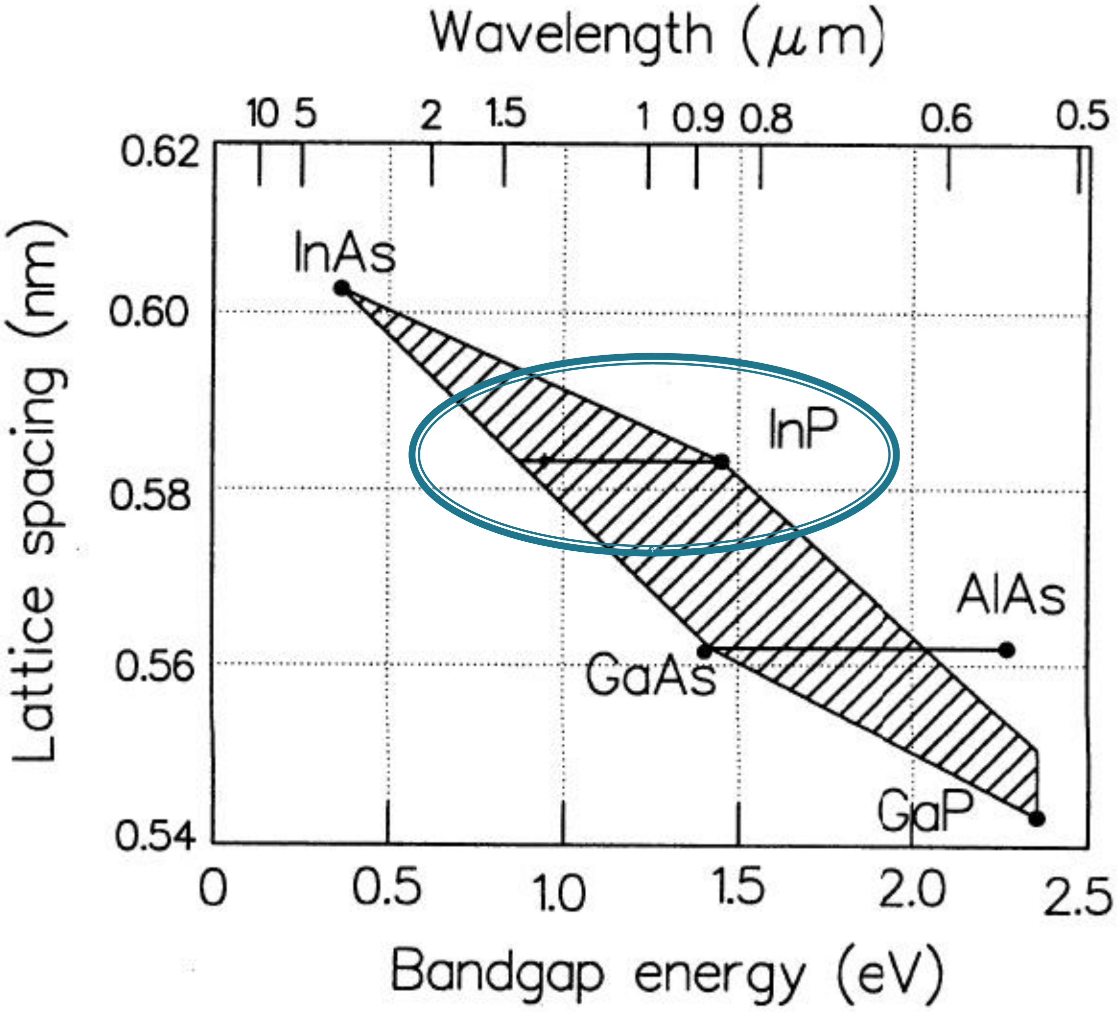
Material	**Formula**	**Wavelength Range λ (μm)**	**Bandgap Energy W_g (eV)**
Indium Phosphide	InP	0.92	1.35
Indium Arsenide	InAs	3.6	0.34
Gallium Phosphide	GaP	0.55	2.24
Gallium Arsenide	GaAs	0.87	1.42
Aluminium Arsenide	AlAs	0.59	2.09
Gallium Indium Phosphide	GaInP	0.64-0.68	1.82-1.94
Aluminium Gallium Arsenide	AlGaAs	0.8-0.9	1.4-1.55
Indium Gallium Arsenide	InGaAs	1.0-1.3	0.95-1.24
Indium Gallium Arsenide Phosphide	InGaAsP	0.9-1.7	0.73-1.35

$$E_g = h\nu; \quad \lambda = \frac{hc}{E_g}; \quad \lambda[\mu\mathrm{m}] = \frac{1.240}{E_g[\mathrm{eV}]}$$

- h constanta lui Plank $6.6261 \cdot 10^{-34}$ Ws^2
- c viteza luminii **in vid** $2.998 \cdot 10^{8}$ m/s
- e sarcina electronului $1.6 \cdot 10^{-19}$ C
- benzi energetice: λ_0, $\boldsymbol{\Delta\lambda}$

Dependenţa benzii interzise de constanta reţelei



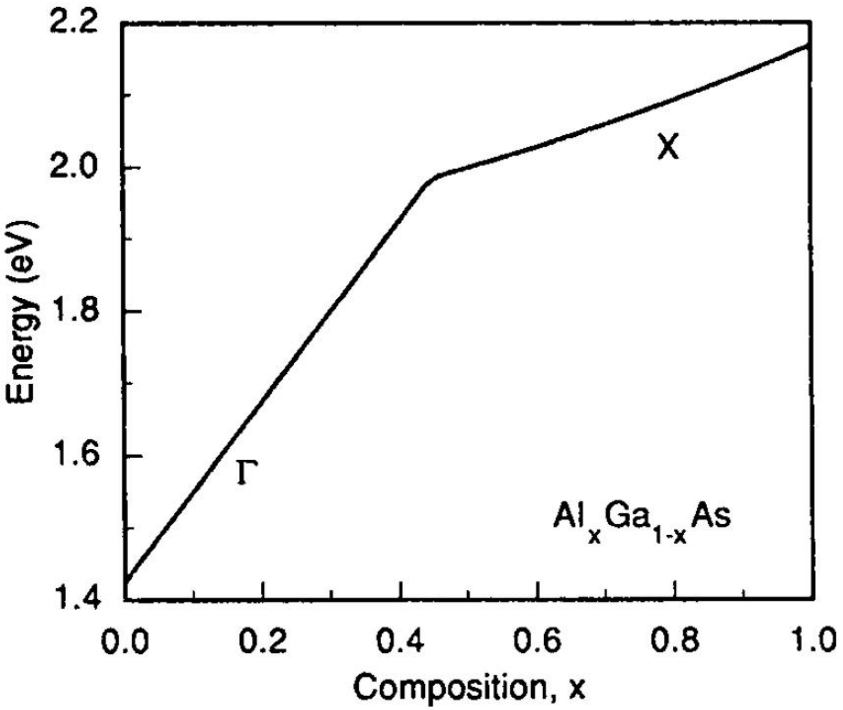


Materiale

- Lungimi de unda mici (spectru vizibil – 1000nm)
  - GaP (665nm), $GaAs_yP_{1-y}$
  - GaAs (900nm), $Ga_{1-x}Al_xAs$ (AlAs – 550nm)
- Lungimi de unda mari (1000÷1700nm)
  - $In_xGa_{1-x}As_yP_{1-y}$
  - x,y concentratii relative in aliaj a materialelor corespunzatoare
  - x,y alese din considerente privind
    - lungimea de unda
    - spatierea atomilor

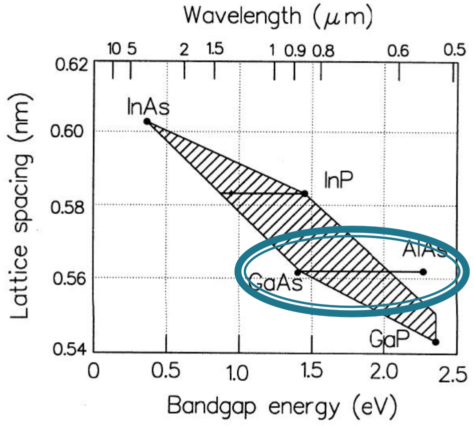
Materiale

- Lungimi de unda mici
  - $Ga_{1-x}Al_xAs$
  - substrat GaAs
  - limitare pentru tranzitie directa, x<0.45
  - E_g (in eV)



$$E_g = 1.424 + 1.247 \cdot x, \quad x < 0.45$$

$$E_g = 1.9 + 0.125 \cdot x + 0.143 \cdot x^2, \quad x > 0.45$$



Materiale

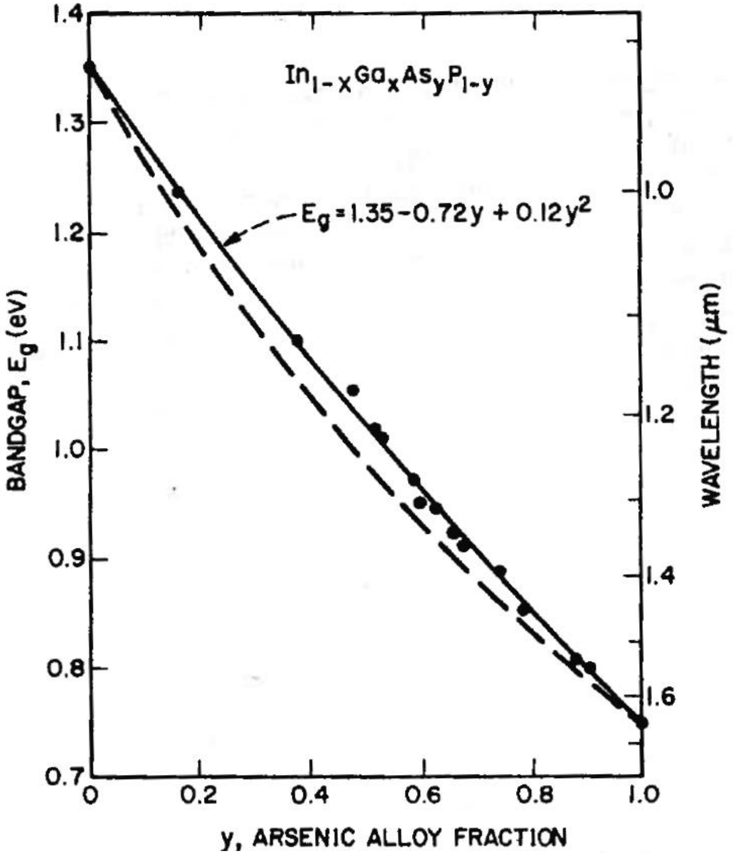
- Lungimi de unda mari
  - $In_xGa_{1-x}As_yP_{1-y}$
  - Tipic substratul este InP
    - Spatierea atomilor (lattice spacing) corespunzatoare InP

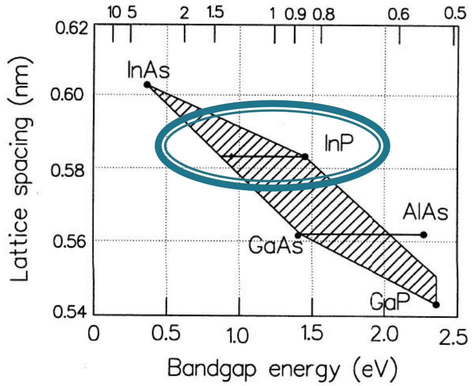
$$x = \frac{0.4526 \cdot y}{1 - 0.031 \cdot y}$$

  - E_g (in eV)

$$E_g = 1.35 - 0.72 \cdot y + 0.12 \cdot y^2$$

  - Exemplu: 1300nm se obtine cu y=0.611 si x=0.282,
    - $In_{0.282}Ga_{0.718}As_{0.611}P_{0.389}$





Principii LASER

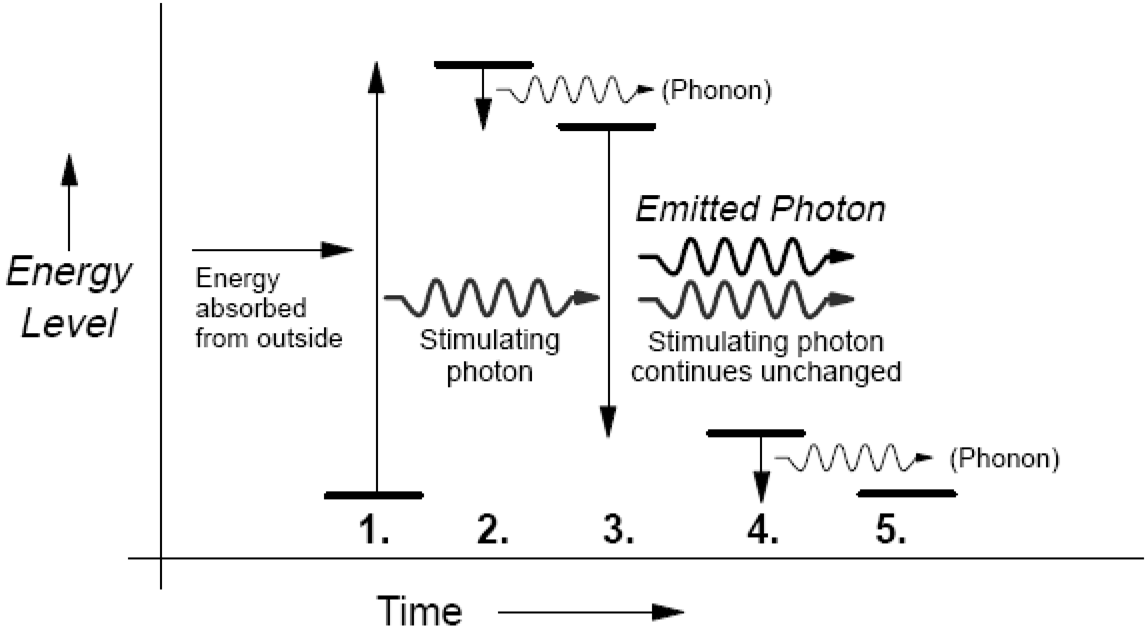
- Inversiune de populatie
    - necesara deoarece electronii au capabilitatea de a absorbi energie la aceeasi frecventa la care are loc emisia stimulata
    - se defineste probabilistic: probabilitatea de emisie stimulata sa fie mai mare decat probabilitatea de absorbtie

$$n_c \cdot p_e > n_v \cdot p_a$$

- Materialele capabile sa genereze inversiune de populatie au starea excitata metastabila

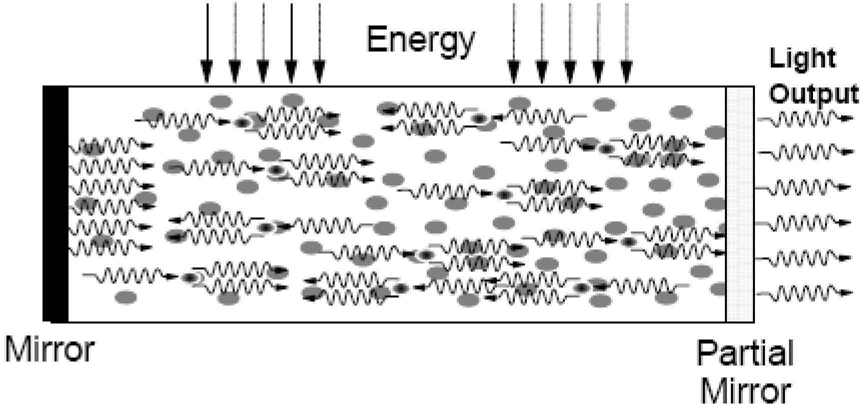
Materiale cu 4 nivele energetice

- 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



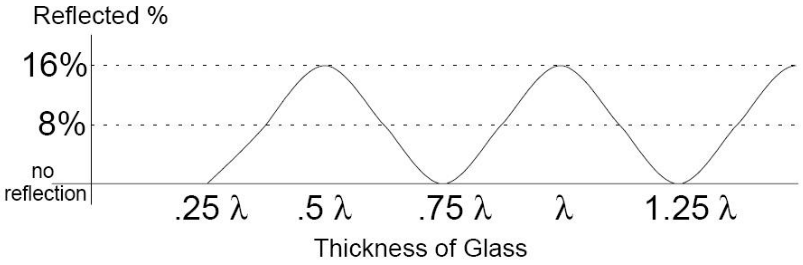
Dioda LASER – Principiu de realizare

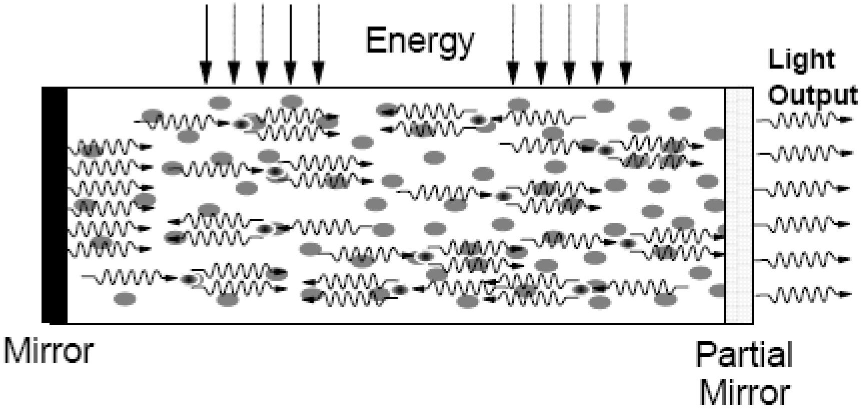
- Pentru ca emisia stimulata sa apara, fotonii emisi trebuie sa ramana in contact cu materialul o perioada mai mare de timp – 2 oglinzi necesare
- Pentru a permite extragerea radiatiei e necesar ca una din oglinzi sa fie partial reflectanta



Dioda LASER – Principiu de realizare

- Pentru diodele laser utilizate in comunicatii reflectivitatea oglinzilor nu trebuie sa fie foarte mare
- Interfata semiconductor aer ofera un coeficient de reflexie de ~6% dar poate ajunge la 36% pentru lungimea de unda de operare (vezi lamela dielectrica)





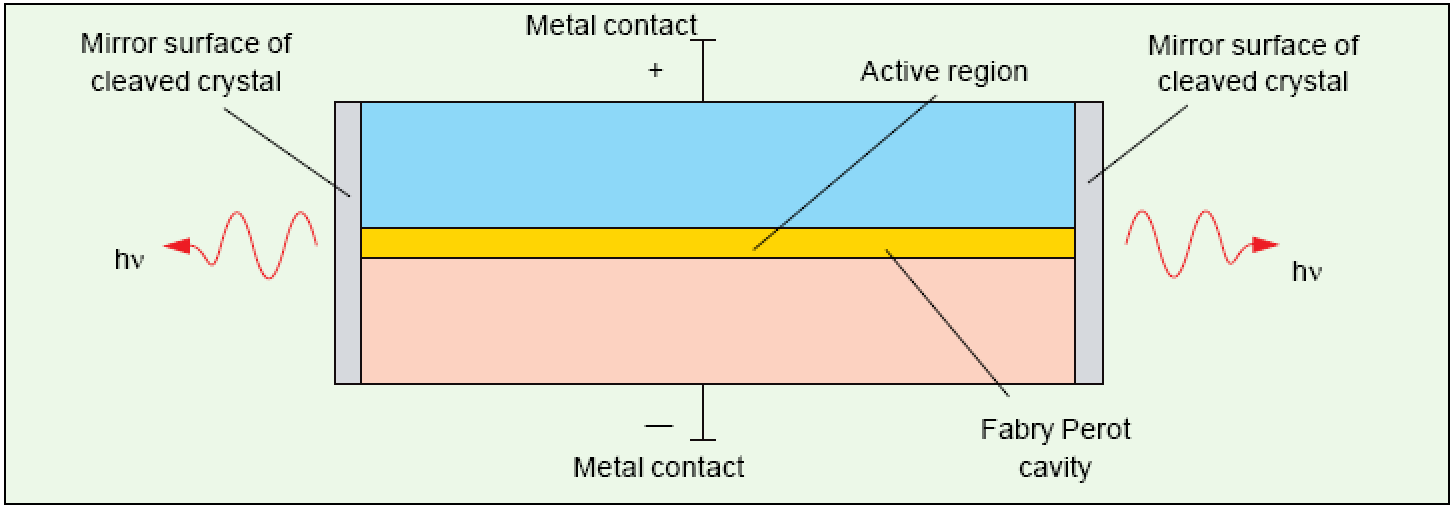
Dioda LASER – Principiu de realizare

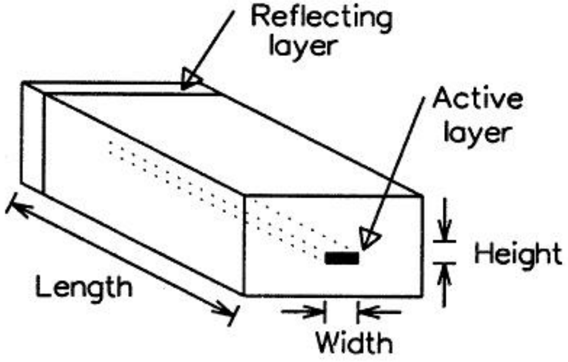
- Pentru a realiza
  - coerenta radiatiei
  - interferenta constructiva intre radiatiile incidente si reflectate de oglinzi,
- distanta intre oglinzi trebuie sa fie un multiplu a jumatate din lungimea de unda

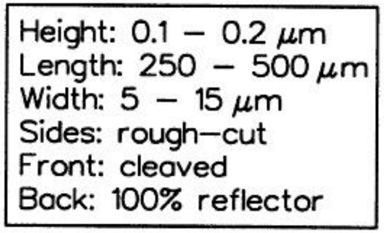
$$L = k \cdot \frac{1}{2} \cdot \frac{\lambda_0}{n} \qquad L = k \cdot \frac{c_0}{2 \cdot n \cdot f} \qquad f = k \cdot \frac{c_0}{2 \cdot n \cdot L}$$

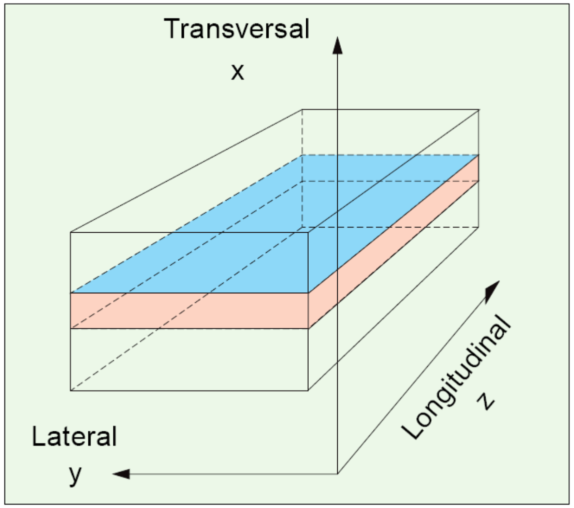
- Pentru eficientizarea pomparii de energie din exterior $L = 100 \div 200 \mu m$, $k \cong 400$

Dioda LASER Fabry Perot



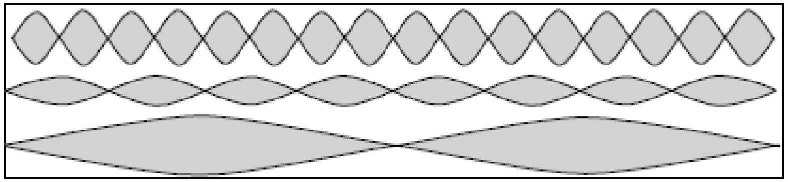



Height: 0.1 – 0.2 μm
Length: 250 – 500 μm
Width: 5 – 15 μm
Sides: rough–cut
Front: cleaved
Back: 100% reflector

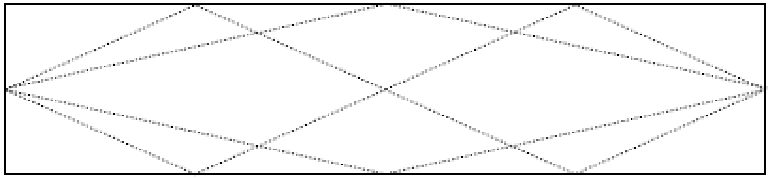


Definirea directiilor in dioda LASER

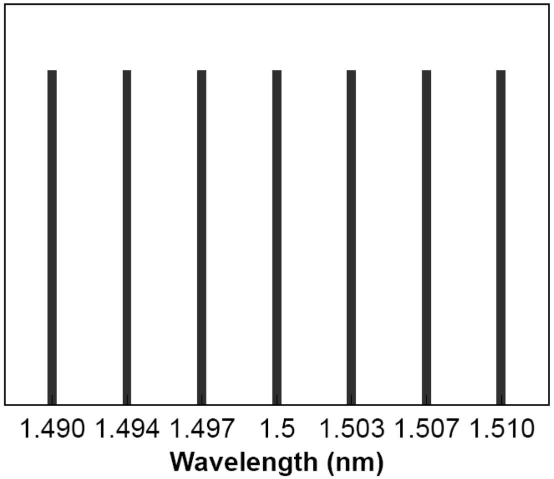
Spectrul diodei LASER



Longitudinal Modes



Lateral Modes



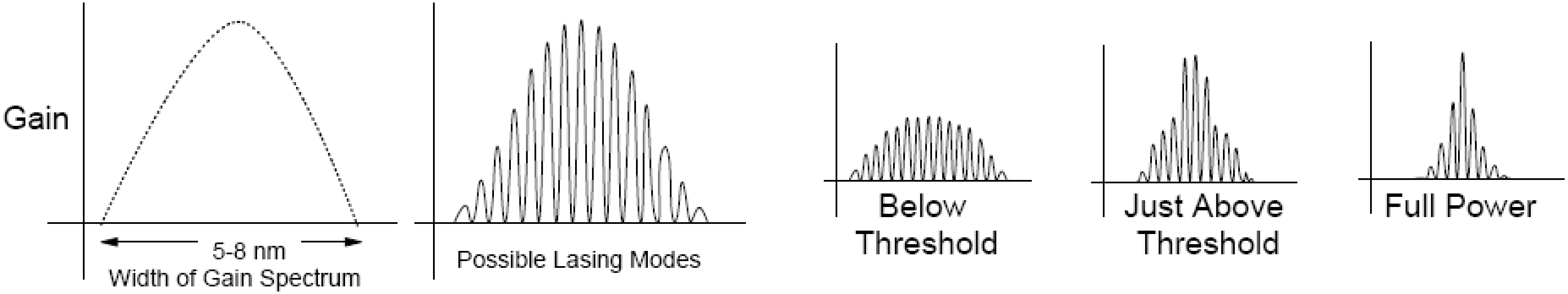
$$f_k = k \cdot \frac{c_0}{2 \cdot n \cdot L}$$

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

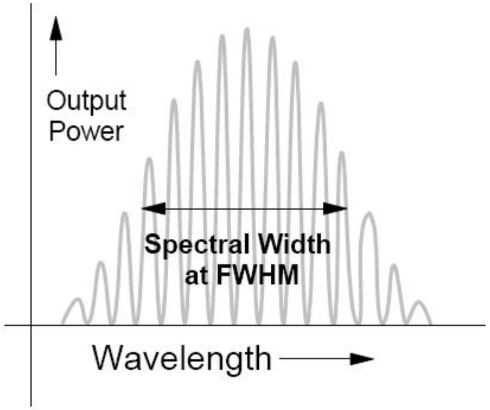
$$\Delta\lambda \cong \frac{\lambda_0^2}{2 \cdot n \cdot L}$$

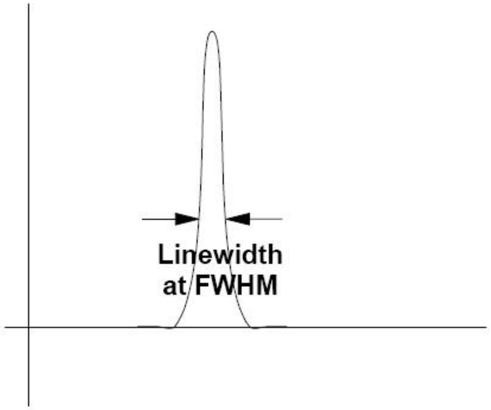
Spectrul diodei LASER

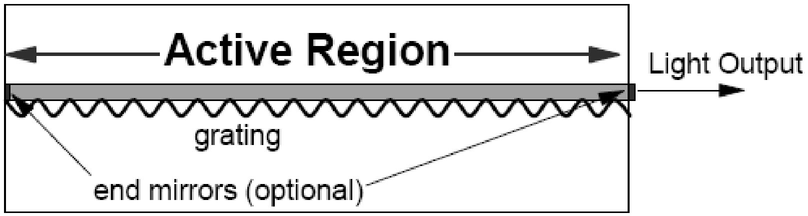
- Castigul diodei laser (eficacitatea aparitiei emisiei stimulate) depinde
  - de caracteristicile energetice ale materialului din care e realizata dioda
  - de energia pompata din exterior (curentul prin dioda)

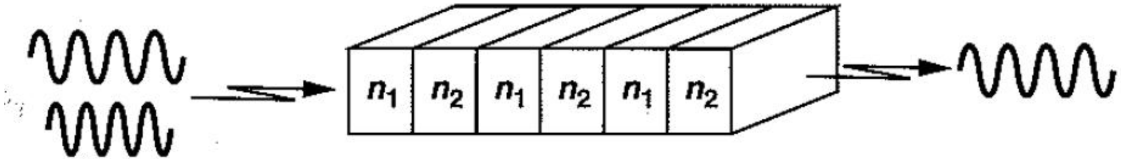


Distributed Feedback (DFB) Lasers

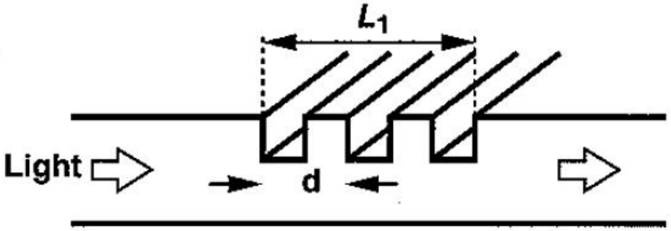








(a)

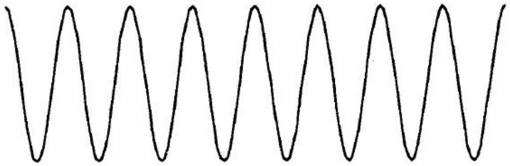


(b)

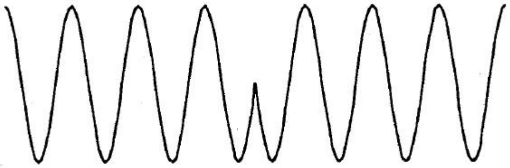
Filtre spatiale in regiunea activa

Distributed Feedback (DFB) Lasers

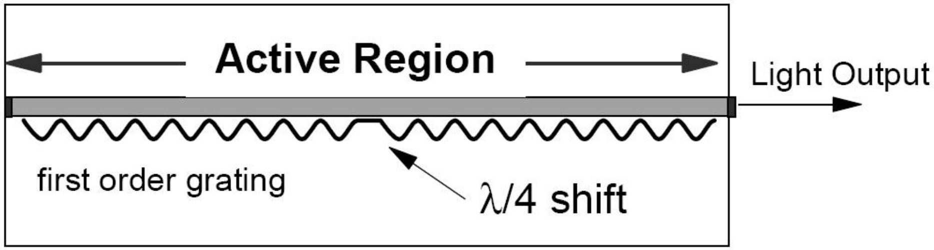
- Pentru operarea in impulsuri, un salt de λ/4 ingusteaza suplimentar spectrul diodei laser

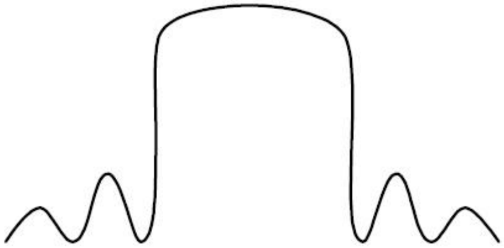


(a)

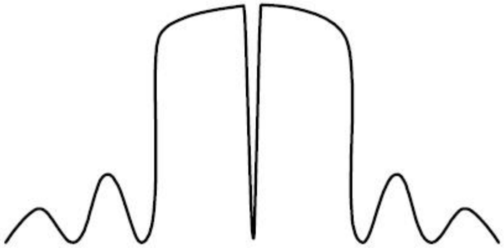


(b)





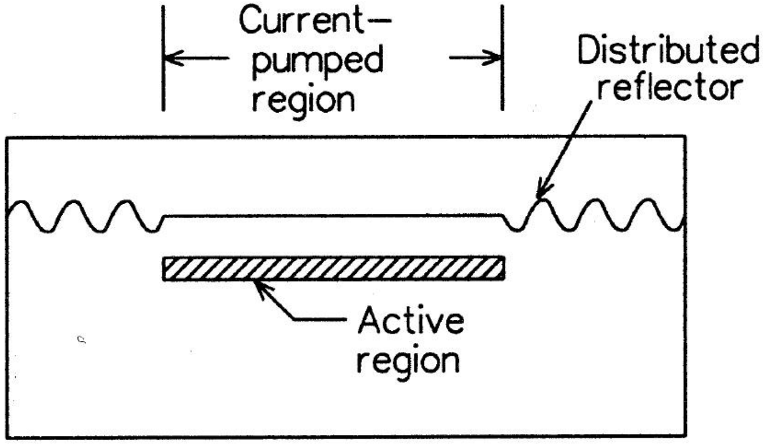
Reflection Characteristic without Phase Shift

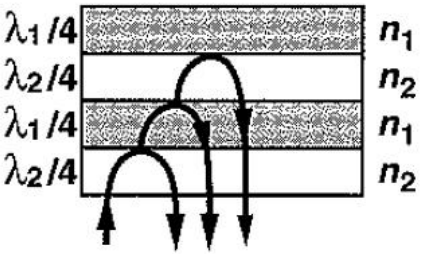


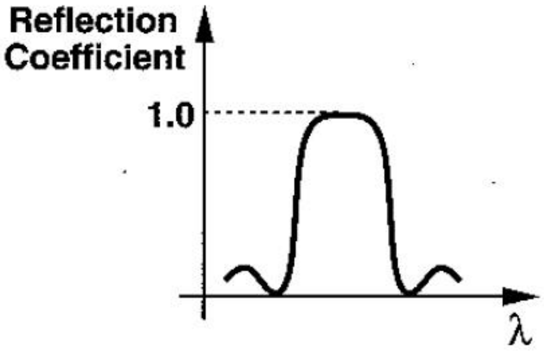
Reflection Characteristic Phase Shifted grating

