Optoelectronică, structuri şi tehnologii

Curs 6

2016/2017

Disciplina 2016/2017

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

Reprezentare logaritmică

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

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

0 dB	= 1	0 dBm	= 1 mW
+ 0.1 dB	= 1.023 (+2.3%)	3 dBm	= 2 mW
+ 3 dB	= 2	5 dBm	= 3 mW
+ 5 dB	= 3	10 dBm	= 10 mW
+ 10 dB	= 10	20 dBm	= 100 mW
−3 dB	= 0.5	−3 dBm	= 0.5 mW
−10 dB	= 0.1	−10 dBm	= 100 μW
−20 dB	= 0.01	−30 dBm	= 1 μW
−30 dB	= 0.001	−60 dBm	= 1 nW

[dBm] + [dB] = [dBm]

[dBm/Hz] + [dB] = [dBm/Hz]

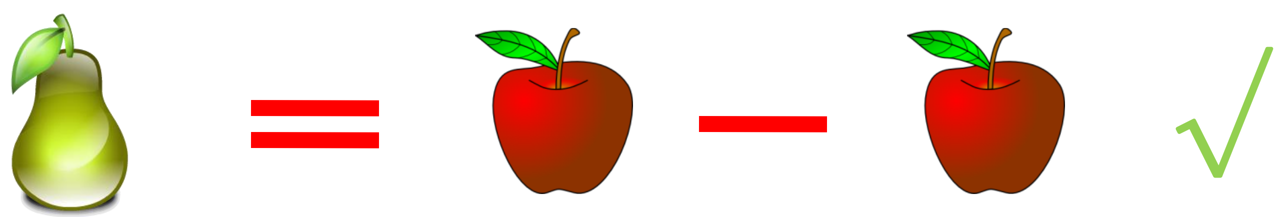
[x] + [dB] = [x]

Calculul atenuarii

$$\text{Pierderi} = \frac{P_{out}}{P_{in}}$$

$$\text{Pierderi}[\text{dB}] = [-]\,10 \cdot \log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

$$\text{Pierderi}[\text{dB}] = [-]\left(P_{out}[\text{dBm}] - P_{in}[\text{dBm}]\right)$$



$$\text{Atenuare}[\text{dB/km}] = \frac{\text{Pierderi}[\text{dB}]}{\text{lungime}[\text{km}]}$$

Recapitulare

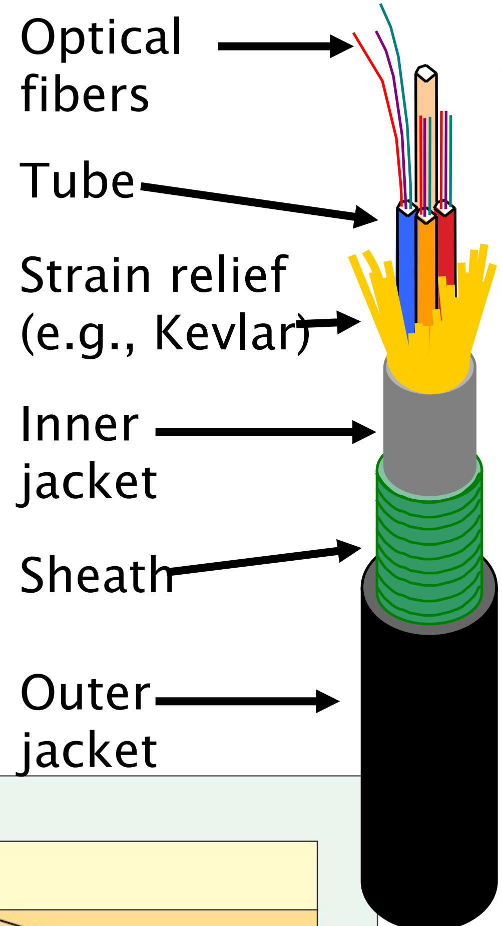
Curs 5

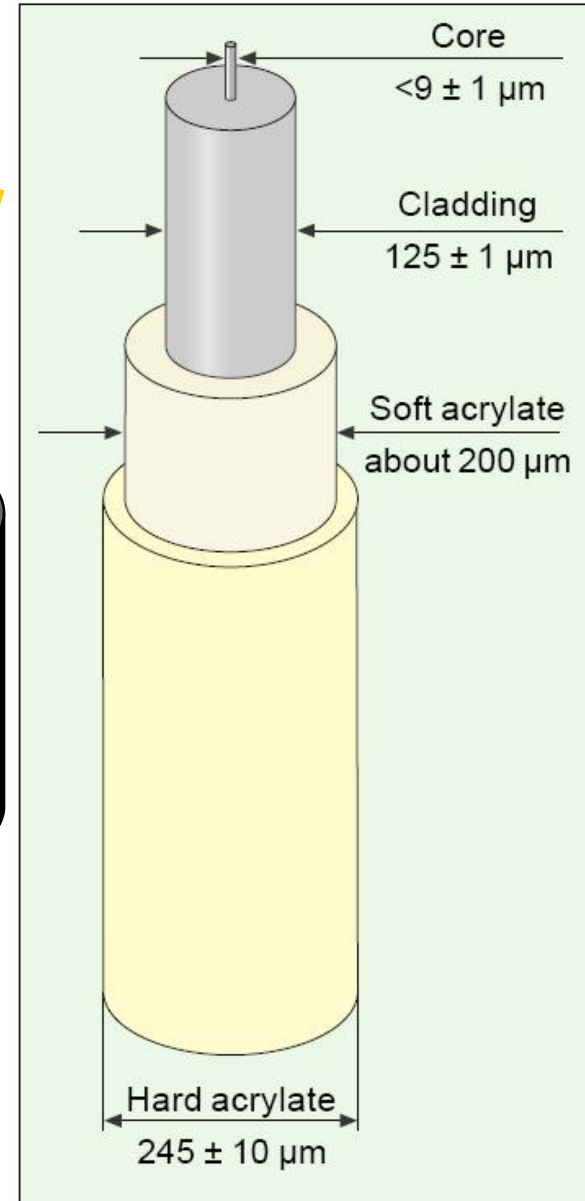
Fibra optică

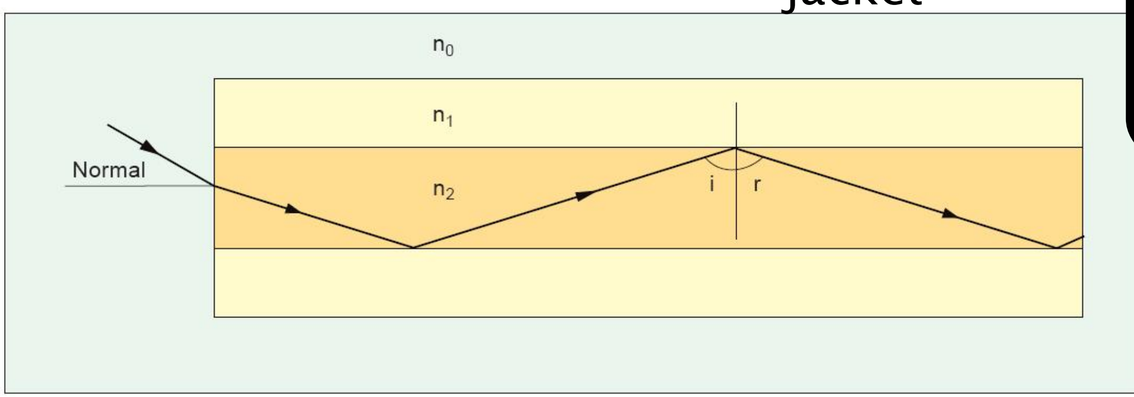
Capitolul 4

Fibra optica

- un ghid de unda dielectric
  - miez
  - teaca







Unghi de acceptanta, apertura numerica

- Unghi de acceptanta

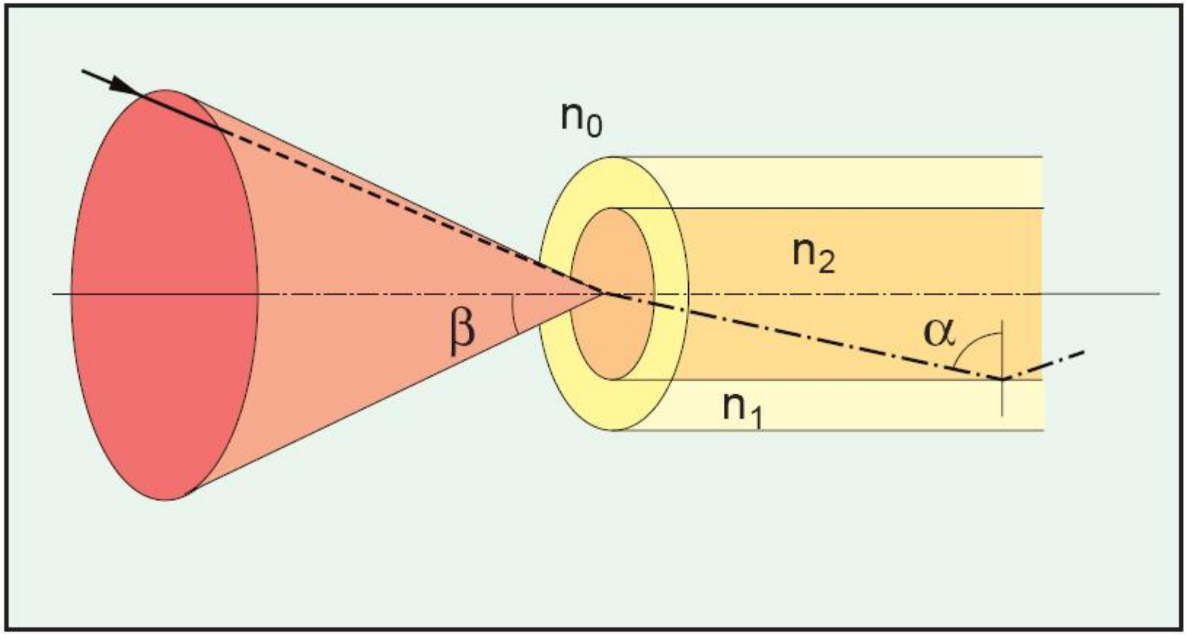
$$n_0 \cdot \sin\theta_{ACC} = n_2 \cdot \sin\phi_c$$

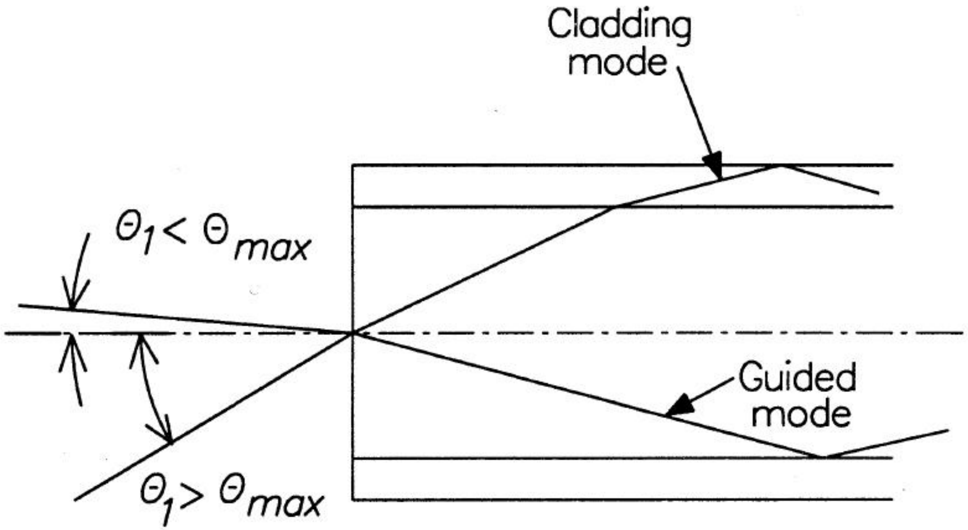
- **Apertura numerica**

$$NA = n_0 \cdot \sin\theta_{ACC}$$

$$NA = n_2 \sqrt{\frac{n_2^2 - n_1^2}{n_2^2}} = \sqrt{n_2^2 - n_1^2}$$

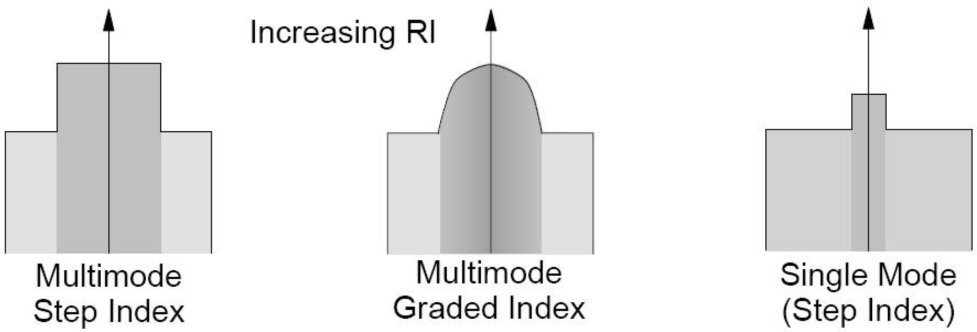
n_2 – miez
n_1 – teaca
$n_2 > n_1$!!

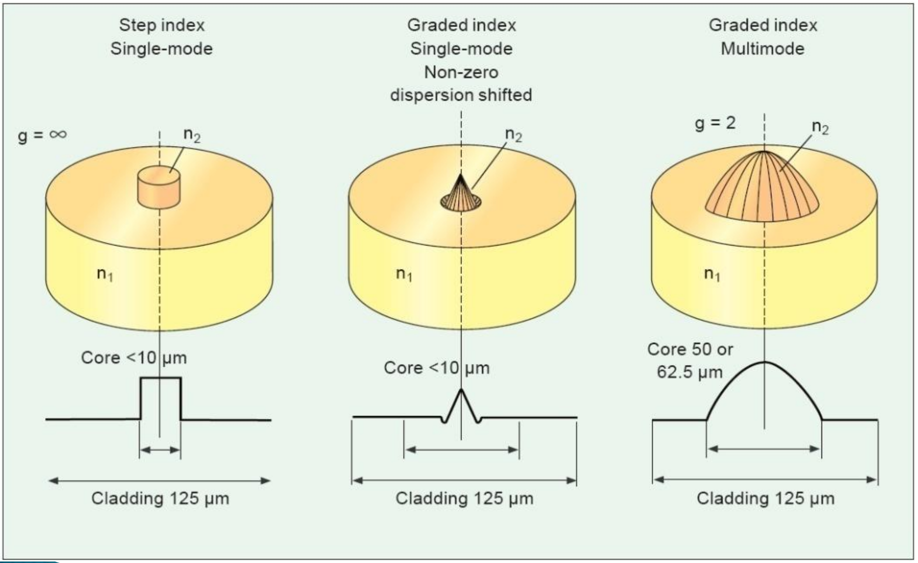


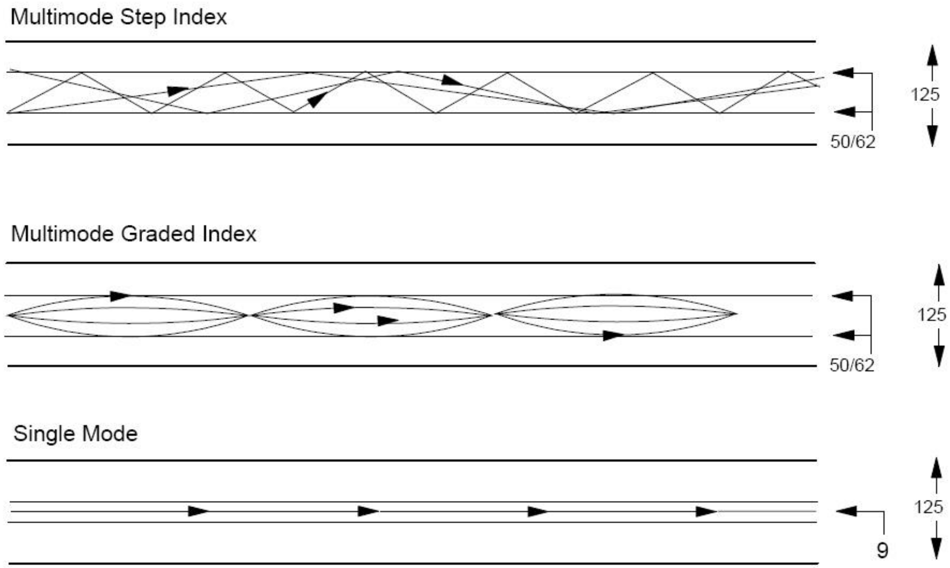


Tipuri de fibra

- Monomod
- Multimod
  - cu salt de indice
  - cu indice gradat



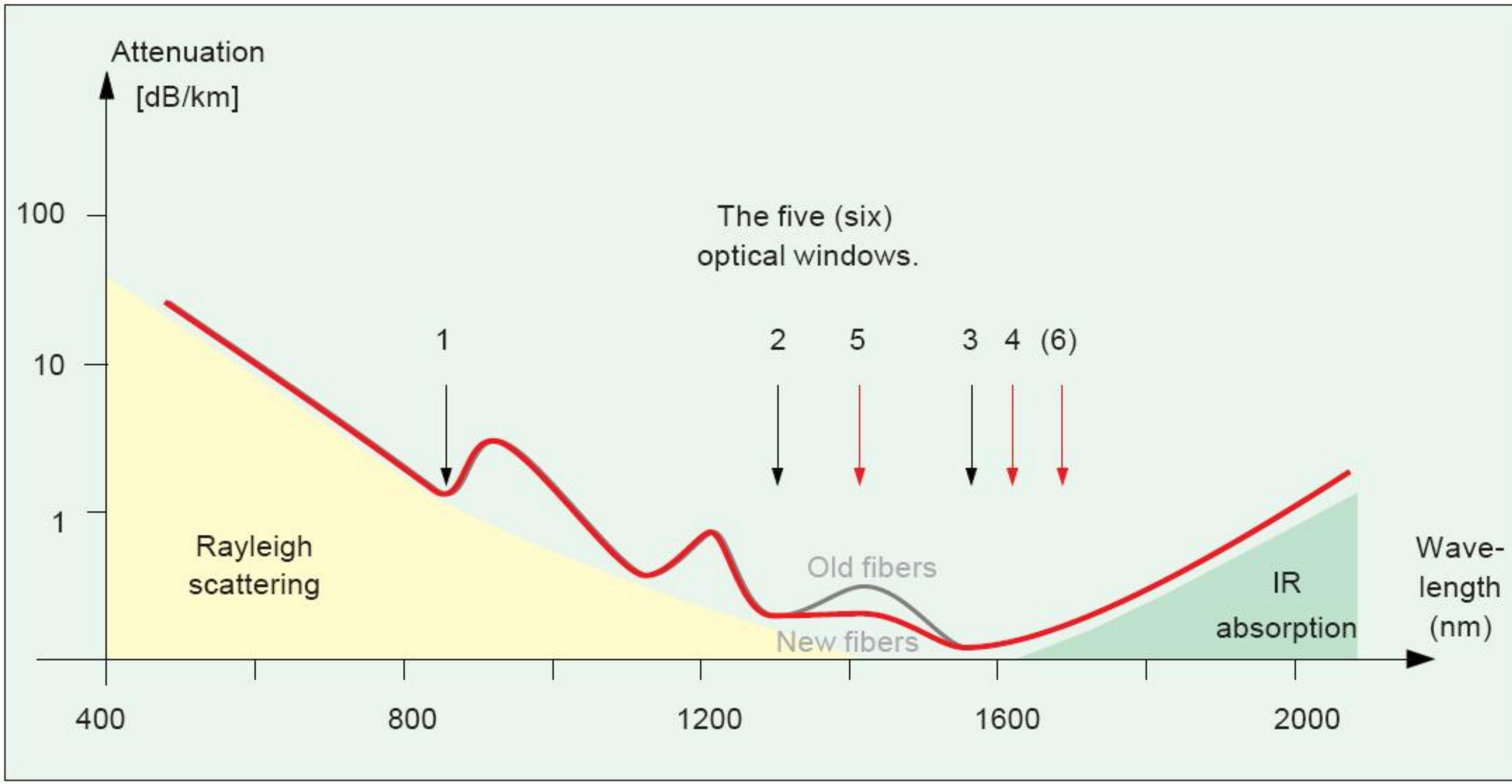




Fenomene de interes

- Cat de departe pot transmite semnalul luminos pe fibra
  - **atenuare**
- Cat de rapid pot transmite informația
  - **dispersie**

Absorbtie



distribuit, material, **dB/km**

$$A[dB] = A_i[dB/km] \cdot L[km]$$

Dispersia

- Dispersia modala
  - salt de indice

$$\Delta\tau_{\text{mod}} \cong \frac{L\cdot n_2\cdot\Delta}{2\sqrt{3}\cdot c} \approx \frac{L\cdot NA^2}{4\sqrt{3}\cdot c\cdot n_2}$$

  - indice gradat

$$\Delta\tau_{\text{mod}} \cong \frac{L\cdot n_2\cdot\Delta^2}{4\sqrt{3}\cdot c} \cong \frac{L\cdot NA^4}{16\sqrt{3}\cdot c\cdot n_2^3}$$

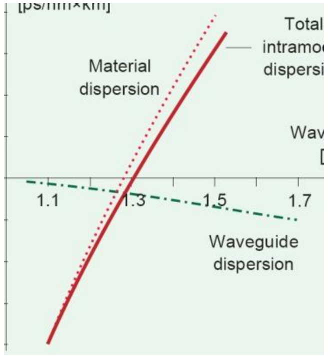
$$\Delta = 0.01 \div 0.02 \ll 1$$

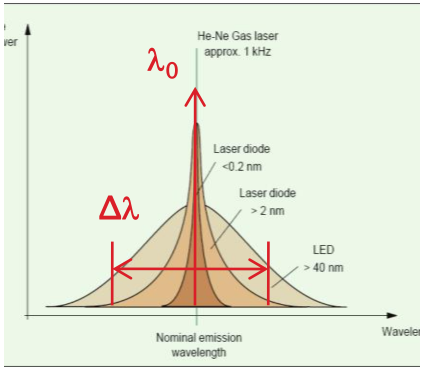
$$NA = 0.1 \div 0.2 < 1$$

- Dispersia cromatica

$$\Delta\tau_{cr} = D(\lambda)\cdot\Delta\lambda\cdot L$$

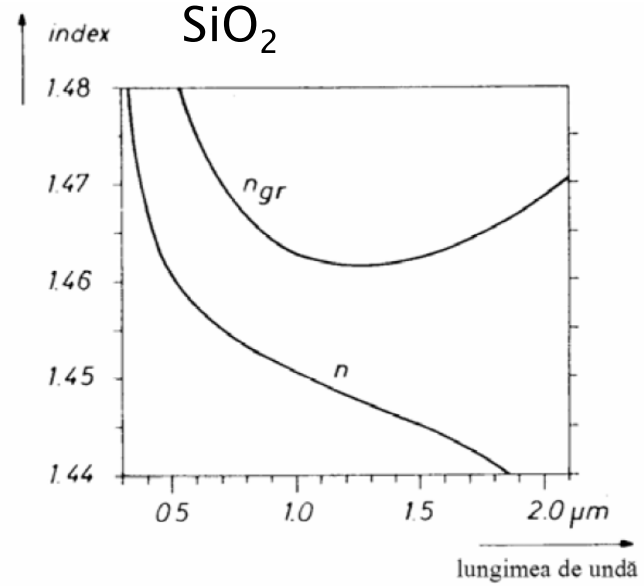
$$\mathrm{D}(\lambda) = \frac{\mathrm{S}_0}{4}\cdot\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right)$$





