

Optoelectronică

Curs 6

2019/2020

Disciplina 2019/2020

- ▶ 2C/1L Optoelectronică **OPTO**
- ▶ ~~Minim 7 prezente curs + laborator~~
- ▶ Curs – conf. **Radu Damian**
 - an IV μE
 - Vineri 8–11, P5
 - E – 70% din nota
 - **20% test la curs**, saptamana 4–5?
 - probleme + (? 1 subiect teorie) + (2p prez. curs)
 - toate materialele permise
- ▶ Laborator – **sl. Daniel Matasaru**
 - an IV μE
 - Joi 8-14 impar
 - L – 30% din nota (+Caiet de laborator)

Reprezentare logaritmică!!!

$$\text{dB} = 10 \cdot \log_{10} (P_2 / P_1)$$

$$\text{dBm} = 10 \cdot \log_{10} (P / 1 \text{ mW})$$

$$0 \text{ dB} = 1$$

$$0 \text{ dBm} = 1 \text{ mW}$$

$$+ 0.1 \text{ dB} = 1.023 (+2.3\%)$$

$$3 \text{ dBm} = 2 \text{ mW}$$

$$+ 3 \text{ dB} = 2$$

$$5 \text{ dBm} = 3 \text{ mW}$$

$$+ 5 \text{ dB} = 3$$

$$10 \text{ dBm} = 10 \text{ mW}$$

$$+ 10 \text{ dB} = 10$$

$$20 \text{ dBm} = 100 \text{ mW}$$

$$-3 \text{ dB} = 0.5$$

$$-3 \text{ dBm} = 0.5 \text{ mW}$$

$$-10 \text{ dB} = 0.1$$

$$-10 \text{ dBm} = 100 \mu\text{W}$$

$$-20 \text{ dB} = 0.01$$

$$-30 \text{ dBm} = 1 \mu\text{W}$$

$$-30 \text{ dB} = 0.001$$

$$-60 \text{ dBm} = 1 \text{ nW}$$

$$[\text{dBm}] + [\text{dB}] = [\text{dBm}]$$

$$[\text{dBm/Hz}] + [\text{dB}] = [\text{dBm/Hz}]$$

$$[\text{x}] + [\text{dB}] = [\text{x}]$$

LED

Dioda electroluminescenta

Capitolul 7

Cuprins

- ▶ **Lumina ca undă electromagnetică** (ecuațiile lui Maxwell, ecuația undelor, parametri de propagare)
- ▶ **Elemente de fotometrie și radiometrie** (mărimi energetice/luminoase)
- ▶ **Fibra optică** (realizare, principiu de funcționare, atenuare, dispersie, banda de frecvență)
- ▶ **Cabluri optice** (tehnologie, conectori, lipire – splice)
- ▶ **Proiectare sistemică a legăturii pe fibra optică** (bandă de frecvență, balanța puterilor)
- ▶ **Emițătoare optice** (LED și dioda laser – realizare fizică și funcționare)
- ▶ **Receptoare optice** (dioda PIN, dioda cu avalanșă – realizare fizică și funcționare)
- ▶ **Amplificatoare transimpedanță** (parametri, scheme tipice, TIA în buclă deschisă, cu reacție, diferențiale, control automat al câștigului)
- ▶ **Realizarea circuitelor pentru controlul emițătoarelor optice** (parametri, scheme tipice, controlul puterii, multiplexoare)
- ▶ **Dispozitive de captare a energiei solare** (principiu de funcționare, utilizare, proiectare)

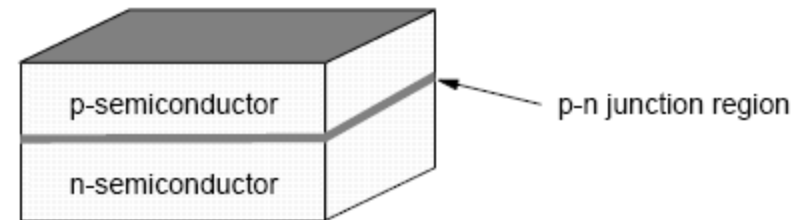
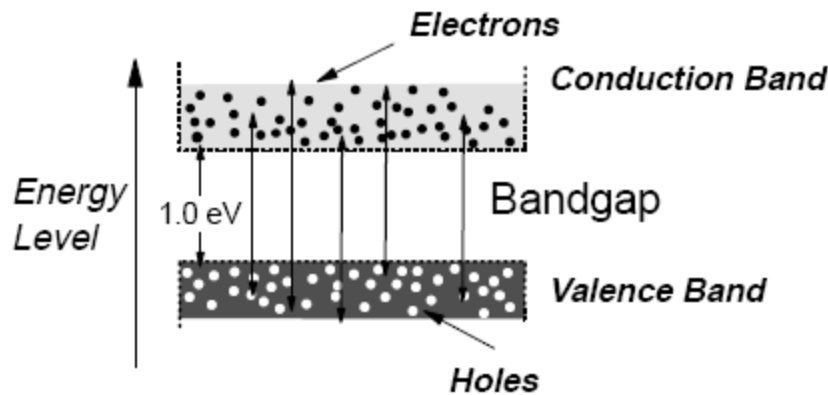
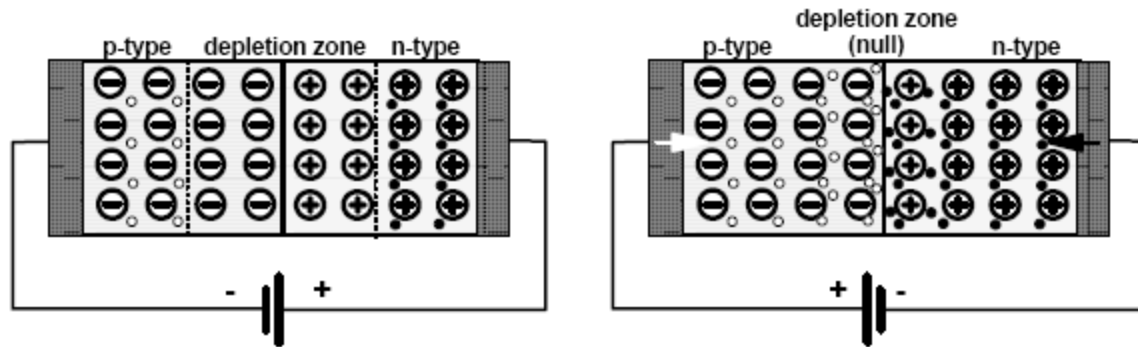
Caracteristici LED

- ▶ Dezavantaje (comunicatii)
 - Putere redusa (cuplata in fibra) $\sim 100\mu\text{W}$
 - Banda (viteza) reduse $\sim 150\text{MHz}$ (300Mb/s)
 - Spectru larg $\sim 0.05 \lambda$
 - Lumina necoerenta si nedirectiva
- ▶ Avantaje
 - Structura interna mult mai simpla (fara suprafete reflective, straturi planare)
 - Cost (dispozitiv si circuit de comanda)
 - Durata de viata
 - Insensibilitate la temperatura
 - Liniaritate (modulatie analogica)

Aplicatii majore LED

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

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 $E_g = h\nu; \lambda = \frac{hc}{E_g}$
- ▶ Recombinare eficienta:
 - alegerea judicioasa a materialului
 - concentrarea purtatorilor in zona jonctiunii
- ▶ Lungimea de unda depinde de temperatura de functionare a dispozitivului: $0.6\text{nm}/^\circ\text{C}$

Lățimea 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 |

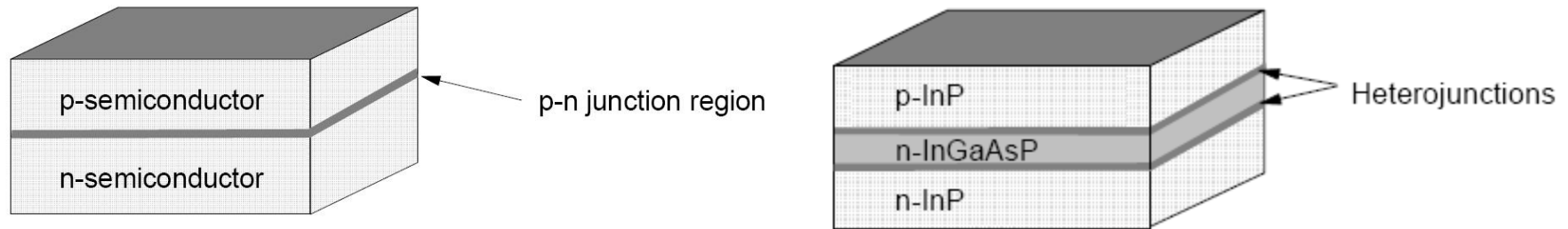
$$E_g = h\nu; \quad \lambda = \frac{hc}{E_g}; \quad \lambda[\mu\text{m}] = \frac{1.240}{E_g[\text{eV}]}$$

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

Detalii constructive – 1

- ▶ Recombinarea unei perechi electron–gol necesita conservarea "impulsului rețelei" (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

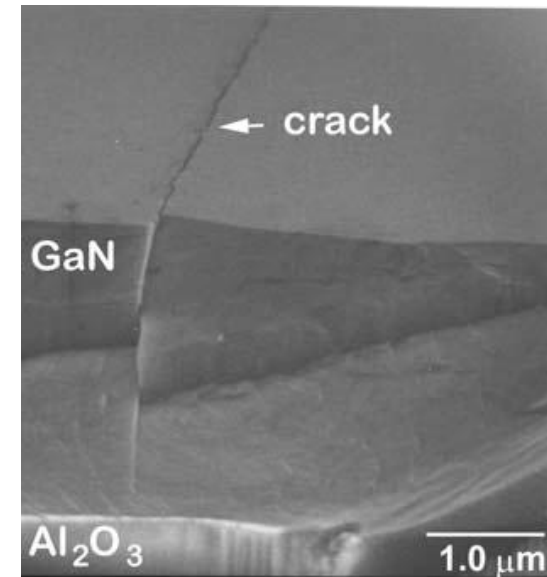
LED cu heterojunțiuni – principiu



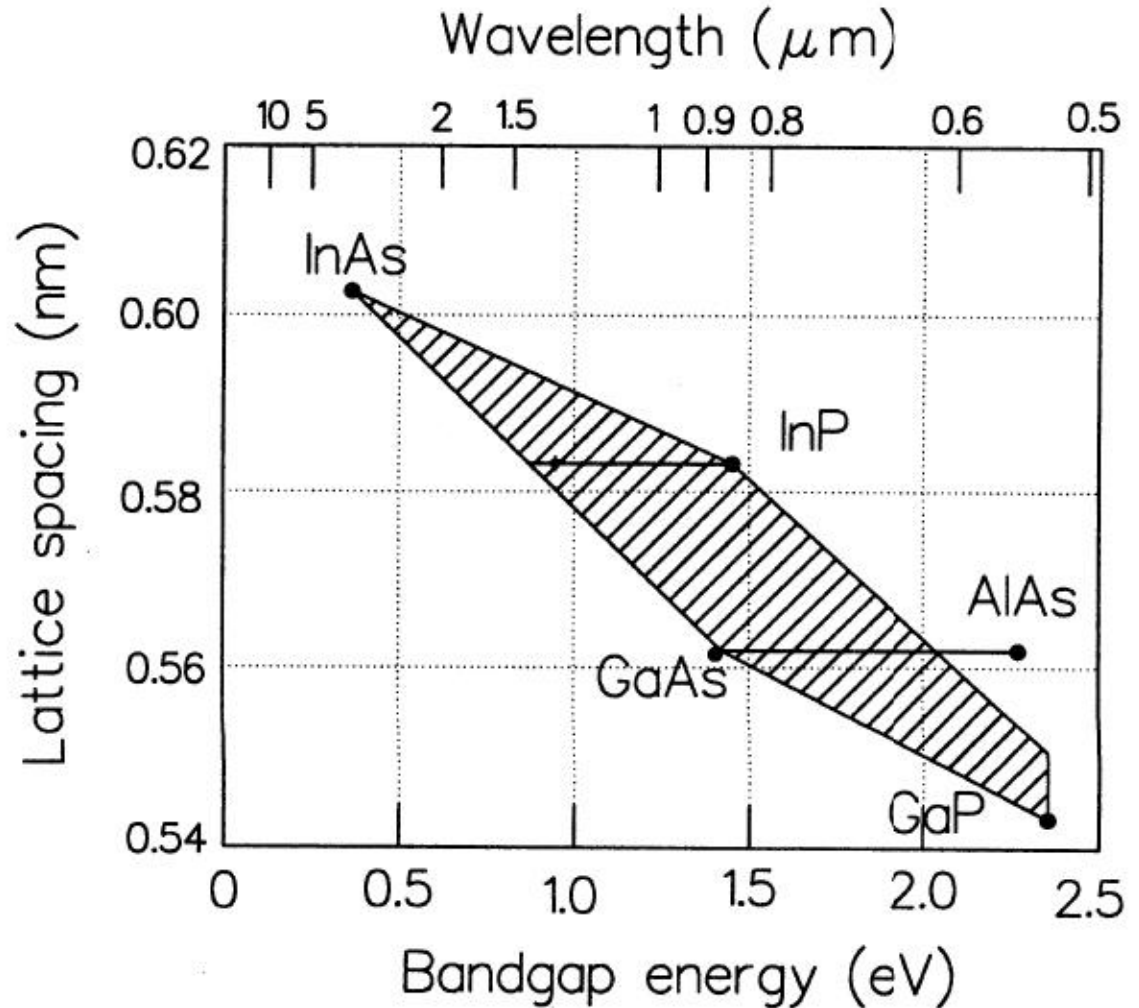
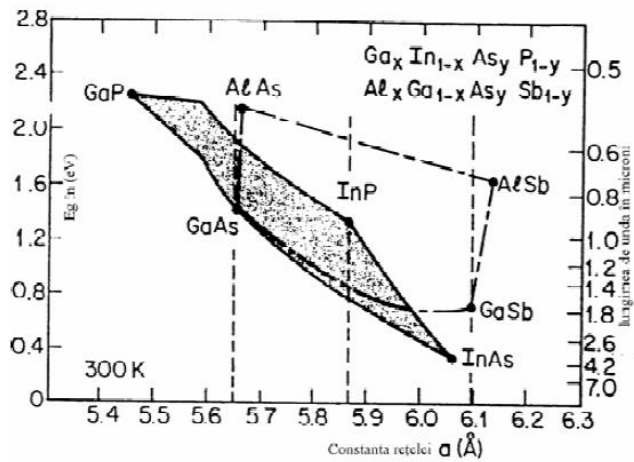
- ▶ **Orice** jonctiune p–n emite lumina
- ▶ O jonctiune p–n obisnuita este foarte subtire
 - volumul in care apar recombinari este foarte mic
 - eficienta luminoasa, redusa
- ▶ lumina este emisa in toate directiile
 - cantitatea de lumina utilizabila (intr–o anumita directie) este redusa

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



Dependența benzii interzise de constanta rețelei



Materiale

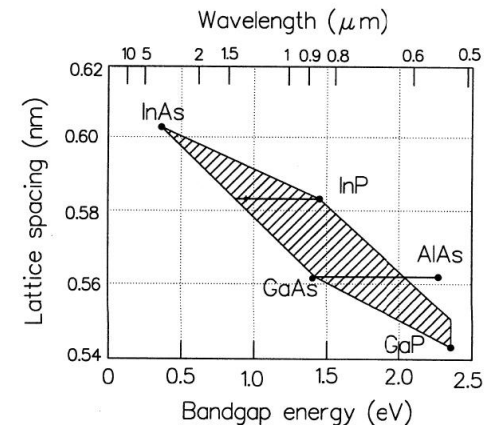
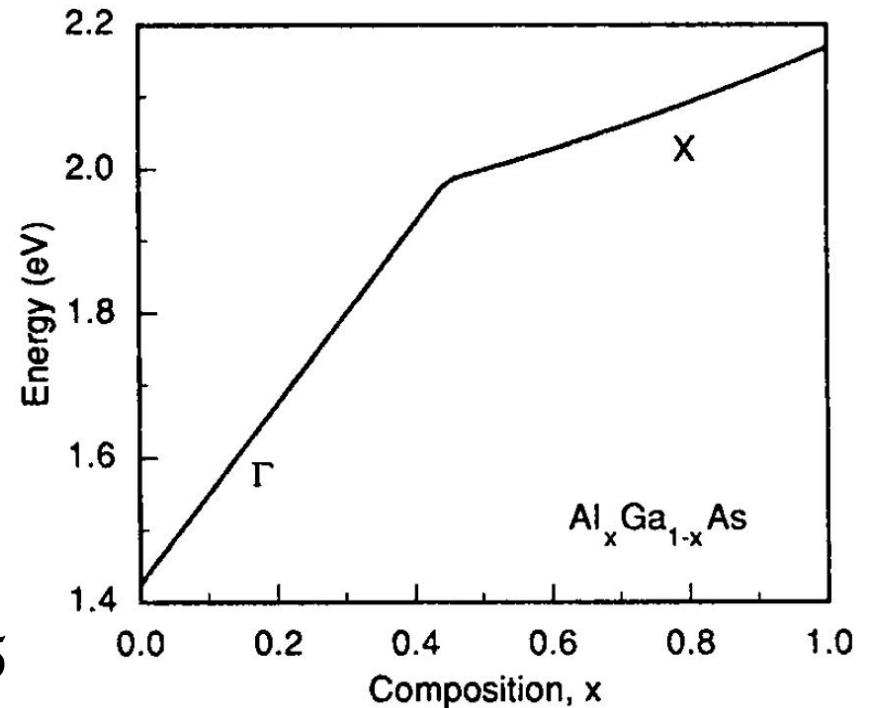
- ▶ Lungimi de unda mici (spectru vizibil – 1 000nm)
 - GaP (665nm), $\text{GaAs}_y\text{P}_{1-y}$
 - GaAs (900nm), $\text{Ga}_{1-x}\text{Al}_x\text{As}$ (AlAs – 550nm)
- ▶ Lungimi de unda mari (1 000÷1 700nm)
 - $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$
 - x,y concentratii relative in aliaj a materialelor corespunzatoare
 - x,y alese din considerente privind
 - lungimea de unda
 - spatierea atomilor
- ▶ Ultraviolet – Albastru: GaInN

Materiale

- ▶ Lungimi de unda mici
 - $\text{Ga}_{1-x}\text{Al}_x\text{As}$
 - 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

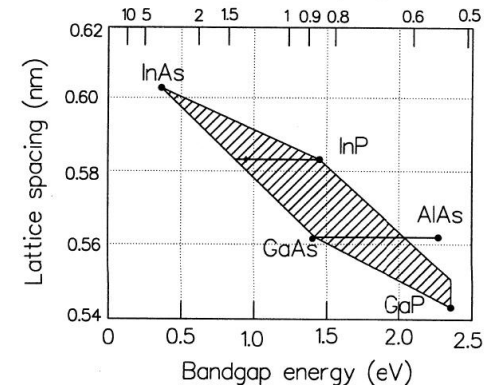
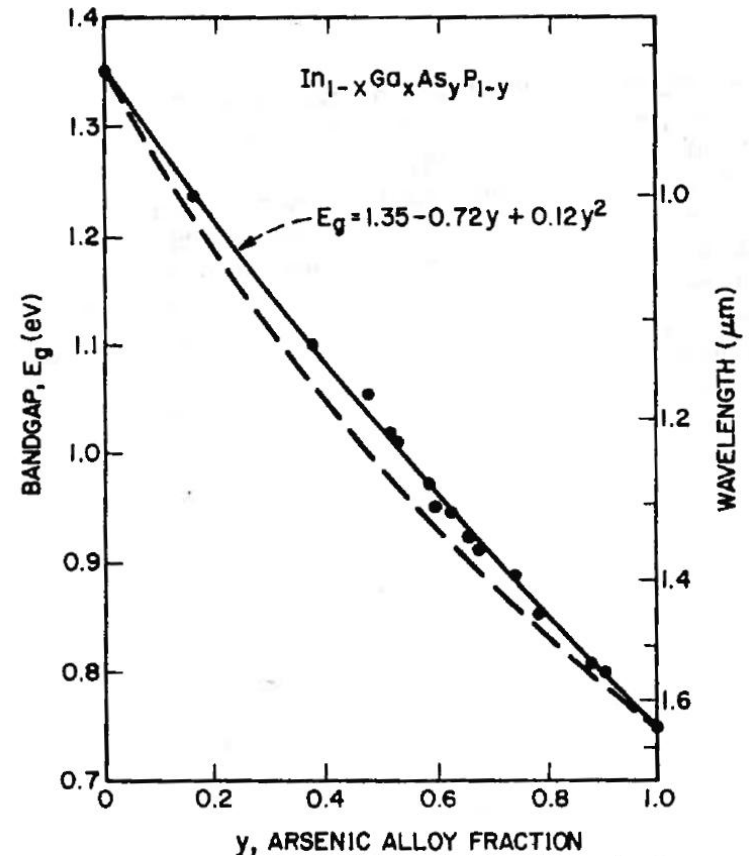
- ▶ Lungimi de unda mari
 - $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$
 - Tipic substratul este InP
 - Spatierea atomilor (lattice spacing) corespunzatoare InP

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

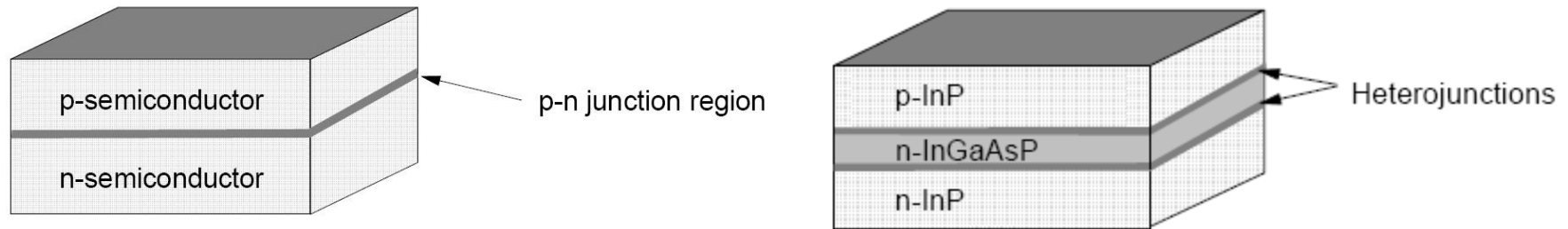
- E_g (in eV)

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

- Exemplu: 1300nm se obtine cu $y=0.611$ si $x=0.282$,
 - $\text{In}_{0.282}\text{Ga}_{0.718}\text{As}_{0.611}\text{P}_{0.389}$

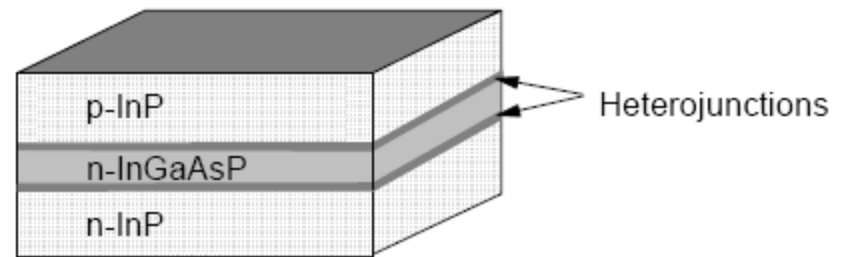
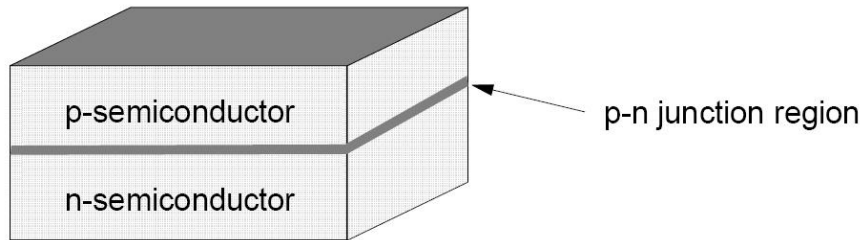


LED cu heterojunțiuni – principiu

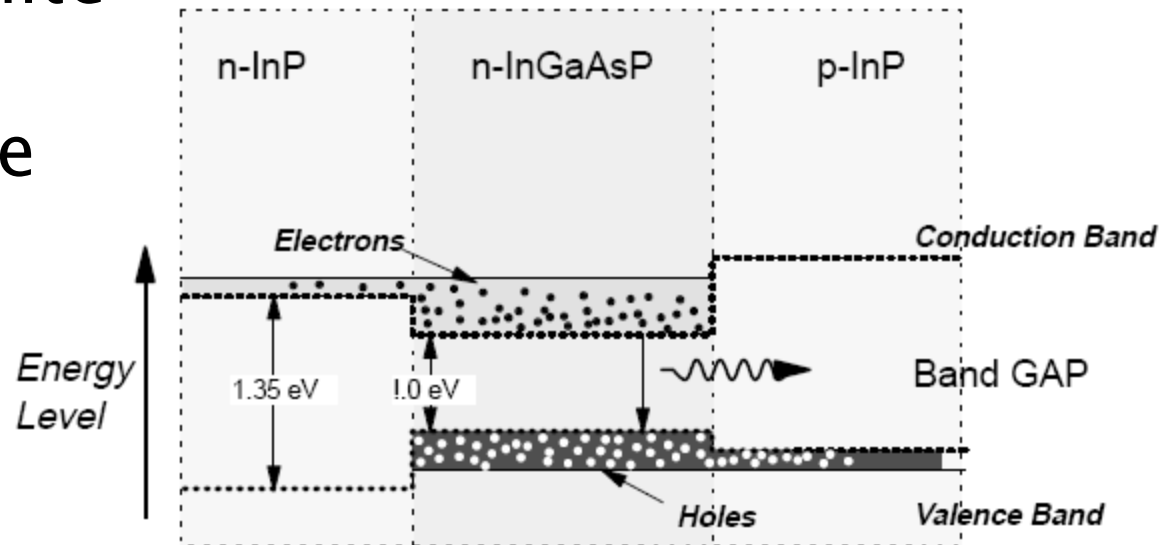


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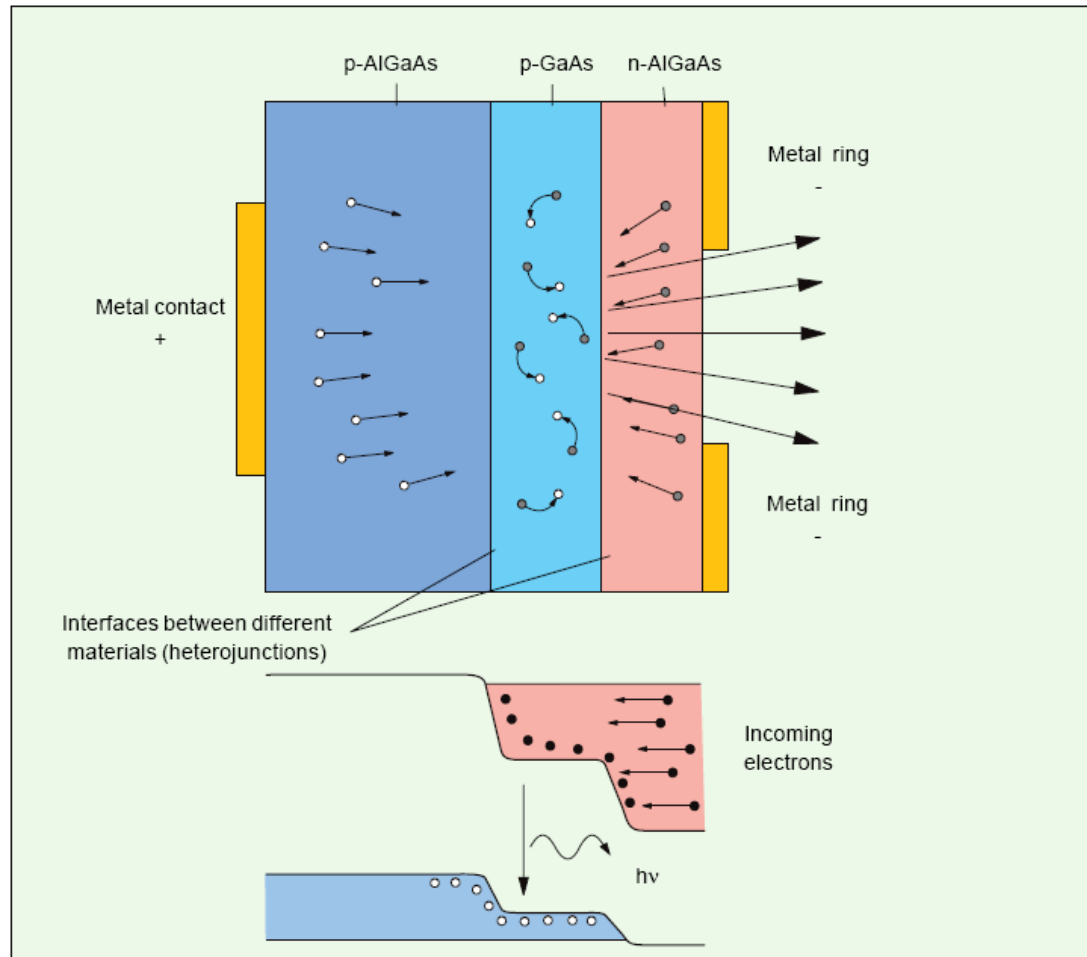
LED cu heterojunțiuni – principiu



- ▶ Structura de nivele energetice permite capturarea purtătorilor între cele două heterojunțiuni



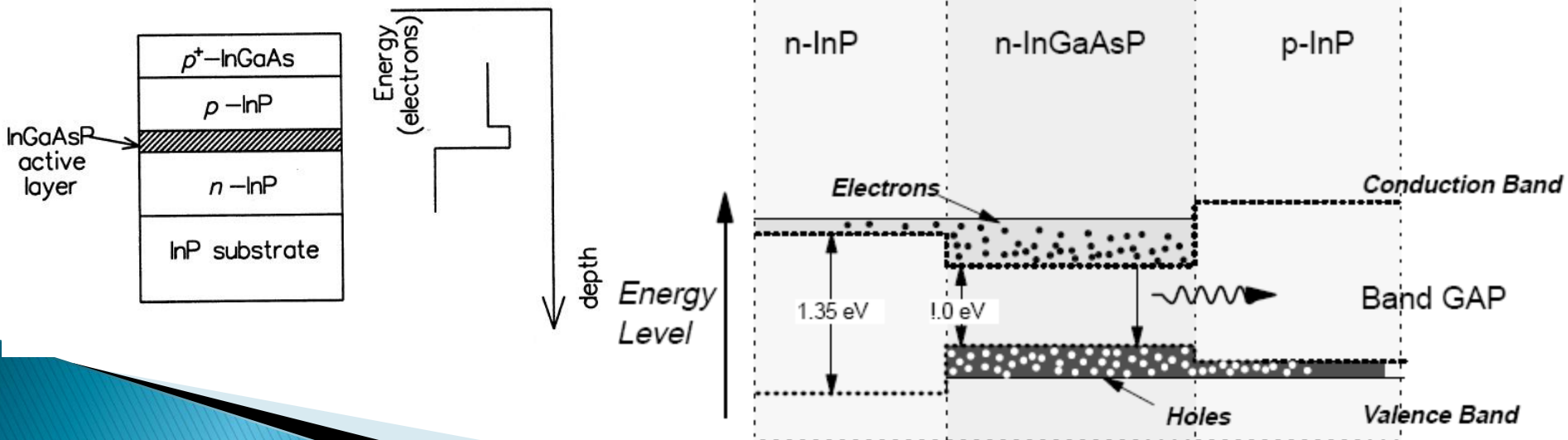
LED cu heterojunțiuni – principiu



LED cu heterojunțiuni – principiu

▶ Concentrare verticală a purtătorilor

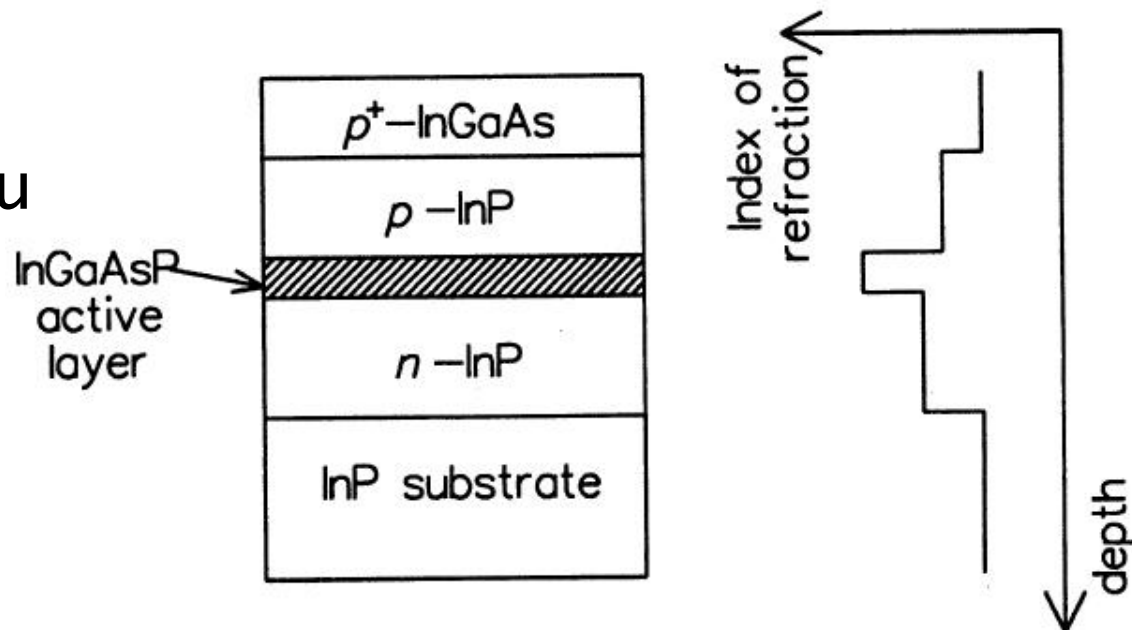
- Electronii sunt atrași din zona n în zona activă
- O barieră energetică existentă între zona activă și zona n concentrează electronii în zona activă
- Situație similară corespunzătoare golurilor
- Purtătorii sunt concentrați în zona activă, crescând eficiența



LED cu heterojunțiuni – principiu

- ▶ Concentrare verticală a luminii
 - în general la diode laser (eficiența procesului LASER depinde de intensitatea luminoasă)
 - prezenta și la LED pentru creșterea eficienței luminoase: dirijarea luminii spre exterior și evitarea absorbției interne

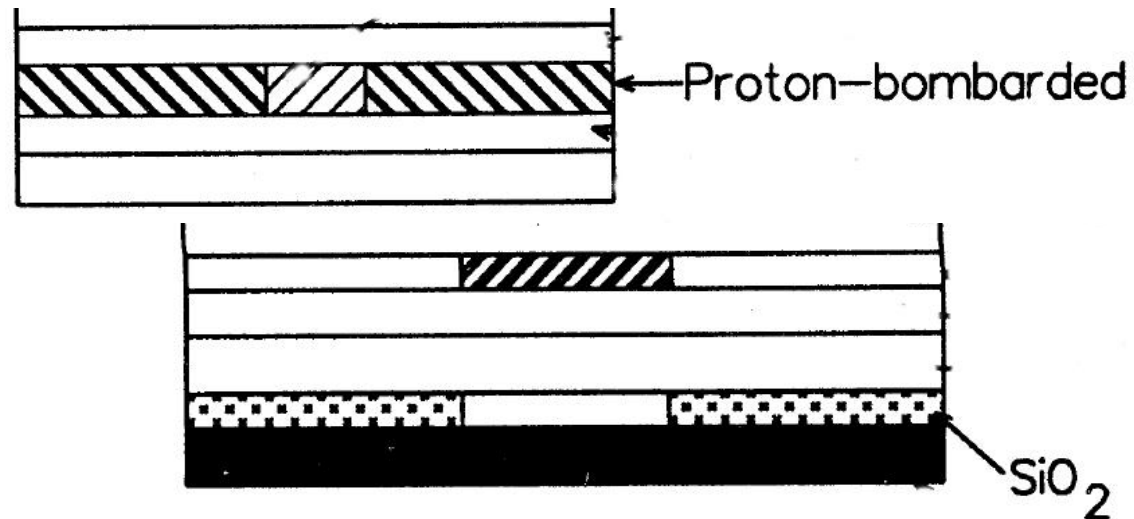
- ▶ Straturile din materiale diferite au indici de refracție diferiți formând un ghid dielectric



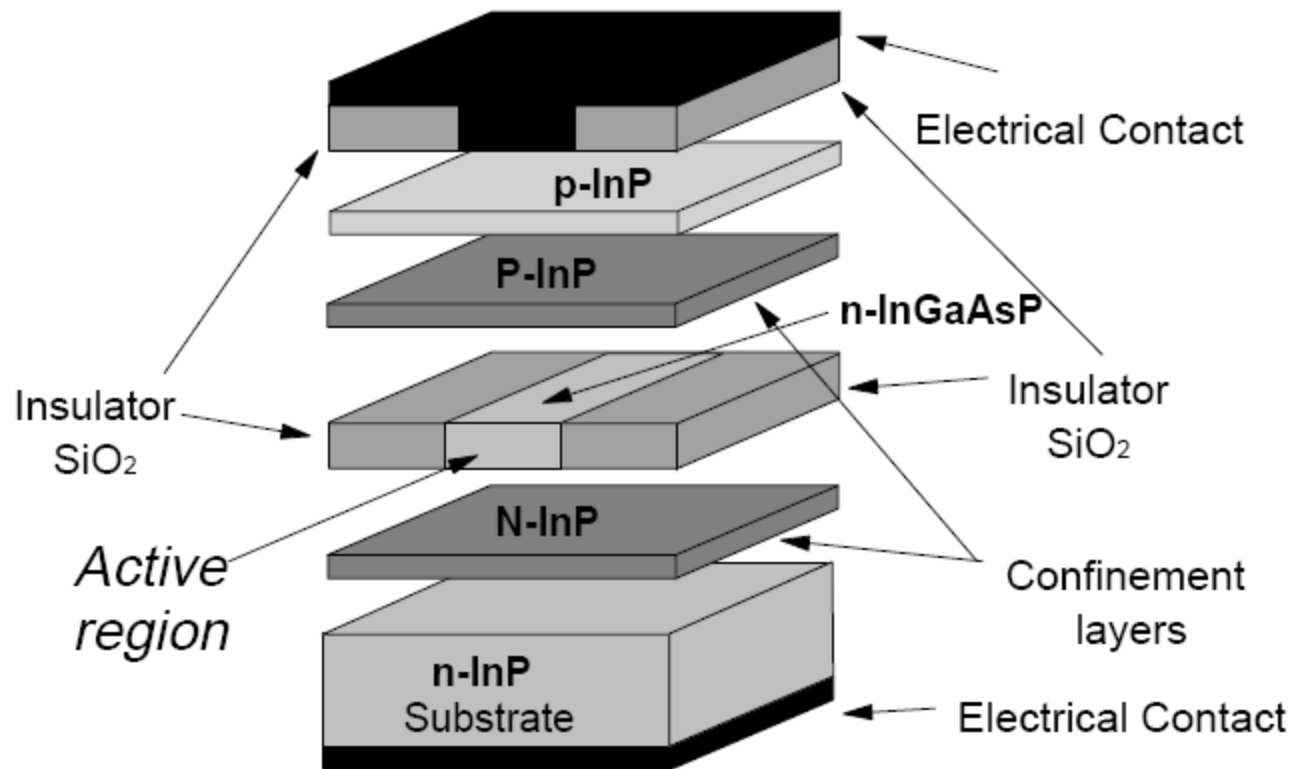
LED cu heterojunțiuni – principiu

► Concentrare orizontală a curentului

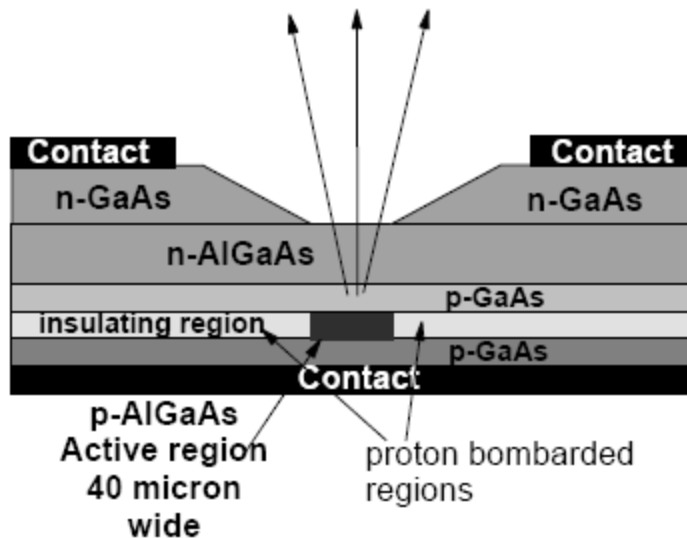
- Eficiența conversiei depinde de concentrația de purtători, deci e necesară creșterea densității de curent în zona activă (20–50 μm)
- Se utilizează:
 - strat izolator (tipic SiO_2) cu o deschidere în dreptul zonei active
 - Bombardarea cu protoni a regiunii din jurul zonei active
- Alte metode:
 - eliminarea materialului în jurul zonei active (mesa structure)
 - difuzie de Zn în zona centrală



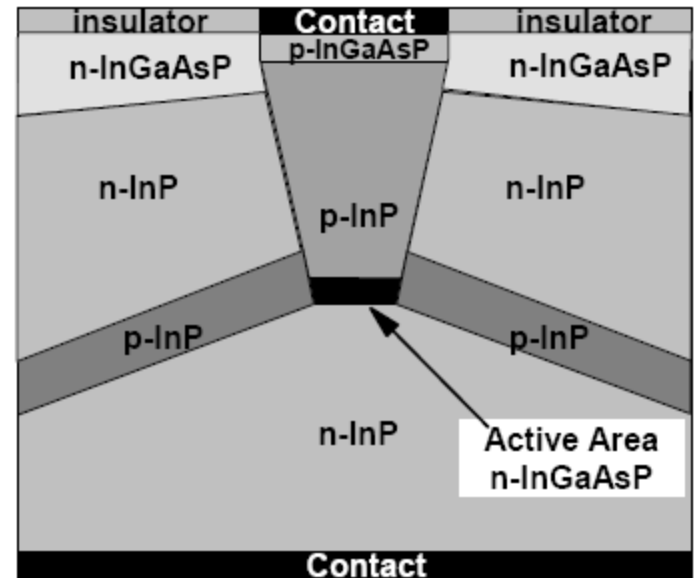
LED cu heterojunțiuni – detalii



Structuri constructive pentru LED

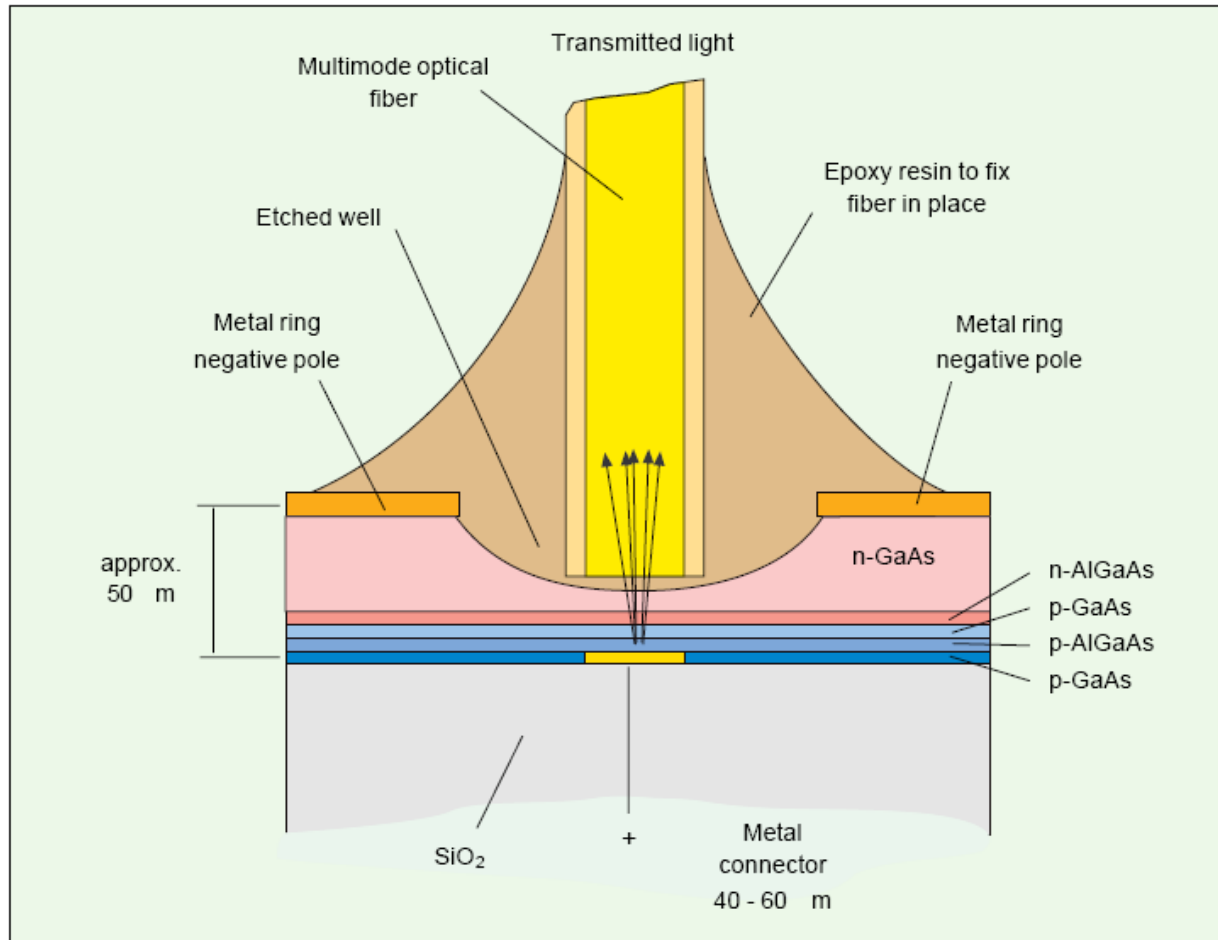


Burrus Surface Emitting LED (SLED)



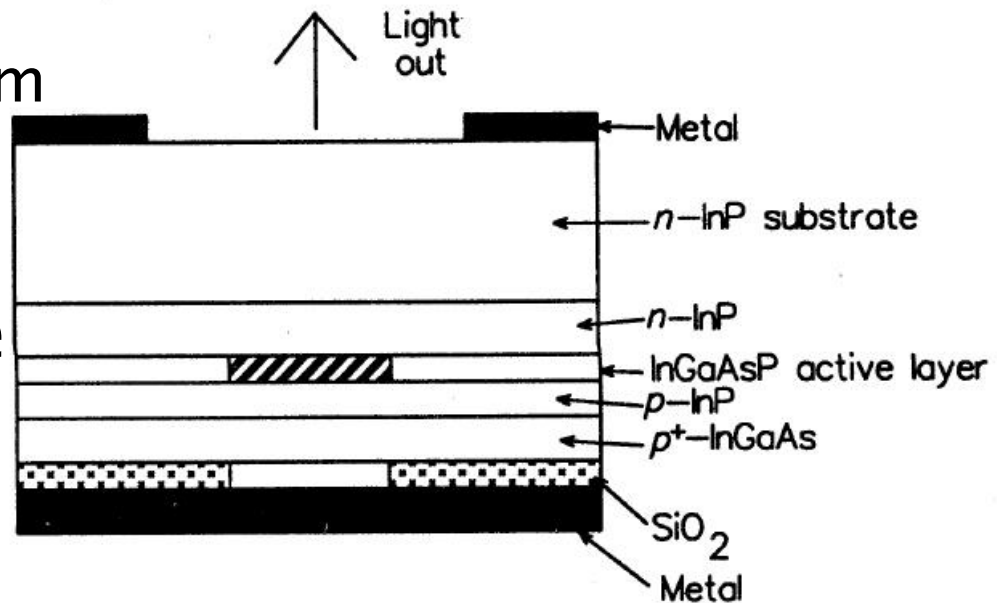
Edge Emitting LED (ELED)

LED cu emisie de suprafață



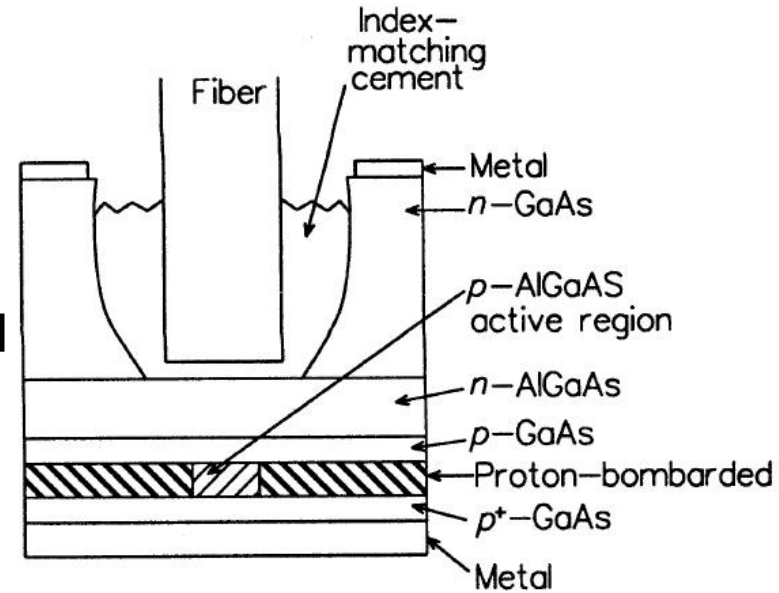
SLED InGaAsP – constructie

- ▶ InGaAsP
- ▶ 4 straturi
 - n InP $\sim 2 \div 5 \mu\text{m}$
 - p InGaAsP $\sim 0.4 \div 1.5 \mu\text{m}$
 - p InP $\sim 1 \div 2 \mu\text{m}$
 - p⁺ InGaAs $\sim 0.2 \mu\text{m}$
- ▶ Latimea zonei active
 - $\sim 20 \div 50 \mu\text{m}$ diametru

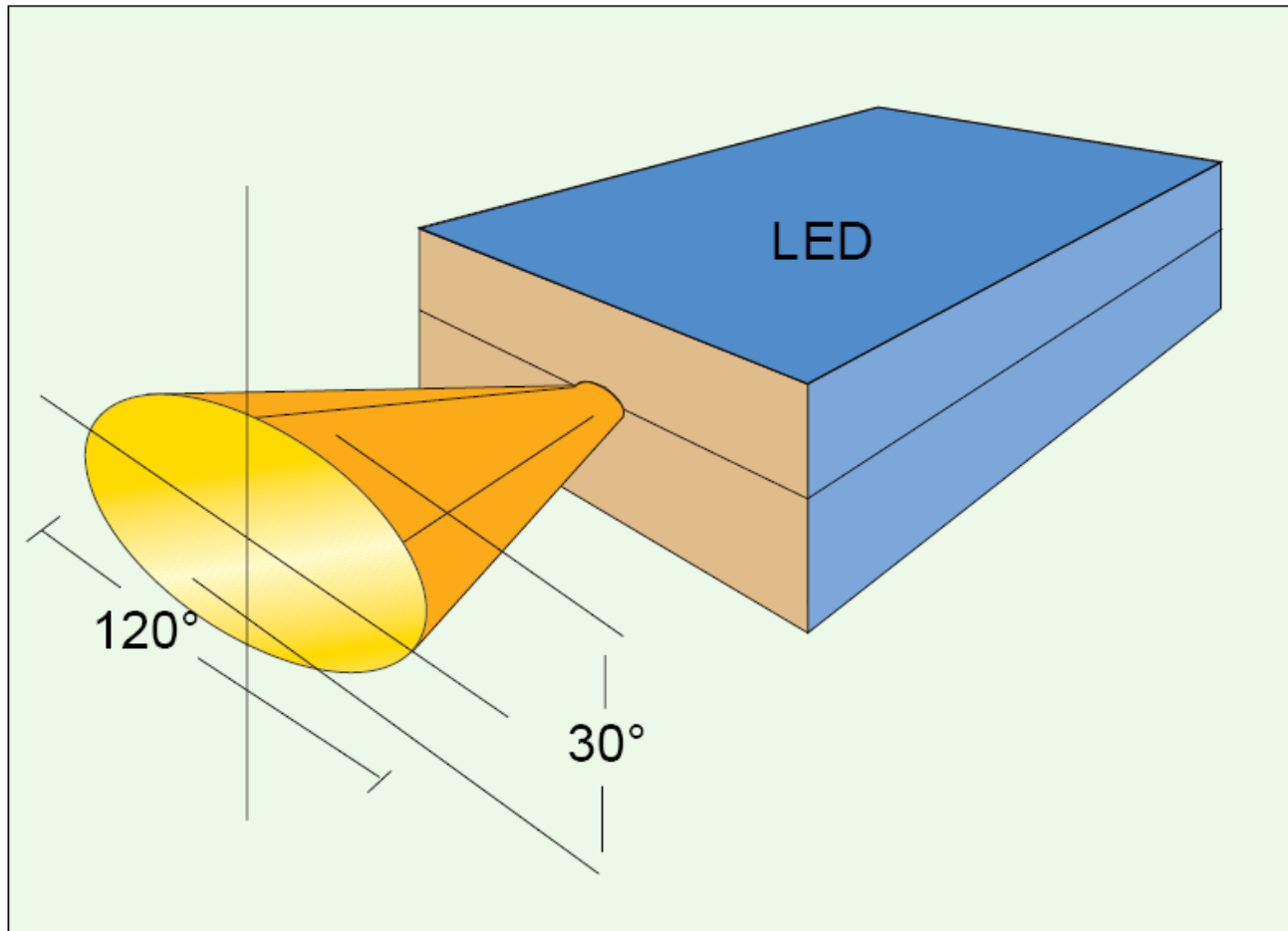


SLED GaAlAs – constructie

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

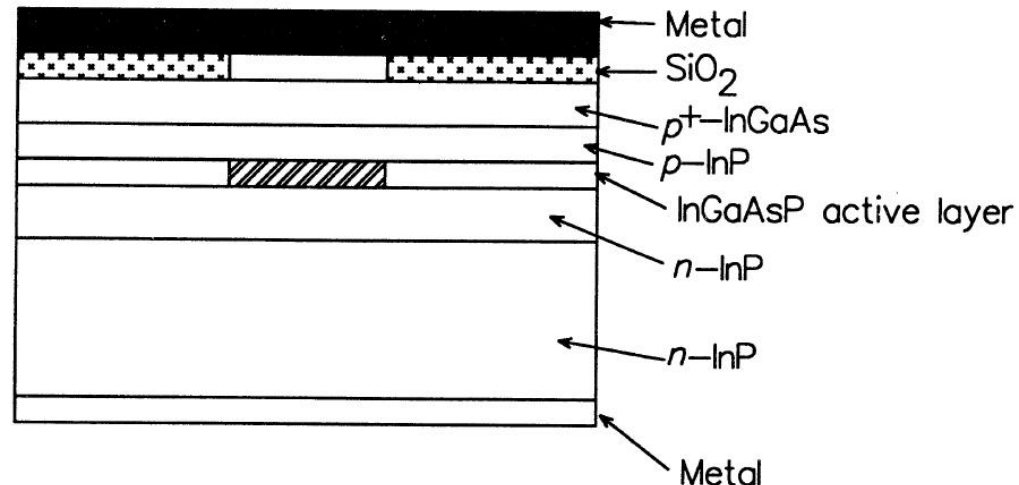


LED cu emisie laterală



ELED – constructie

- ▶ InGaAsP
- ▶ strict pentru comunicatii
- ▶ Cele patru straturi sunt in general similare
- ▶ Stratul activ este mult mai subtire decat la SLED $\sim 0.05 \div 0.25 \mu\text{m}$
- ▶ Regiunea activa
 - latime $50 \div 70 \mu\text{m}$
 - lungime $100 \div 150 \mu\text{m}$
 - p InP $\sim 1 \div 2 \mu\text{m}$
 - p⁺ InGaAs $\sim 0.2 \mu\text{m}$
- ▶ 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