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

$I < I_{th}$ regim LED

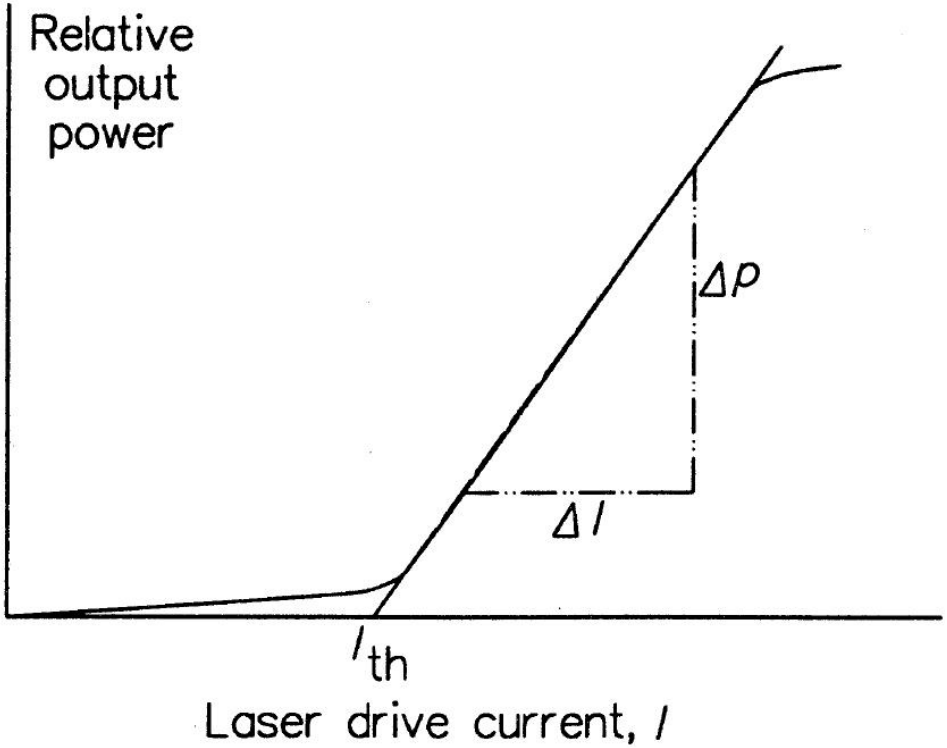
ineficient!, $P_o \cong 0$

$I > I_{th}$ regim LASER

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

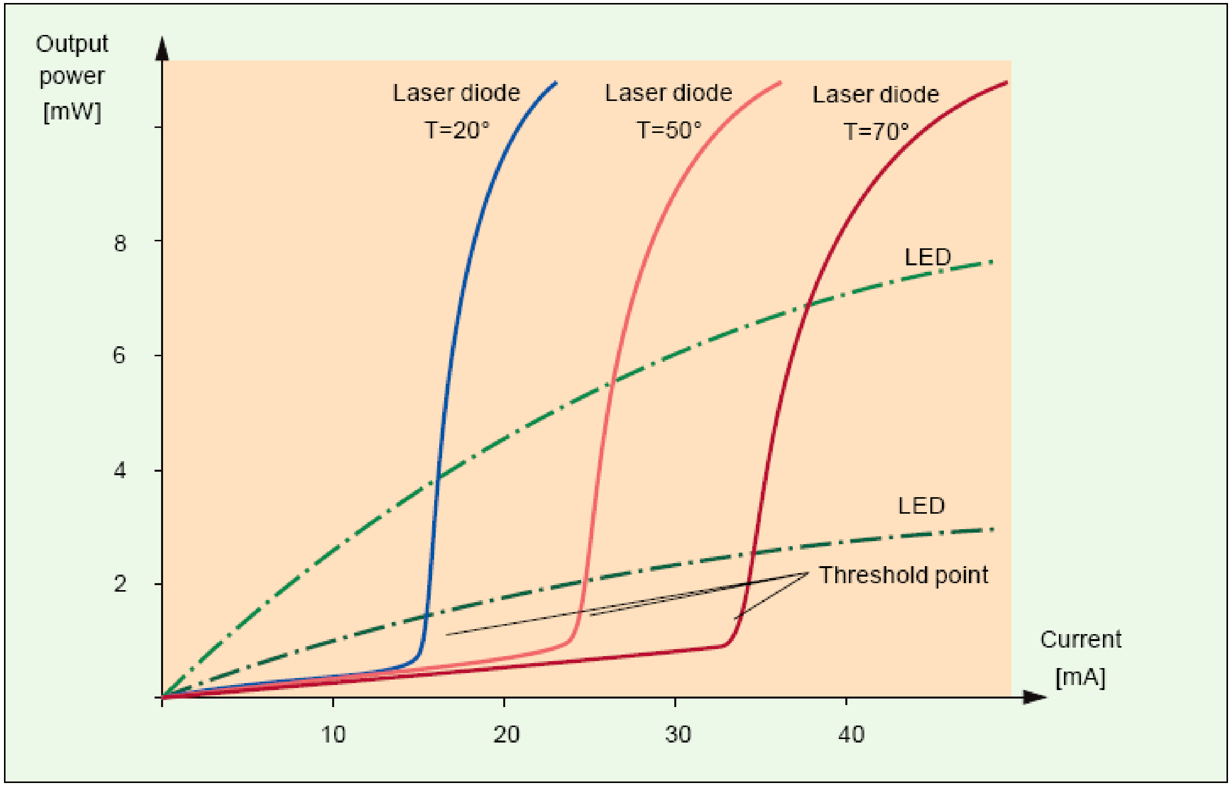
$$P_o = r \cdot (I - I_{th})$$

Apare saturare la nivele mari de curent



Temperatura si îmbatrânire

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

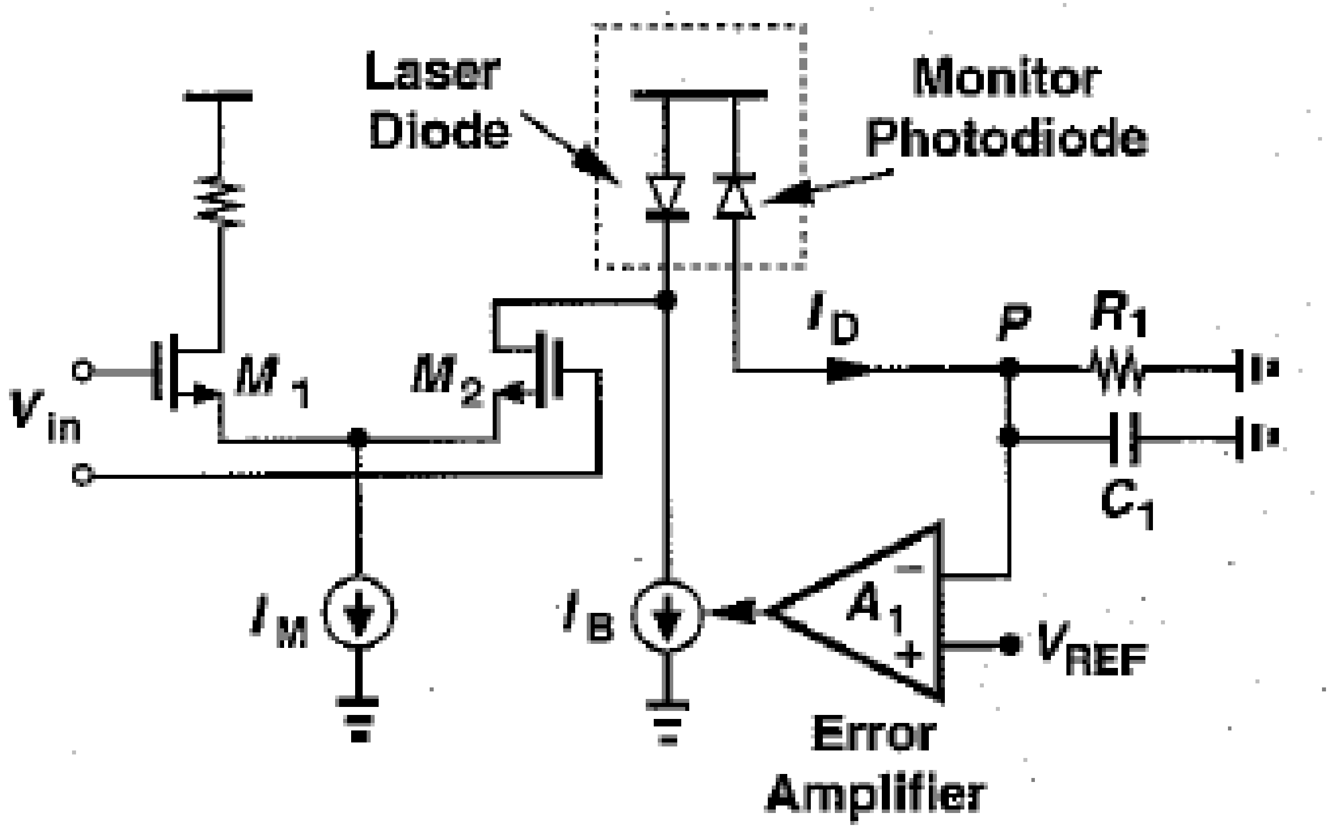


Dependenta de temperatura

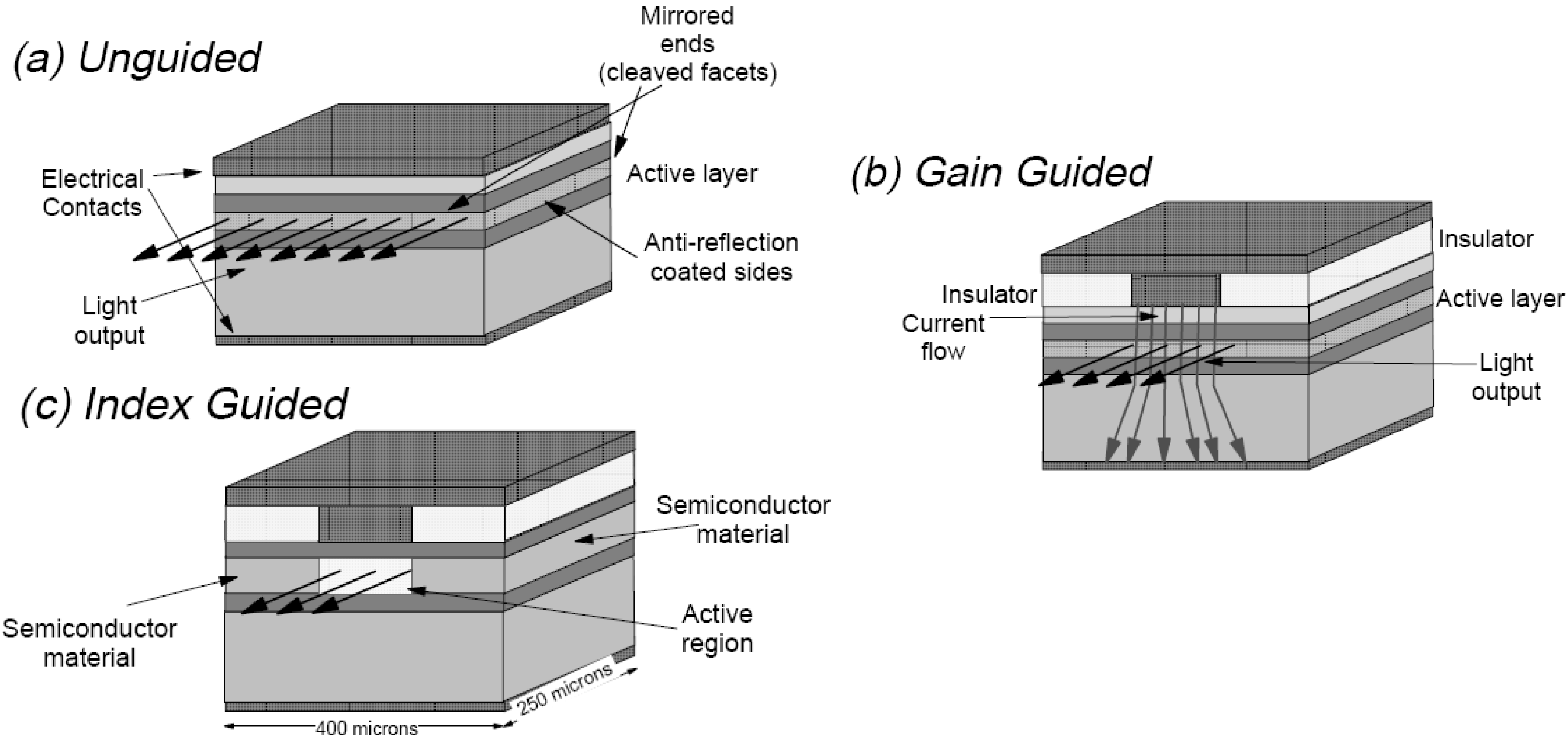
- Dependenta de temperatura a curentului de prag este exponentiala
- $$I_{th} = I_0 \cdot e^{T/T_0}$$
- I_0 e o constanta determinata la temperatura de referinta

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

Monitorizarea radiaţiei de spate

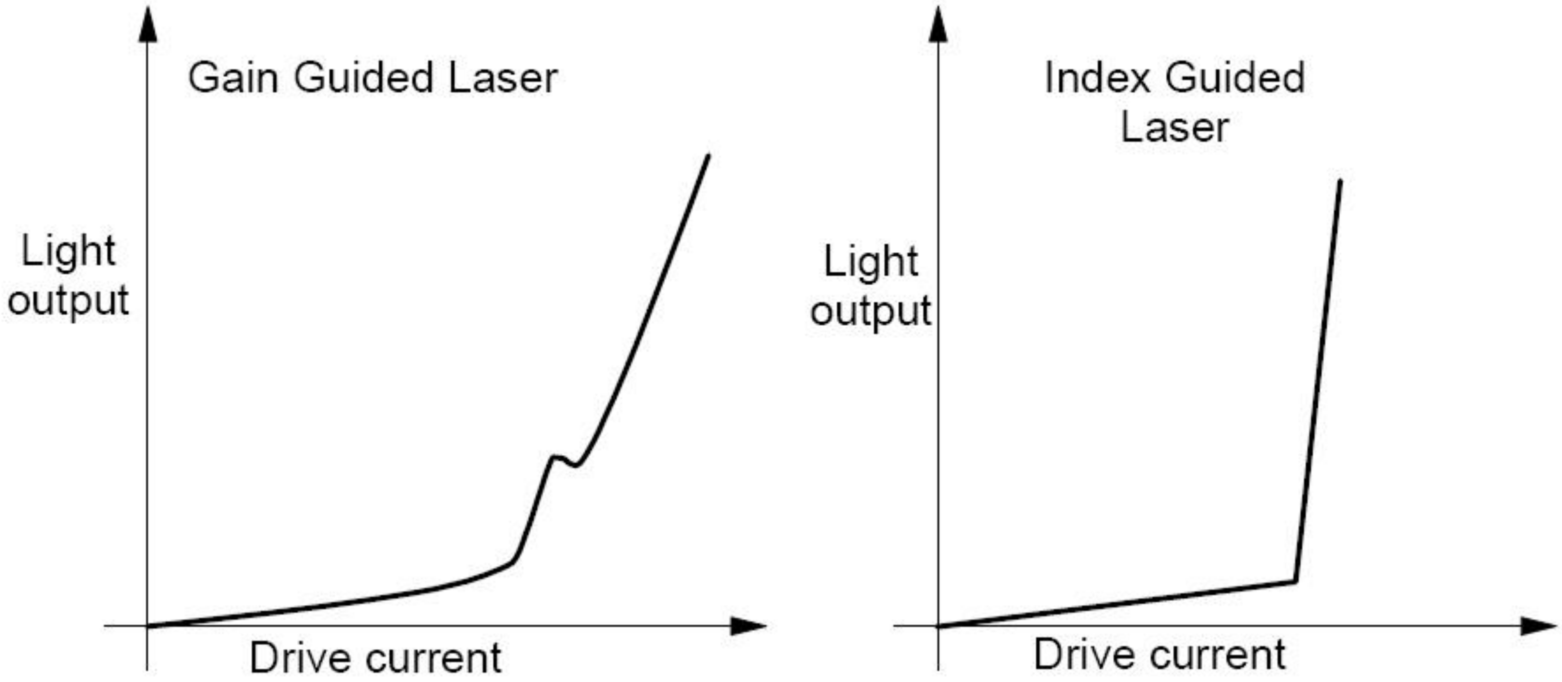


Direcţionarea luminii în laser-ul Fabry Perot

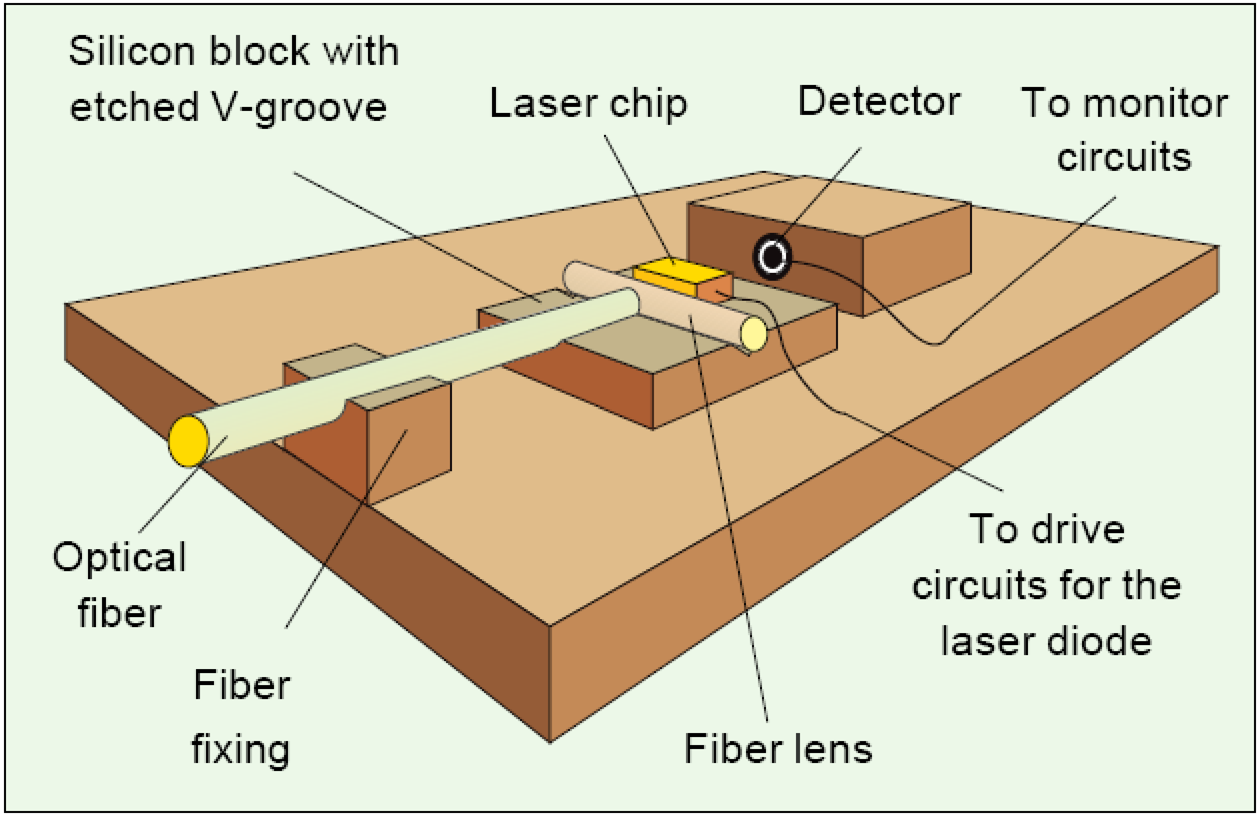


Efectul ghidarii

- Gain guided – 8÷20 linii spectrale (5÷8 nm)
- Index guided – 1÷5 linii spectrale (1÷3 nm)

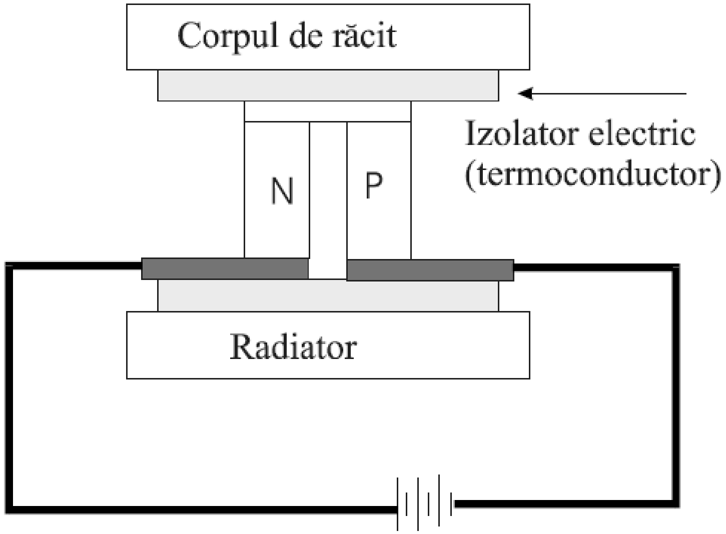


Cuplarea luminii în fibră



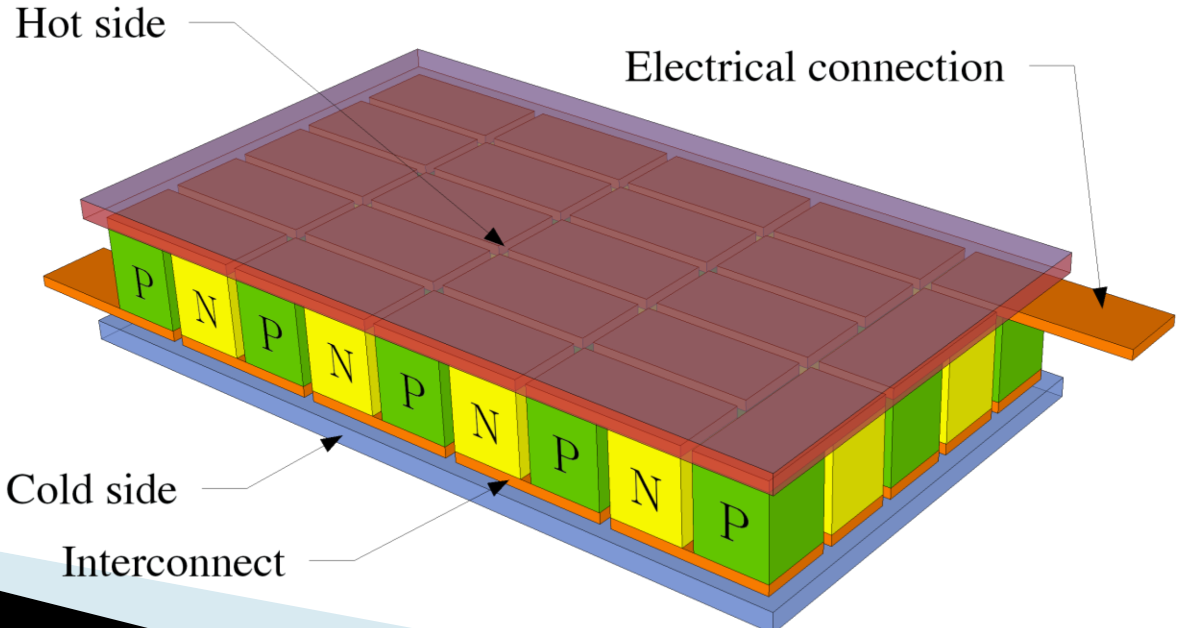
Dispozitiv termoelectric (Peltier)

- Jonctiunea intre doua materiale conductoare diferite poate genera sau absorbi caldura in functie de sensul curentului
- Tipic se utilizeaza doua regiuni semiconductoare puternic dopate (tipic telurit de bismut) conectate electric in serie iar termic in paralel

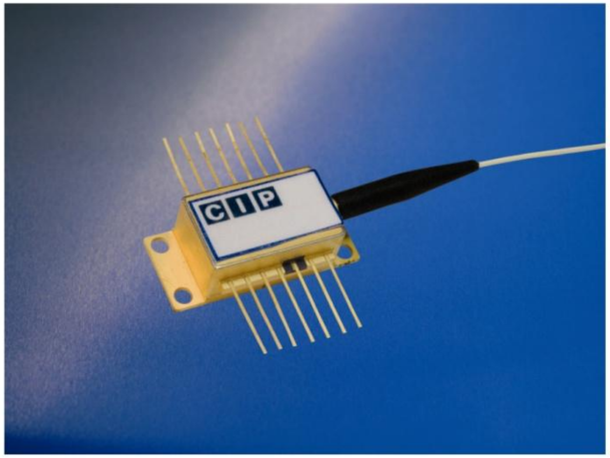


Dispozitiv termoelectric (Peltier)

- Poate produce o diferenta maxima de temperatura de 70°C
- Lucreaza la nivele mici de caldura disipata
- Devine cu atat mai ineficient cu cat fluxul termic disipat e mai mare
- De 4 ori mai putin eficiente decat sistemele cu compresie de vapori

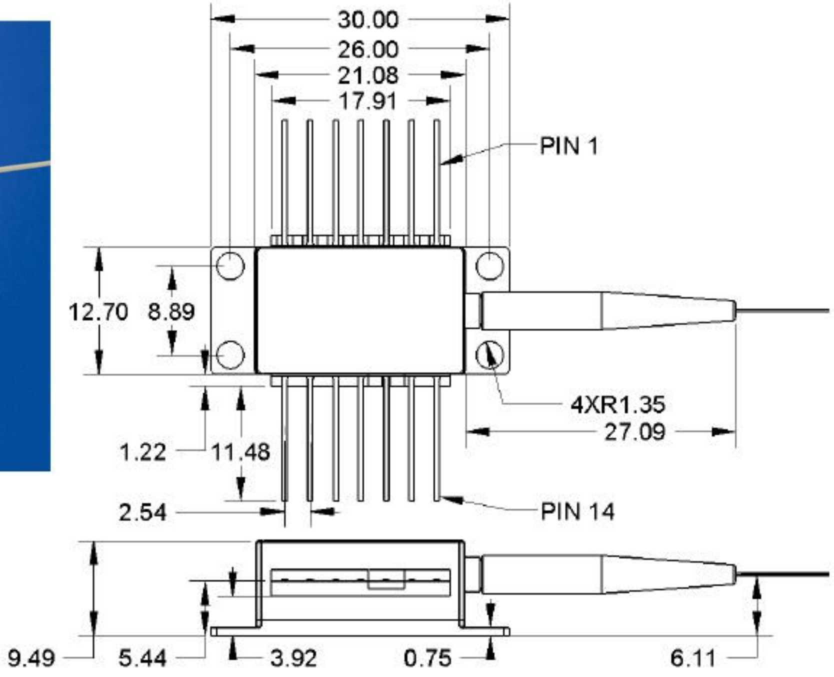


1550nm DFB Laser



Mechanical Drawing

All units in mm



Pin out

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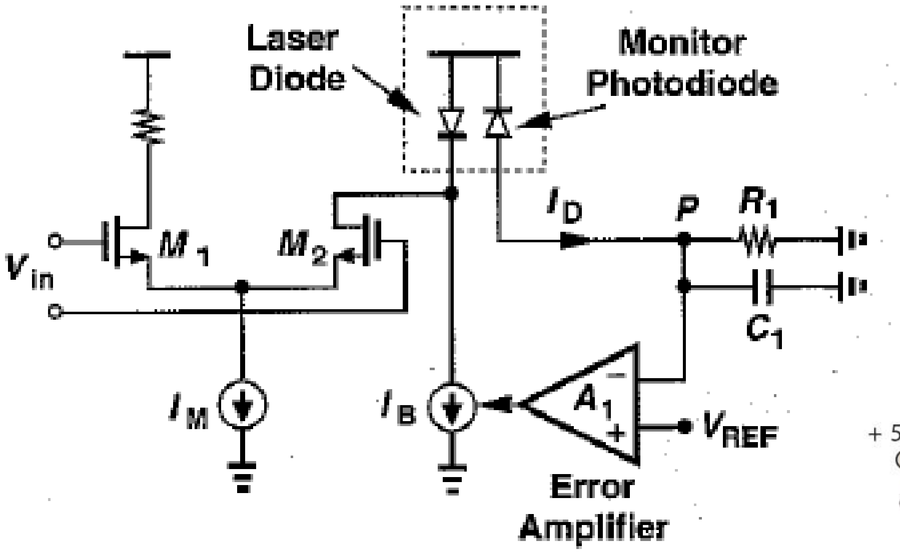
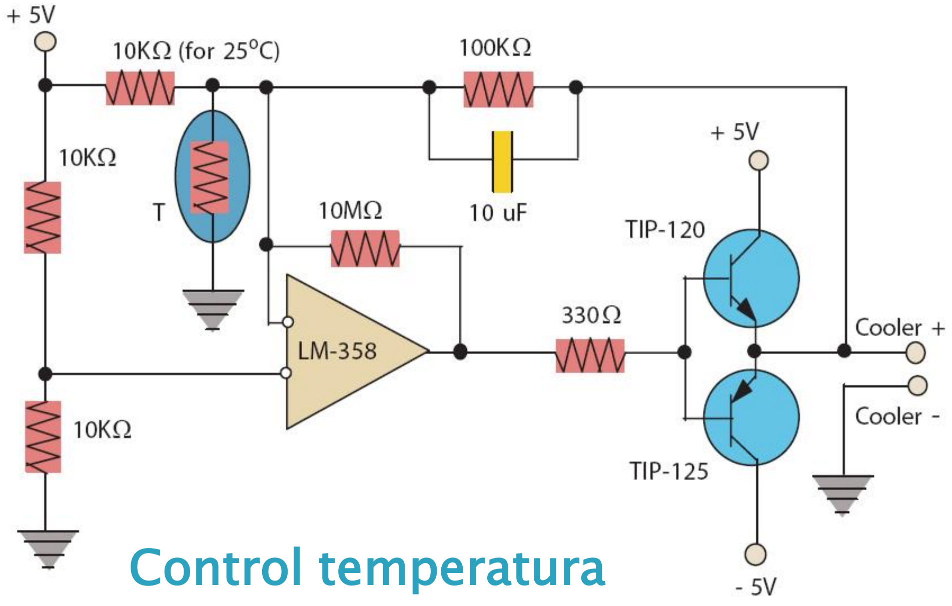
3	Laser Cathode (Bias)
4	Monitor PD Anode
5	Monitor PD Cathode
6	TEC +
7	TEC -
8	Case GND, Laser Anode
9	Case GND, Laser Anode
10	Case GND, Laser Anode
11	Case GND, Laser Anode
12	Laser Cathode (modulation)
13	Case GND, Laser Anode
14	Case GND, Laser Anode

Control dioda LASER

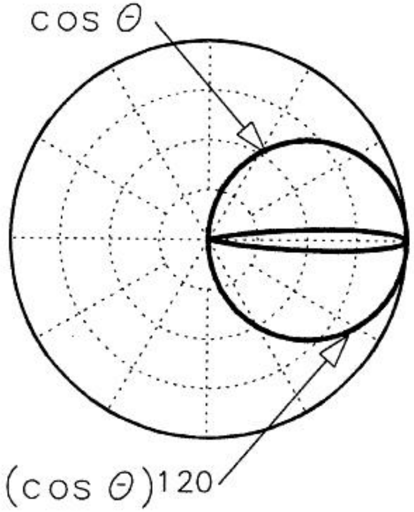


Control putere optica



Control temperatura

Directivitatea radiatiei exterioare



- Sursa lambertiana

$$P(\theta) = P_0 \cdot \cos\theta$$

  - Eficienta cuplarii in fibra

$$\eta = \frac{P_f}{P_s} = NA^2 \bigg/ \cdot \left(\frac{a}{r_s}\right)^2$$

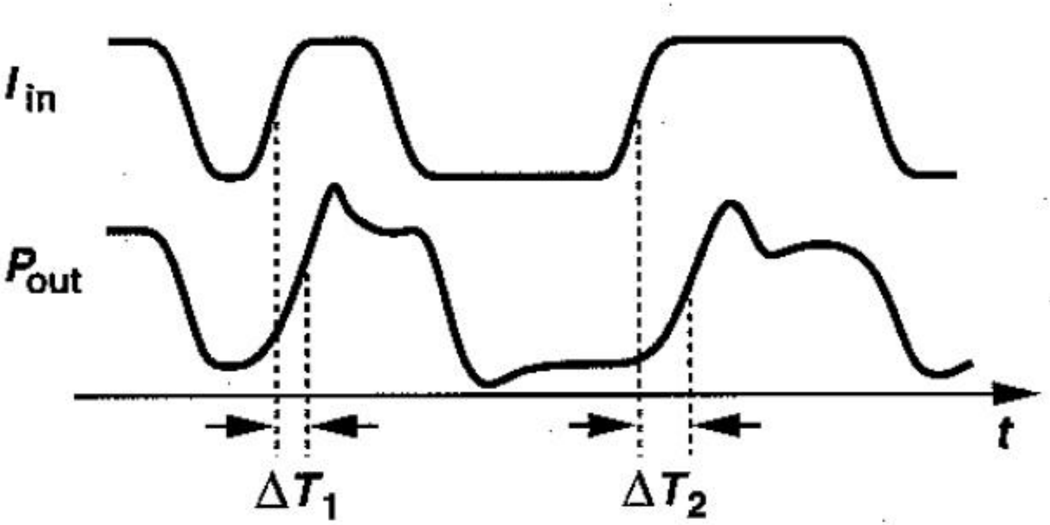
$$\eta = \frac{P_f}{P_s} = NA^2 \cdot \left(\frac{a}{r_s}\right)^2 \cdot \left(\frac{g}{g+2}\right)$$

- Aproximatie Lambertiana pentru surse cu directivitate crescuta

$$P(\theta) = P_0 \cdot \cos^m \theta \qquad \eta = \frac{P_f}{P_s} = \left(\frac{m+1}{2}\right) \cdot NA^2$$