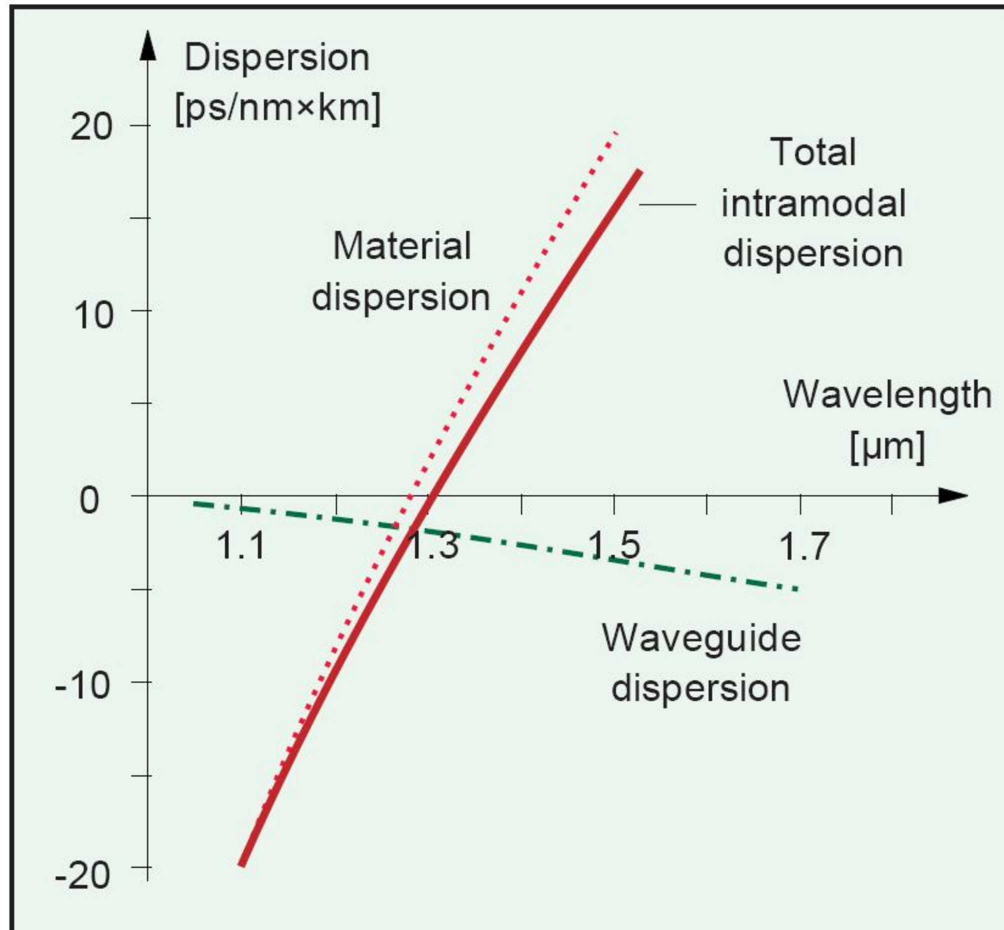
$$\Delta\tau_{tot} = \sqrt{\Delta\tau_{cr}^2 + \Delta\tau_{\text{mod}}^2}$$

Dispersia de material



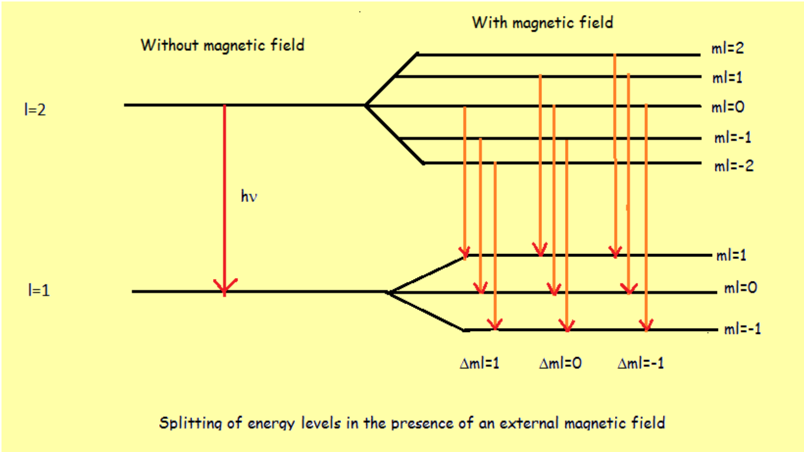
$$n_{gr} = n - \lambda \frac{dn}{d\lambda}$$

$$\Delta\tau_{mat} = \frac{L \cdot \lambda \cdot \Delta\lambda}{c} \cdot \frac{d^2 n}{d\lambda^2}$$



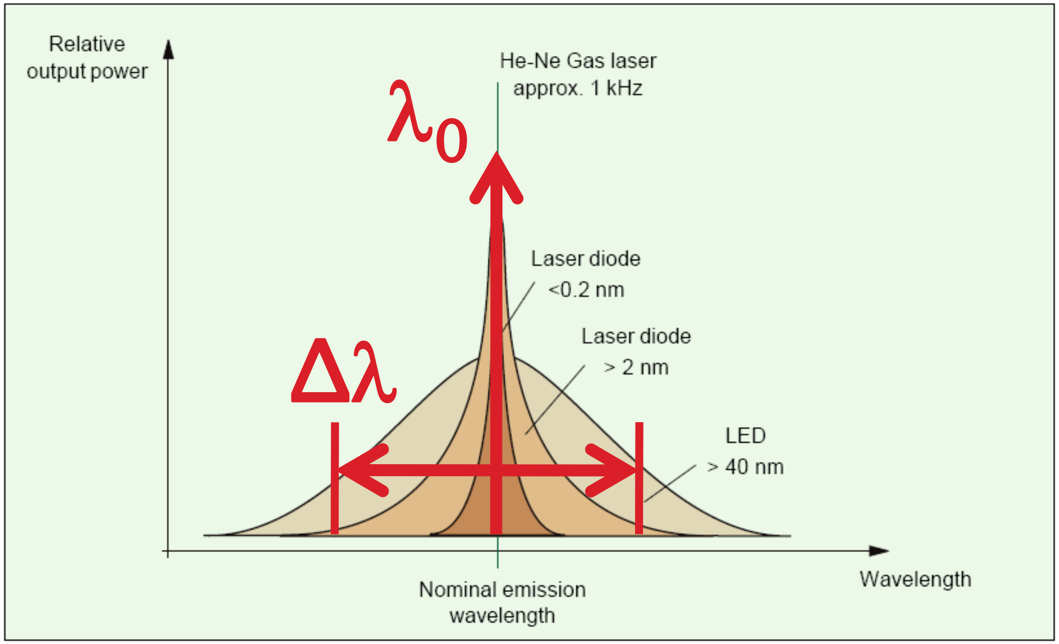
Calitatea spectrală a emiţătorilor optici

- degenerarea nivelelor energetice duce la aparitia benzilor energetice



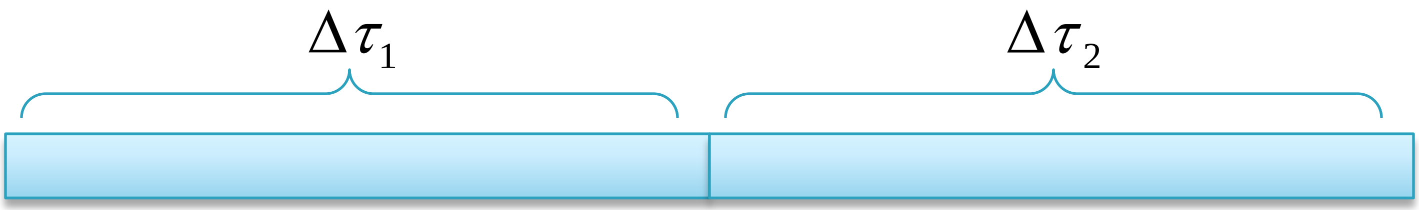
- Multitudinea de tranzitii posibile intre cate doua nivele situate in benzi energetice diferite duce la largirea caracteristicii spectrale a surselor

$$\lambda_0 \rightarrow \left[\lambda_0 - \frac{\Delta\lambda}{2}, \lambda_0 + \frac{\Delta\lambda}{2}\right]$$



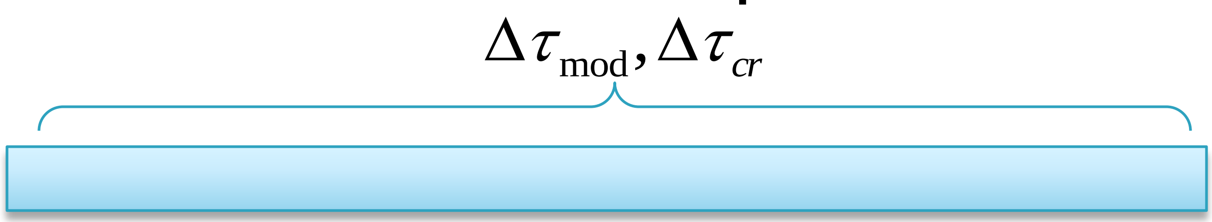
Sumarea efectelor

- efecte **succesive** se adună liniar



$$\Delta\tau_{tot} = \Delta\tau_1 + \Delta\tau_2$$

- efecte **simultane** se adună pătratic



$$\Delta\tau_{tot} = \sqrt{\Delta\tau_{cr}^2 + \Delta\tau_{\mathrm{mod}}^2}$$

Produs Banda · Distanta

$$\Delta\tau_{\mathrm{mod}} \cong \frac{L \cdot n_2 \cdot \Delta}{2\sqrt{3} \cdot c} \approx \frac{L \cdot NA^2}{4\sqrt{3} \cdot c \cdot n_2}$$

$$\Delta\tau_{tot} = \sqrt{\Delta\tau_{cr}^2 + \Delta\tau_{\mathrm{mod}}^2}$$

$$\Delta\tau_{cr} = D(\lambda) \cdot \Delta\lambda \cdot L$$

$$\Delta\tau_{tot} = const \cdot L$$

$$B_{opt} = \frac{0.44}{\Delta\tau_{tot}[ns]} \quad [GHz]$$

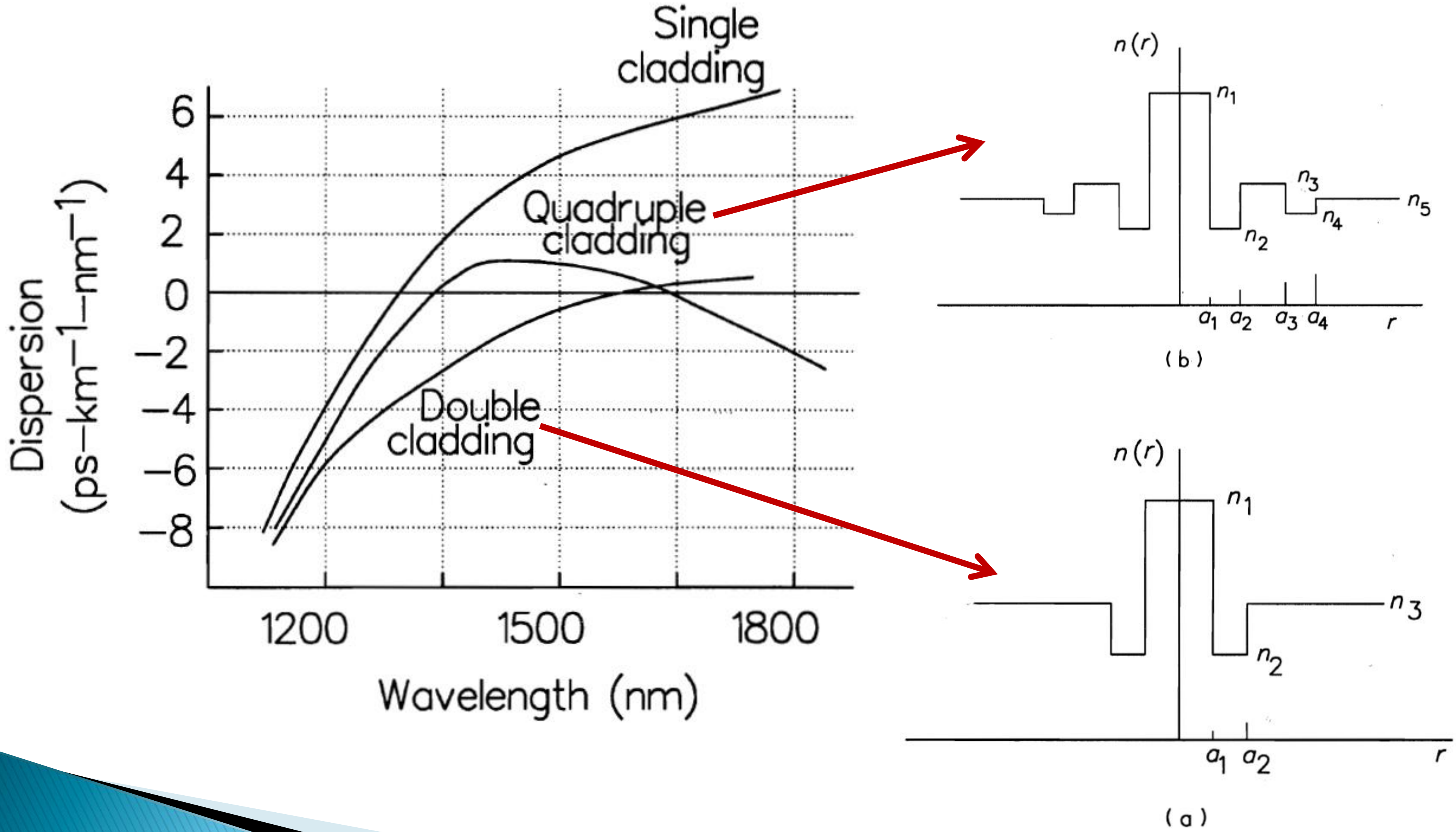
$$B_{opt} = \sqrt{2} B_{el}$$

$$V[Gb/s] \cong 2 \cdot B_{el}$$

$$V[Gb/s] \cong \frac{const}{L}$$

$$V[Gb/s] \cdot L[km] \cong const$$

Dispersion shifted fibers



Fibra optică – Tehnologie

Capitolul 5

Continuare

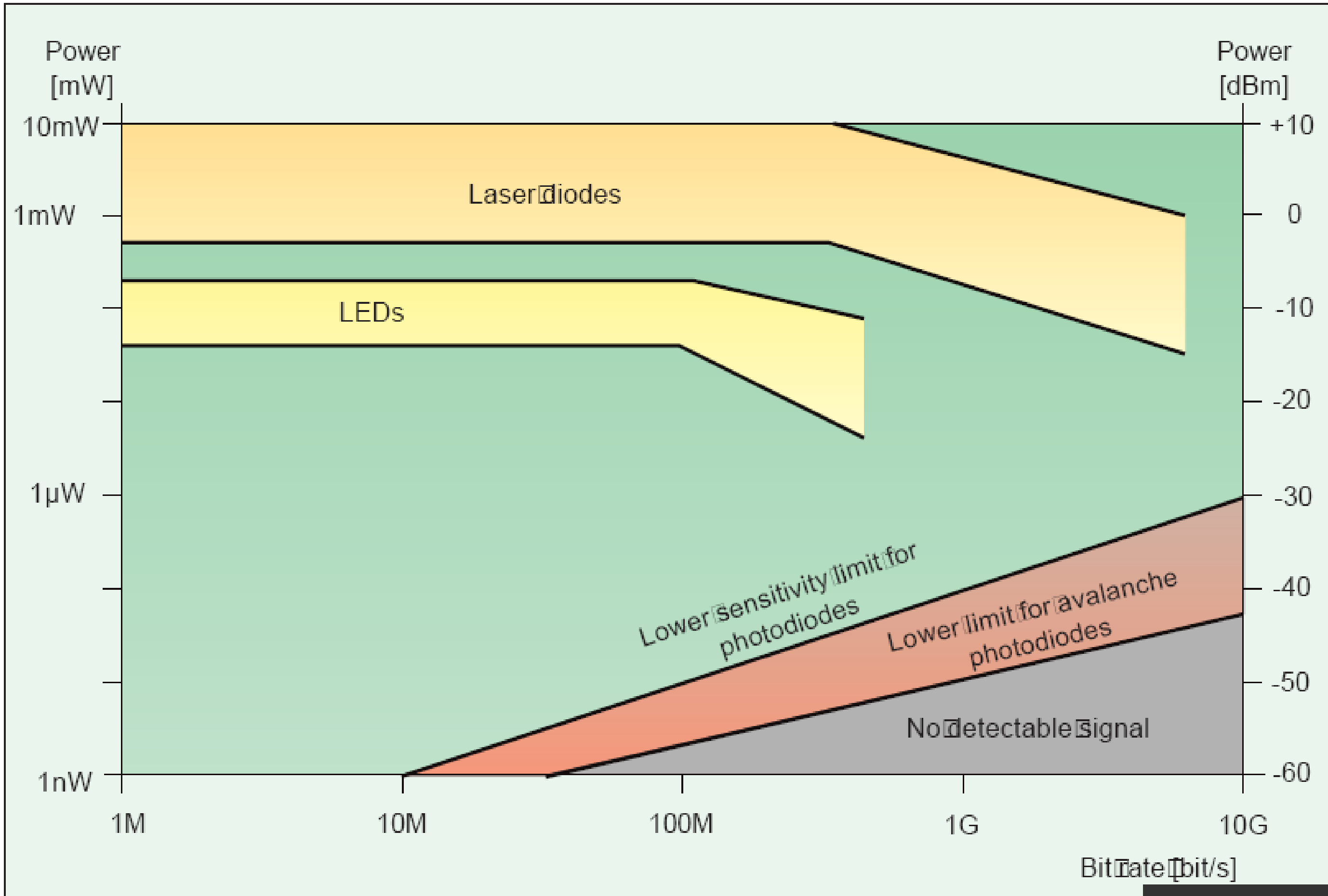
Dimensionarea unei legături pe fibra optică

Capitolul 6

Fenomene de interes

- Cat de departe pot transmite semnalul luminos pe fibra
  - **atenuare**
- Cat de rapid pot transmite informația
  - **dispersie**

Limite putere/bandă a dispozitivelor optoelectronice

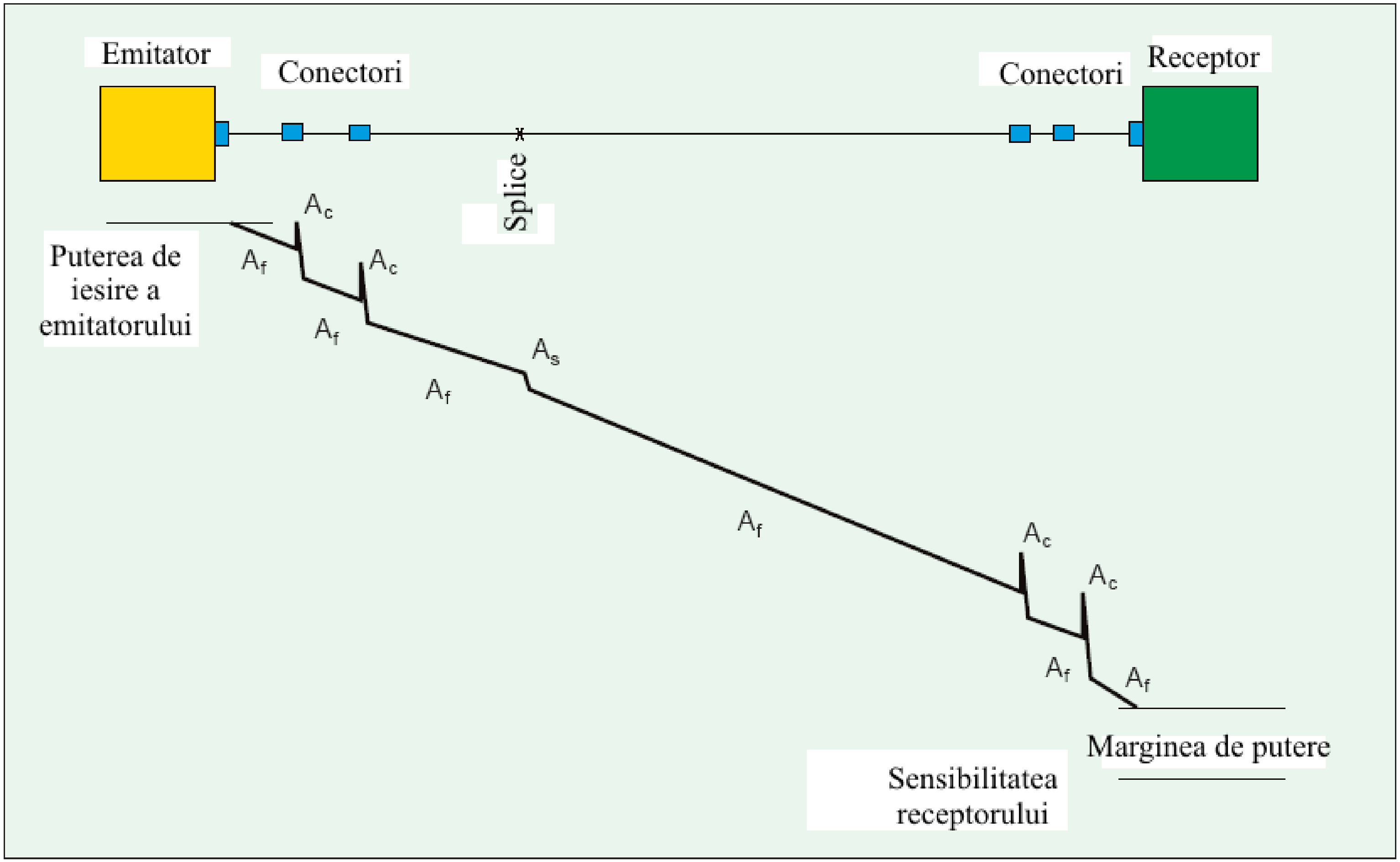


$$dB = 10 \cdot \log_{10}(P_2 / P_1)$$

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

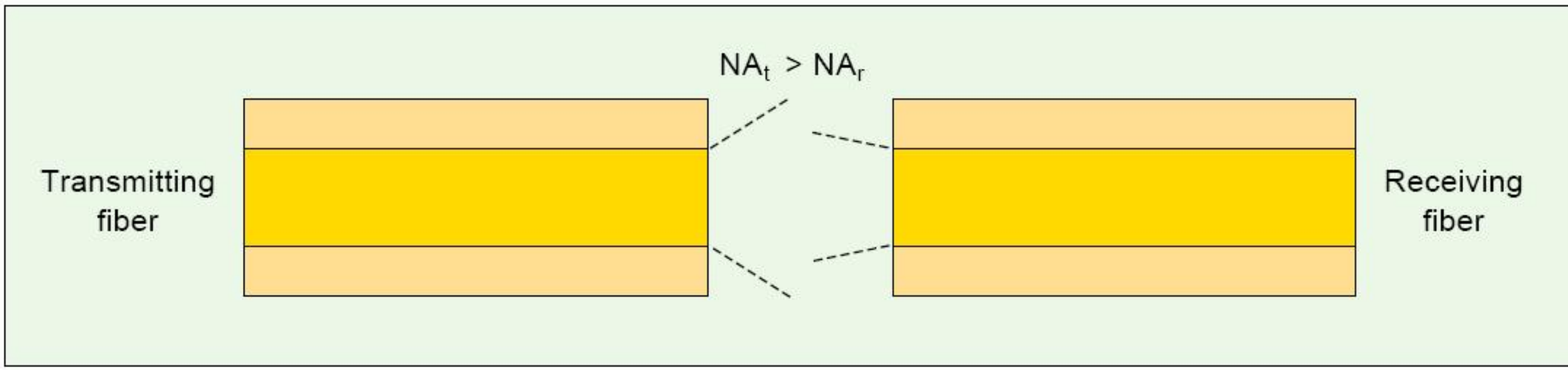
$$[dBm] + [dB] = [dBm]$$

Legatura pe fibra optica



Pierderi – Apertura numerica

- **Numai** la trecerea de la apertura numerica mai mare la apertura numerica mai mica