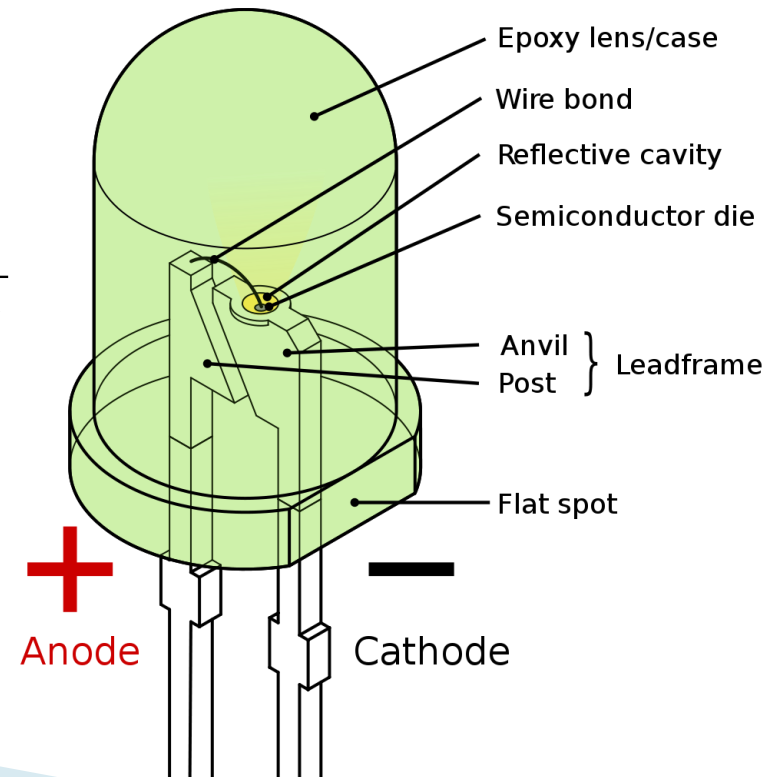
- utilizarea unui material intermediar pentru adaptarea indicelui de refractie (rasina epoxidica)
- adaptarea formei de iesire din dispozitiv – forma de dom
 - eficienta de cuplaj

interfata plana
semiconductor
aer

$$\frac{1}{n \cdot (n+1)^2}$$

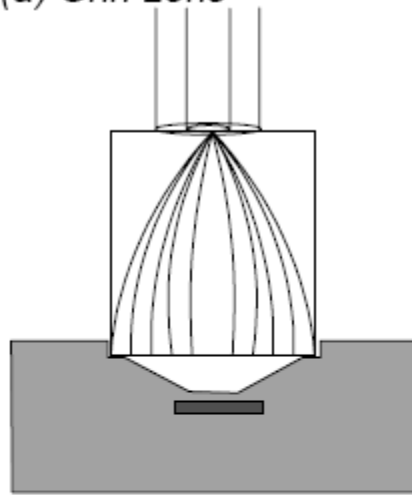
dom

$$\frac{2n}{(n+1)^2}$$

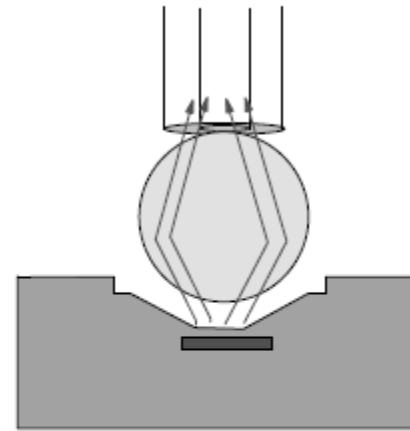


Cuplarea luminii în fibră

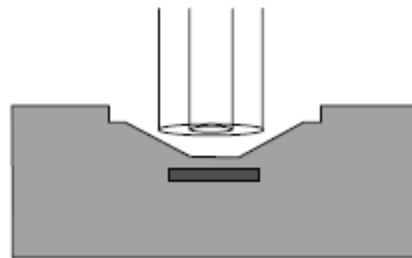
(a) Grin Lens



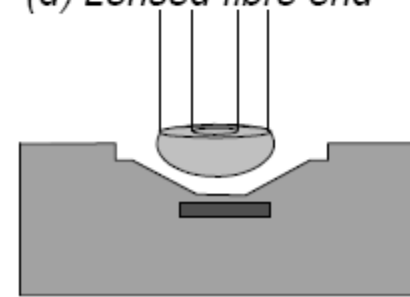
(b) Ball Lens



(c) Direct coupling



(d) Lensed fibre end



numai pentru fibre multimod cu salt de indice

Directivitatea radiatiei exterioare

- ▶ Sursa lambertiana

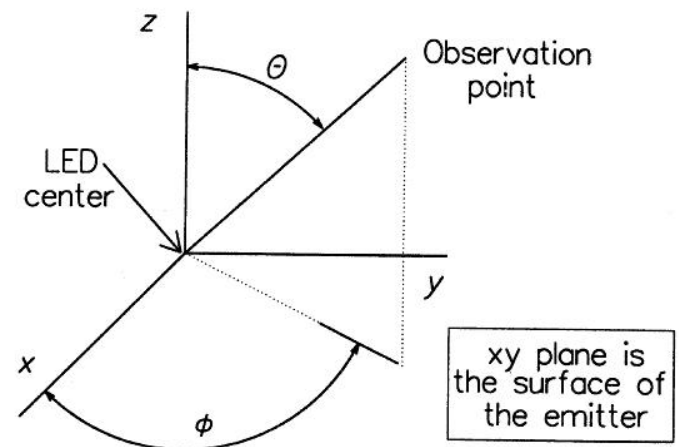
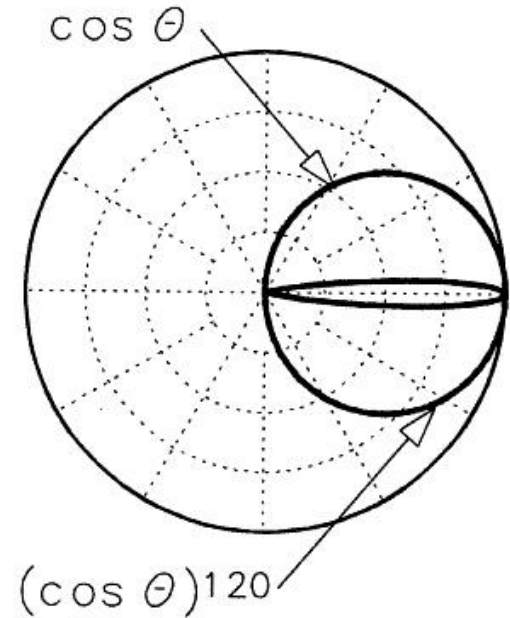
$$P(\theta) = P_0 \cdot \cos \theta$$

- ▶ Aproximatie Lambertiana pentru surse cu directivitate crescuta

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

- ▶ Surse cu emisie asimetrica

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



Directivitatea radiatiei exterioare

▶ SLED

- radiatia este emisa cu simetrie circulara, in interiorul unui con cu unghi la varf tipic de 60°
- Viewing Half Angle $\sim 10 \div 15^\circ$

▶ ELED

- radiatia emisa nesimetric in forma de con eliptic
 - perpendicular pe jonctiune $\sim 60^\circ$
 - paralel cu jonctiunea $\sim 30^\circ$

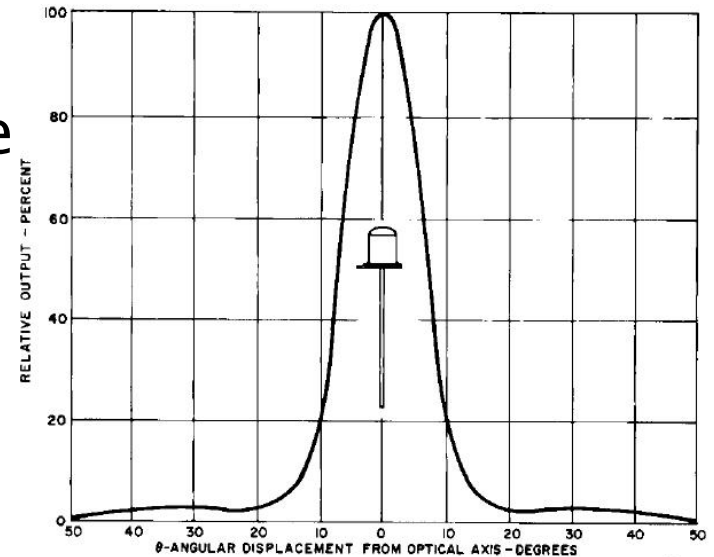
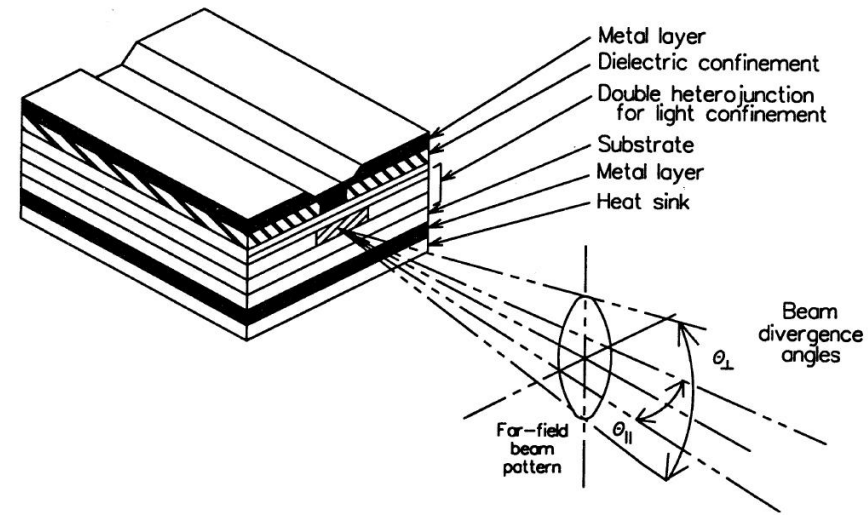
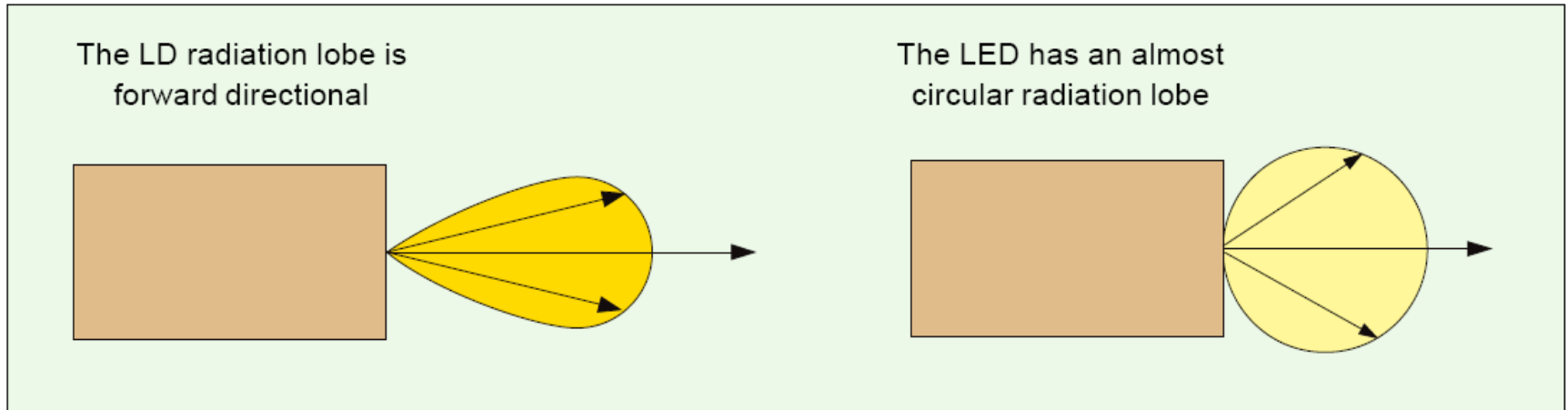


Fig. 5. Typical Radiation Pattern

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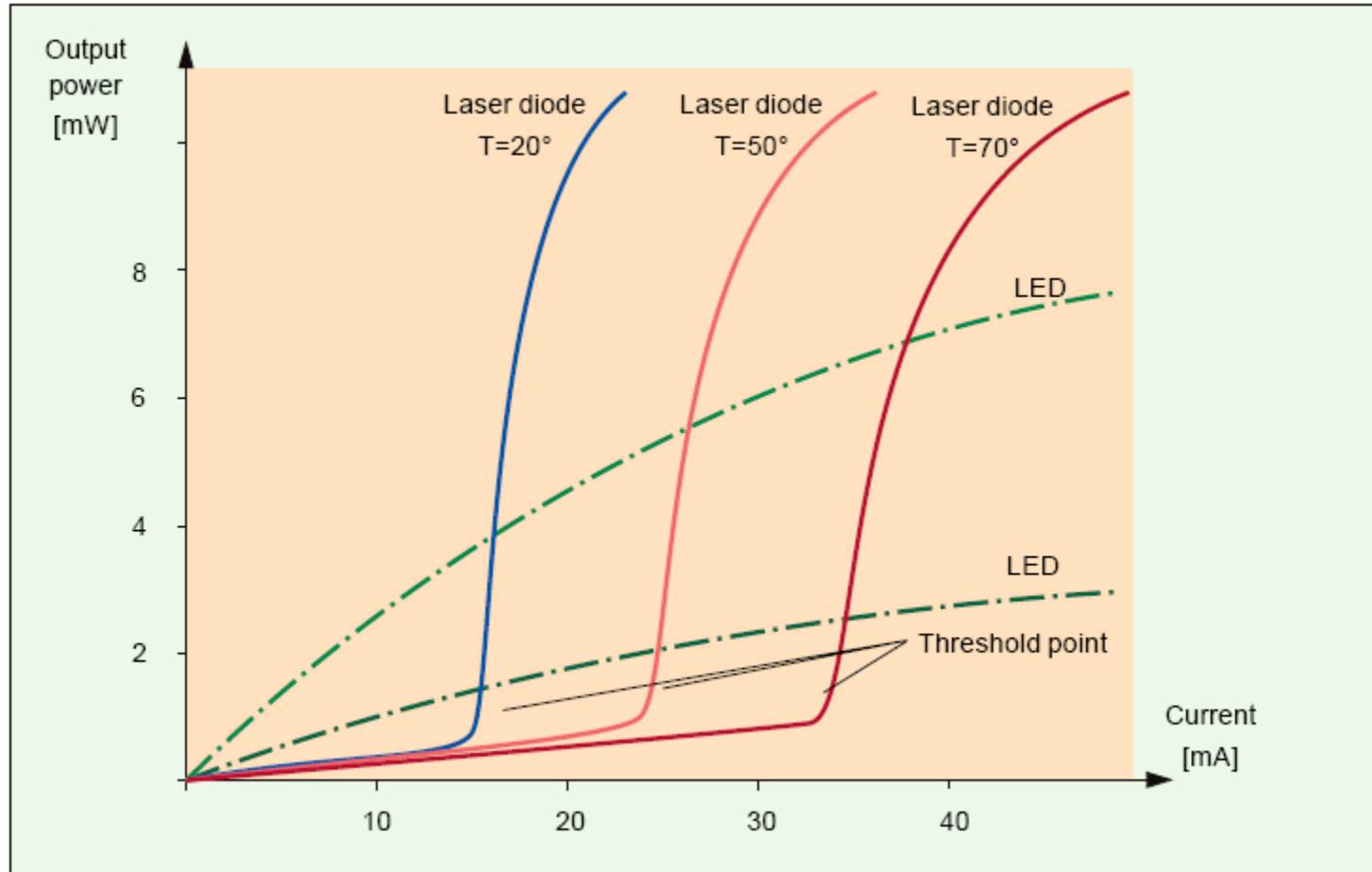


Profil de radiație a emițătorilor optici



- ▶ 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 și pentru un NA de 0.2, aria emisivă este mare comparativ cu a unui laser. În consecință, densitatea de putere emisă este mică astfel încât se reduce drastic puterea care poate fi cuplată într-o fibră cu indice gradat, și devine practic imposibilă cuplarea cu o fibră monomod.

Caracteristici putere optică/curent a emițătorilor optici



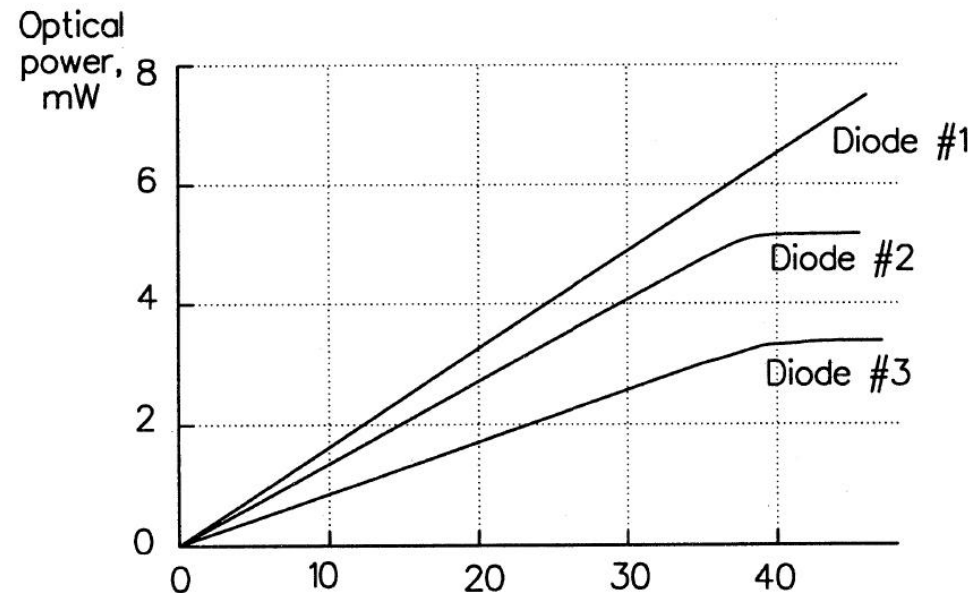
Caracteristica de raspuns a LED-urilor

- ▶ 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

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

- ▶ Tipic $r = 50 \mu W / mA$



Caracteristica de raspuns a LED-urilor

- ▶ Tipic SLED au eficienta mai buna decat ELED

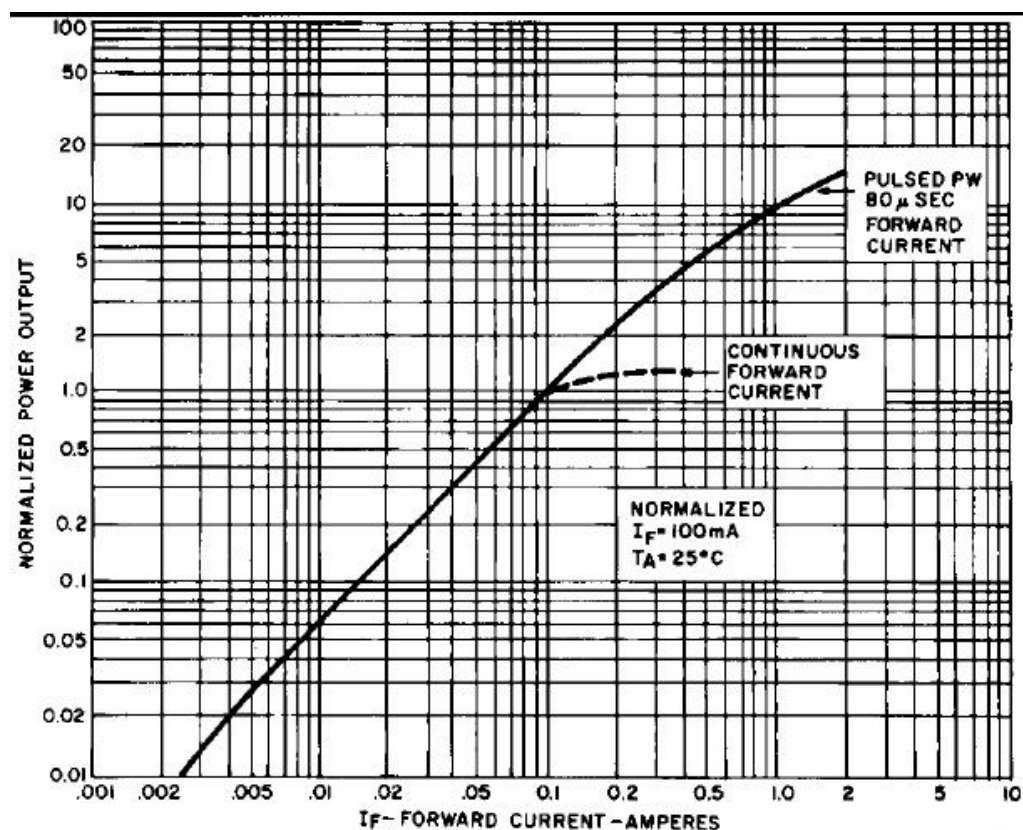
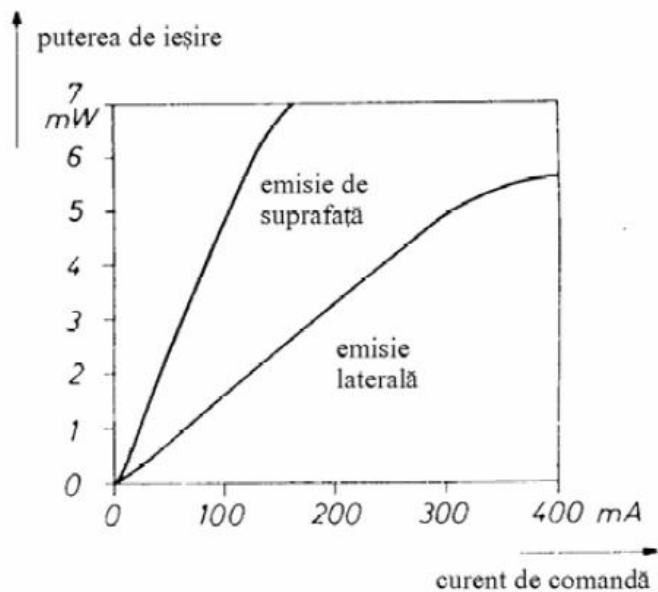


Fig. 1. Power Output vs. Input Current

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 rezonanzivitatea de $90\mu\text{W}/\text{mA}$ și este parcursă de un curent de 85mA .
- ▶ a) Estimați intensitatea luminoasă a dispozitivului pe direcție normală.
- ▶ Dacă se consideră emisia **uniformă** în interiorul conului de emisie, fluxul optic energetic este constant în interiorul acestui con și va fi egal cu puterea optică emisă (ambele mărimi reprezintă viteze ale energiei, măsurate în W, cu diferența că puterea optică reprezintă o medie a fluxurilor emise după diferite direcții, valoarea medie a unei mărimi constante fiind egală cu acea mărime)

Aplicatii majore LED

▶ Comunicatii

- Infrarosu (InGaAsP)

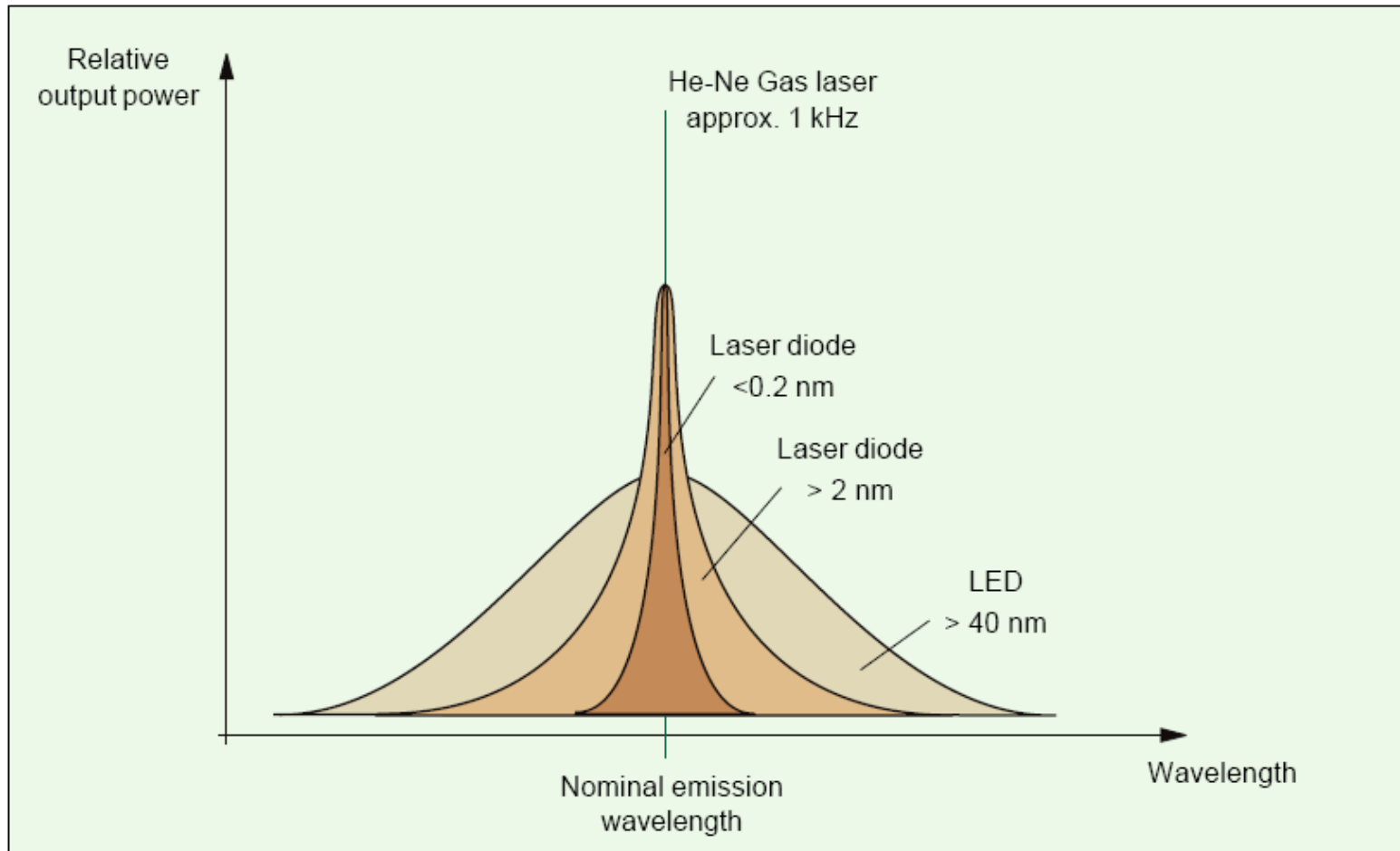
▶ Vizibil

- Spectru vizibil (GaAlAs)

▶ Iluminare

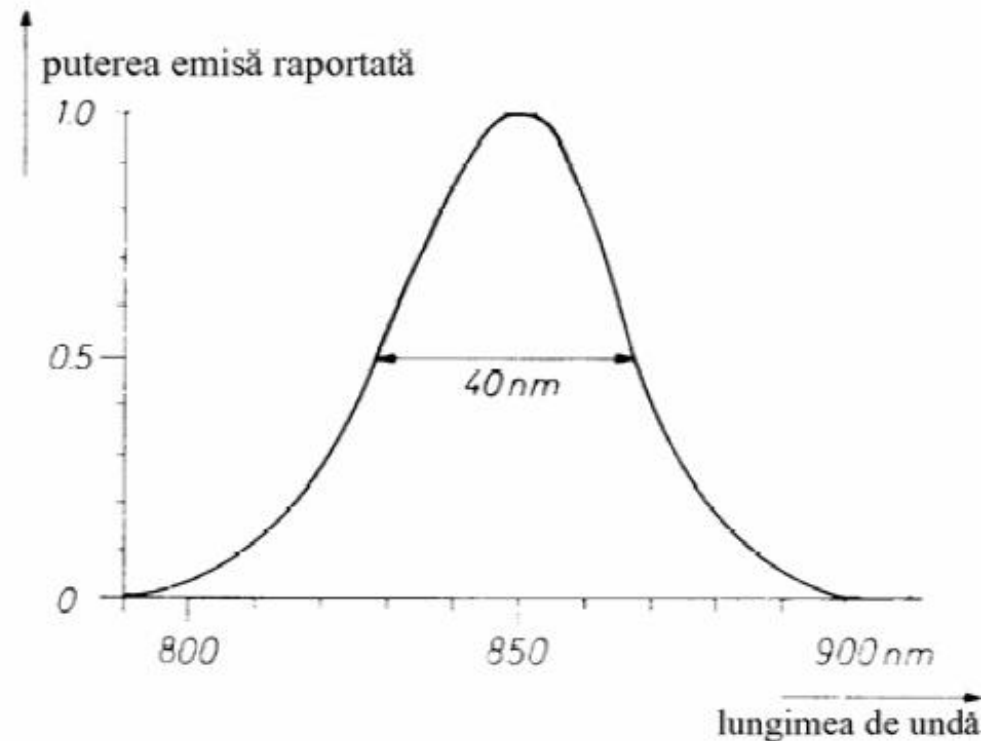
- Putere ridicata, lumina alba (GaInN)

Calitatea spectrală a emițătorilor 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

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

$$f_{3dB-el} = \frac{1}{2 \cdot \pi \cdot \tau_{lf}}$$

- 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)

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

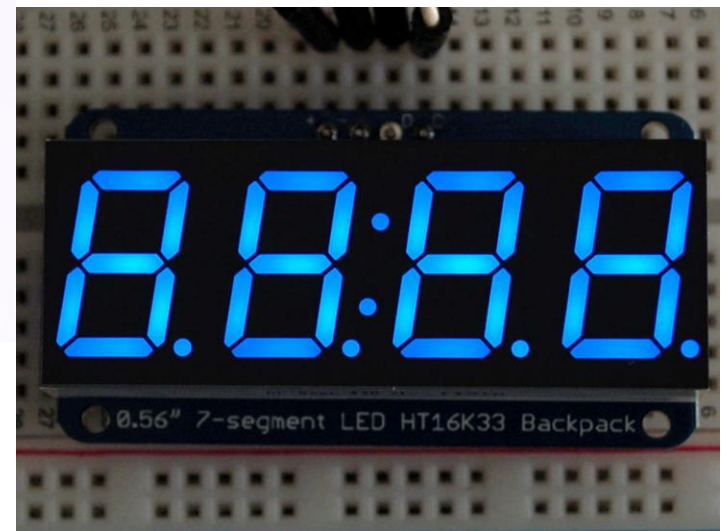
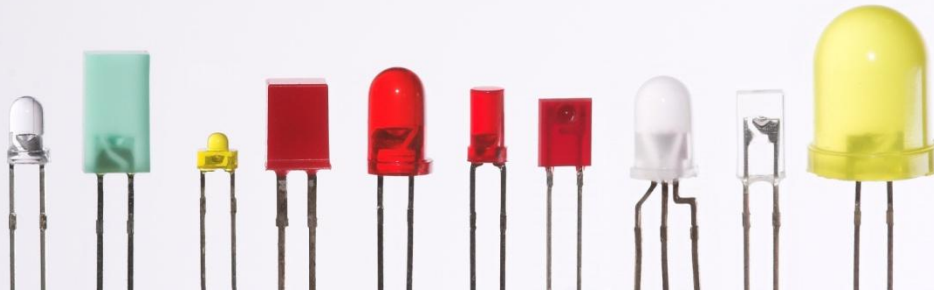
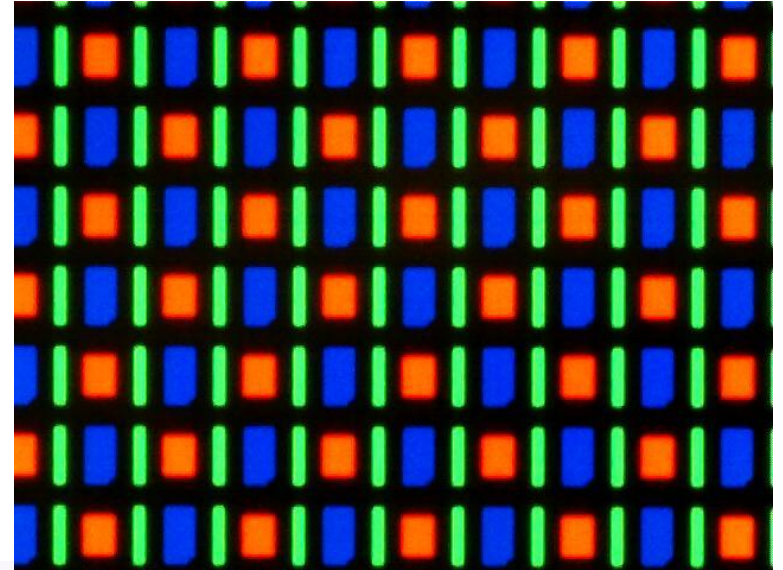
- ▶ Capacitatea asociata sarcinilor in regiunea activa: 350 ÷ 1000pF
- ▶ Produs Putere × Banda

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

Aplicatii majore LED

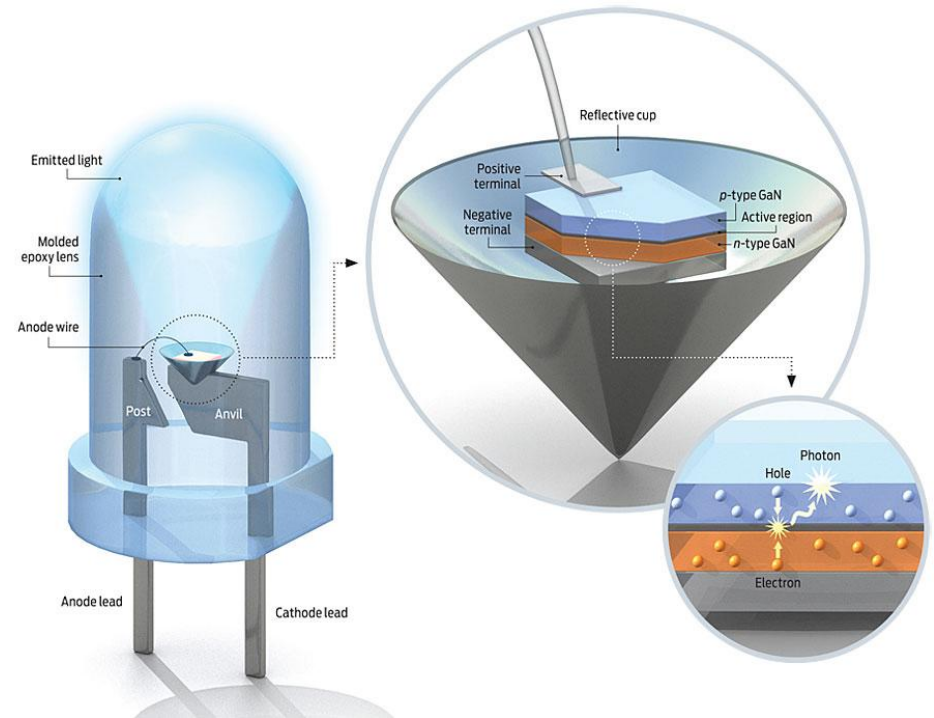
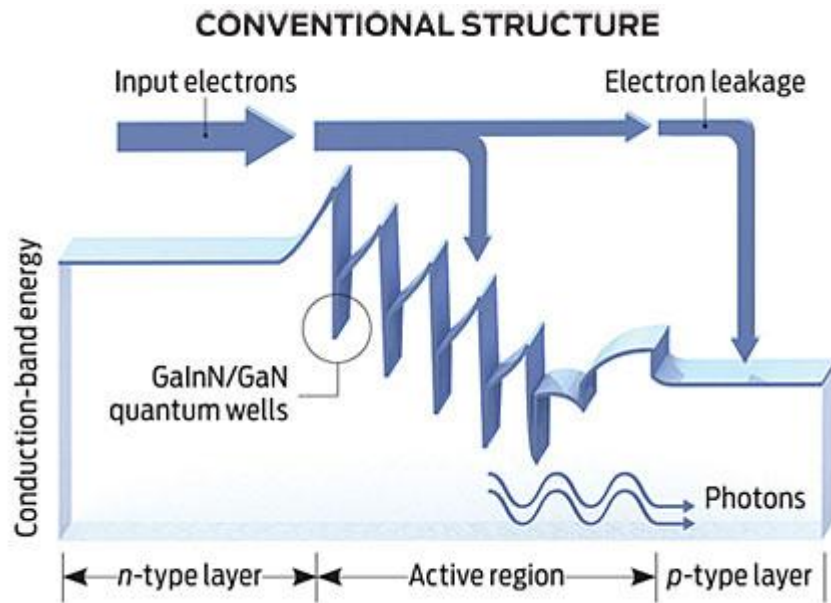
- ▶ Comunicatii
 - Infrarosu (InGaAsP)
- ▶ Vizibil
 - Spectru vizibil (GaAlAs)
- ▶ Iluminare
 - Putere ridicata, lumina alba (GaN)

Aplicatii in spectru vizibil



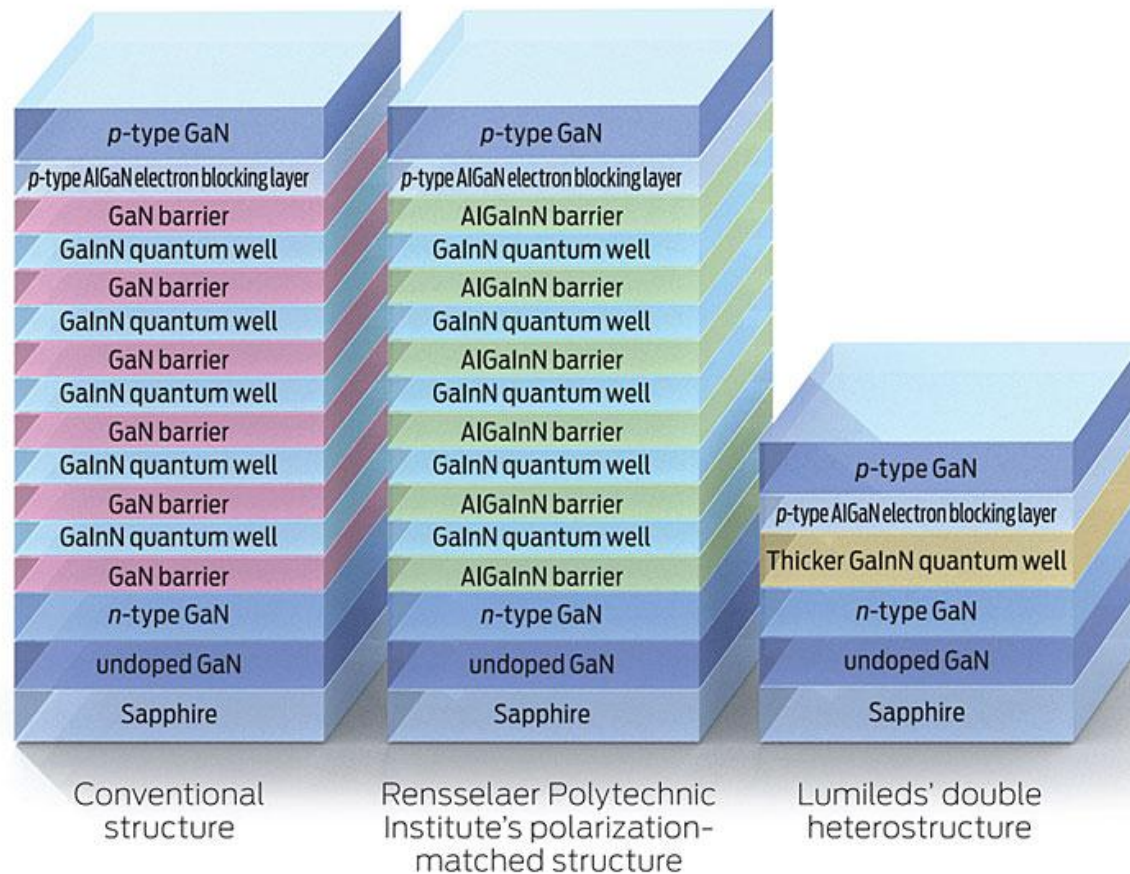
LED albastru

- ▶ bazat pe GaInN
- ▶ dezvoltare tardiva (GaN)



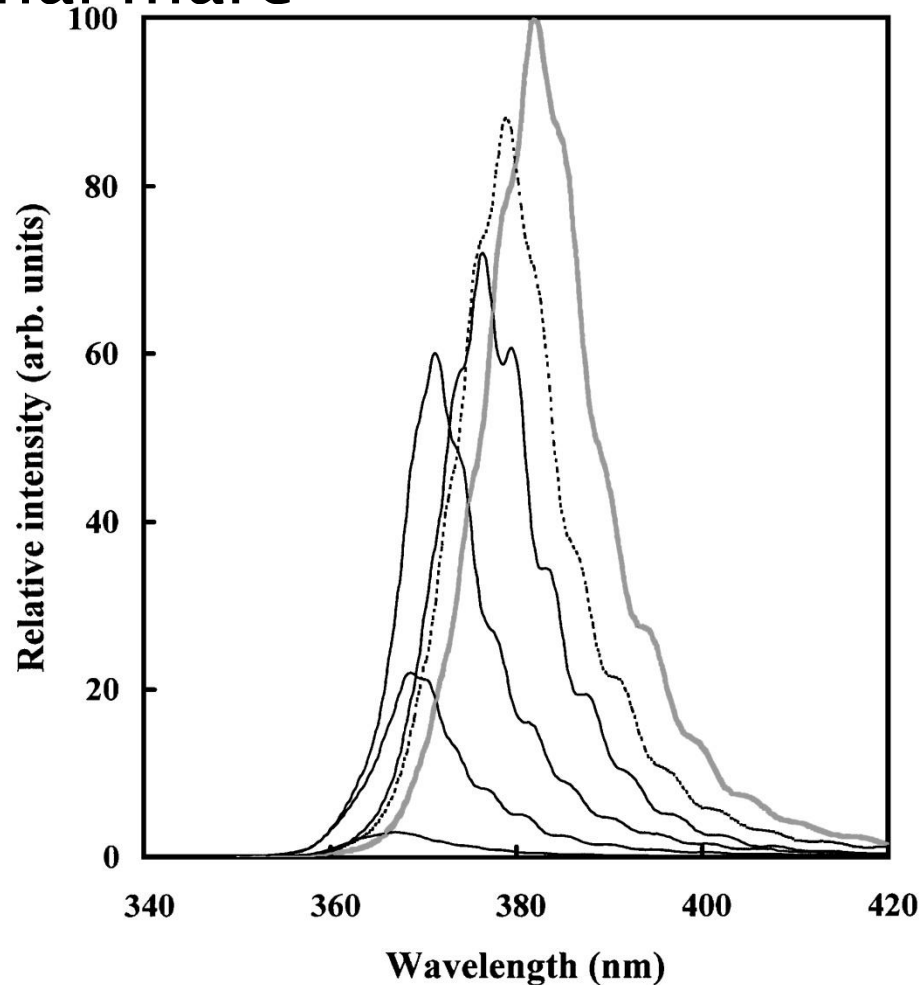
LED albastru

- ▶ realizare: GaInN Quantum Well/GaN

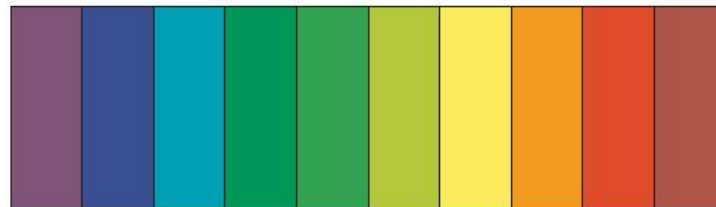
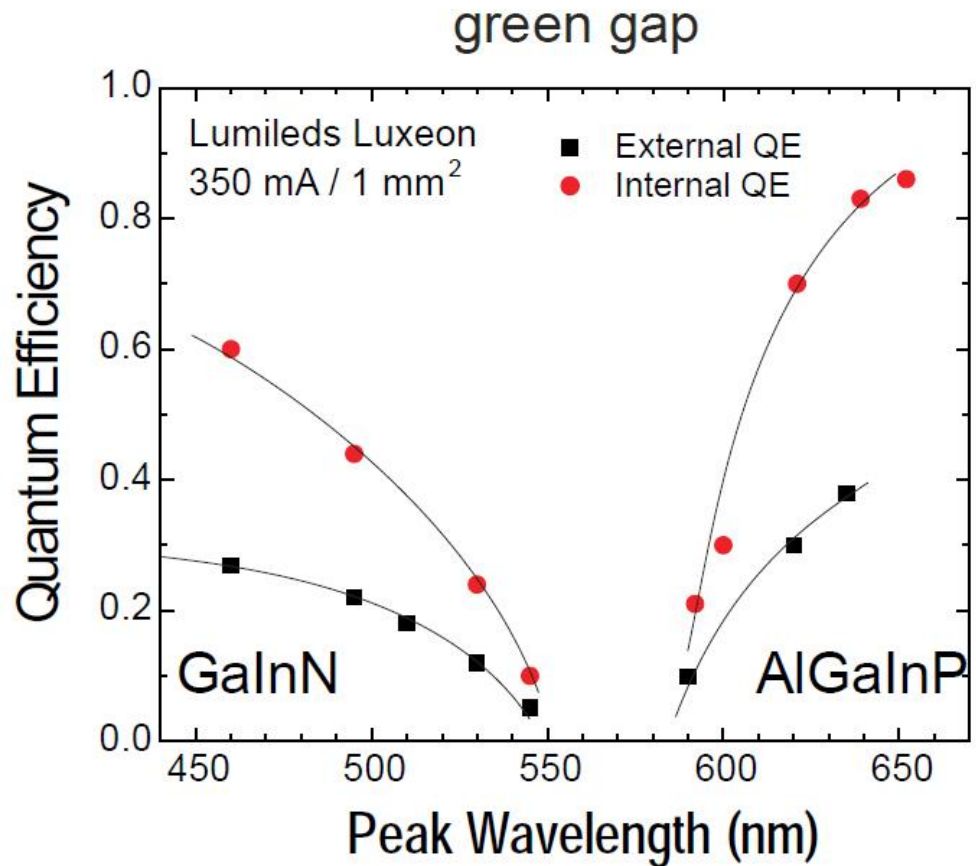


Spectru LED albastru

- ▶ $\Delta\lambda$ relativ la λ mai mare



Eficiencia cuantica




Culori/materiale - 1

| Color | Wavelength (nm) | Voltage (V) | Semiconductor Material |
|----------|-----------------------|--------------------------|--|
| Infrared | $\lambda > 760$ | $\Delta V < 1.9$ | 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)
- ▶ Illuminare
 - Putere ridicata, lumina alba (GaN)

Premiul Nobel, Fizica, 2014

Nobelpriset i fysik 2014

The Nobel Prize in Physics 2014



Nobelpriset i fysik 2014



KUNGL. VETENSKAPSKAS AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES



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"

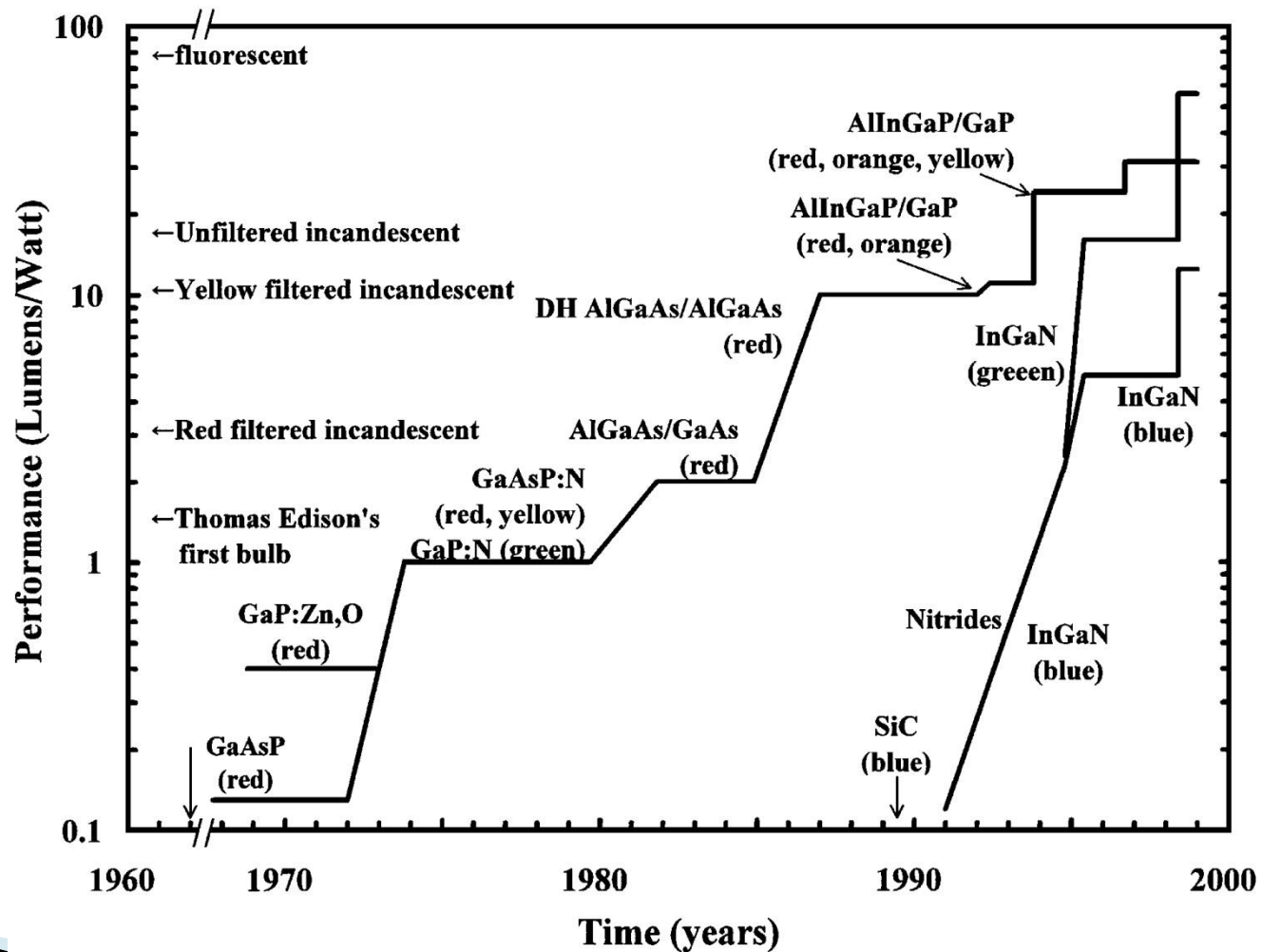
2014-10-07

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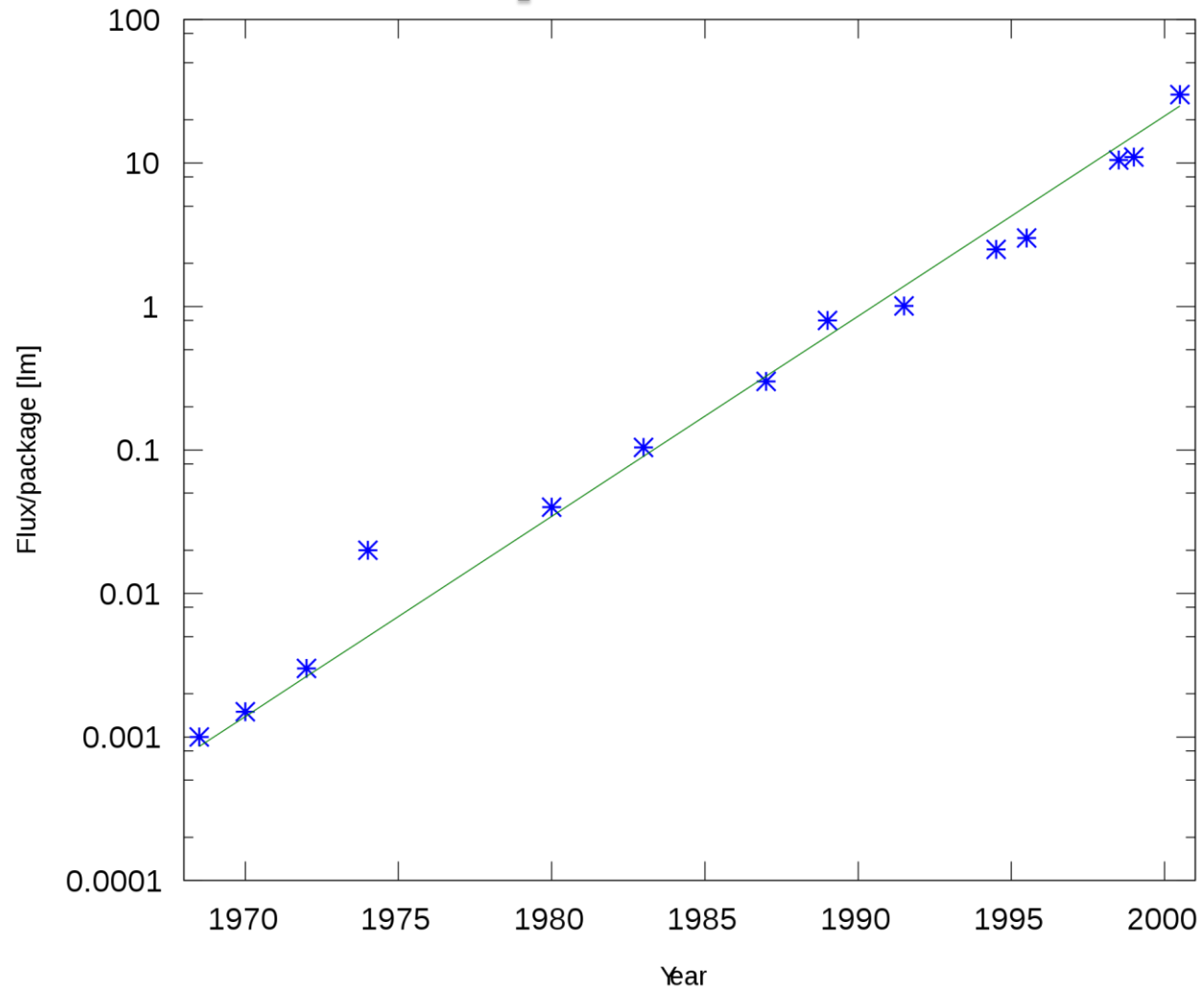
Eficiența