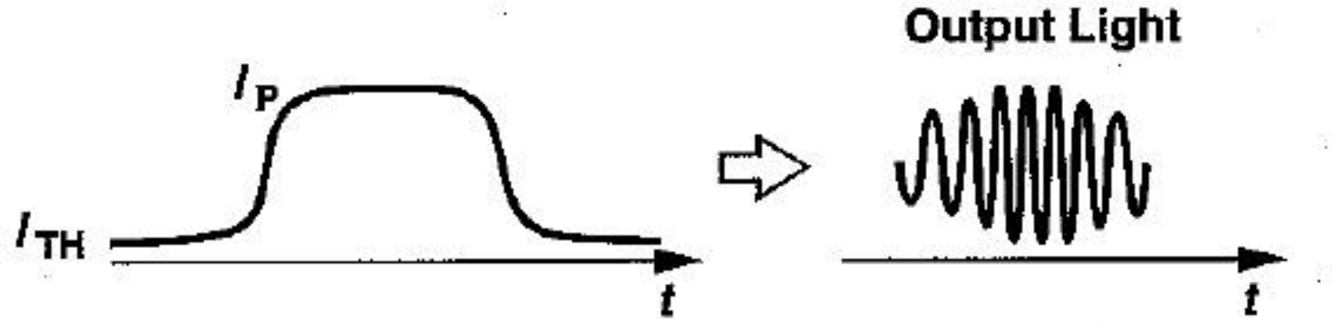
Turn-on delay

- La alimentarea cu curent a diodei laser emisia este initial spontana, devenind stimulata dupa amorsarea acesteia
- emisia spontana este un fenomen intrinsec aleator
- Intarzierea este variabila – jitter



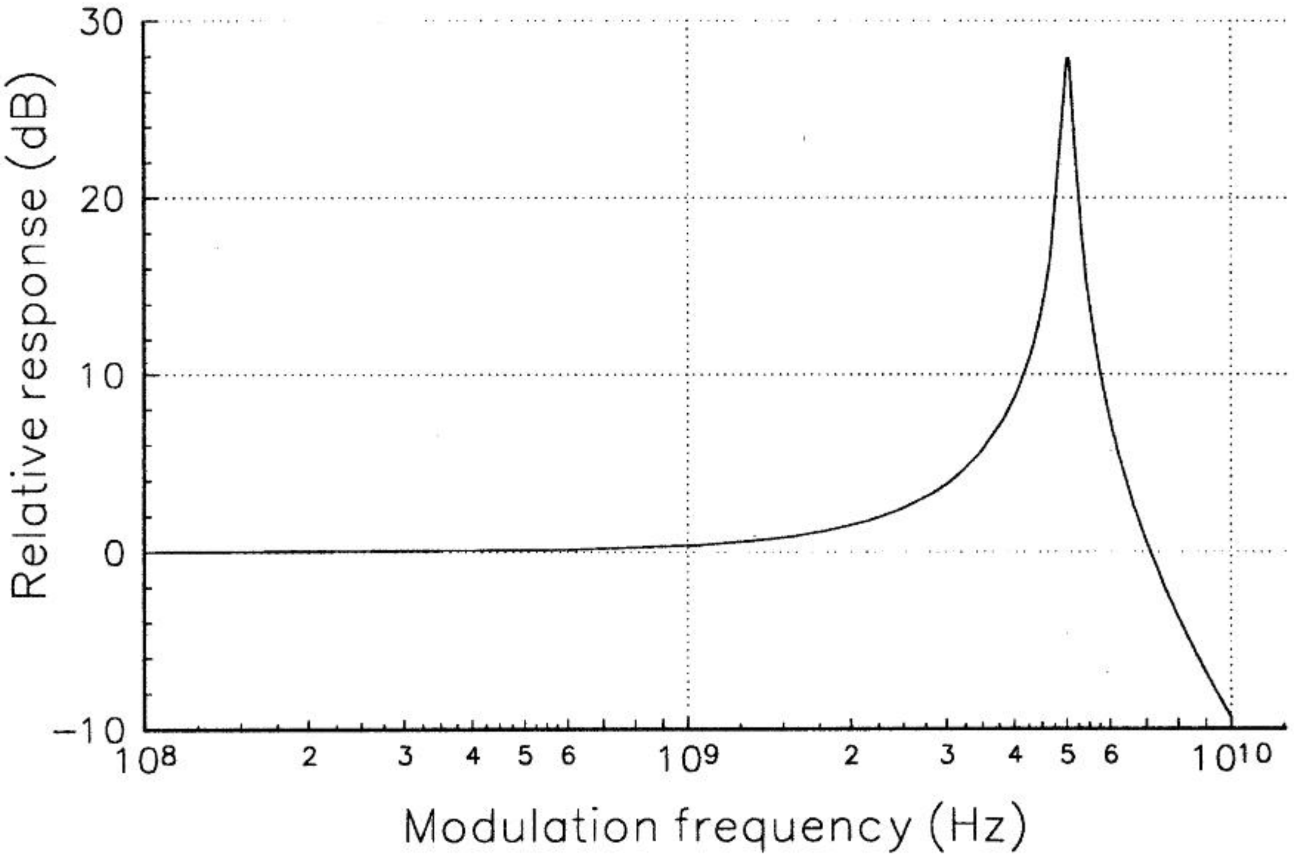
Chirping

- Frecventa de oscilatie depinde de indicele de refractie al materialului
- Indicele de refractie depinde de concentratia de purtatori
- Cand curentul este modulat in impuls apare o modulatie a frecventei luminii cu efectul cresterii latimii spectrale a diodei (un ordin de magnitudine)



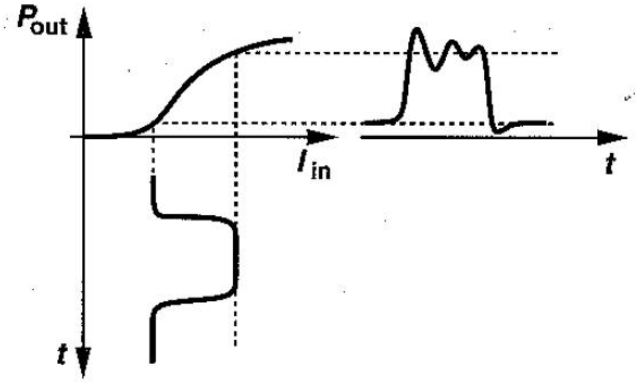
Raspunsul unei diode laser

- oscilatii de relaxare – x GHz

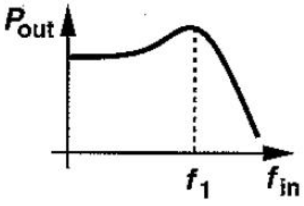


Oscilatii de relaxare

- Generate de schimbul de energie intre electroni si fotoni
- Amorsarea emisiei stimulate duce la descresterea numarului de electroni in starea excitata, ceea ce duce la micsorarea emisiei de fotoni
- Acumularea din nou a electronilor in starea excitata duce din nou la cresterea puterii
- $f_1 = 1 \div 4$ GHz



(a)



(b)

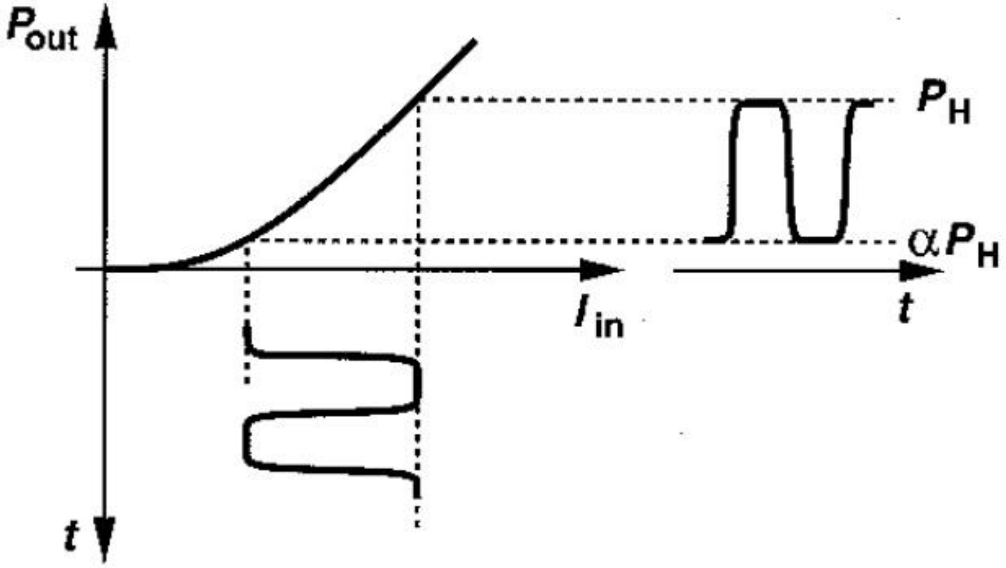
Oscilatii de relaxare

- Cresterea vitezei si minimizarea erorilor date de oscilatiile de relaxare si variatiile timpului de amorsare dioda este partial stinsa in timpul transmisiei unui nivel 0 logic

- Raport de stingere

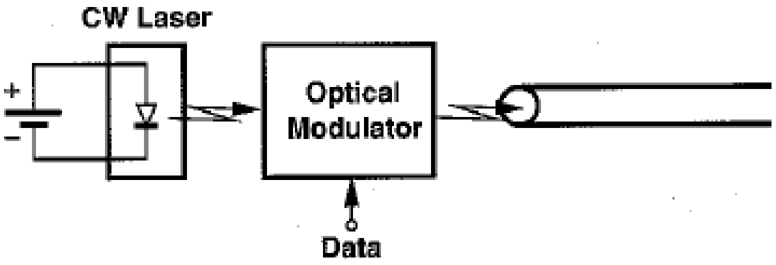
$$ER = \frac{P_H}{\alpha \cdot P_H} = \frac{1}{\alpha}$$

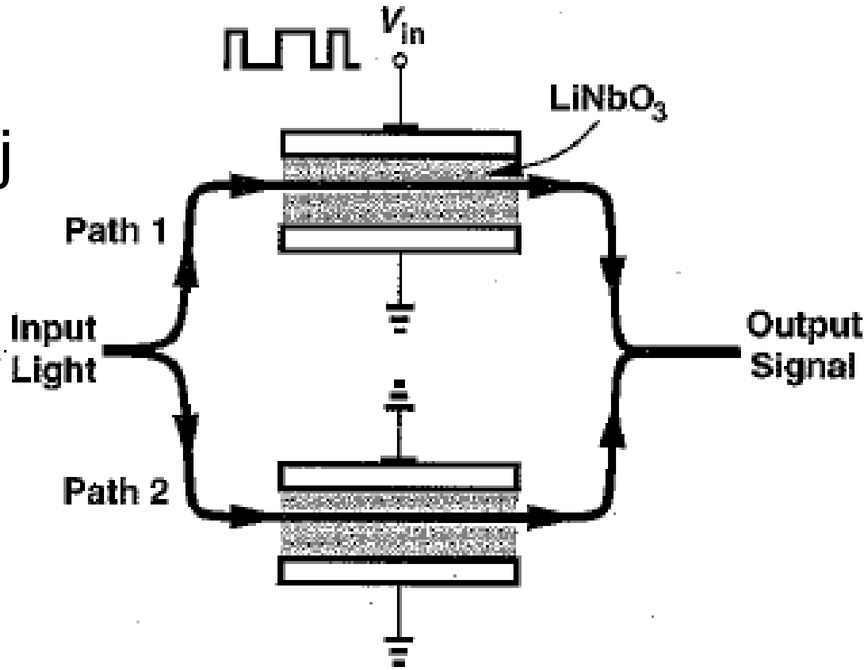
- Raportul semnal zgomot scade cu (1−α)
- Tipic ER = 10÷15dB



Modulaţie optică

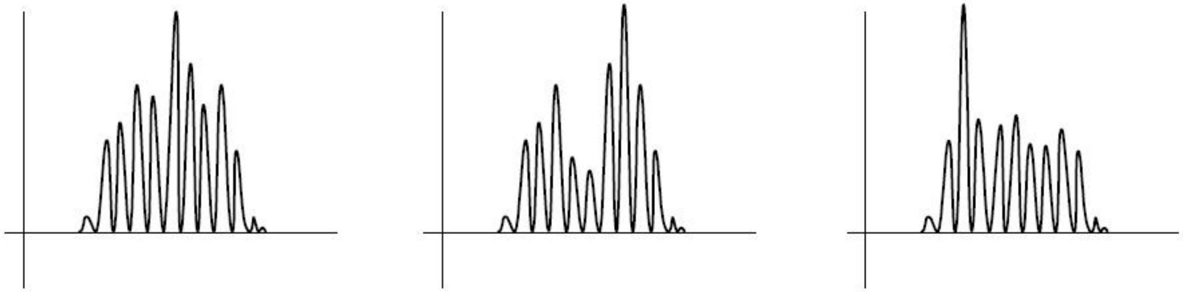
- Pentru viteze mari se prefera utilizarea emisiei continue si modularea optica a radiatiei
- In LiNbO$_3$ viteza luminii depinde de campul electric, ceea ce permite introducerea unui defazaj egal π
- Creste complexitatea circuitului de control
- Tensiuni de 4÷6 V necesare





Alte caracteristici DL

- Mode hopping – salt de mod (hole burning)

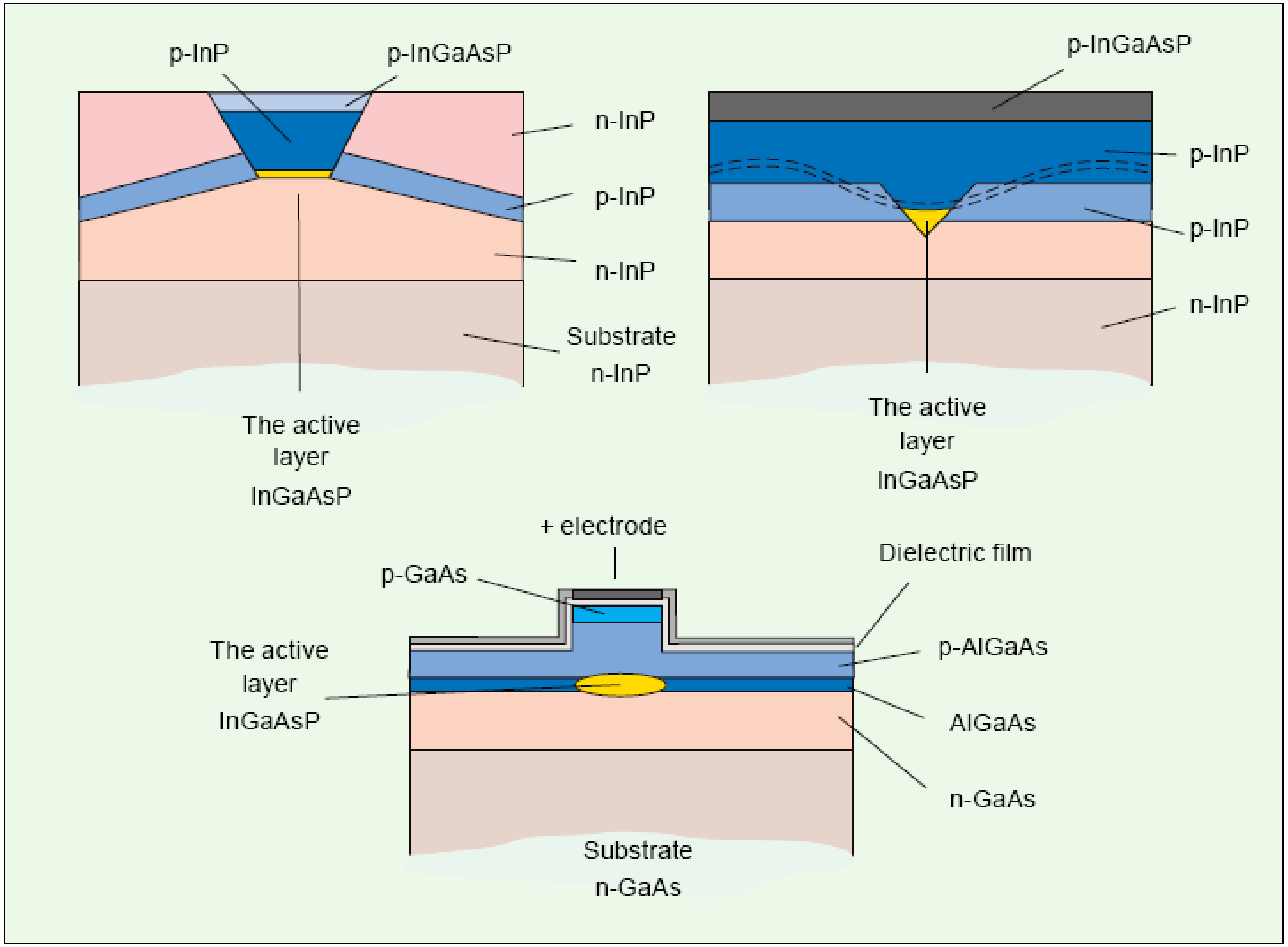


- RIN – Relative Intensity Noise (generat de emisia spontana)
- Zgomot de faza (idem) – necesitatea modulatiei in amplitudine
- Zgomot intercavitati (reflexiile din exterior in zona activa)
- Drift – variatia parametrilor cu varsta si temperatura (in special distanta intre oglinzi)

Diode LASER cu heterojuncţiune

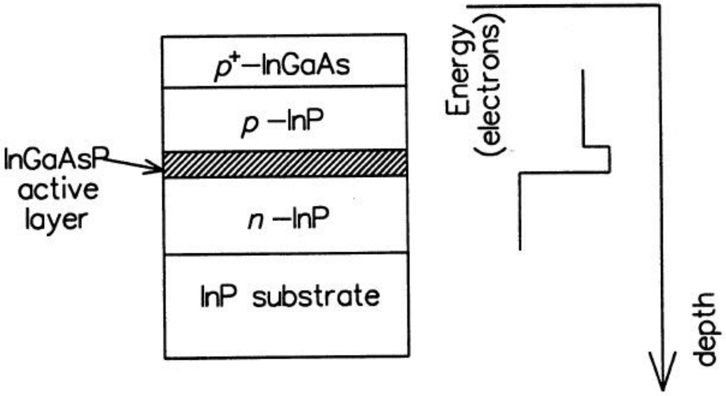
Heterojunctiune ingropata

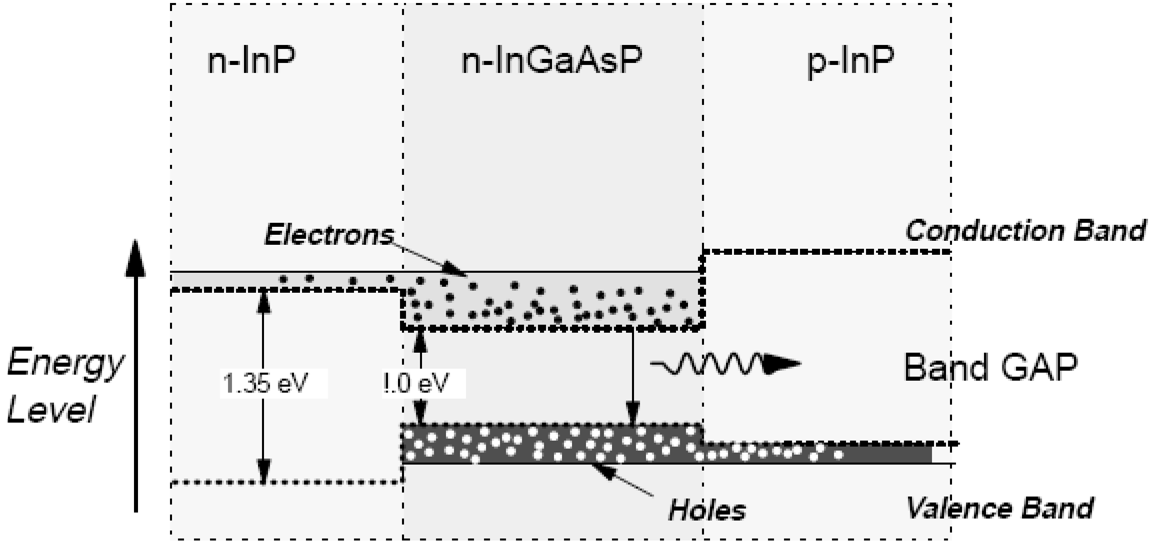
Heterojunctiune muchie (ridge)



Heterojuncţiuni – principiu

- Concentrare verticala a purtatorilor
  - Electronii sunt atrasi din zona n in zona activa
  - O bariera energetica existenta intre zona activa si zona n concentreaza electronii in zona activa
  - Situatie similara corespunzatoare golurilor
  - Purtatorii sunt concentrati in zona activa, crescand eficienta



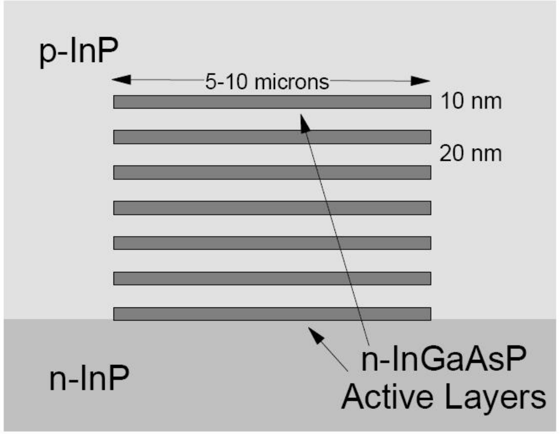


Quantum Well Laser

- Cand lumina e pastrata in cavitati mai mici decat lungimea de unda nu mai poate fi modelata prin unda, modelul devine cuantic
- Daca inaltimea zonei active scade la 5-20 nm comportarea diodei laser se schimba
  - energia necesara pentru inversarea de populatie se reduce, deci curentul de prag scade
  - dimensiunea redusa a zonei active duce la scaderea puterii maxime

Quantum Well Laser

- multiple straturi subtiri suprapuse – Multiple Quantum Well

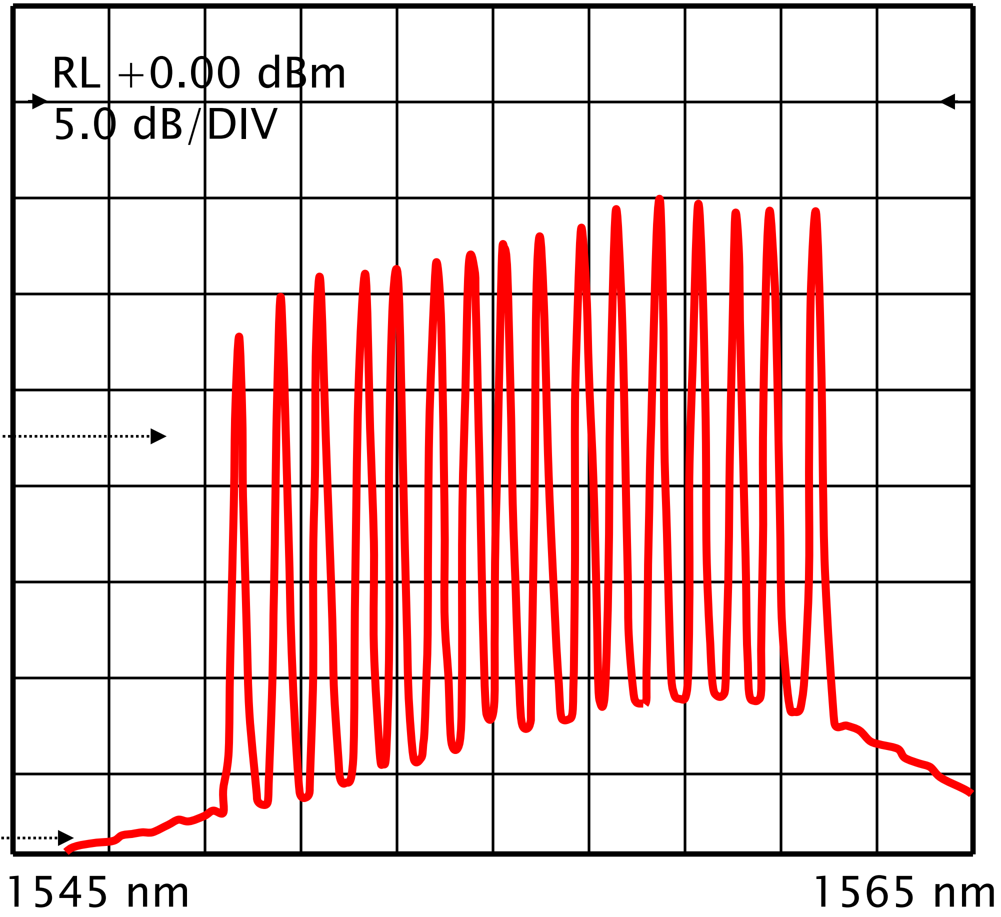


- Avantaje
  - curent de prag redus
  - stabilitate crescuta a frecventei la functionarea in impuls
  - latime mica a liniilor spectrale
  - zgomot redus

Spectrul WDM – Wavelength Division Multiplexing

Canale: 16
Spaţiere: 0.8 nm

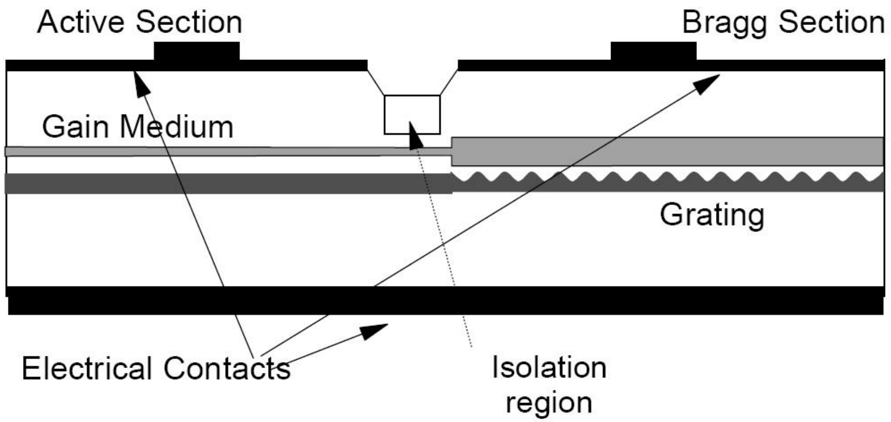
Emisie spontană
Amplificată (ASE)

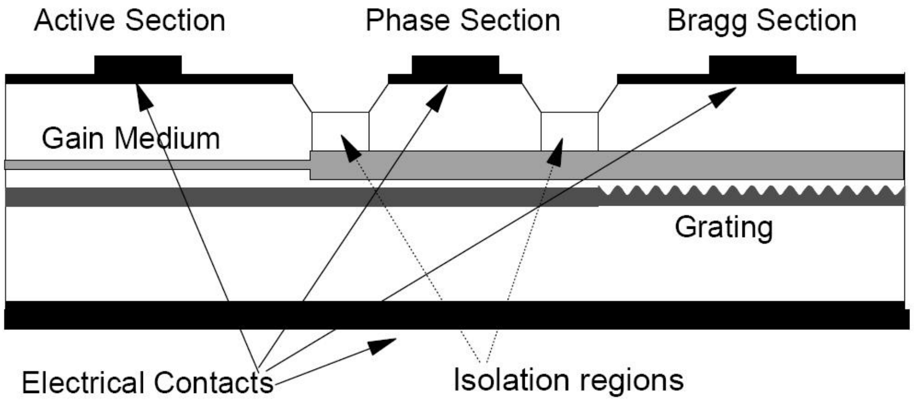


Diode laser reglabile

- Necesitate
  - In sistemele WDM exista necesitatea (in propuneri pentru arhitecturi viitoare de retele) pentru reglaj foarte rapid al lungimii de unda pe un anume canal – zeci de ns
  - In aceleasi sisteme intervine necesitatea rutarii prin lungime de unda – timp de reglaj necesar de ordinul secundelor)
  - realizarea cererilor de date – timp de reglaj de ordinul sute de µs
  - reglarea emitatorilor individuali in sistemele WDM
    - lipsa necesitatii controlului strict la productia diodelor
    - degradarea lungimii de unda in timp

Diode laser reglabile

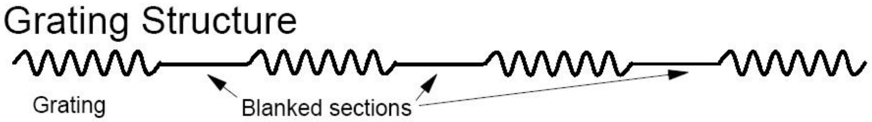




- Curentul trece prin zona activa ducand la amplificarea luminii
- curentul ce parcurge zona corespunzatoare reflectorului Bragg modifica indicele de refractie al acestei zone deci lungimea de unda
- zona centrala suplimentara permite reglaj fin suplimentar in jurul valorii impuse de reflectorul Bragg

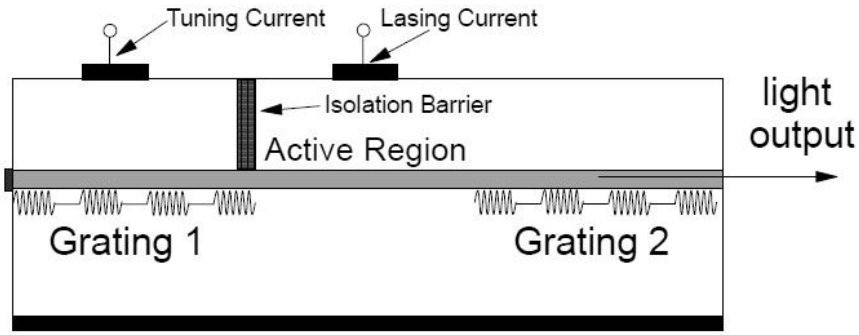
Diode laser reglabile

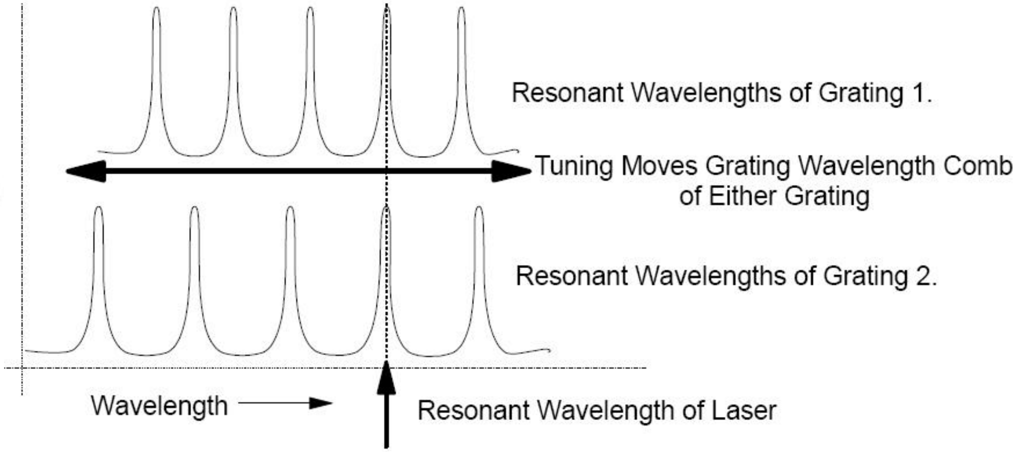
- Dezavantajul metodelor anterioare e dat de limita redusa a reglajului (~10nm)
- Reflectorul Bragg esantionat (periodic) produce spectru de filtrare discret



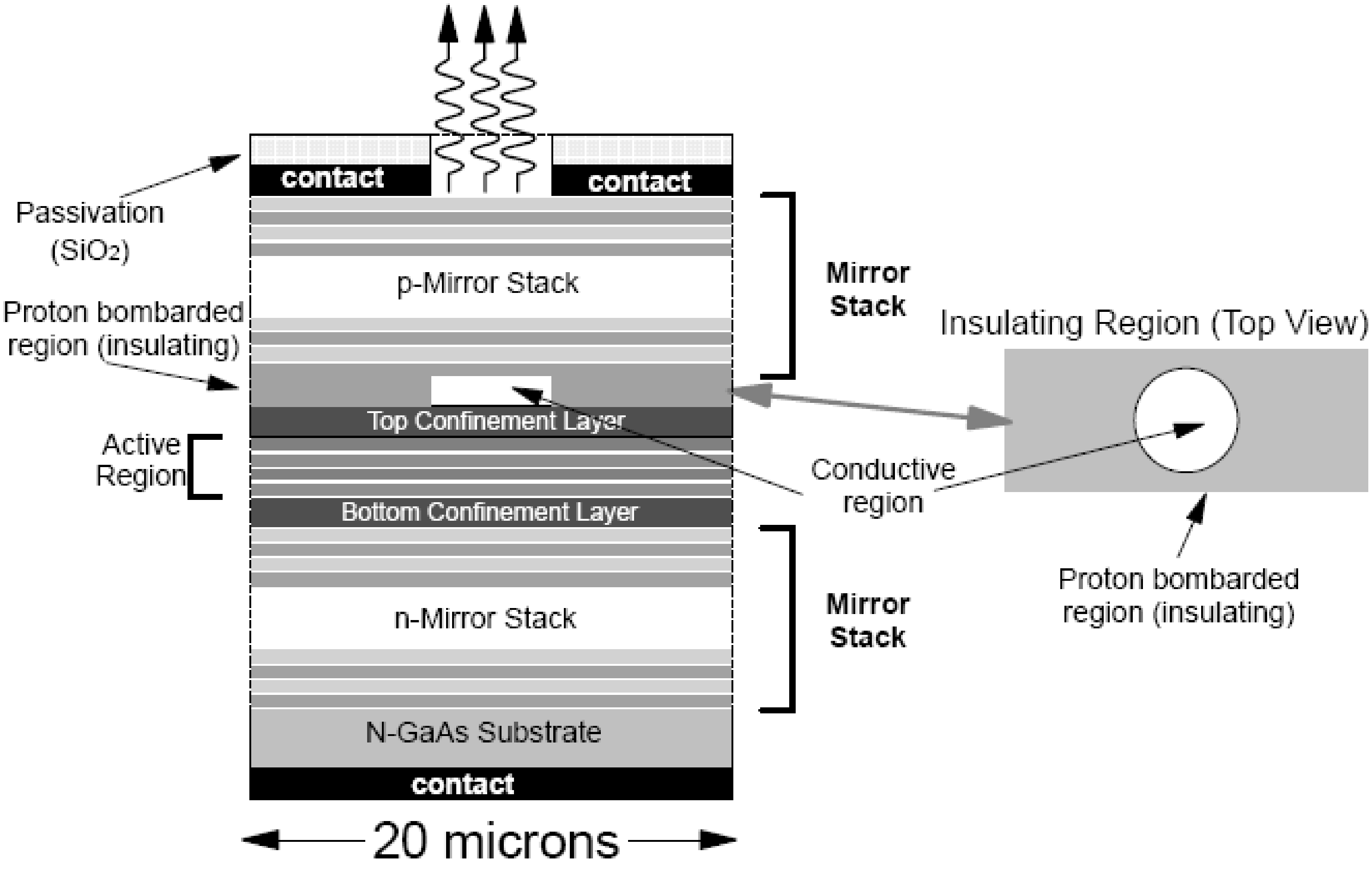
Dezavantaj : reglajul e discret

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

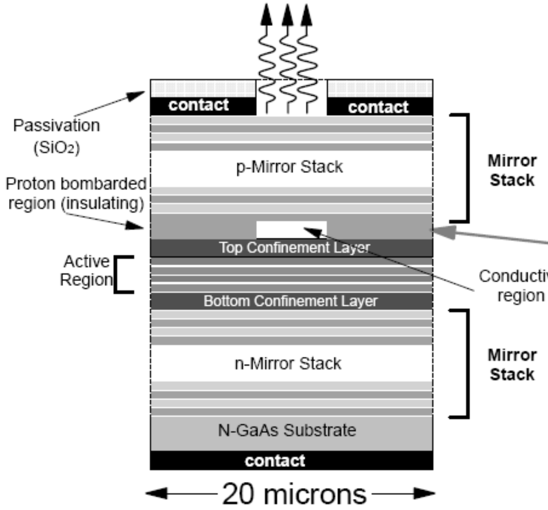




Vertical Cavity Surface Emitting Lasers (VCSEL)