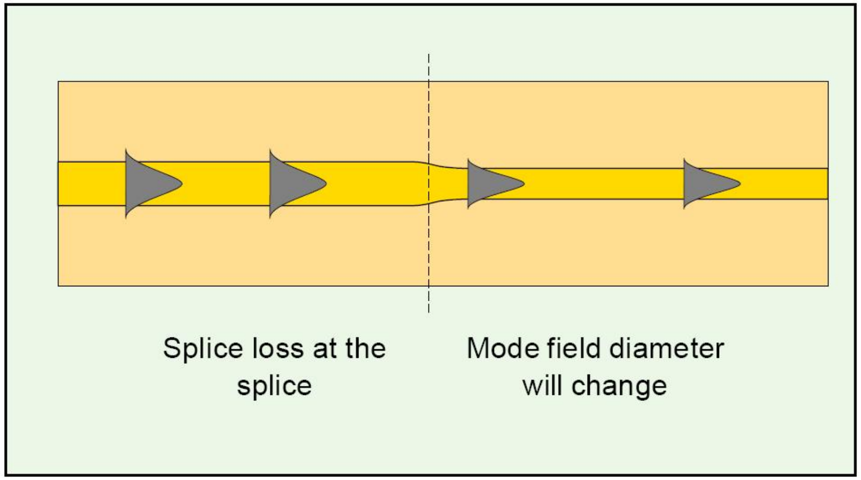
$$Atenuare_{NA}[dB] = -10 \cdot \log_{10}\left(\frac{NA_r}{NA_t}\right)^2$$

numai pentru $NA_r < NA_t$

$$Atenuare_{NA}[dB] > 0$$

Pierderi – Diametrul miezului

- **Numai** la trecerea de la diametru mai mare la diametru mai mic (multimod)
- **Bidirectional** (monomod)



- multimod

$$Atenuare_{\Phi}[dB] = -10 \cdot \log_{10}\left(\frac{\Phi_r}{\Phi_t}\right)^2$$

numai pentru $\Phi_r < \Phi_t$

- monomod

$$Atenuare_{\Phi}[dB] = -20 \cdot \log_{10}\left(\frac{2 \cdot w_1 \cdot w_2}{w_1^2 + w_2^2}\right)$$

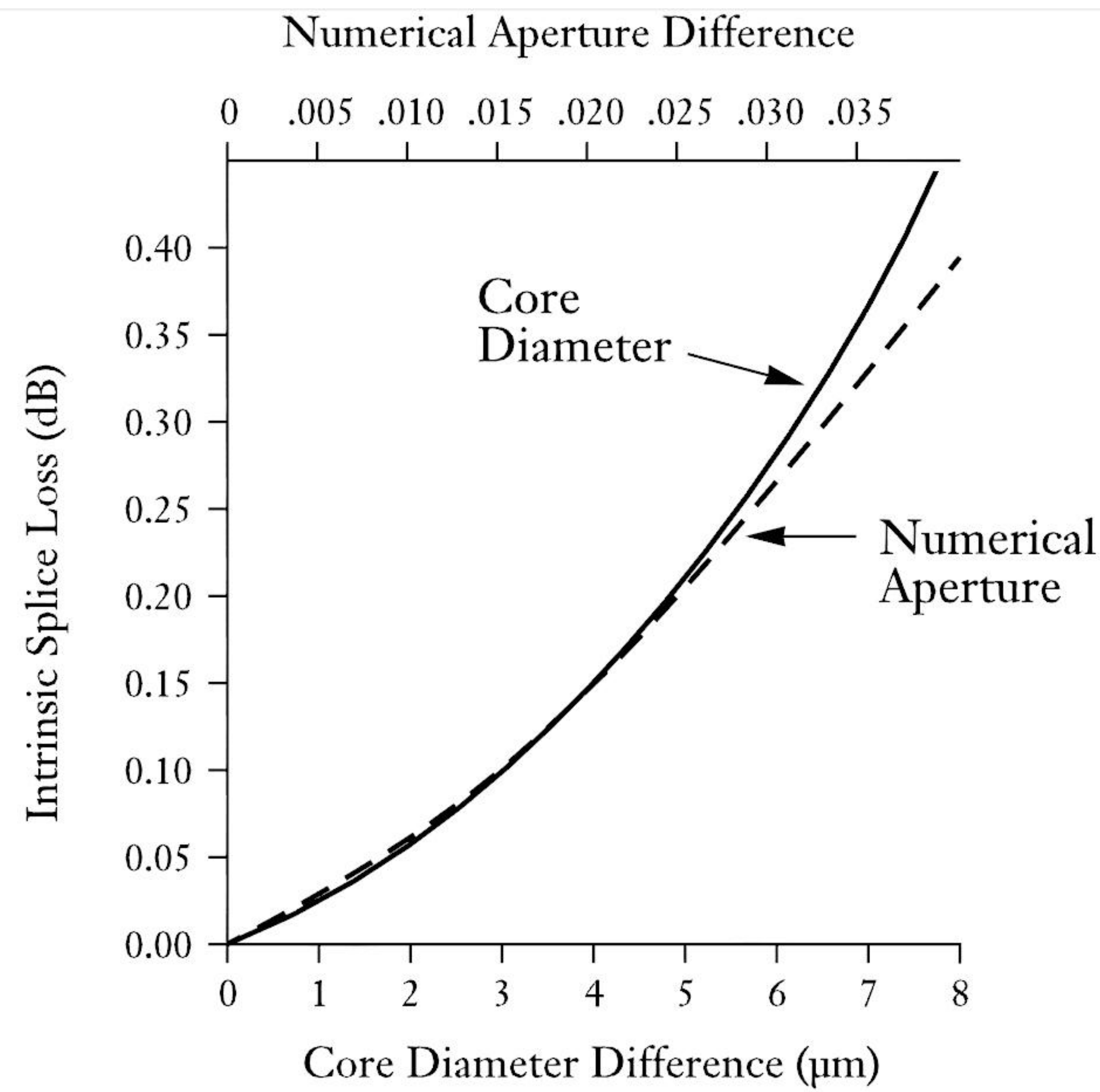
bidirectional $\forall w_1, w_2$

w = MFD !!

$$Atenuare_{\Phi}[dB] > 0$$

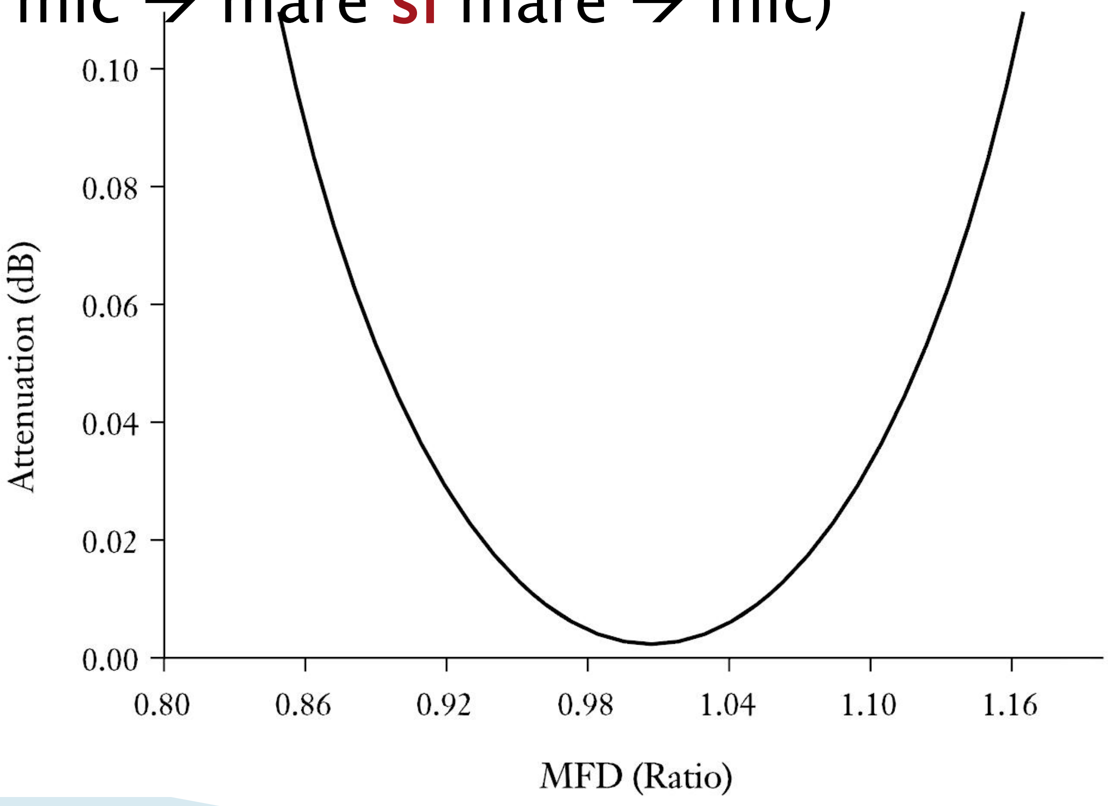
Pierderi

- multimod



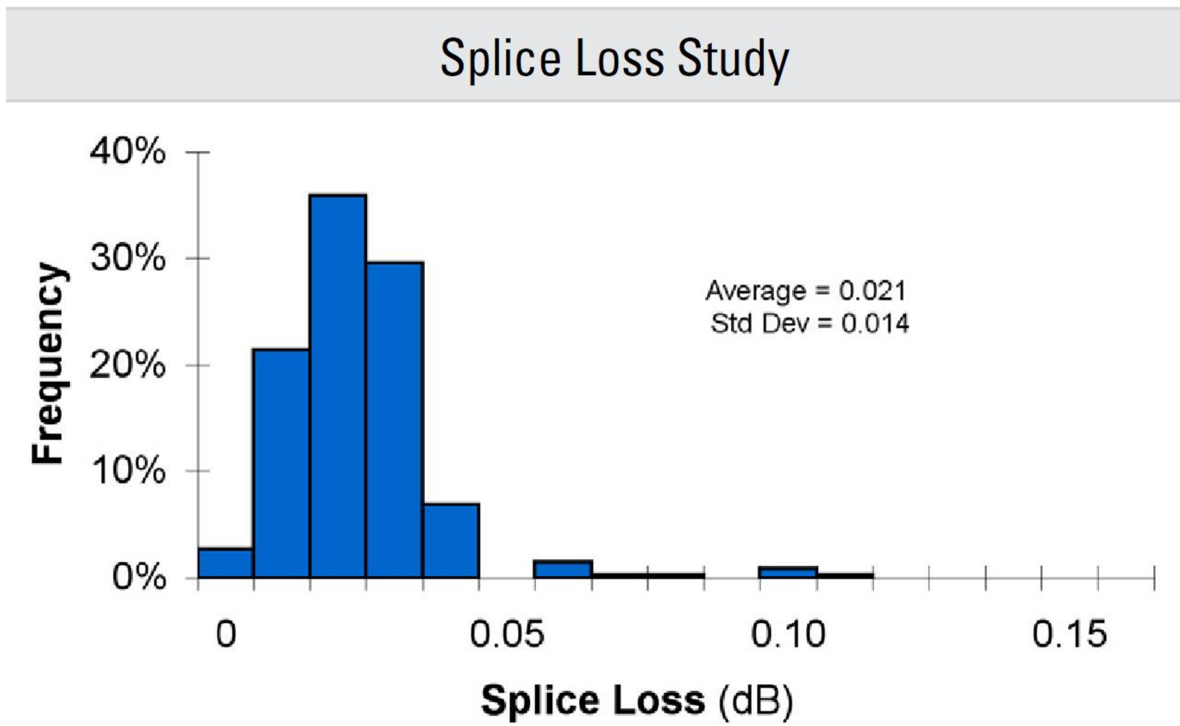
Pierderi

- monomod
  - predomina pierderile datorate diferentelor de MFD
  - se poate neglija NA
  - **Bidirectional** (MFD mic → mare **si** mare → mic)

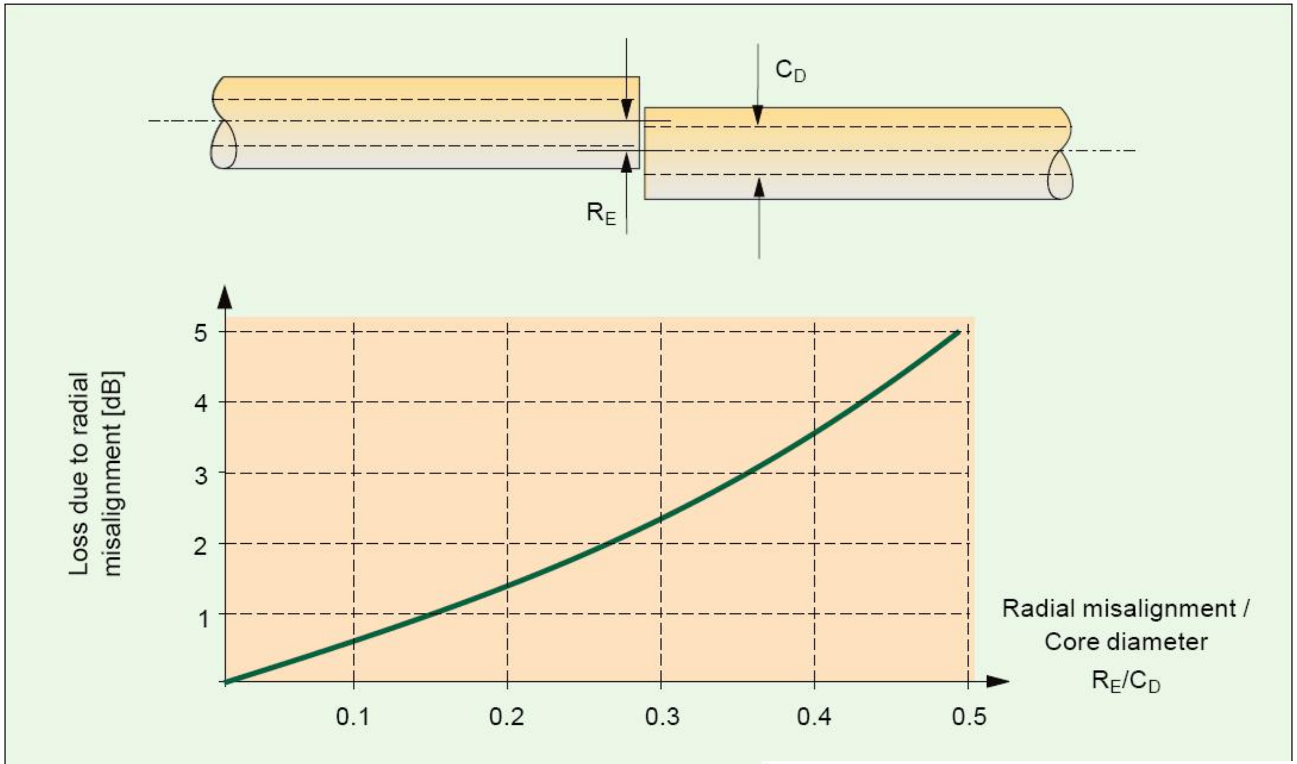


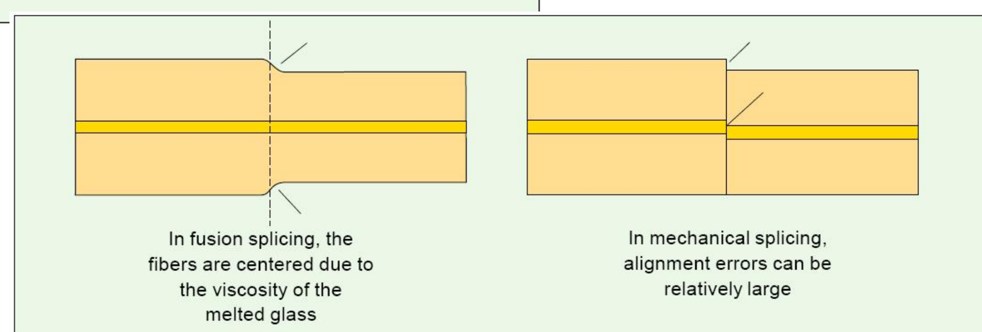
Pierderi

- monomod
- tipic: cel mai dezavantajos pentru MFD = 9.3±0.5μm → A=0.04dB

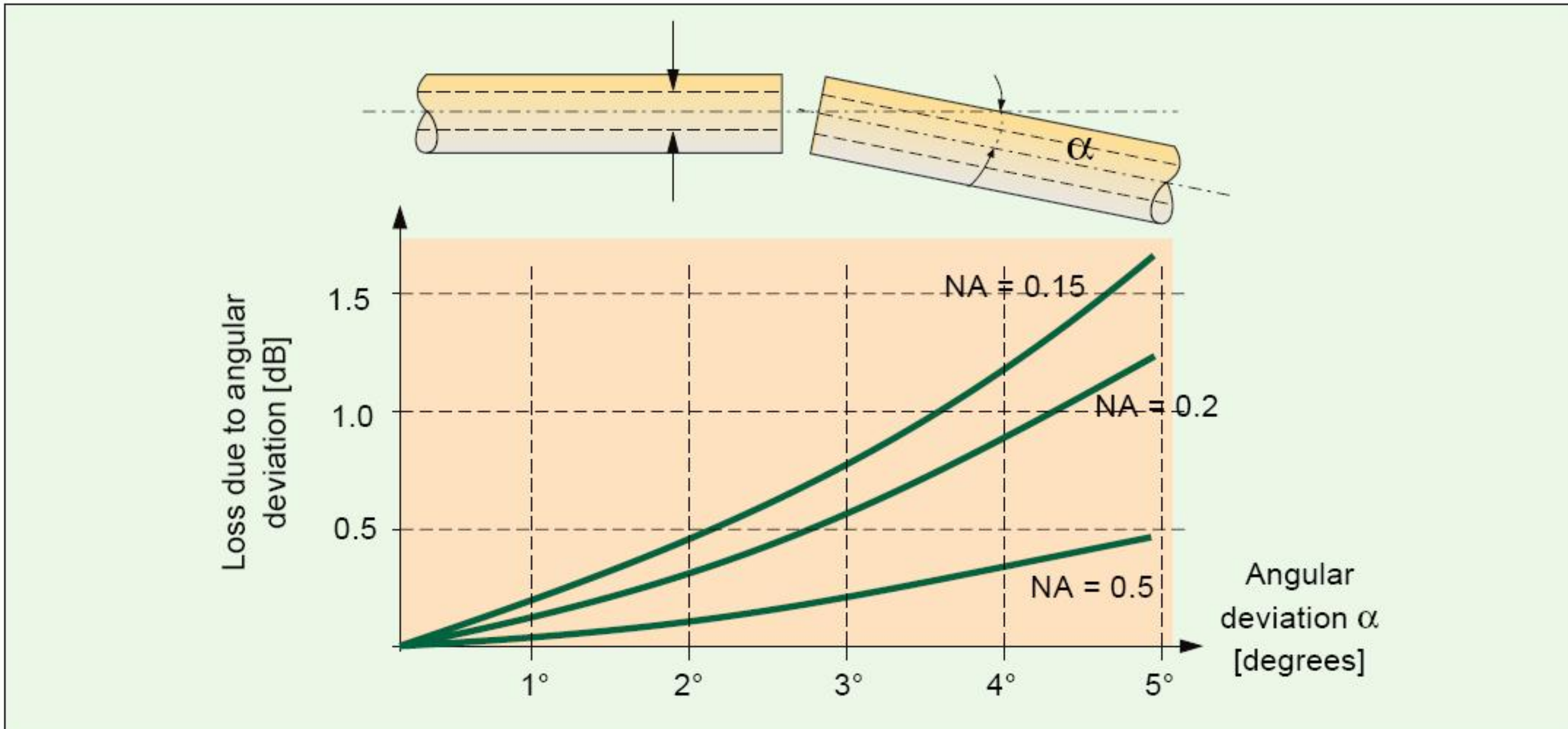


Pierderi – Nealinierea axelor



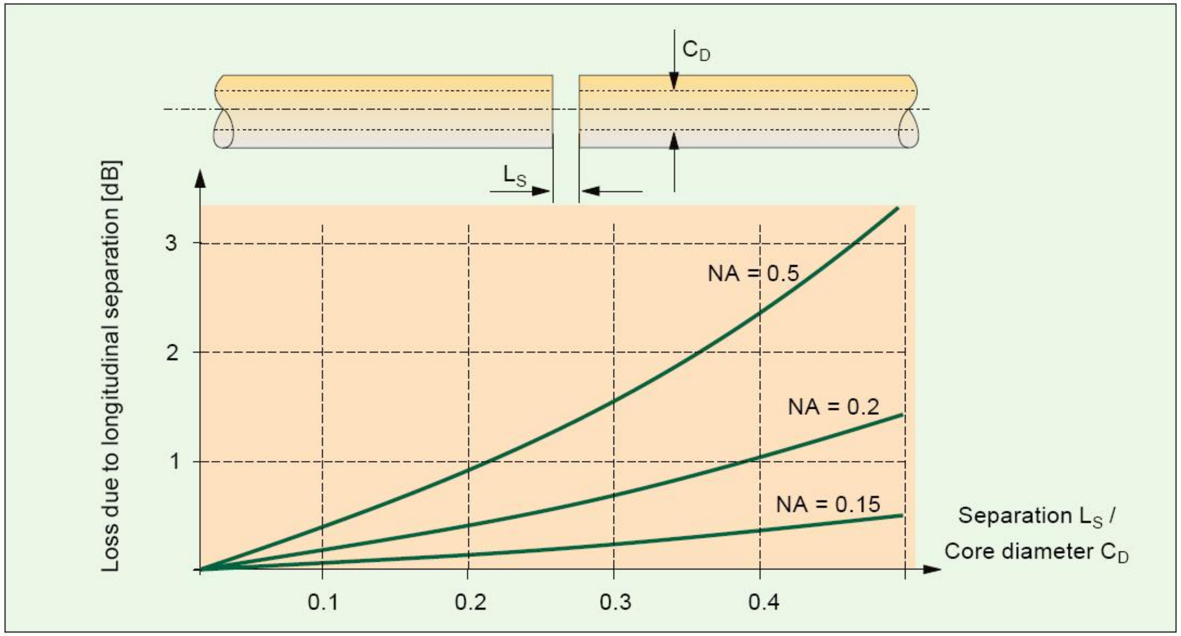


Pierderi – unghi



Pierderi – distanta

- Se foloseste un gel cu indice de refractie egal cu al fibrelor
- Se aduna pierderile generate de reflexie pe o lamela (pana la 16% – sticla)



Exemplu

- Trebuie să realizaţi o legătură pe fibră optică pe o distanţă de 50 km la o viteză de 1Gb/s.