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

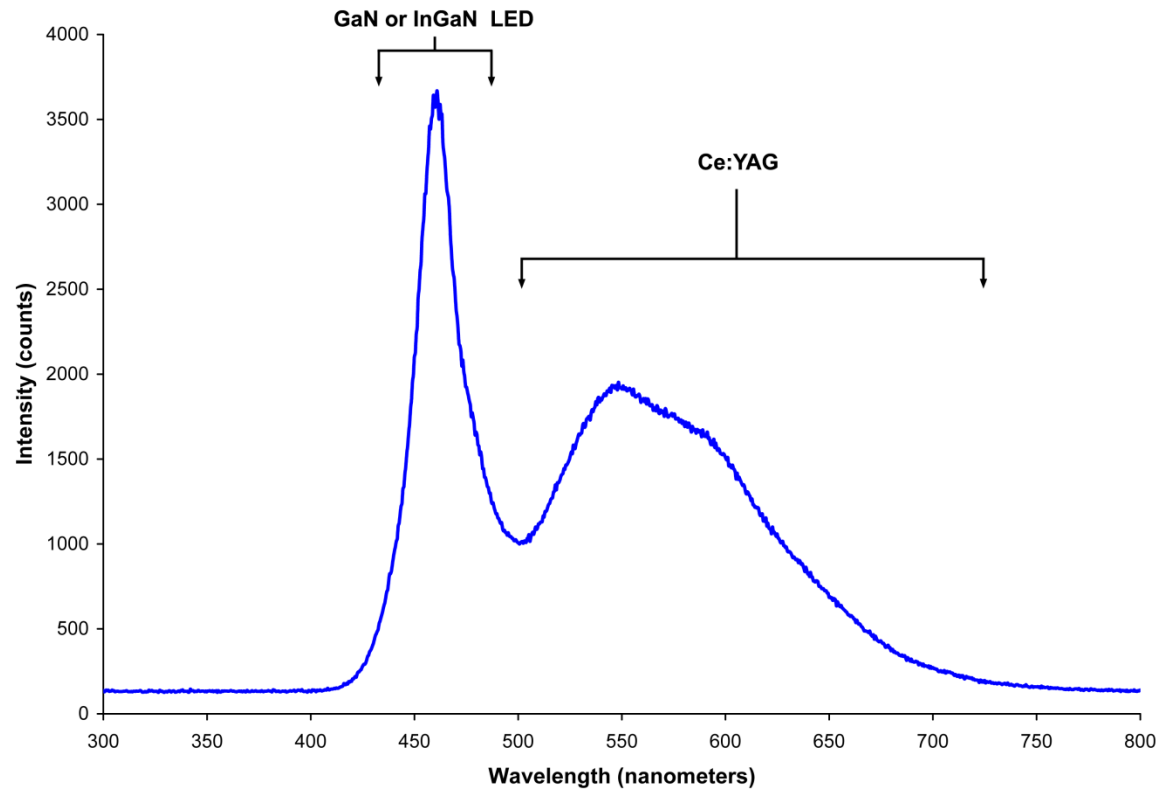
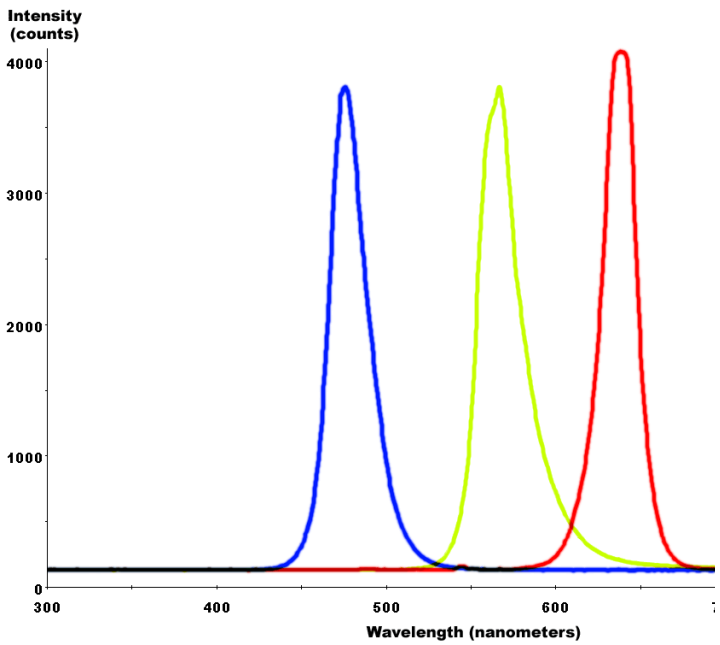
Eficienta in timp



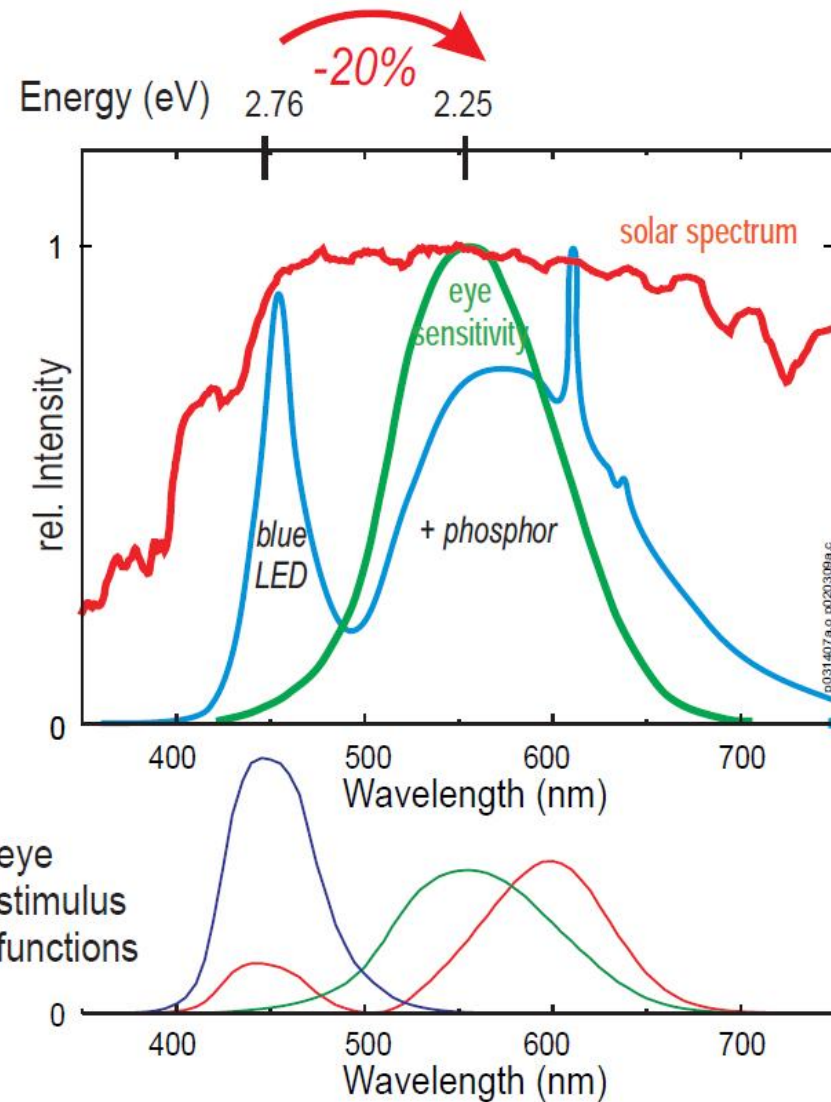
Eficienta in timp



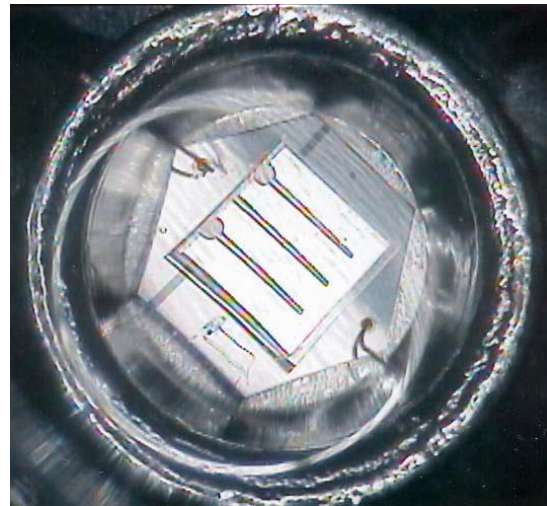
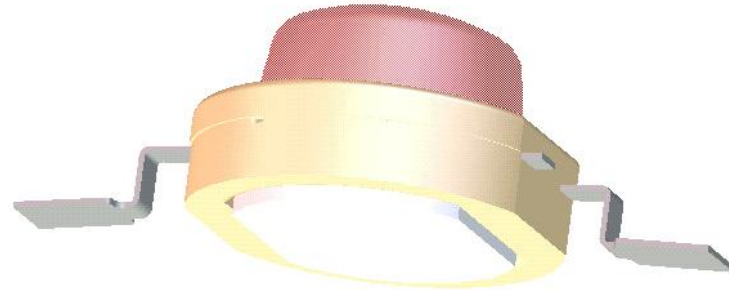
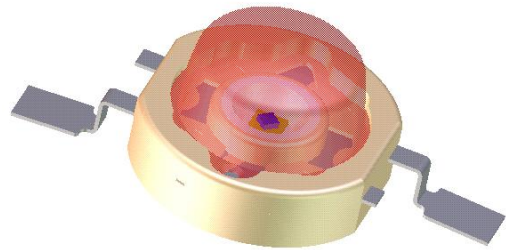
Culoare alba



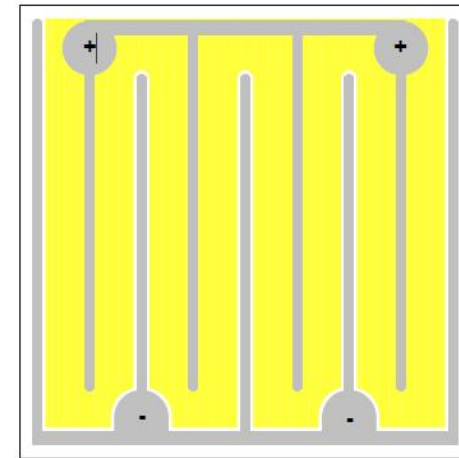
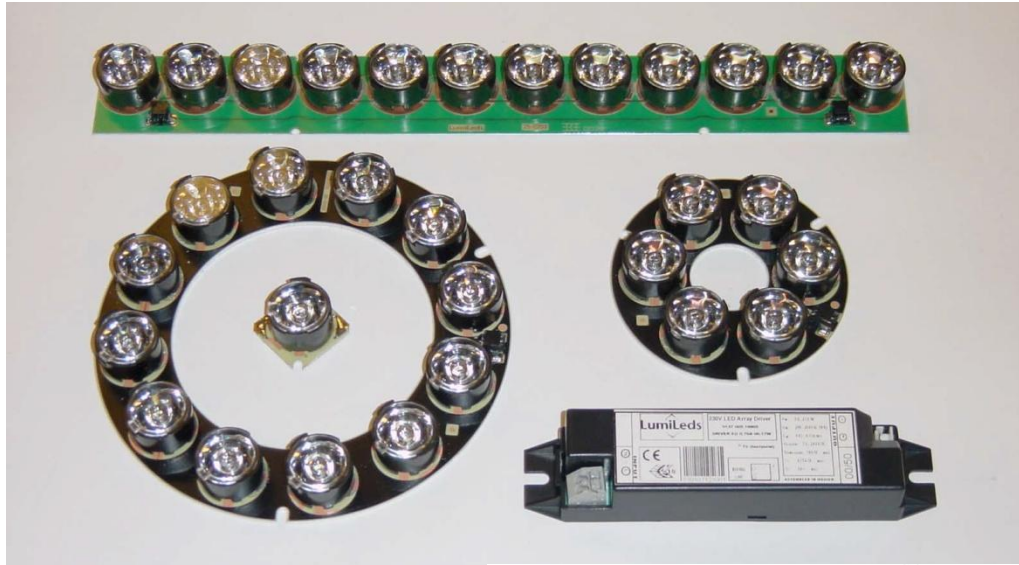
Fosfor activat de LED albastru/UV



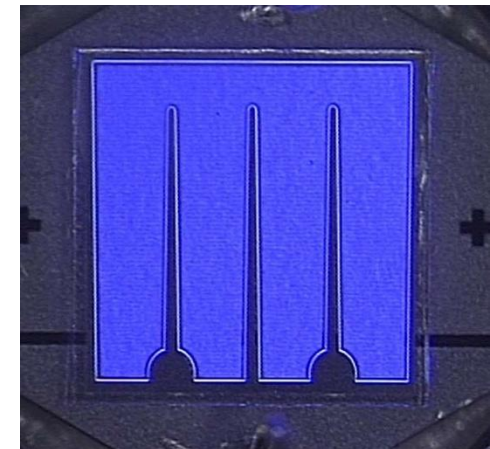
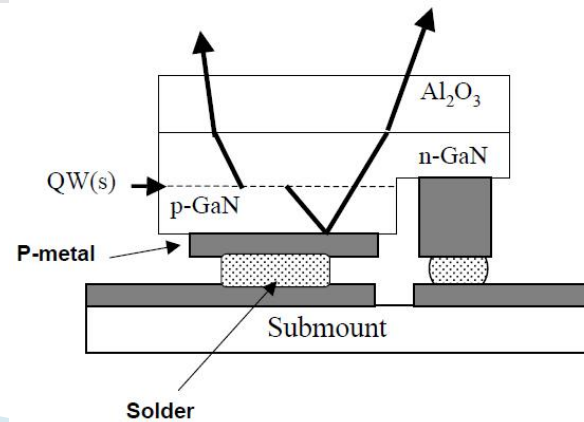
Realizare LED de putere



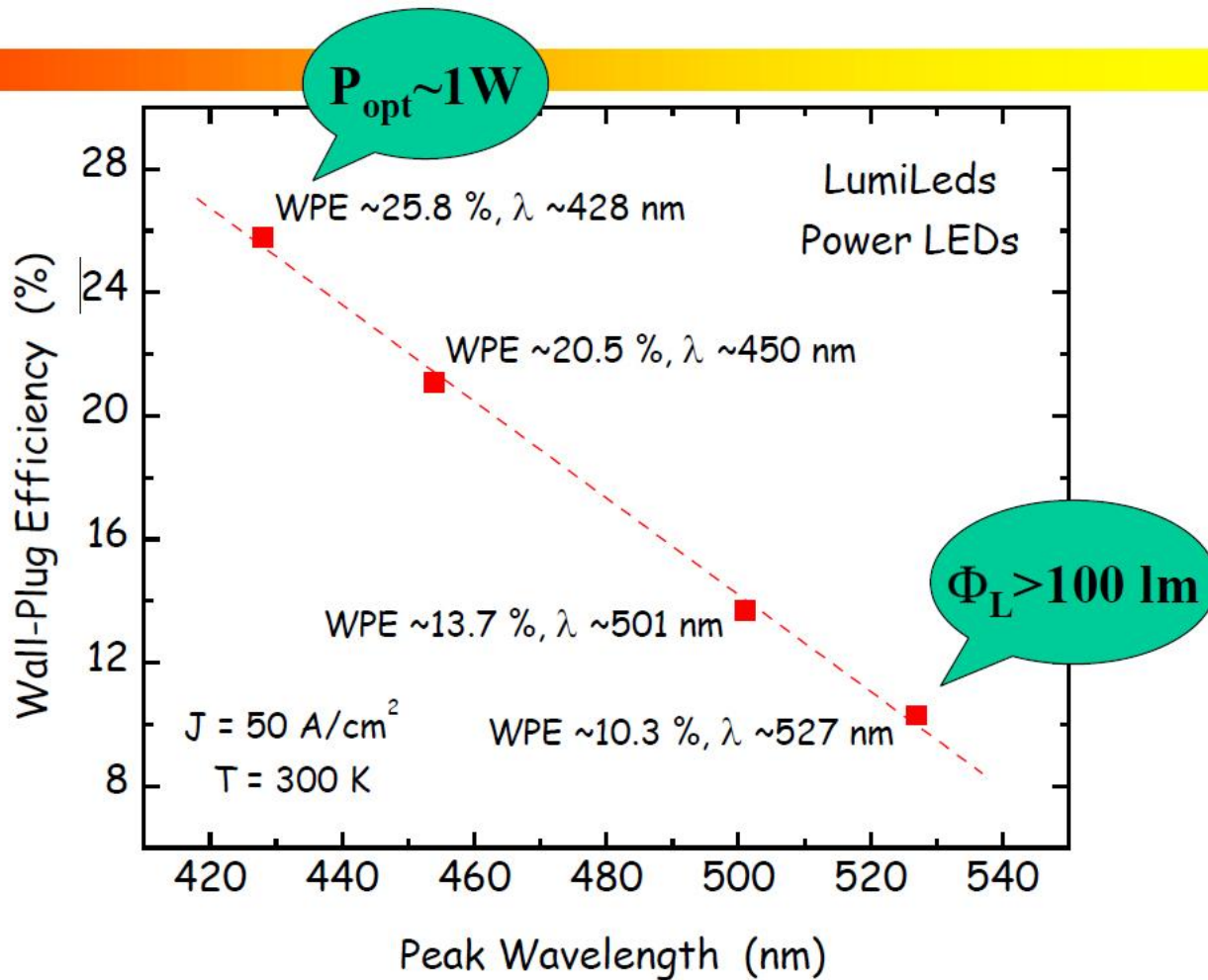
Realizare LED de putere



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



Performanta

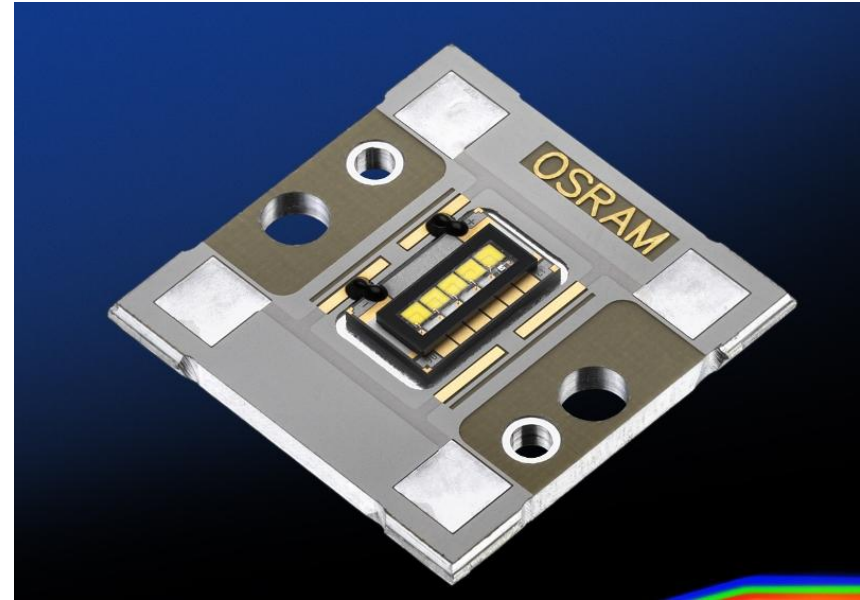


Aplicatii

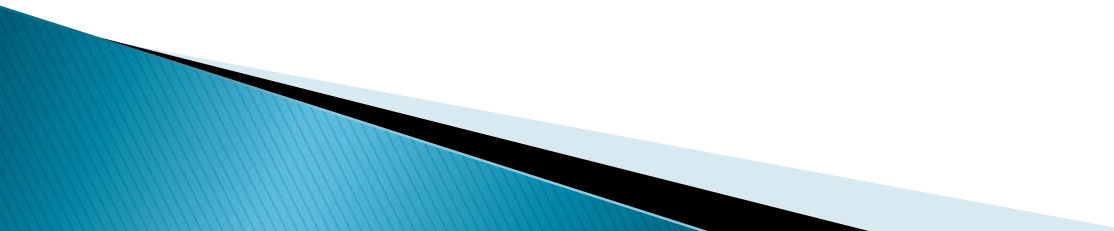
- ▶ auto



Aplicatii

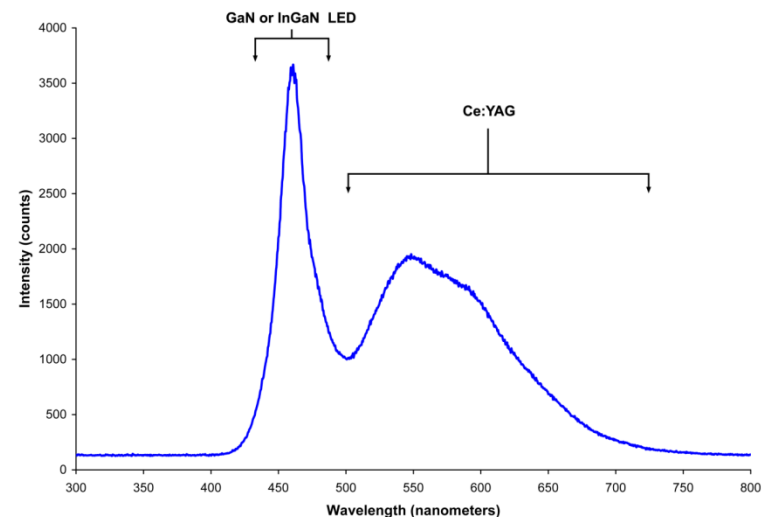
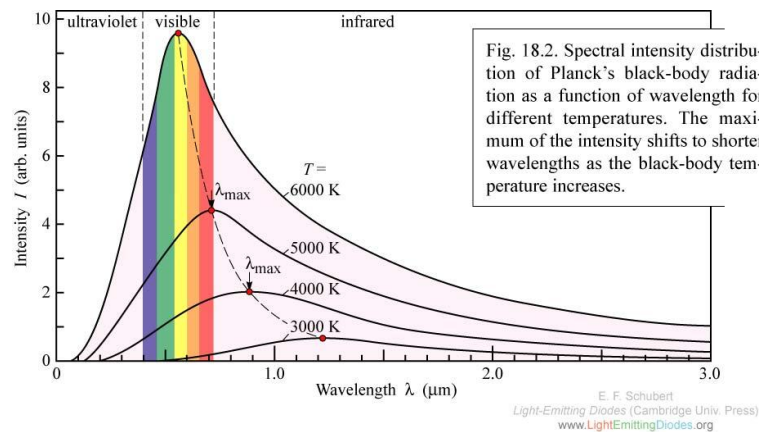


Avantaje

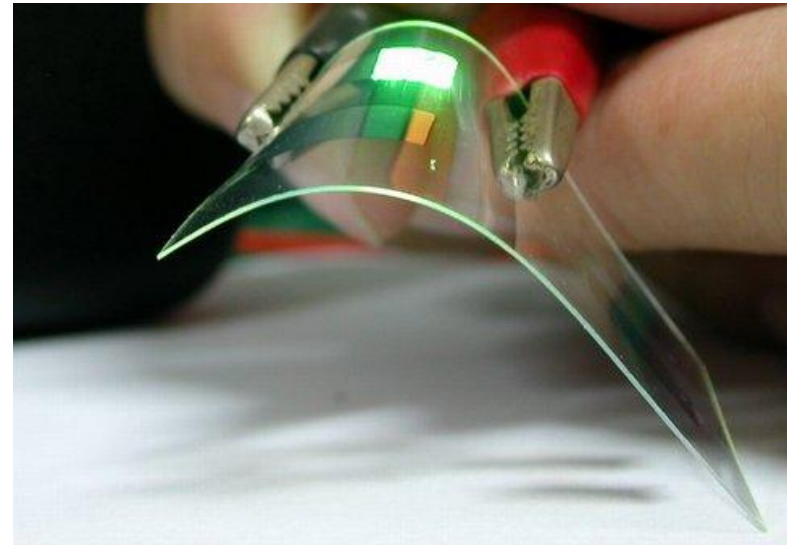
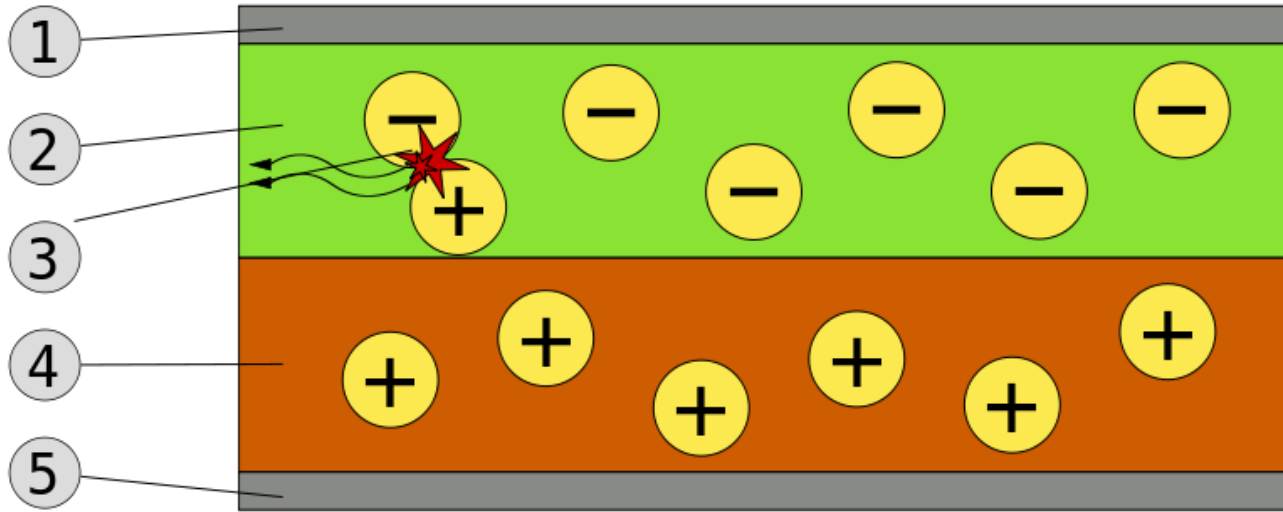
- ▶ Eficienta
 - ▶ Culoare usor de implementat (nativ)
 - ▶ Dimensiune
 - ▶ Timp de raspuns
 - ▶ Reglaj al intensitatii luminoase
 - ▶ Radiatie de caldura (IR) redusa
 - ▶ Timp de viata
 - ▶ Rezistenta la socuri
 - ▶ Directivitatea luminii (nativ)
- 

Dezavantaje

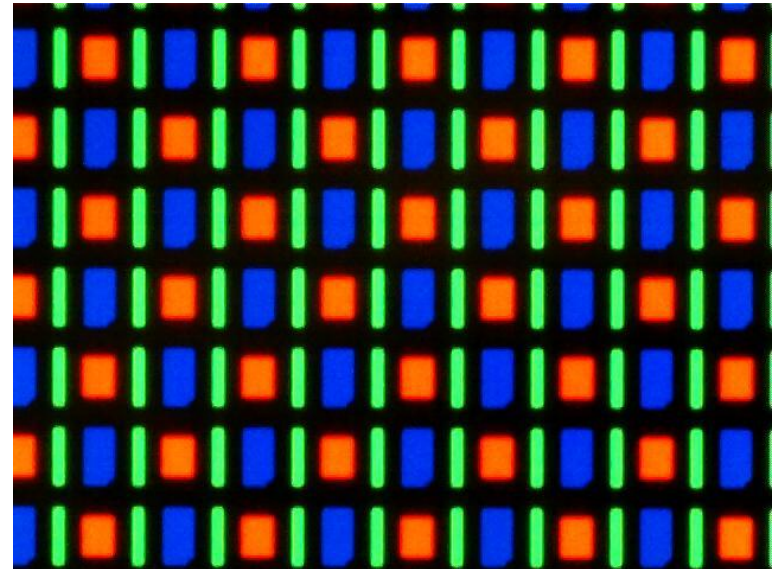
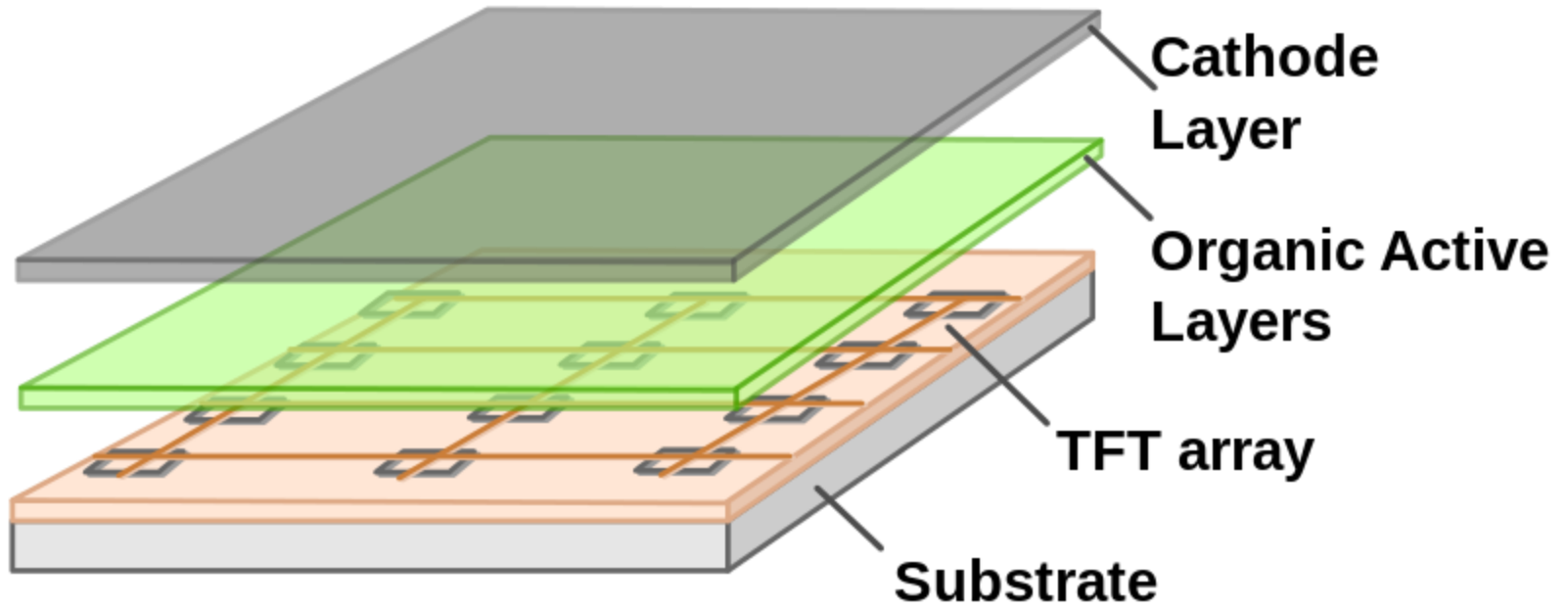
- ▶ Pret
- ▶ Dependenta de temperatura
- ▶ Sensibilitate la tensiune (prag)
- ▶ Calitatea luminii (corp negru)
- ▶ Directivitate (sursa de suprafata/punctuala)



OLED



AMOLED



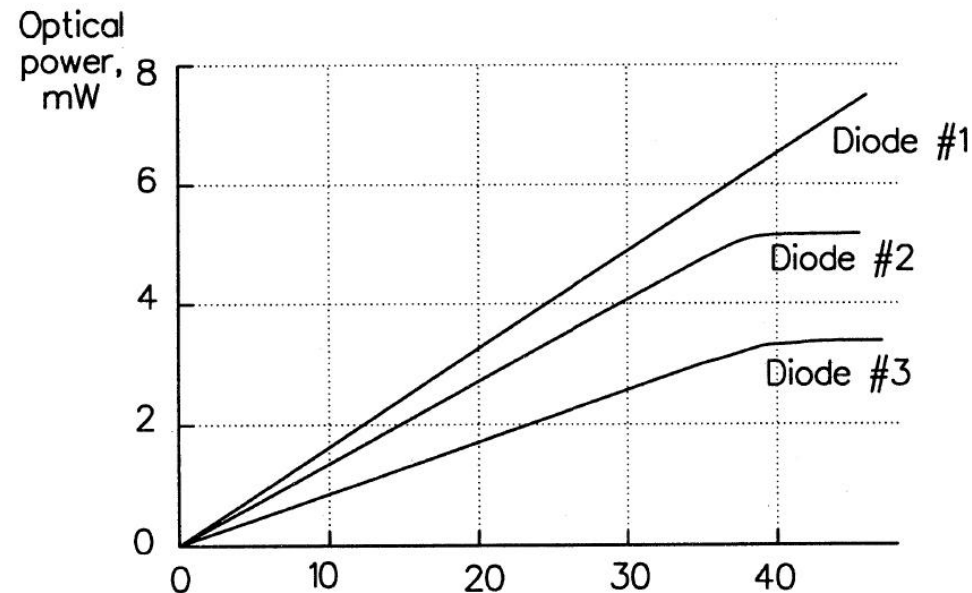
Caracteristica de raspuns a LED-urilor

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

- ▶ Responzivitatea

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

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



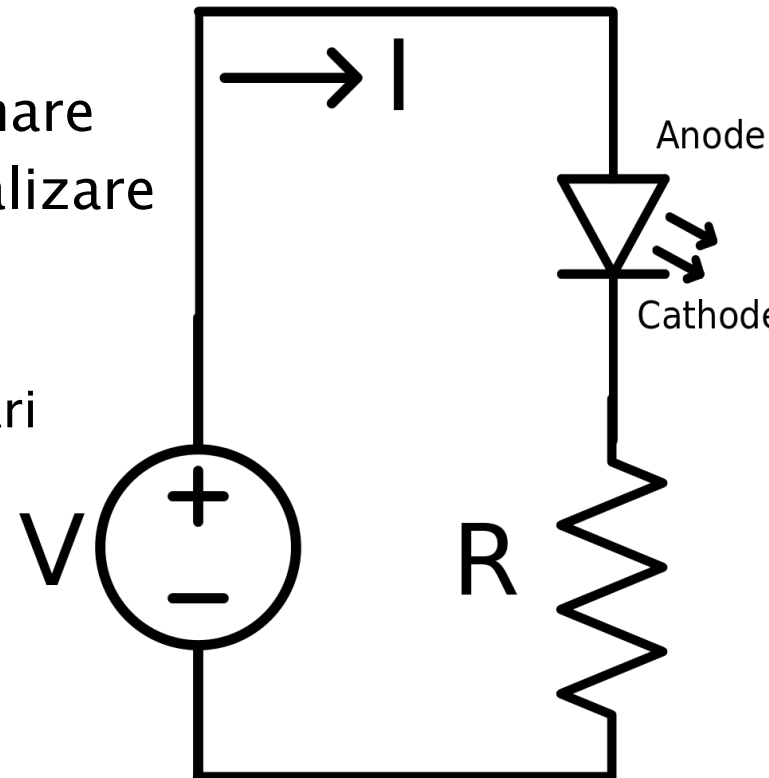
Control static LED

▶ Cea mai simpla schema de control: un rezistor in serie cu LED

- **Atentie!** Tensiunea directa poate varia semnificativ ($\gg 0.7V$) 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

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

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



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) | 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 | 25 | |
| | 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 | 2000 | 25 | |
| | BL-BK83V1 | InGaAlP/ Super Yellow | 590 | 587 ± 5 | 15 | 100 | 30 | 150 | 2.2 | 2.6 | 2000 | 25 | |
| | BL-BKH3V1 | InGaAlP/ Super Yellow | 590 | 587 ± 5 | 15 | 100 | 30 | 150 | 2.2 | 2.6 | 2500 | 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 | 2.0 | 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 | 24 | | |
| BL-BG63V4V | InGaN/SiC/ Green | 525 | 525 ± 5 | 35 | 120 | 30 | 150 | 3.5 | 4.0 | 5600 | 24 | | |

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

◆ Electro-Optical Characteristics

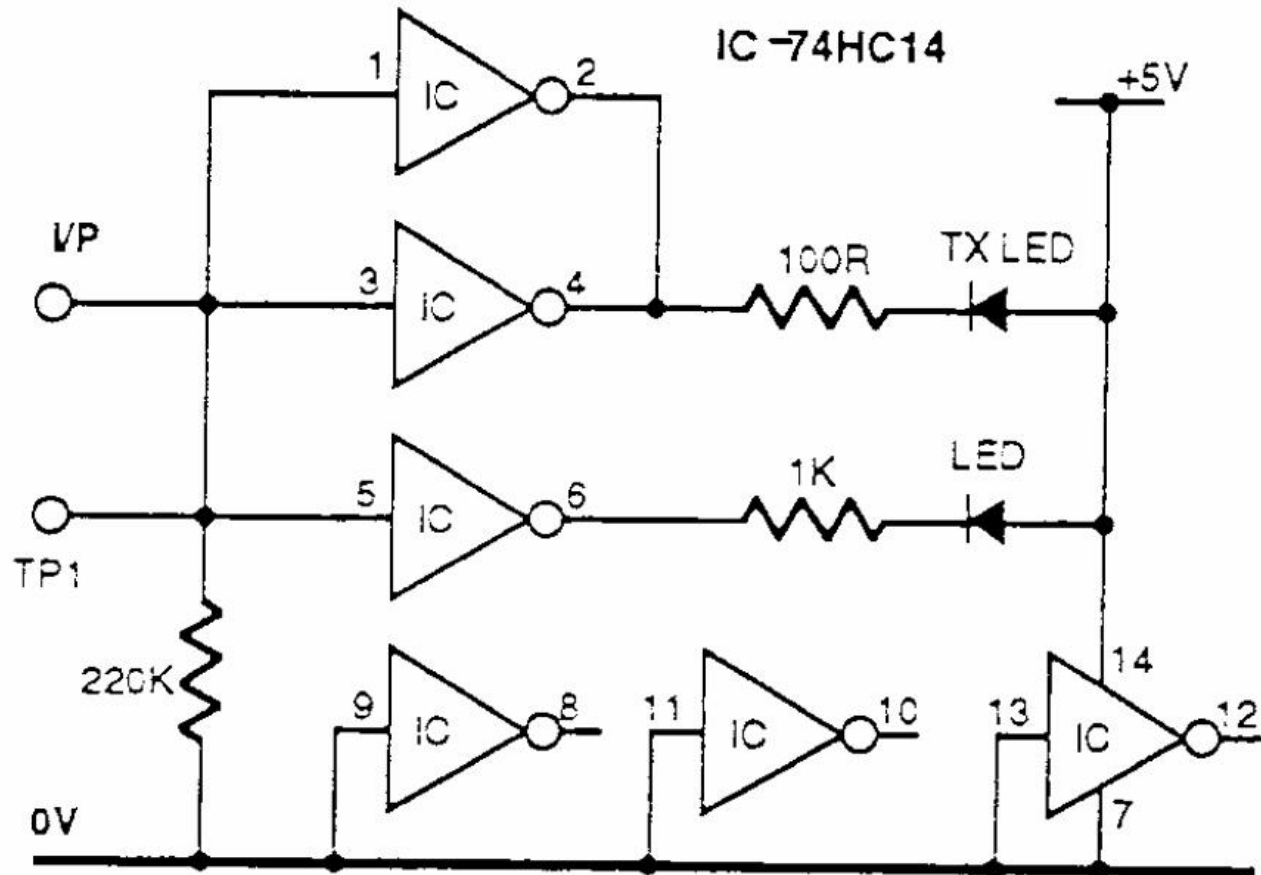
| Item | Symbol | Condition | Minimum | Typical | Maximum | Unit |
|----------------------|----------------|-------------------------|---------|---------|---------|------|
| Forward Voltage | V _F | I _F = 240 mA | | 19.0 | | V |
| Brightness | I _v | I _F = 240 mA | | 13 | | cd |
| Total Radiated Power | 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 varii mari ale curentului
- ▶ Se prefera de multe ori controlul in curent al LED-ului

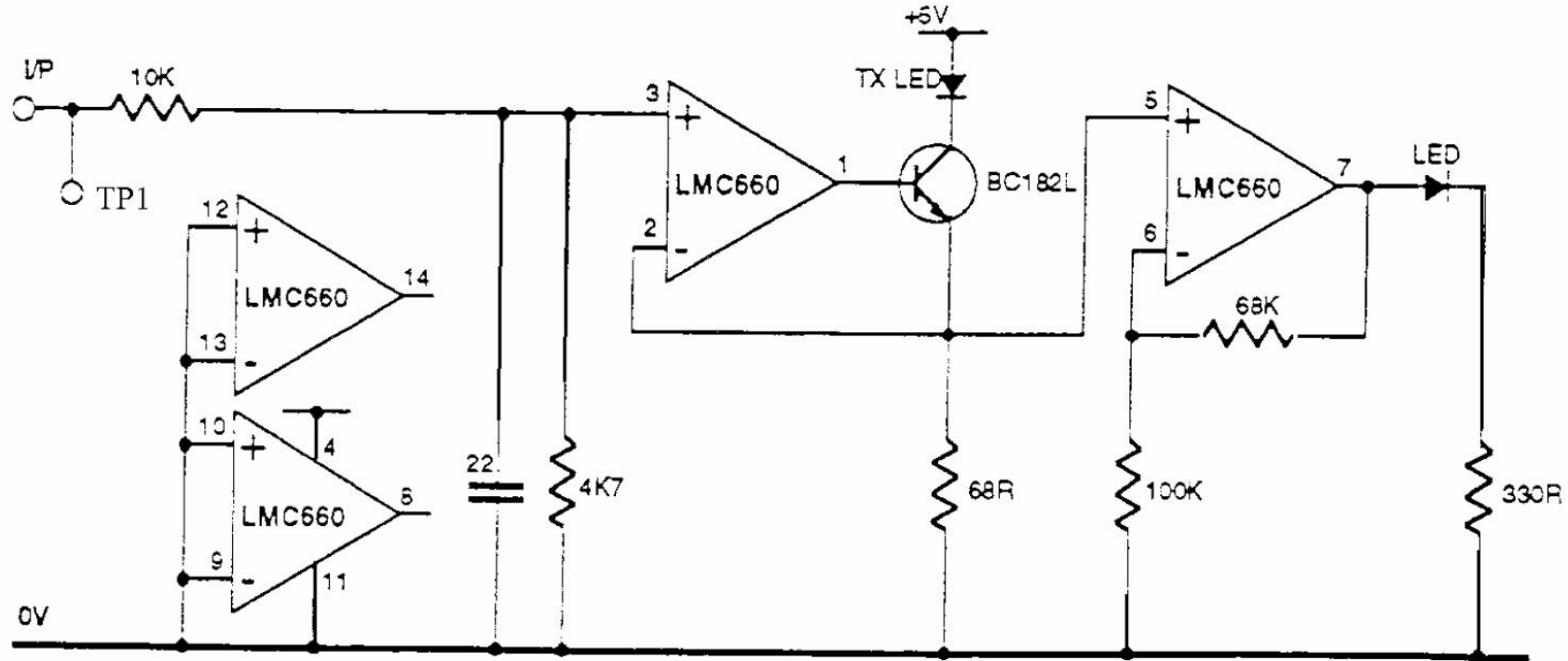
Control dinamic LED, Lab 1

- ▶ Control in tensiune
 - Schema electrică a emițătorului în impuls



Control dinamic LED, Lab 1

- ▶ Control in curent
 - Schema electrică a emițătorului optic analogic



Dioda Laser

Capitolul 8

Cuprins

- ▶ **Lumina ca undă electromagnetică** (ecuațiile lui Maxwell, ecuația undelor, parametri de propagare)
- ▶ **Elemente de fotometrie și radiometrie** (mărimi energetice/luminoase)
- ▶ **Fibra optică** (realizare, principiu de funcționare, atenuare, dispersie, banda de frecvență)
- ▶ **Cabluri optice** (tehnologie, conectori, lipire – splice)
- ▶ **Proiectare sistemică a legăturii pe fibra optică** (bandă de frecvență, balanța puterilor)
- ▶ **Emițătoare optice** (LED și dioda laser – realizare fizică și funcționare)
- ▶ **Receptoare optice** (dioda PIN, dioda cu avalanșă – realizare fizică și funcționare)
- ▶ **Amplificatoare transimpedanță** (parametri, scheme tipice, TIA în buclă deschisă, cu reacție, diferențiale, control automat al câștigului)
- ▶ **Realizarea circuitelor pentru controlul emițătoarelor optice** (parametri, scheme tipice, controlul puterii, multiplexoare)
- ▶ **Dispozitive de captare a energiei solare** (principiu de funcționare, utilizare, proiectare)

Caracteristici dioda laser

▶ Avantaje

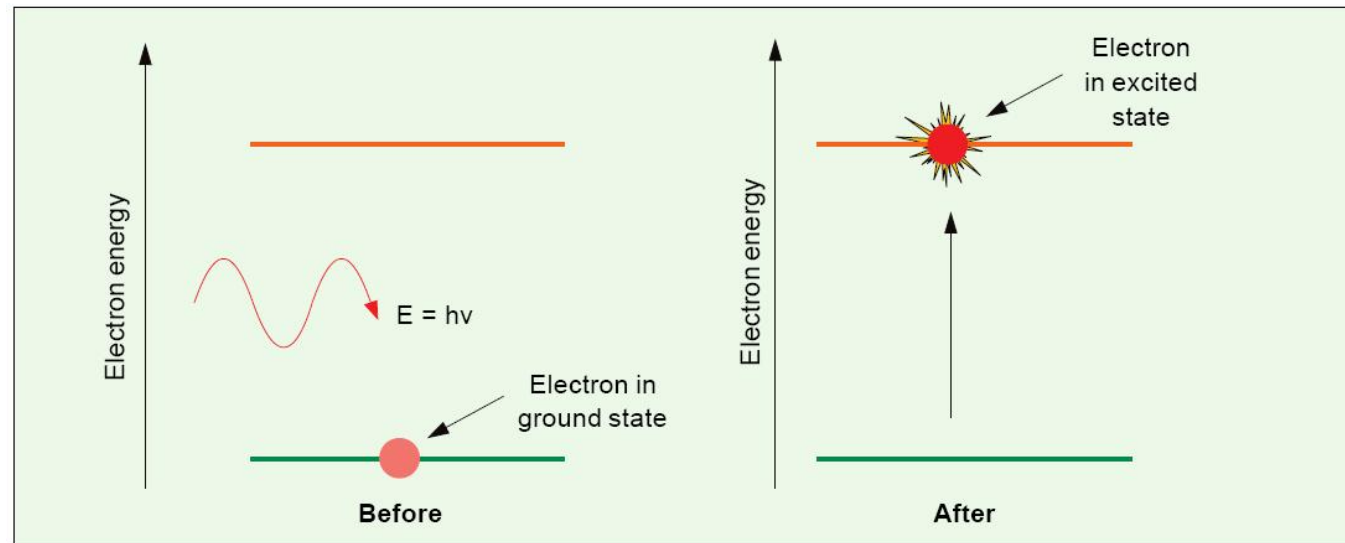
- Putere optica ridicata (50mW functionare continua, 4W functionare in impulsuri)
- Precizie ridicata a controlului (impulsuri cu latimea de ordinul fs – femptosecunde) – viteza mare de lucru
- Spectru ingust, teoretic LASER ofera o singura linie spectrala
- Lumina coerenta si directiva (~80% poate fi cuplata in fibra)

▶ Dezavantaje

- Cost (dispozitiv si circuit de comanda: controlul puterii si al temperaturii)
- Durata de viata
- Sensitivitate crescuta cu temperatura
- Modulatie analogica dificila (de obicei cu dispozitive externe)
- Lungime de unda fixa