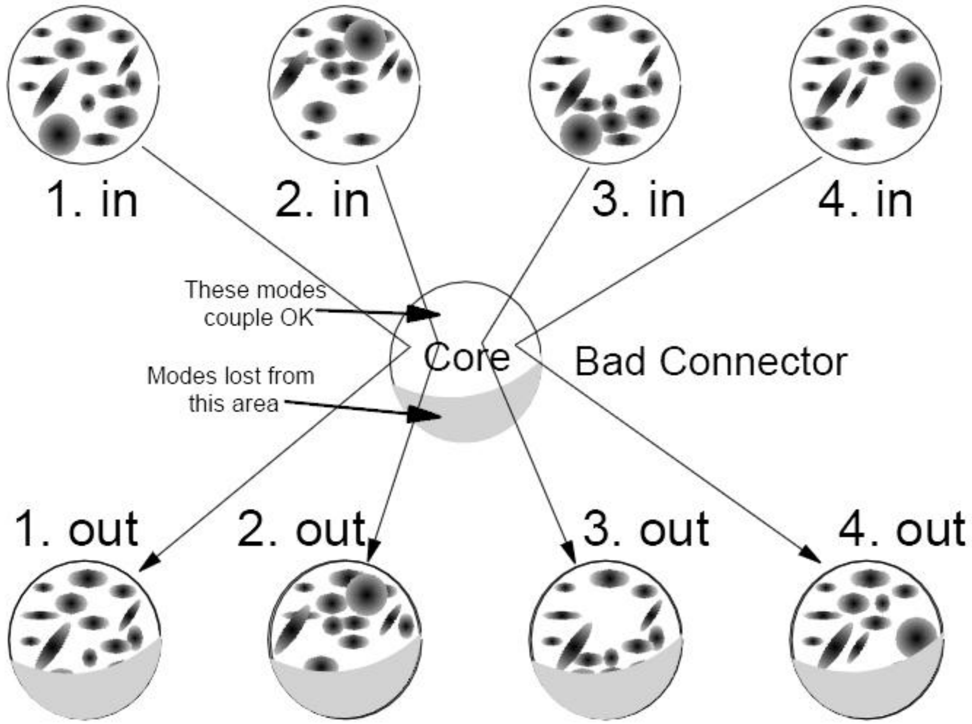
Vertical Cavity Surface Emitting Lasers (VCSEL)



- 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

VCSEL

- Caracteristici
  - VCSEL produce mai multe moduri transversale
    - insensibila la pierderile selective la mod din fibrele multimod (principala limitare in utilizarea diodelor laser in fibrele multimod)



Parametri dioda LASER

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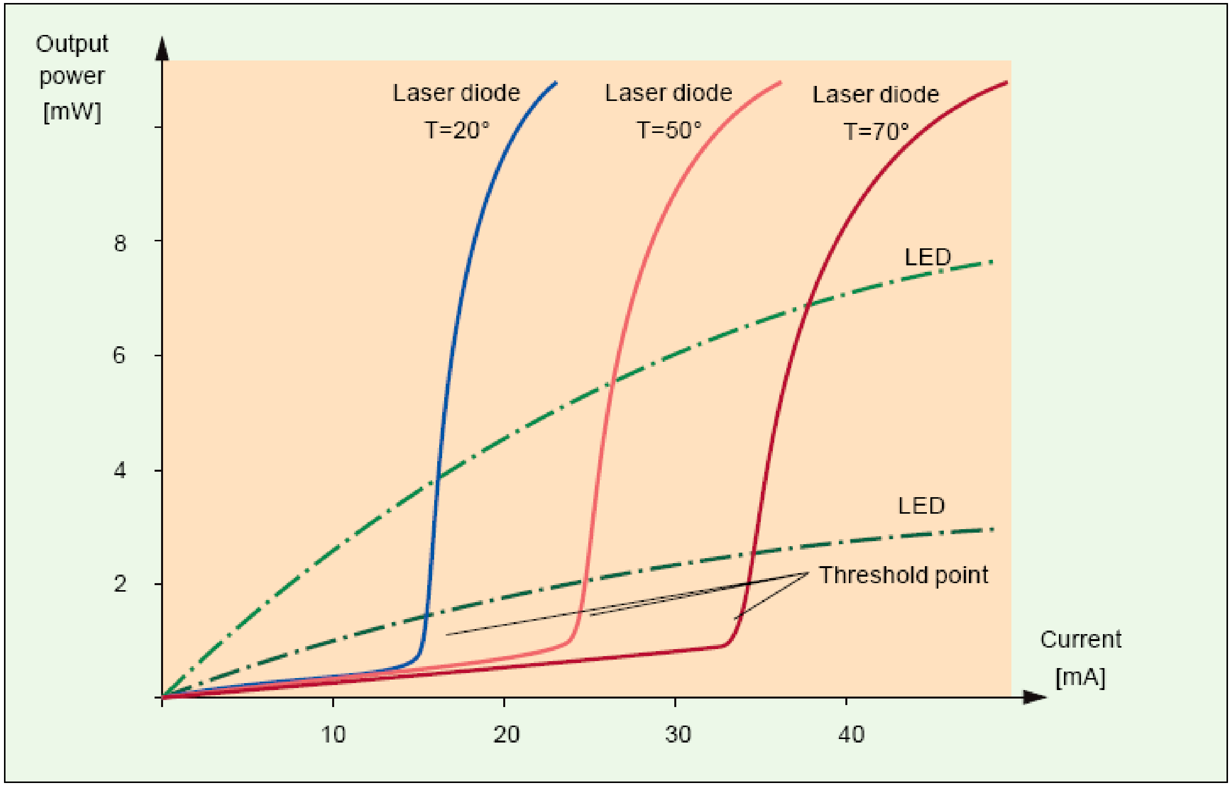
- Variatia tipica 1–2%/°C



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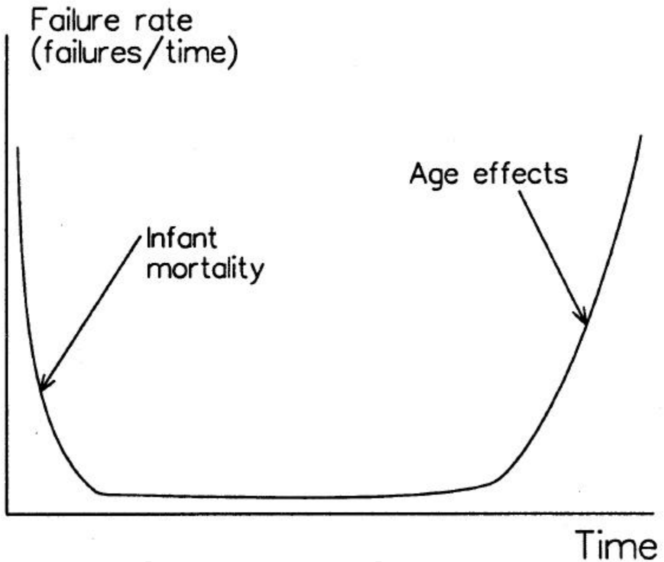
Degradare in timp

- 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 $2000 \div 5000 A/cm^2$
  - densitati de putere optica: $10^5 \div 10^6 W/cm^3$
- 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÷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÷0.95eV (valoarea tipica in teste 0.7eV)
  - cresterea temperaturii cu 10 grade injumatateste durata de viata

Parametri

- Coerenta radiatiei emise
  - LED: $t_c \approx 0.5$ps, $L_c \approx 15$µm
  - LASER : $t_c \approx 0.5$ns, $L_c \approx 15$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

Eficienta

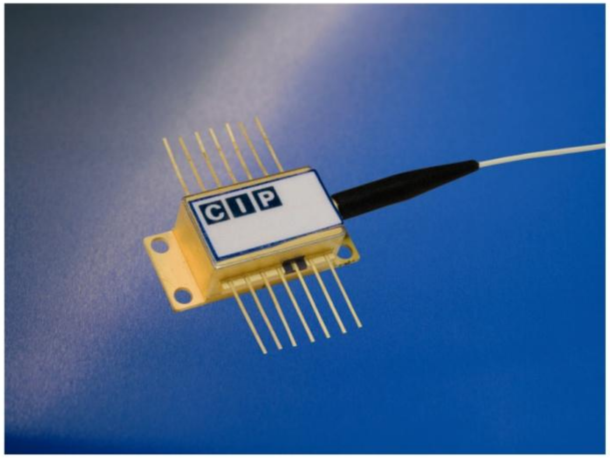
- eficienta de conversie electro-optic (randament)

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

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

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

1550nm DFB Laser



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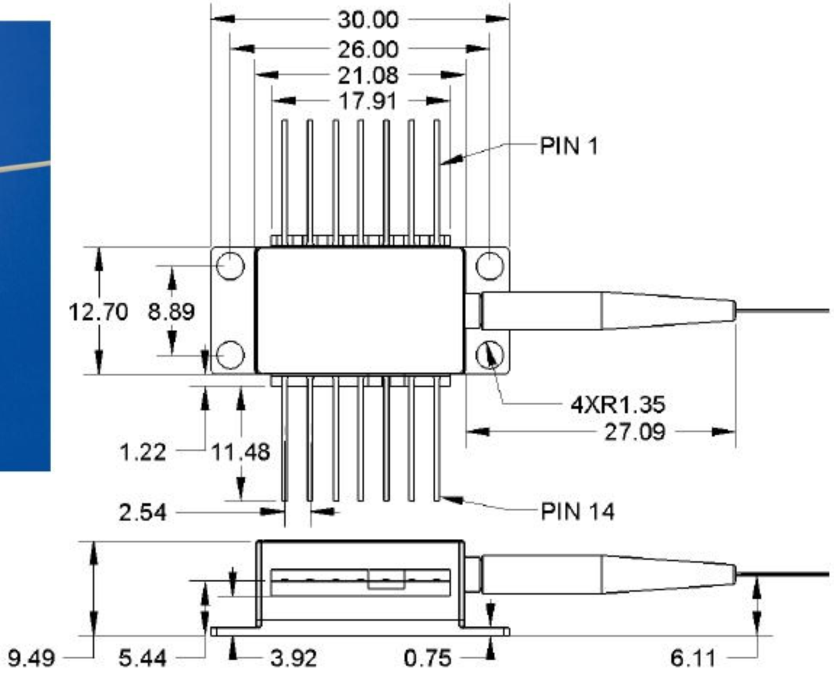
All units in mm



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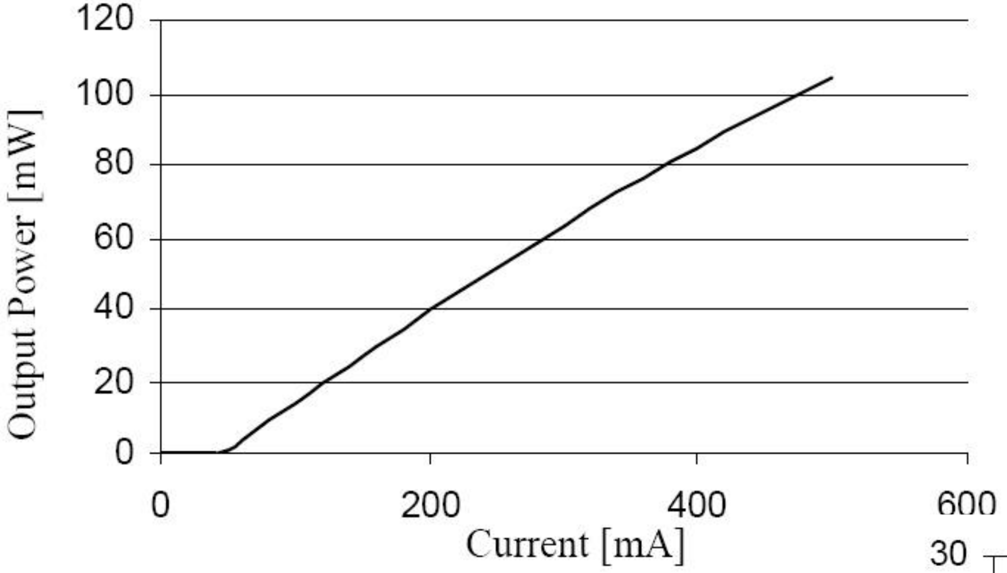
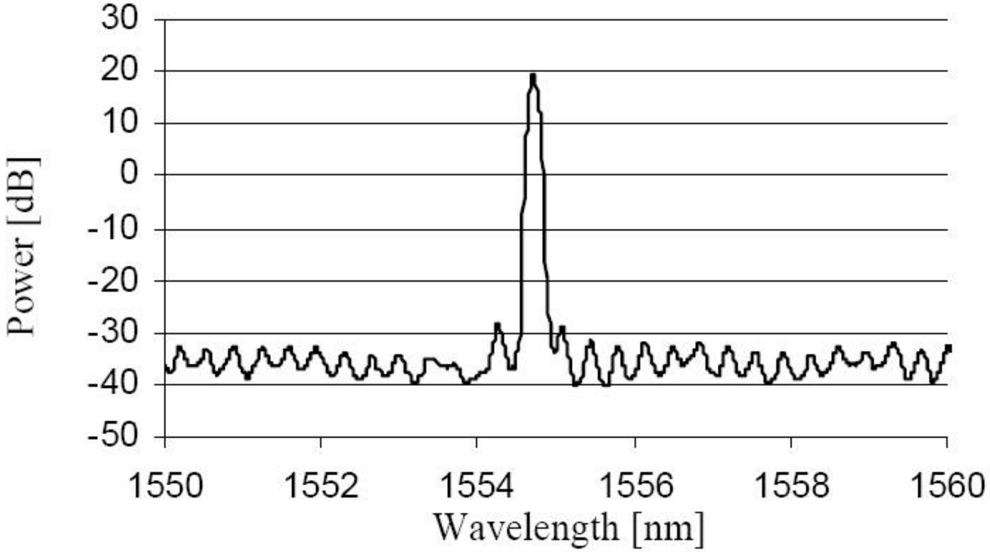
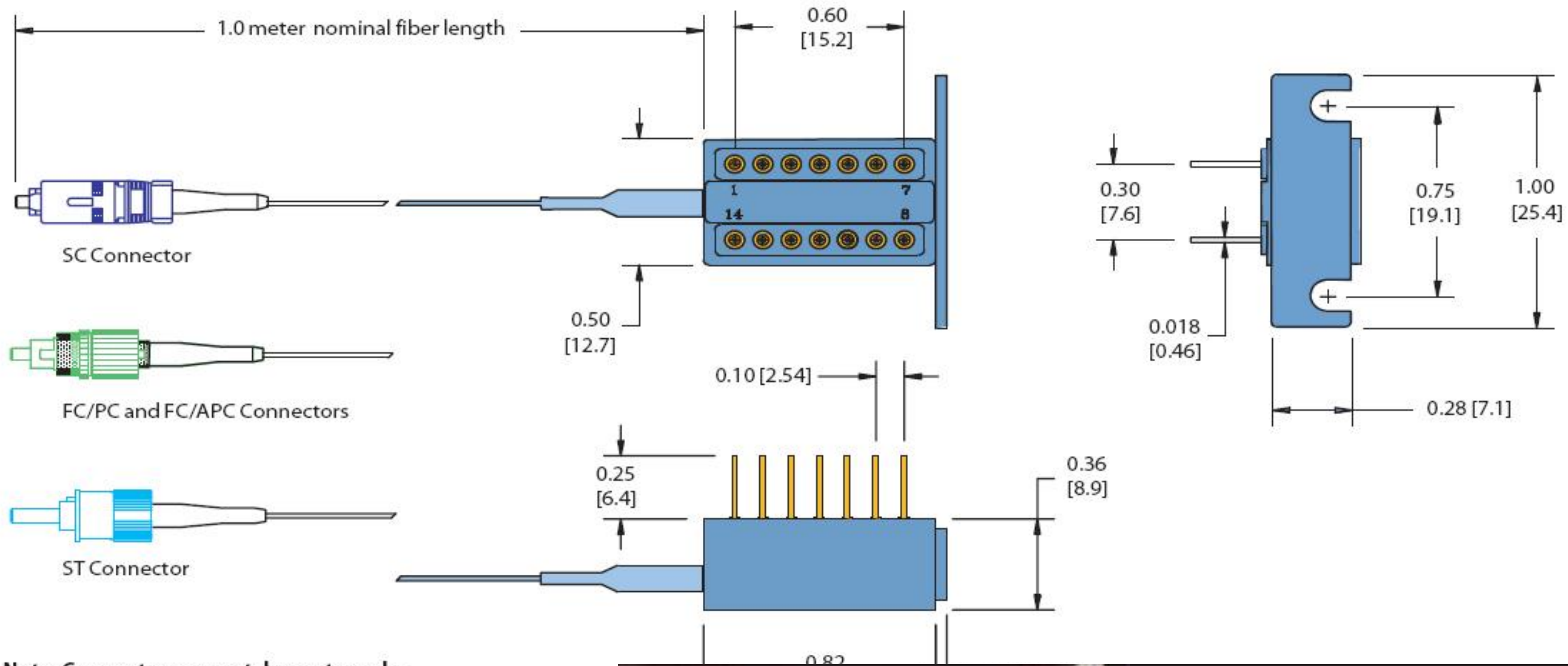
7	TEC -
8	Case GND, Laser Anode
9	Case GND, Laser Anode
10	Case GND, Laser Anode
11	Case GND, Laser Anode
12	Laser Cathode (modulation)
13	Case GND, Laser Anode
14	Case GND, Laser Anode

1550nm DFB Laser

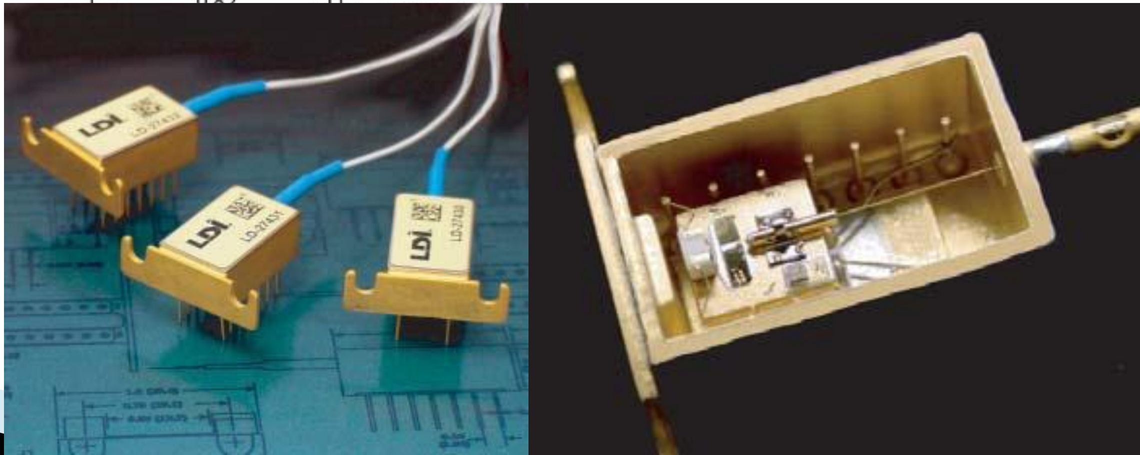




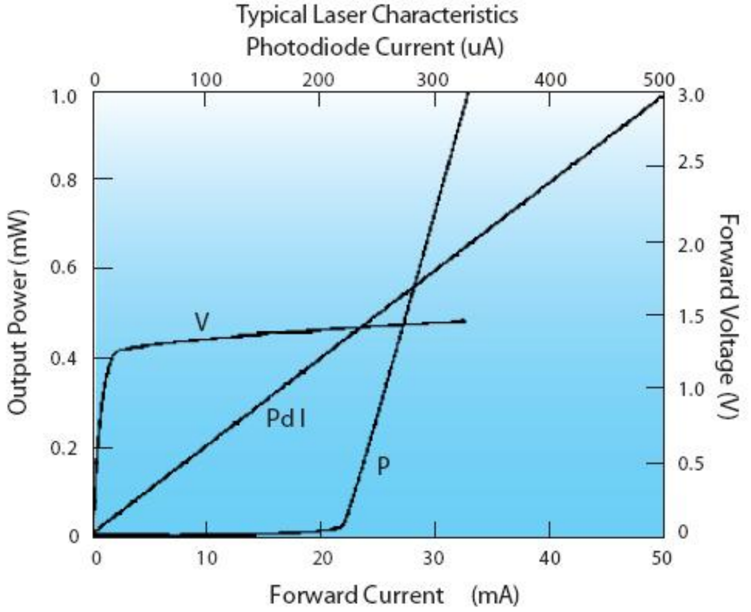
1550nm MQW Laser

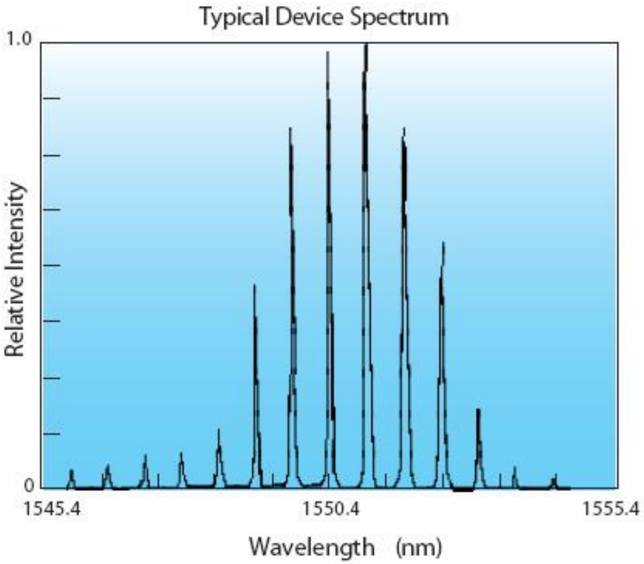


Note: Connectors are not drawn to scale.



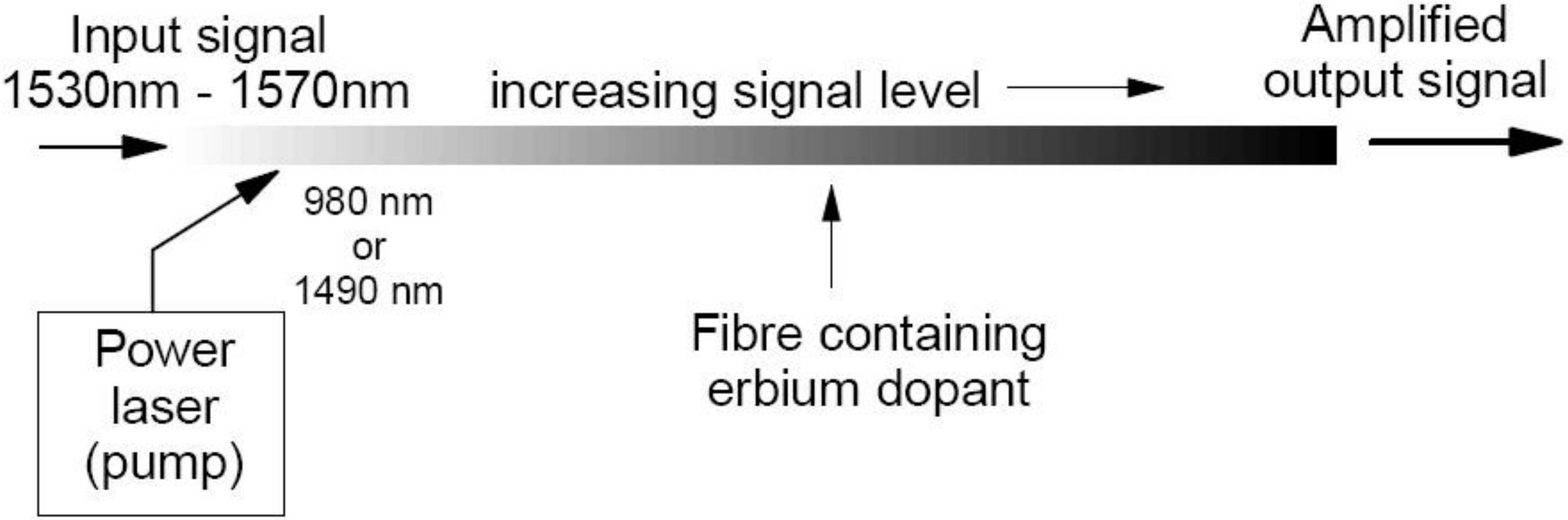
1550nm MQW Laser



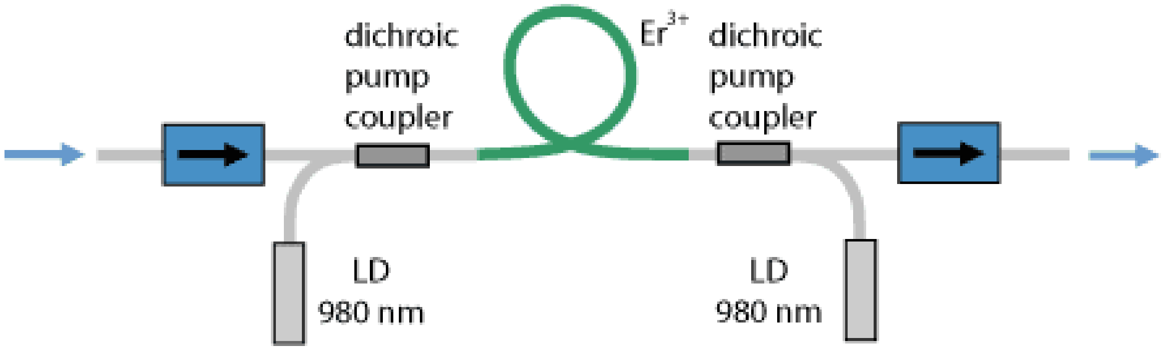


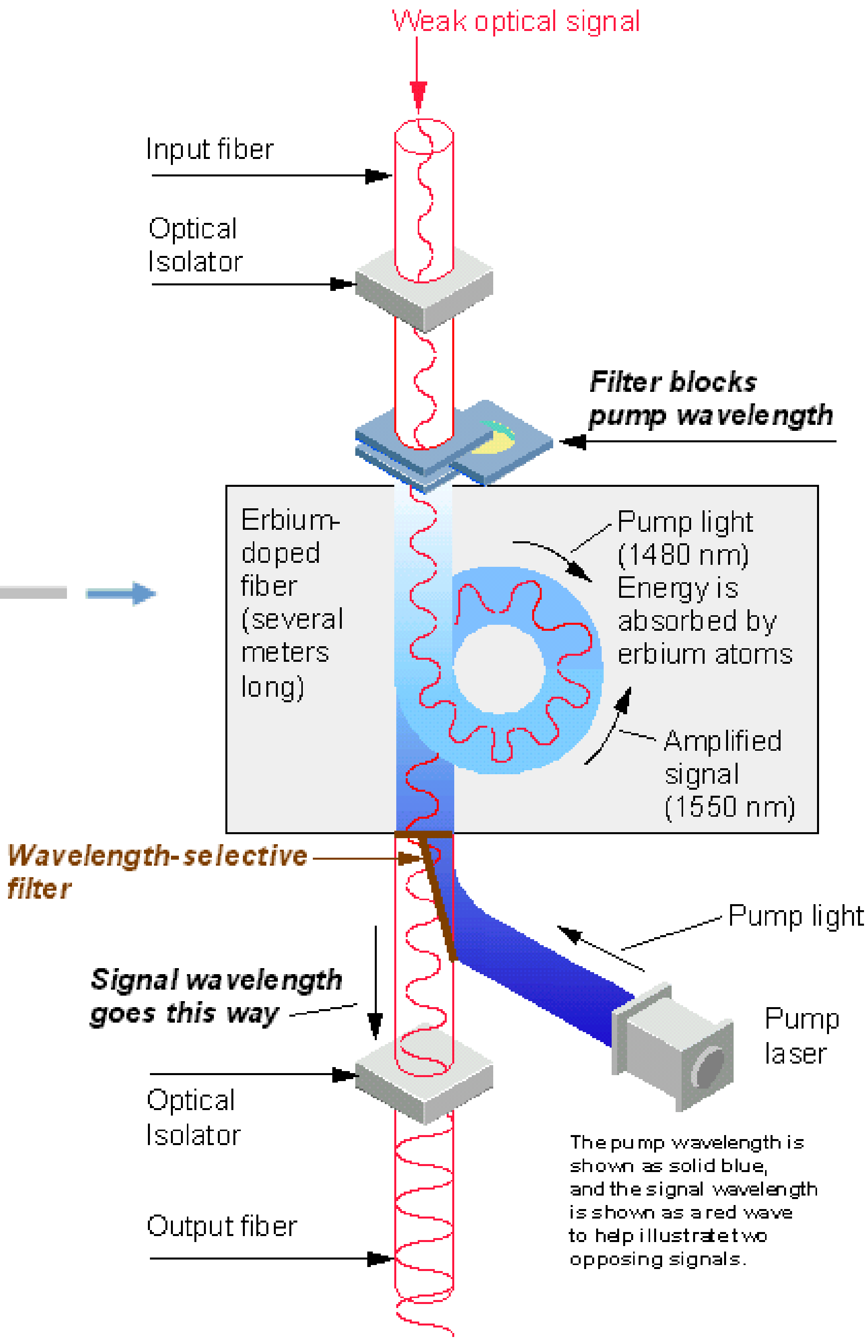
EDFA

- Erbidium Dopped Fiber Amplifier



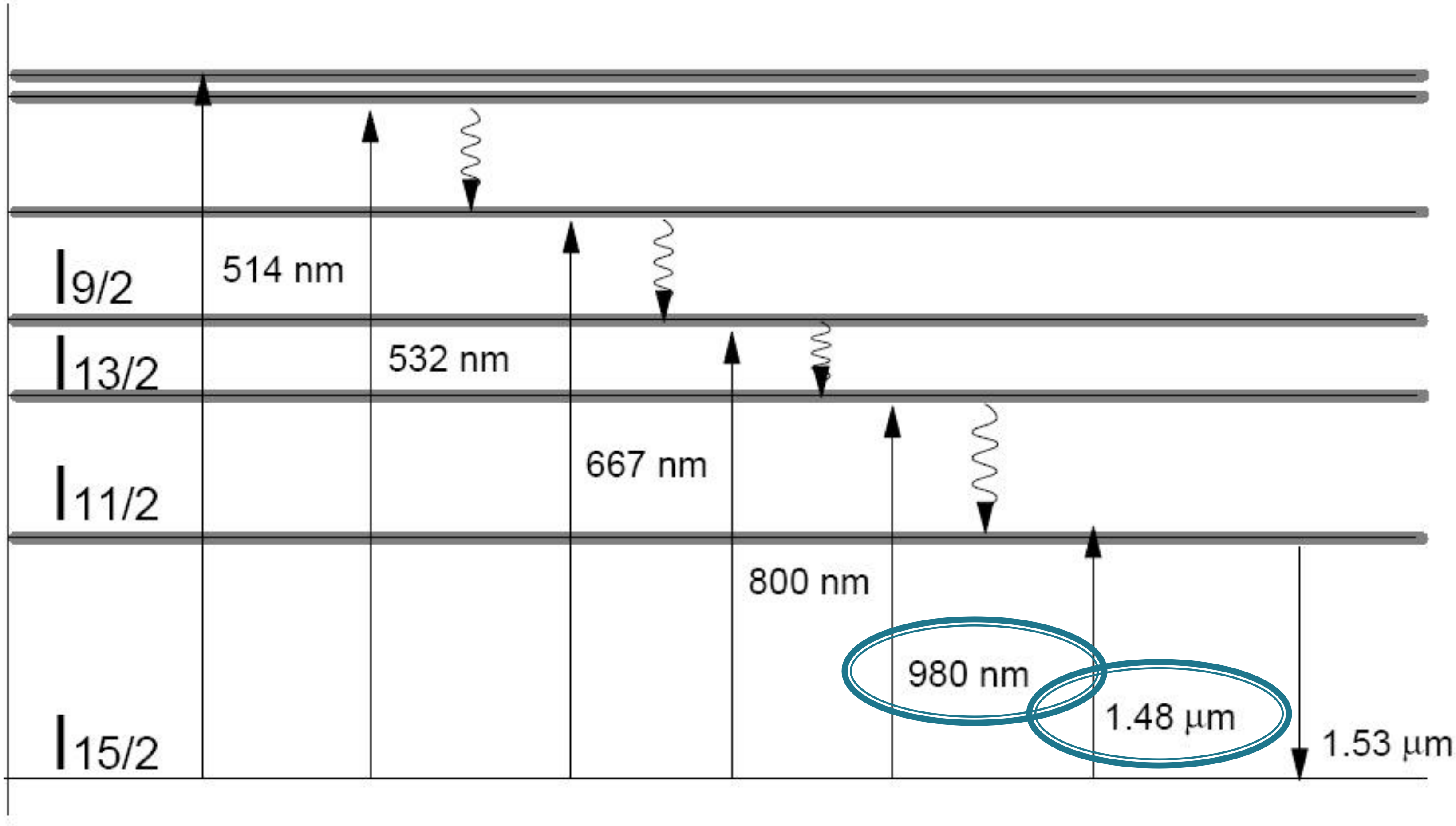
EDFA





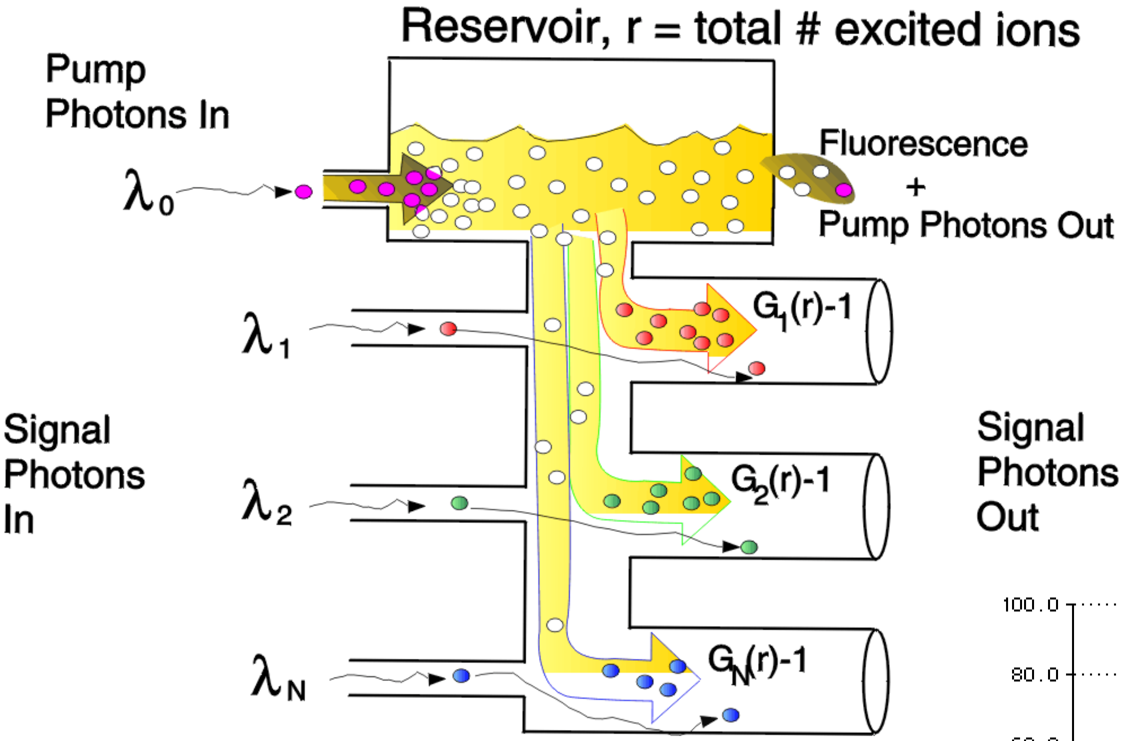
The pump wavelength is shown as solid blue, and the signal wavelength is shown as a red wave to help illustrate two opposing signals.