Emiţători: = 1.5mW (Δλ=2nm, diverse λ)	NA = 0.17	Φ = 13μm
Pierderi splice (tehnologie)	0.15 dB/splice	
Pierderi conector	0.5 dB/conector	
Cablu conexiune: L = 20m	NA = 0.12	fibră: 11/125 μm
Cablu conexiune: L = 20m	NA = 0.15	fibră: 11/125 μm
Fibra 1	8 X 5km	
Fibra 2	4 X 10km	
Fibra 3	8 X 5km	
Fibra 4	4 X 10km	
Receptor: Sensitivitate = 1μW	NA = 0.25	Φ = 30μm

Catalog

Fibra nr. 3

Optical Specifications

Fiber Attenuation

Maximum Attenuation

Wavelength (nm)	Maximum Value* (dB/km)
1310	0.33 – 0.35
1383**	0.31 – 0.35
1490	0.21 – 0.24
1550	0.19 – 0.20
1625	0.20 – 0.23

*Maximum specified attenuation value available within the stated ranges.
**Attenuation values at this wavelength represent post-hydrogen aging performance.
Alternate attenuation offerings available upon request.

Attenuation vs. Wavelength

Range (nm)	Ref. λ (nm)	Max. α Difference (dB/km)
1285 – 1330	1310	0.03
1525 – 1575	1550	0.02

The attenuation in a given wavelength range does not exceed the attenuation of the reference wavelength (λ) by more than the value α.

Macrobend Loss

Mandrel Diameter (mm)	Number of Turns	Wavelength (nm)	Induced Attenuation* (dB)
32	1	1550	≤0.03
50	100	1310	≤0.03
50	100	1550	≤0.03
60	100	1625	≤0.03

*The induced attenuation due to fiber wrapped around a mandrel of a specified diameter.

Point Discontinuity

Wavelength (nm)	Point Discontinuity (dB)
1310	≤0.05
1550	≤0.05

Cable Cutoff Wavelength (λ_{ccf})

$\lambda_{ccf} \leq 1260$ nm

Mode-Field Diameter

Wavelength (nm)	MFD (µm)
1310	9.4 ± 0.4
1550	10.6 ± 0.5

Dispersion

Wavelength (nm)	Dispersion Value [ps/(nm•km)]
1550	≤18
1625	≤23

Zero Dispersion Wavelength (λ_0): 1310 nm $\leq \lambda_0 \leq$ 1324 nm
Zero Dispersion Slope (S_0): ≤ 0.092 ps/(nm²•km)

Polarization Mode Dispersion (PMD)

	Value (ps/√km)
PMD Link Design Value	≤0.06*
Maximum Individual Fiber	≤0.2

*Complies with IEC 60794-3: 2001, Section 5.5, Method 1, September 2001.

The PMD link design value is a term used to describe the PMD of concatenated lengths of fiber (also known as PMD_Q). This value represents a statistical upper limit for total link PMD. Individual PMD values may change when cabled. Corning's fiber specification supports network design requirements for a 0.5 ps/√km maximum PMD.

Dimensional Specifications

Glass Geometry

Fiber Curl	≥ 4.0 m radius of curvature
Cladding Diameter	125.0 ± 0.7 µm
Core-Clad Concentricity	≤ 0.5 µm
Cladding Non-Circularity	≤ 0.7%

Coating Geometry

Coating Diameter	245 ± 5 µm
Coating-Cladding Concentricity	<12 µm

Environmental Specifications

Environmental Test	Test Condition	Induced Attenuation 1310 nm, 1550 nm & 1625 nm (dB/km)
Temperature Dependence	-60°C to +85°C*	≤0.05
Temperature Humidity Cycling	-10°C to +85°C* up to 98% RH	≤0.05
Water Immersion	23°± 2°C	≤0.05
Heat Aging	85°± 2°C*	≤0.05

*Reference temperature = +23°C

Operating Temperature Range: -60°C to +85°C

Mechanical Specifications

Proof Test

The entire fiber length is subjected to a tensile stress ≥100 kpsi (0.7 GPa)*.
*Higher proof test levels available.

Length

Fiber lengths available up to 50.4* km/spool.
*Longer spliced lengths available.

Performance Characterizations

Characterized parameters are typical values.

Core Diameter	8.2 µm
Numerical Aperture	0.14 *NA is measured at the one percent power level of a one-dimensional far-field scan at 1310 nm.*
Zero Dispersion Wavelength (λ_0)	1317 nm
Zero Dispersion Slope (S_0)	0.088 ps/(nm²•km)
Effective Group Index of Refraction (N_{eff})	1310 nm: 1.4670 1550 nm: 1.4677
Fatigue Resistance Parameter (N_d)	20
Coating Strip Force	Dry: 0.6 lbs. (3N) Wet, 14-day room temperature: 0.6 lbs. (3N)
Rayleigh Backscatter Coefficient (for 1 ns Pulse Width)	1310 nm: -77 dB 1550 nm: -82 dB
Stimulated Brillouin Scattering Threshold	20 dBm[1]

Notes:
(1) When characterized with a transmitter specifying 17 dBm SBS threshold over standard single-mode fiber. While absolute SBS threshold is a function of distance and signal format, NexCor fiber offers a 3 dB improvement over standard single-mode fiber independent of these variables.

Formulas

Dispersion

$$\text{Dispersion} = D(\lambda) := \frac{S_0}{4}\left[\lambda - \frac{\lambda_0^4}{\lambda^3}\right] \text{ps/(nm•km)},$$

for 1200 nm ≤ λ ≤ 1625 nm

λ = Operating Wavelength

Cladding Non-Circularity

$$\text{Cladding Non-Circularity} = \left[1 - \frac{\text{Min. Cladding Diameter}}{\text{Max. Cladding Diameter}}\right] \times 100$$

How to Order

Contact your sales representative, or call the Optical Fiber Customer Service Department:
Ph: 607-248-2000 (U.S. and Canada)
+44-1244-287-437 (Europe)
Email: opticalfiber@corning.com
Please specify the fiber type, attenuation and quantity when ordering.

Corning Incorporated
www.corning.com/opticalfiber
One Riverfront Plaza
Corning, NY 14831
U.S.A.

Ph: 800-525-2524 (U.S. and Canada)
607-786-8125 (International)
Fx: 800-539-3632 (U.S. and Canada)
607-786-8344 (International)
Email: cofic@corning.com

Europe
Ph: 00 800 6620 6621 (U.K., Ireland, Italy, France, Germany, The Netherlands, Spain and Sweden)
+1 607 786 8125 (All Other Countries)
Fx: +1 607 786 8344

Asia Pacific
Australia
Ph: 1-800-148-690
Fx: 1-800-148-568
Indonesia
Ph: 001-803-015-721-1261
Fx: 001-803-015-721-1262
Malaysia
Ph: 1-800-80-3156
Fx: 1-800-80-3155
Philippines
Ph: 1-800-1-116-0338
Fx: 1-800-1-116-0339
Singapore
Ph: 800-1300-955
Fx: 800-1300-956
Thailand
Ph: 001-800-1-3-721-1263
Fx: 001-800-1-3-721-1264

Latin America
Brazil
Ph: 000817-762-4732
Fx: 000817-762-4996
Mexico
Ph: 001-800-235-1719
Fx: 001-800-339-1472
Venezuela
Ph: 800-1-4418
Fx: 800-1-4419

Greater China
Email: GCCofic@corning.com
Beijing
Ph: (86) 10-6505-5066
Fx: (86) 10-6505-5077
Hong Kong
Ph: (852) 2807-2723
Fx: (852) 2807-2152
Shanghai
Ph: (86) 21-3222-4668
Fx: (86) 21-6288-1575
Taiwan
Ph: (886) 2-2716-0338
Fx: (886) 2-2716-0339

Intrebari

- (1p) Ce lungime de undă veţi alege pentru emiţător? Justificaţi.
- (2p) Alegeţi fibrele pe care le veţi utiliza. Justificaţi. Realizaţi schiţa legăturii
- (1p) Puteţi realiza o legătură funcţională? Justificaţi.

Zero Dispersion Wavelength (λ_0)	1317 nm
Zero Dispersion Slope (S_0)	0.088 ps/(nm^2•km)

Legatura

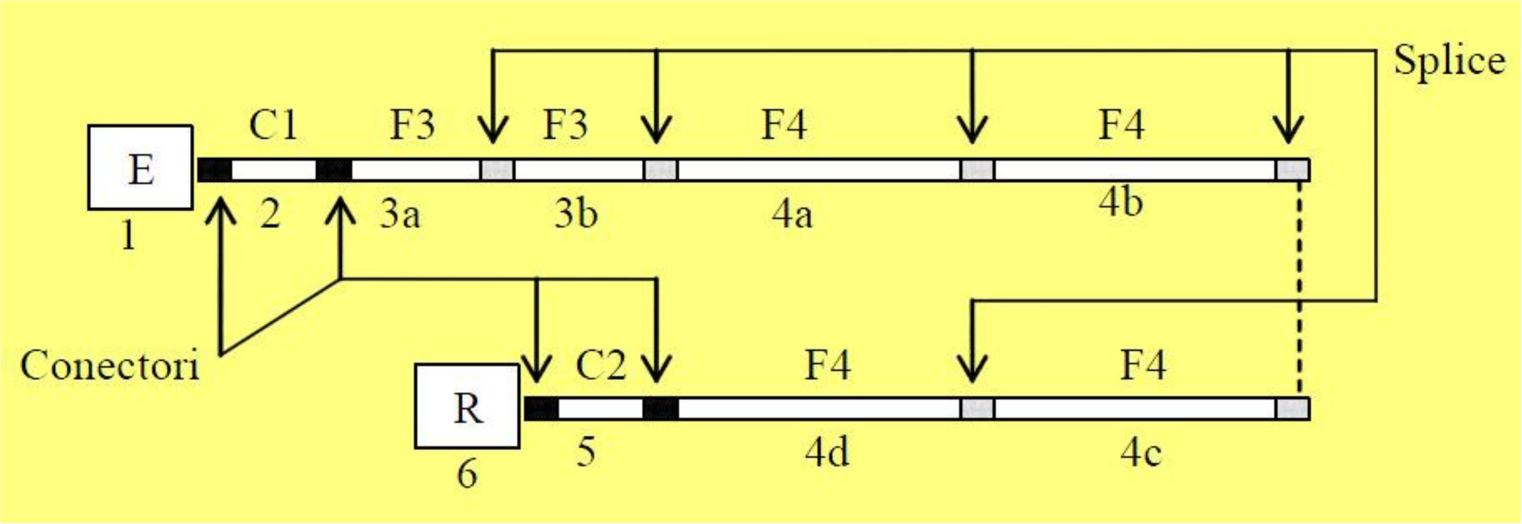
- Bilantul puterilor

$$A_{tot}[dB] = \sum_i A_i[dB]$$

$$P_e[dBm] \pm A_{tot}[dB] \geq S_r[dBm] + M[dB]$$

Maximum Attenuation

Wavelength (nm)	Maximum Value* (dB/km)
1310	0.33 – 0.35
1383**	0.31 – 0.35
1490	0.21 – 0.24
1550	0.19 – 0.20
1625	0.20 – 0.23



Sistem

- 1. Emitator
- 2. Cablu 1 de conexiune
- 3. Fibra 3 (2 cabluri a 5 km fiecare: 3a,3b)
- 4. Fibra 4 (4 cabluri a 10 km fiecare: 4a,4b,4c,4d)
- 5. Cablu 2 de conexiune
- 6. Receptor

Atenuare

- Distribuita
  - microcurburi
  - imprastiere
  - absorbtie
- Localizata
  - macrocurburi
  - conectori
  - splice
  - tranzitii

$$\text{Atenuare}_D[\text{dB/km}] = \frac{\text{Pierderi}[\text{dB}]}{\text{lungime}[\text{km}]}$$

$$\text{Atenuare}_L[\text{dB}] = \text{Pierderi}[\text{dB}]$$

$$A_{TOT}[\text{dB}] = A_L[\text{dB}] + A_D[\text{dB/km}] \cdot L[\text{km}]$$

Pierderi

- Atenuare in fibra
- Atenuare datorata conectorilor
- Atenuare datorata splice-urilor
- Atenuare datorata diferentelor de apertura numerica
  - apare **numai** la trecerea de la un dispozitiv cu NA mai mare la un dispozitiv cu NA mai mic
  - **neglijabil** intre 2 fibre monomod sudate
- Atenuare datorata diferentelor de diametru
  - apare **numai** la trecerea de la un dispozitiv cu diametru mai mare la un dispozitiv cu diametru mai mic
  - **bidirectional** la fibre monomod sudate

Dispersie

$$\Delta\tau_{\text{mod}} \cong \frac{L\cdot n_2\cdot\Delta}{2\sqrt{3}\cdot c} \approx \frac{L\cdot NA^2}{4\sqrt{3}\cdot c\cdot n_2}$$

$$\Delta\tau_{\text{mod}} \cong \frac{L\cdot n_2\cdot\Delta^2}{4\sqrt{3}\cdot c} \cong \frac{L\cdot NA^4}{16\sqrt{3}\cdot c\cdot n_2^3}$$

$$\Delta\tau_{cr} = D(\lambda)\cdot\Delta\lambda\cdot L$$

$$\mathrm{D}(\lambda) = \frac{\mathrm{S}_0}{4}\cdot\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right)$$

$$\Delta\tau_{tip} = \sum_i \Delta\tau_i$$

$$\Delta\tau_{tot} = \sqrt{\Delta\tau_{cr}^2 + \Delta\tau_{\text{mod}}^2}$$

$$B_{opt} = \frac{0.44}{\Delta\tau_{tot}[ns]} \quad [GHz]$$

$$B_{opt} = \sqrt{2}B_{el}$$

$$V[Gb/s] \cong 2\cdot B_{el}$$

$$\mathrm{B}_{\text{3dB, electric}}(\mathrm{GHz}) = \frac{0.35}{\mathrm{T(ns)}}$$

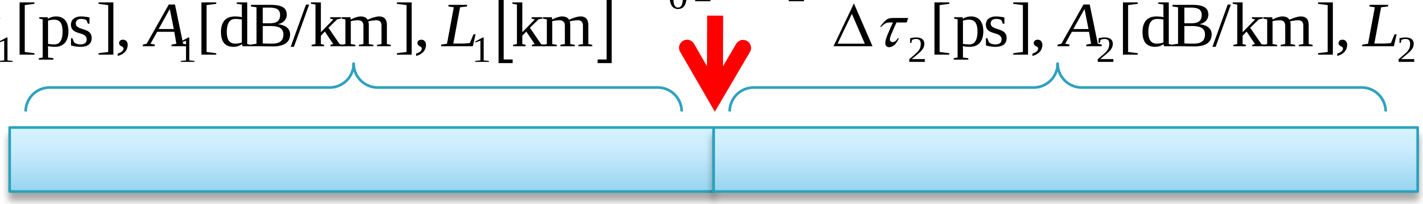
$$\mathrm{NRZ}_{\text{viteza date}}(\mathrm{Gbit/s}) = \frac{1}{\mathrm{T}_{\text{impuls}}(\mathrm{ns})} \le \frac{0.67}{\mathrm{T(ns)}}$$

Sisteme cu mai multe tipuri de fibra

- Fibra tip 1 conectata/sudata cu fibra tip 2
- efecte **succesive** se adună liniar
- la nivelul splice-ului apare o atenuare **localizata**:
  - atenuare pe splice/conector
  - atenuare datorita **NA** diferit (**daca** este cazul)
  - atenuare datorita **Φ** diferit (**daca** este cazul)

$$A_0[\text{dB}]$$

$$\Delta\tau_1[\text{ps}],\ A_1[\text{dB/km}],\ L_1[\text{km}] \qquad \Delta\tau_2[\text{ps}],\ A_2[\text{dB/km}],\ L_2[\text{km}]$$

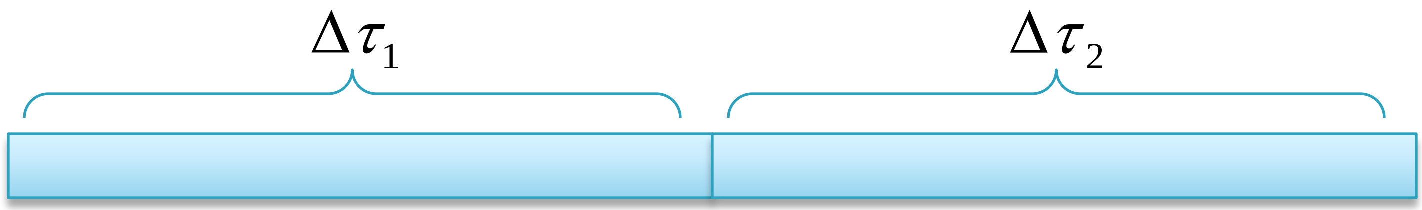


$$A_{tot}[\text{dB}] = A_1[\text{dB/km}]\cdot L_1[\text{km}] + A_2[\text{dB/km}]\cdot L_2[\text{km}] + A_0[\text{dB}]$$

$$\Delta\tau_{tot} = \Delta\tau_1 + \Delta\tau_2$$

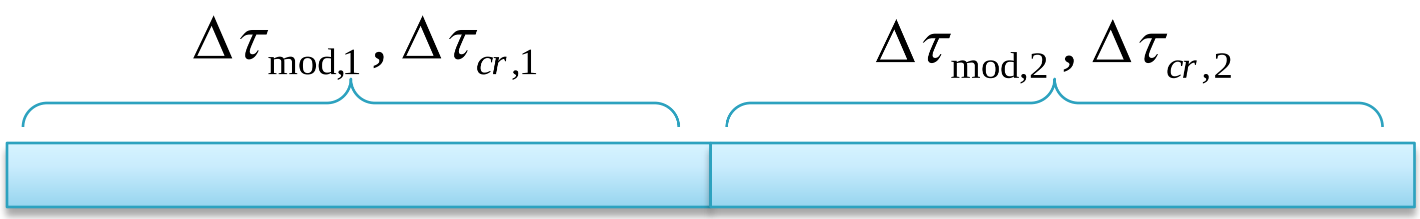
Sisteme cu mai multe tipuri de fibra

- efecte **succesive** se adună liniar



$$\Delta\tau_{tot} = \Delta\tau_1 + \Delta\tau_2$$

- dar pe fiecare fibra exista efecte **simultane** (pentru dispersie) care se adună pătratic

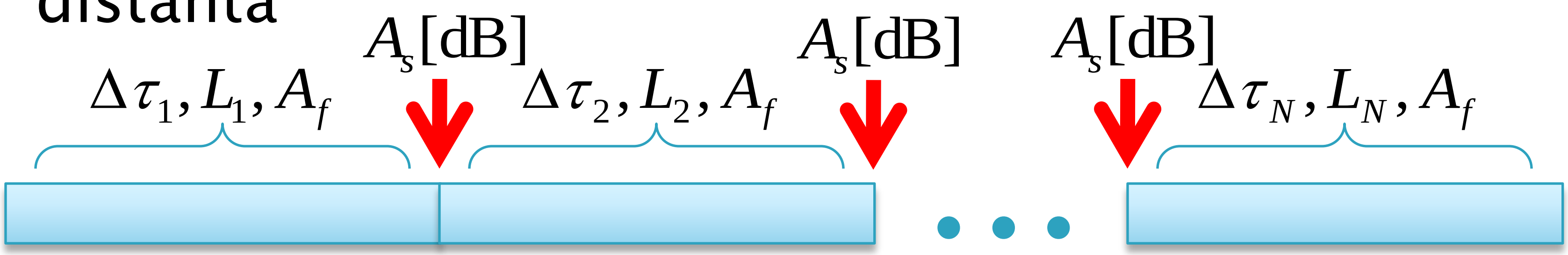


$$\Delta\tau_1 = \sqrt{\Delta\tau_{cr,1}^2 + \Delta\tau_{\text{mod},1}^2}$$

$$\Delta\tau_2 = \sqrt{\Delta\tau_{cr,2}^2 + \Delta\tau_{\text{mod},2}^2}$$

Sisteme cu acelasi tip de fibra

- N tronsoane cu acelasi tip de fibra conectate/sudate
  - atenuare datorita NA **nula** (**acelasi tip**)
  - atenuare datorita Φ **nula** (**acelasi tip**)
  - atenuare pe splice/conector: N−1 conectori
  - lungime totala: $L_{tot}[\text{km}] = \sum_{1}^{N} L_i[\text{km}]$
- efecte **succesive** se adună liniar
- efectele (dispesie si atenuare) proportionale cu distanta



$$\Delta\tau_{tot} = \sum_{i=1}^{N} \Delta\tau(L_i) = \Delta\tau(L_{tot}) = \sqrt{\Delta\tau_{cr}(L_{tot})^2 + \Delta\tau_{\text{mod}}(L_{tot})^2}$$

$$A_{tot}[\text{dB}] = A_f[\text{dB/km}] \cdot L_{tot}[\text{km}] + (N-1) \cdot A_s[\text{dB}]$$