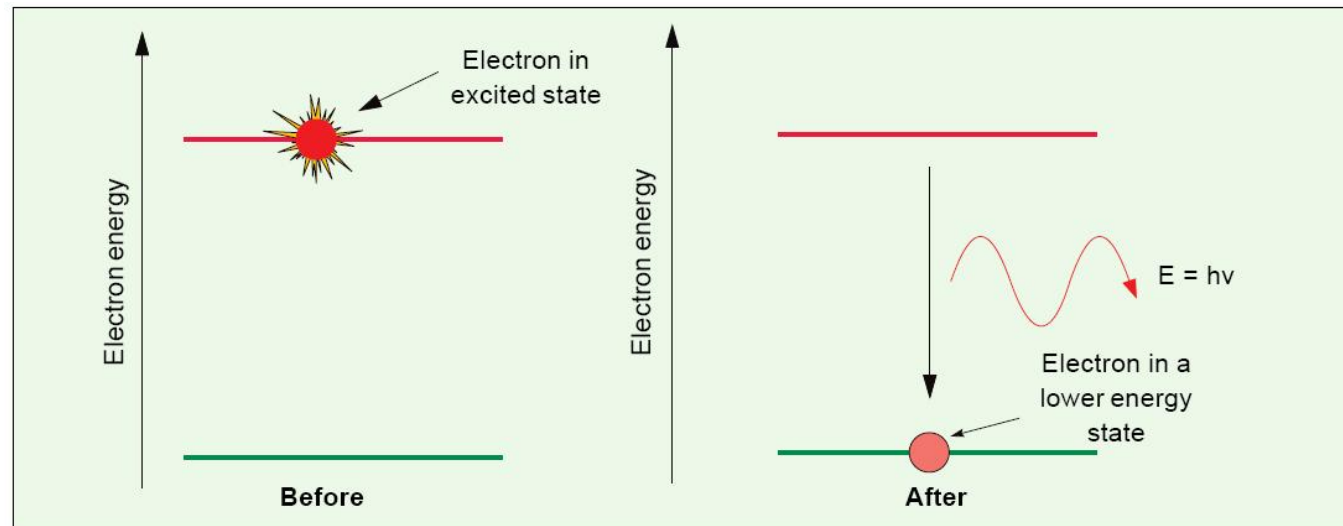
Dioda LASER – Principiu de operare

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



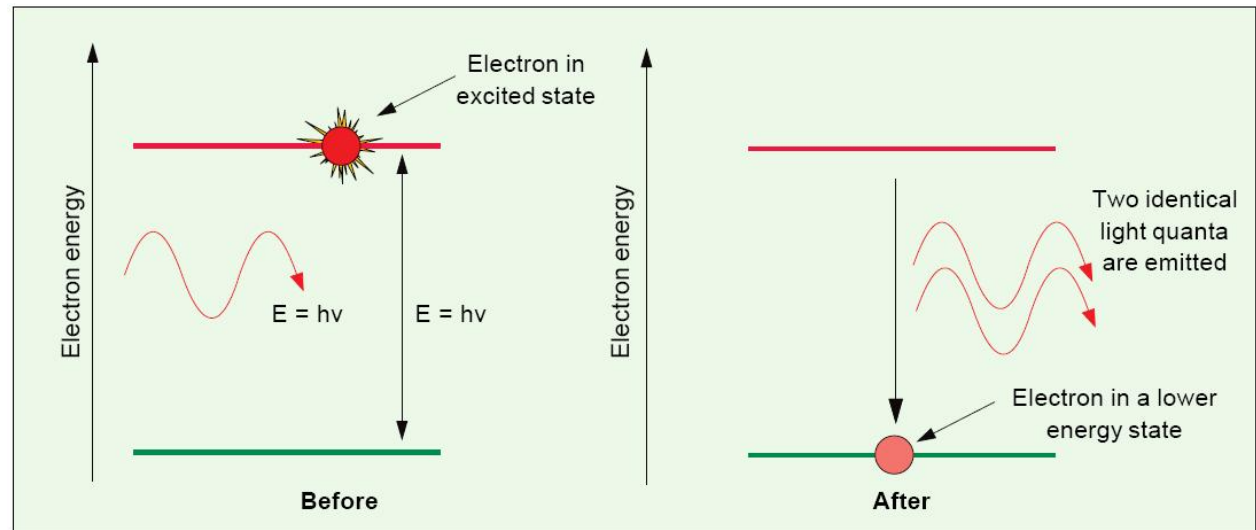
Dioda LASER – Principiu de operare

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



Dioda LASER – Principiu de operare

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



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

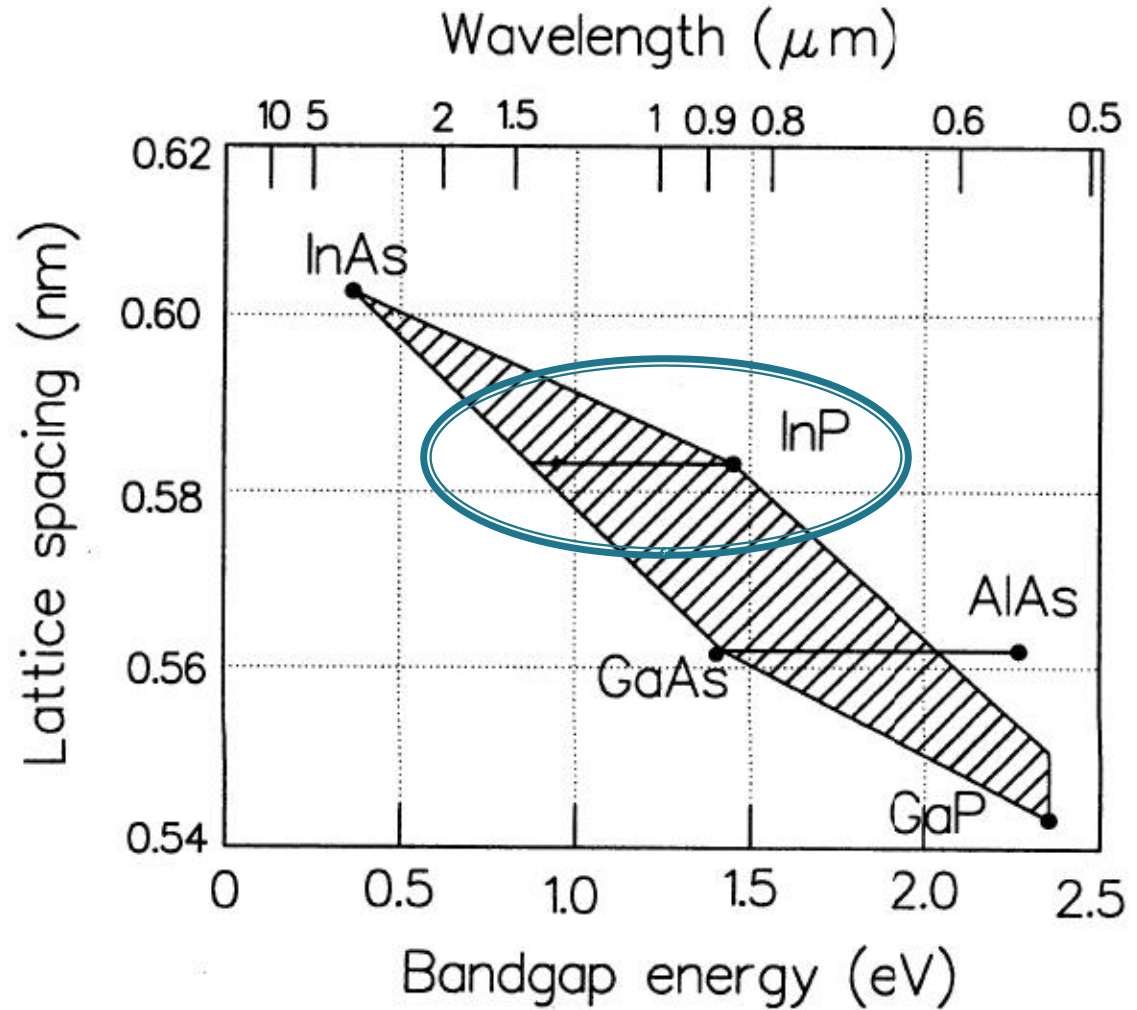
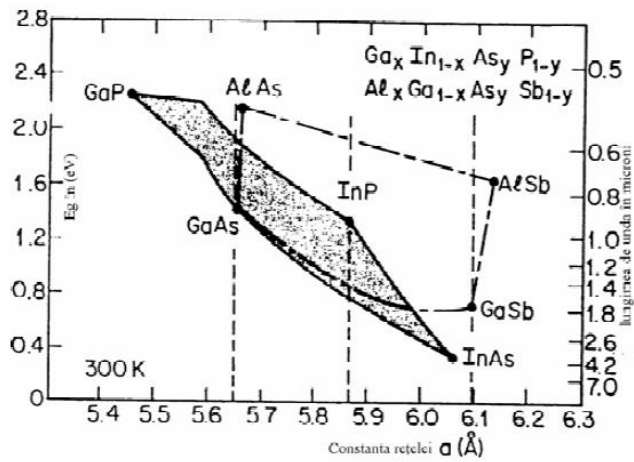
Lățimea benzii interzise/lungime de undă pentru materialele uzuale

| 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 |

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

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

Dependența benzii interzise de constanta rețelei



Materiale

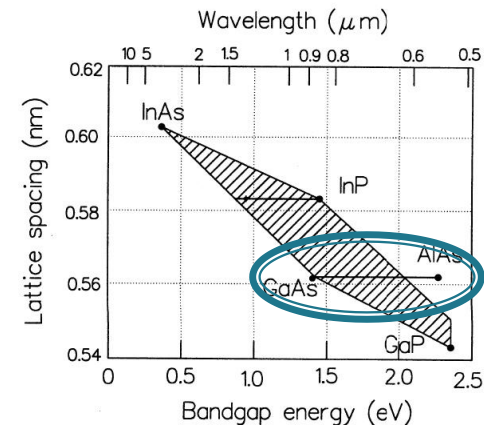
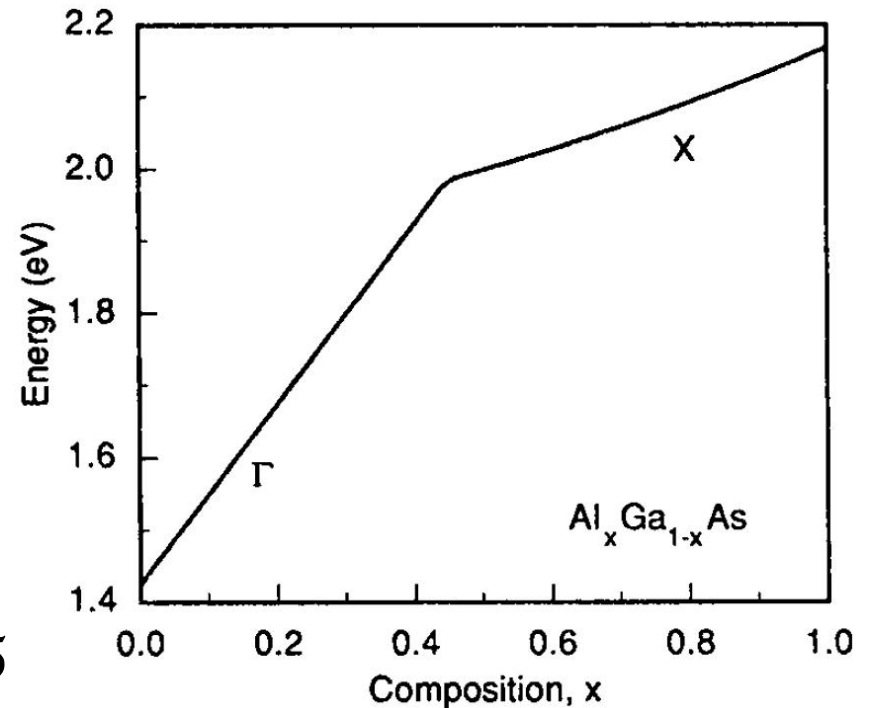
- ▶ Lungimi de unda mici (spectru vizibil – 1000nm)
 - GaP (665nm), $\text{GaAs}_y\text{P}_{1-y}$
 - GaAs (900nm), $\text{Ga}_{1-x}\text{Al}_x\text{As}$ (AlAs – 550nm)
- ▶ Lungimi de unda mari (1000÷1700nm)
 - $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$
 - x,y concentratii relative in aliaj a materialelor corespunzatoare
 - x,y alese din considerente privind
 - lungimea de unda
 - spatierea atomilor

Materiale

- ▶ Lungimi de unda mici
 - $\text{Ga}_{1-x}\text{Al}_x\text{As}$
 - substrat GaAs
 - limitare pentru tranzitie directa, $x < 0.45$
 - E_g (in eV)

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

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



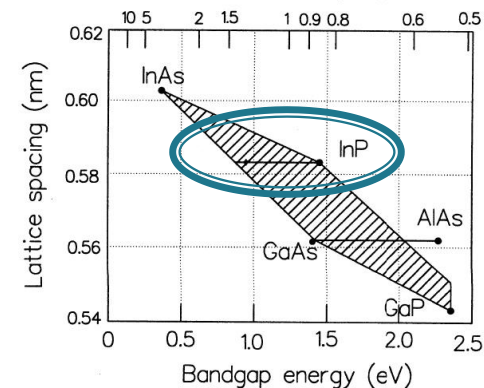
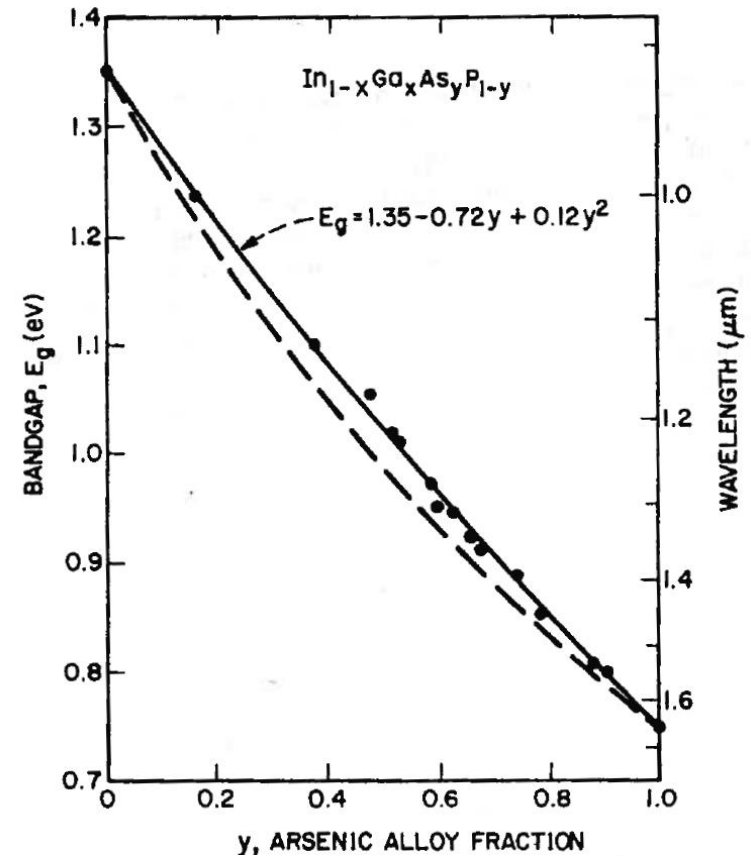
Materiale

- ▶ Lungimi de unda mari
 - $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$
 - 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 $x=0.282$,
 - $\text{In}_{0.282}\text{Ga}_{0.718}\text{As}_{0.611}\text{P}_{0.389}$



Principii LASER

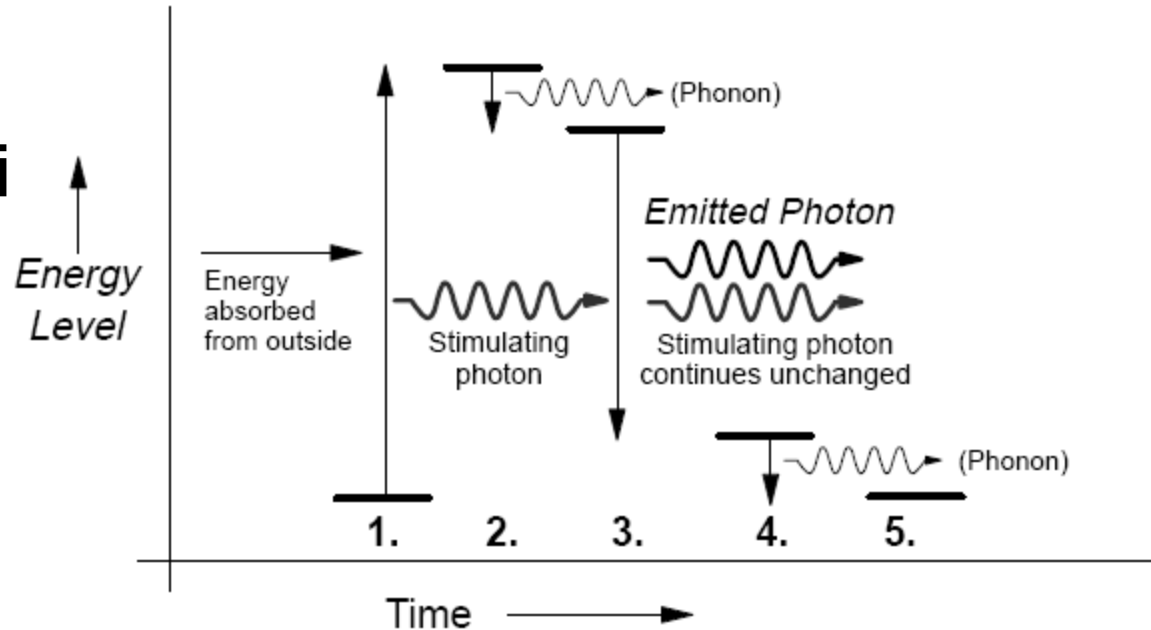
- ▶ Inversiune de populatie
 - necesara deoarece electronii au capabilitatea de a absorbi energie **la aceeasi frecventa** la care are loc emisia stimulata
 - se defineste probabilistic: probabilitatea de emisie stimulata sa fie mai mare decat probabilitatea de absorbtie

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

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

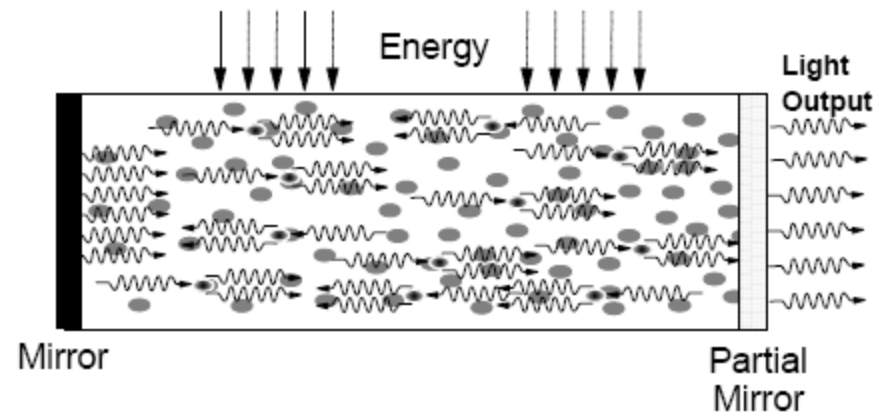
Materialie cu 4 nivele energetice

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



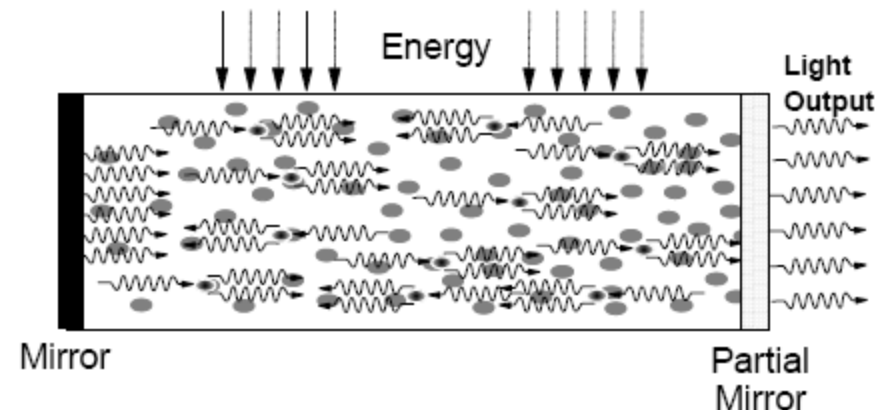
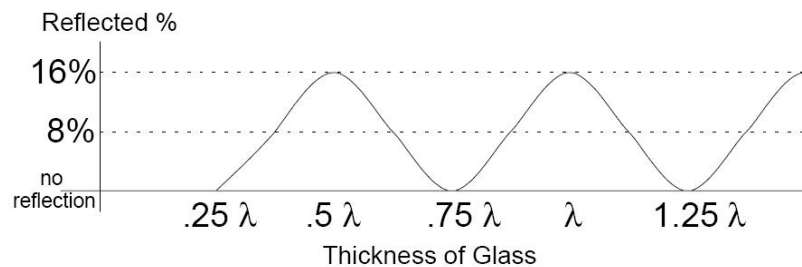
Dioda LASER – Principiu de realizare

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



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 $\sim 6\%$ dar poate ajunge la 36% pentru lungimea de unda de operare (vezi lamela dielectrica)



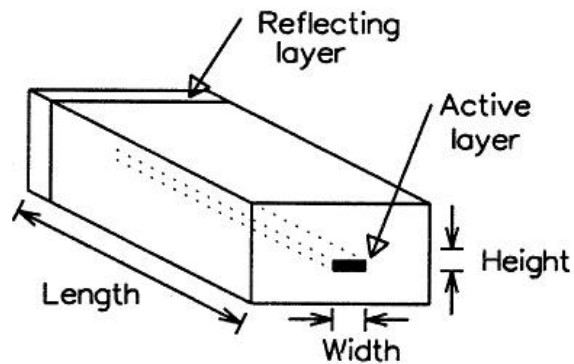
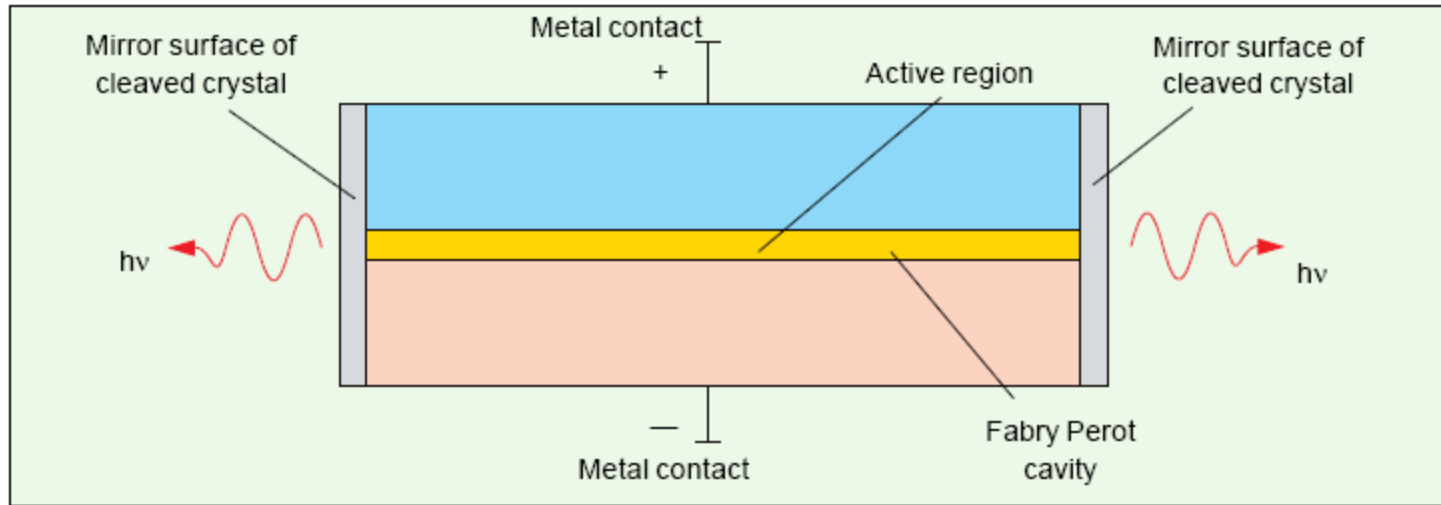
Dioda LASER – Principiu de realizare

- ▶ Pentru a realiza
 - coerența radiației
 - interferența constructivă între radiațiile incidente și reflectate de oglinzi,
- ▶ distanța între oglinzi trebuie să fie un multiplu al jumătății din lungimea de undă

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

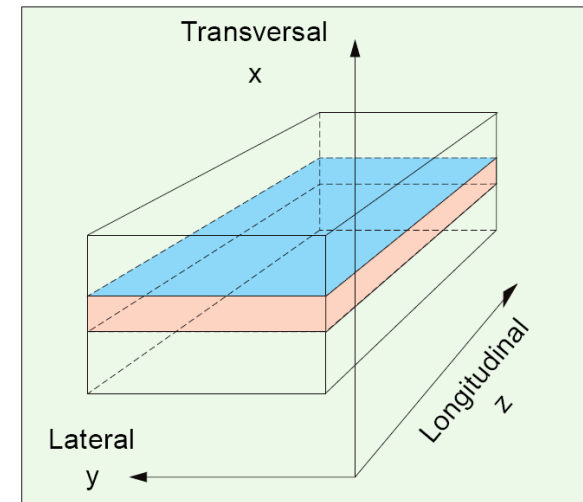
- ▶ Pentru eficientizarea pomparii de energie din exterior $L = 100 \div 200 \mu\text{m}$, $k \cong 400$

Dioda LASER Fabry Perot

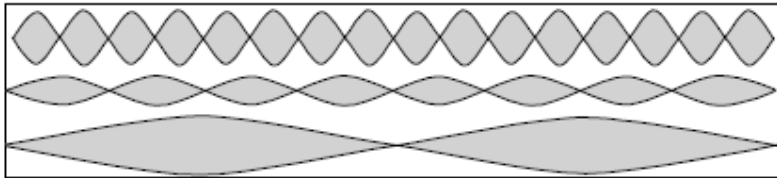


Height: $0.1 - 0.2 \mu\text{m}$
Length: $250 - 500 \mu\text{m}$
Width: $5 - 15 \mu\text{m}$
Sides: rough-cut
Front: cleaved
Back: 100% reflector

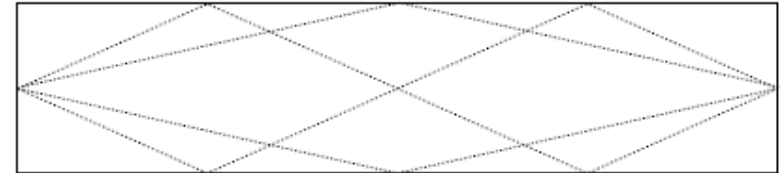
Definirea directiilor in
dioda LASER



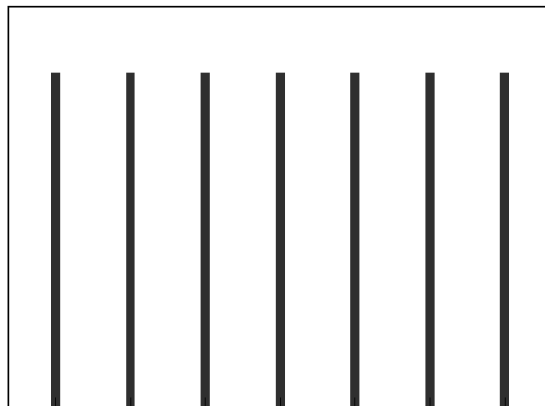
Spectrul diodei LASER



Longitudinal Modes



Lateral Modes



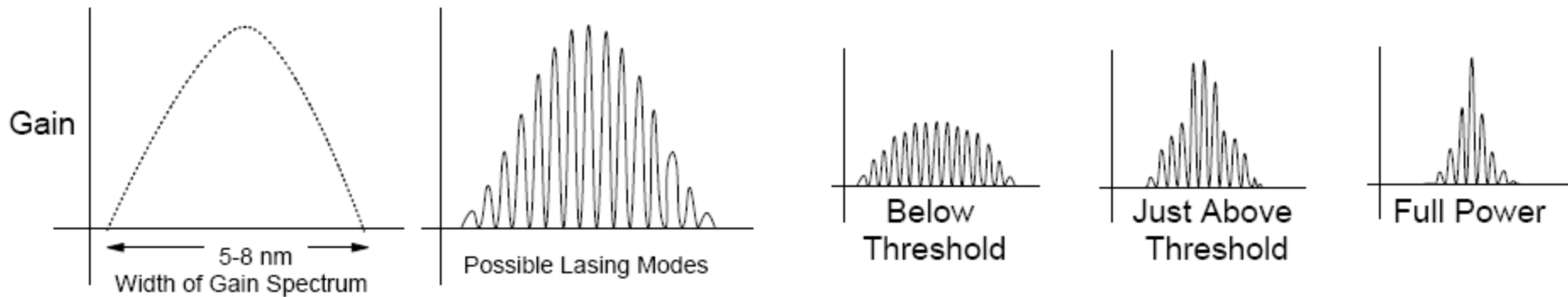
1.490 1.494 1.497 1.5 1.503 1.507 1.510
Wavelength (nm)

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

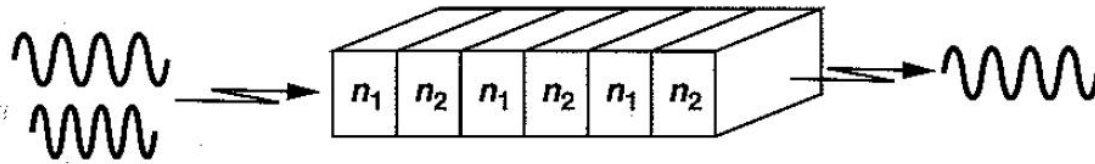
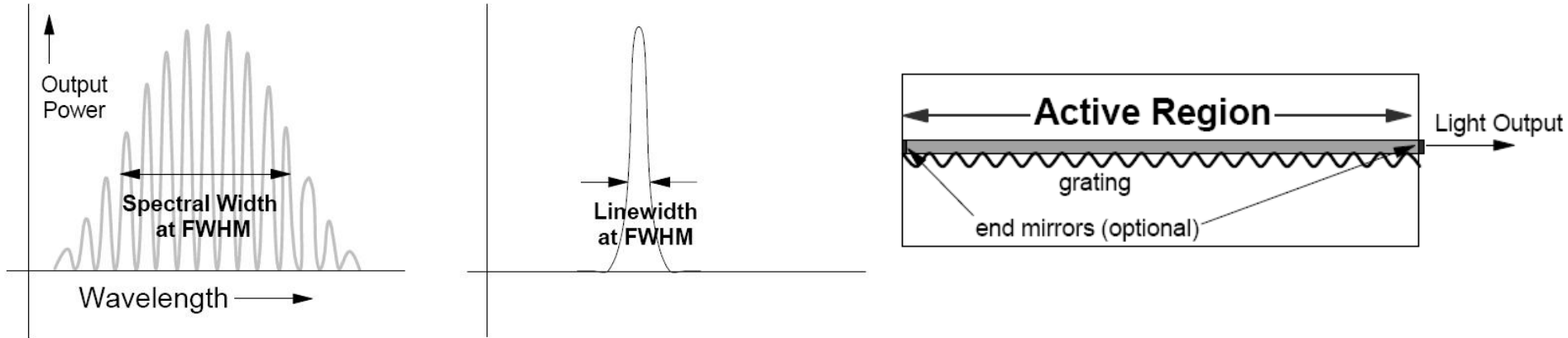
$$\Delta \lambda \cong \frac{\lambda_0^2}{2 \cdot n \cdot L}$$

Spectrul diodei LASER

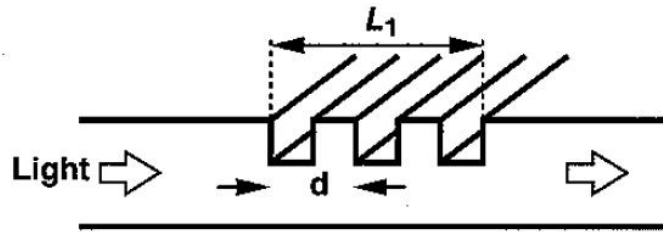
- ▶ Castigul diodei laser (eficacitatea aparitiei emisiei stimulate) depinde
 - de caracteristicile energetice ale materialului din care e realizata dioda
 - de energia pompata din exterior (curentul prin dioda)



Distributed Feedback (DFB) Lasers



(a)

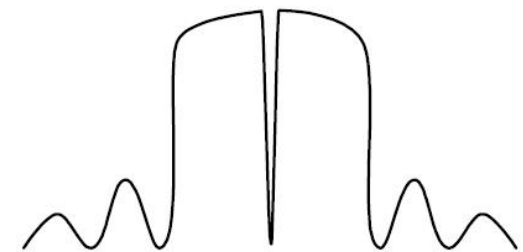
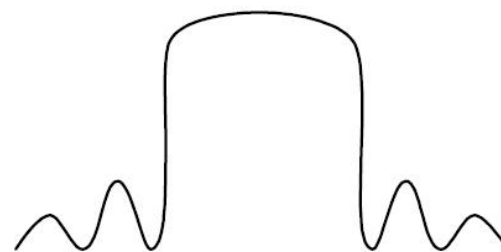
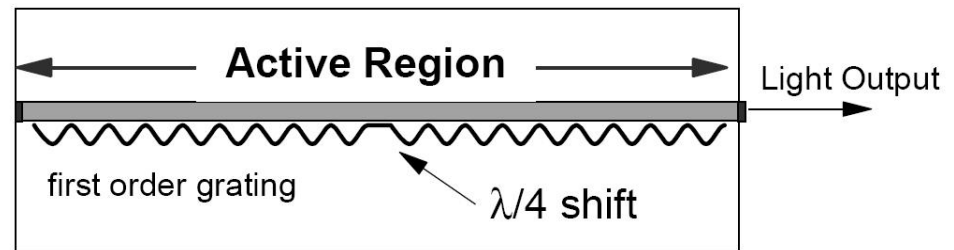
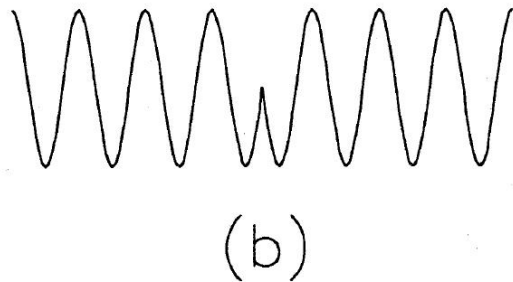
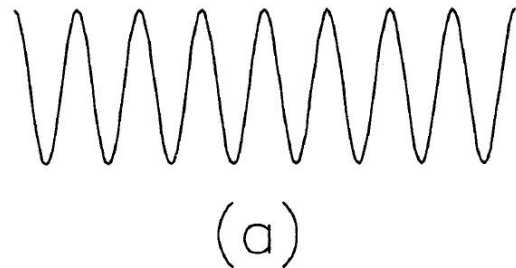


(b)

Filtre spatiale in
regiunea activa

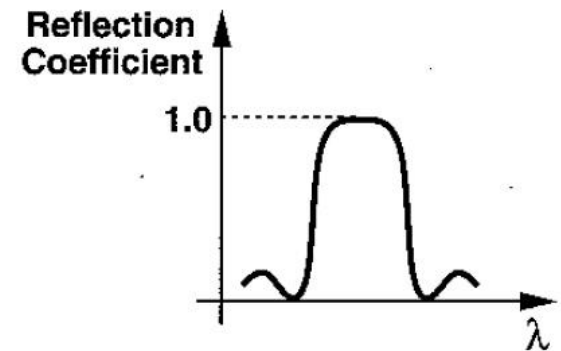
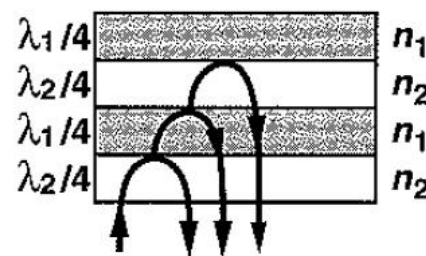
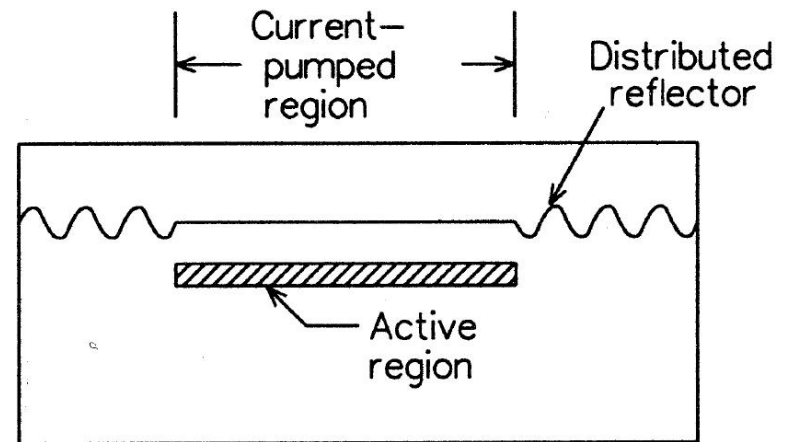
Distributed Feedback (DFB) Lasers

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



Distributed Bragg Reflector (DBR) Lasers

- ▶ Se utilizeaza suprafete reflective selective pentru filtrare optica



Caracteristici curent tensiune

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

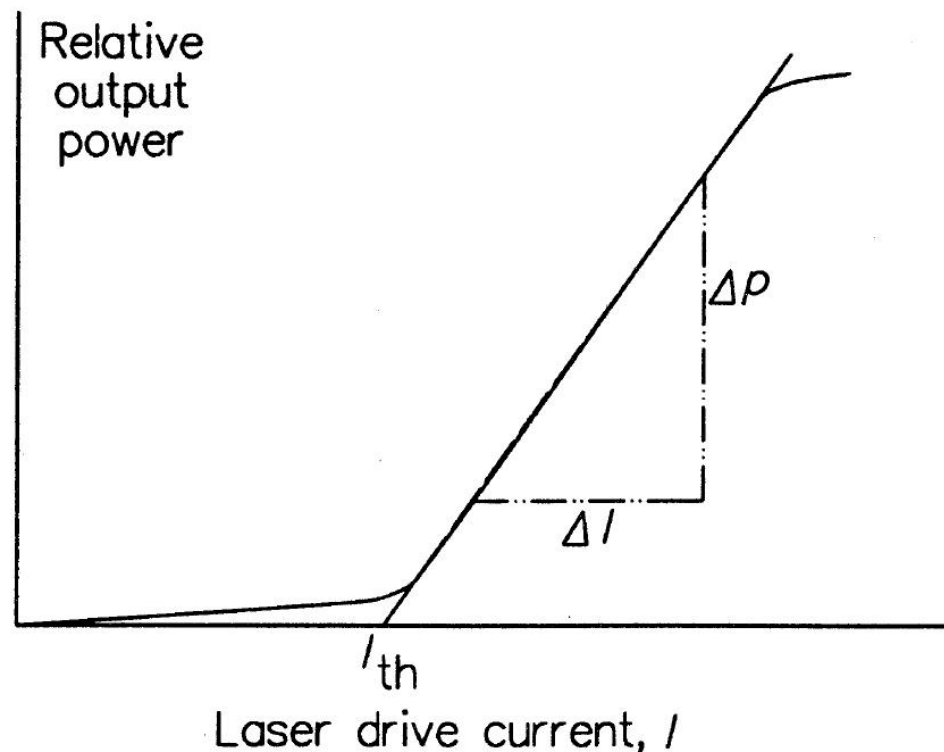
$I < I_{th}$ regim LED
ineficient!, $P_o \cong 0$

$I > I_{th}$ regim LASER

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

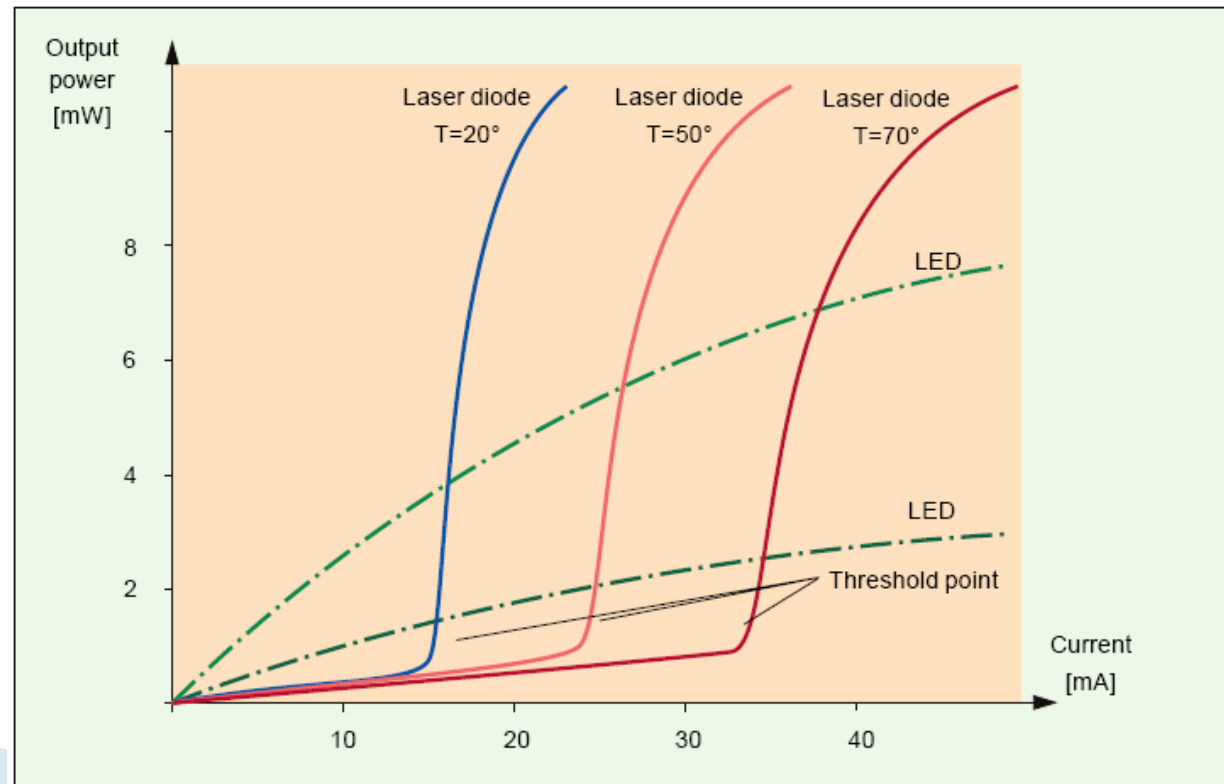
$$P_o = r \cdot (I - I_{th})$$

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

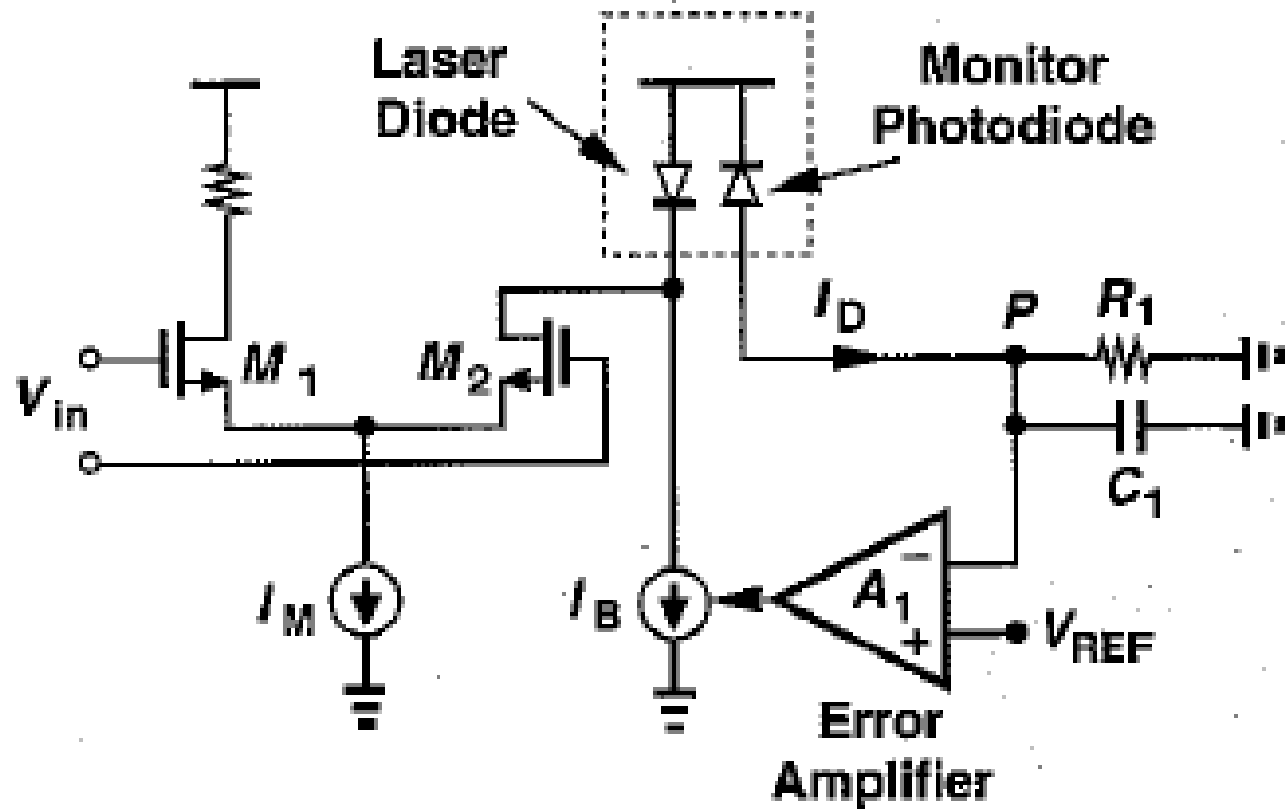
- ▶ Dependenta de temperatura a curentului de prag este exponentiala

- ▶
$$I_{th} = I_0 \cdot e^{T/T_0}$$

- ▶ I_0 e o constanta determinata la temperatura de referinta

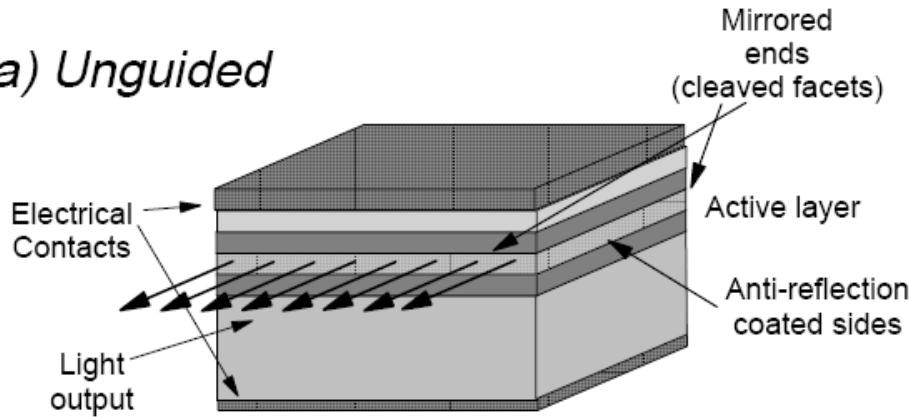
| Material | Lungime de unda | T_0 |
|----------|-----------------|-----------|
| InGaAsP | 1300 nm | 60÷70 K |
| InGaAsP | 1500 nm | 50÷70 K |
| GaAlAs | 850 nm | 110÷140 K |

Monitorizarea radiației de spate

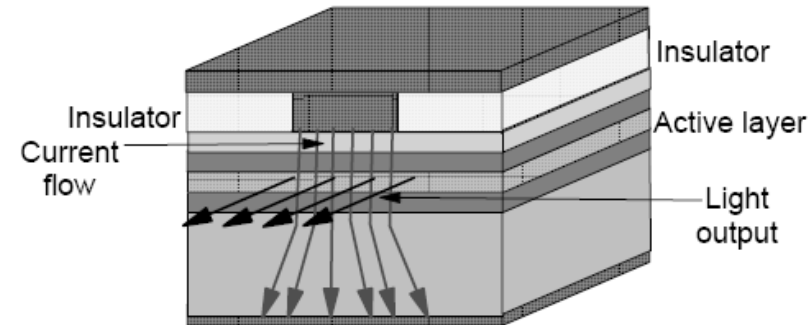


Dirrecționarea luminii în laser-ul Fabry Perot

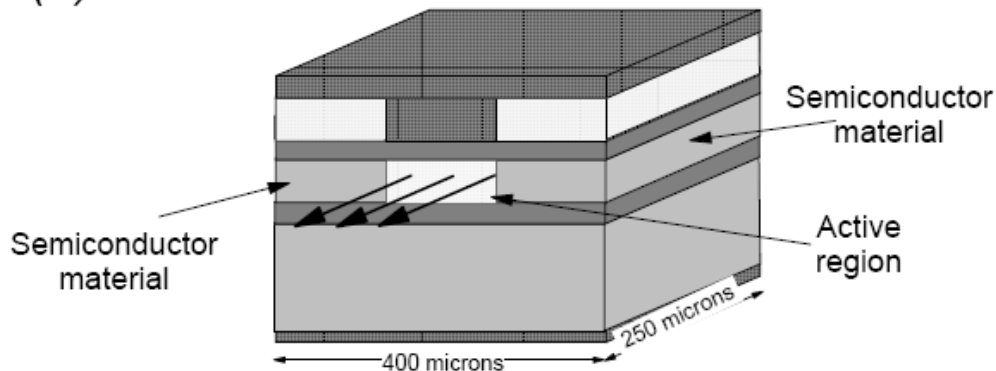
(a) Unguided



(b) Gain Guided

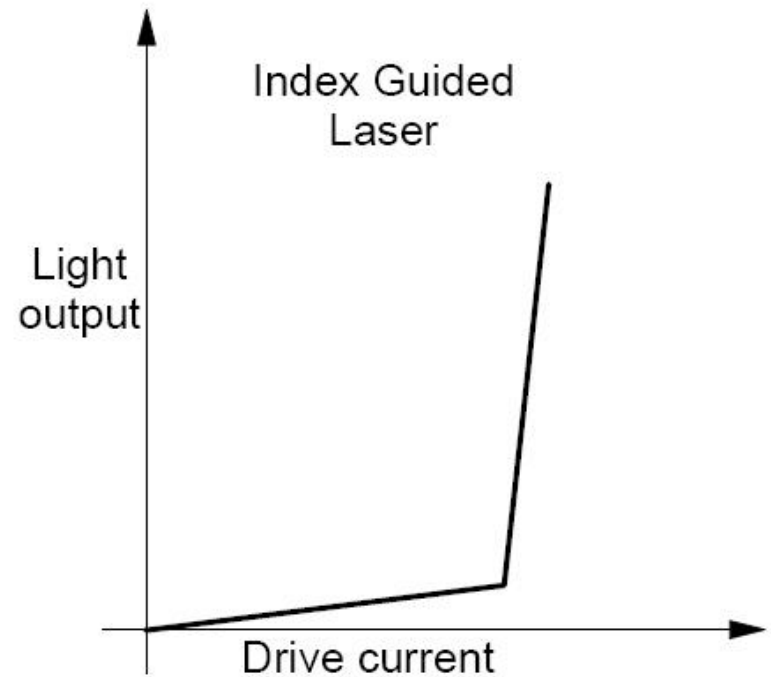
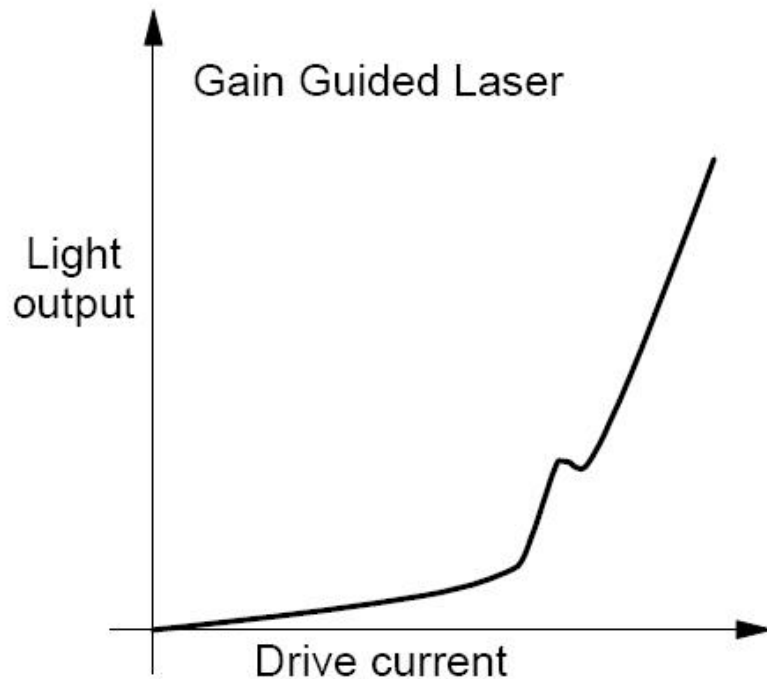


(c) Index Guided

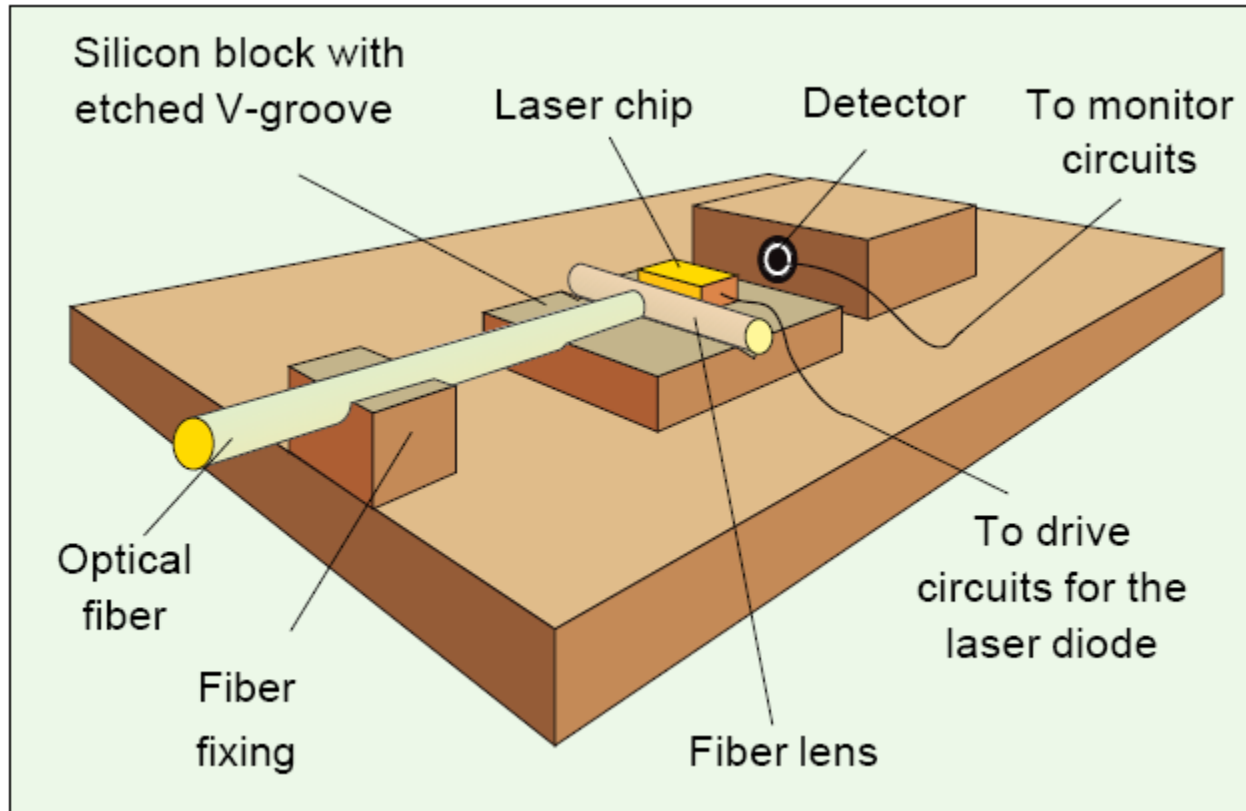


Efectul ghidarii

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

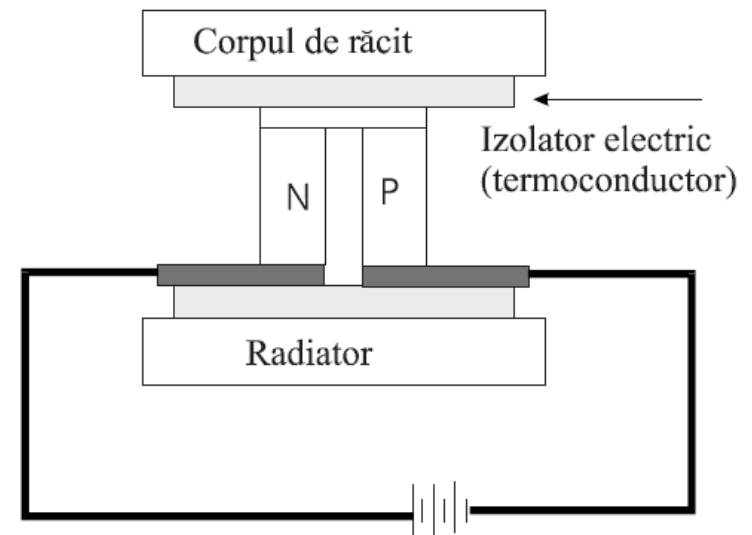


Cuplarea luminii în fibră



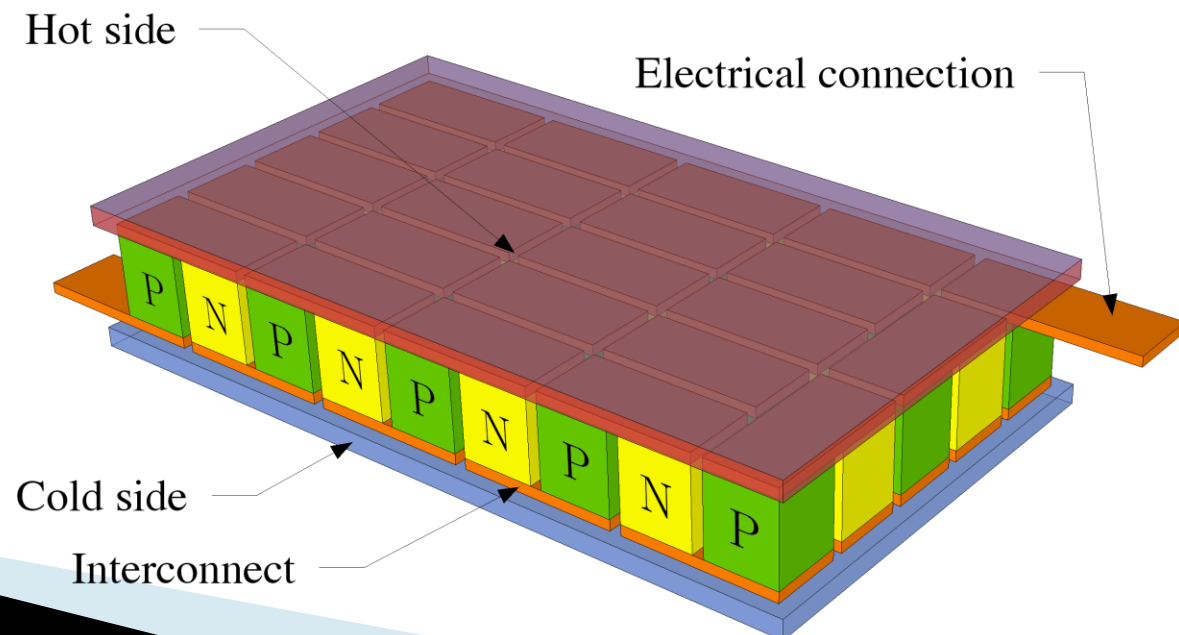
Dispozitiv termoelectric (Peltier)