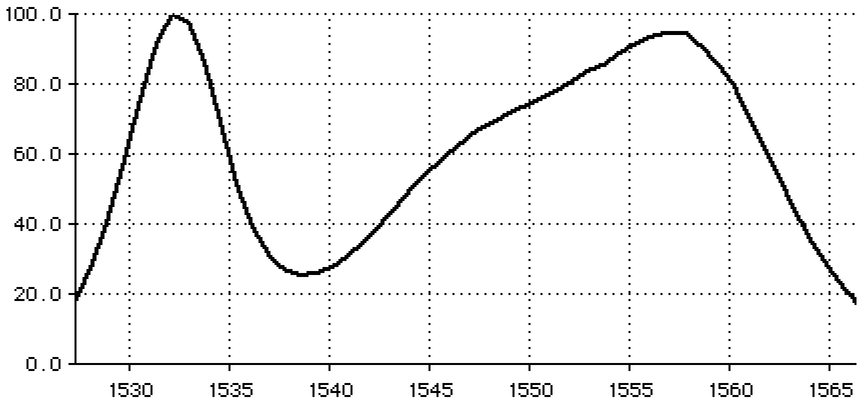
EDFA


I9/2
514 nm
I13/2
532 nm
I11/2
667 nm
800 nm
I15/2
980 nm
1.48 µm
1.53 µm

EDFA

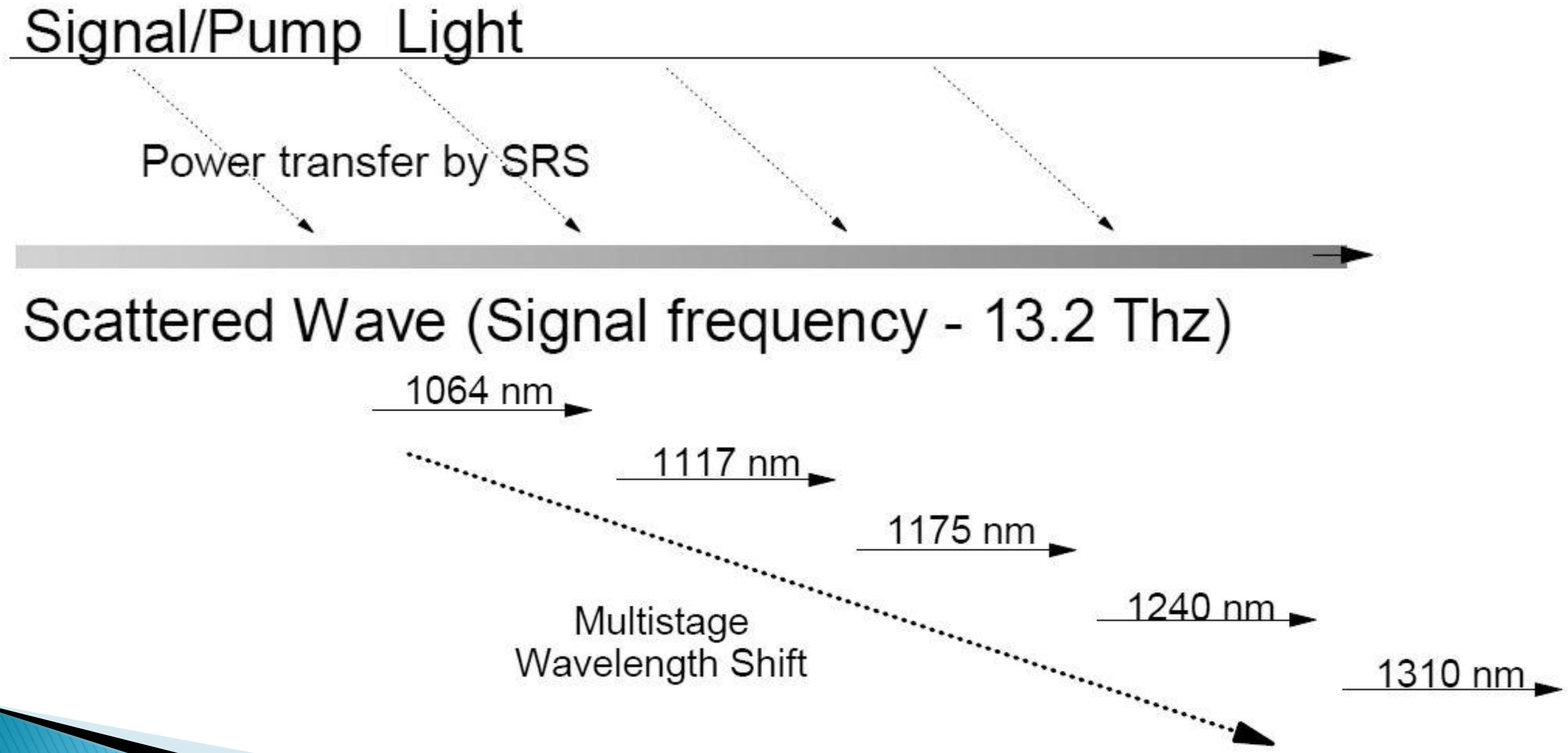
How to think of an EDFA



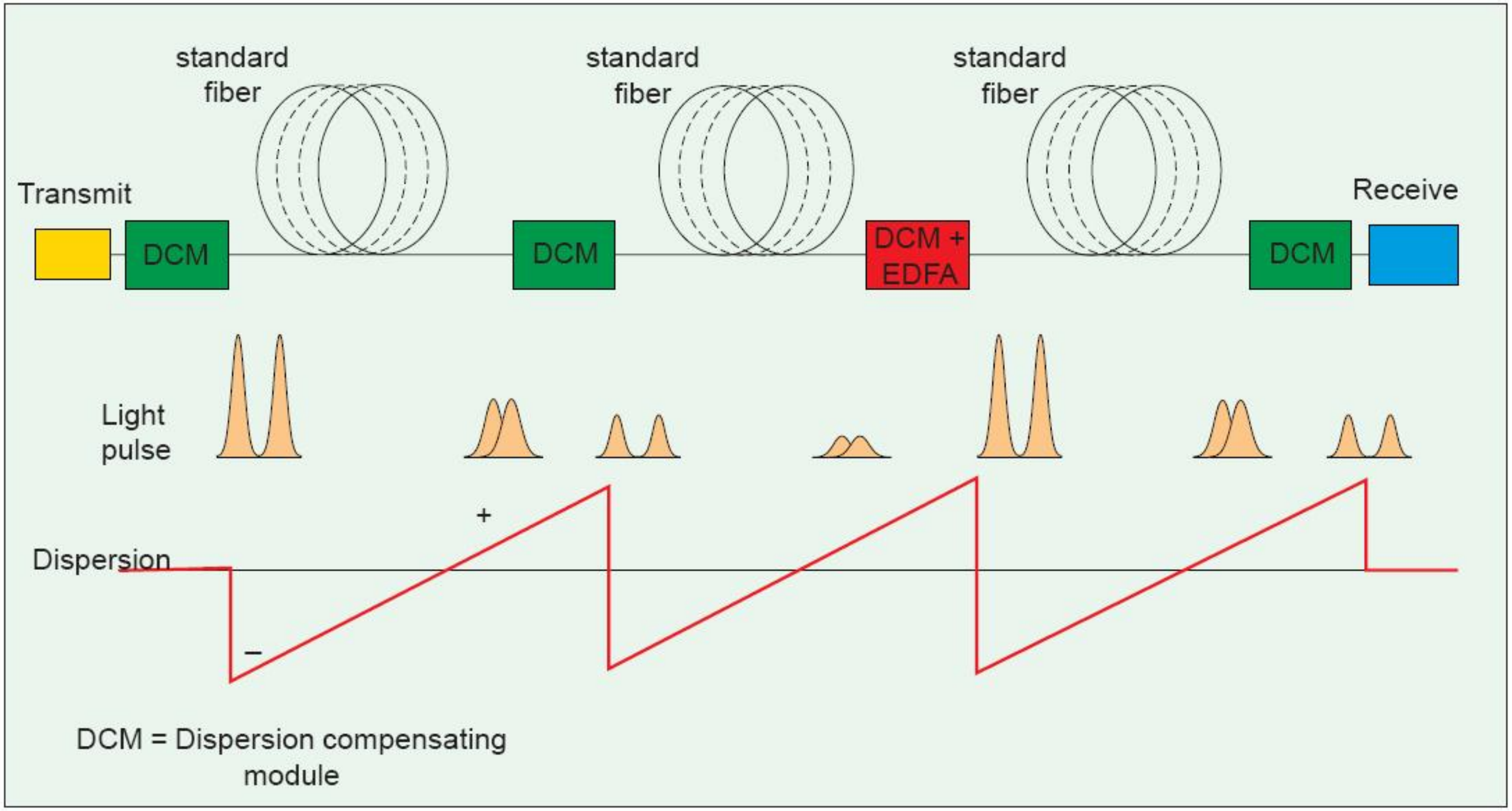


Amplificator cu efect Raman

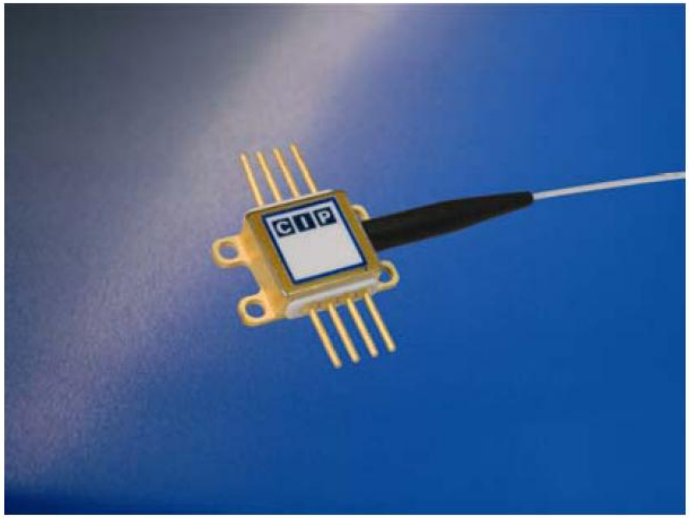
- Bazat pe efect Raman

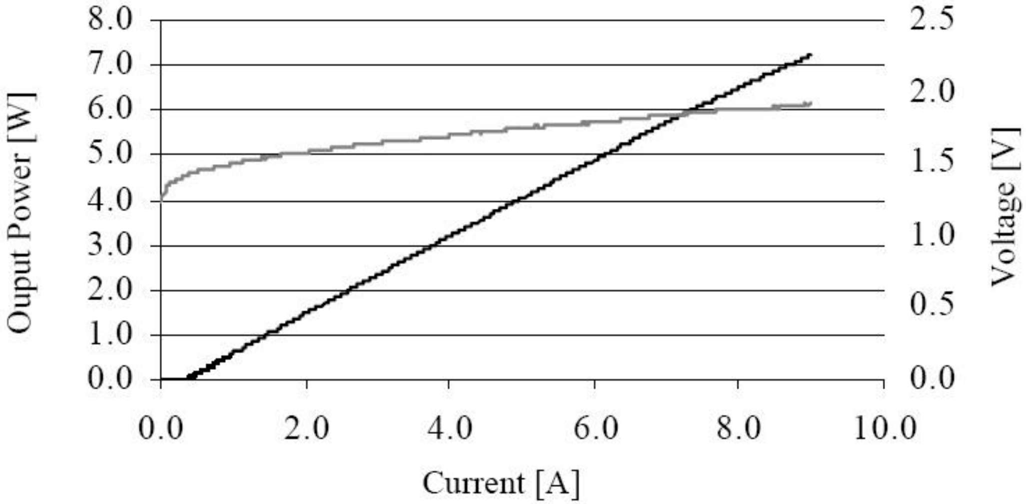


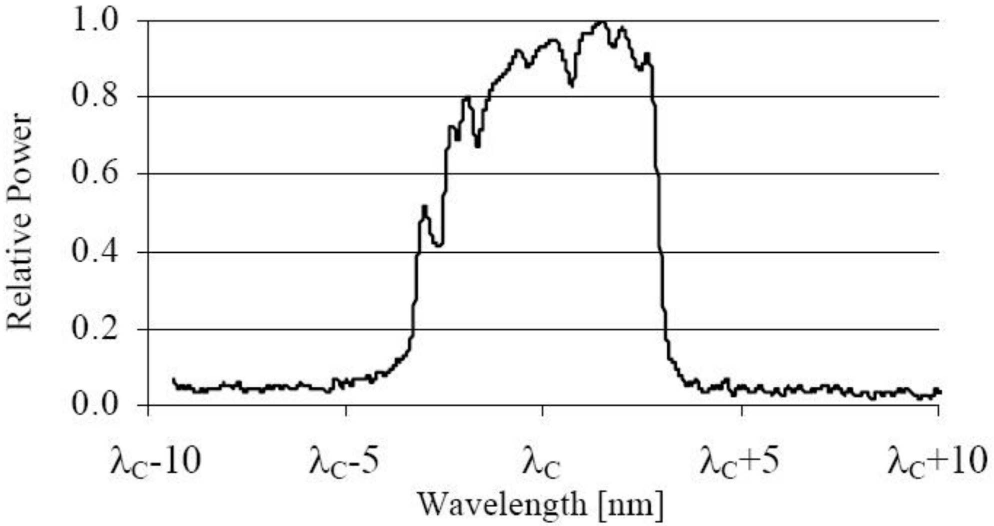
Utilizare amplificatoare optice



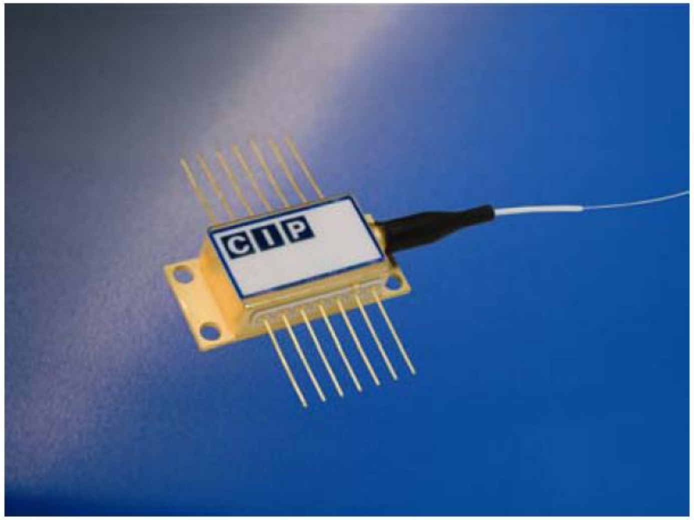
7W 980 nm Multimode Pump Laser

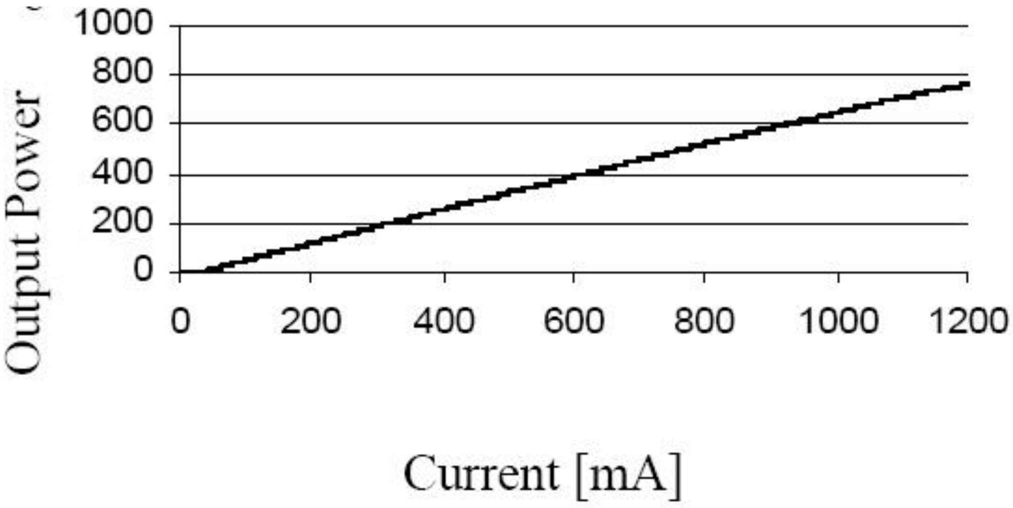


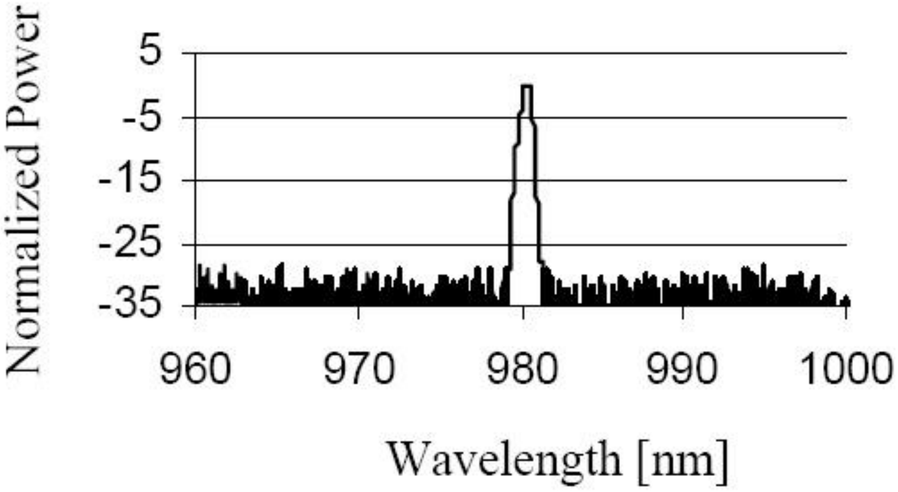




600mW 980 nm Singlemode Pump Laser

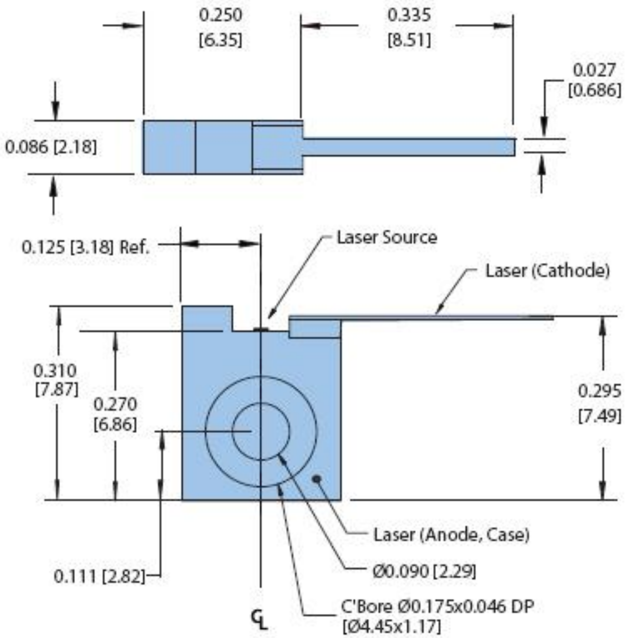




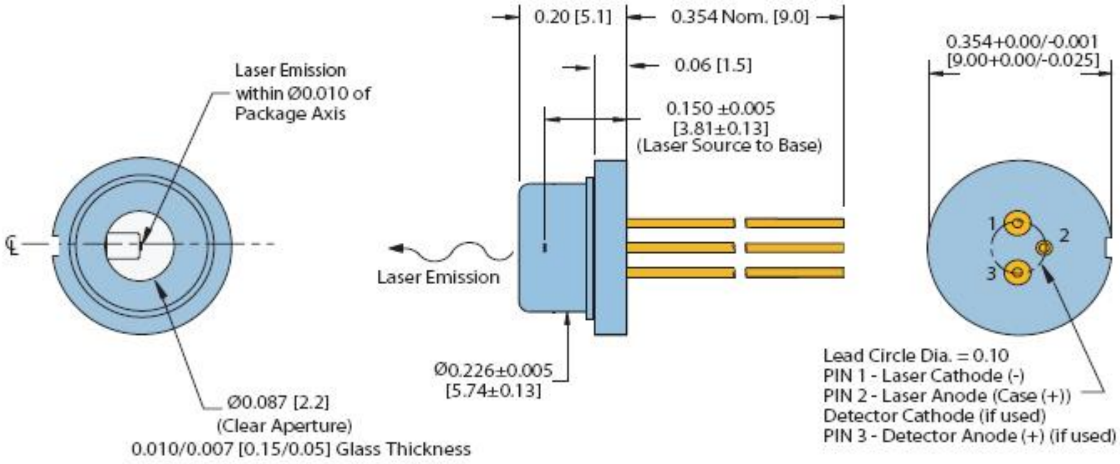


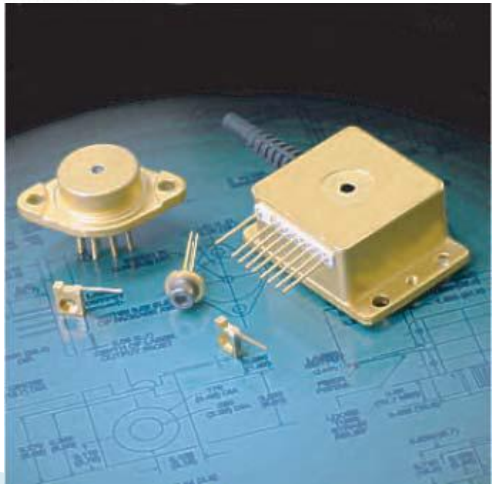
6 W, CW, 800nm

C-Mount Package



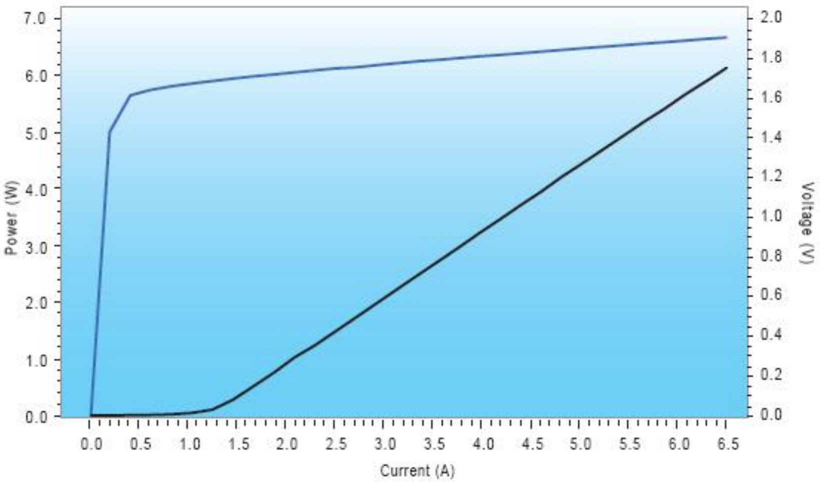
9mm Package



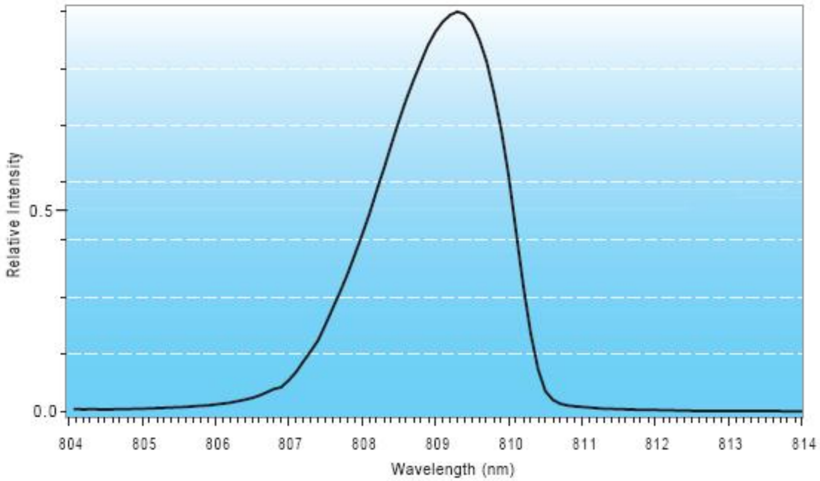


6 W, CW, 800nm

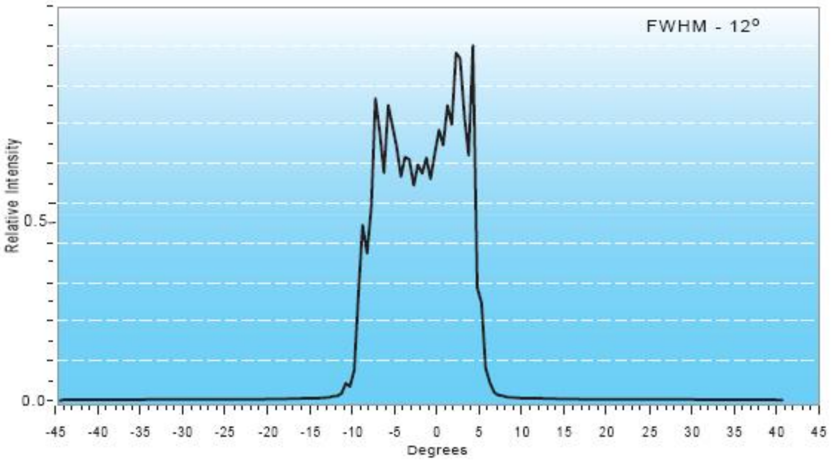
Typical L/I, V/I Graph



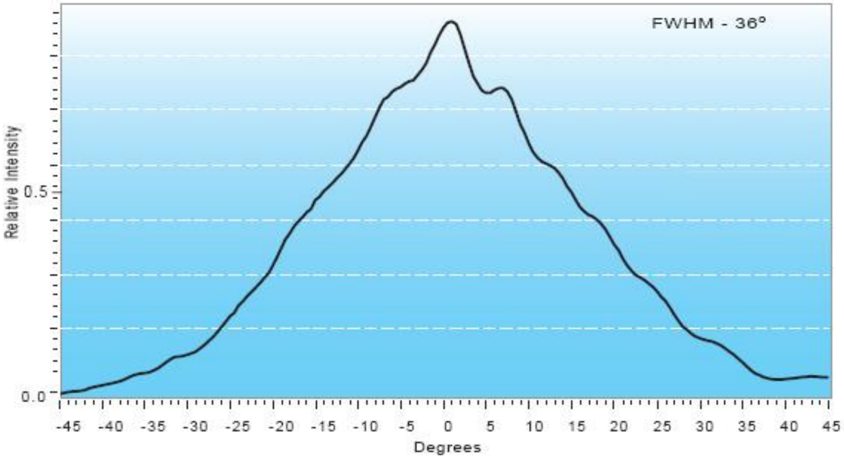
Wavelength Distribution



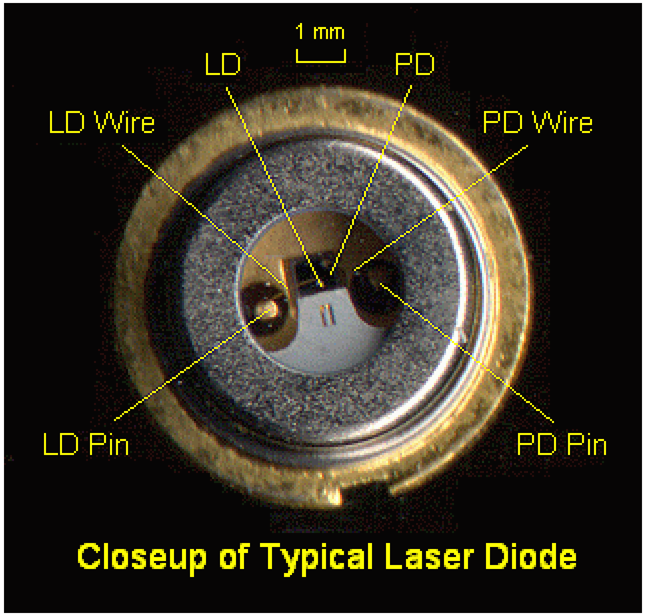
Typical Beam Divergence **Parallel**



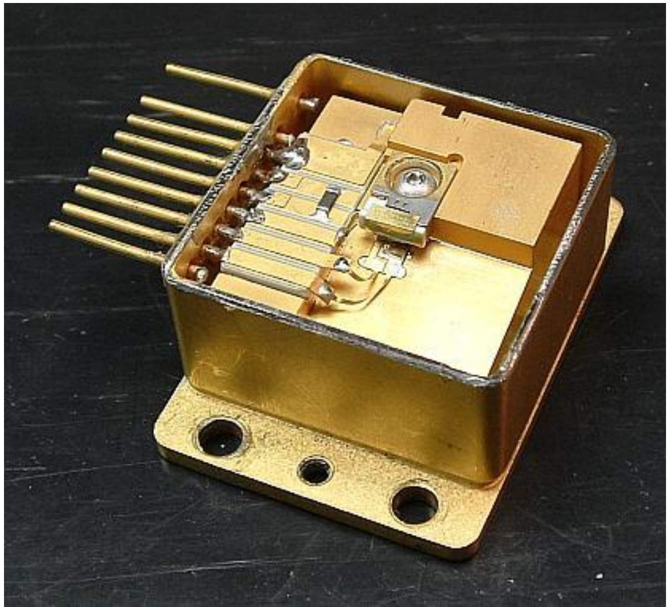
Typical Beam Divergence **Perpendicular**



CW Laser, 650 nm



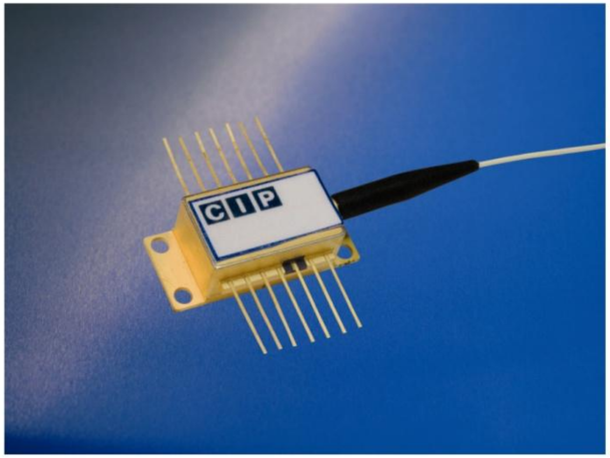
Closeup of Typical Laser Diode



Lungimi de unda

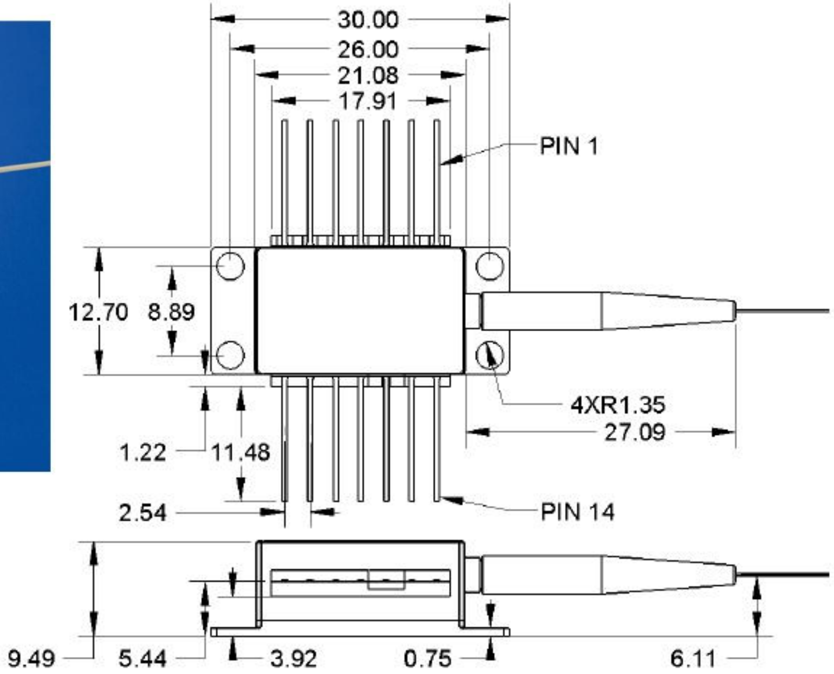
- **405 nm** – InGaN blue-violet laser, in Blu-ray Disc and HD DVD drives
- **445–465 nm** – InGaN blue laser multimode diode recently introduced (2010) for use in mercury-free high-brightness data projectors
- **510–525 nm** – Green diodes recently (2010) developed by Nichia and OSRAM for laser projectors.
- **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: O_2
- **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: NH_3
- **1,550 nm** – InGaAsP, InGaAsNSb fiber-optic communication
- **1,625 nm** – InGaAsP fiber-optic communication, service channel
- **1,654 nm** – InGaAsP gas sensing: CH_4
- **1,877 nm** – GaInAsSb gas sensing: H_2O
- **2,004 nm** – GaInAsSb gas sensing: CO_2
- **2,330 nm** – GaInAsSb gas sensing: CO
- **2,680 nm** – GaInAsSb gas sensing: CO_2
- **3,030 nm** – GaInAsSb gas sensing: C_2H_2
- **3,330 nm** – GaInAsSb gas sensing: CH_4