Produs Banda · Distanta

$$\Delta\tau_{\text{mod}} \cong \frac{L \cdot n_2 \cdot \Delta}{2\sqrt{3} \cdot c} \approx \frac{L \cdot NA^2}{4\sqrt{3} \cdot c \cdot n_2}$$

$$\Delta\tau_{tot} = \sqrt{\Delta\tau_{cr}^2 + \Delta\tau_{\text{mod}}^2}$$

$$\Delta\tau_{cr} = D(\lambda) \cdot \Delta\lambda \cdot L$$

$$\Delta\tau_{tot} = const \cdot L$$

$$B_{opt} = \frac{0.44}{\Delta\tau_{tot}[ns]} \quad [GHz]$$

$$B_{opt} = \sqrt{2} B_{el}$$

$$V[Gb/s] \cong 2 \cdot B_{el}$$

$$V[Gb/s] \cong \frac{const}{L}$$

$$V[Gb/s] \cdot L[km] \cong const$$

Lungime maxima

- limitata de atenuare
- lungimea cea mai mare la care pot face transmisia este obtinuta in cazul cel mai defavorabil
  - cele mai mici pierderi permise
  - atenuare distribuita maxima

$$A_{TOT}[dB] = A_L[dB] + A_D[dB/km] \cdot L[km]$$

$$Atenuare[dB/km] = \frac{Pierderi_D[dB]}{lungime[km]} \qquad L_{max} \quad \Rightarrow \quad \Delta P_{min}, A_{D\,max}$$

$$L_{max} = \frac{\Delta P_{min}[dB]}{A_{D\,max}[dB/km]} = \frac{P_{e\,min}[dBm] - S_{r\,max}[dBm] - A_L[dB]}{A_{D\,max}[dB/km]}$$

de obicei problema distantei maxime limitate de atenuare se pune pentru fibre monomod

Lungime maxima

- limitata de viteza
- lungimea cea mai mare la care pot face transmisia este obtinuta in cazul cel mai defavorabil
  - dispersie maxima
- doua cazuri in functie de cum e specificata dispersia
  - $B \times L$ [MHz·km]
  - S_0[ps/nm^2/km], λ_0[nm]

$$B_{el\,\min} \cong \frac{V_{\min}[Gb/s]}{2}$$

$$\Delta\tau_{tot\max}[\mathrm{ns}]$$

$$B_{opt\min} = \sqrt{2} B_{el\,\min}$$

$$\Delta\tau_{tot\max}[\mathrm{ns}] = \frac{0.44}{B_{opt\min}[\mathrm{GHz}]}$$

$$L_{\max} = \frac{\Delta\tau_{tot\max}}{D(\lambda)\cdot\Delta\lambda}$$

$$B \times L\,[\mathrm{MHz}\cdot\mathrm{km}]$$

$$L_{\max}[\mathrm{km}] = \frac{B \times L[\mathrm{MHz}\cdot\mathrm{km}]}{B_{el\,\min}[\mathrm{MHz}]}$$

Lungime maxima

- limitata de atenuare $L_{\max}^{a}[\text{km}]$
- limitata de viteza $L_{\max}^{v}[\text{km}]$

- lungimea cea mai mare la care pot face transmisia este obtinuta in cazul cel mai defavorabil (din cele doua limitari)

$$L_{\max}[\text{km}] = \min\left(L_{\max}^{a}[\text{km}], L_{\max}^{v}[\text{km}]\right)$$

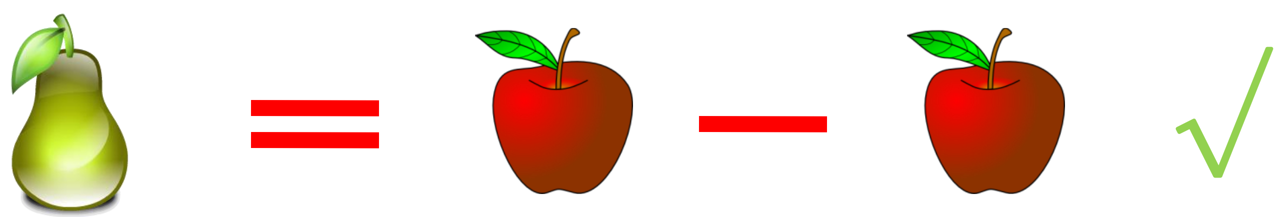
- de obicei
  - monomod: limita impusa de atenuare
    - cu exceptia cazurilor in care nu se functioneaza la λ optim dpdv al dispersiei
  - multimod: limita impusa de viteza

Calculul atenuarii

$$\text{Pierderi} = \frac{P_{out}}{P_{in}}$$

$$\text{Pierderi}[\text{dB}] = [-]10 \cdot \log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

$$\text{Pierderi}[\text{dB}] = [-]\left(P_{out}[\text{dBm}] - P_{in}[\text{dBm}]\right)$$



$$\text{Atenuare}[\text{dB/km}] = \frac{\text{Pierderi}[\text{dB}]}{\text{lungime}[\text{km}]}$$

Reprezentare logaritmică !!!!

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

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

0 dB	= 1
+ 0.1 dB	= 1.023 (+2.3%)
+ 3 dB	= 2
+ 5 dB	= 3
+ 10 dB	= 10
–3 dB	= 0.5
–10 dB	= 0.1
–20 dB	= 0.01
–30 dB	= 0.001

0 dBm	= 1 mW
3 dBm	= 2 mW
5 dBm	= 3 mW
10 dBm	= 10 mW
20 dBm	= 100 mW
–3 dBm	= 0.5 mW
–10 dBm	= 100 μW
–30 dBm	= 1 μW
–60 dBm	= 1 nW

[dBm] + [dB] = [dBm]

[dBm/Hz] + [dB] = [dBm/Hz]

[x] + [dB] = [x]

Problema simpla?

- Sursa luminoasa: 7.7 dBm
- Atenuarea fibrei: 1.16 dB/km
- Puterea la iesire: 105 μW

- Lungimea fibrei: ?

Problema simpla?

- Logaritmic
  - $P_{out} = 10 \cdot \log(105\ \mu W / 1\ mW) = -9.8\ dBm$!
  - Atenuarea : $A_f = P_{in}[dBm] - P_{out}[dBm] = 17.5 dB$!
  - $L = A_f\ /\ A_{dB/km} = 17.5dB\ /\ 1.16dB/km = 15.08\ km$
- Liniar
  - $P_{in} = 1mW \cdot 10^{7.7/10} = 5.888\ mW$
  - Atenuarea : $A_f = P_{in}\ /\ P_{out} = 5.888\ mW\ /\ 0.105\ mW = 56.0762\ [1]$!
  - Atenuarea pe unitatea de lungime $A_{1/km} = 10^{1.16/10} = 1.3062\ [1]$!
  - $A_f = (A_{1/km})^{L/1km} \rightarrow L = 1km \cdot \log(A_f)/\log(A_{1/km}) = 1.749/0.116\ km = 15.08\ km$

Problema simpla? 2

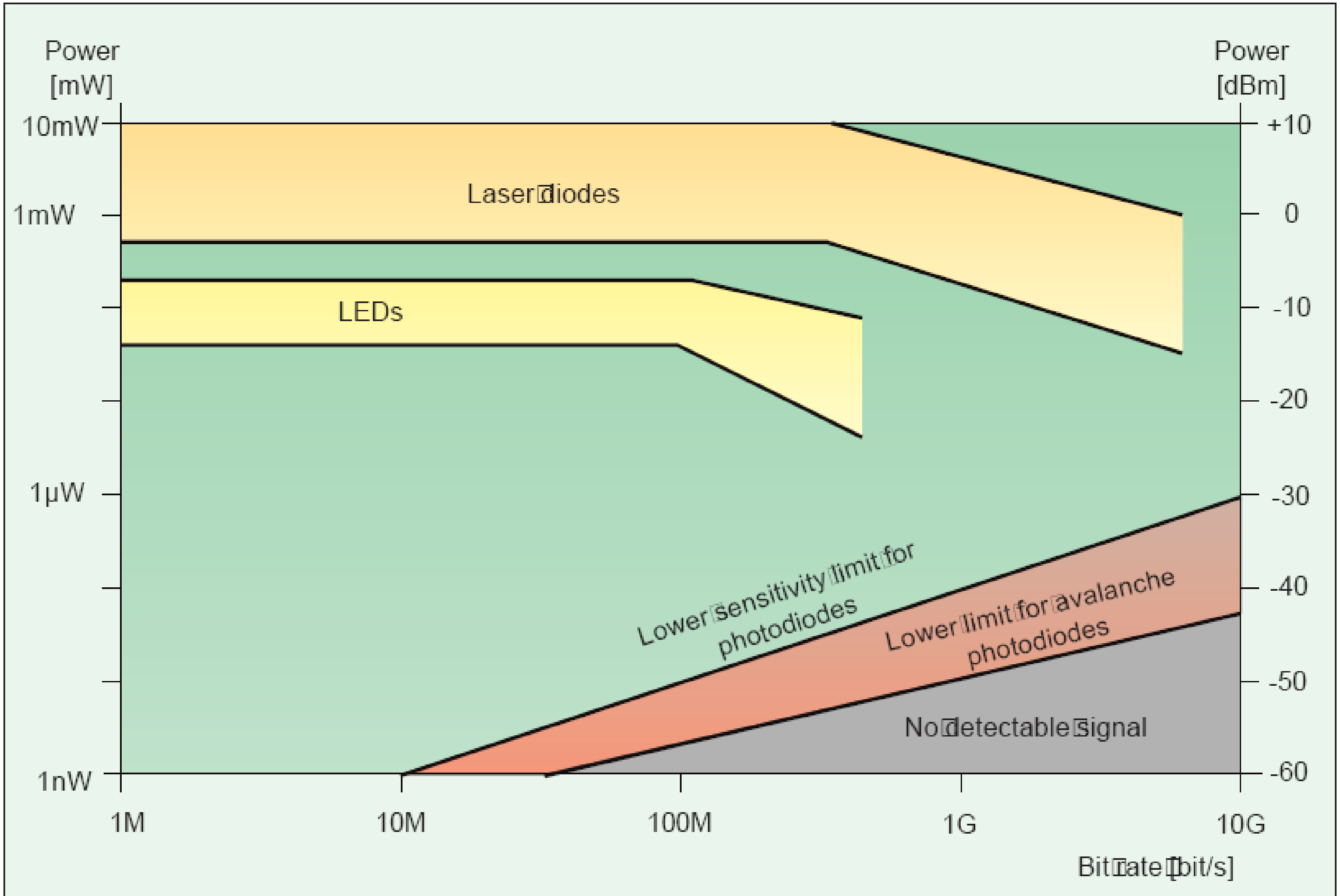
- Sursa luminoasa: 4.9 dBm
- Atenuarea fibrei: 0.32 dB/km
- Lungimea fibrei: 17 km

- Puterea la iesire: ? [μW]

Problema simpla? 2

- Logaritmic
  - Atenuarea : $A_f = A_{dB/km} \cdot L[km] = 5.44$ dB
  - $P_{out}[dBm] = P_{in}[dBm] - A_f [dB] = -0.54$ dBm !
  - $P_{out} = 1mW \cdot 10^{-0.54/10} = 0.883$ mW = 883 μW
- Liniar
  - Atenuarea : $A_f [dB] = A_{dB/km} \cdot L[km] = 5.44$ dB !
  - Atenuarea : $A_f [1] = 10^{Af [dB]/10} = 3.499$ [1] !
  - $P_{in} = 1mW \cdot 10^{4.9/10} = 3.09$ mW
  - $P_{out} = P_{in} / A_f = 3.09$ mW / 3.499 = 0.883 mW = 883 μW

Limite putere/bandă a dispozitivelor optoelectronice



LED

Dioda electroluminescenta
Capitolul 7

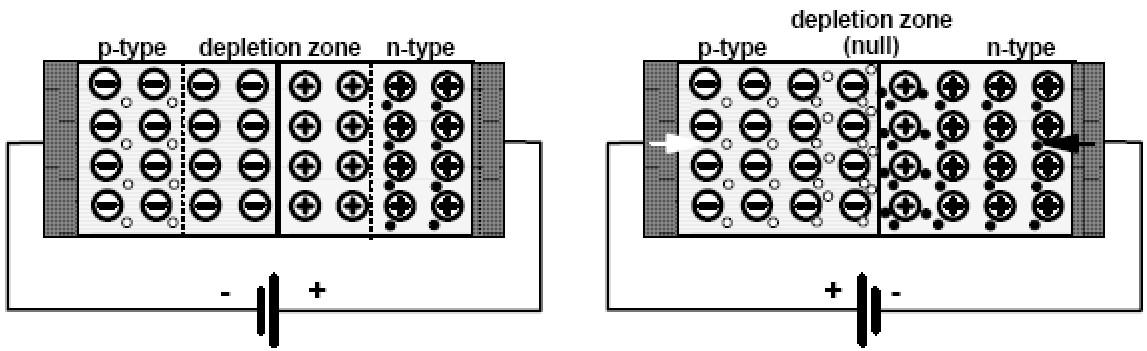
Caracteristici LED

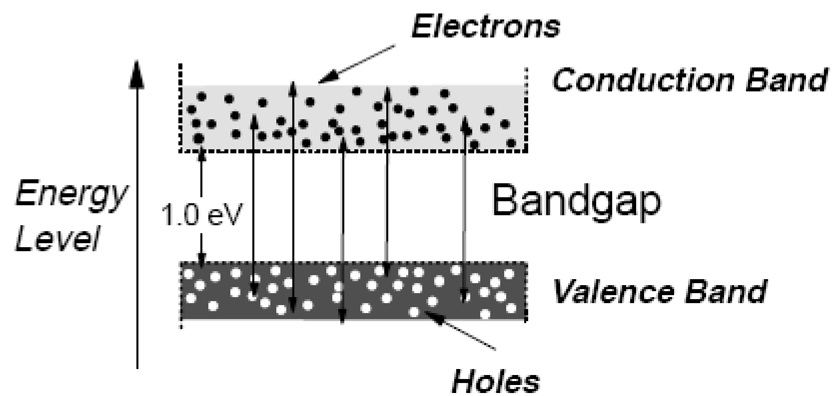
- Dezavantaje
  - Putere redusa (cuplata in fibra) ~ 100μW
  - Banda (viteza) reduse ~ 150MHz (300Mb/s)
  - Spectru larg ~ 0.05 λ
  - Lumina necoerenta si nedirectiva
- Avantaje
  - Structura interna mult mai simpla (fara suprafete reflective, straturi planare)
  - Cost (dispozitiv si circuit de comanda)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

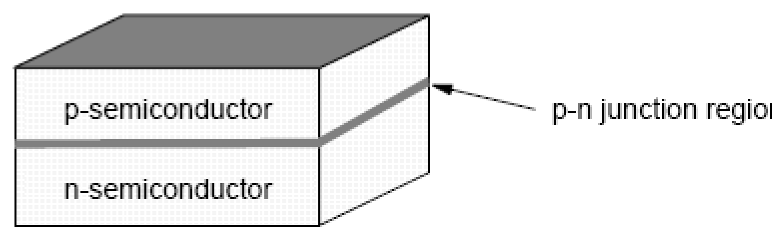
Aplicatii majore LED

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

LED – Principiul de operare







LED – Principiul de operare

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

Lăţimea benzii interzise/lungime de undă pentru materialele uzuale

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

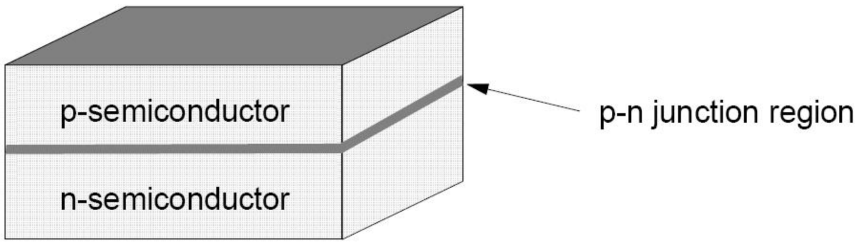
$$E_g = h\nu; \quad \lambda = \frac{hc}{E_g}; \quad \lambda[\mu\text{m}] = \frac{1.240}{E_g[\text{eV}]}$$

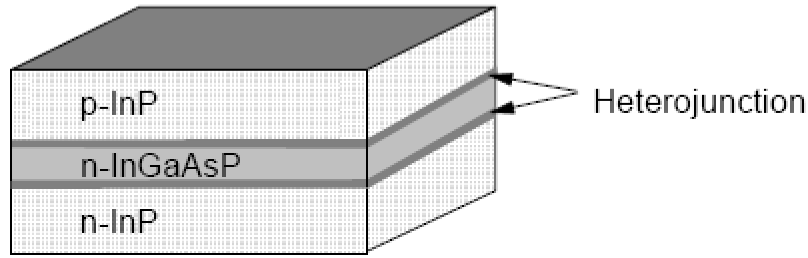
- h constanta lui Plank $6.6261 \cdot 10^{-34}$ Ws^2
- c viteza luminii **in vid** $2.998 \cdot 10^{8}$ m/s
- e sarcina electronului $1.6 \cdot 10^{-19}$ C
- benzi energetice: λ_0, **$\Delta\lambda$**

Detalii constructive – 1

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

LED cu heterojuncţiuni – principiu

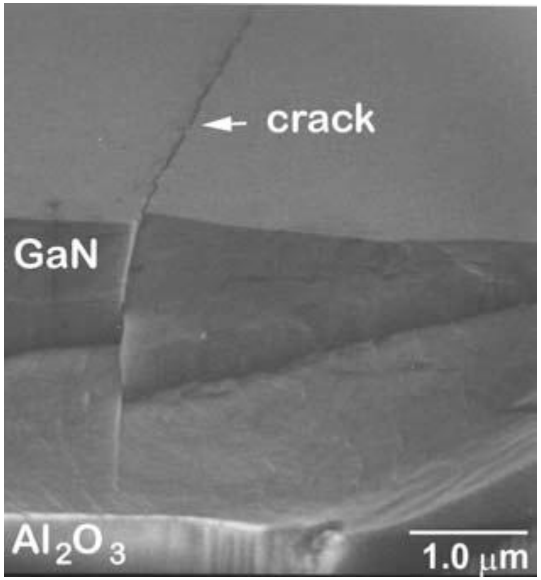




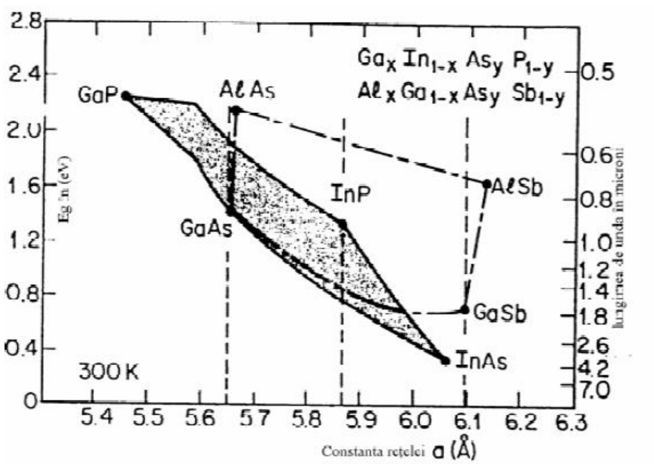
- Orice jonctiune p–n emite lumina
- O jonctiune p–n obisnuita este foarte subtire
  - volumul in care apar recombinari este foarte mic
  - eficienta luminoasa, redusa
- lumina este emisa in toate directiile
  - cantitatea de lumina utilizabila (intr–o anumita directie) este redusa