- ▶ 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)

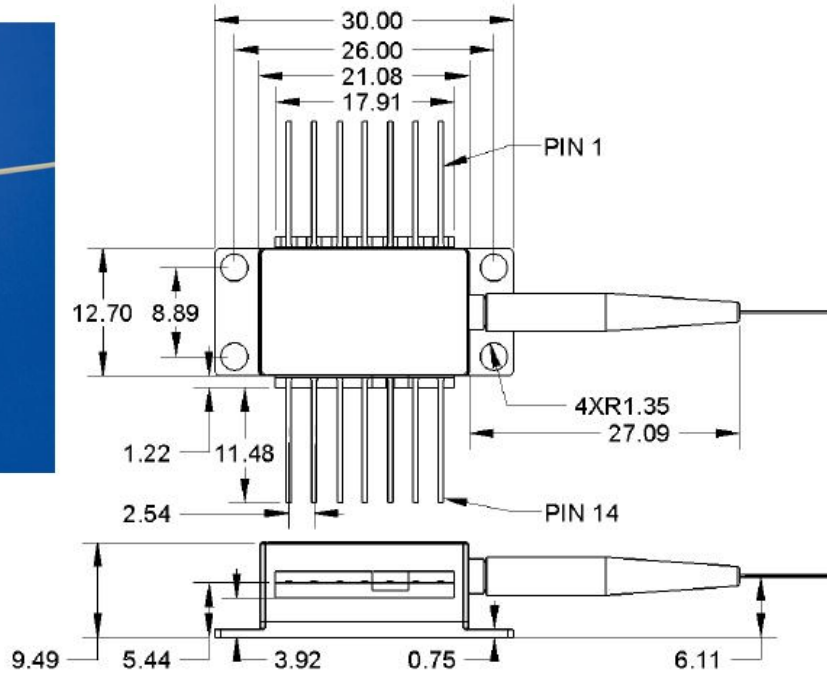
- ▶ Poate produce o diferenta maxima de temperatura de 70°C
- ▶ Lucreaza la nivele mici de caldura disipata
- ▶ Devine cu atat mai ineficient cu cat fluxul termic disipat e mai mare
- ▶ De 4 ori mai putin eficiente decat sistemele cu compresie de vapori



1550nm DFB Laser

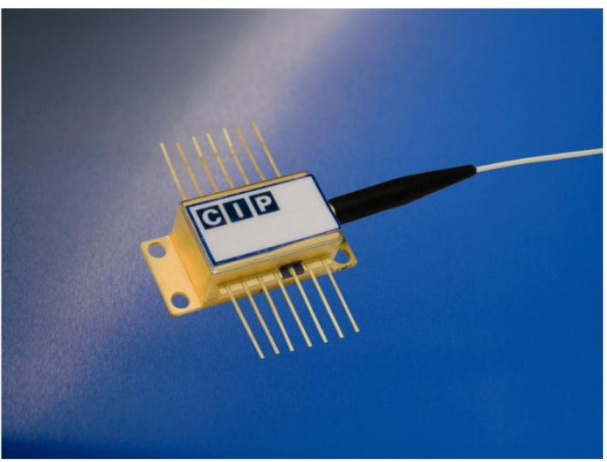
Mechanical Drawing

All units in mm

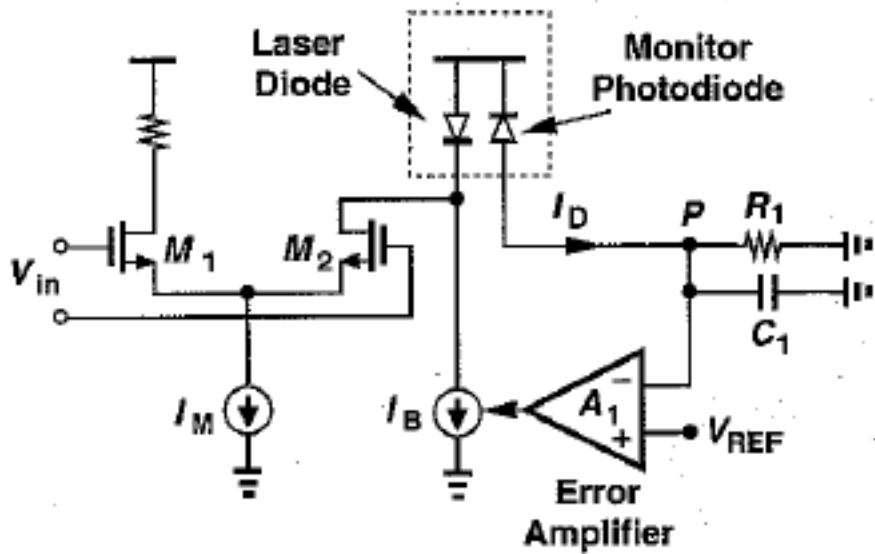


Pin out

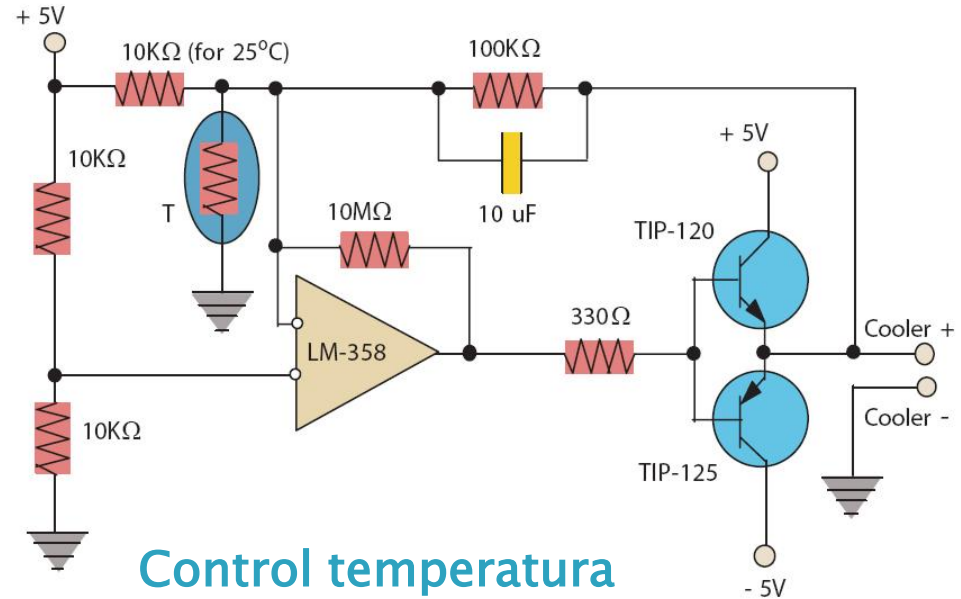
| Pin | Description |
|-----|----------------------------|
| 1 | Thermistor |
| 2 | Thermistor |
| 3 | Laser Cathode (Bias) |
| 4 | Monitor PD Anode |
| 5 | Monitor PD Cathode |
| 6 | TEC + |
| 7 | TEC - |
| 8 | Case GND, Laser Anode |
| 9 | Case GND, Laser Anode |
| 10 | Case GND, Laser Anode |
| 11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

Directivitatea radiatiei exterioare

- ▶ Sursa Lambertiana

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

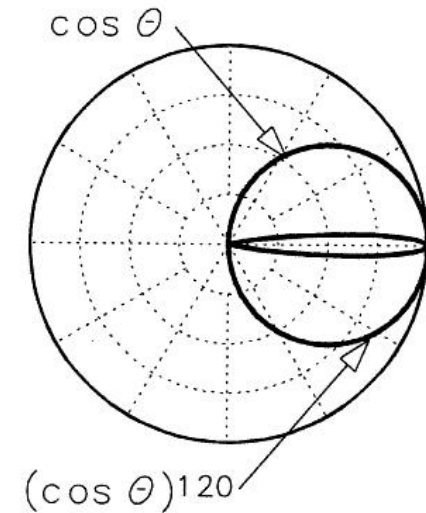
- Eficienta cuplarii in fibra

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

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

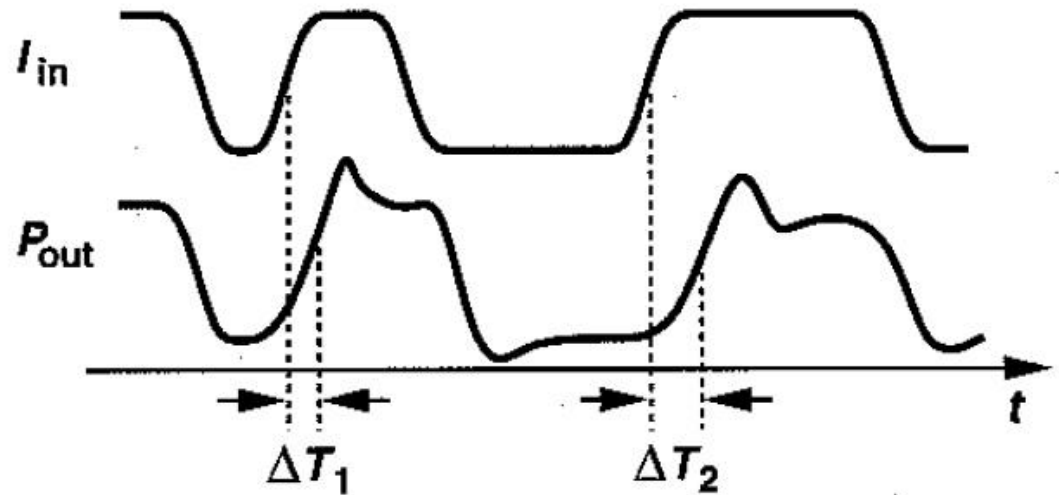
- ▶ Aproximatie Lambertiana pentru surse cu directivitate crescuta

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



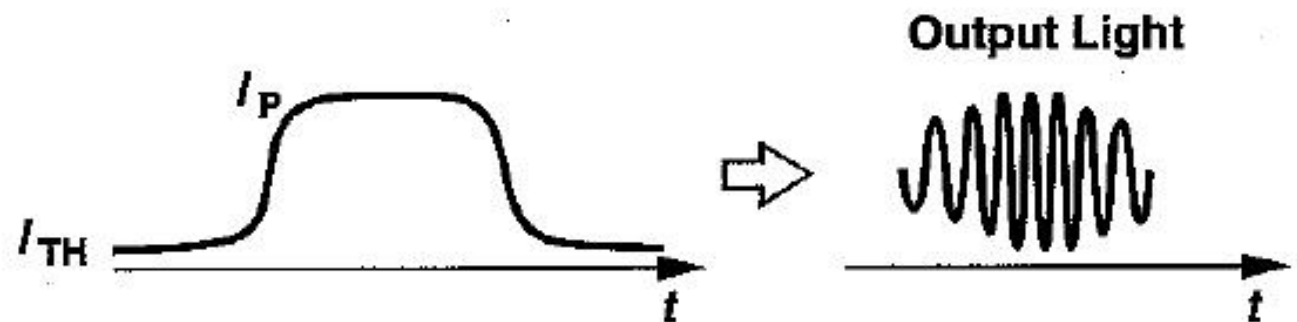
Turn-on delay

- ▶ 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



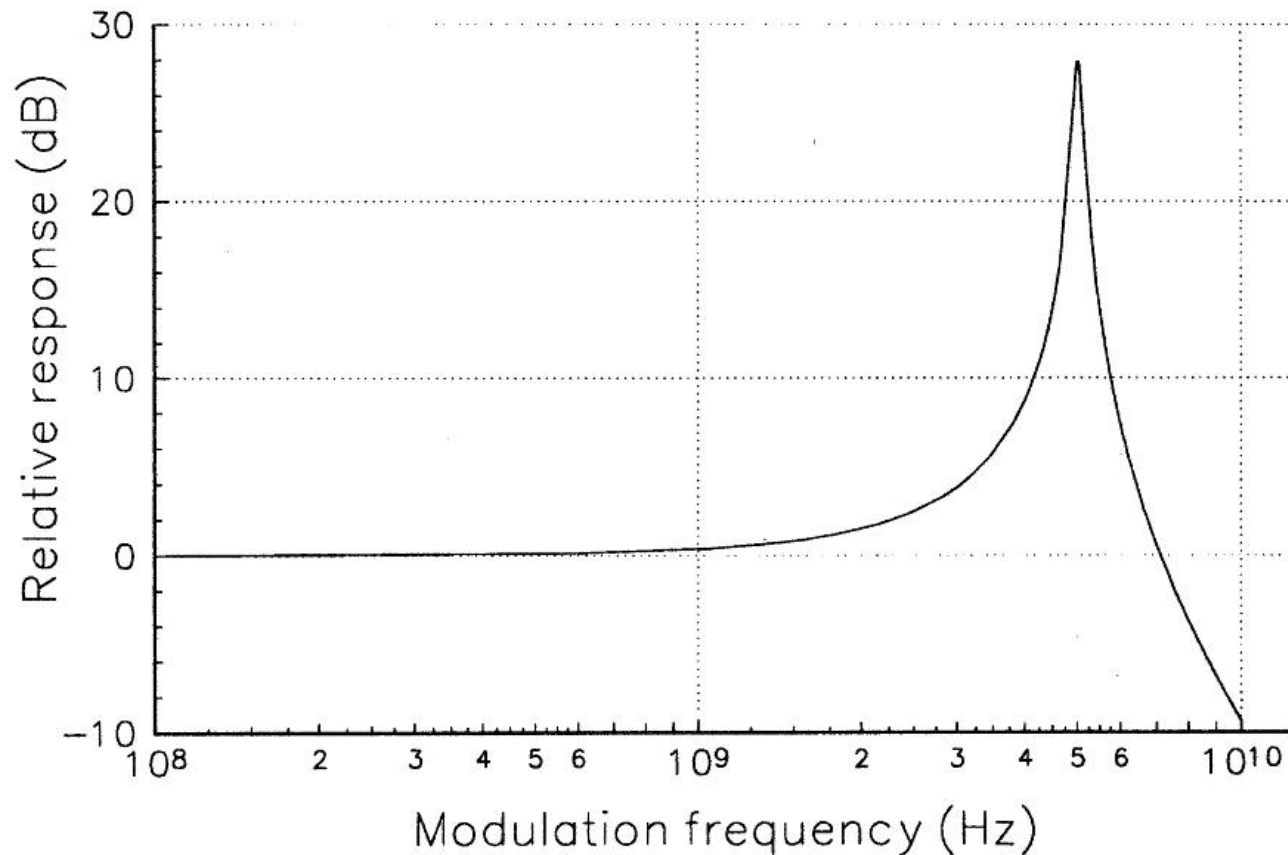
Chirping

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



Raspunsul unei diode laser

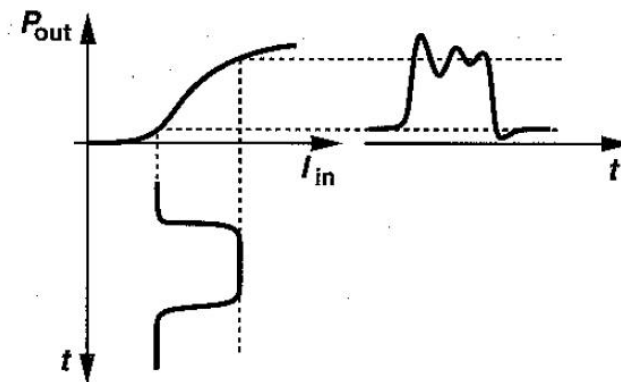
- ▶ oscilatii de relaxare - x GHz



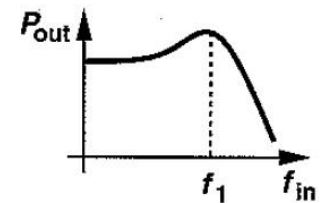
Oscilatii de relaxare

- ▶ Generate de schimburi de energie între electroni și fotoni
- ▶ Amorsarea emisie stimulate duce la descreșterea numărului de electroni în starea excitată, ceea ce duce la micșorarea emisie de fotoni
- ▶ Acumularea din nou a electronilor în starea excitată duce din nou la creșterea puterii

▶ $f_1 = 1 \div 4 \text{ GHz}$



(a)



(b)

Oscilatii de relaxare

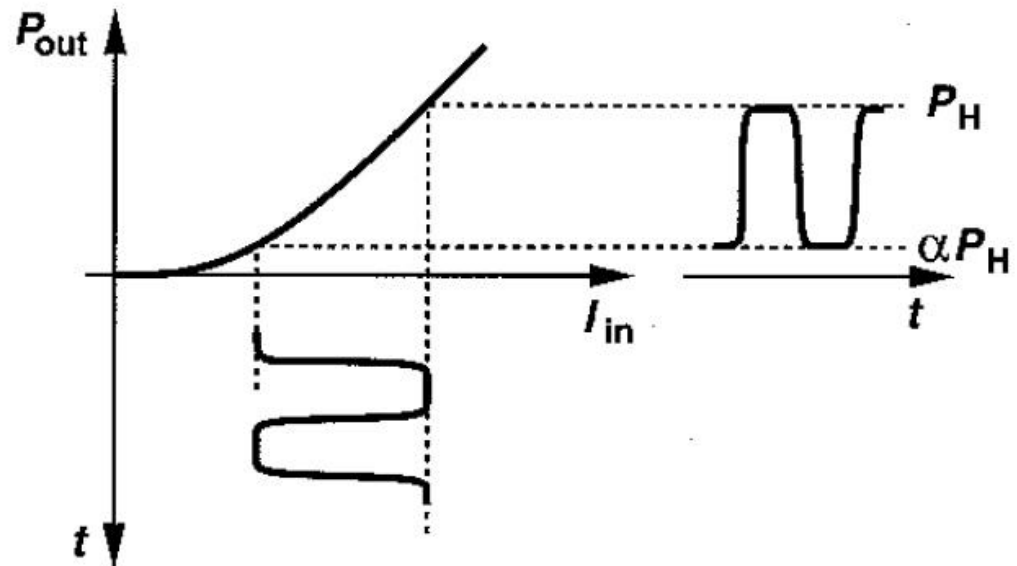
- ▶ Cresterea vitezei si minimizarea erorilor date de oscilatiile de relaxare si variatiile timpului de amorsare dioda este **partial** stinsa in timpul transmisiei unui nivel 0 logic

- ▶ Raport de stingere

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

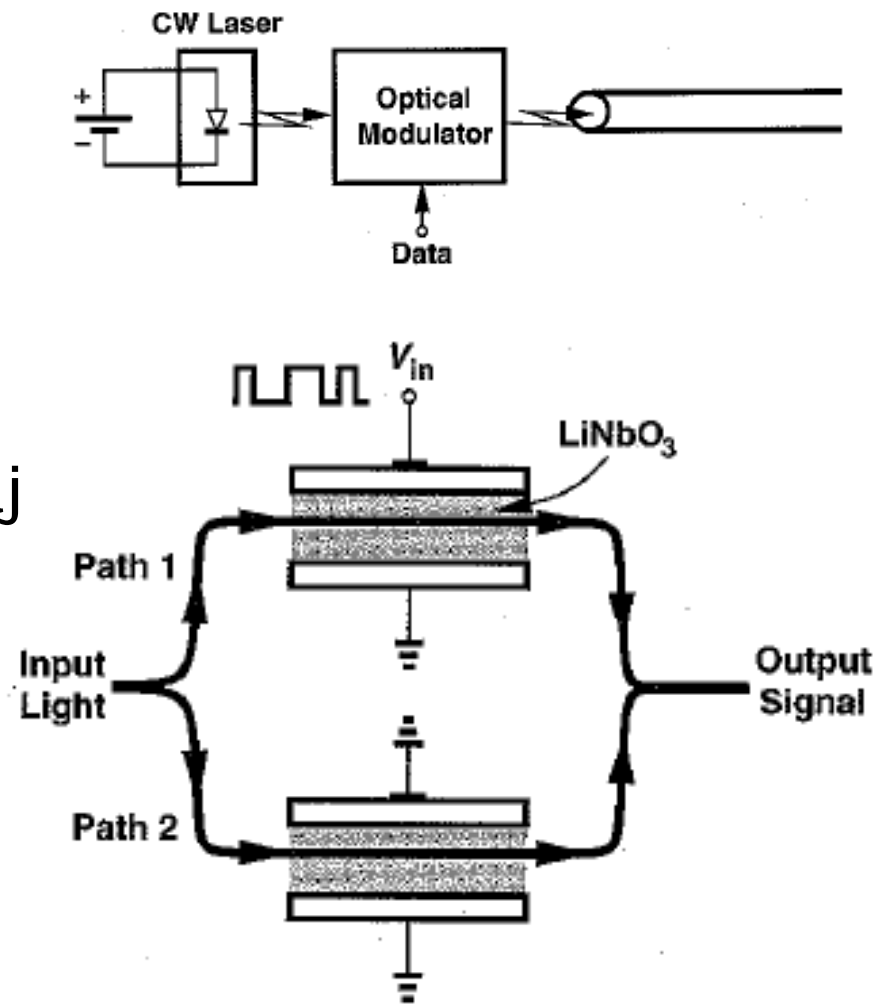
- ▶ Raportul semnal zgomot scade cu $(1-\alpha)$

- ▶ Tipic $ER = 10 \div 15 \text{dB}$



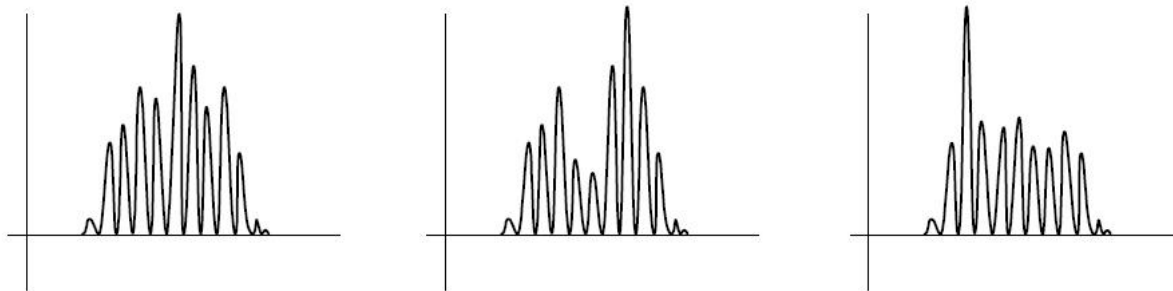
Modulație optică

- ▶ Pentru viteze mari se prefera utilizarea emisiei continue și modularea optică a radiației
- ▶ În LiNbO_3 viteza luminii depinde de câmpul electric, ceea ce permite introducerea unui defazaj egal π
- ▶ Crește complexitatea circuitului de control
- ▶ Tensiuni de 4÷6 V necesare



Alte caracteristici DL

- ▶ Mode hopping – salt de mod (hole burning)

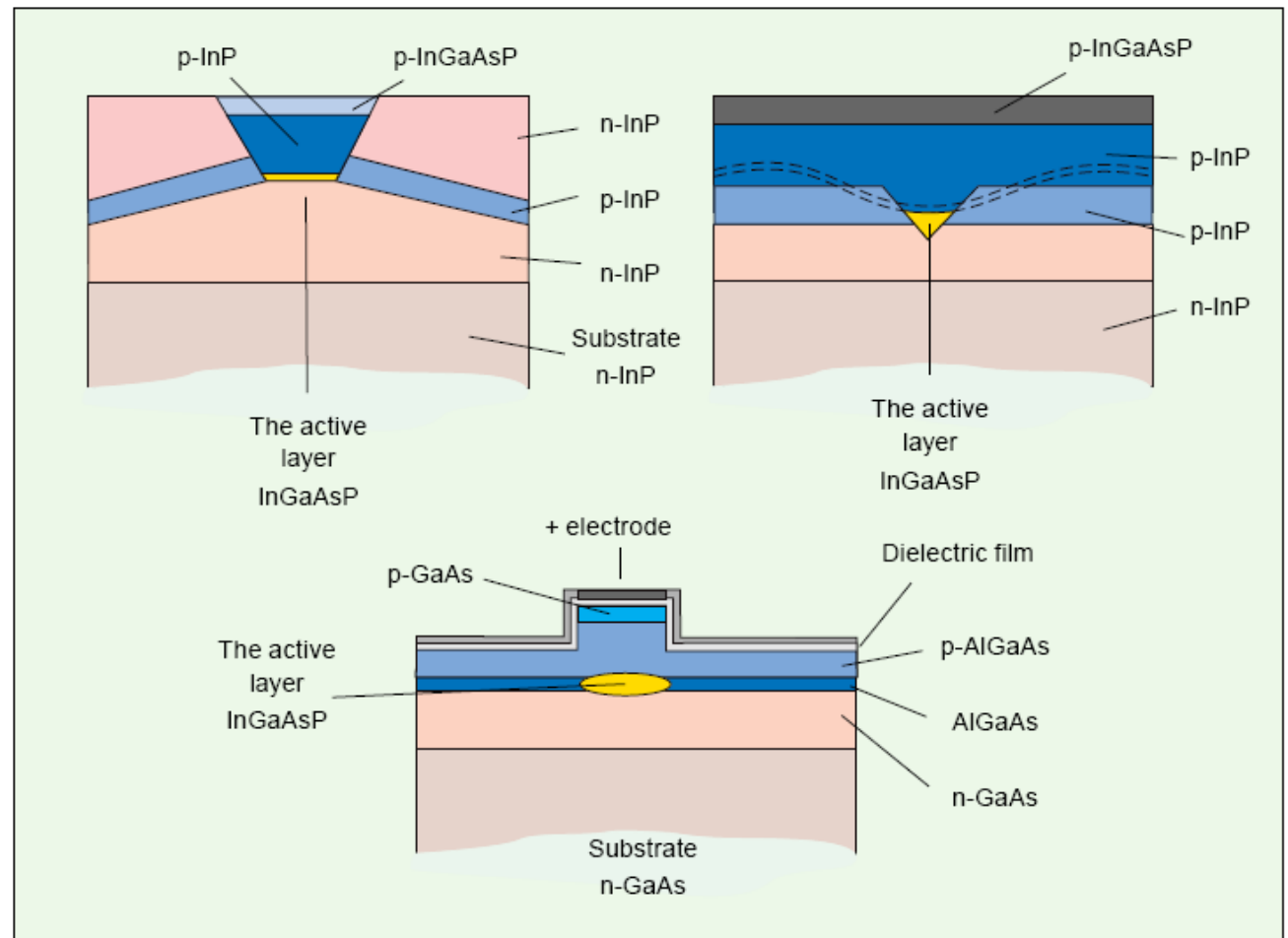


- ▶ RIN – Relative Intensity Noise (generat de emisia spontana)
- ▶ Zgomot de faza (idem) – necesitatea modulatiei in amplitudine
- ▶ Zgomot intercavitati (reflexiile din exterior in zona activa)
- ▶ Drift – variatia parametrilor cu varsta si temperatura (in special distanta intre oglinzi)

Diode LASER cu heterojunctiune

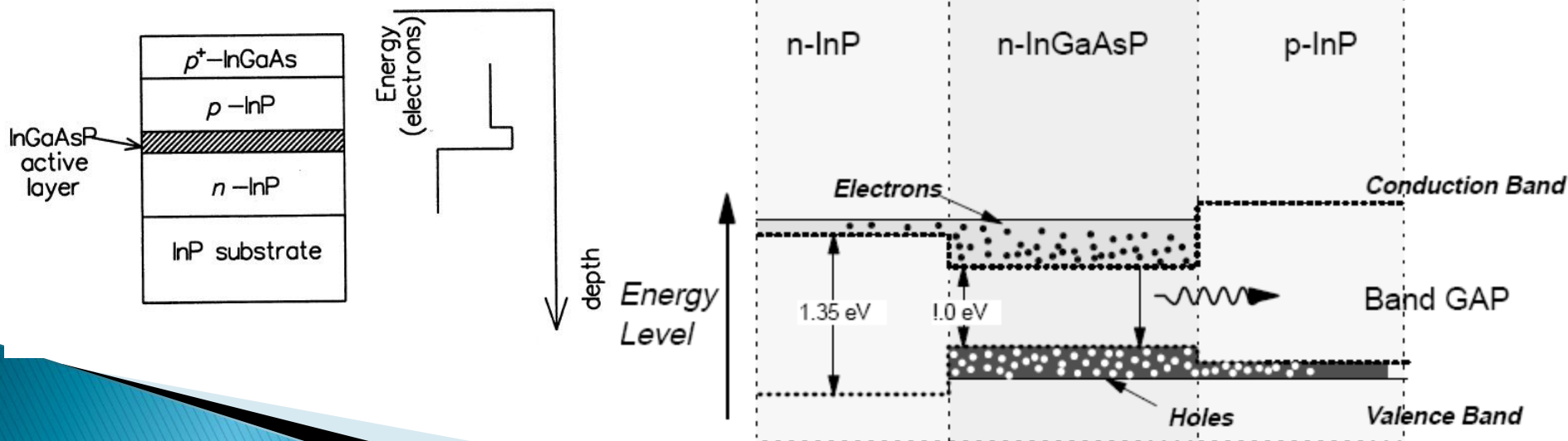
Heterojunctiune
ingropata

Heterojunctiune
muchie (ridge)



Heterojunții – principiu

- ▶ Concentrare verticală a purtătorilor
 - Electronii sunt atrași din zona n în zona activă
 - O barieră energetică existentă între zona activă și zona n concentrează electronii în zona activă
 - Situație similară corespunzătoare golurilor
 - Purtătorii sunt concentrați în zona activă, crescând eficiența

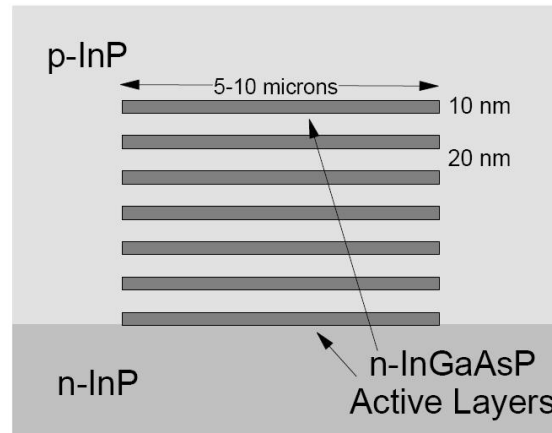


Quantum Well Laser

- ▶ 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

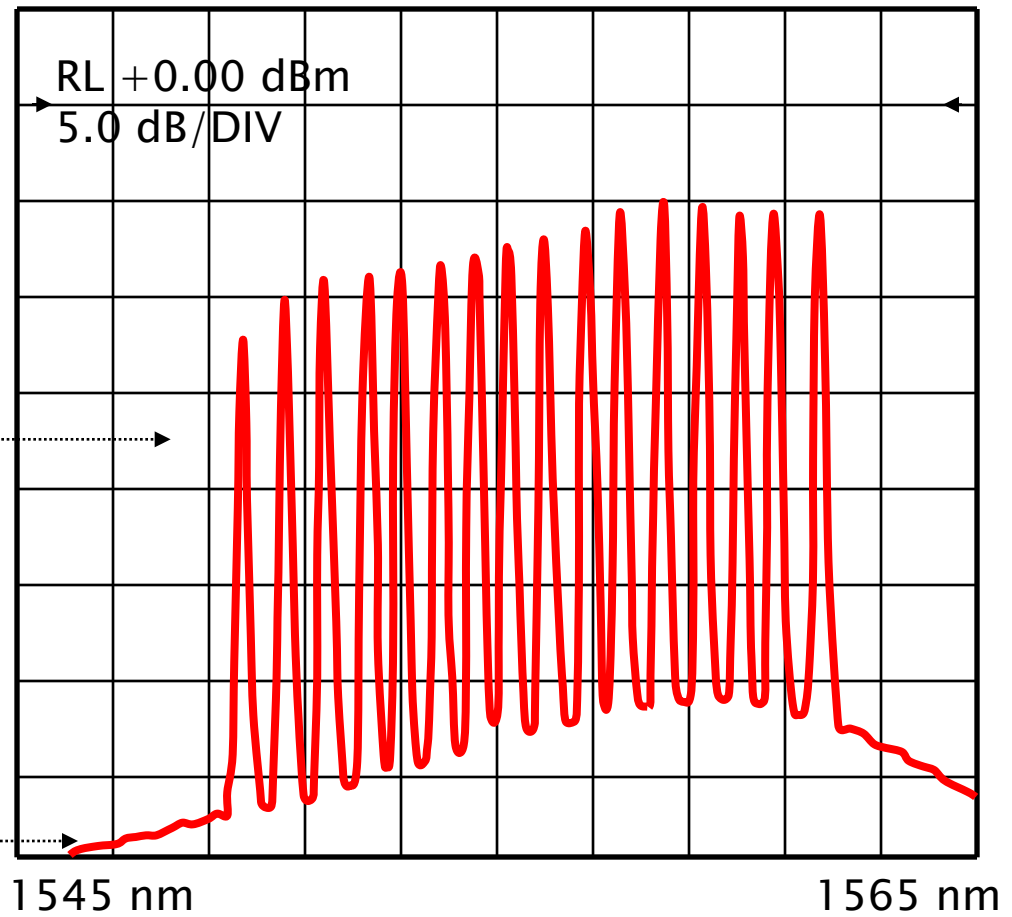
Quantum Well Laser

- ▶ 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
Spațiere: 0.8 nm

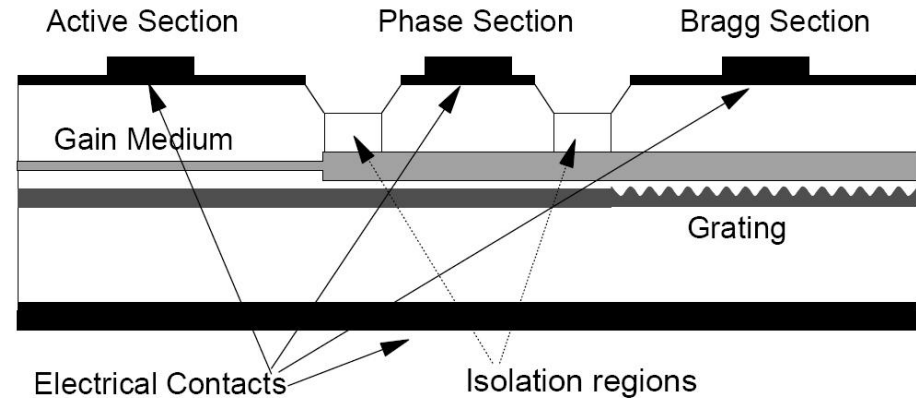
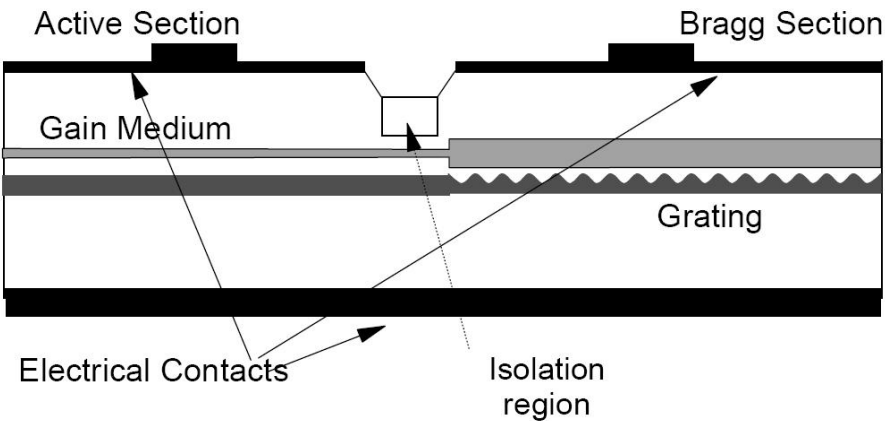
Emisie spontană
Amplificată (ASE)

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 anumit 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 μ s
- reglarea emitatorilor individuali in sistemele WDM
 - lipsa necesitatii controlului strict la productia diodelor
 - degradarea lungimii de unda in timp

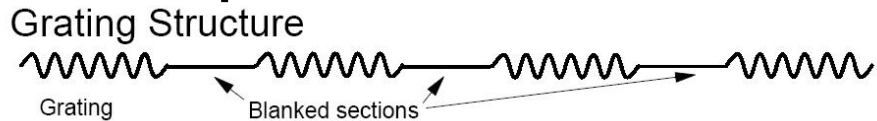
Diode laser reglabile



- ▶ 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

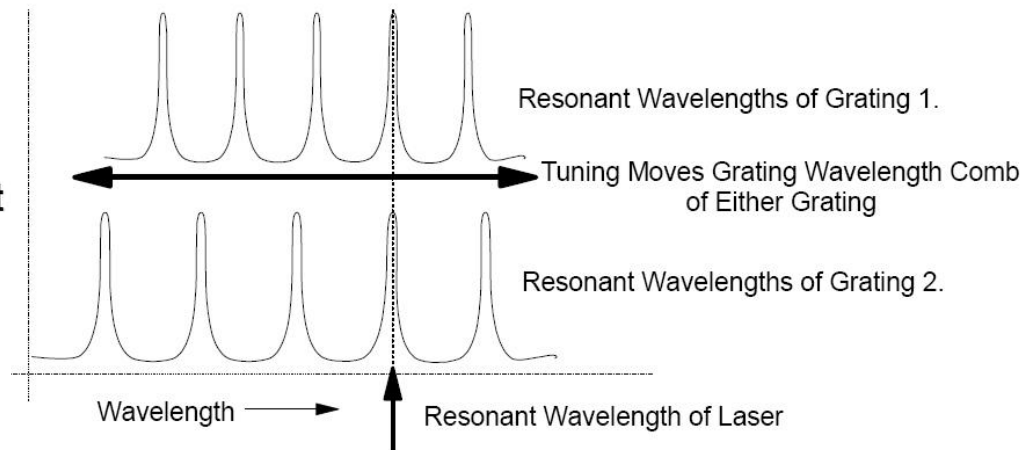
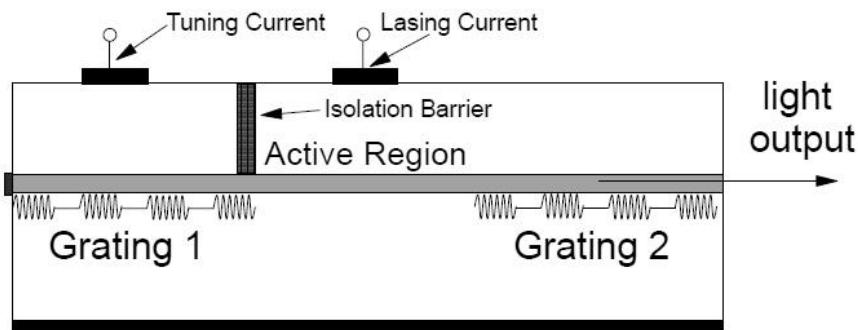
Diode laser reglabile

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

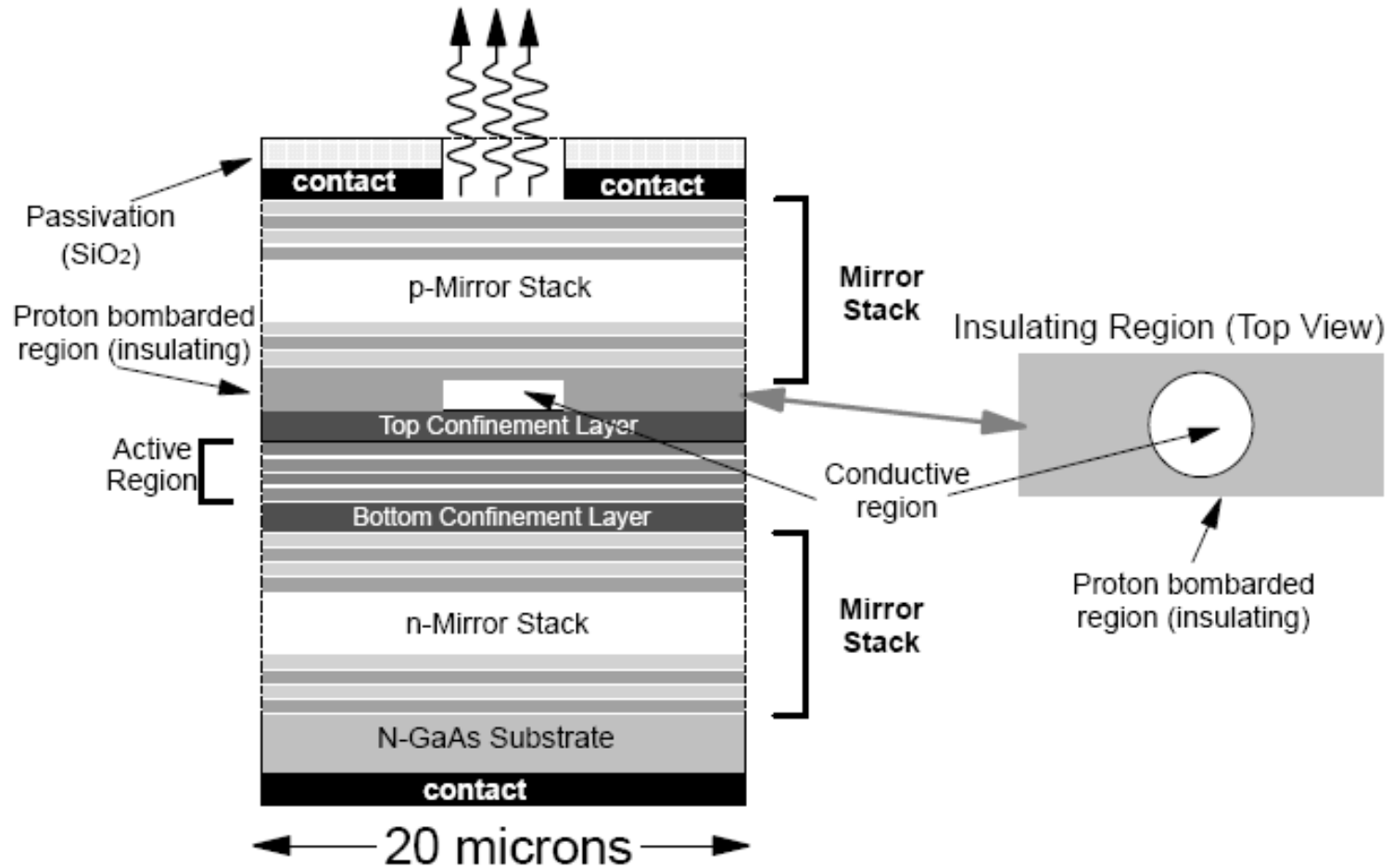


Dezavantaj :
reglajul e discret

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

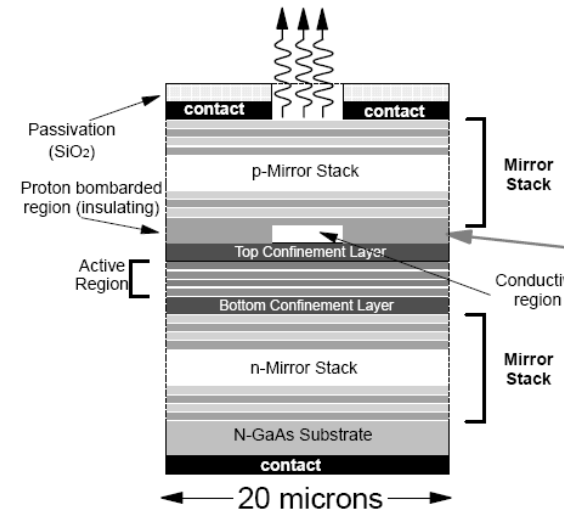


Vertical Cavity Surface Emitting Lasers (VCSEL)



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



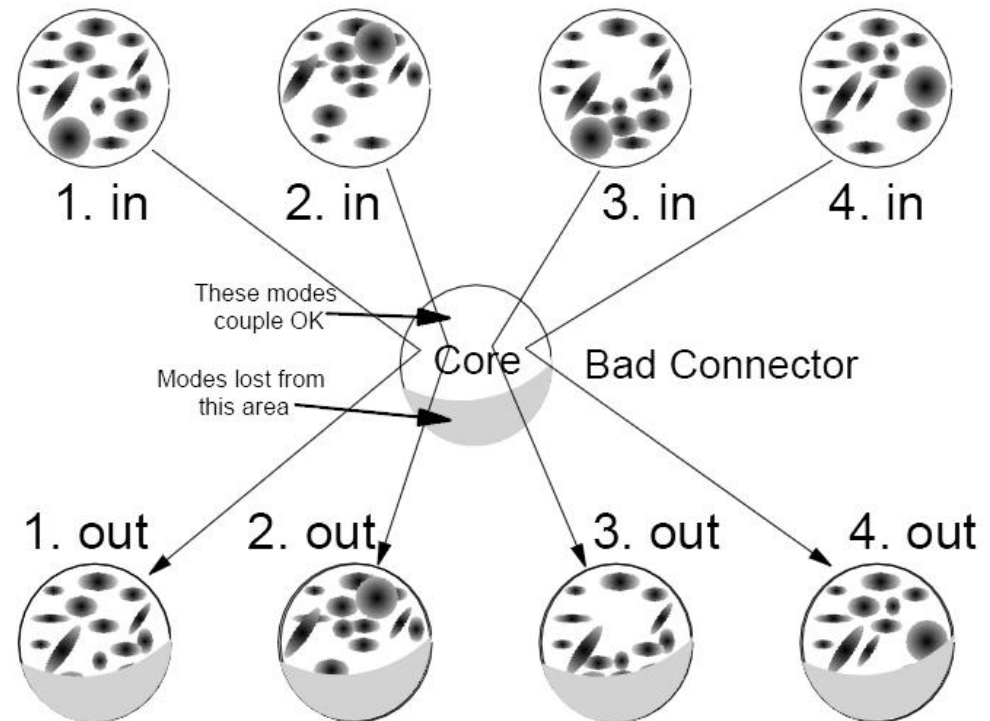
- ▶ Caracteristici

- ▶ 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

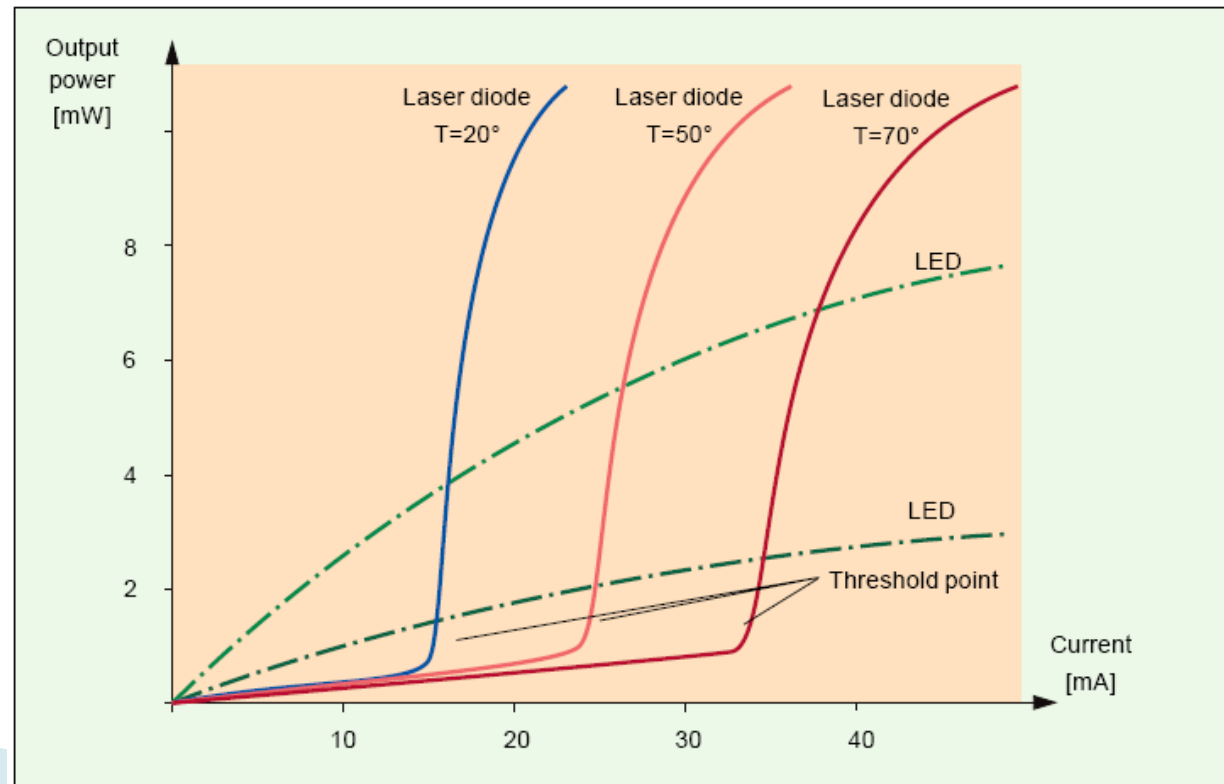
- VCSEL produce mai multe moduri transversale
 - insensibila la pierderile selective la mod din fibrele multimod (principala limitare in utilizarea diodelor laser in fibrele multimod)



Parametri dioda LASER

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 |

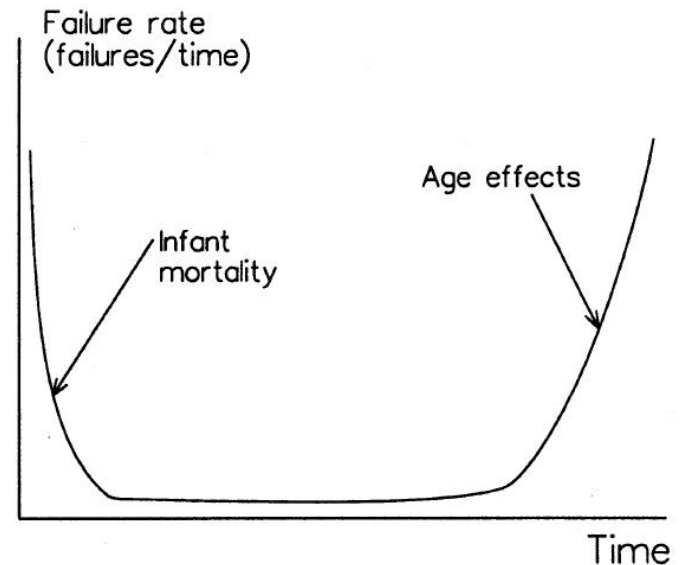
Degradare in timp

- ▶ Puterea scade in timp exponential

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

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

Degradare in timp



- ▶ Cresterea curentului duce la scaderea duratei de viata

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

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

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

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

Parametri

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

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

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

Eficienta

- ▶ eficienta de conversie electro-optic (randament)