1550nm DFB Laser



Mechanical Drawing

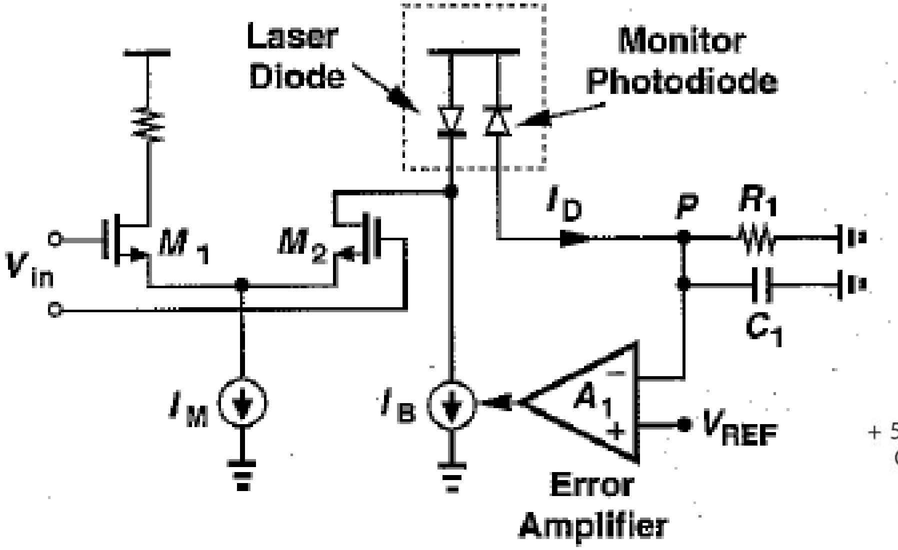
All units in mm



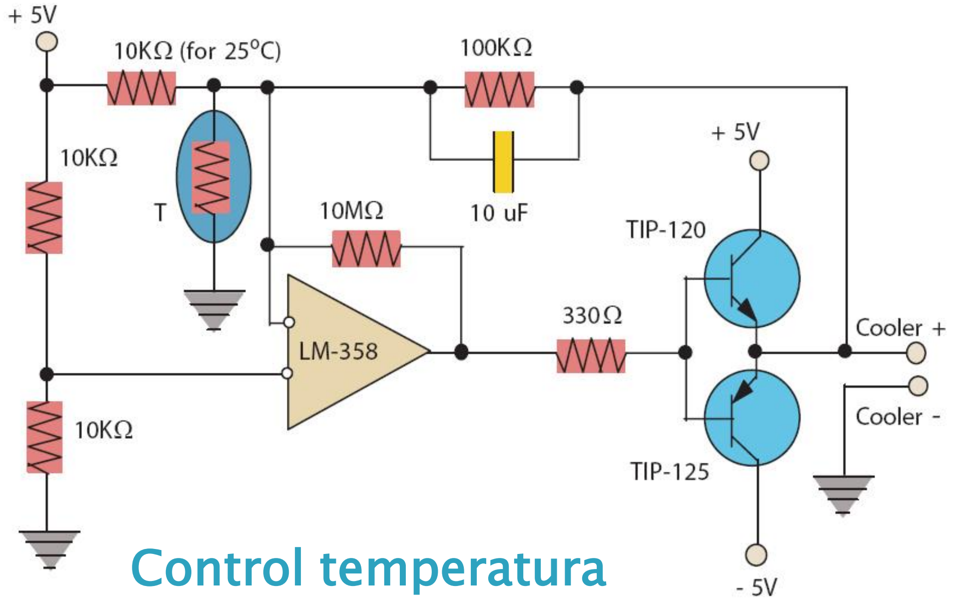
Pin out

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



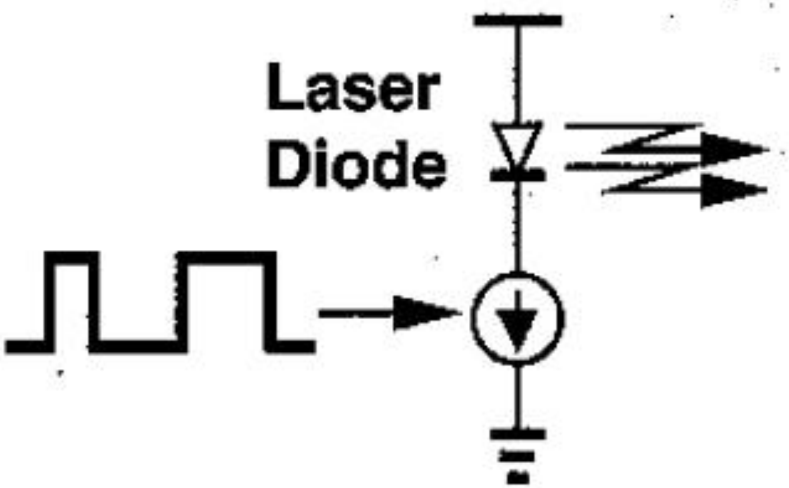
Control putere optica



Control temperatura

Dioda LASER

- Ca si in cazul LED, pentru DL intensitatea luminoasa emisa este o functie de curentul prin dioda
    - aproape exclusiv, DL sunt controlate in curent
    - controlul in curent are avantajul unei viteze mai mari de lucru

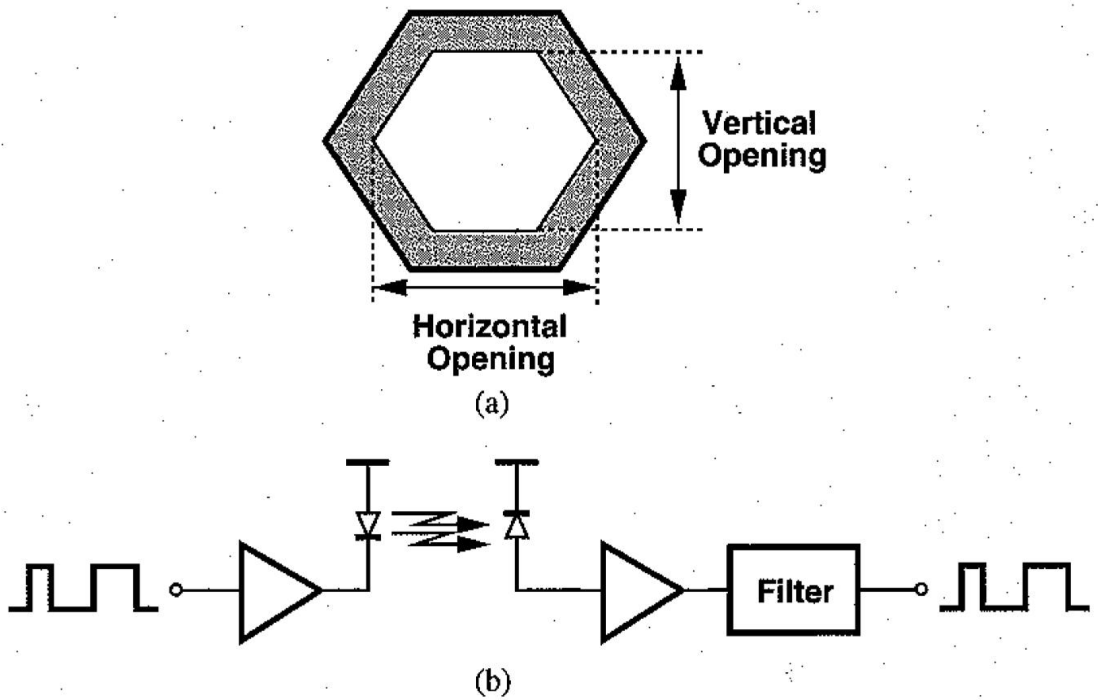


Dioda LASER

- 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 micsorarea dimensiunii componentelor
  - micsorarea dimensiunii
    - scade tensiunea de strapungere
    - scade capabilitatea de curent/putere disipata

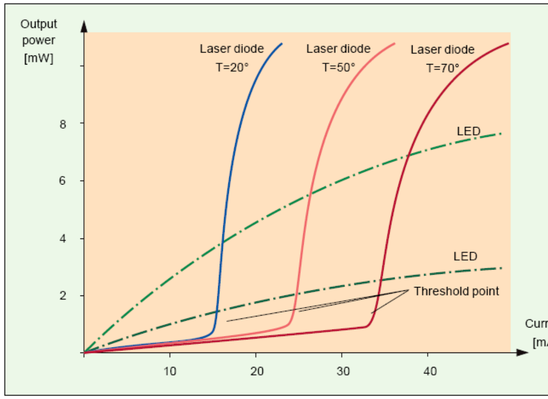
Caracteristici driver-e DL

- 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”



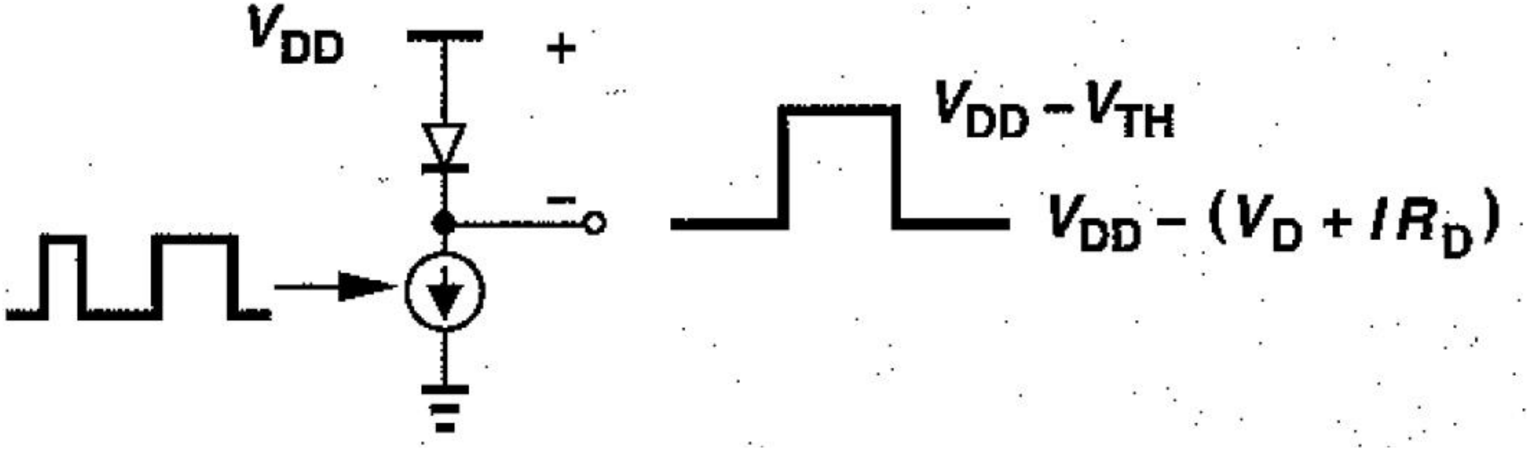
Caracteristici driver-e DL

- 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



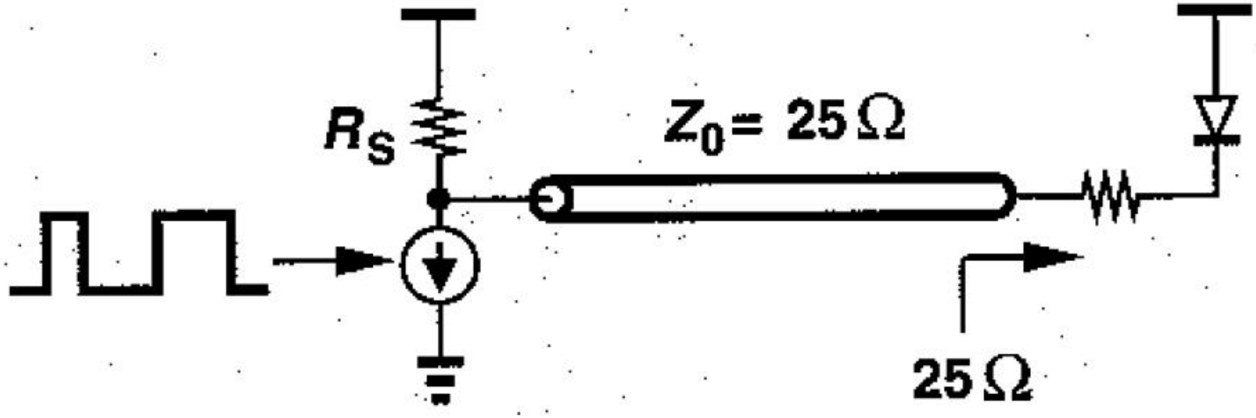
Caracteristici driver-e DL

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



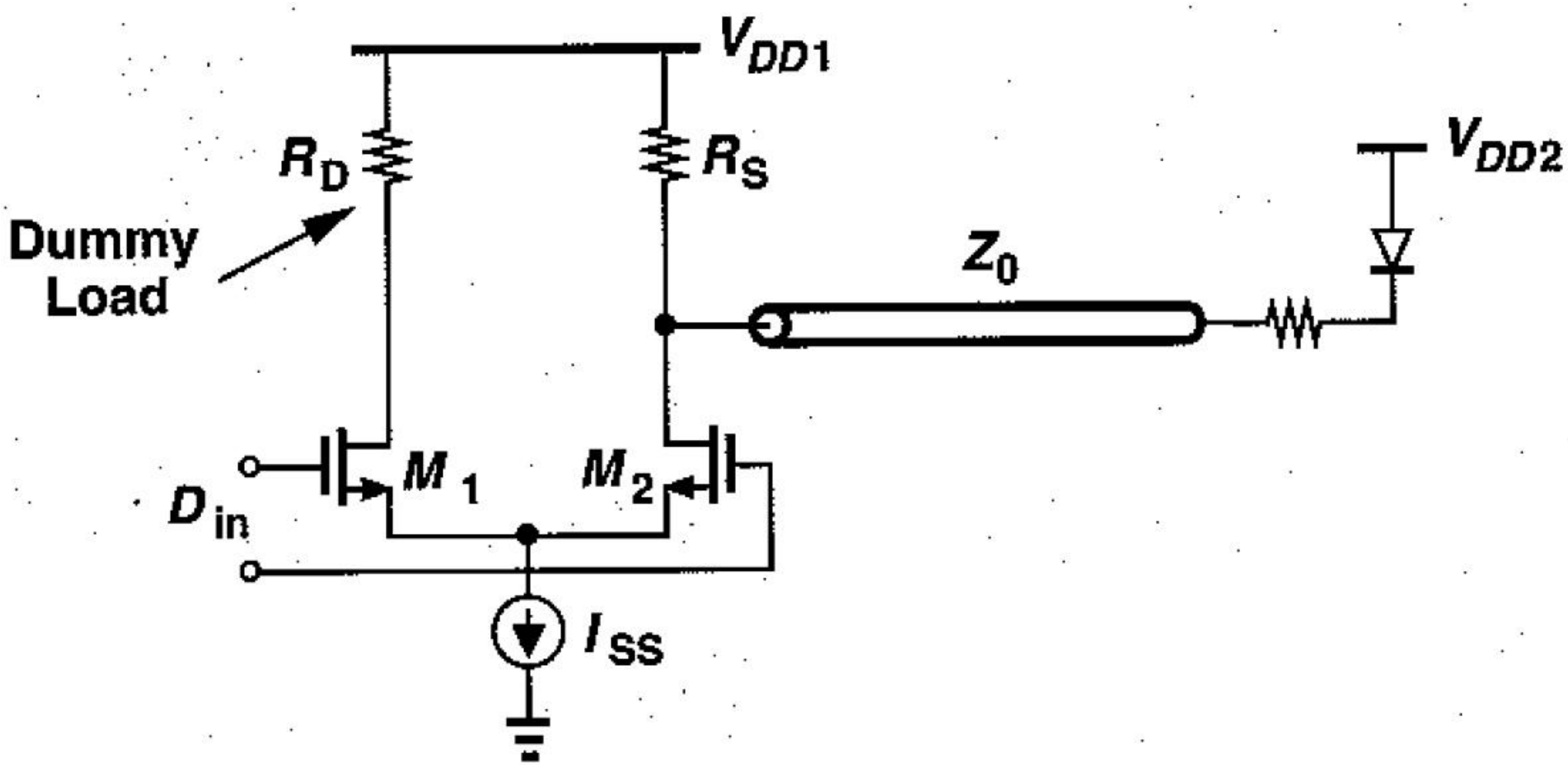
Caracteristici driver-e DL

- Impedante de intrare si iesire
- Se lucreaza la viteze mari (1Gb/s, 10Gb/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 (~25Ω) prin introducerea unui rezistor in serie



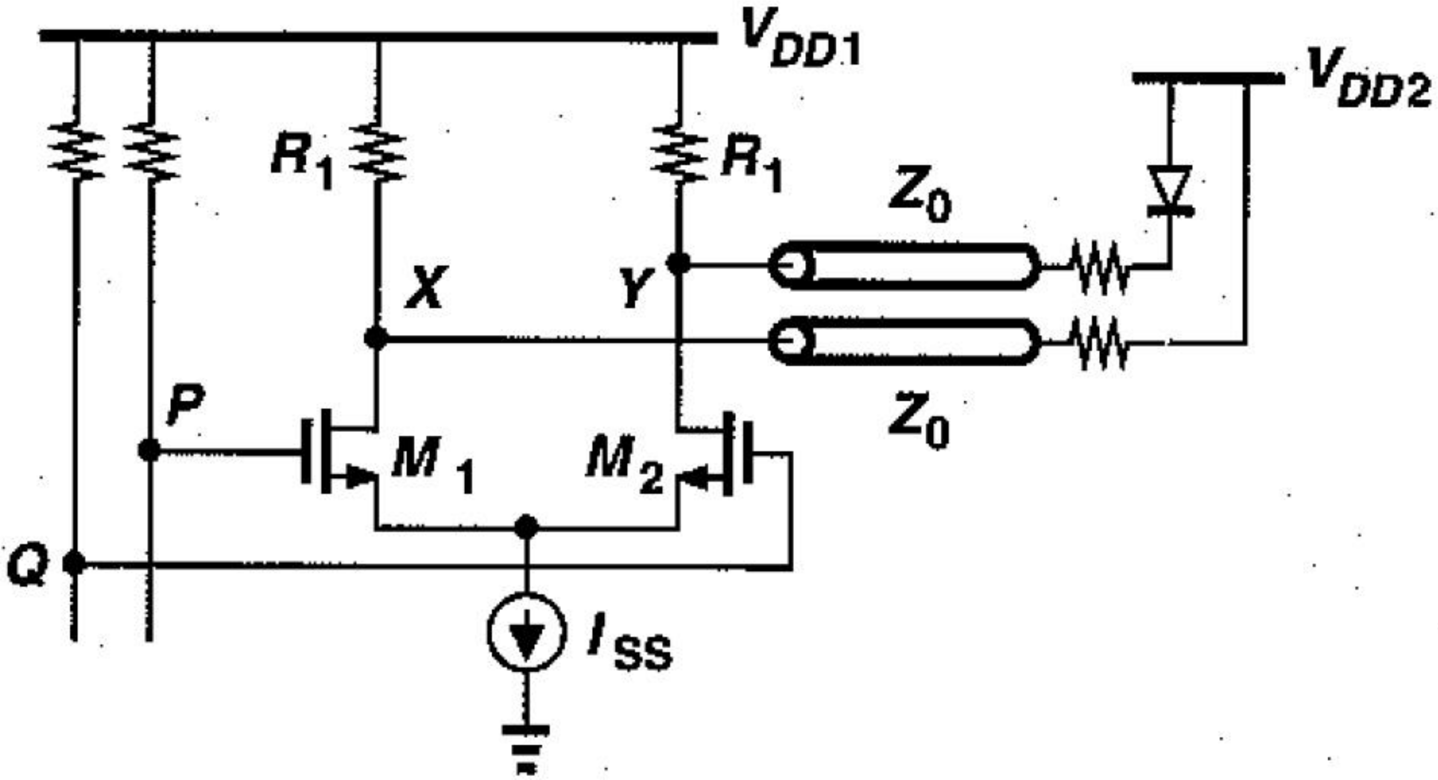
Principii de proiectare

- Tipic etajul de iesire se realizeaza diferential



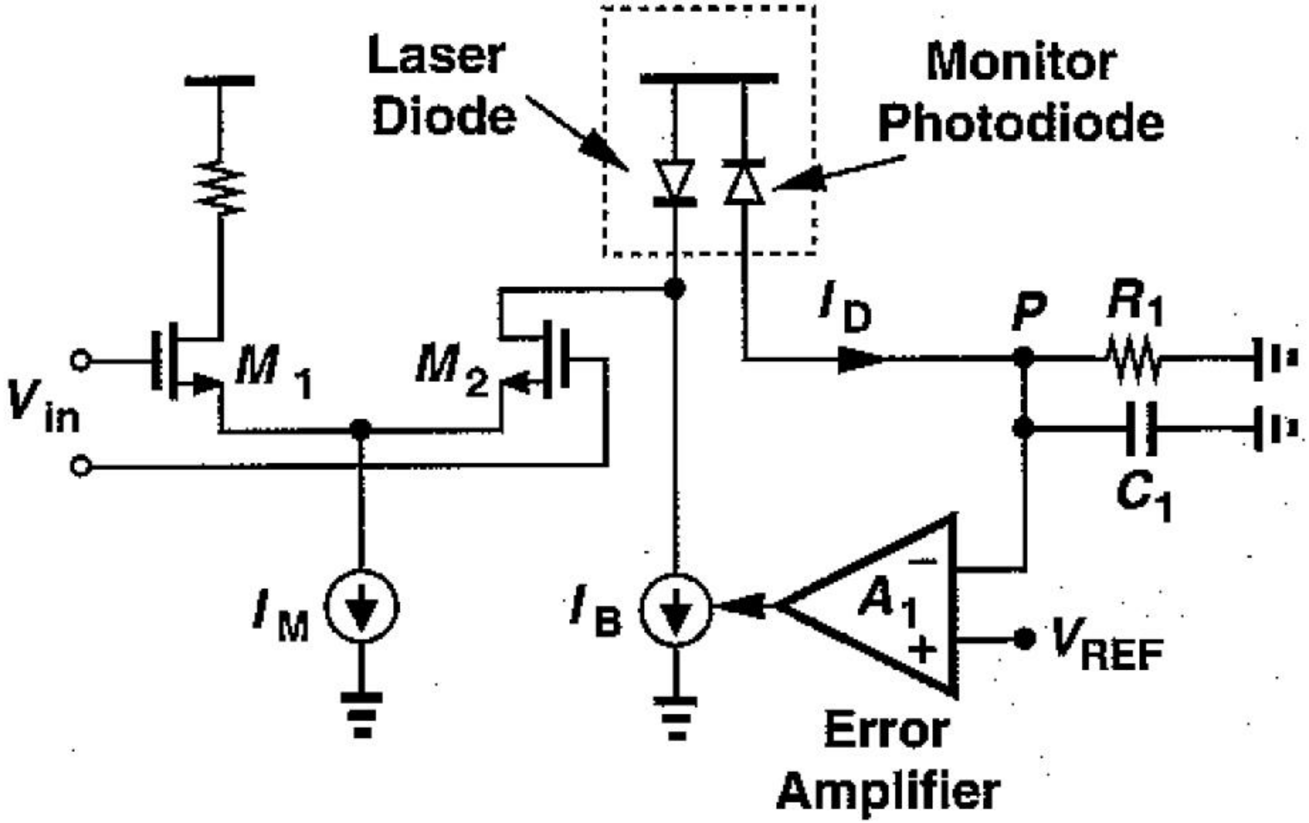
Principii de proiectare

- La viteze mari se utilizeaza tipic tranzistoare unipolare si etajul diferential se realizeaza simetric



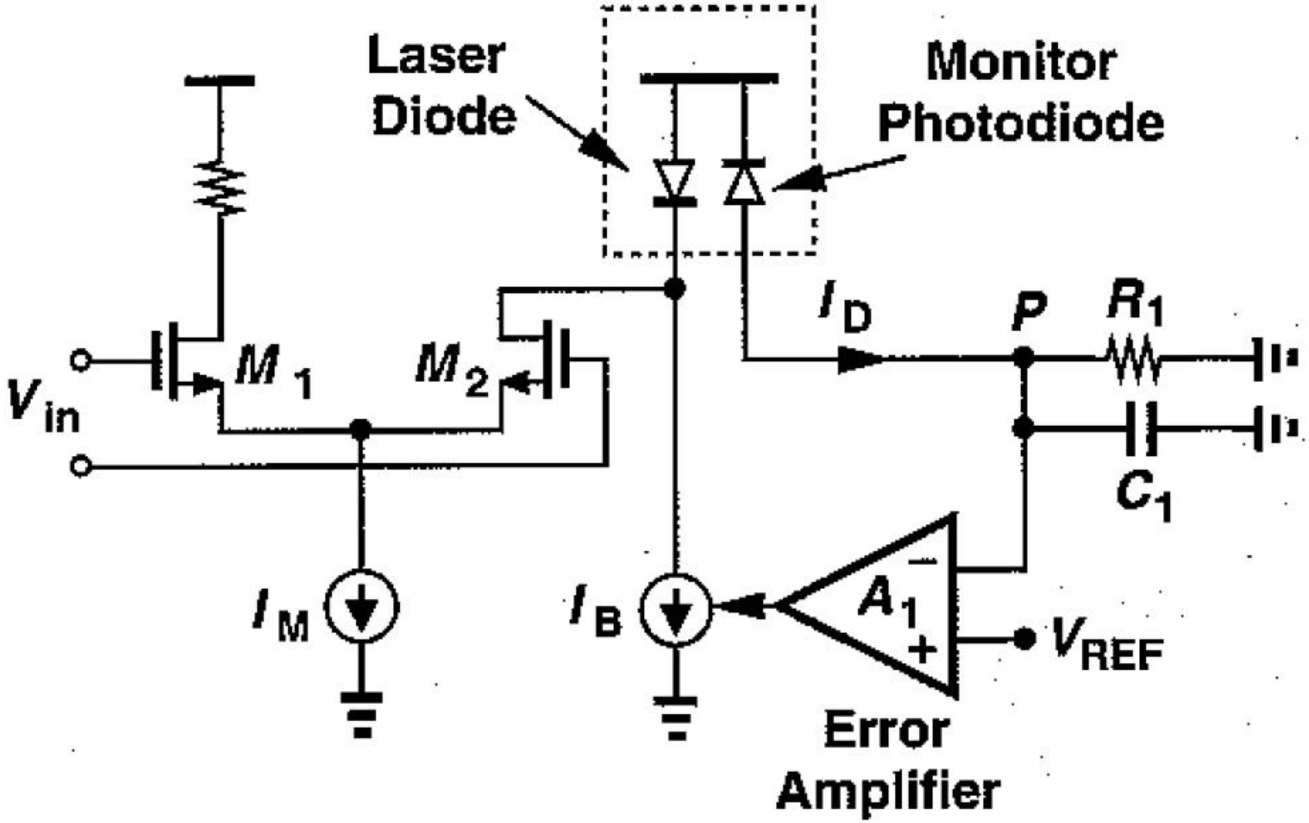
Controlul puterii in DL

- Necesar datorita variatiei curentului de “polarizare”



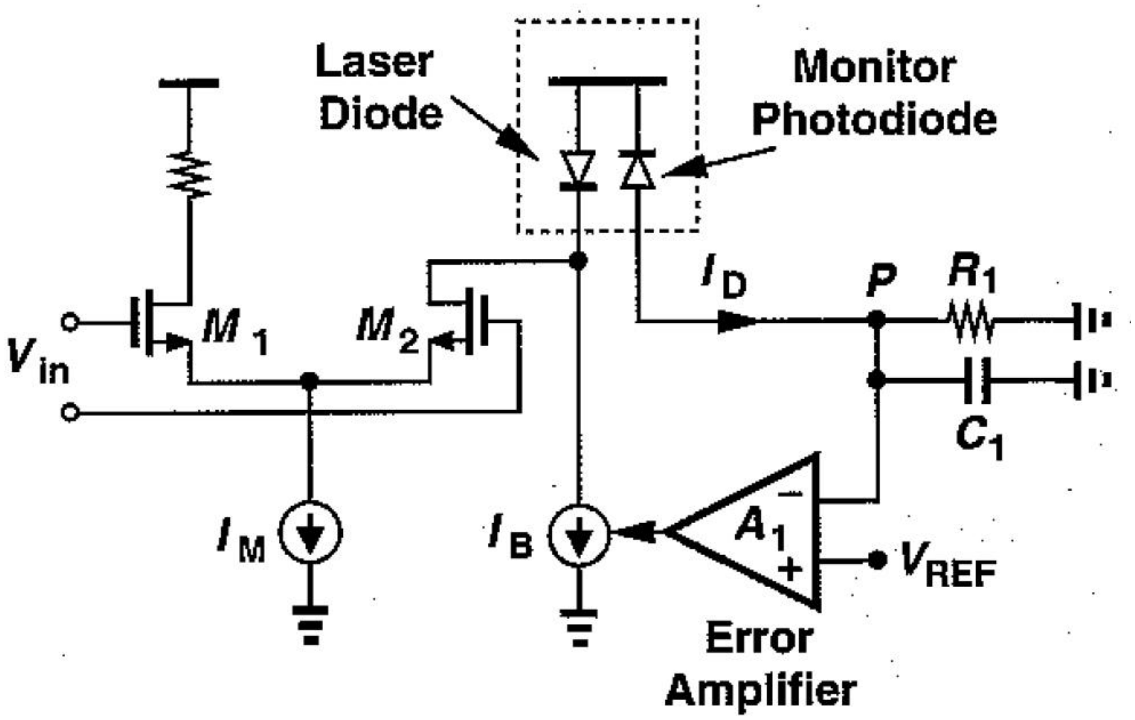
Controlul puterii in DL

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



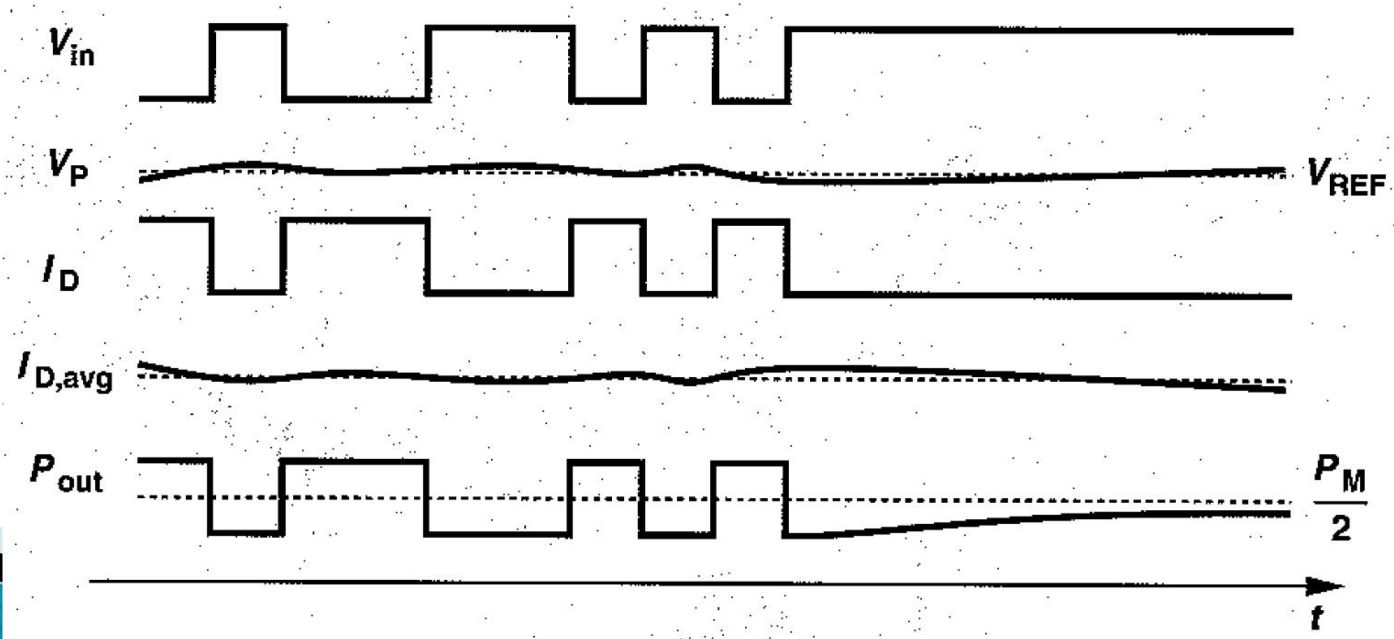
Controlul puterii in DL

- 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 jumatate 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