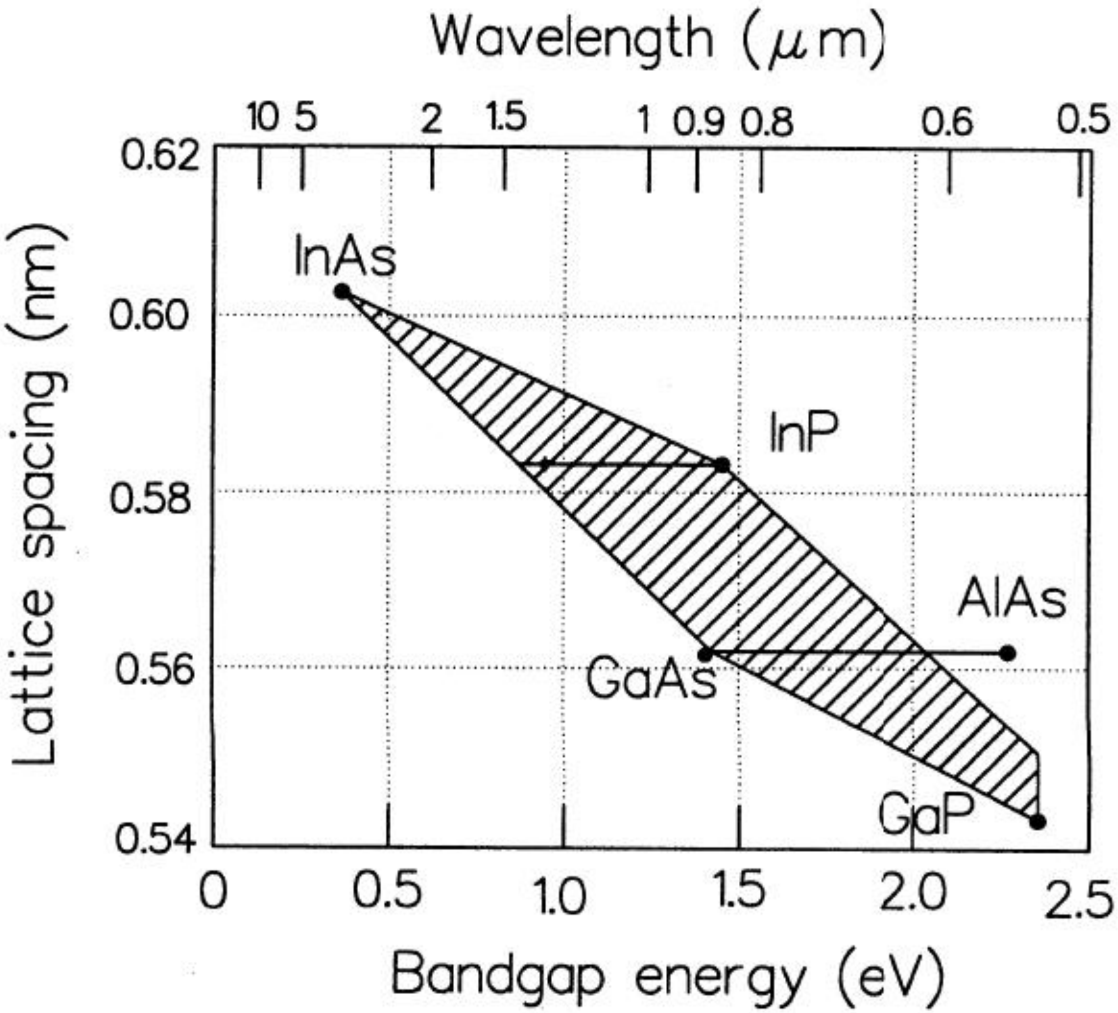
Detalii constructive – 2

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



Dependenţa benzii interzise de constanta reţelei



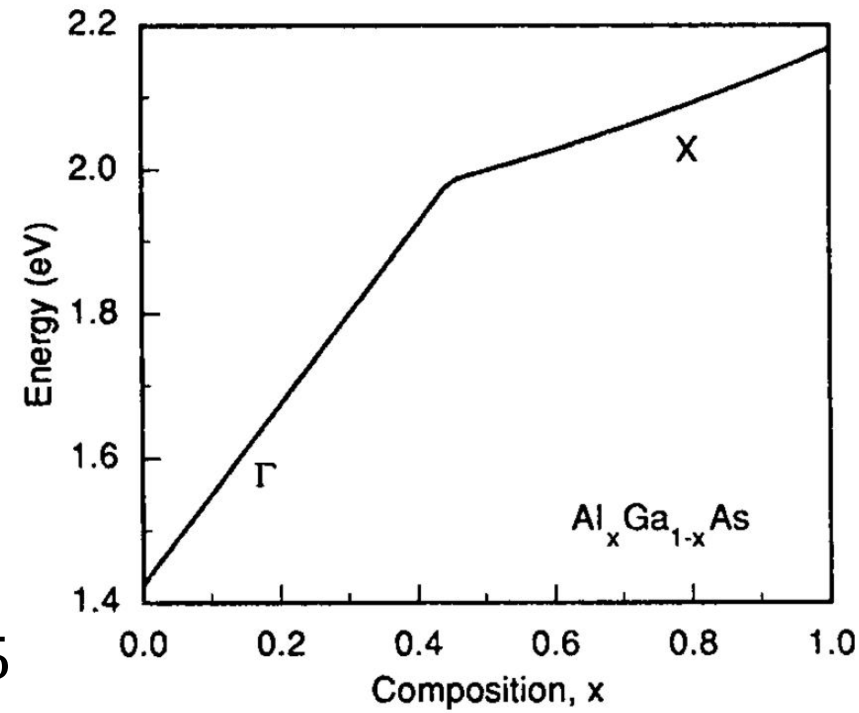


Materiale

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

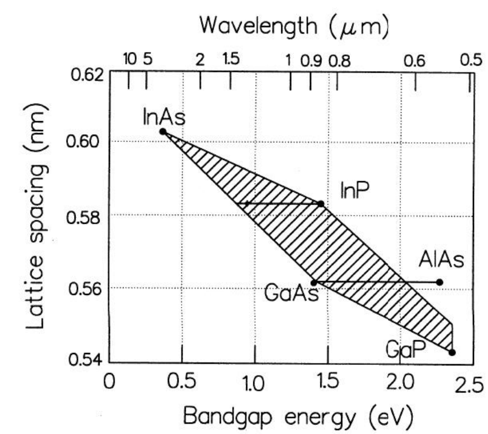
Materiale

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



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

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



Materiale

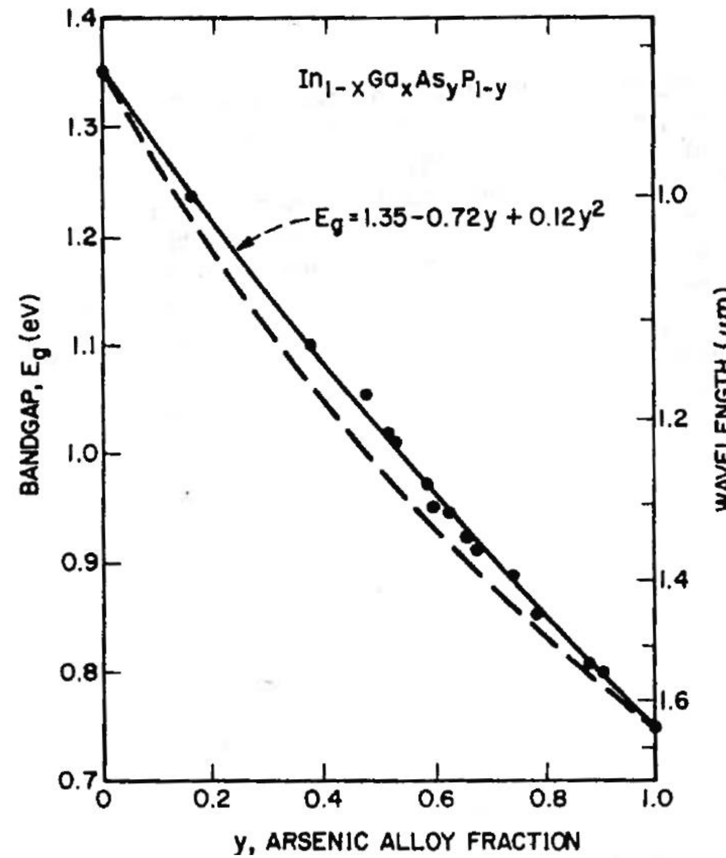
- Lungimi de unda mari
  - $In_xGa_{1-x}As_yP_{1-y}$
  - Tipic substratul este InP
    - Spatierea atomilor (lattice spacing) corespunzatoare InP

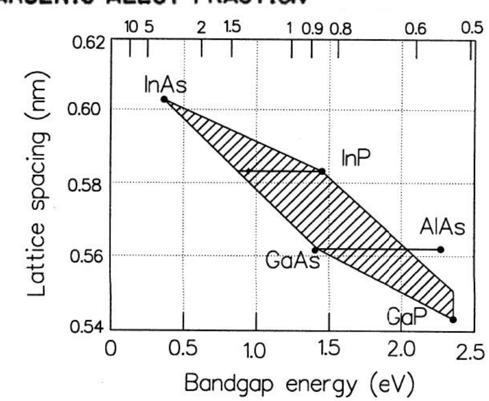
$$x = \frac{0.4526 \cdot y}{1 - 0.031 \cdot y}$$

  - E_g (in eV)

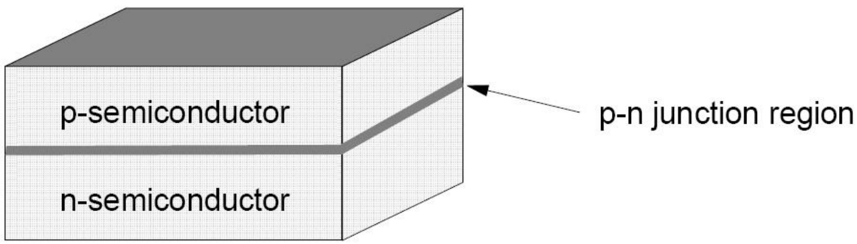
$$E_g = 1.35 - 0.72 \cdot y + 0.12 \cdot y^2$$

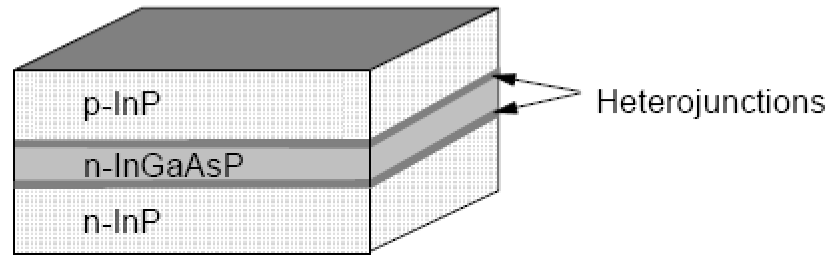
  - Exemplu: 1300nm se obtine cu y=0.611 si x=0.282,
    - $In_{0.282}Ga_{0.718}As_{0.611}P_{0.389}$



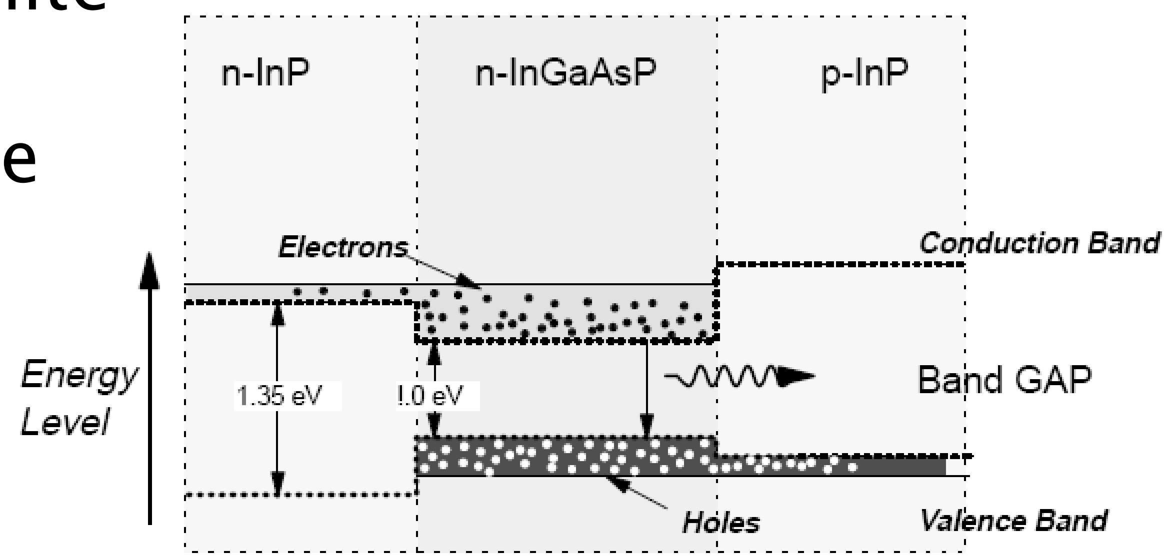


LED cu heterojuncţiuni – principiu

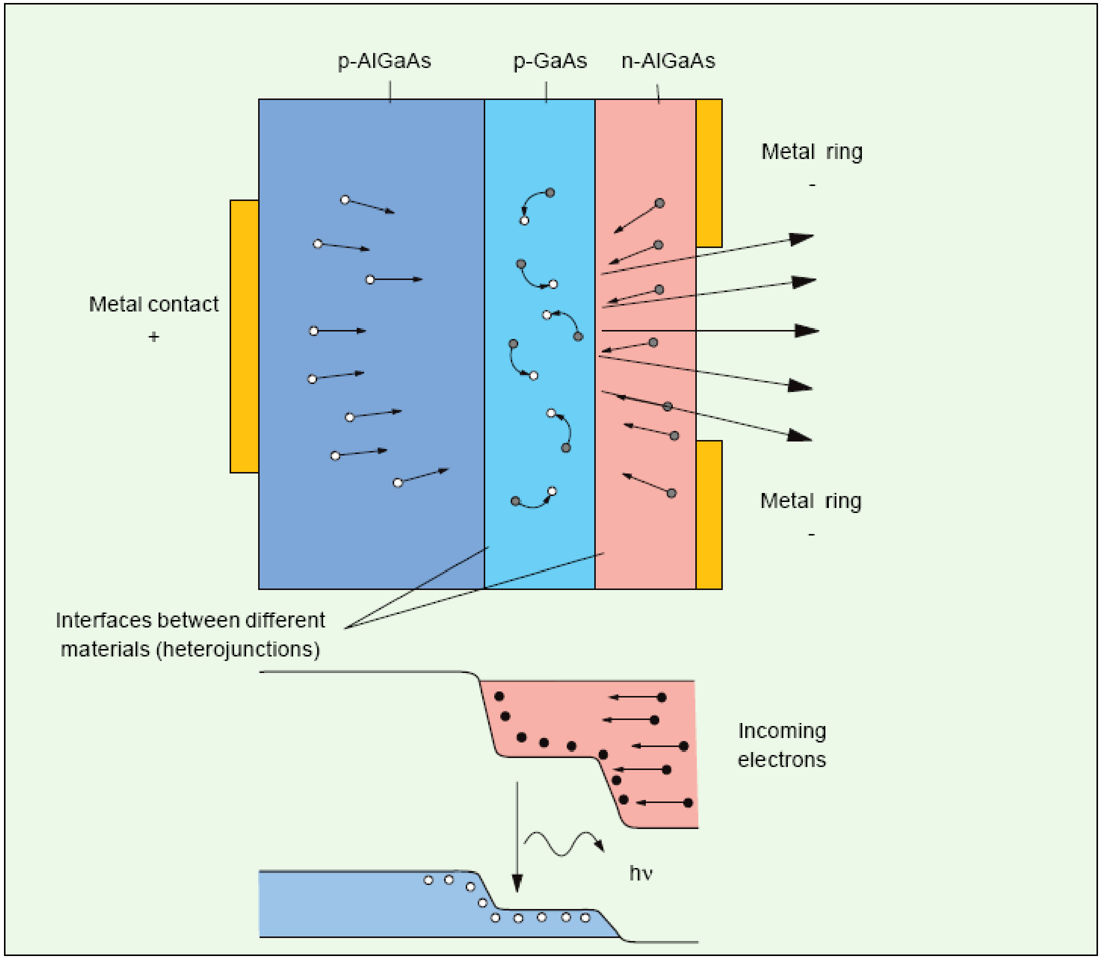




- Structura de nivele energetice permite capturarea purtatorilor intre cele doua heterojonctiuni

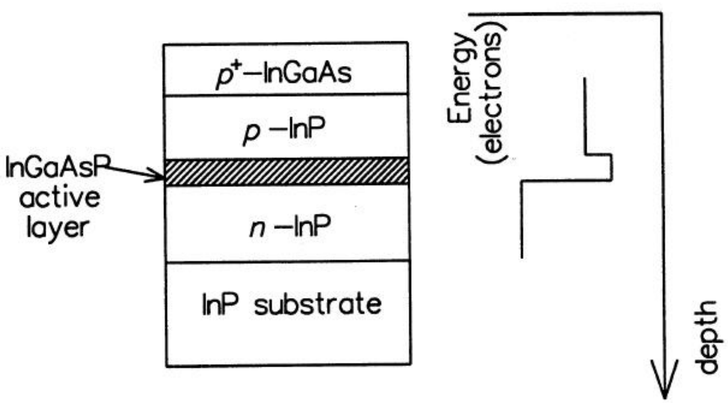


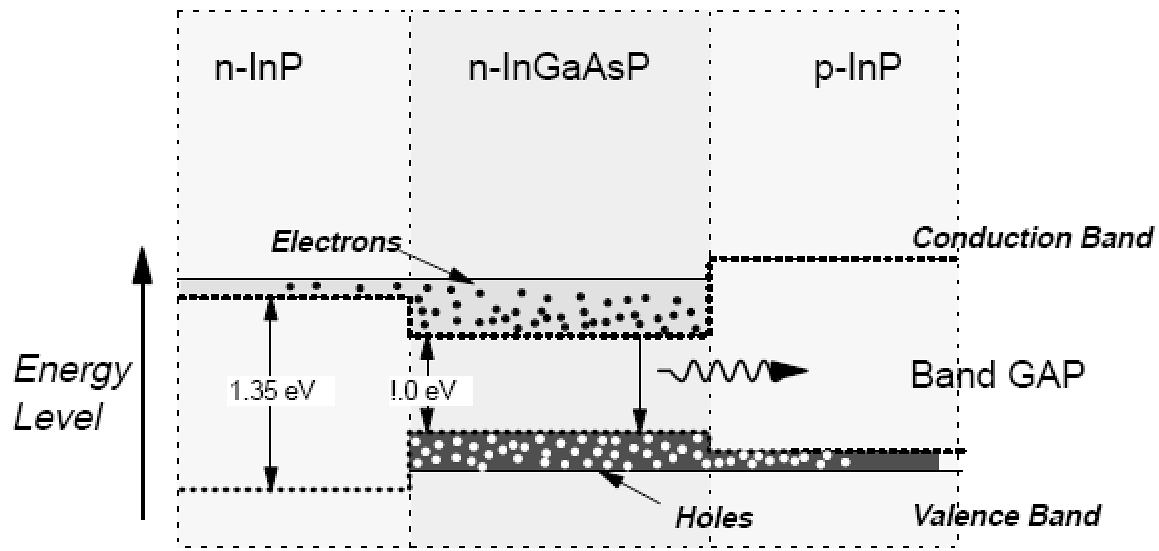
LED cu heterojuncţiuni – principiu



LED cu heterojuncţiuni – principiu

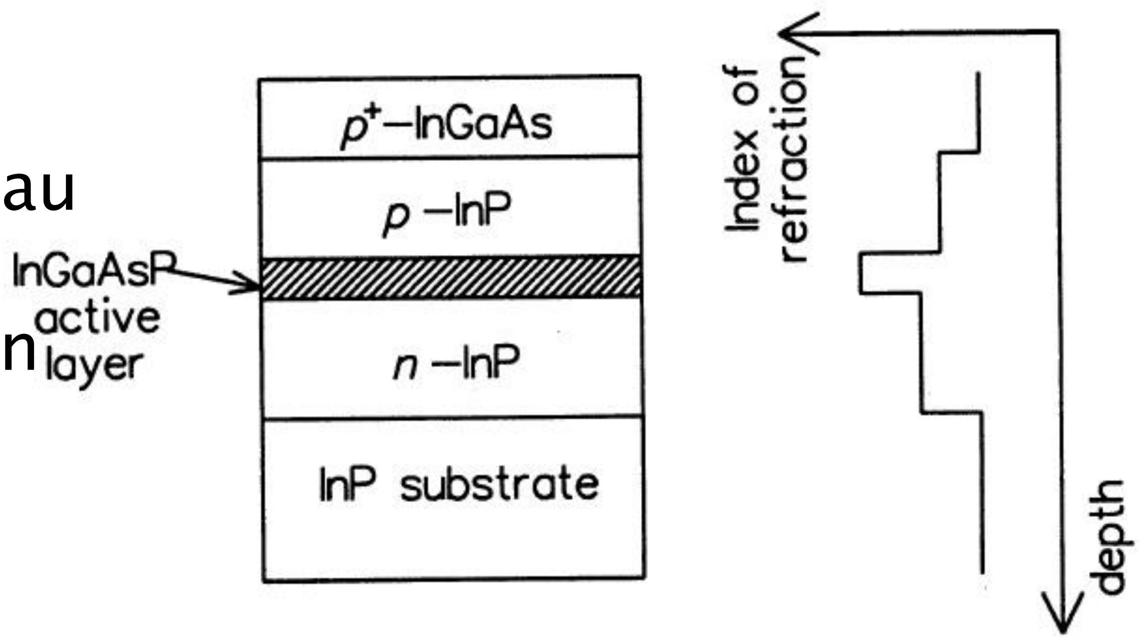
- Concentrare verticala a purtatorilor
  - Electronii sunt atrasi din zona n in zona activa
  - O bariera energetica existenta intre zona activa si zona n concentreaza electronii in zona activa
  - Situatie similara corespunzatoare golurilor
  - Purtatorii sunt concentrati in zona activa, crescand eficienta





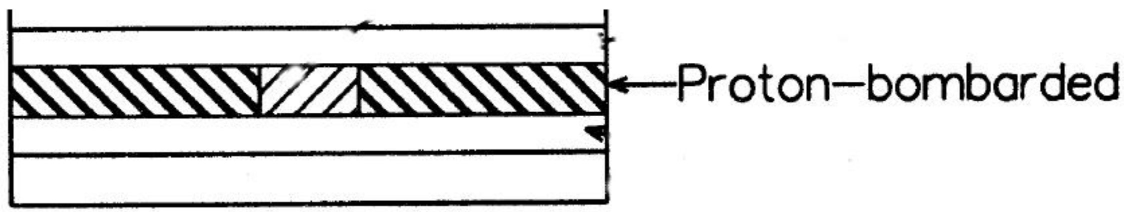
LED cu heterojuncţiuni – principiu

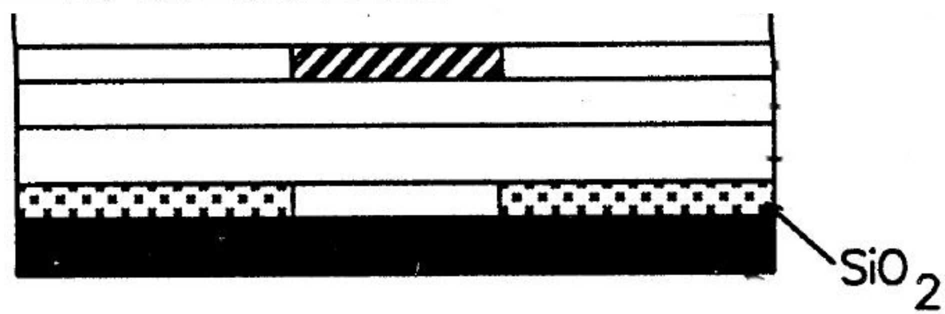
- Concentrare verticala a luminii
  - in general la diode laser (eficienta procesului LASER depinde de intensitatea luminoasa)
  - prezenta si la LED pentru cresterea eficientei luminoase: dirijarea luminii spre exterior si evitarea absorbtiei interne
- Straturile din materiale diferite au indici de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