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

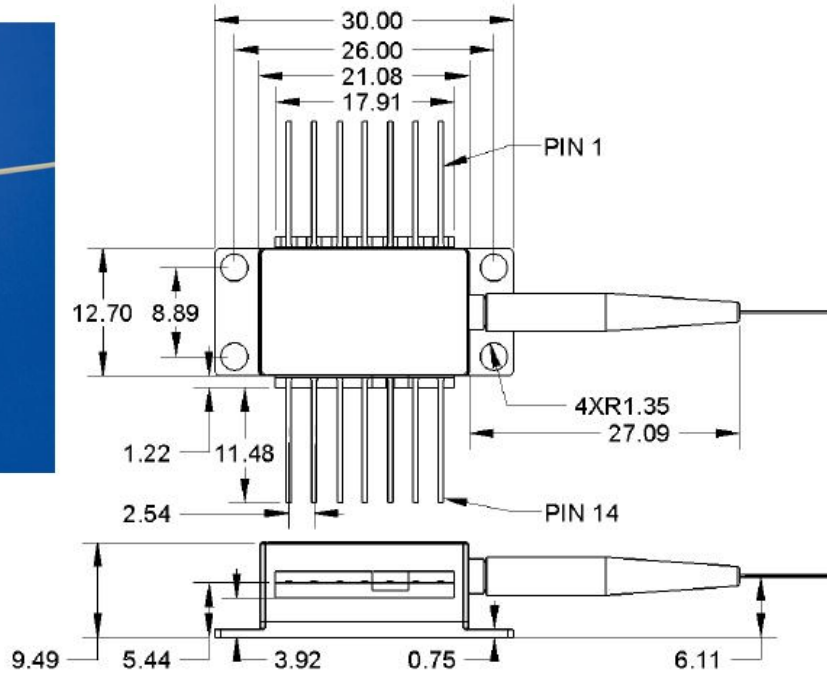
- ▶ tipic, randamente sub 10% sunt intalnite
- ▶ eficienta cuantica
 - interna
 - externa

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

1550nm DFB Laser

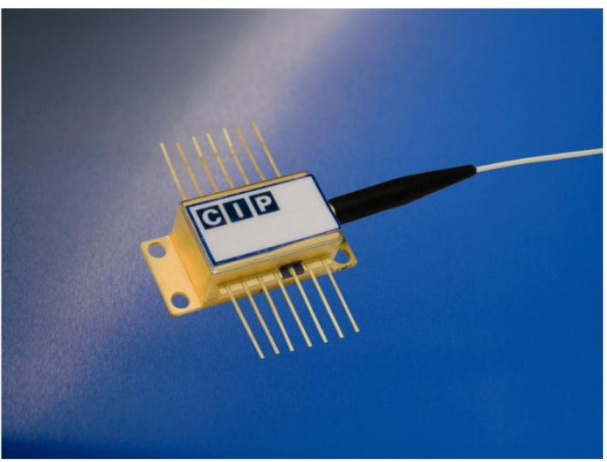
Mechanical Drawing

All units in mm

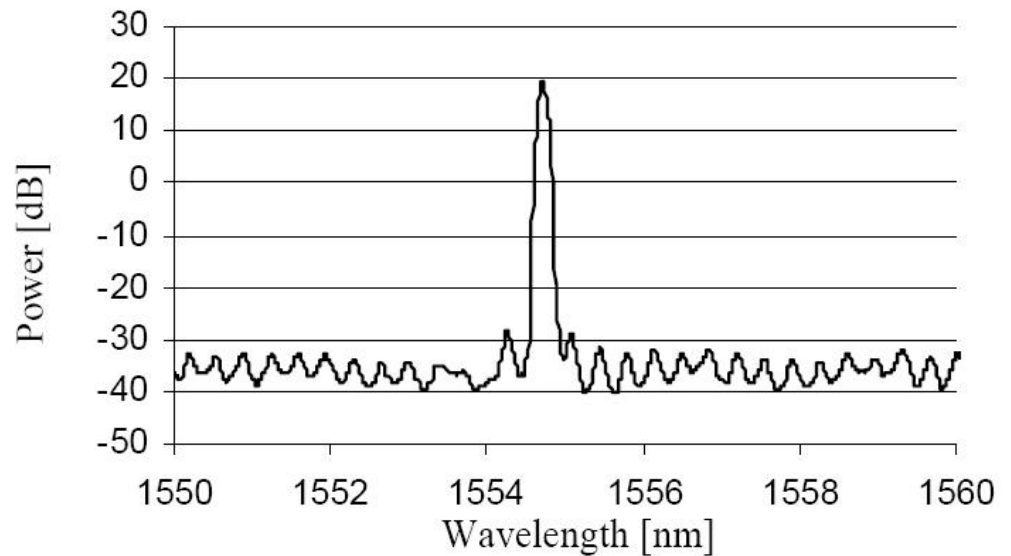
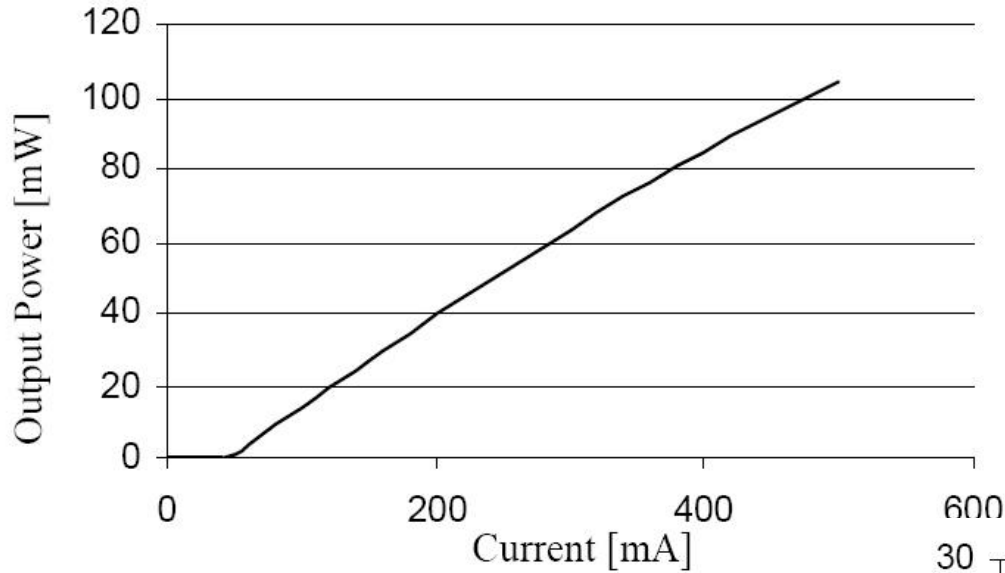


Pin out

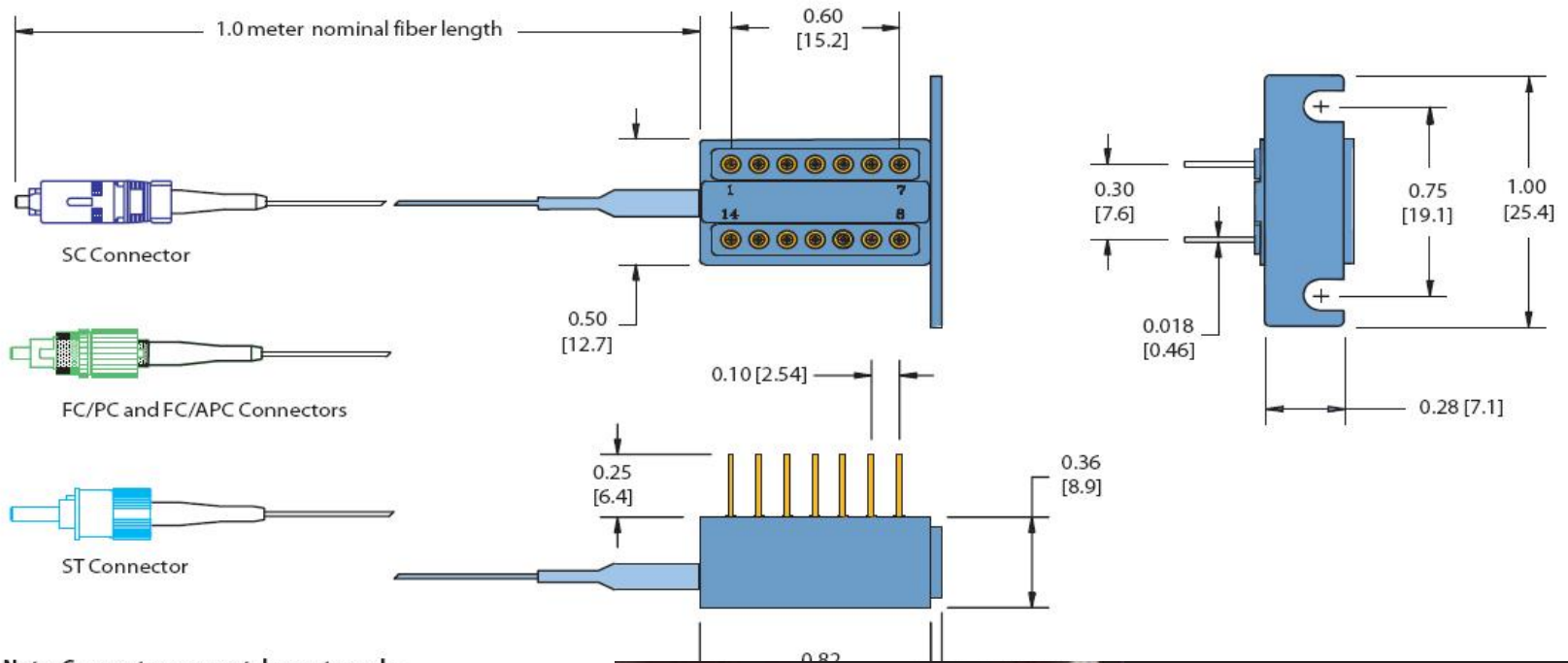
| Pin | Description |
|-----|----------------------------|
| 1 | Thermistor |
| 2 | Thermistor |
| 3 | Laser Cathode (Bias) |
| 4 | Monitor PD Anode |
| 5 | Monitor PD Cathode |
| 6 | TEC + |
| 7 | TEC - |
| 8 | Case GND, Laser Anode |
| 9 | Case GND, Laser Anode |
| 10 | Case GND, Laser Anode |
| 11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



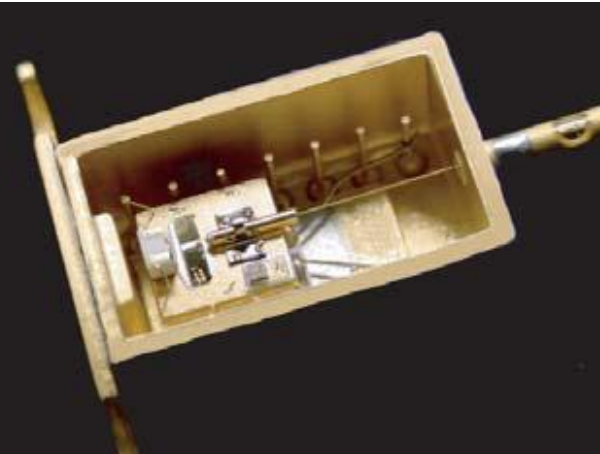
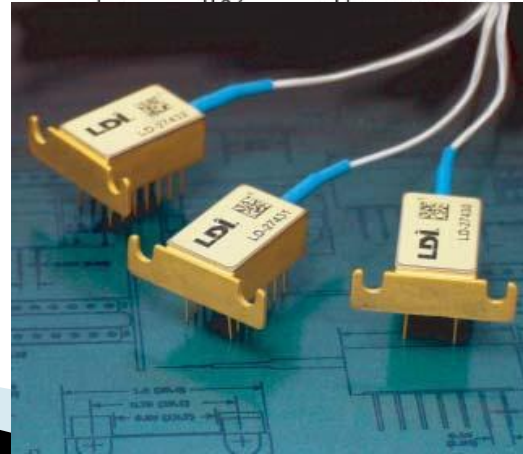
1550nm DFB Laser



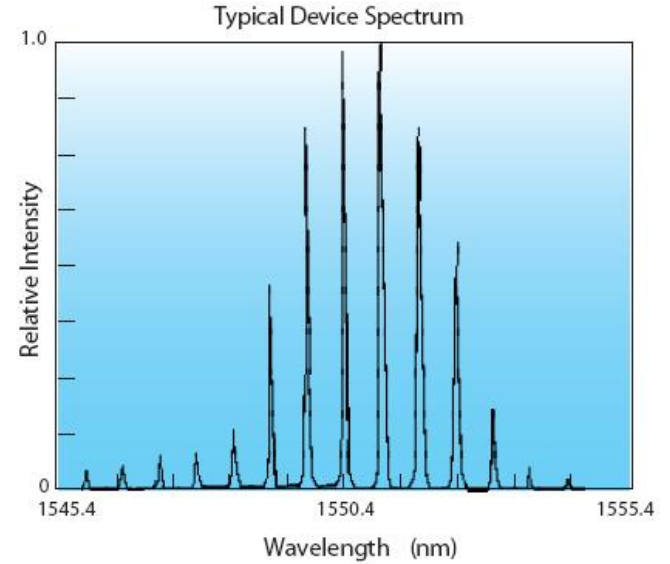
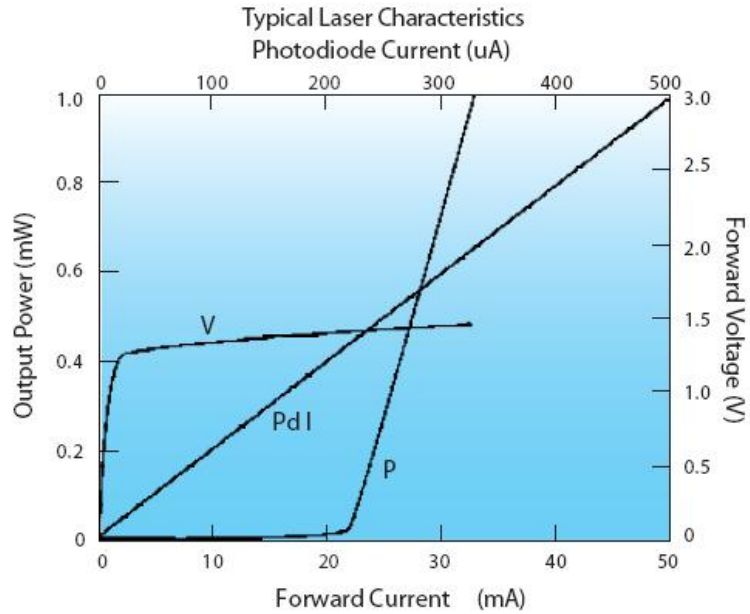
1550nm MQW Laser



Note: Connectors are not drawn to scale.

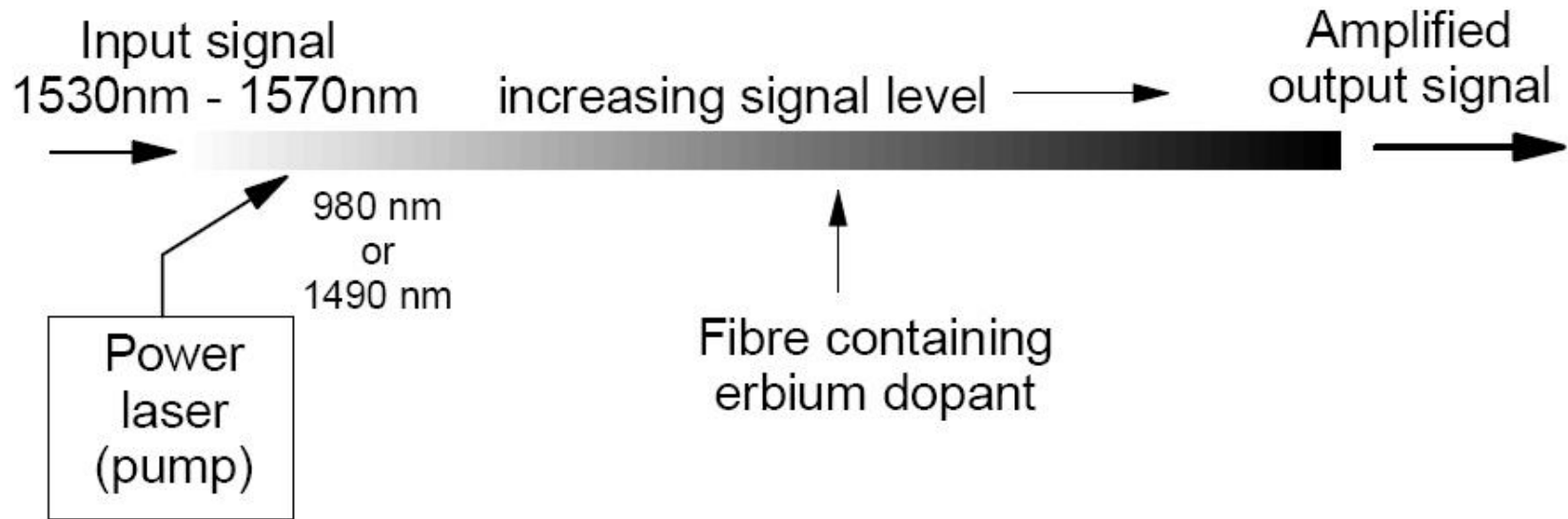


1550nm MQW Laser

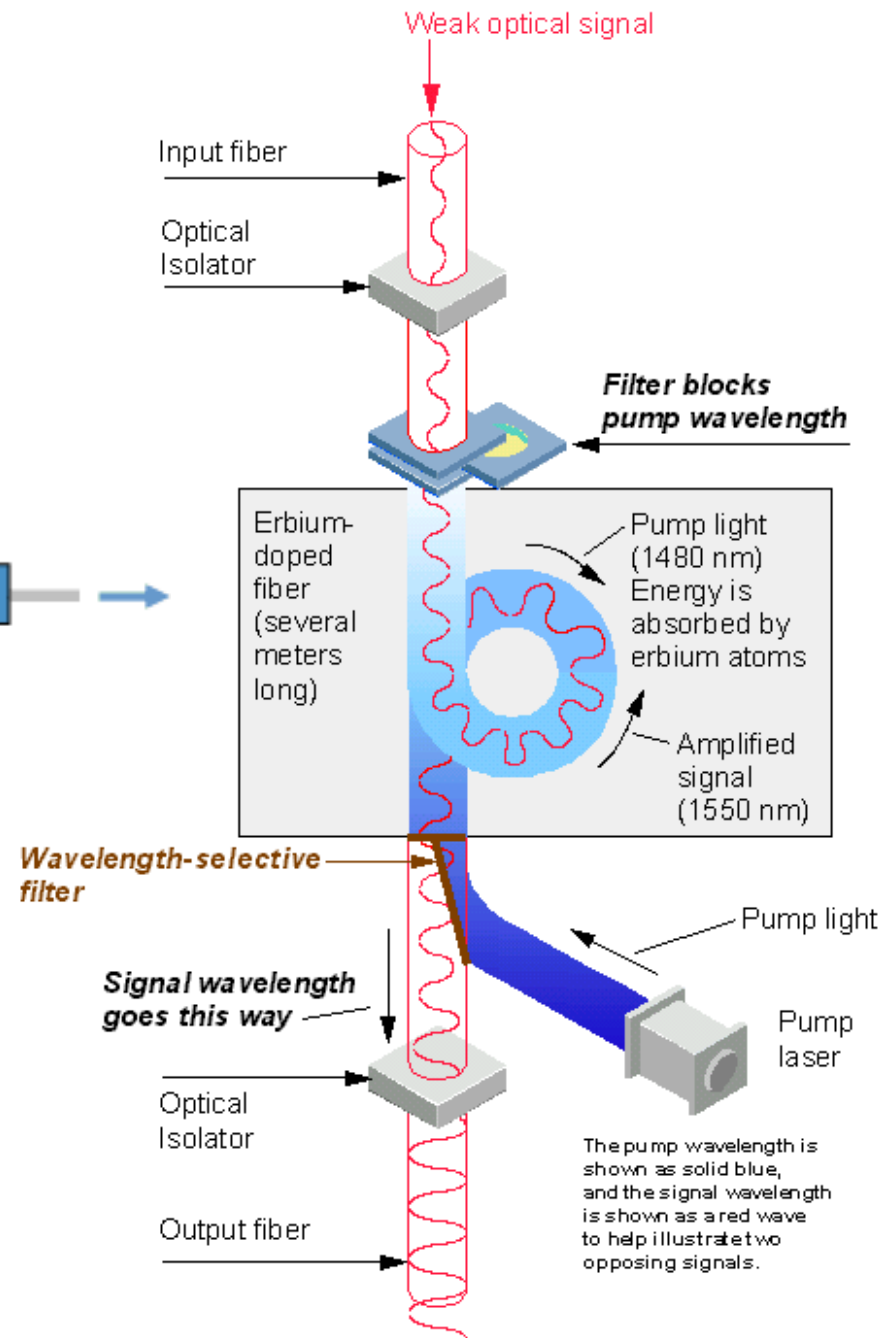
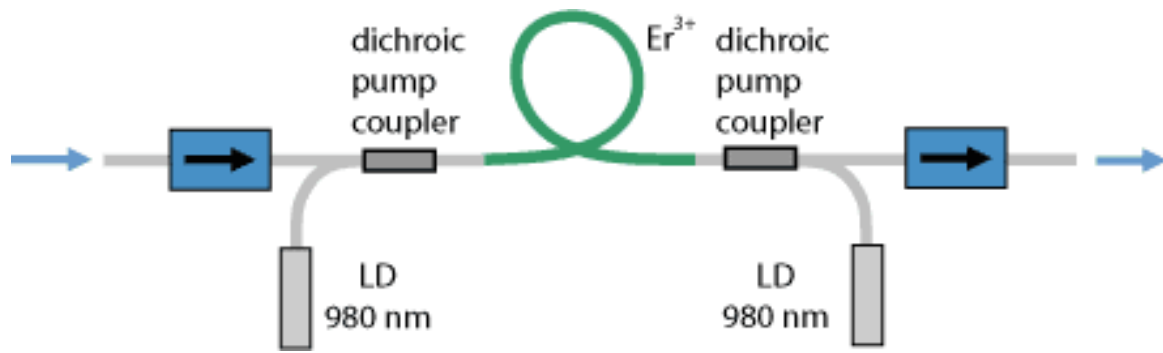


EDFA

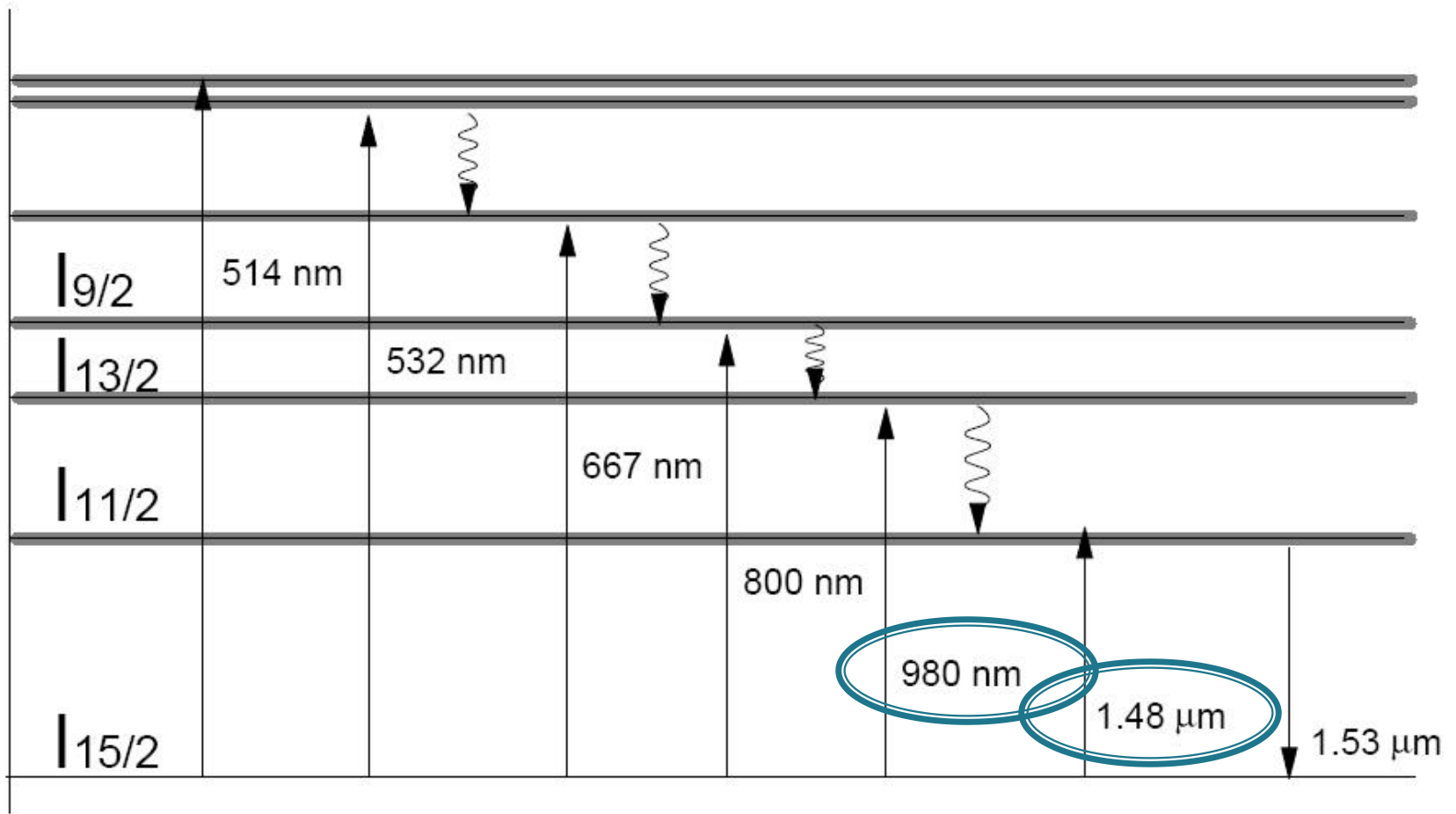
▶ Erbium Doped Fiber Amplifier



EDFA

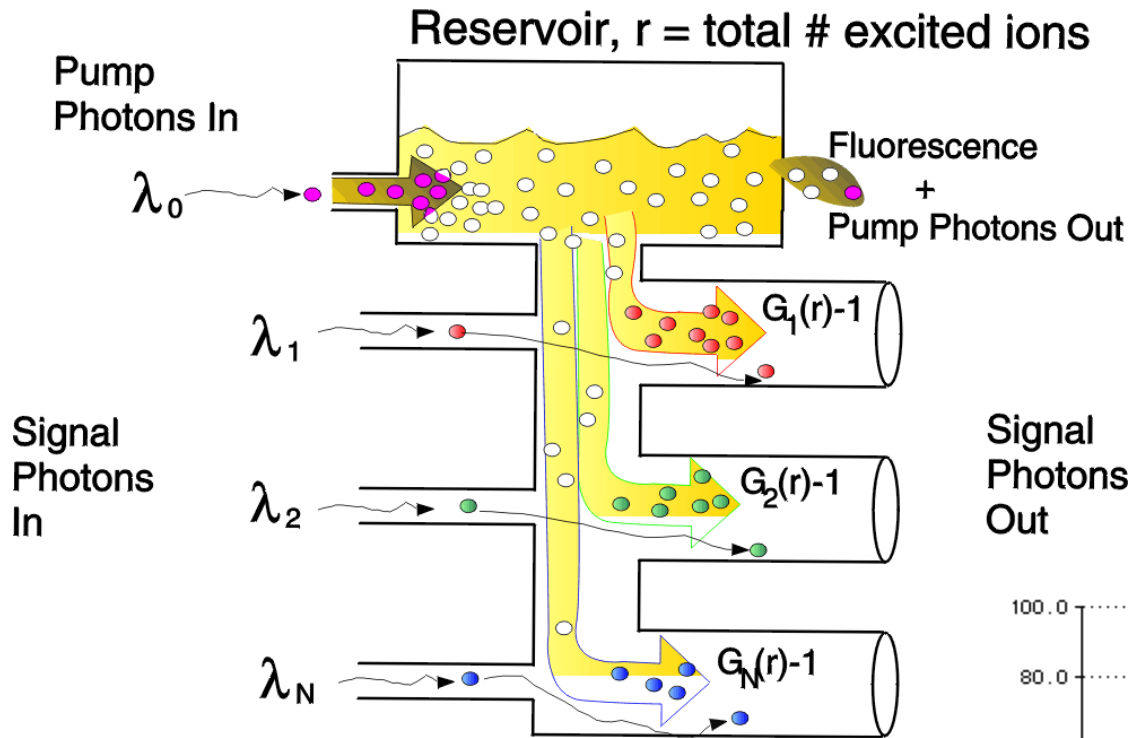


EDFA

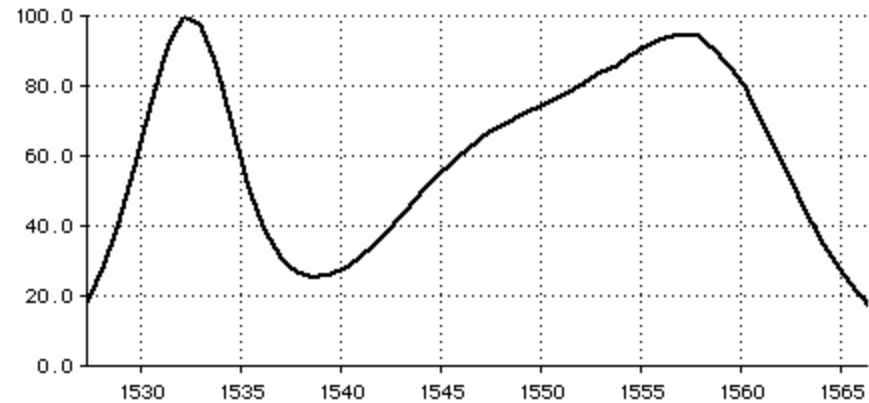


EDFA

How to think of an EDFA

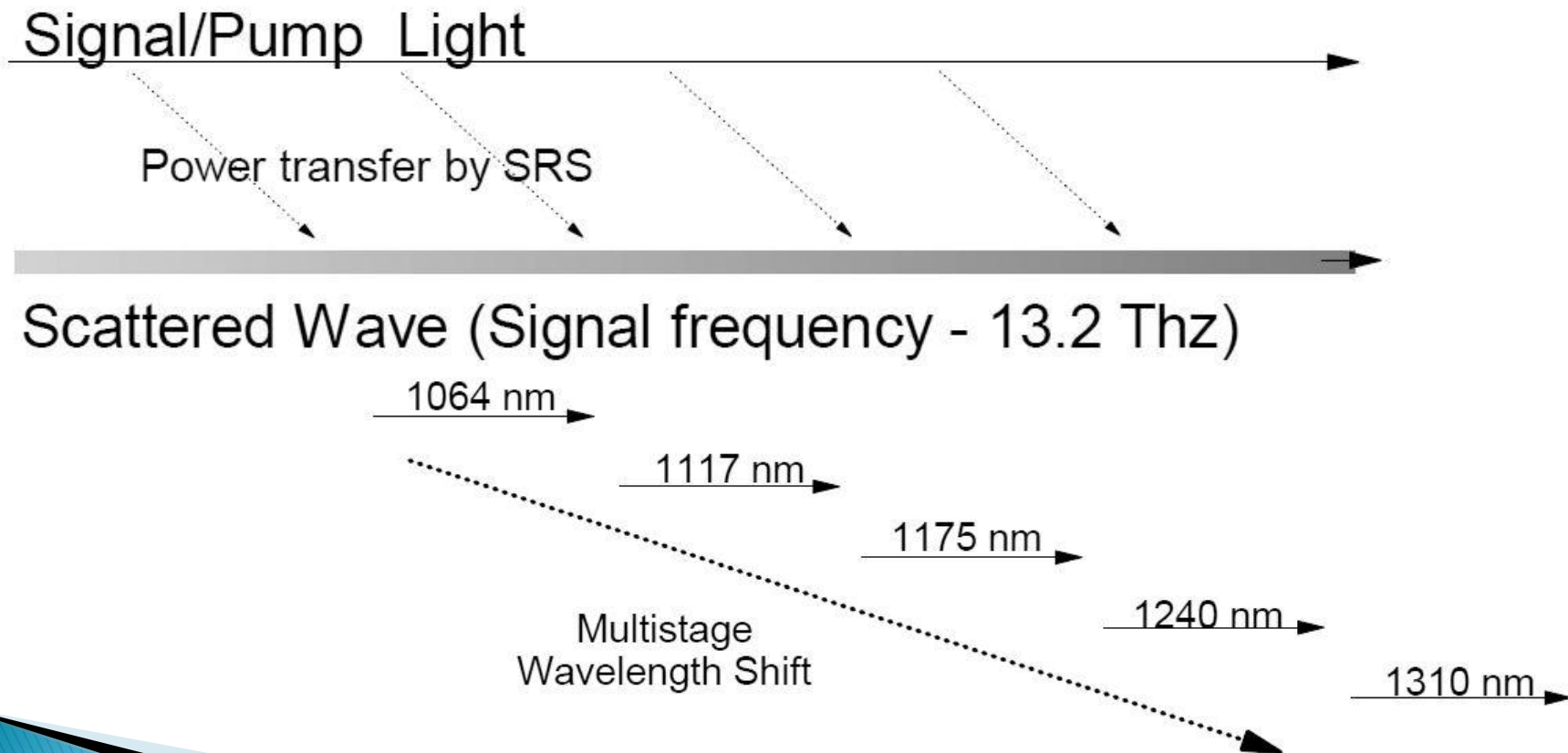


Signal Photons Out

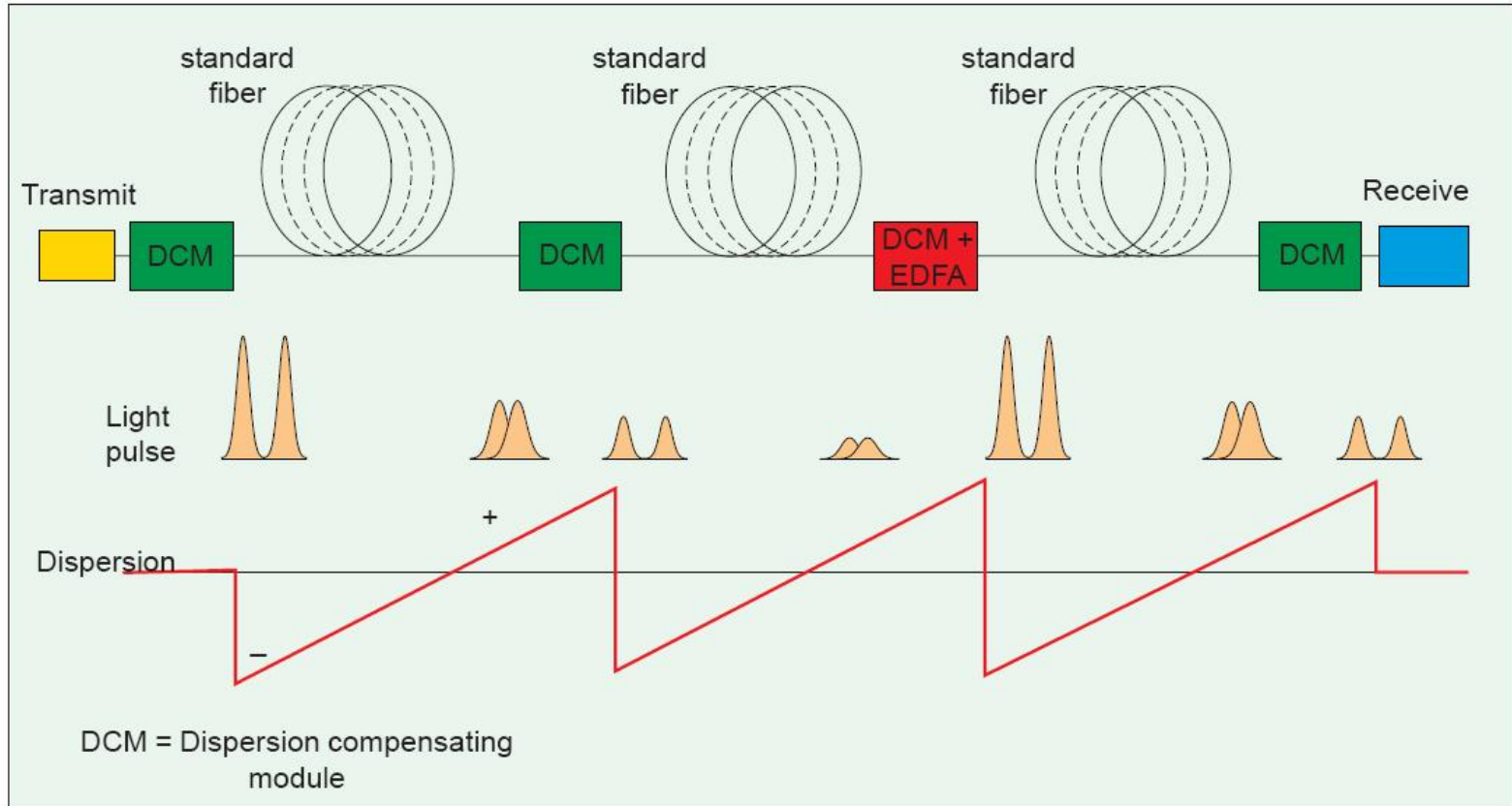


Amplificator cu efect Raman

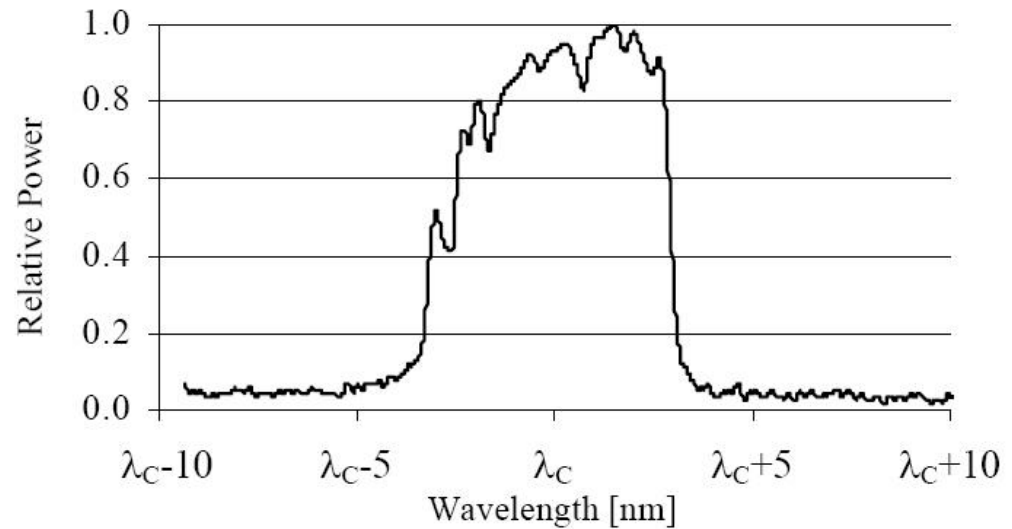
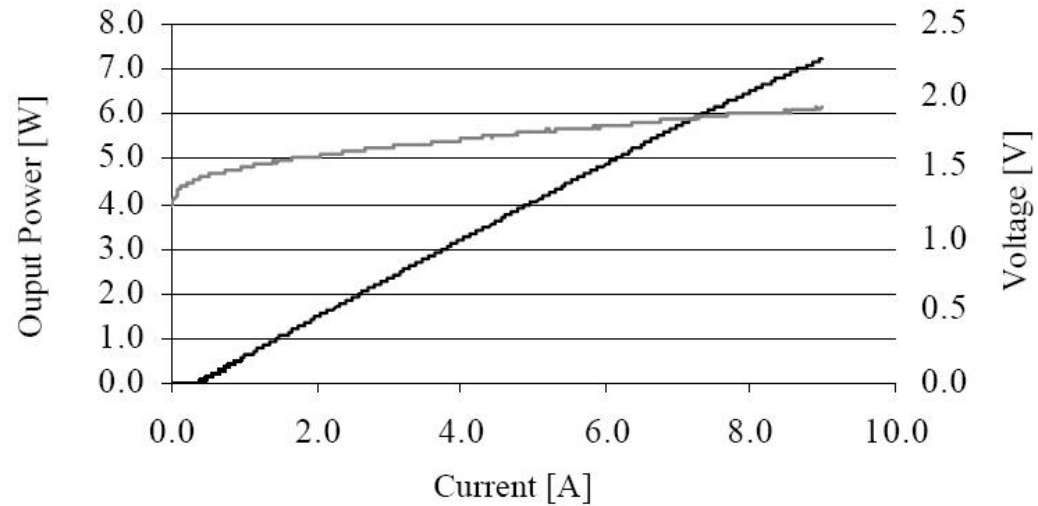
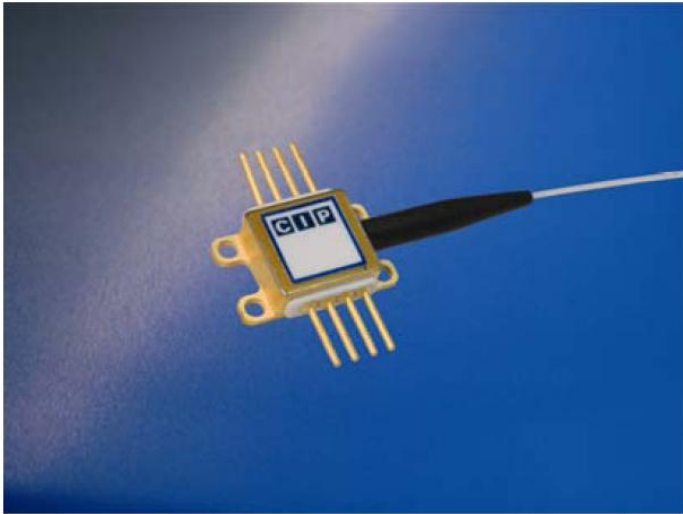
- ▶ Bazat pe efect Raman



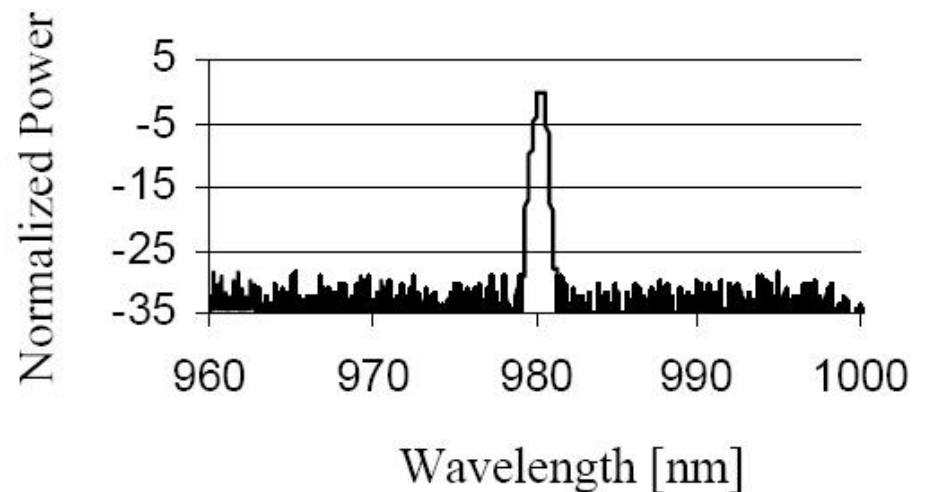
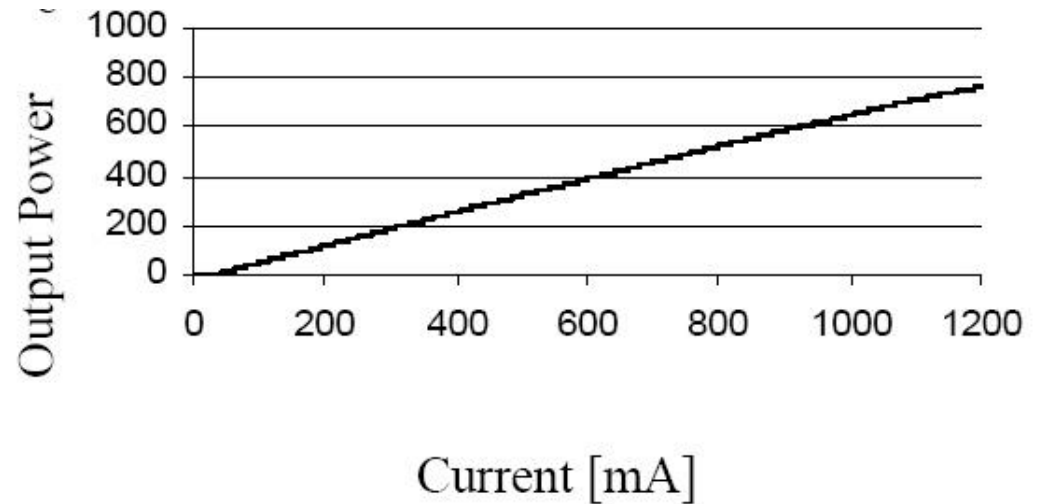
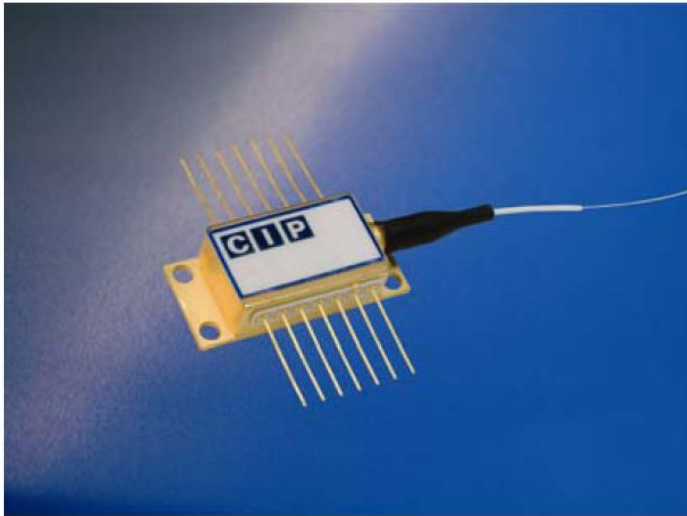
Utilizare amplificatoare optice



7W 980 nm Multimode Pump Laser

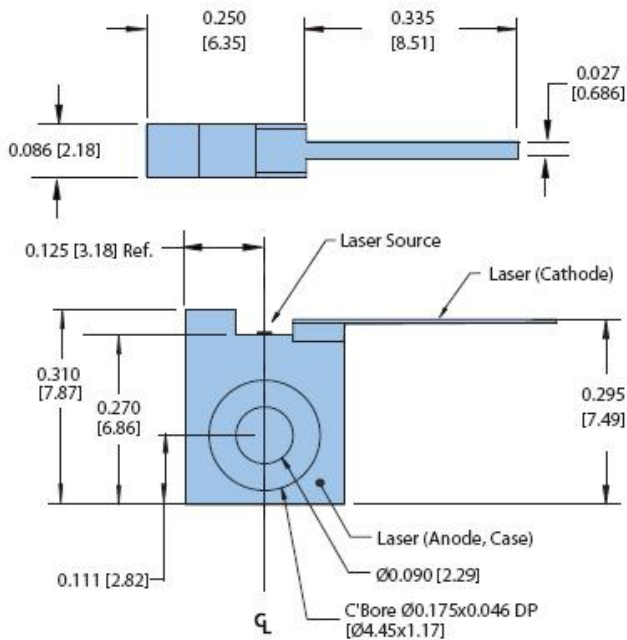


600mW 980 nm Singlemode Pump Laser

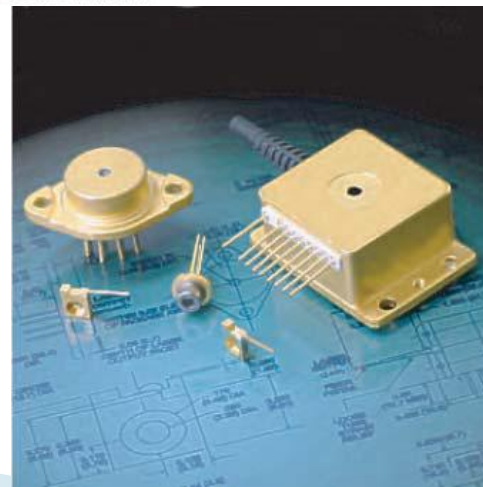
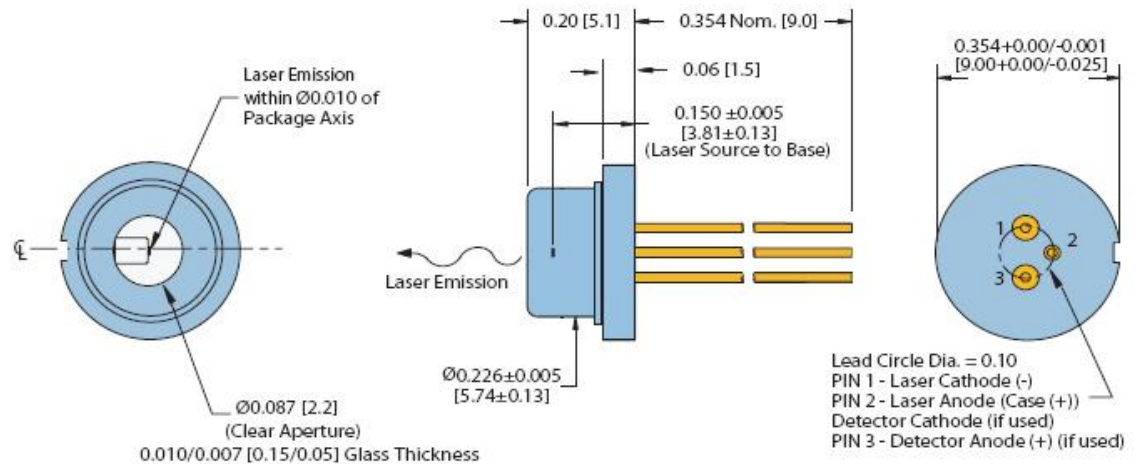


6 W, CW, 800nm

C-Mount Package

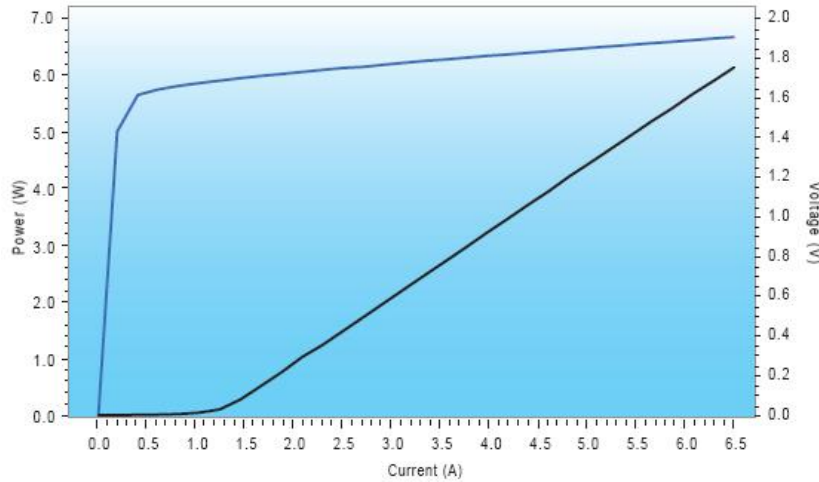


9mm Package

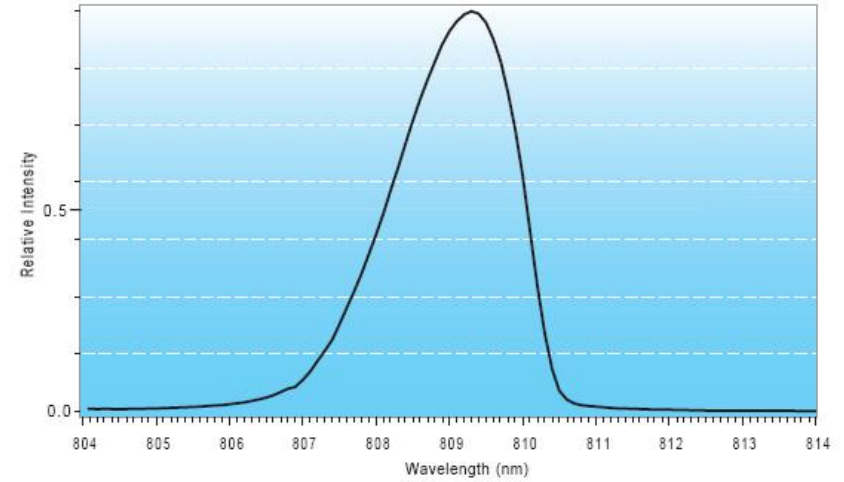


6 W, CW, 800nm

Typical L/I, V/I Graph

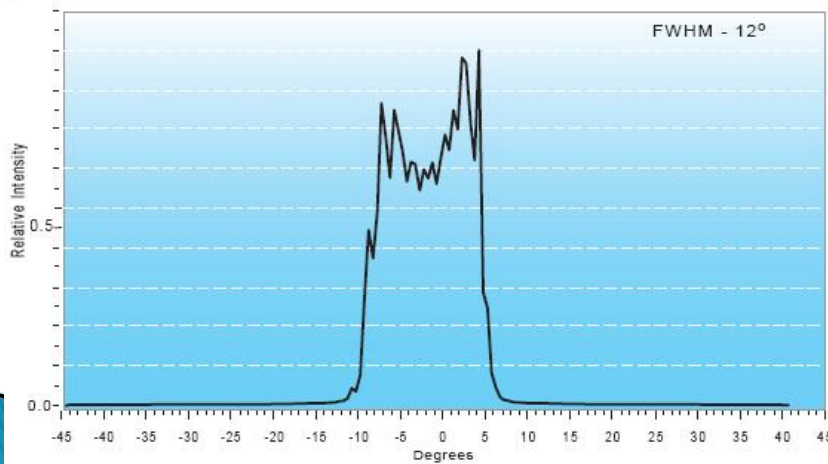


Wavelength Distribution



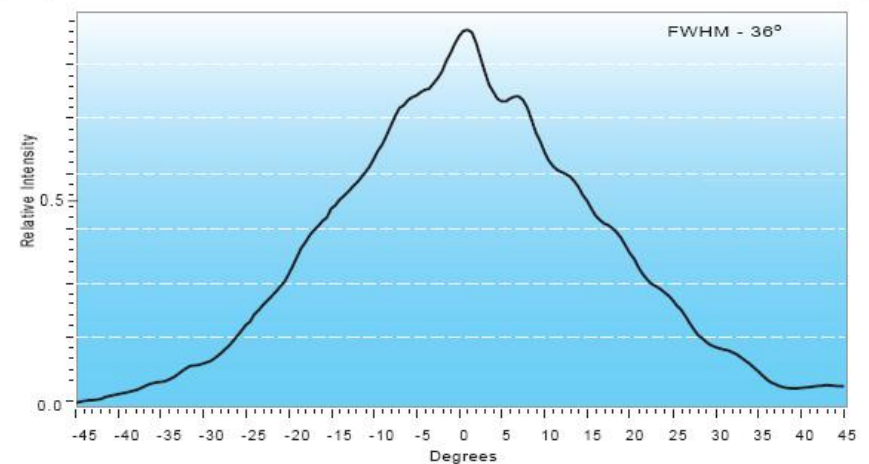
Typical Beam Divergence

Parallel

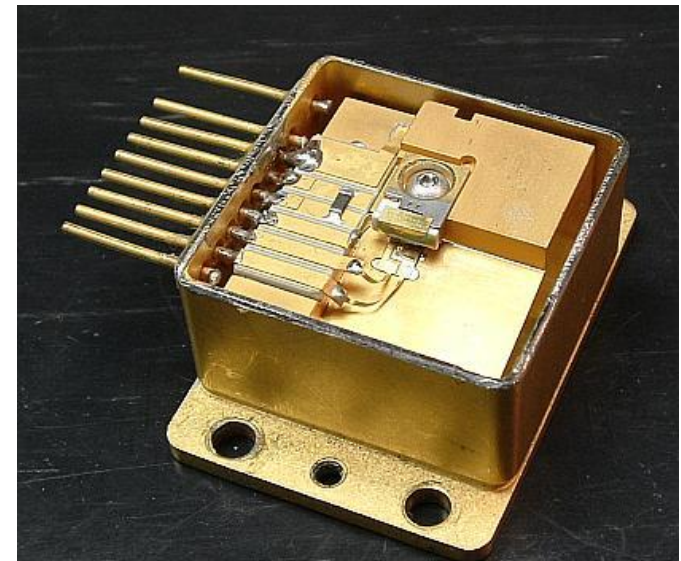
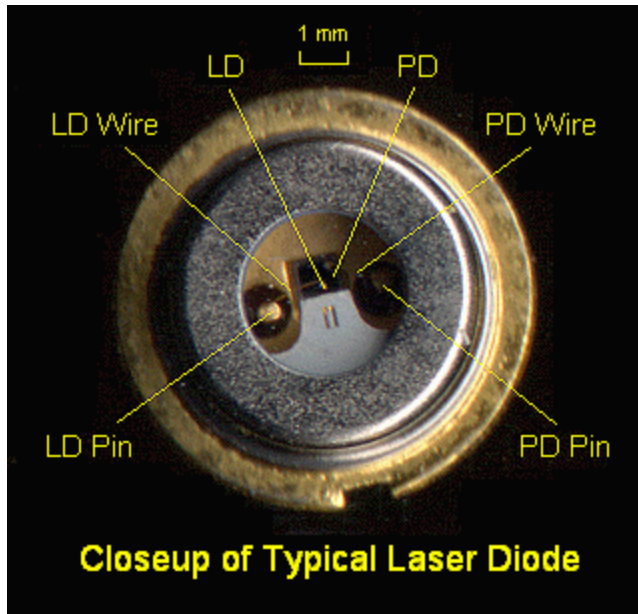