Cuprins

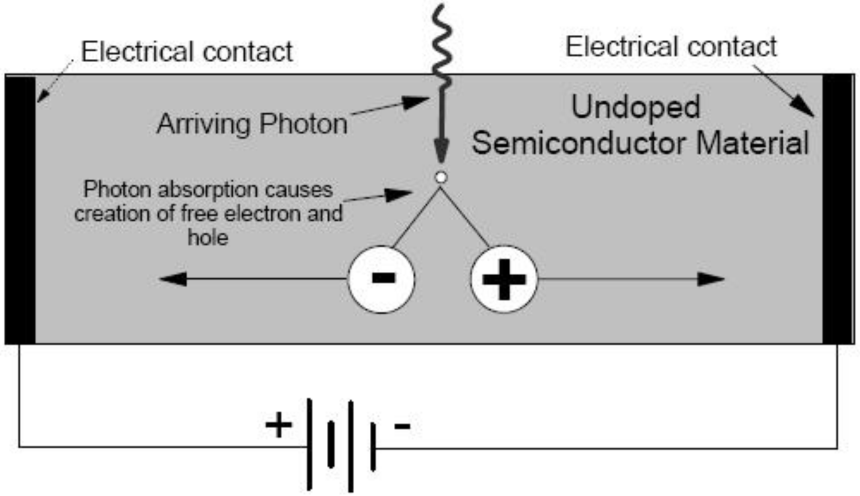
- **Lumina ca undă electromagnetică** (ecuaţiile lui Maxwell, ecuaţia undelor, parametrii de propagare)
- **Elemente de fotometrie şi radiometrie** (mărimi energetice/luminoase)
- **Fibra optică** (realizare, principiu de funcţionare, atenuare, dispersie, banda de frecvenţă)
- **Cabluri optice** (tehnologie, conectori, lipire - splice)
- **Proiectare sistemică a legăturii pe fibra optică** (bandă de frecvenţă, balanţa puterilor)
- **Emiţătoare optice** (LED şi dioda laser - realizare fizică şi functionare)
- **Receptoare optice** (dioda PIN, dioda cu avalanşă - realizare fizică şi functionare)
- **Amplificatoare transimpedanţă** (parametri, scheme tipice, TIA în buclă deschisă, cu reacţie, diferenţiale, control automat al câştigului)
- **Realizarea circuitelor pentru controlul emiţătoarelor optice (**parametri, scheme tipice, controlul puterii, multiplexoare**)**
- **Dispozitive de captare a energiei solare** (principiu de functionare, utilizare, proiectare)

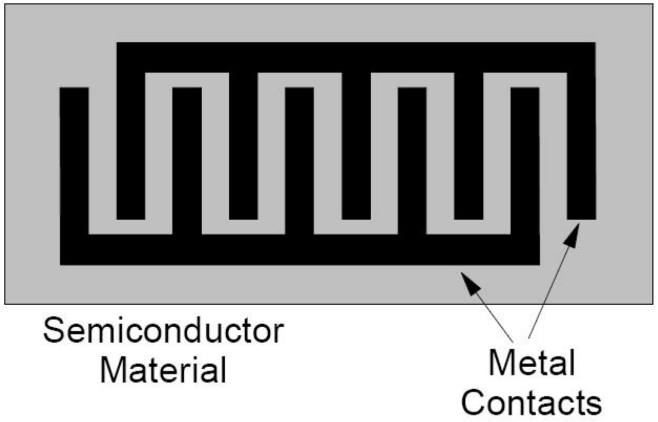
Detectori optici

- 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

Fotoconductori

- Principiu

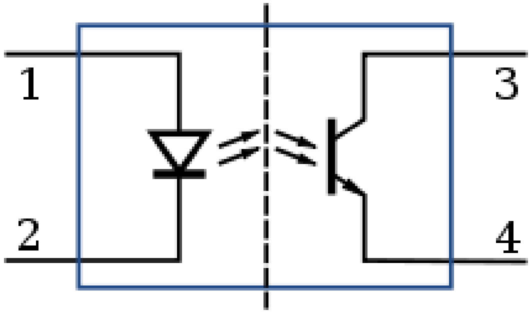


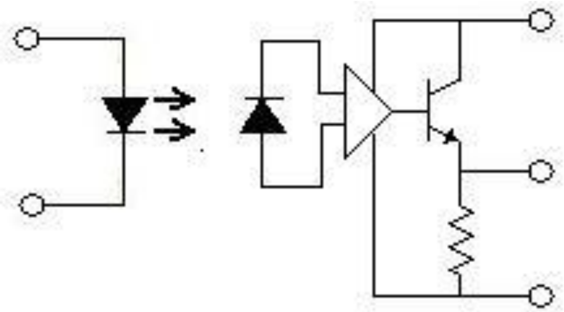


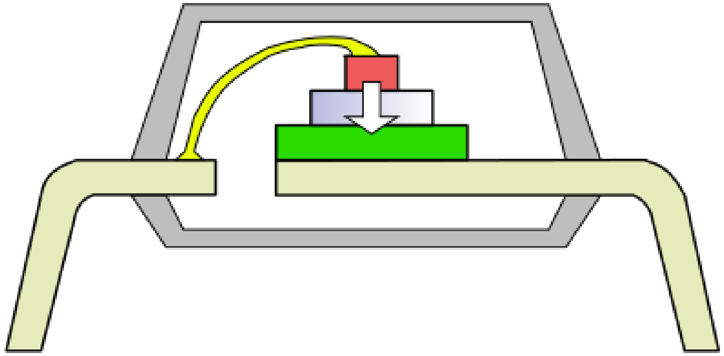
- Recent dispozitive Metal Semiconductor Metal (filtru interdigital) au inceput sa fie utilizate pentru usurinta de fabricare si integrare in aplicatii mai putin pretentioase

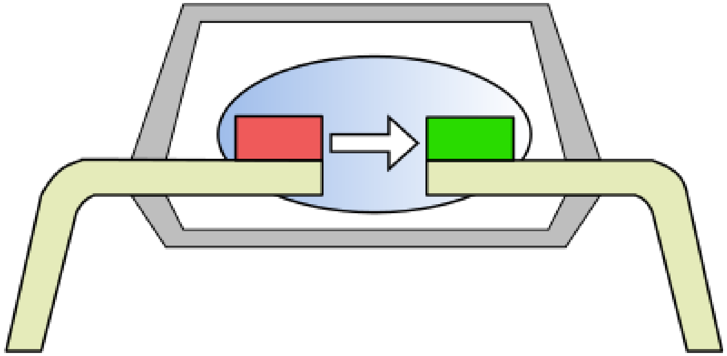
Optocuploare

- utilizate pentru a oferi izolare electrica intre doua sectiuni ale unui circuit
  - izolarea portiunii de comanda si/sau masura de partea de “forta” a circuitului



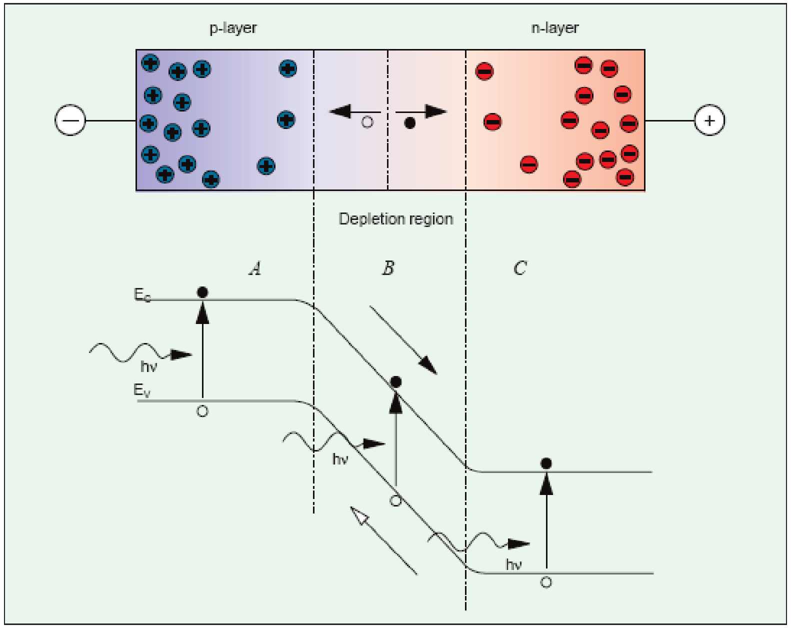


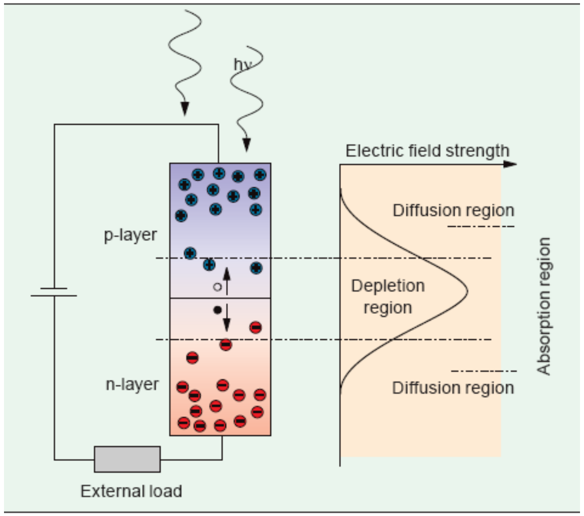




Fotodioda – Principiul de operare

- 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

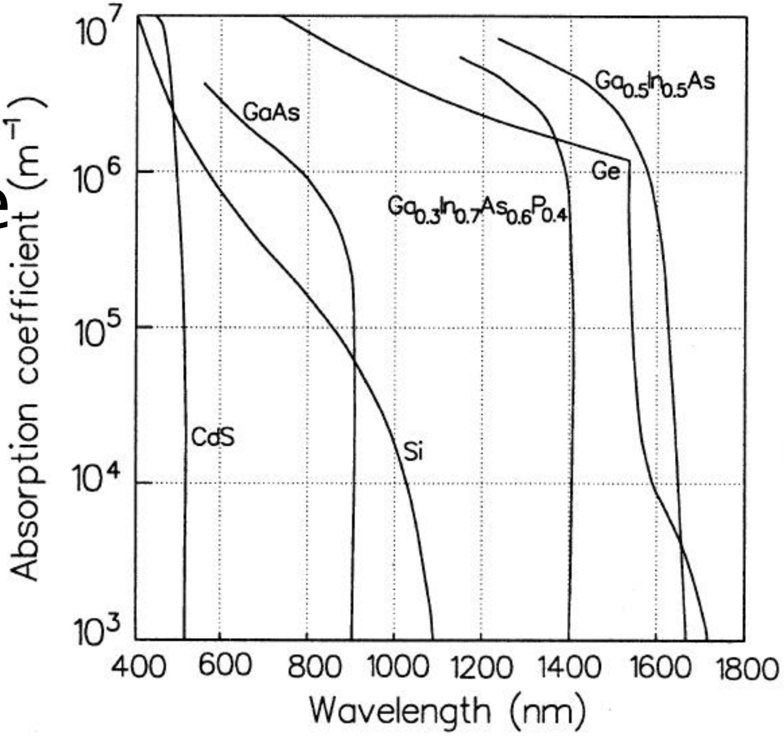
$$\lambda_{\max} = \frac{hc}{E_g}$$

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

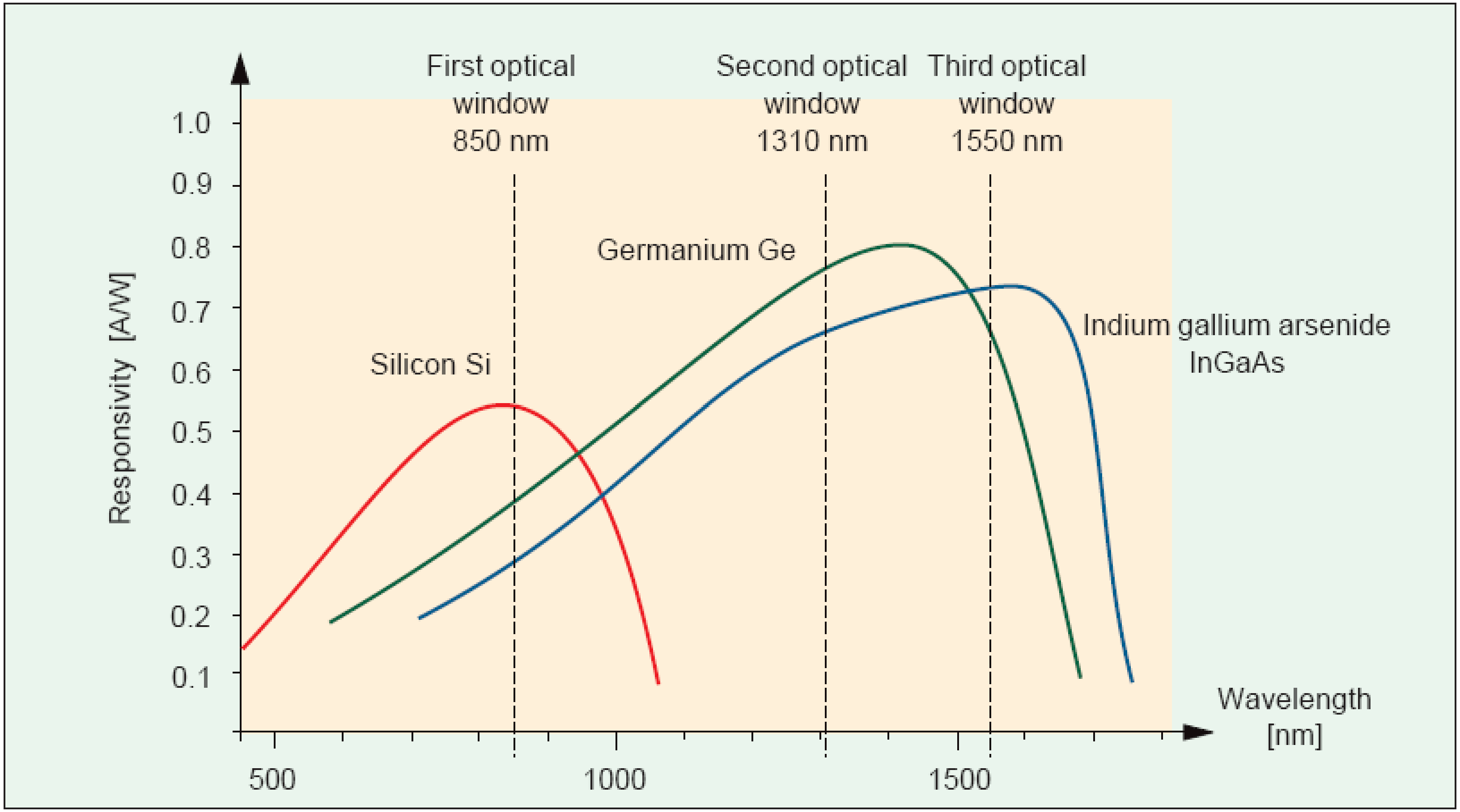
$$P(w) = P_i \cdot e^{-\alpha \cdot d} \cdot \left(1 - e^{-\alpha \cdot w}\right) \cdot \left(1 - R_f\right)$$

Fotodioda – Principiul de operare

- Coeficientul de absorbtie pentru materialele uzuale
- Valoarea mare a coeficientului de absorbtie la lungimi de unda reduse implica scaderea responzivitatii
- 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 şi numărul de fotoni incidenţi

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

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

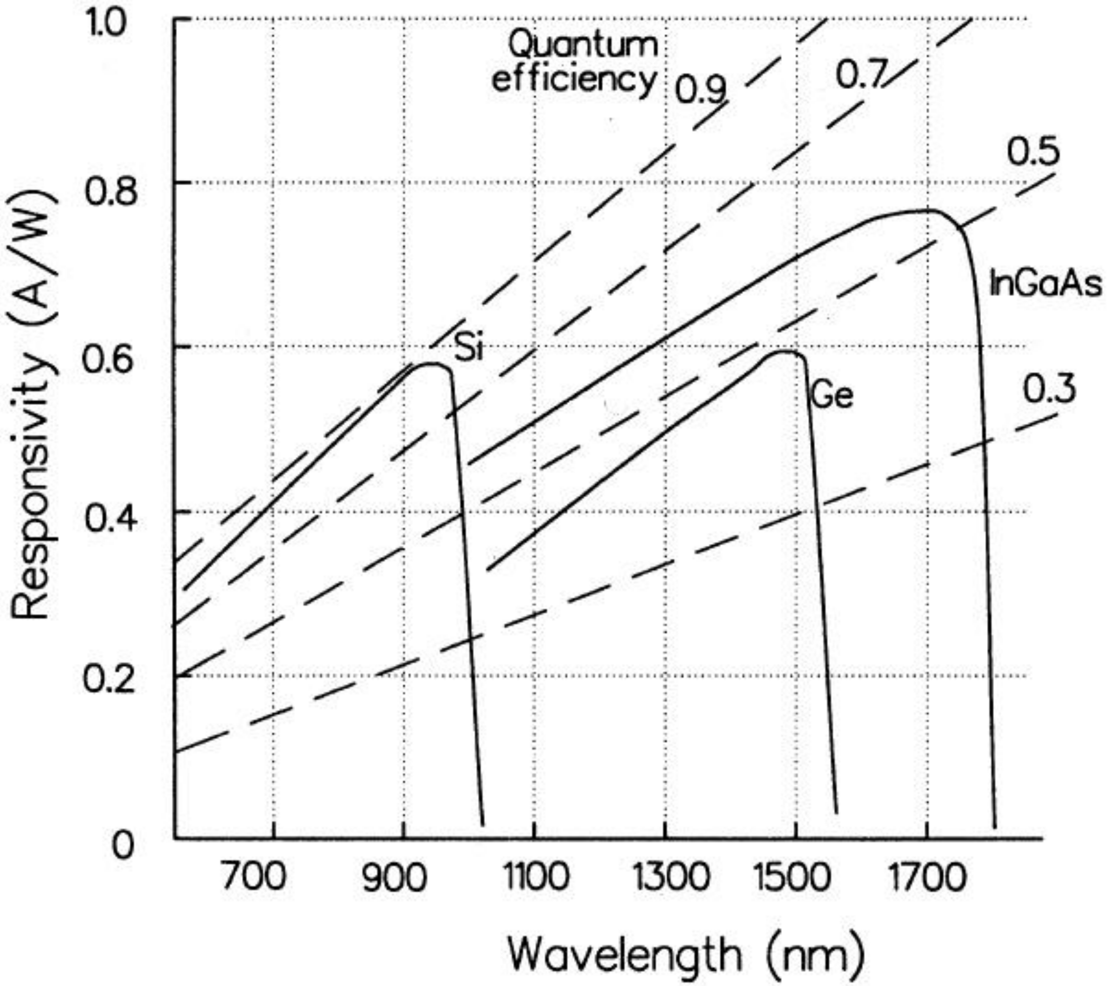
$$\eta = \frac{I/e}{P/h\nu}$$

- Responzivitatea

$$R = \frac{I}{P_o} = \frac{\eta \cdot e \cdot \lambda}{hc} \qquad R = 0.8 \cdot \eta \cdot \lambda[\mu m] \qquad \left[\frac{A}{W}\right]$$

Fotodiode – marimi caracteristice

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



Materiale 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	Eg (eV)
GaAs	1.43
GaSb	0.73
$GaAs_{0.88}Sb_{0.12}$	1.15
Ge	0.67
InAs	0.35
InP	1.35
$In_{0.53}Ga_{0.47}As$	0.75
$In_{0.14}Ga_{0.86}$ As	1.15
Si	1.14

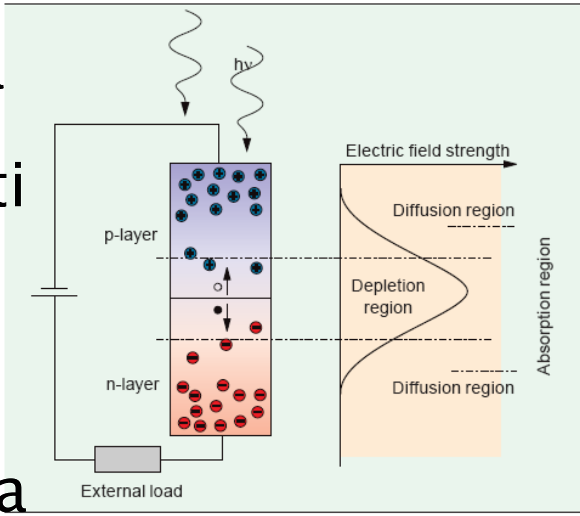
Curent de intuneric

- Curentul invers al jonctiunii p–n, datorat agitatiei termice, prezent in absenta iluminarii
- Constituie 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

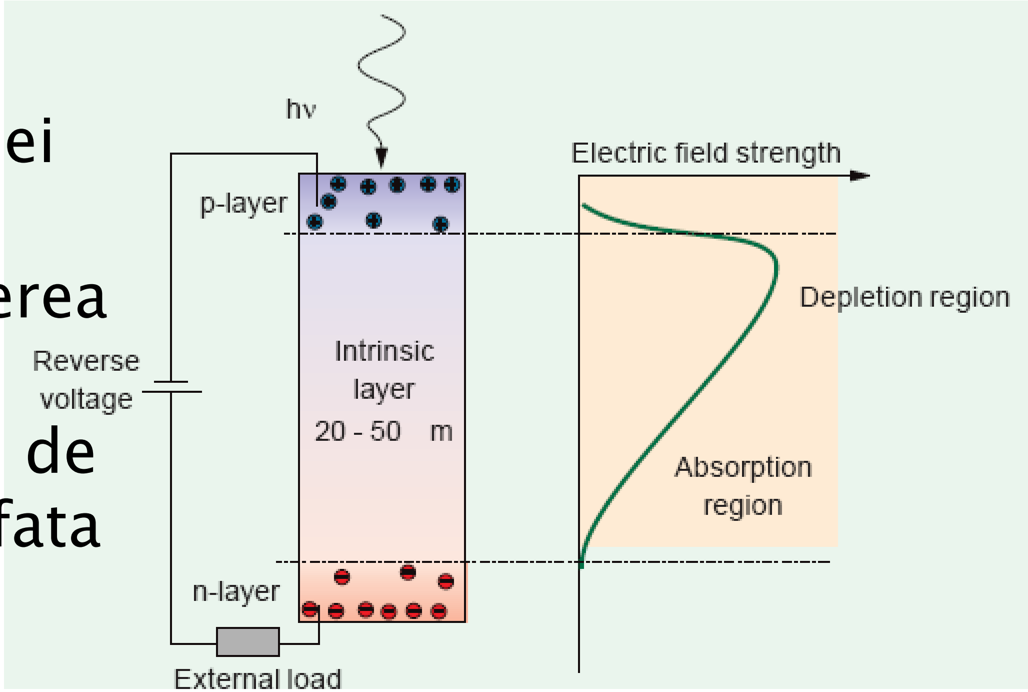


- Existenta campului electric in regiunea golita de purtatori face ca eventualii purtatori generati optic sa fie accelerati spre terminale pentru constituirea fotocurentului
- Problemele utilizarii diodei pn polarizate invers ca fotodetector sunt generate de adancimea extrem de mica a zonei golite (w)
- 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

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

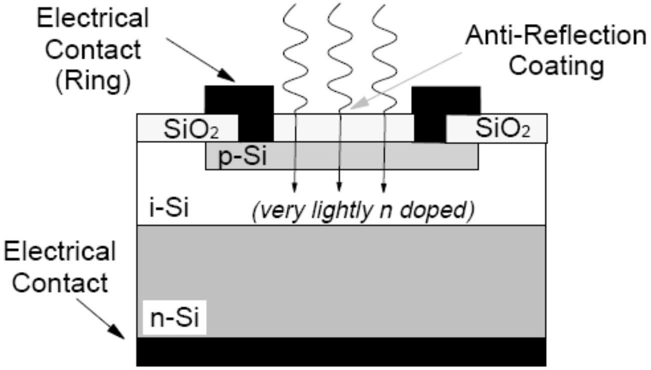
Fotodioda PIN

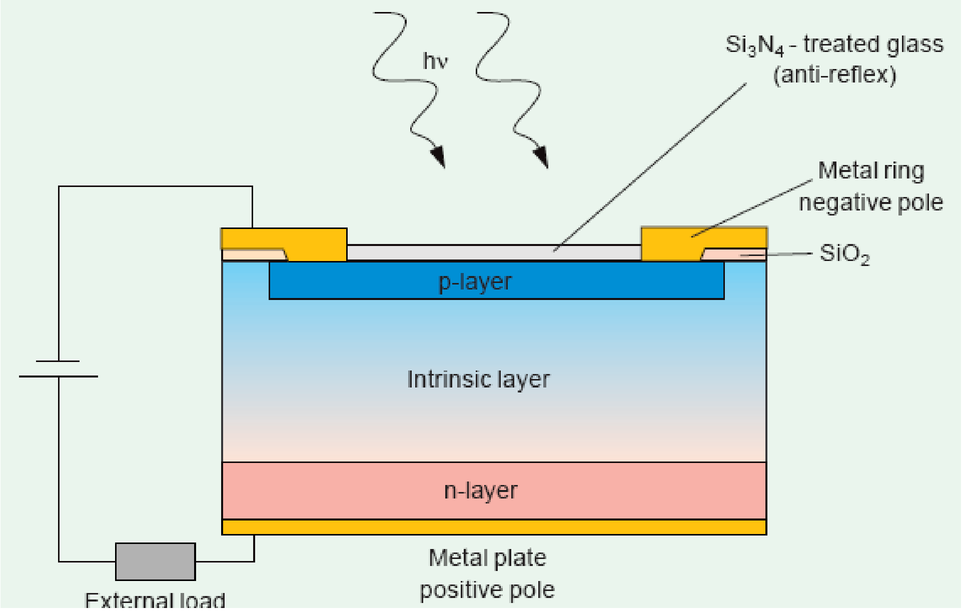
- Solutia consta in introducerea unui strat foarte slab dopat (intrinsec) intre cele doua zone ale diodei
  - creste volumul de absorbtie deci creste sensibilitatea fotodiodei
  - capacitatea jonctiunii scade ducand la cresterea vitezei
  - este favorizat curentul de conductie (mai rapid) fata de cel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



Structura fotodiodei PIN

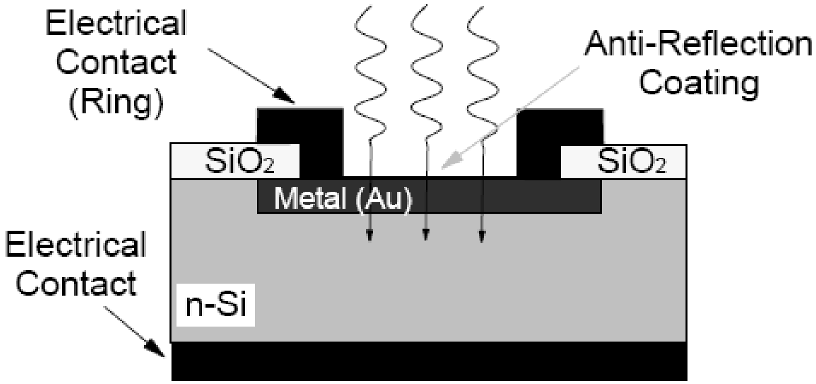
- tipic, adancimea stratului intrinsec este de 20-50µm
- cresterea suplimentara a adancimii ar duce la cresterea timpului de tranzit
  - w=20µm -> $T_{tr} \cong 0.2$ns





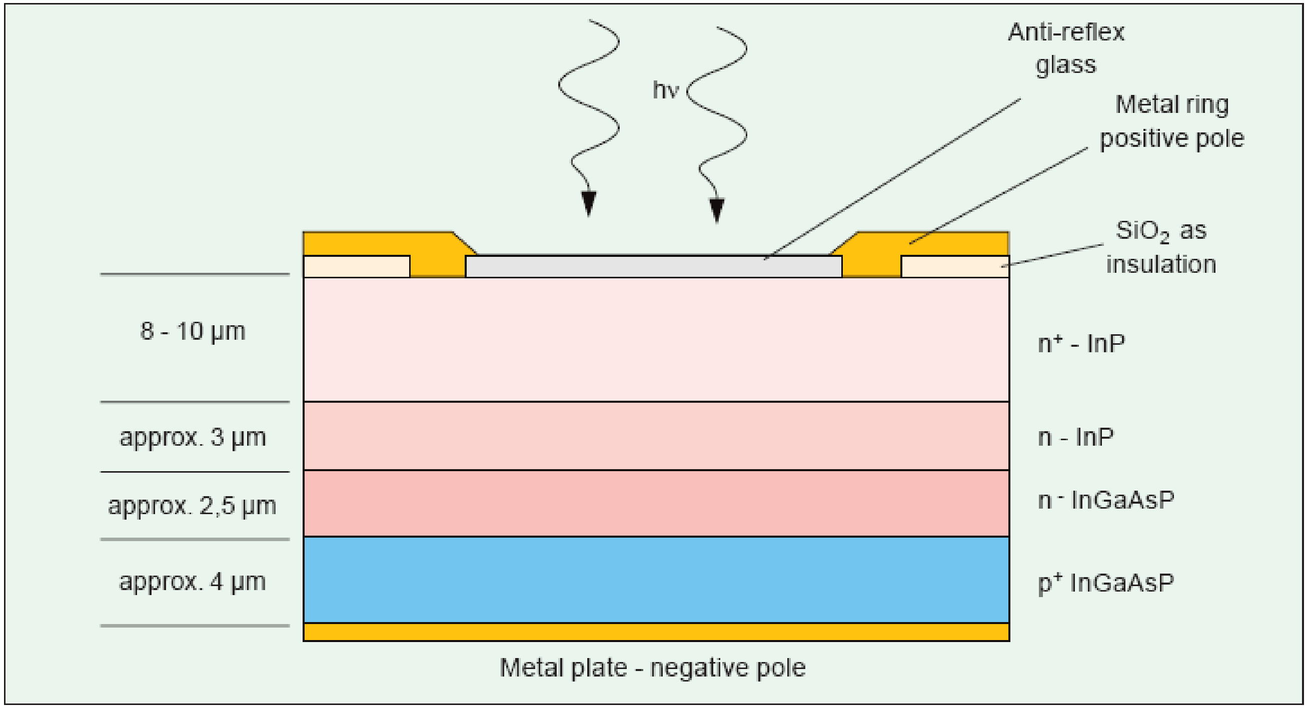
Structura fotodiodelor Schottky

- 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



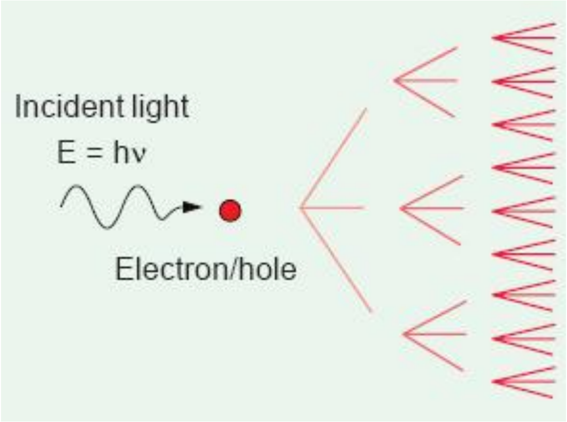
Fotodioda PIN pentru lungimi de unda crescute (1550nm)

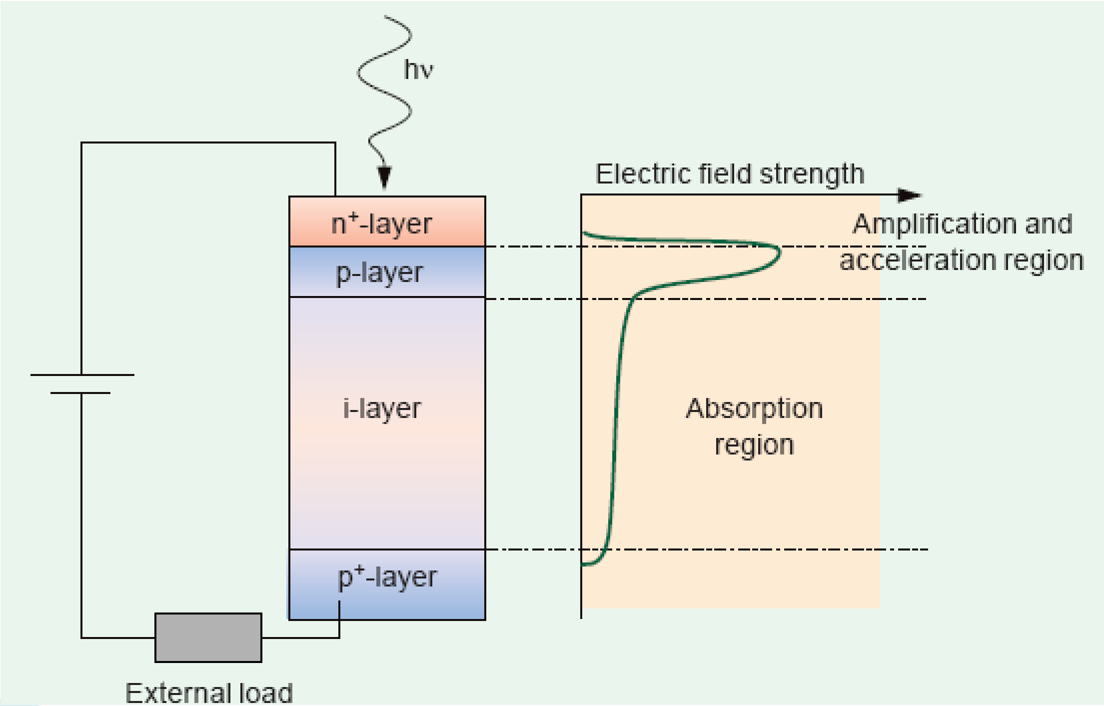
- se utilizeaza tipic
  - InGaAsP pe substrat InP
  - GaAlAsSb pe substrat GaSb



Fotodioda PIN cu multiplicare in avalansa

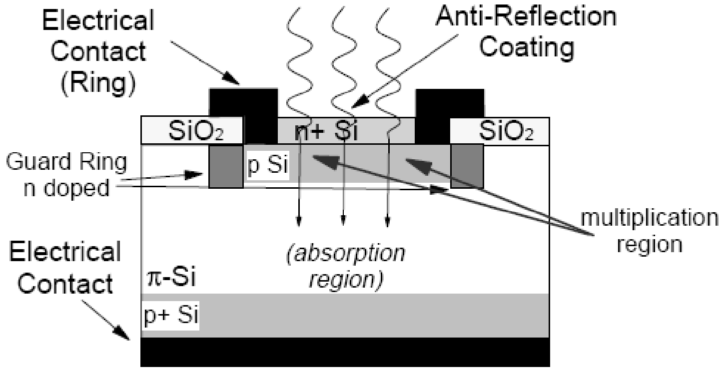
- daca viteza purtatorilor este suficient de mare genereaza noi perechi electron/gol prin ionizare de impact
- amplificarea are loc in acelasi timp cu detectia