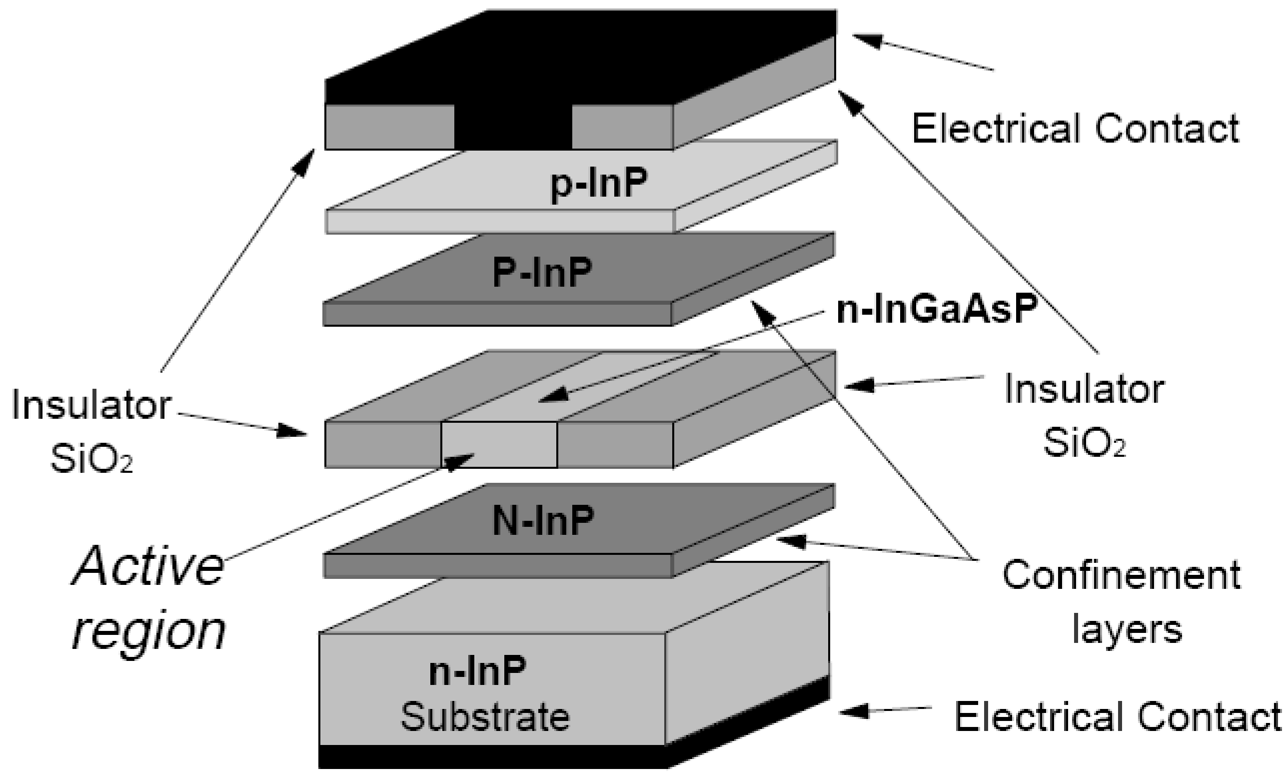
LED cu heterojuncţiuni – principiu

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

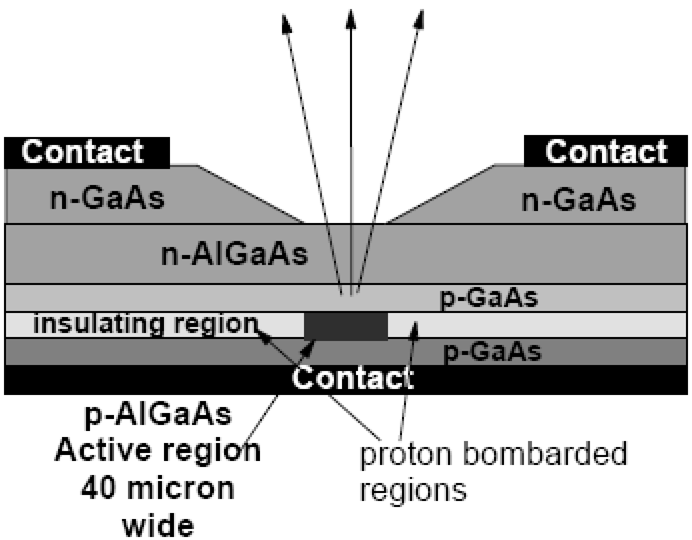




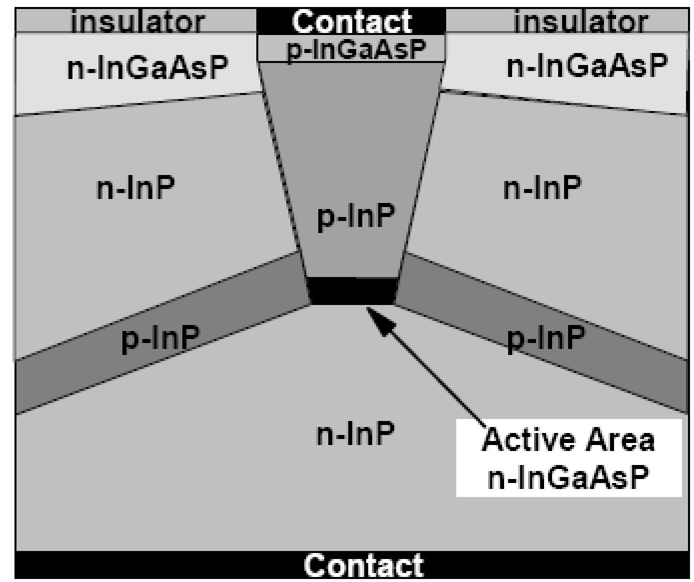
LED cu heterojuncţiuni – detalii



Structuri constructive pentru LED

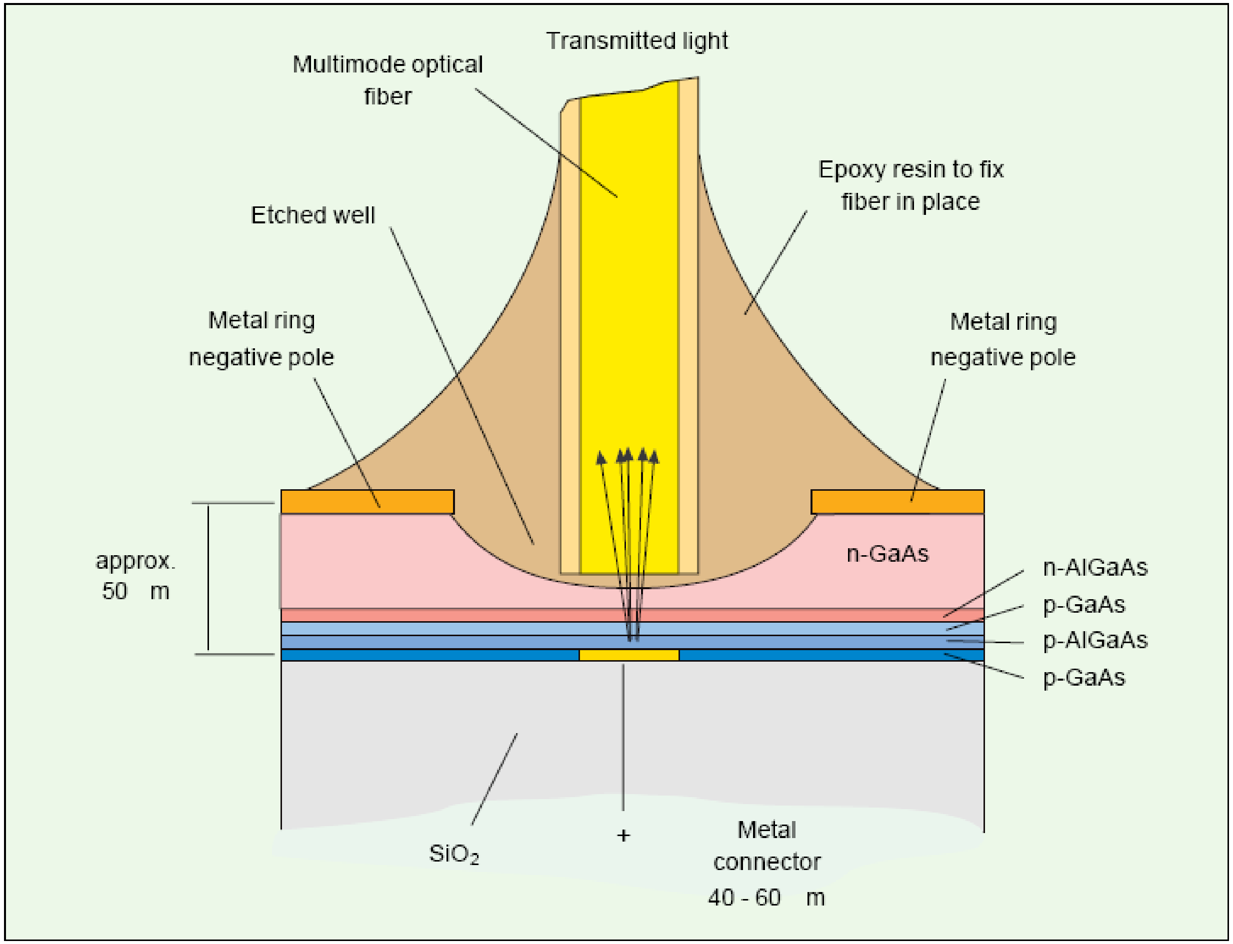


Burrus Surface Emitting LED (SLED)



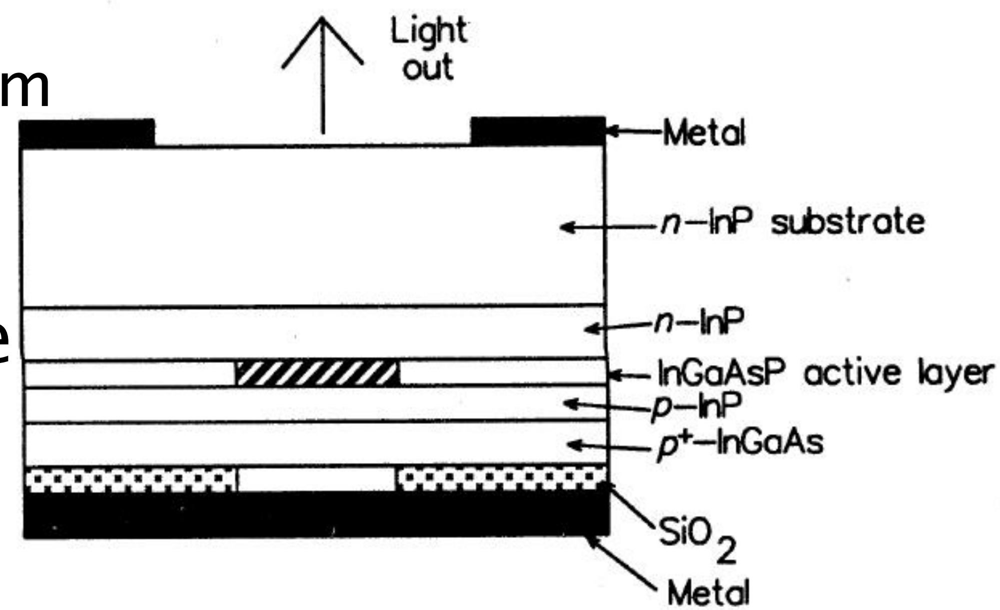
Edge Emitting LED (ELED)

LED cu emisie de suprafaţă



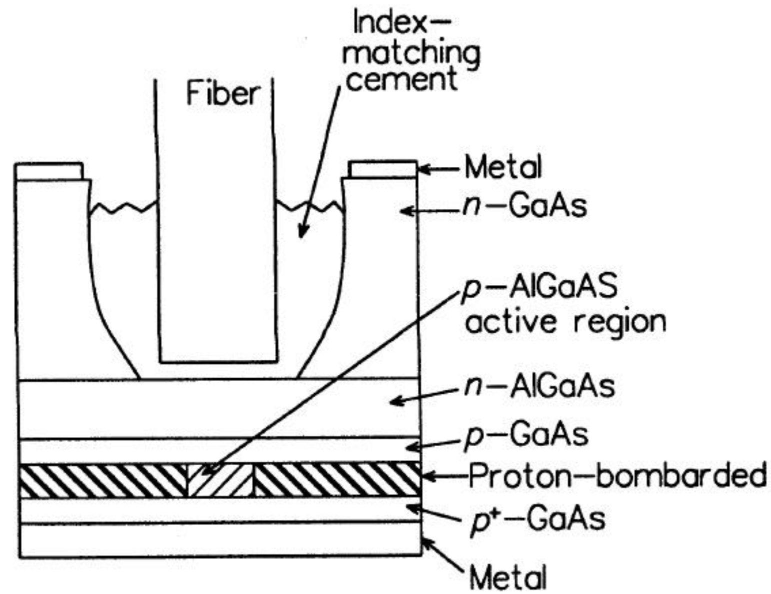
SLED InGaAsP – constructie

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

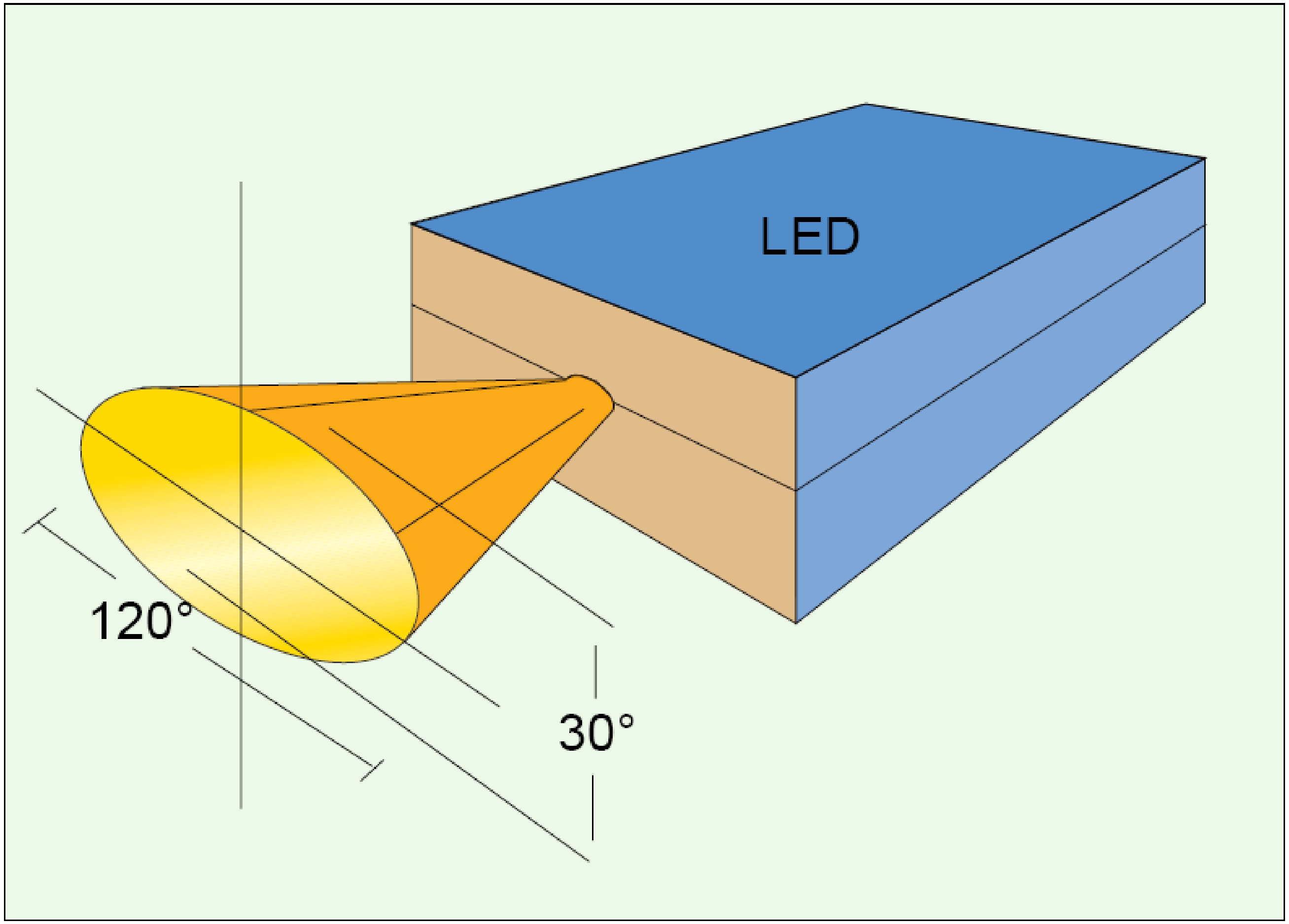


SLED GaAlAs – constructie

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

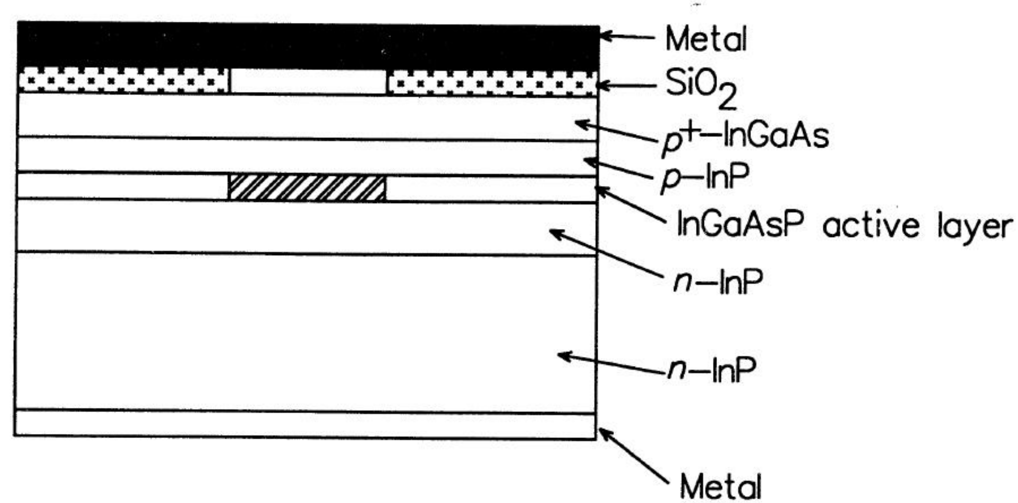


LED cu emisie laterală



ELED – constructie

- InGaAsP
- strict pentru comunicatii
- Cele patru straturi sunt in general similare
- Stratul activ este mult mai subtire decat la SLED ~0.05÷0.25μm
- Regiunea activa
  - latime 50÷70μm
  - lungime 100÷150μm
  - p InP ~1÷2μm
  - p^+ InGaAs ~0.2μm
- Apare concentrarea verticala a luminii