Typical Beam Divergence

Perpendicular



CW Laser, 650 nm



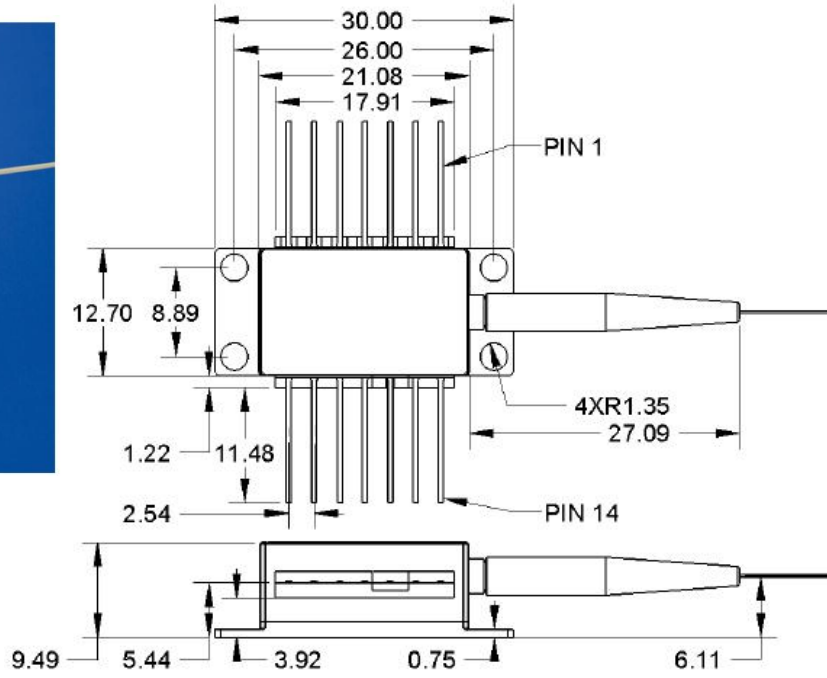
Lungimi de unda

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

1550nm DFB Laser

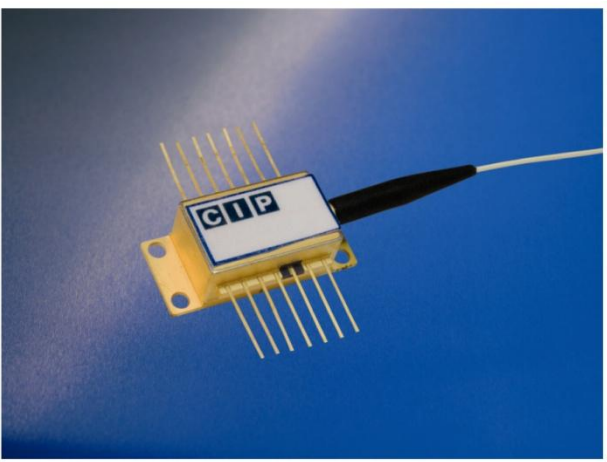
Mechanical Drawing

All units in mm

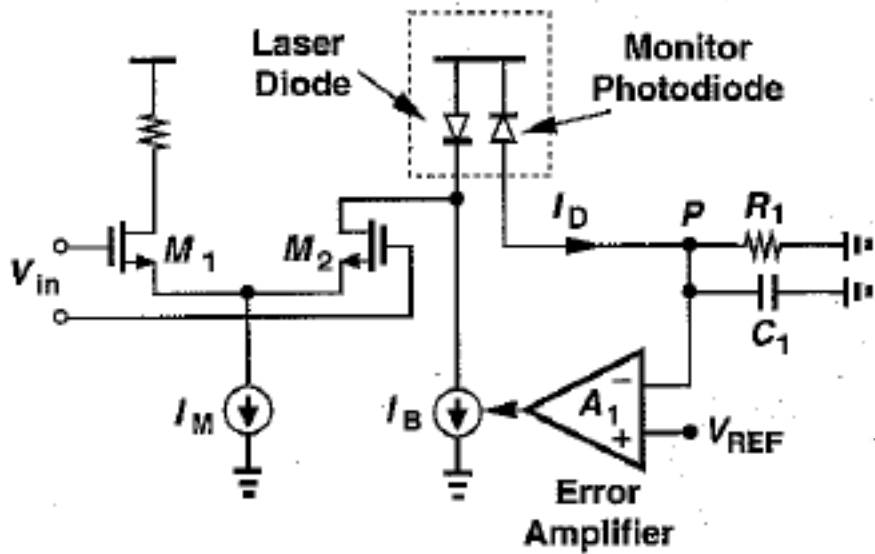


Pin out

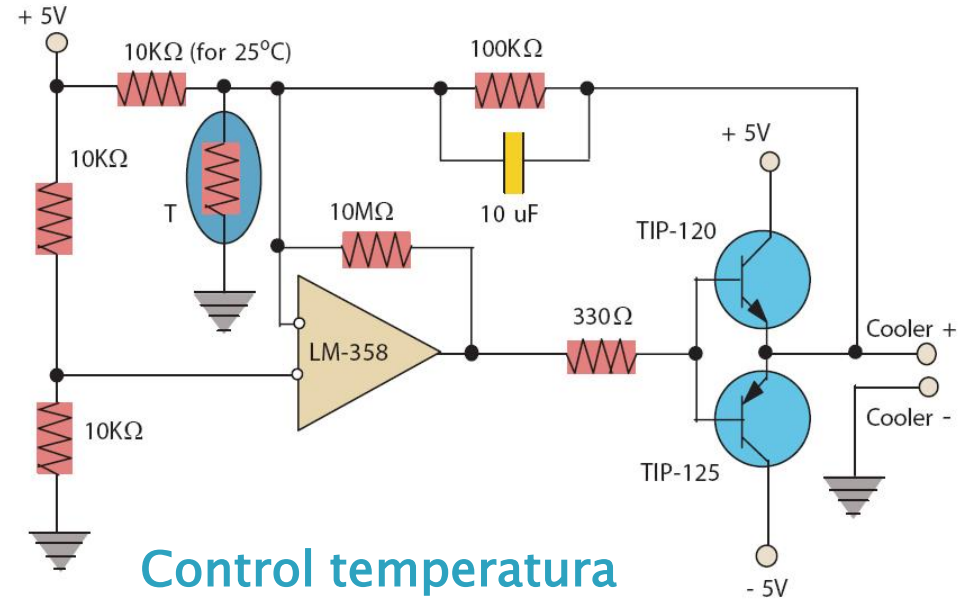
| Pin | Description |
|-----|----------------------------|
| 1 | Thermistor |
| 2 | Thermistor |
| 3 | Laser Cathode (Bias) |
| 4 | Monitor PD Anode |
| 5 | Monitor PD Cathode |
| 6 | TEC + |
| 7 | TEC - |
| 8 | Case GND, Laser Anode |
| 9 | Case GND, Laser Anode |
| 10 | Case GND, Laser Anode |
| 11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



Control dioda LASER



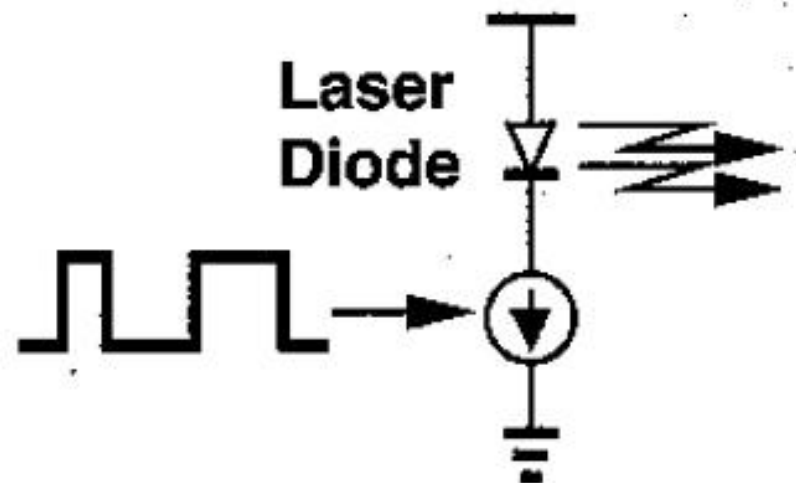
Control putere optica



Control temperatura

Dioda LASER

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



Dioda LASER

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

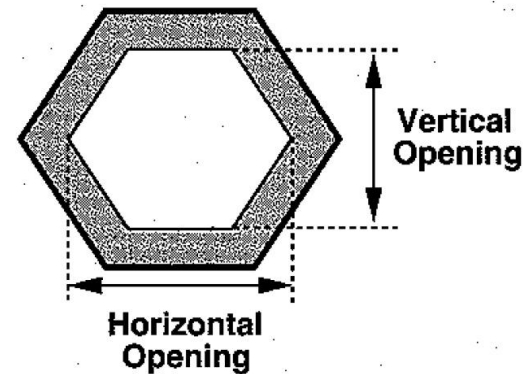
Caracteristici driver-e DL

▶ Viteza

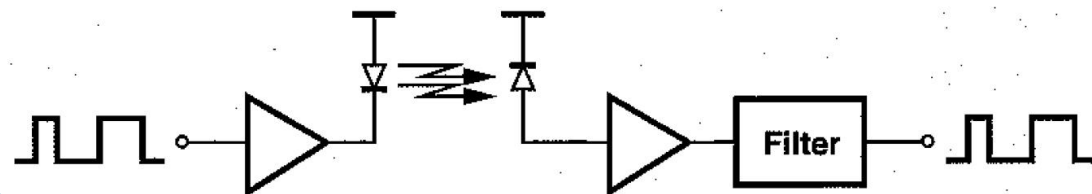
- caracterizata de timpii de crestere si de cadere
- suma acestora trebuie sa fie mult mai mica decat perioada de bit la viteza nominala de lucru

▶ Testarea vitezei de lucru

- standardizata
- “eye diagram”



(a)

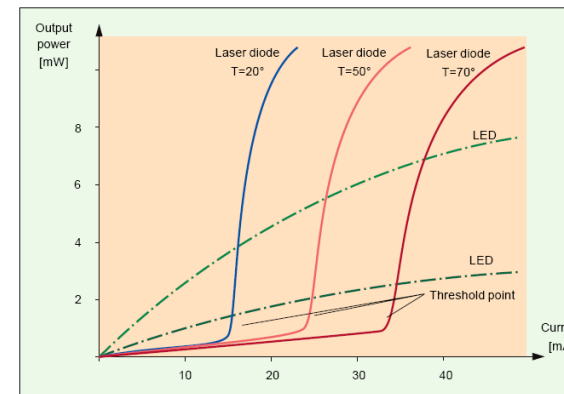


(b)

Caracteristici driver-e DL

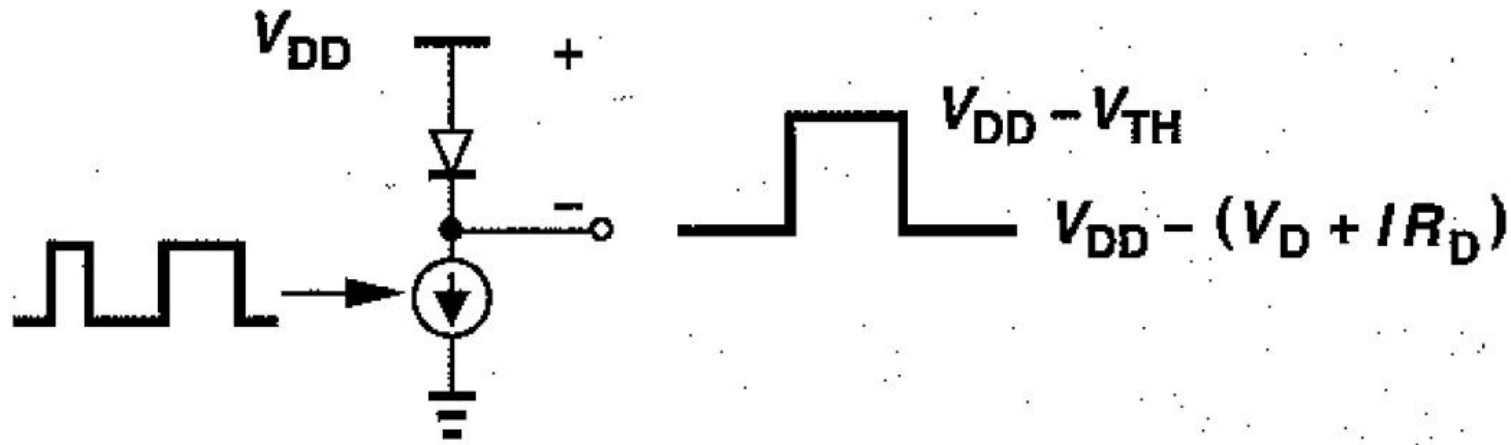
▶ Curent de iesire

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



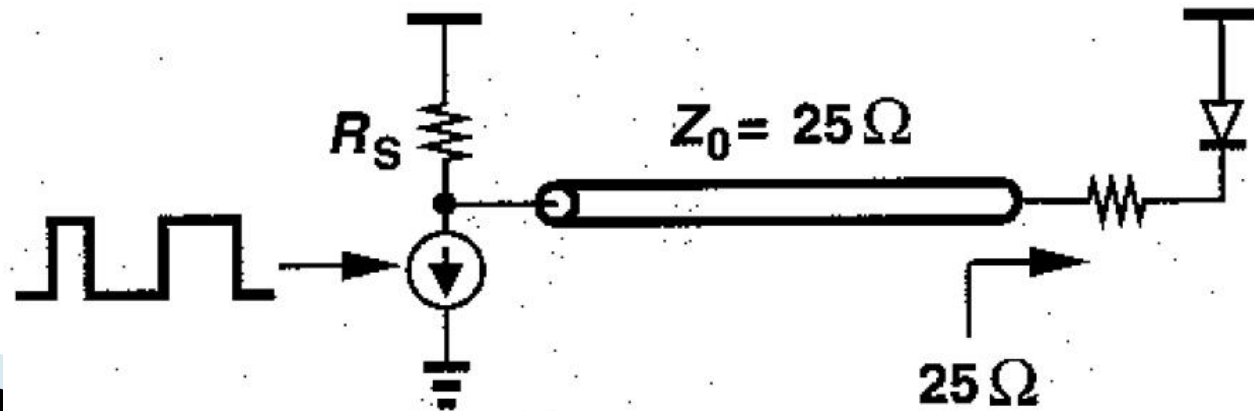
Caracteristici driver-e DL

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



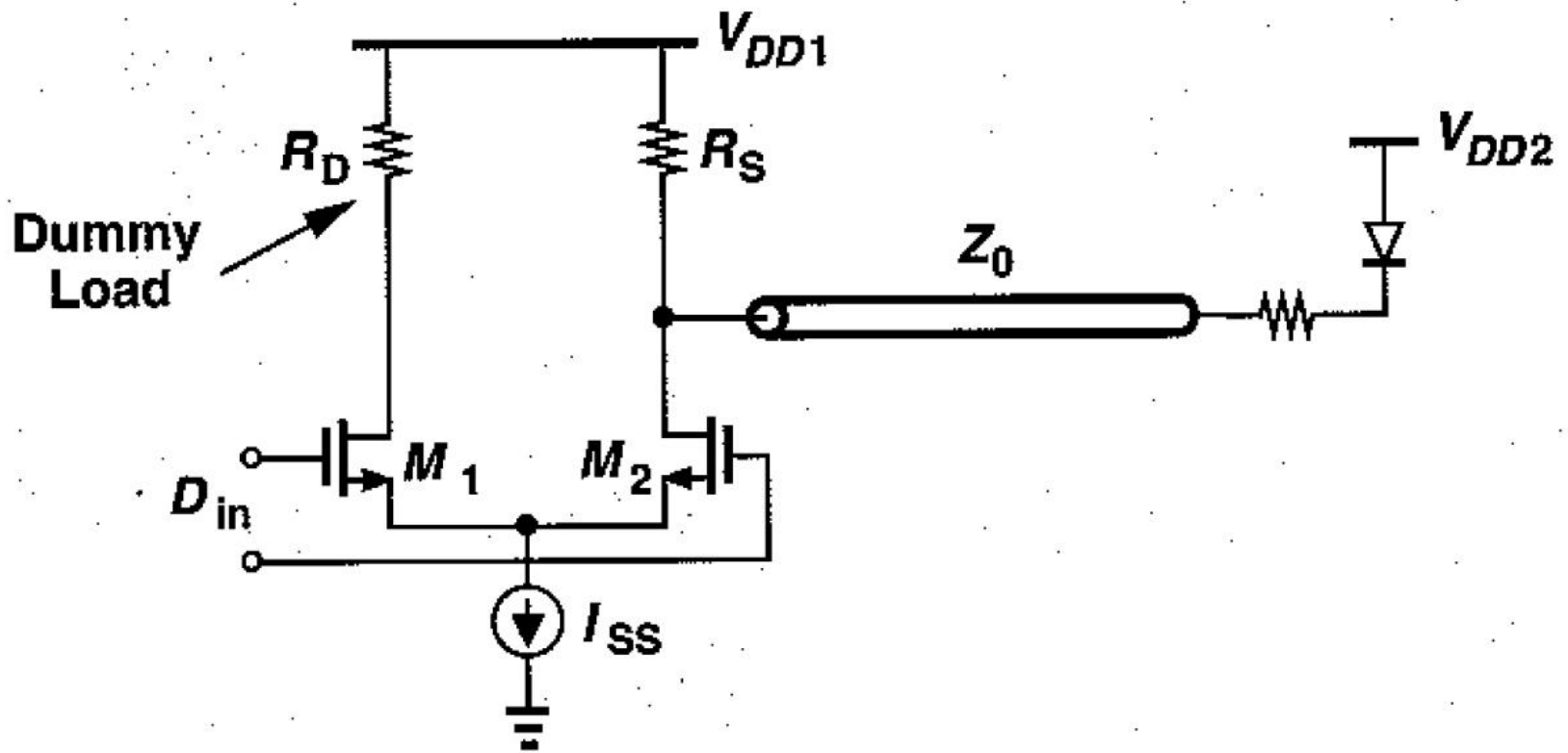
Caracteristici driver-e DL

- ▶ Impedante de intrare si iesire
- ▶ Se lucreaza la viteze mari (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 ($\sim 25\Omega$) prin introducerea unui rezistor in serie



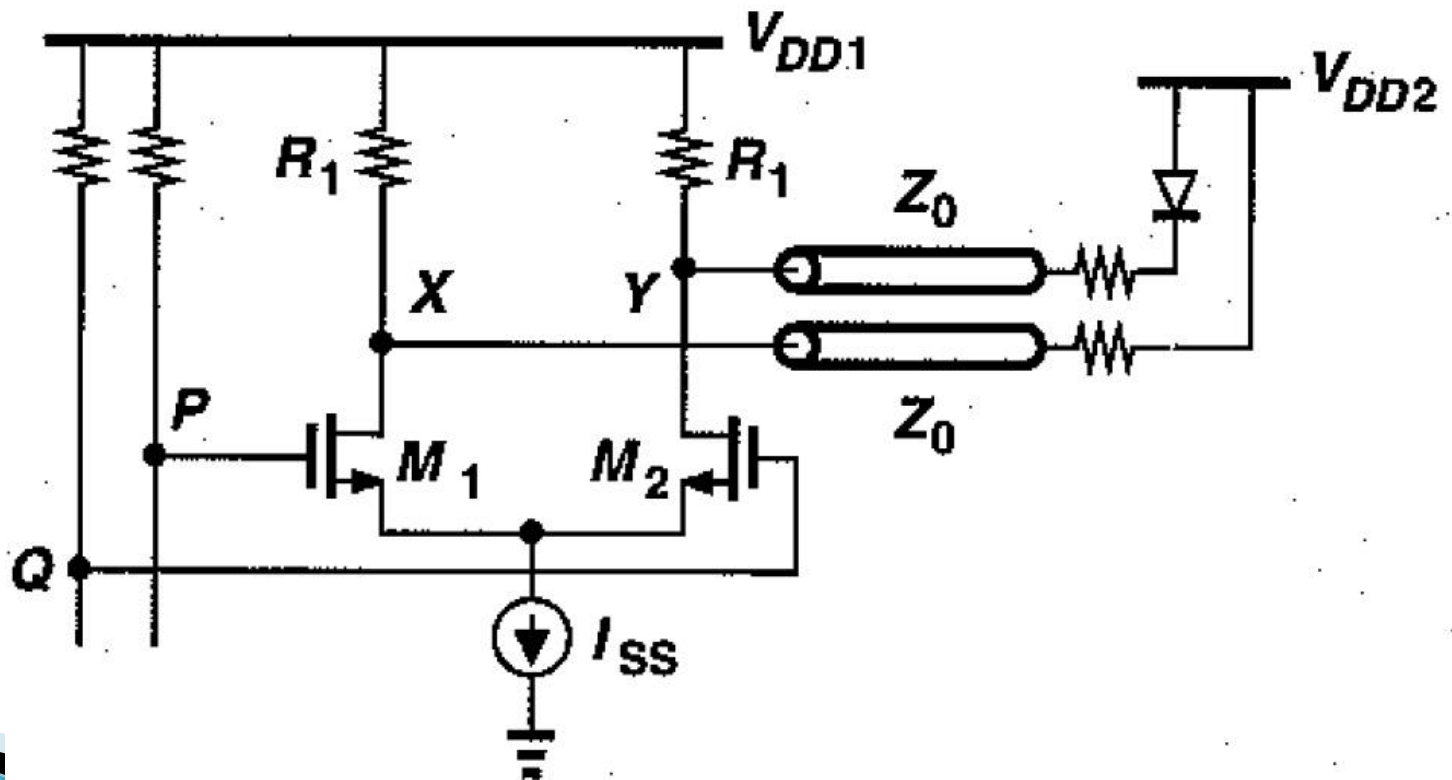
Principii de proiectare

- ▶ Tipic etajul de iesire se realizeaza diferential



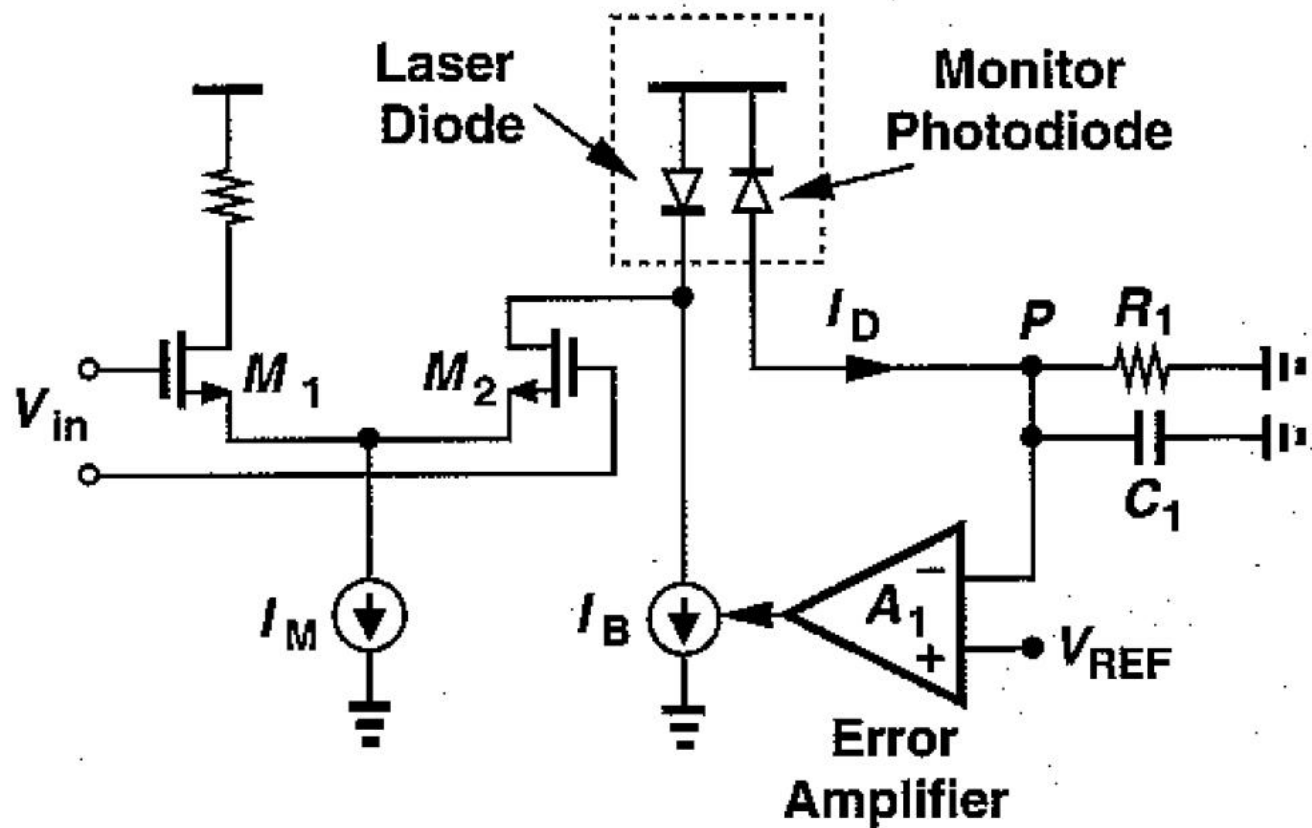
Principii de proiectare

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



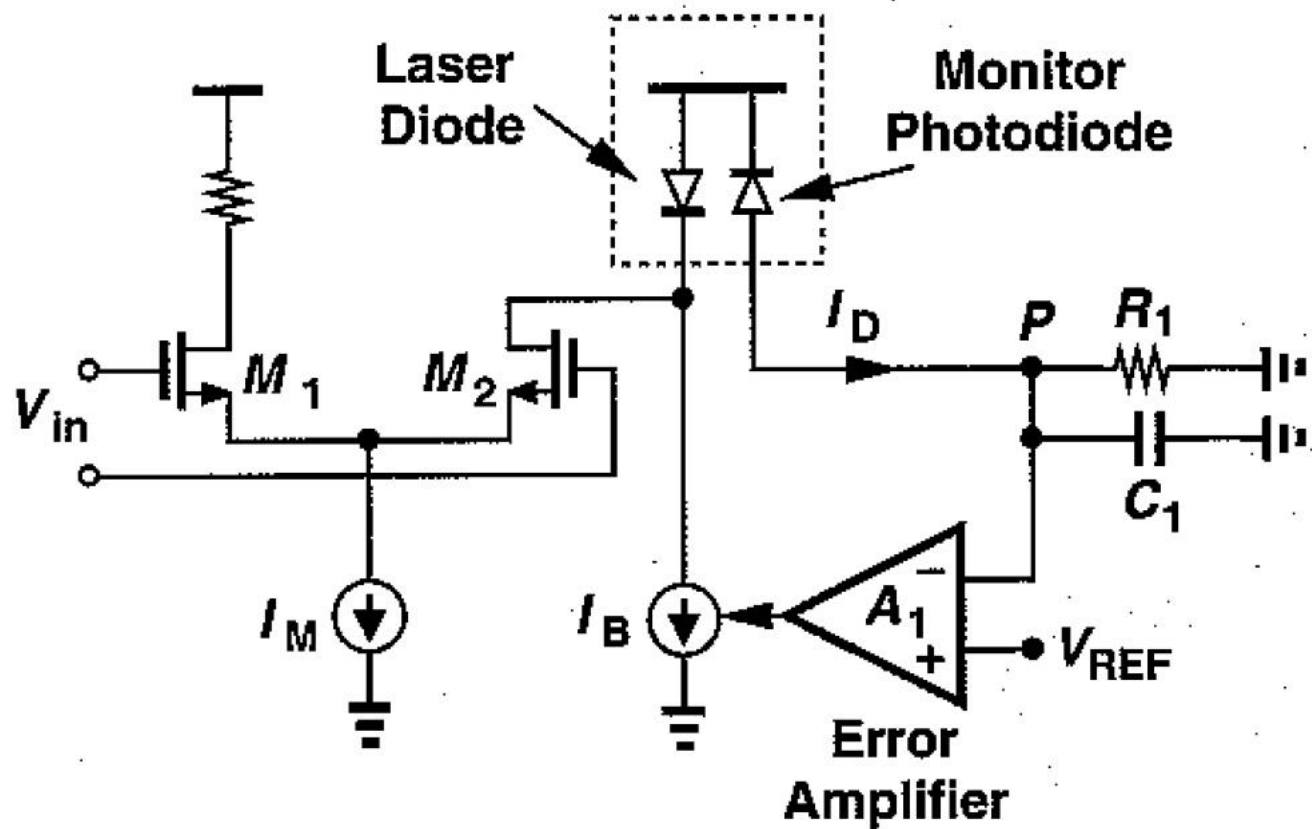
Controlul puterii in DL

- ▶ Necesara datorita variatiei curentului de “polarizare”



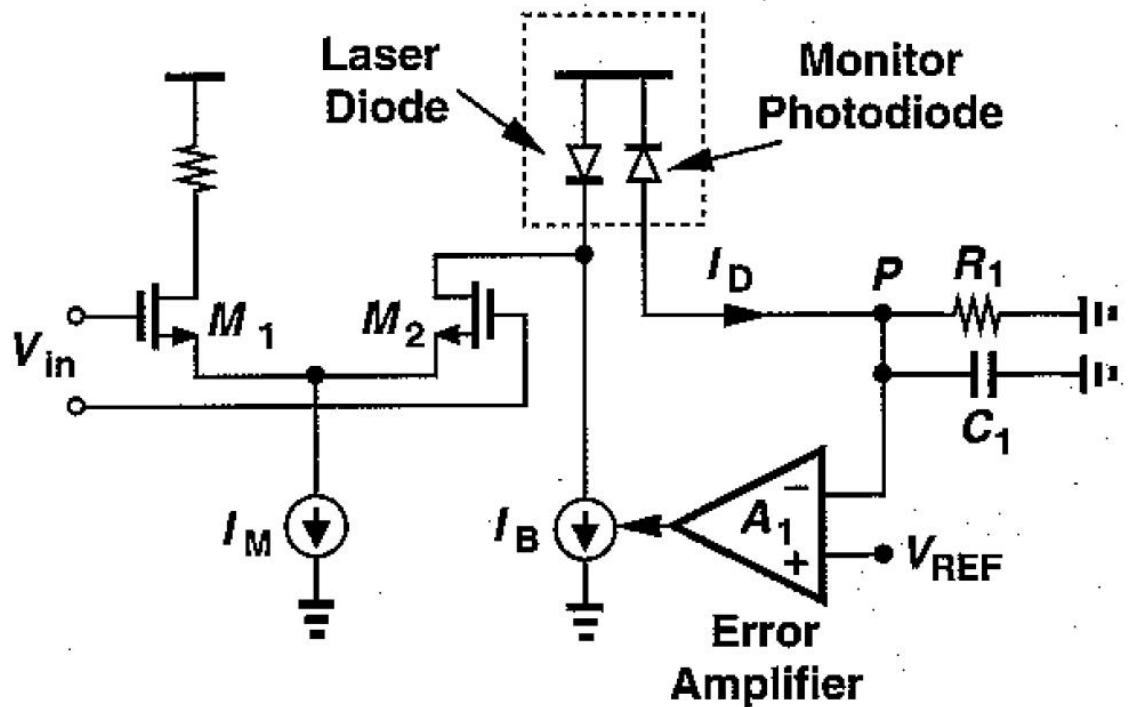
Controlul puterii in DL

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



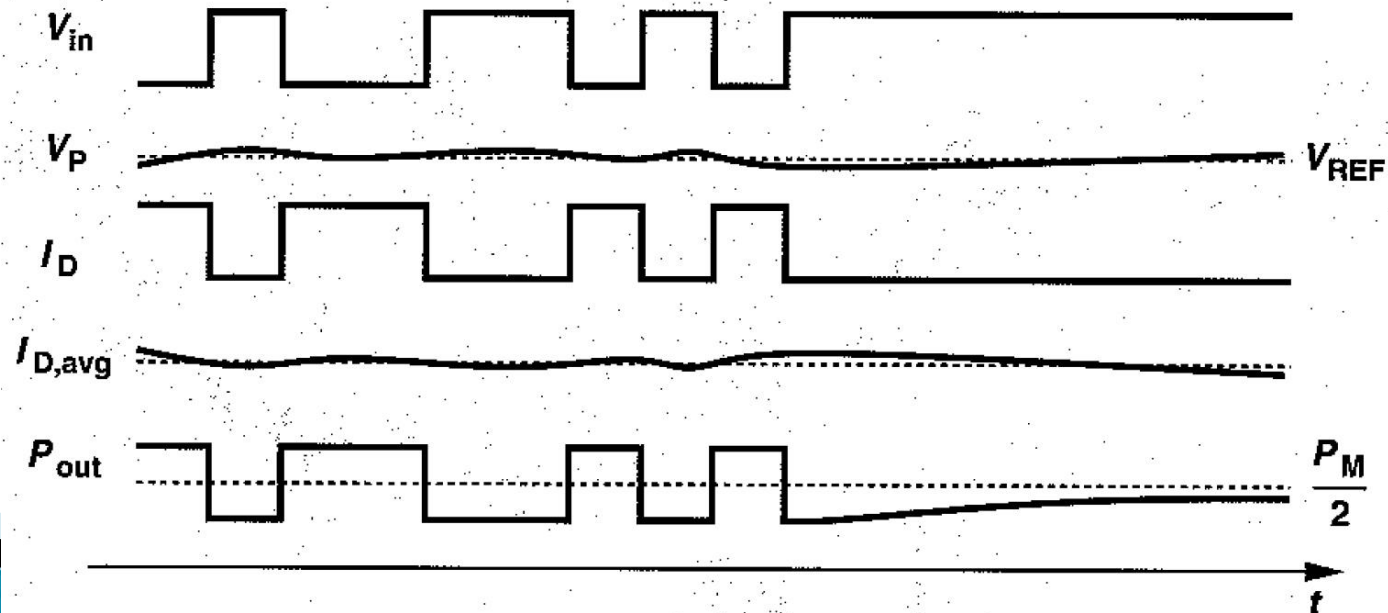
Controlul puterii in DL

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



Controlul puterii in DL

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



Fotodioda

Capitolul 9

Cuprins

- ▶ **Lumina ca undă electromagnetică** (ecuațiile lui Maxwell, ecuația undelor, parametri de propagare)
- ▶ **Elemente de fotometrie și radiometrie** (mărimi energetice/luminoase)
- ▶ **Fibra optică** (realizare, principiu de funcționare, atenuare, dispersie, banda de frecvență)
- ▶ **Cabluri optice** (tehnologie, conectori, lipire – splice)
- ▶ **Proiectare sistemică a legăturii pe fibra optică** (bandă de frecvență, balanța puterilor)
- ▶ **Emitătoare optice** (LED și dioda laser – realizare fizică și funcționare)
- ▶ **Receptoare optice** (dioda PIN, dioda cu avalanșă – realizare fizică și funcționare)
- ▶ **Amplificatoare transimpedanță** (parametri, scheme tipice, TIA în buclă deschisă, cu reacție, diferențiale, control automat al câștigului)
- ▶ **Realizarea circuitelor pentru controlul emițătoarelor optice** (parametri, scheme tipice, controlul puterii, multiplexoare)
- ▶ **Dispozitive de captare a energiei solare** (principiu de funcționare, utilizare, proiectare)

Detectori optici

▶ Cerinte

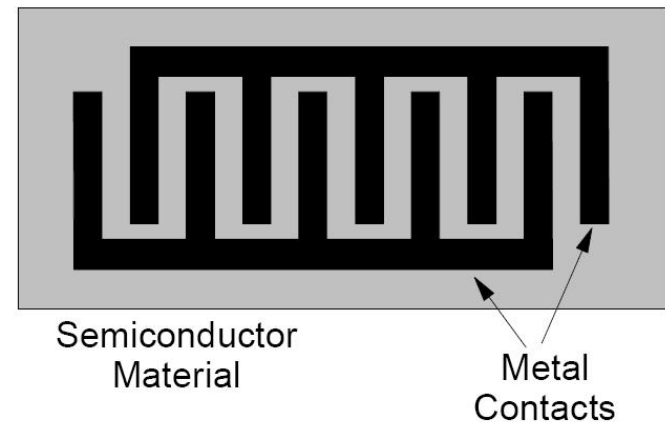
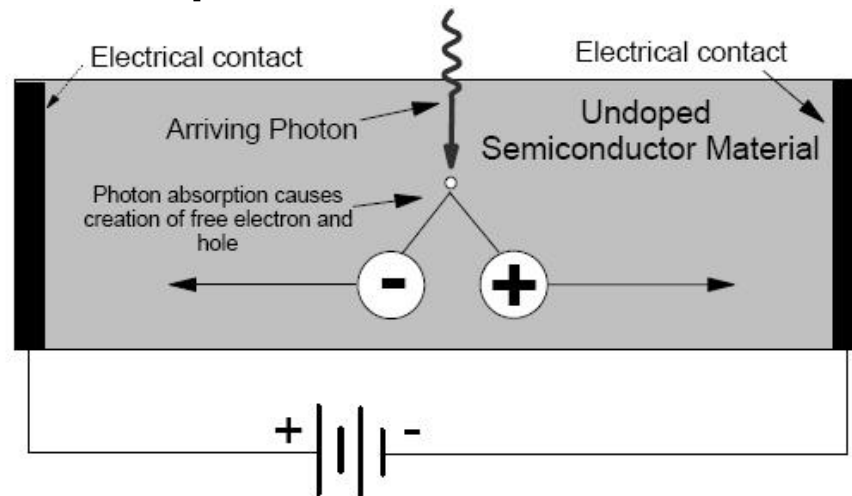
- eficienta crescuta a conversiei optic/electric
- zgomot redus
- raspuns uniform la diferite lungimi de unda
- viteza de raspuns ridicata
- liniaritate

▶ 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

Fotoconductor

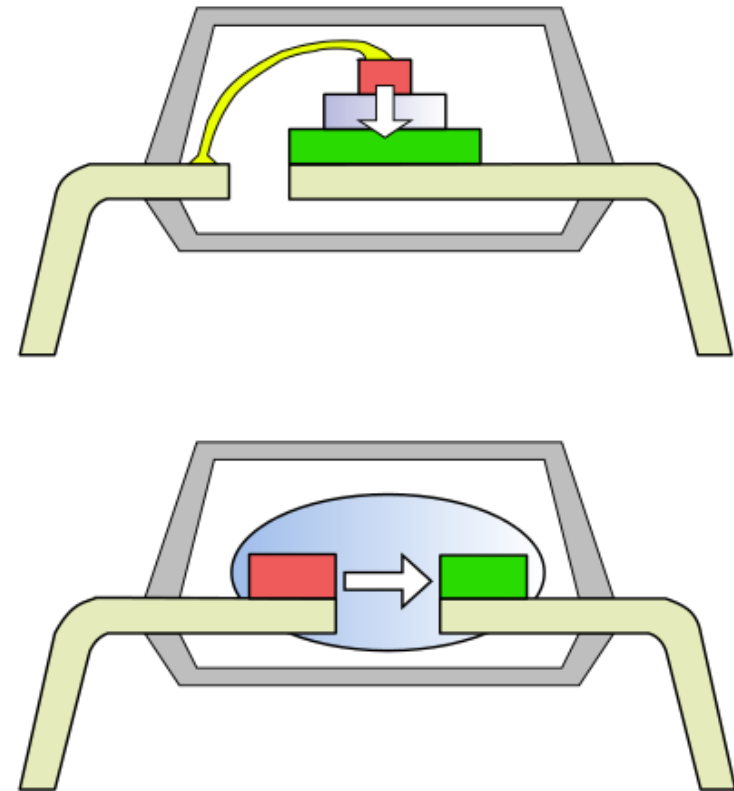
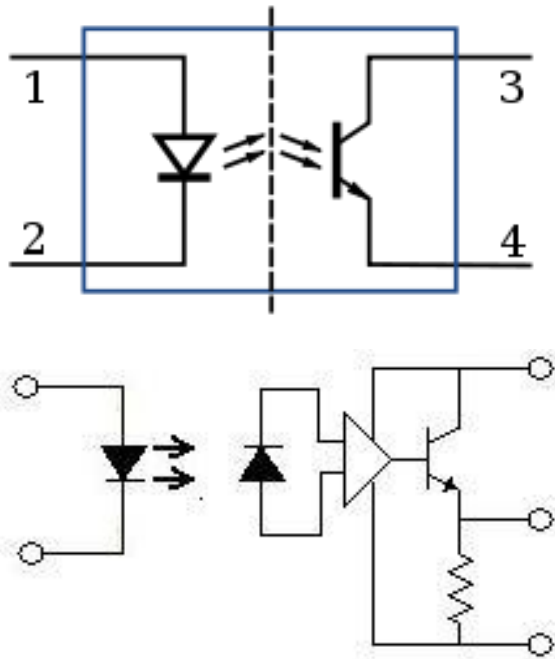
▶ Principiu



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

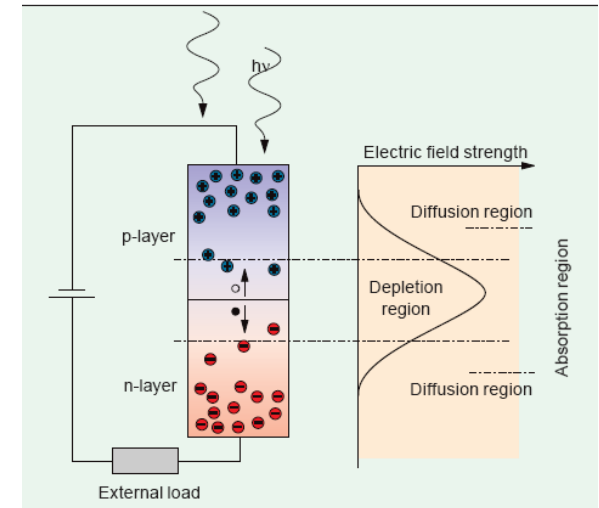
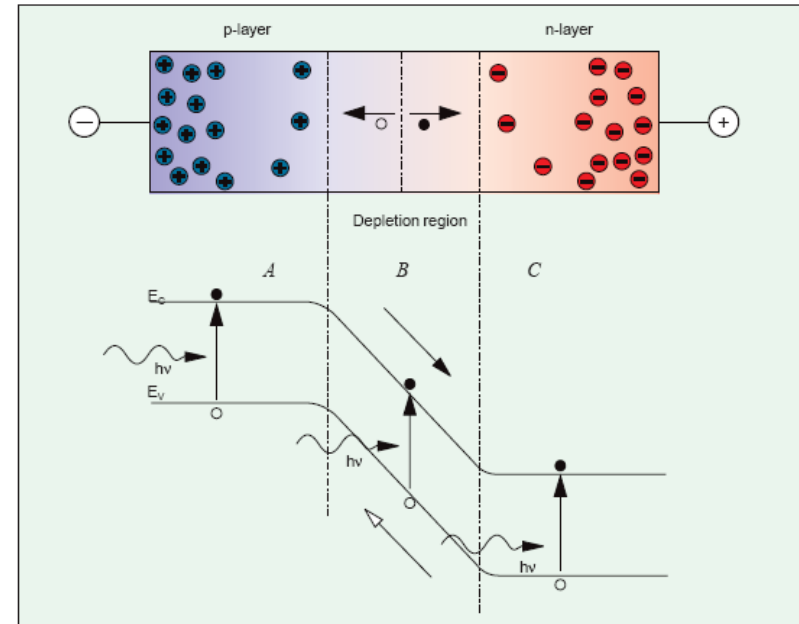
Optocuploare

- ▶ 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

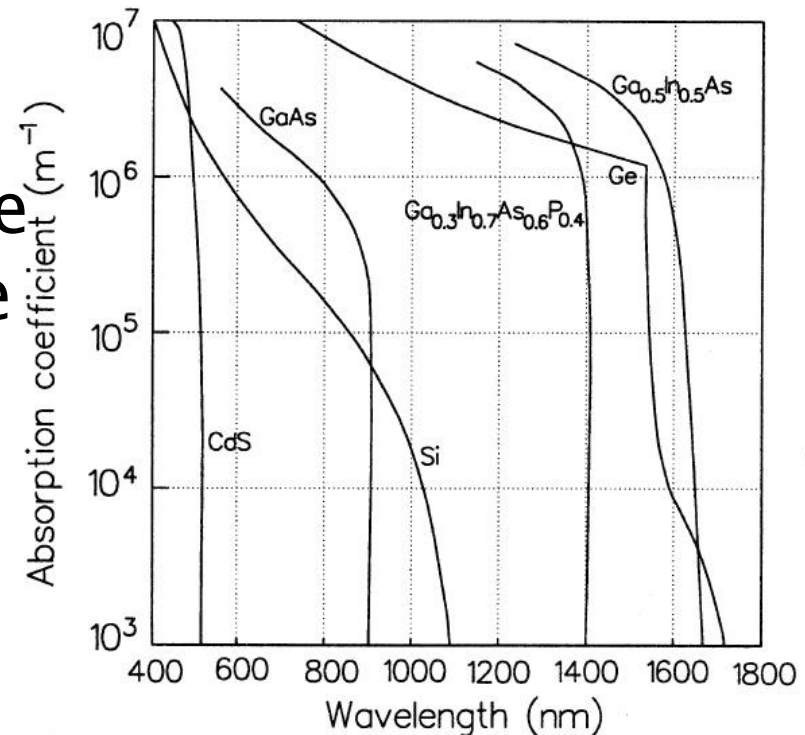
$$\lambda_{\max} = \frac{hc}{E_g}$$

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

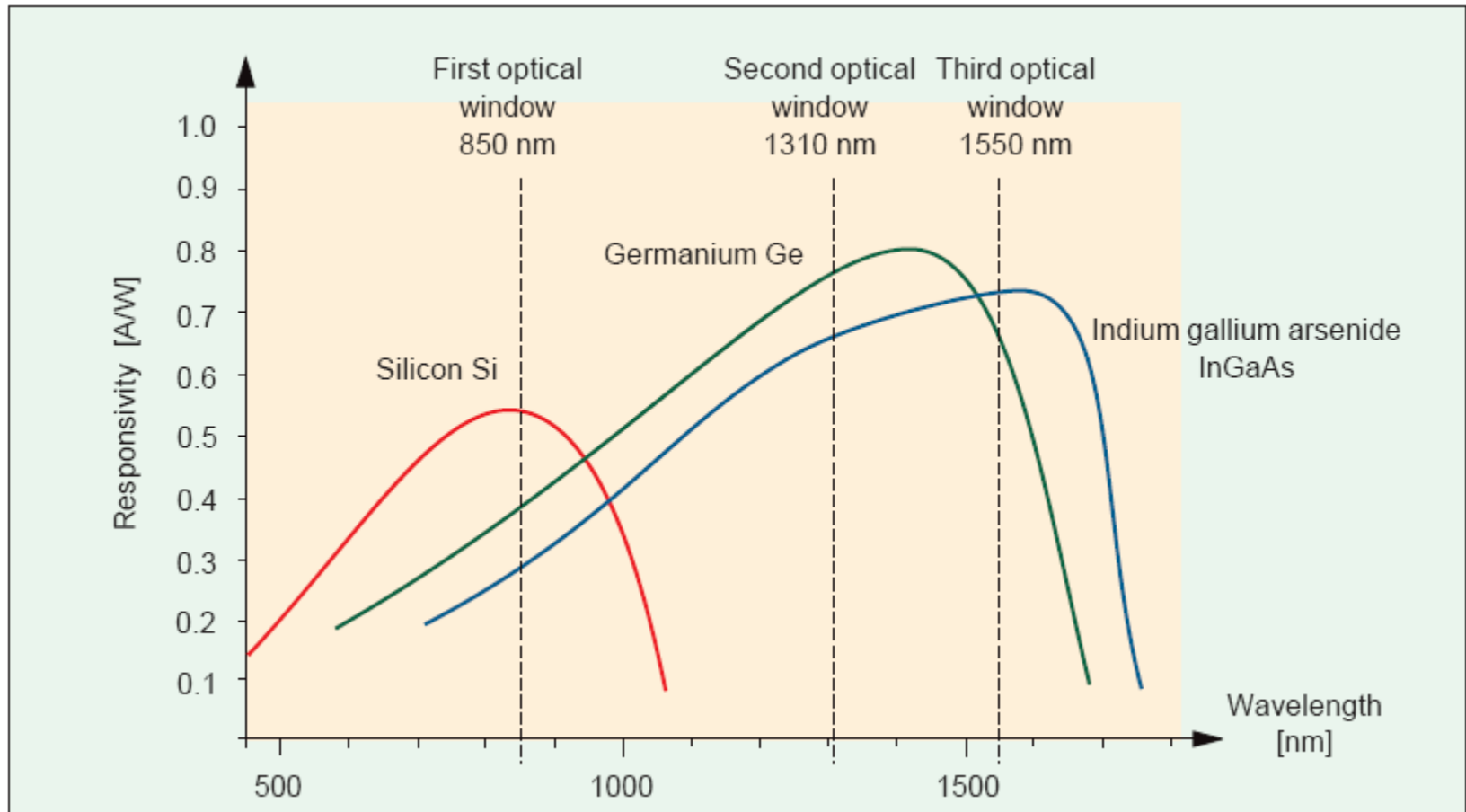
$$P(w) = P_i \cdot e^{-\alpha \cdot d} \cdot (1 - e^{-\alpha \cdot w}) \cdot (1 - R_f)$$