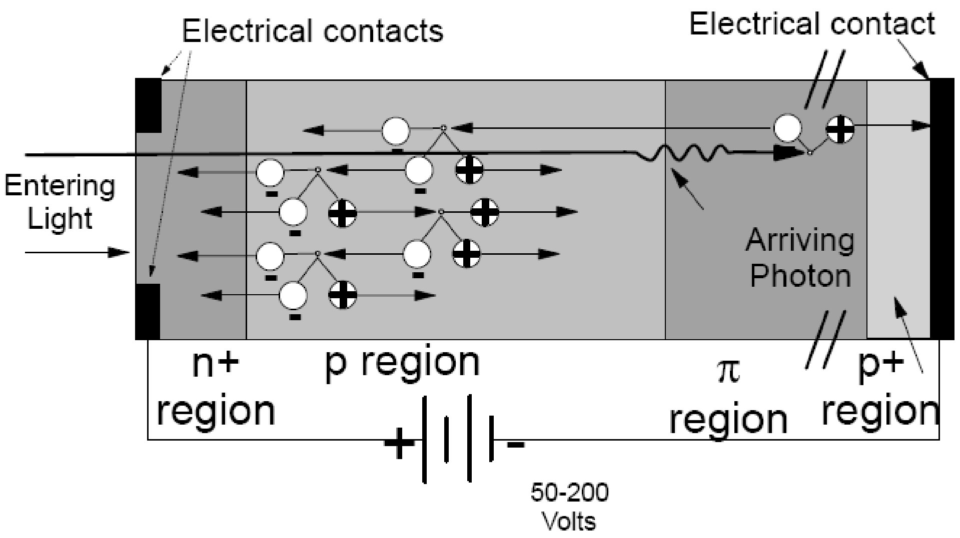




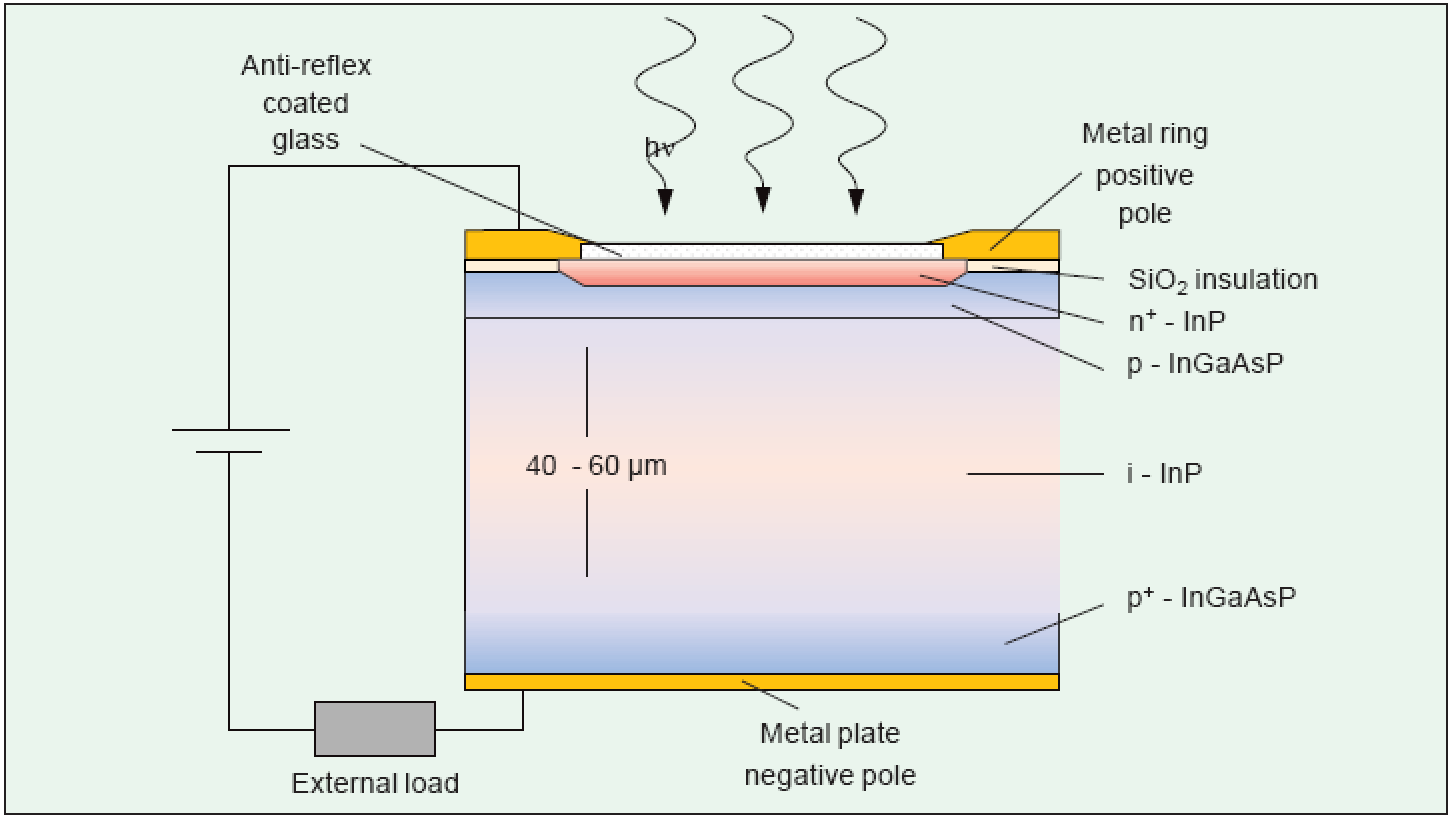
Functionarea fotodiodei cu multiplicare in avalansa

- 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



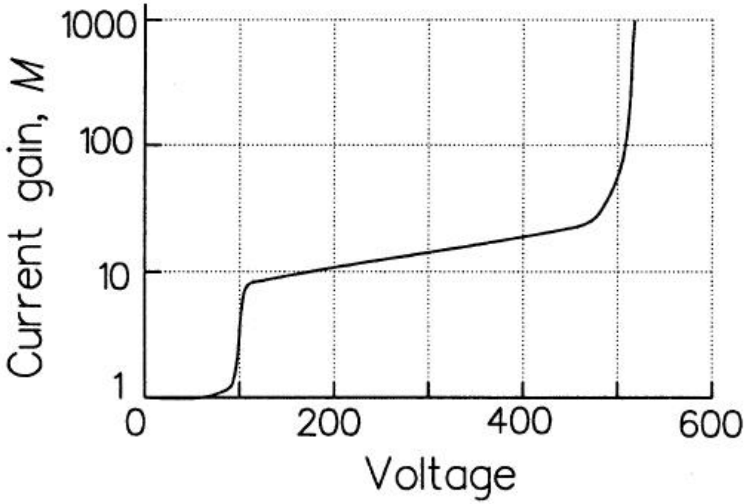
Caracteristicile fotodiodei cu multiplicare in avalansa

- factorul de multiplicare caracterizeaza amplificarea fotocurentului generat

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

- Responzivitatea

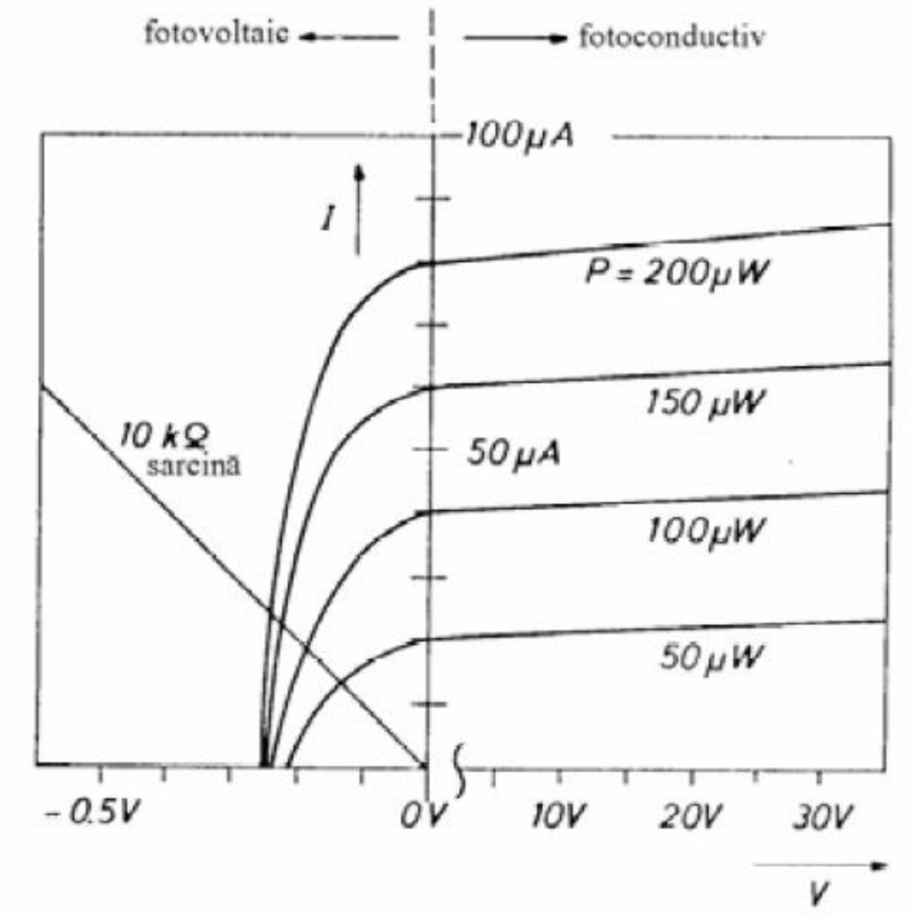
$$R = \frac{I}{P_o} = \frac{\eta \cdot e \cdot \lambda}{hc} \cdot M$$



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 multiplicitate are o componenta aleatorie (zgomot suplimentar)
- viteza mai redusa (timp de generare al avalansei)

Caracteristici curent/tensiune Fotodioda

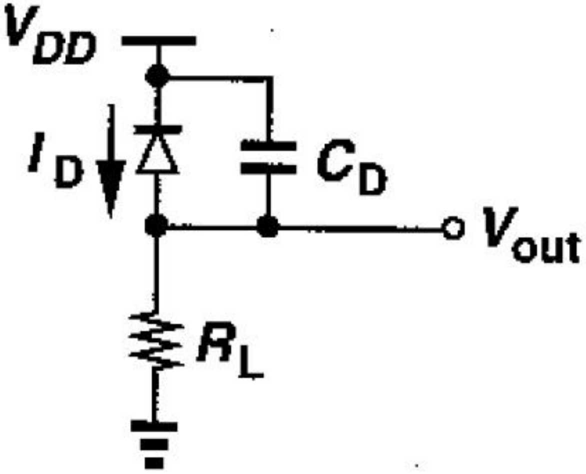


Amplificatoare transimpedanta

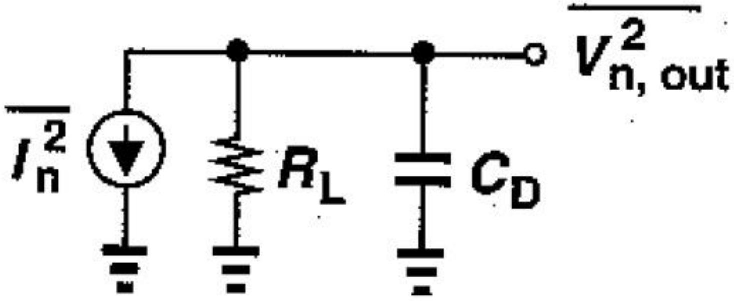
- Fotodiodele genereaza un curent proportional cu puterea optica receptionata
- Primul pas necesar este conversia acestui curent la o tensiune
- Amplificatoarele transimpedanta sunt amplificatoarele atacate in curent si care ofera la iesire o tensiune proportionala cu acesta
- Amplificarea este masurata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

Amplificatoare transimpedanta

- Cel mai simplu amplificator transimpedanta este un rezistor



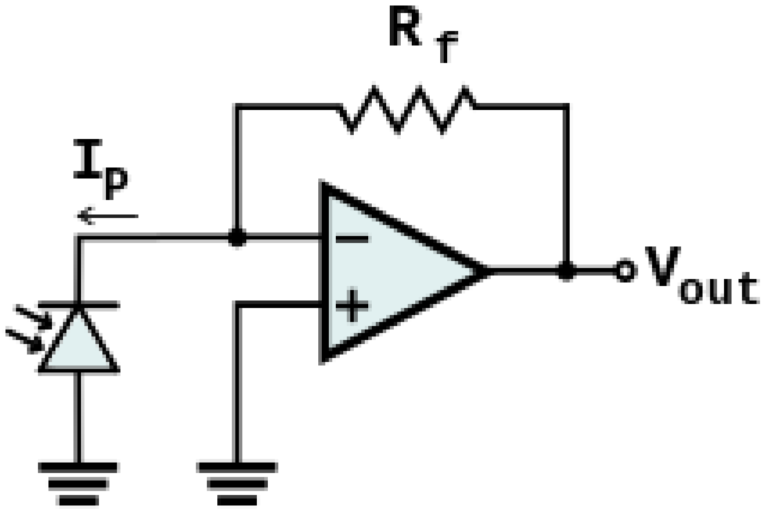
(a)



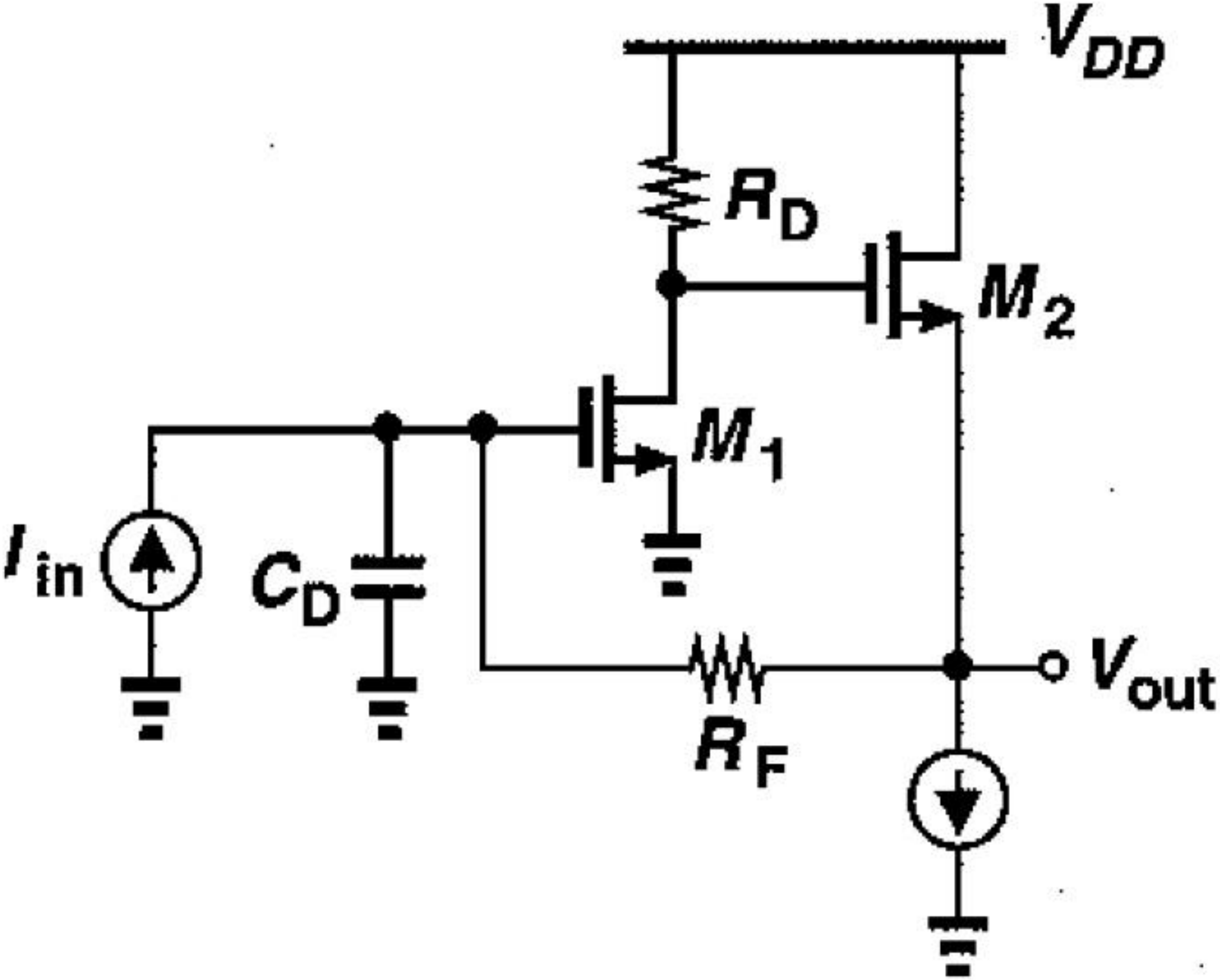
(b)

Amplificatoare transimpedanta

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



Amplificatoare transimpedanta



Zgomotul traductorilor electro-optici

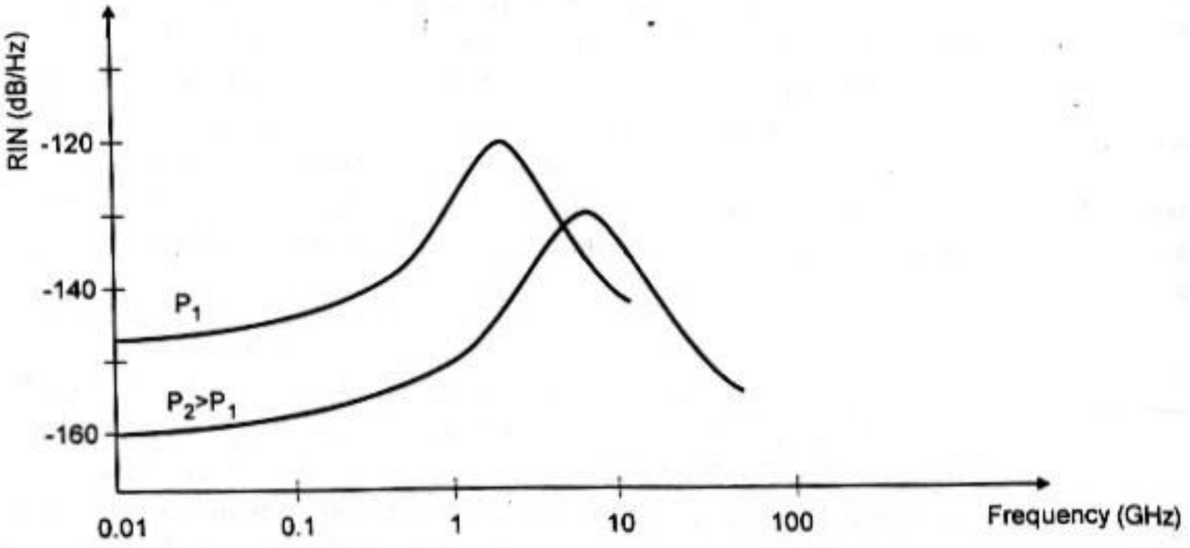
Zgomotul emitatorilor optici

- 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

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

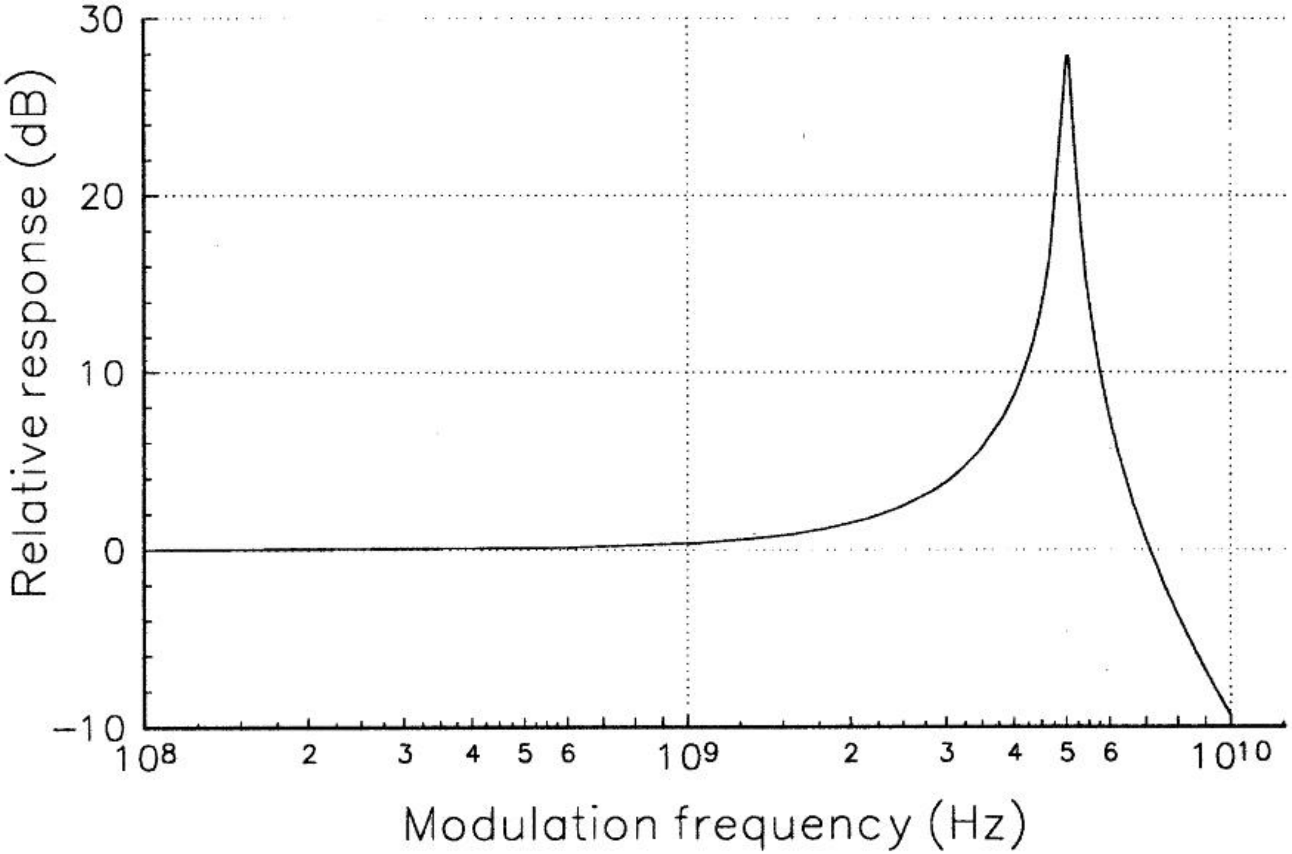
RIN

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

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

$$EIN[W] = R_i \cdot \langle I_n^2 \rangle$$

1 Hz banda

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

Zgomotul fotodiodei

- NEP
  - Noise Equivalent Power
  - r – responzivitatea diodei

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

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

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

Zgomotul fotodiodei

- NEP
  - cea mai mica putere detectabila

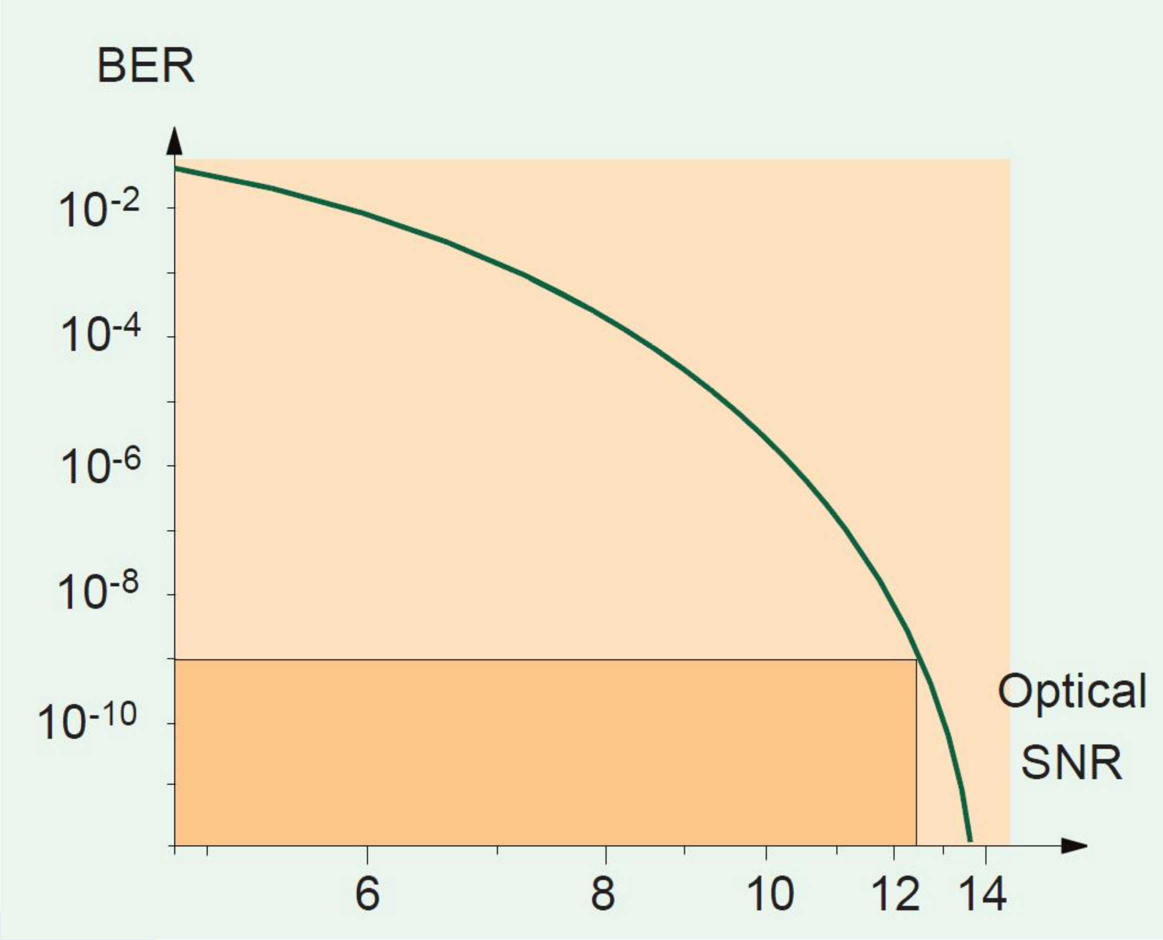
$$\left\langle i_n^2 \right\rangle = 2 \cdot e \cdot I \cdot BW_{PD} = 2 \cdot e \cdot \left(I_S + I_{dark} \right) \cdot BW_{PD}$$

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

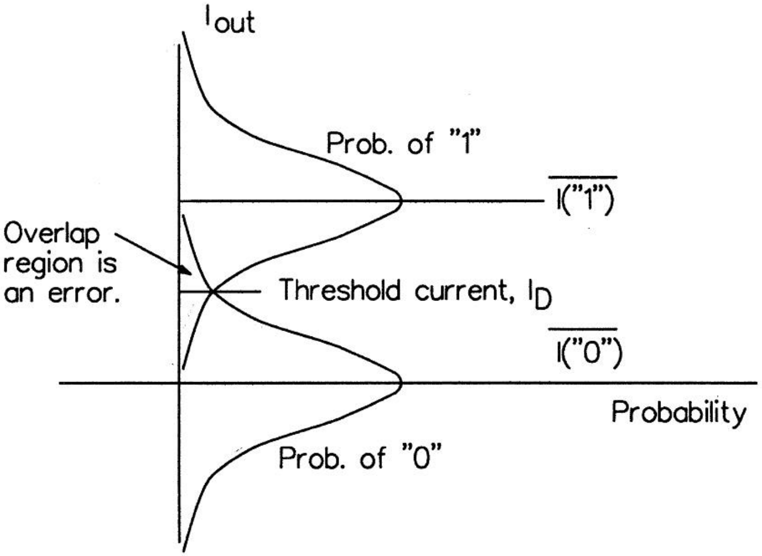
$$NEP[W / \sqrt{Hz}] == \frac{1}{r} \cdot \sqrt{2 \cdot e \cdot I_{dark}}$$

BER

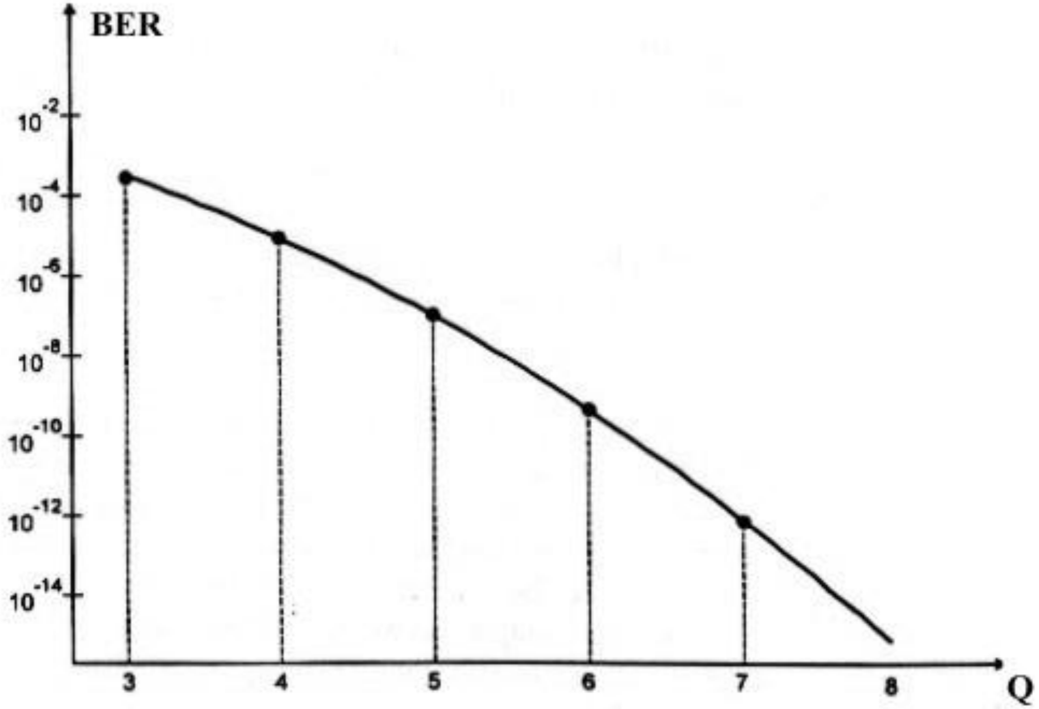
- Bit Error Rate



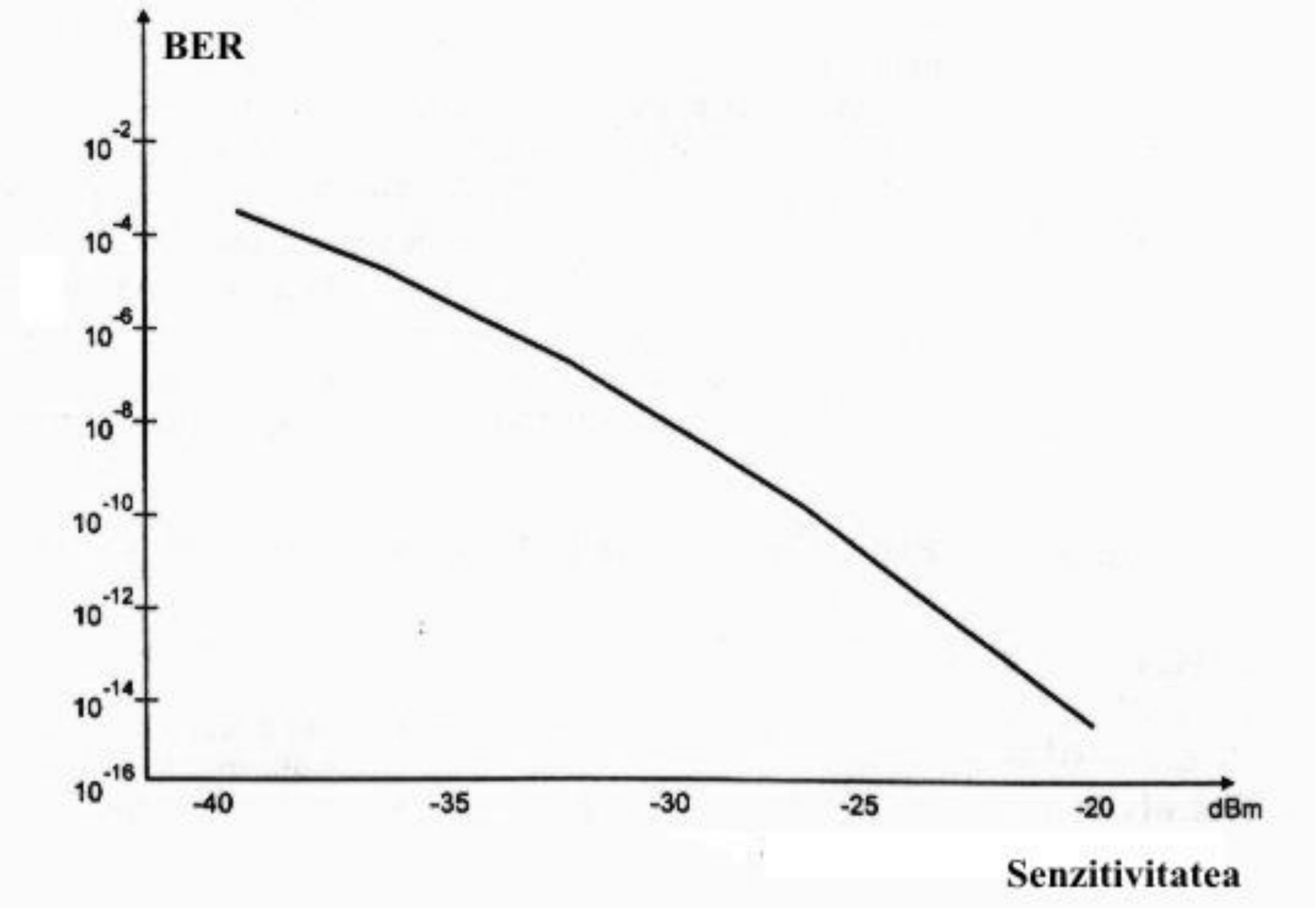
Probabilitate de eroare



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



Senzitivitatea unei diode



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