Fotodioda – Principiul de operare

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



Material utilizate pentru fotodiode



Fotodioda – Marimi caracteristice

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

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

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

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

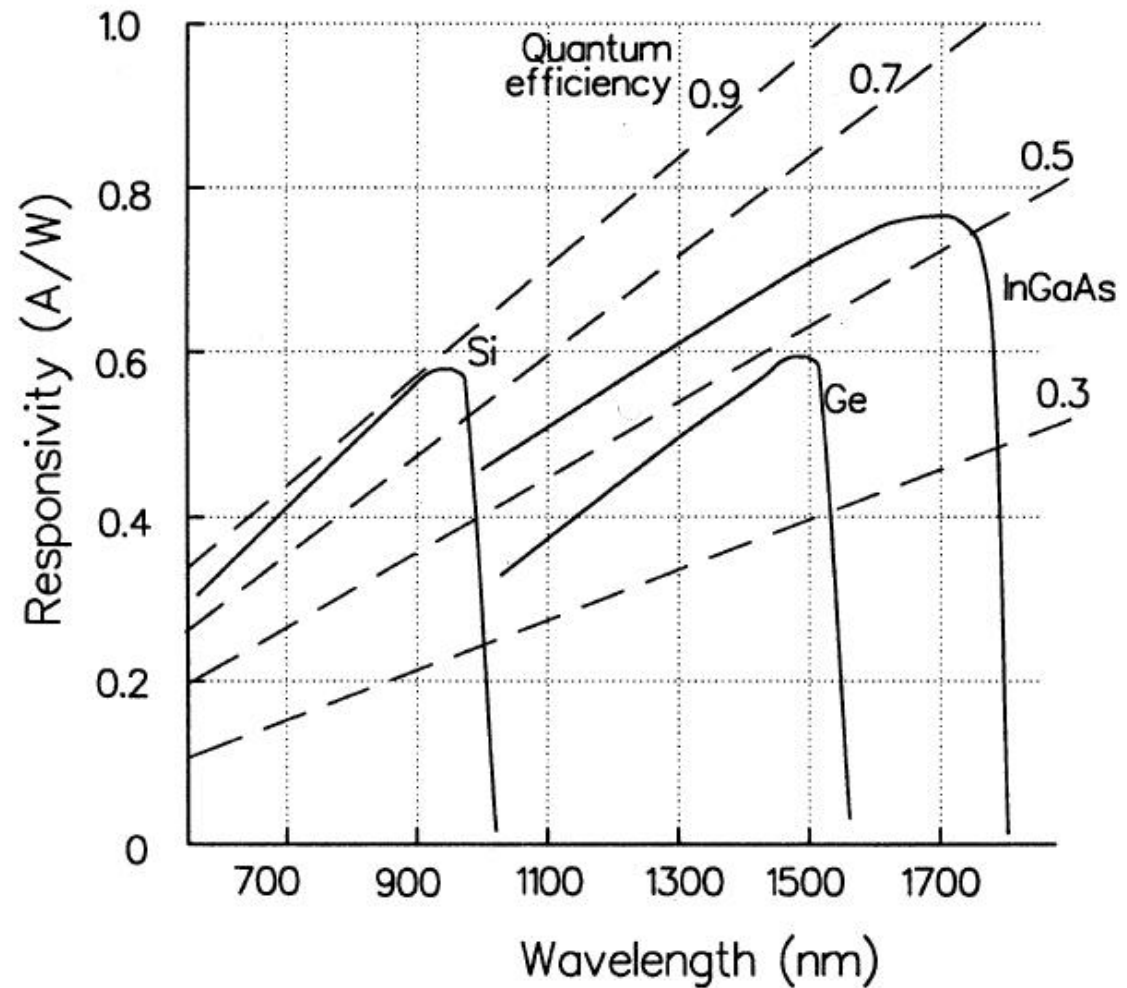
- ▶ Responzivitatea

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

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

Fotodiode - marimi karakteristik

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



Material utilizate pentru fotodiode

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

- ▶ Dezavantajul major pentru Ge este curentul de intuneric mare

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

Curent de intuneric

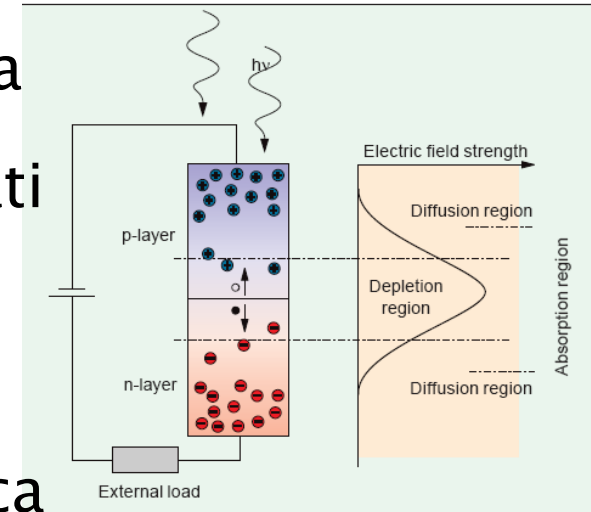
- ▶ Curentul invers al jonctiunii p-n, datorat agitatiei termice, prezent in absenta iluminarii
- ▶ Constitutie o importanta sursa de zgomot (limiteaza aplicatiile Ge)

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

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

Fotodioda PIN

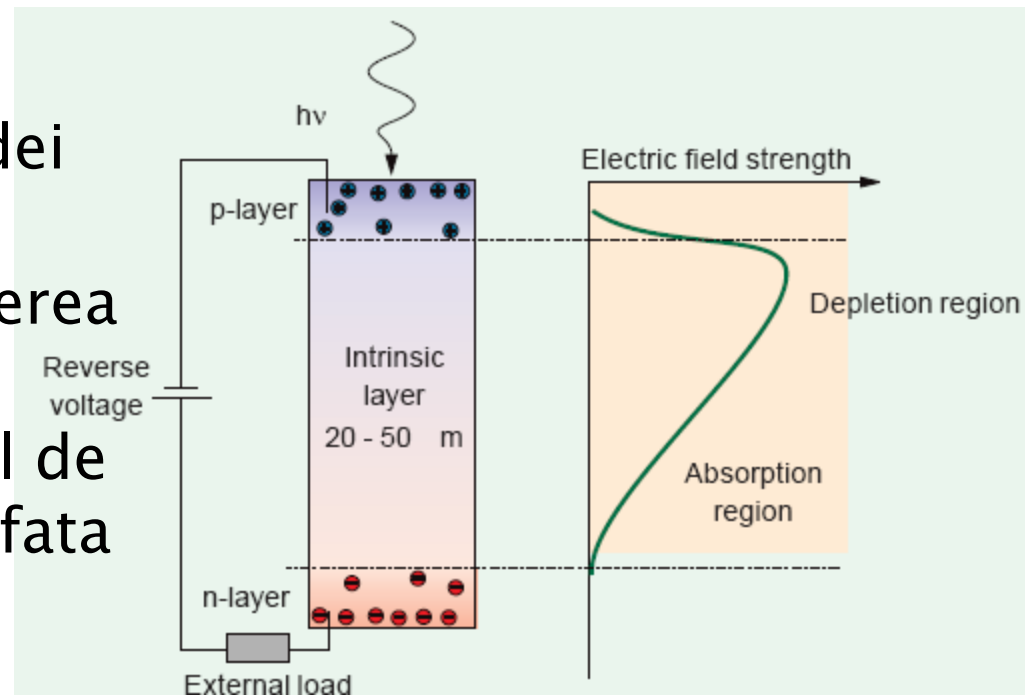
- ▶ Existenta campului electric in regiunea golita de purtatori face ca eventualii purtatori generati optic sa fie accelerati spre terminale pentru constituirea fotocurentului
- ▶ Problemele utilizarii diodei pn polarizate invers ca fotodetector sunt generate de adancimea extrem de mica a zonei golite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



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

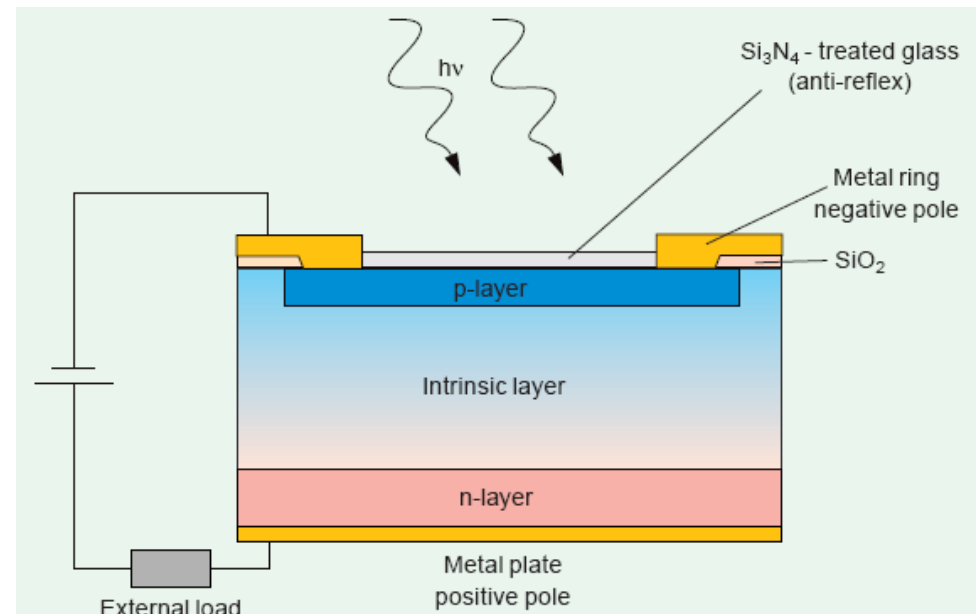
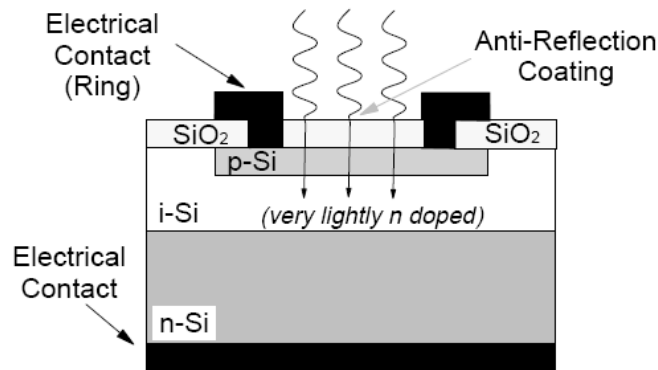
Fotodioda PIN

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



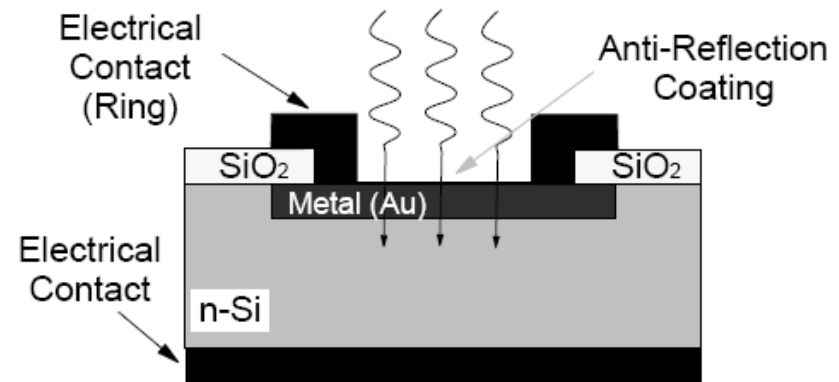
Structura fotodiodei PIN

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



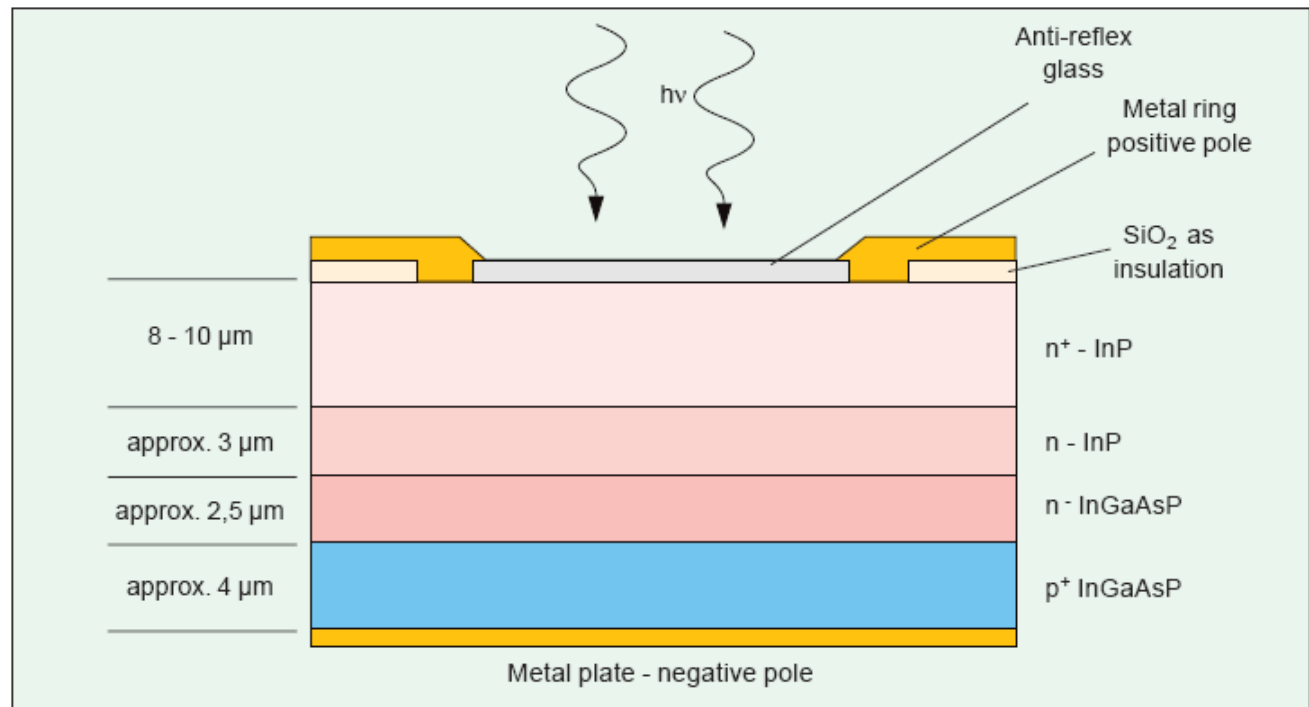
Structura fotodiodelor Schottky

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



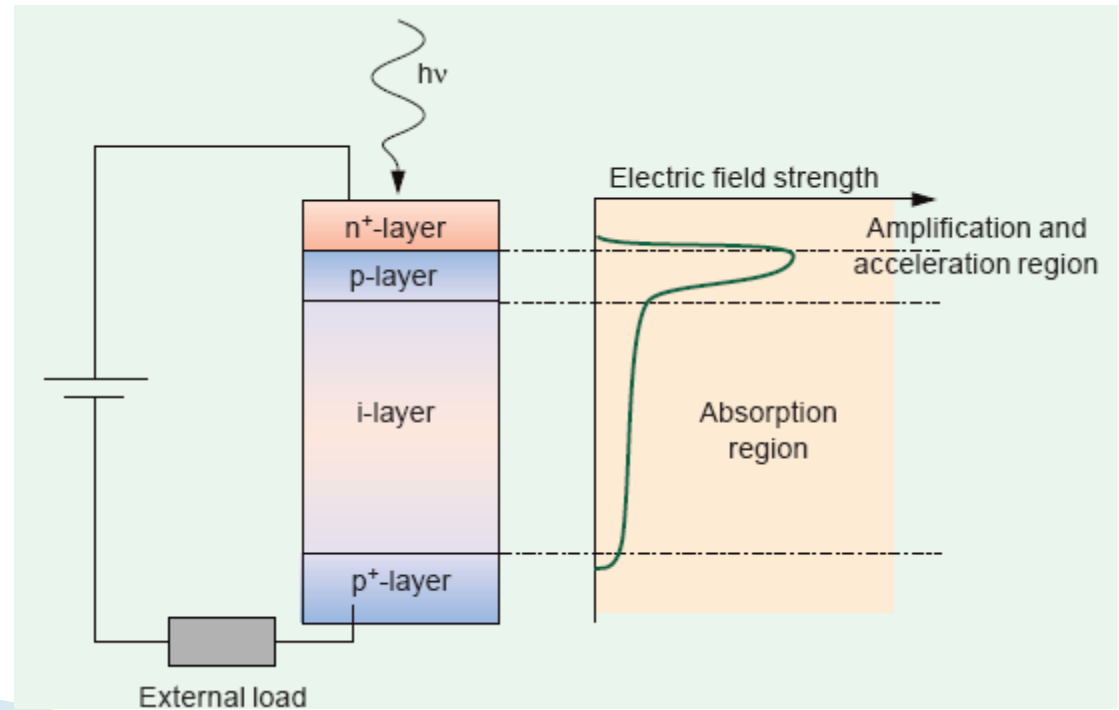
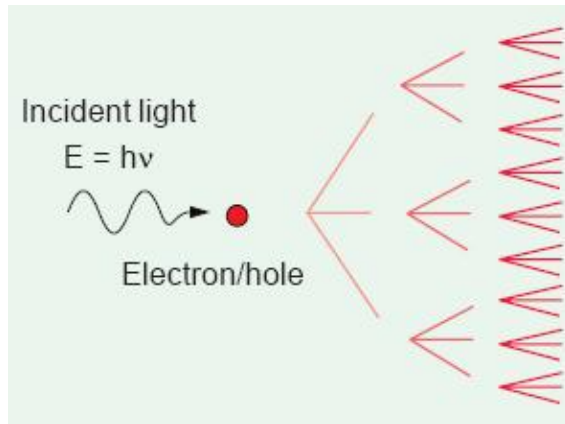
Fotodioda PIN pentru lungimi de unda crescute (1550nm)

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



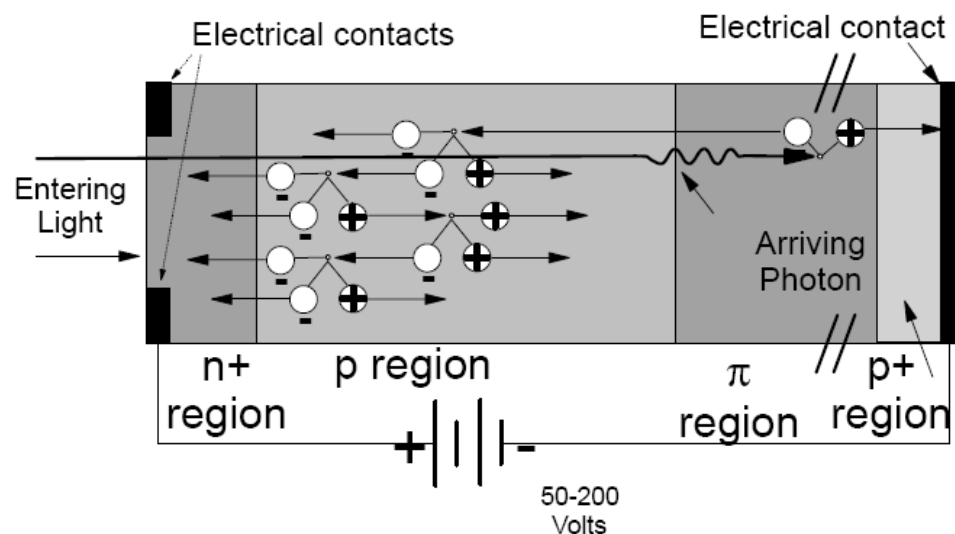
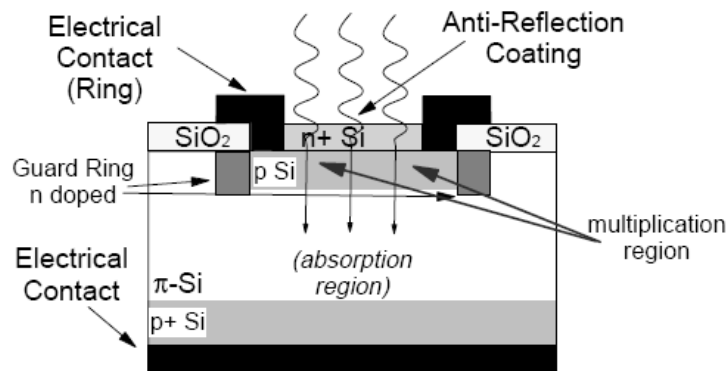
Fotodioda PIN cu multiplicare in avalansa

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

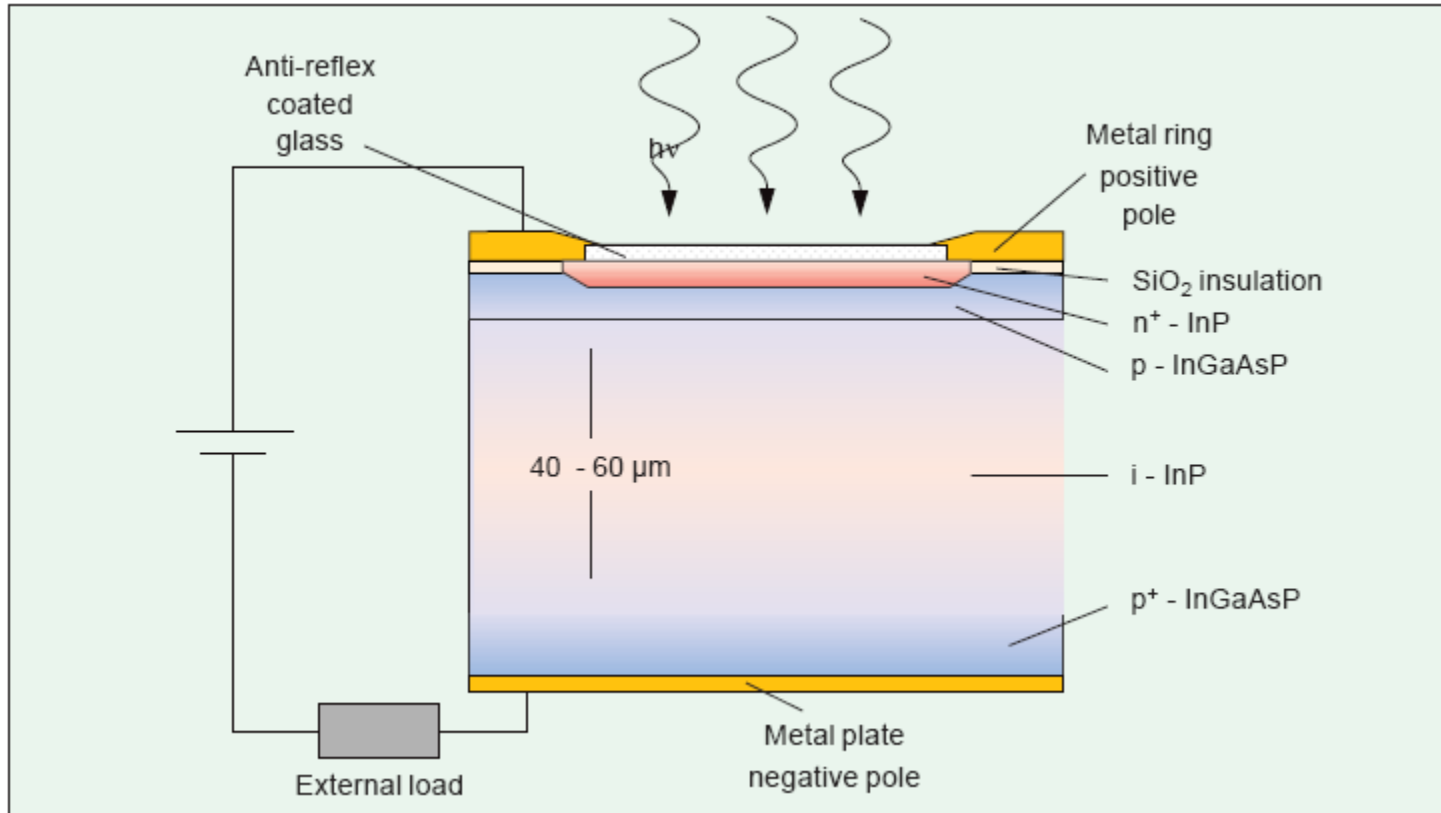


Functionarea fotodiodei cu multiplicare in avalansa

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



Structura fotodiodei cu multiplicare in avalansa



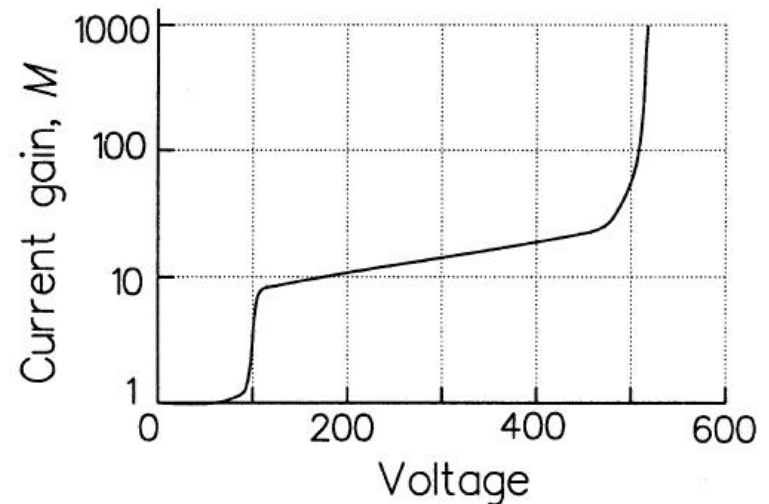
Caracteristicile fotodiodei cu multiplicare in avalansa

- ▶ factorul de multiplicare caracterizeaza amplificarea fotocurentului generat

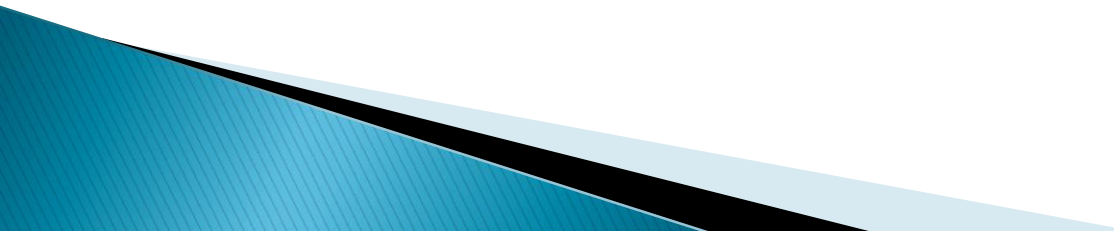
$$M = \frac{I_M}{I}$$

- ▶ Responzivitatea

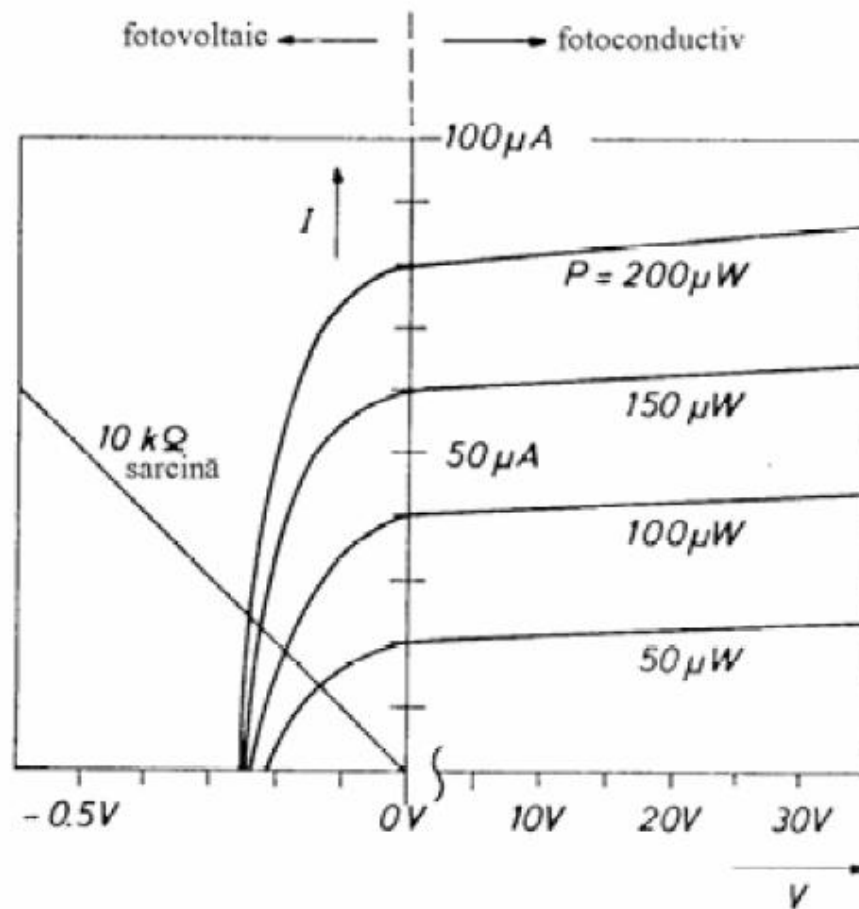
$$R = \frac{I}{P_o} = \frac{\eta \cdot e \cdot \lambda}{hc} \cdot M$$



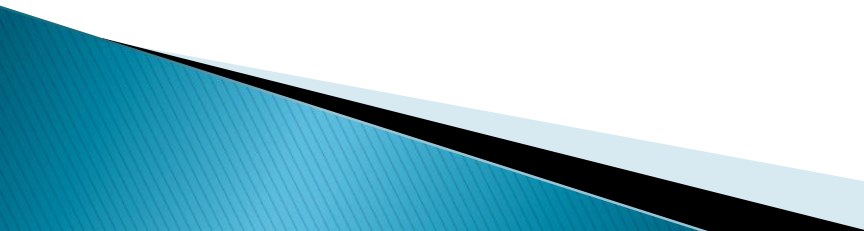
Dezavantaje

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

Caracteristici curent/tensiune Fotodioda

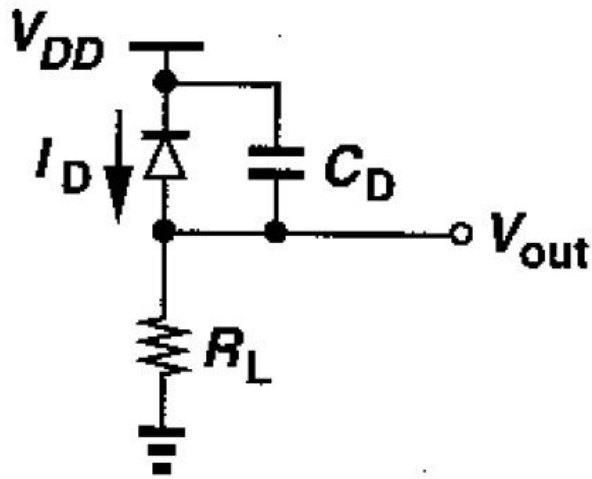


Amplificatoare transimpedanta

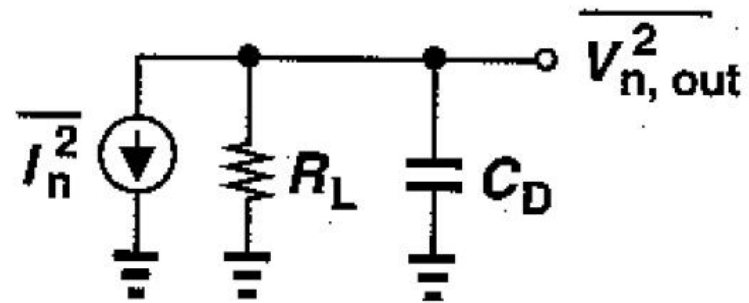
- ▶ Fotodiodele genereaza un curent proportional cu puterea optica receptionata
 - ▶ Primul pas necesar este conversia acestui curent la o tensiune
 - ▶ Amplificatoarele transimpedanta sunt amplificatoarele atacate in curent si care ofera la iesire o tensiune proportionala cu acesta
 - ▶ Amplificarea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

Amplificatoare transimpedanta

- ▶ Cel mai simplu amplificator transimpedanta este un rezistor



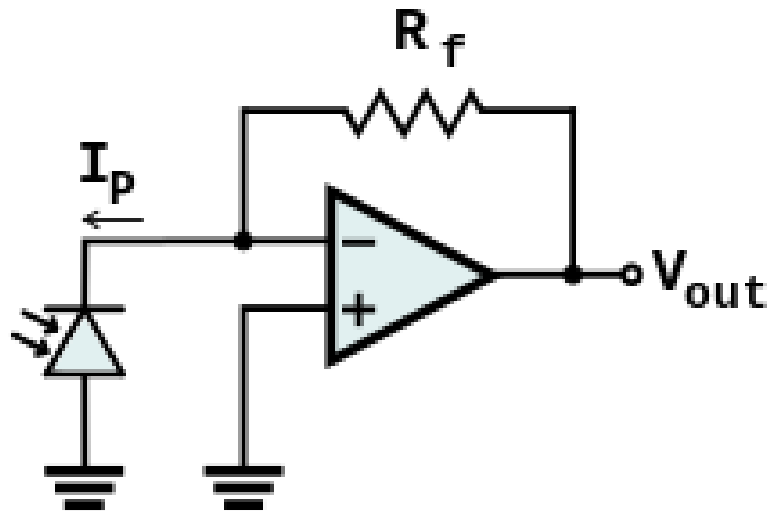
(a)



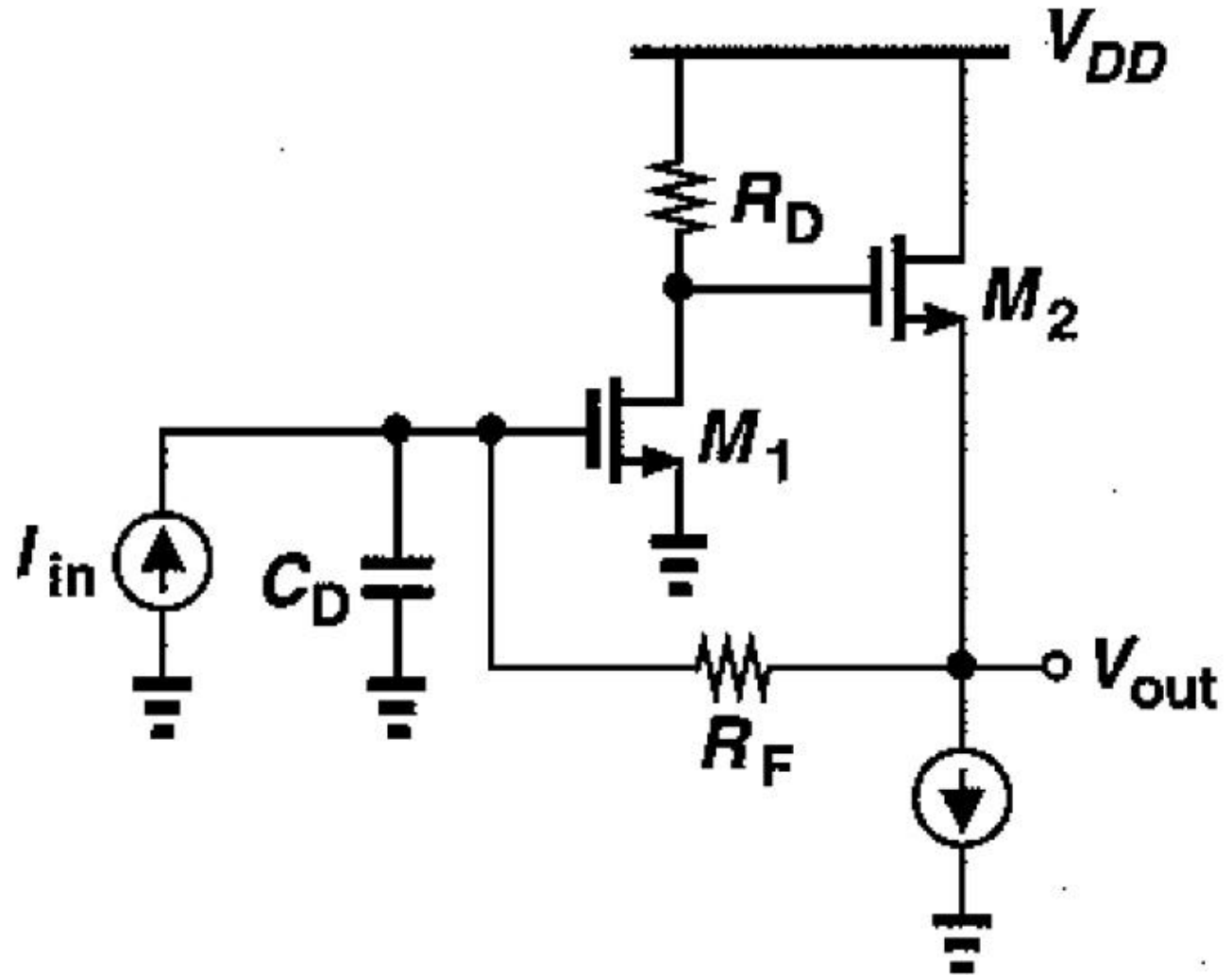
(b)

Amplificatoare transimpedanta

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



Amplificatoare transimpedanta



Zgomotul traductorilor electro-optici

Zgomotul emitatorilor optici

▶ LED

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

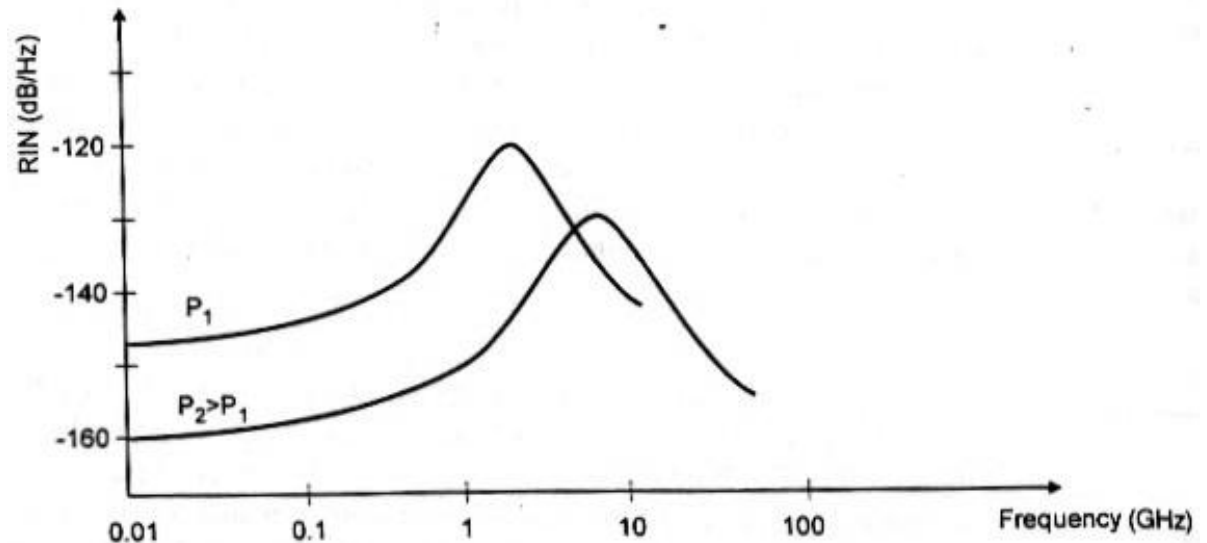
▶ Dioda LASER

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

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

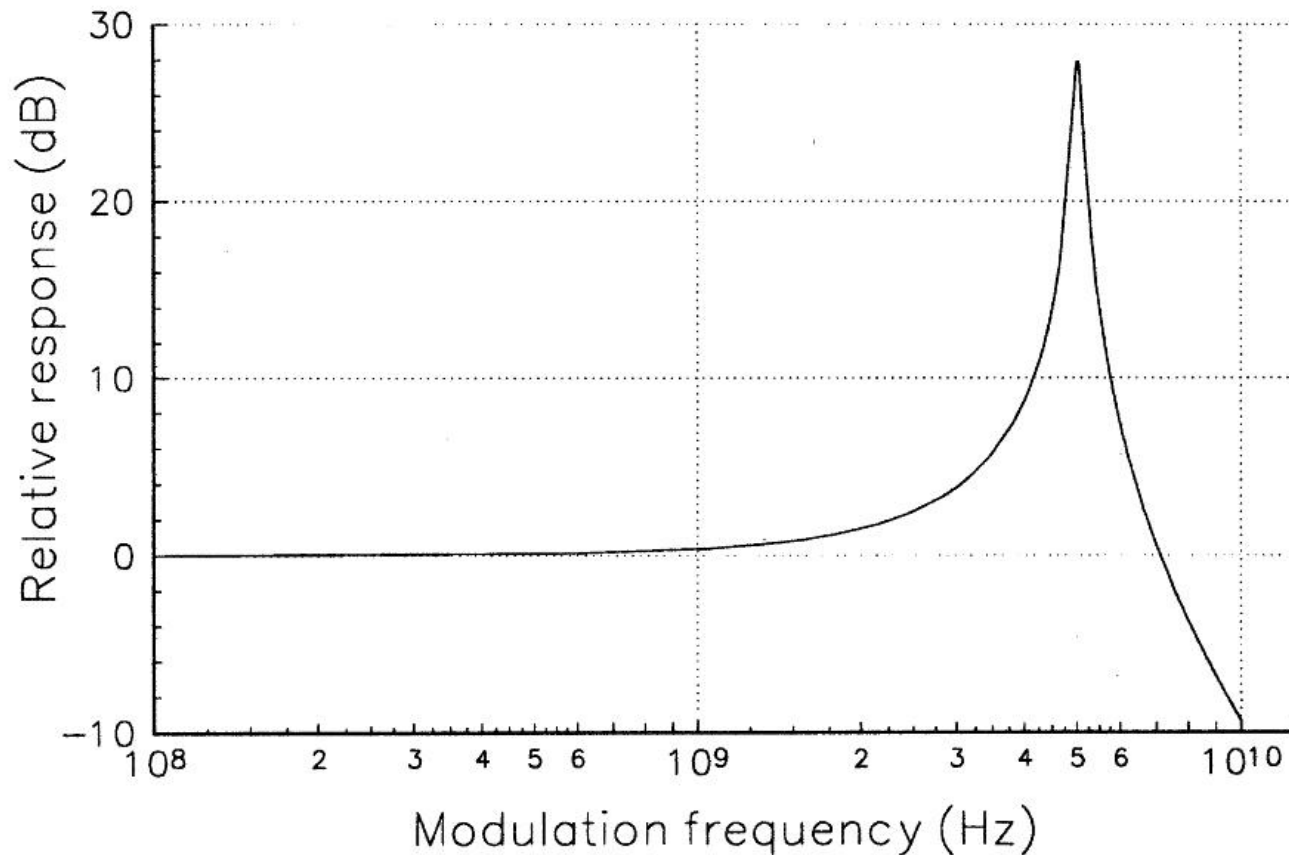
RIN

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



Raspunsul unei diode laser

- ▶ oscilatii de relaxare - x GHz



EIN

▶ Equivalent Input Noise

- R_i – rezistența de intrare în circuitul de modulație a diodei
- Variațiile de putere (zgomot) echivalente unor variații de curent (zgomot) prin dioda

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

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

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

Zgomotul fotodiodei

▶ NEP

- Noise Equivalent Power
- r – rezonvizitatea diodei

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

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

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

Zgomotul fotodiodei

▶ NEP

- cea mai mica putere detectabila

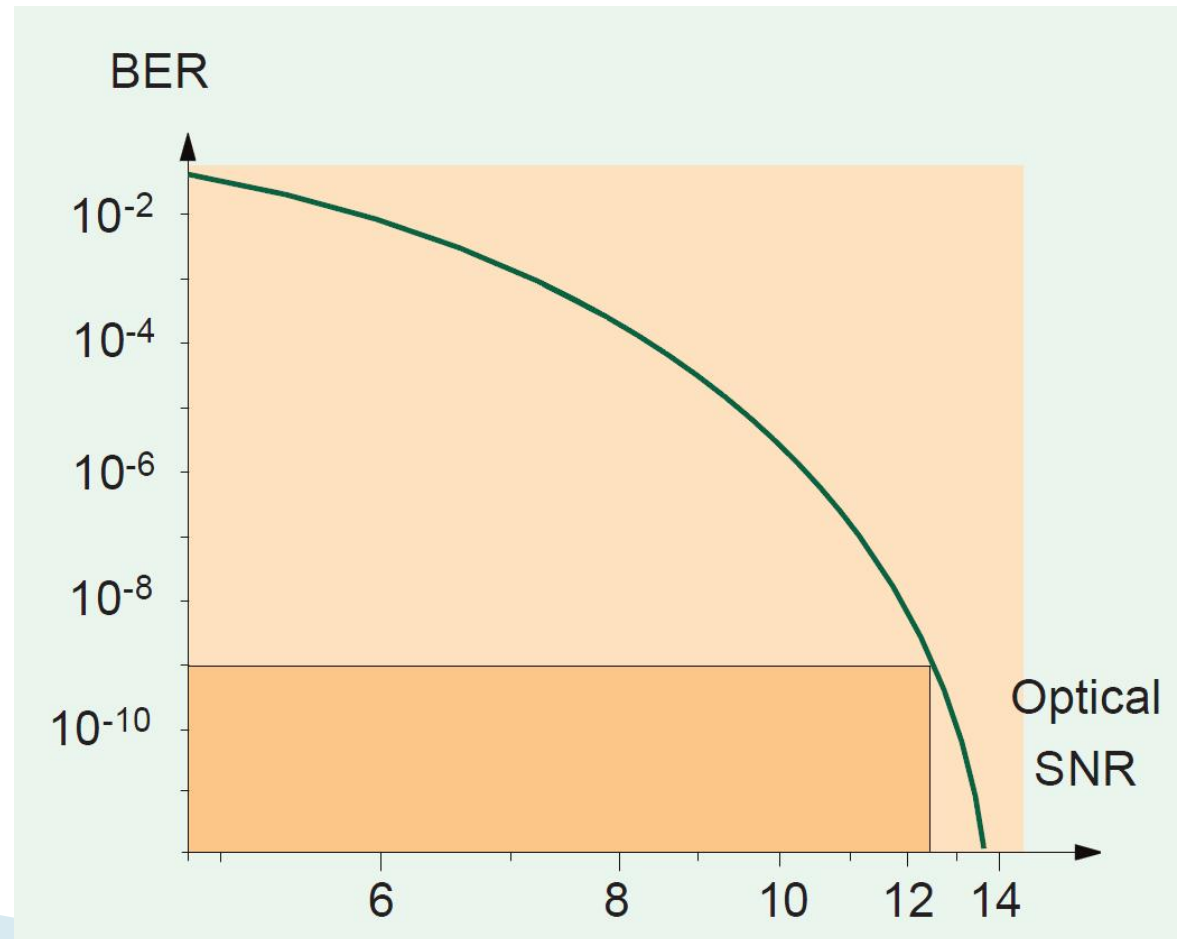
$$\langle i_n^2 \rangle = 2 \cdot e \cdot I \cdot BW_{PD} = 2 \cdot e \cdot (I_S + I_{dark}) \cdot BW_{PD}$$

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

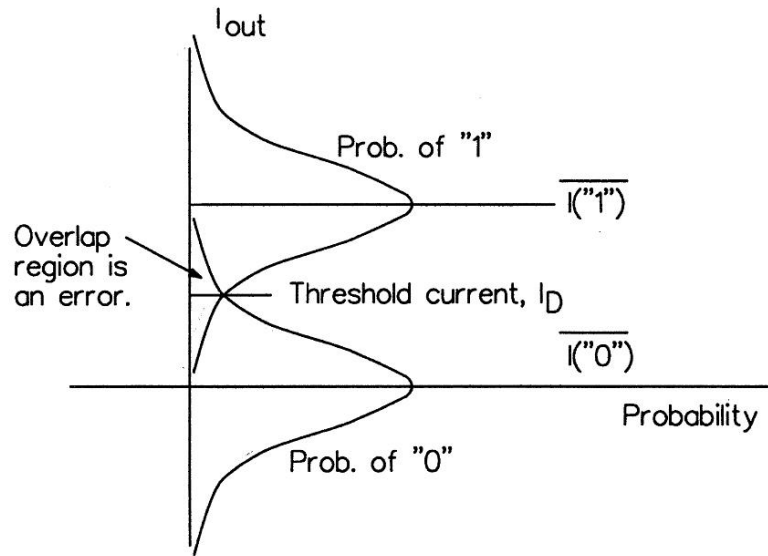
$$NEP[W / \sqrt{Hz}] = \frac{1}{r} \cdot \sqrt{2 \cdot e \cdot I_{dark}}$$

BER

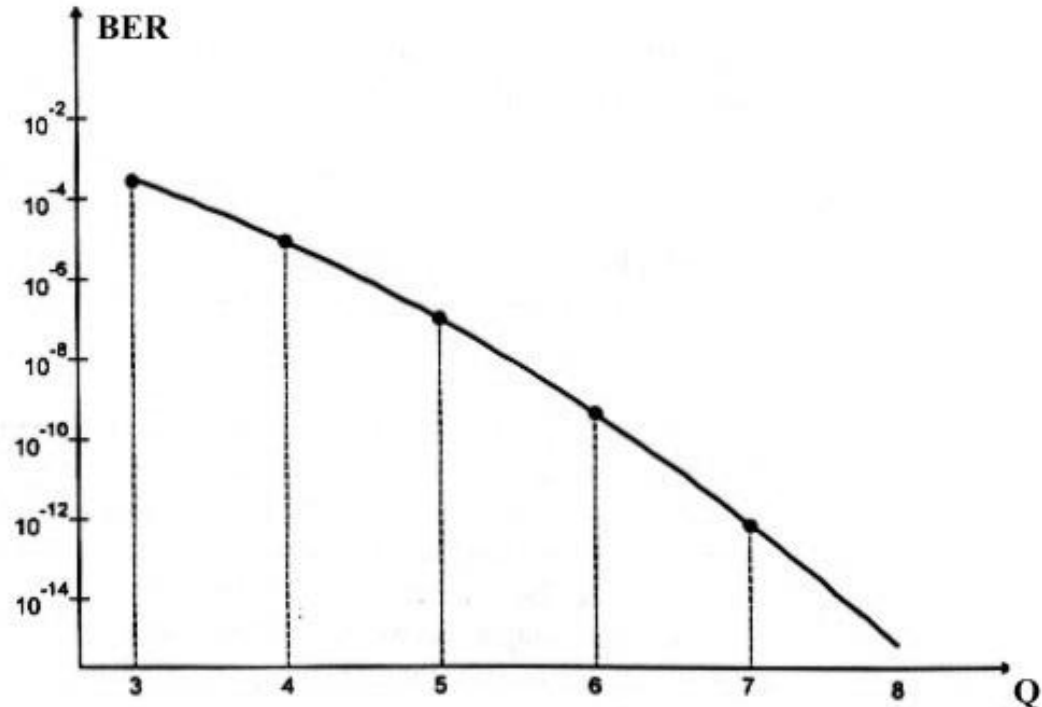
▶ Bit Error Rate



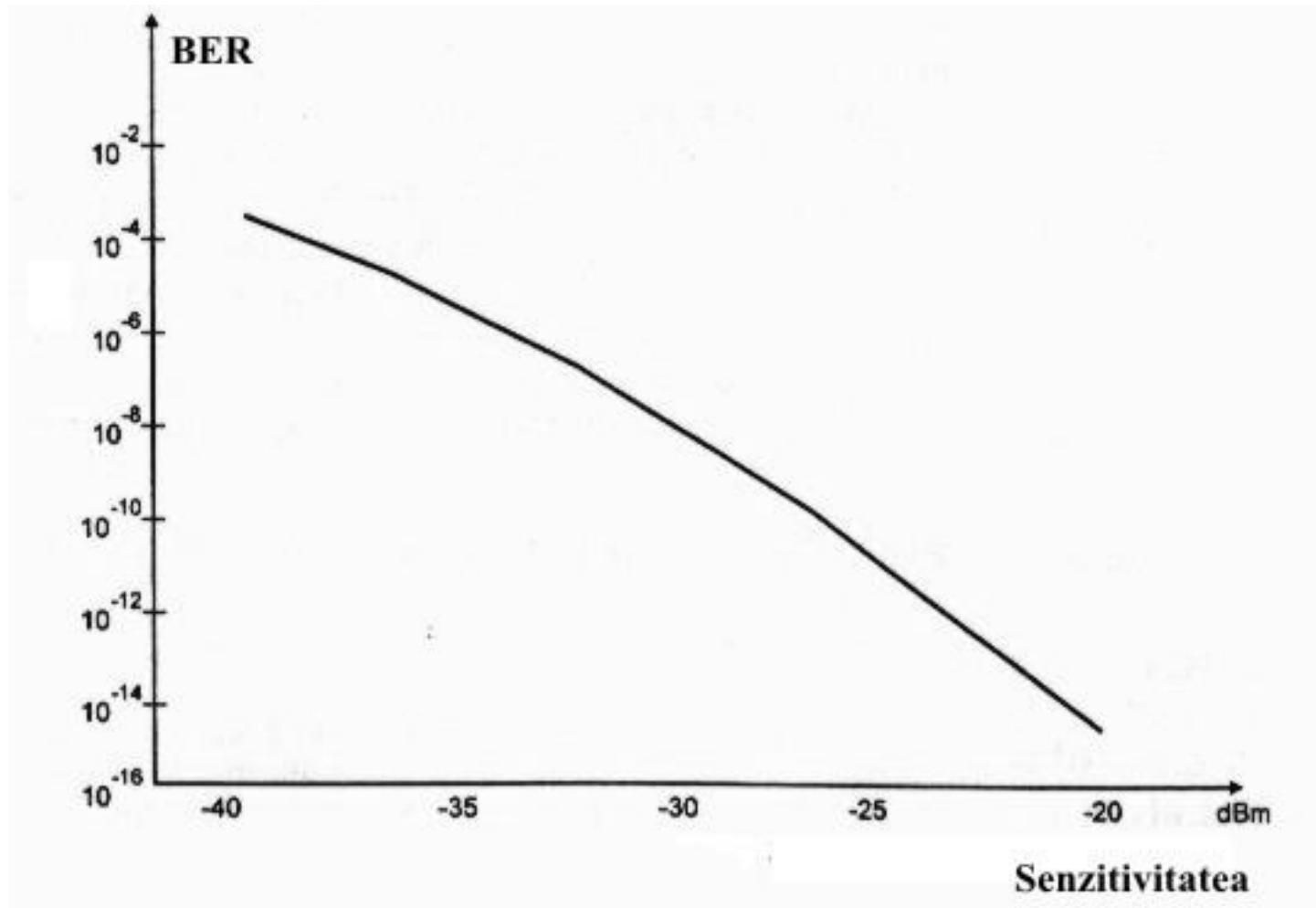
Probabilitate de eroare



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



Senzitivitatea unei diode



Contact

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