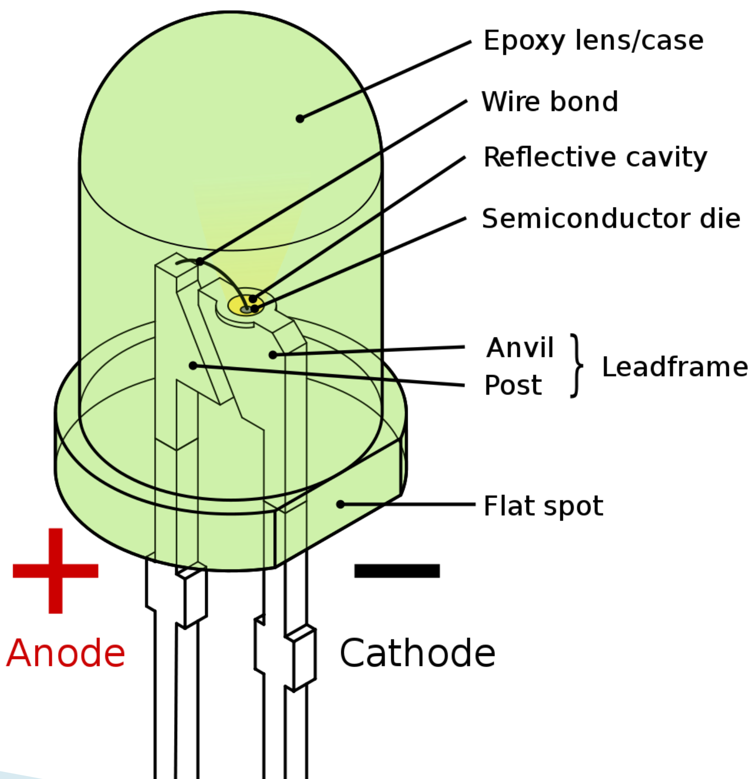
Emisia luminii spre exterior

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

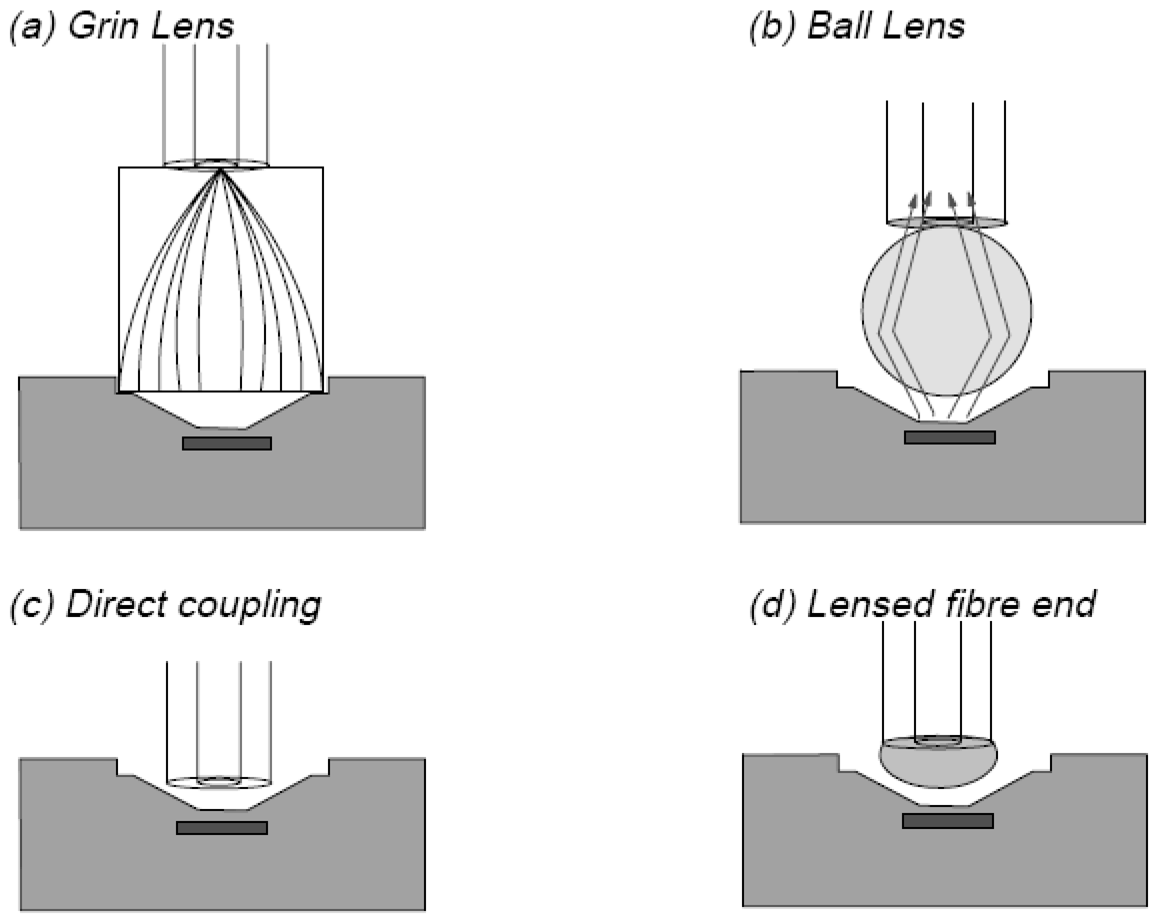
Emisia luminii spre exterior

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

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



Cuplarea luminii în fibră



numai pentru fibre multimod cu salt de indice

Directivitatea radiatiei exterioare

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

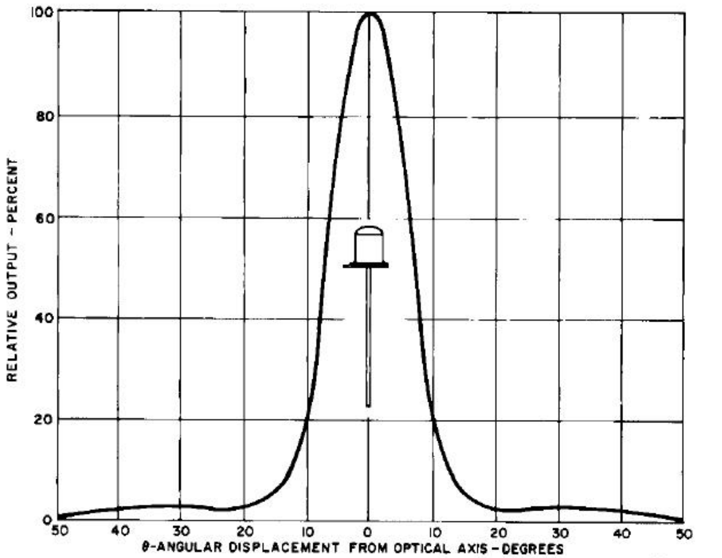
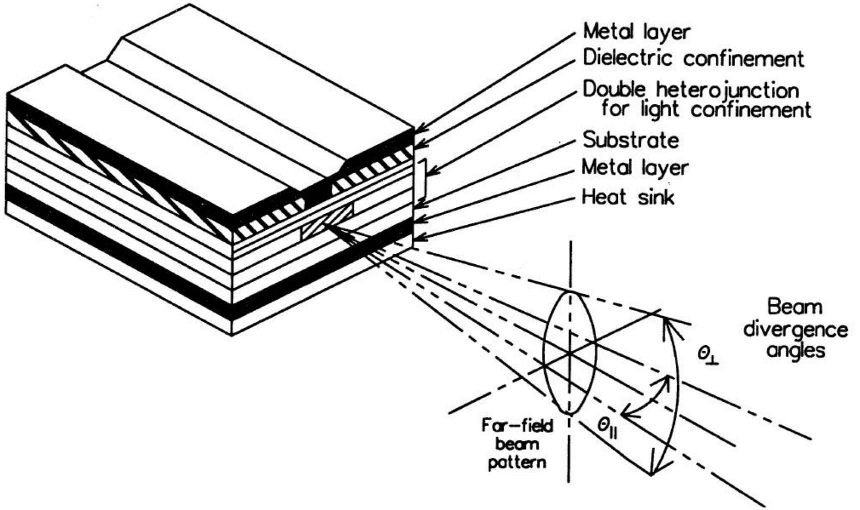


Fig. 5. Typical Radiation Pattern



Directivitatea radiatiei exterioare

- Sursa lambertiana

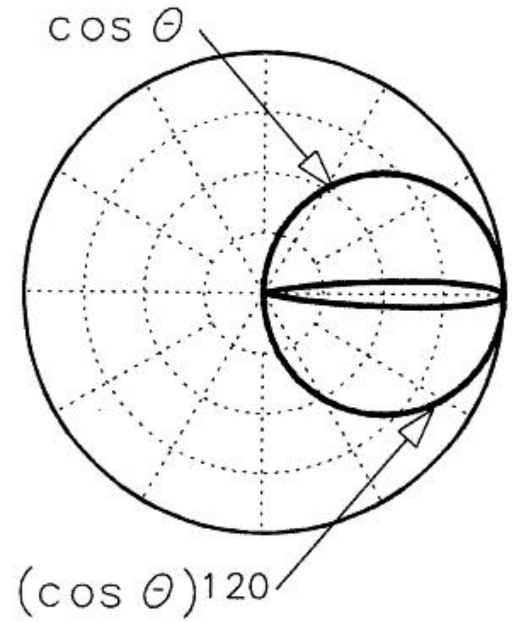
$$P(\theta) = P_0 \cdot \cos\theta$$

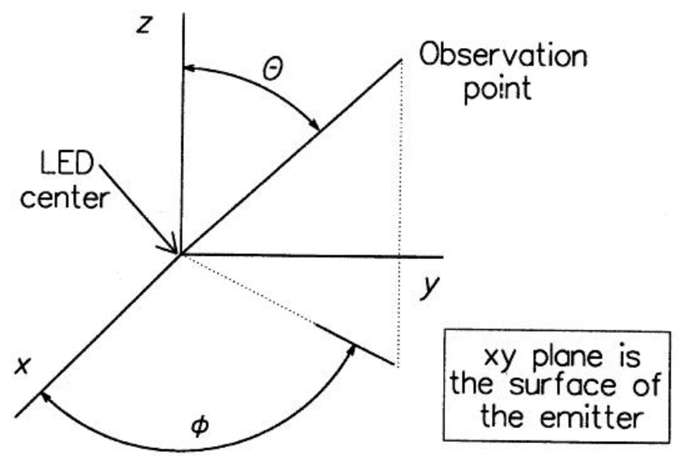
- Aproximatie Lambertiana pentru surse cu directivitate crescuta

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

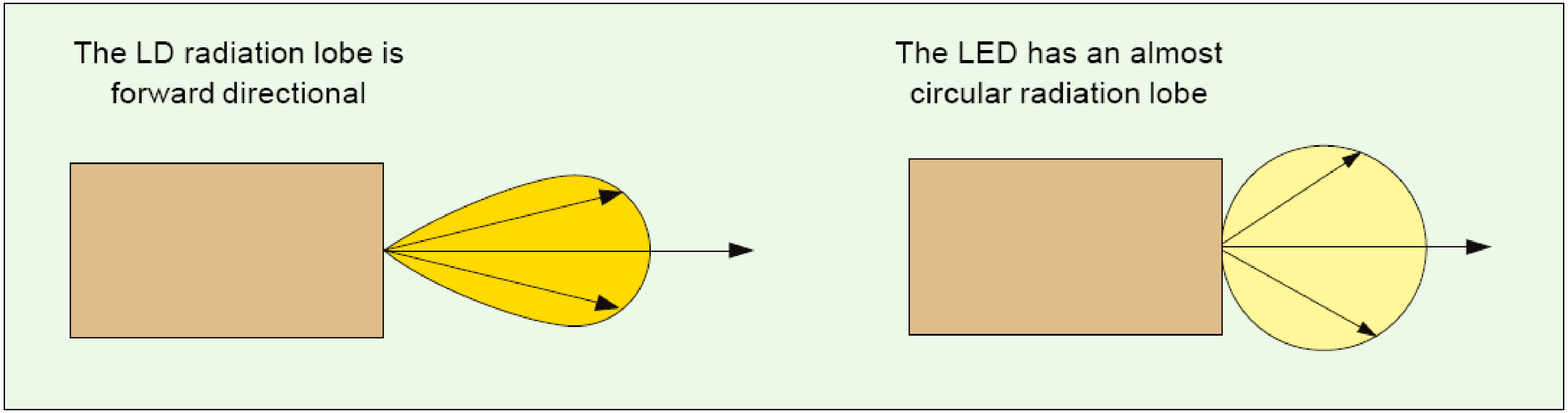
- Surse cu emisie asimetrica

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



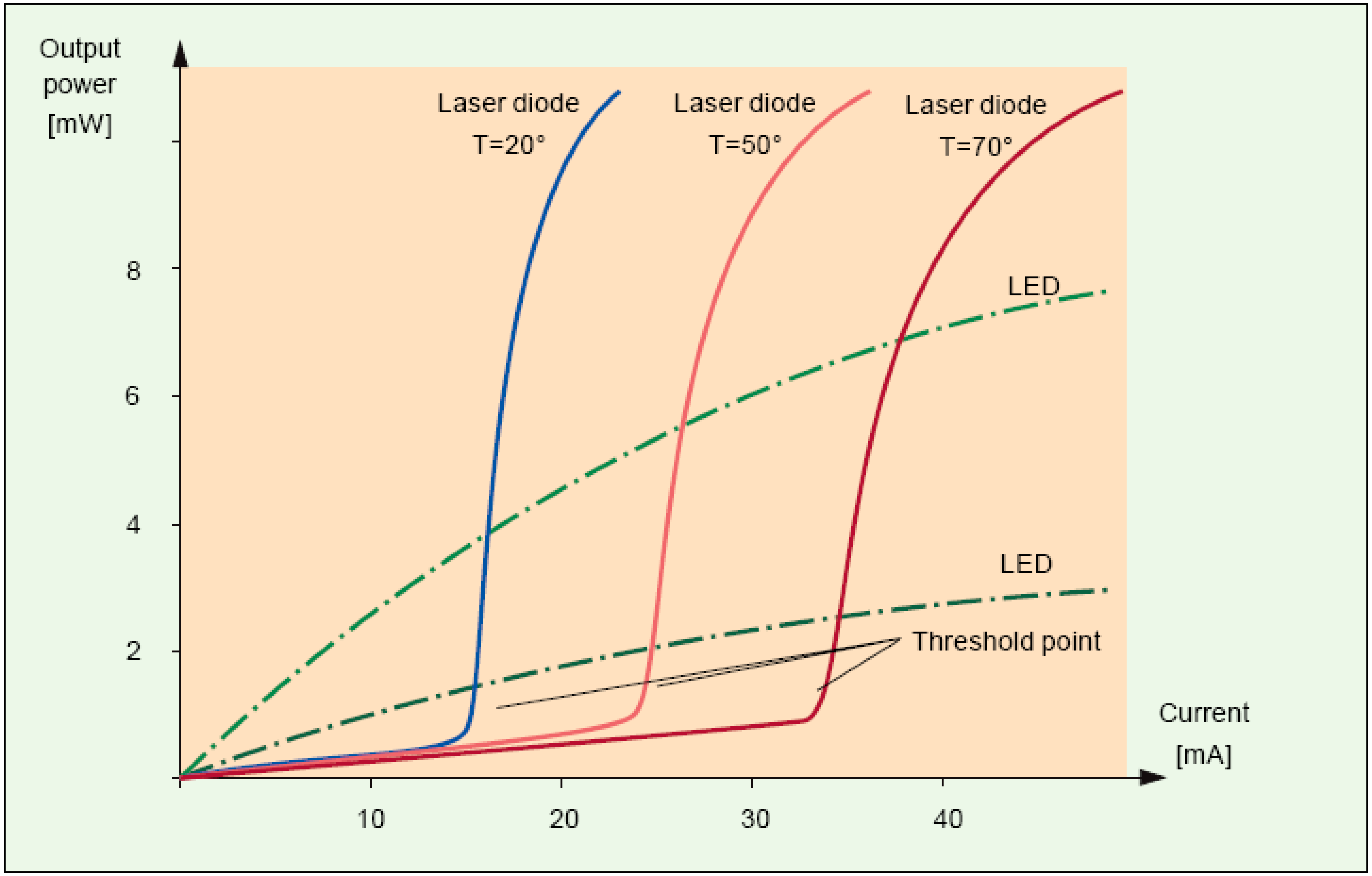


Profil de radiaţie a emiţătorilor optici



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

Caracteristici putere optică/curent a emiţătorilor optici

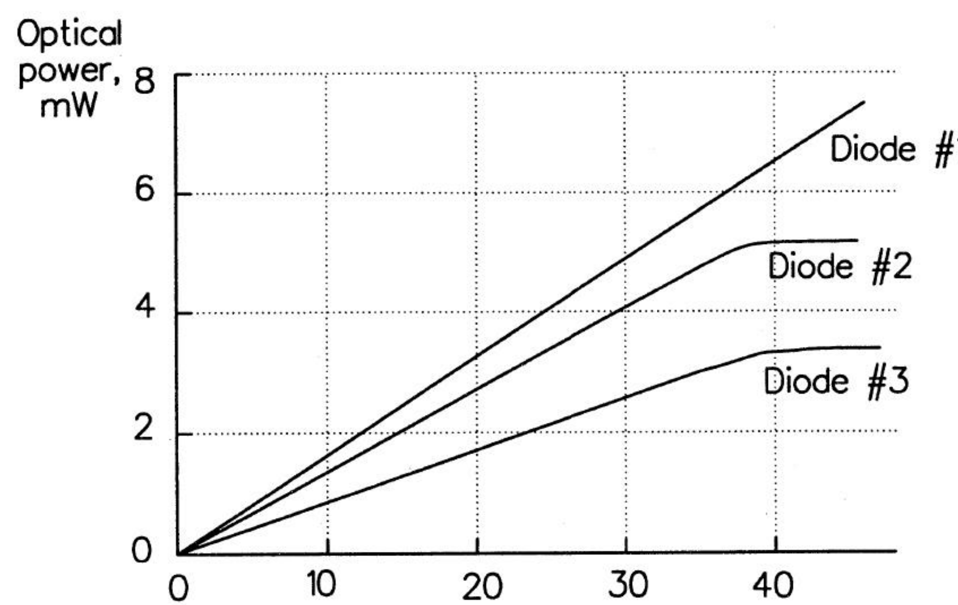


Caracteristica de raspuns a LED-urilor

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

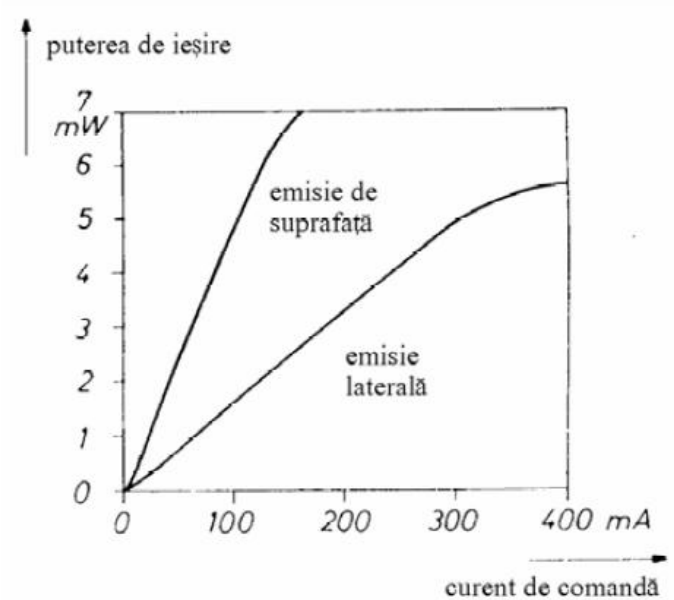
$$r = \frac{P_o}{I} \quad \left[\frac{W}{A}\right]$$

- Tipic r=50μW/mA



Caracteristica de raspuns a LED-urilor

- Tipic SLED au eficienta mai buna decat ELED



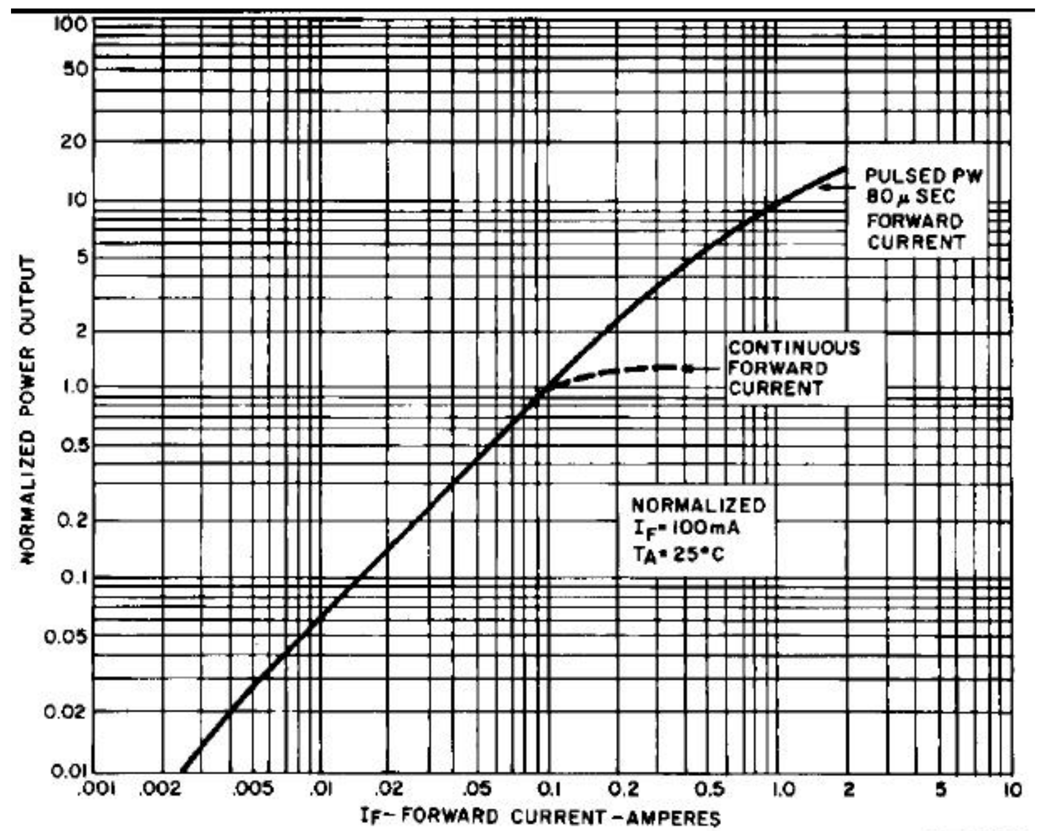


Fig. 1. Power Output vs. Input Current ST1052

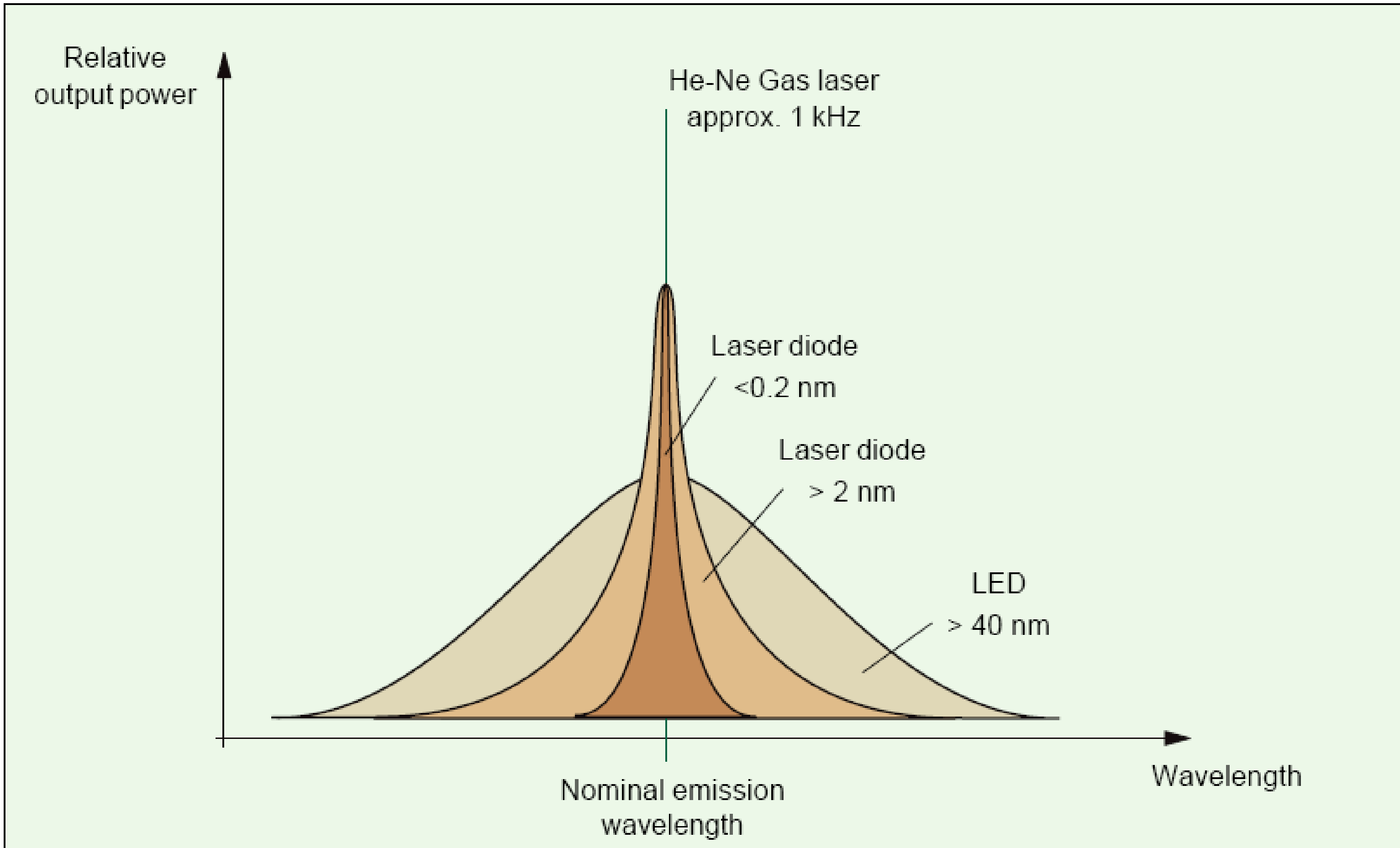
Probleme

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

Aplicatii majore LED

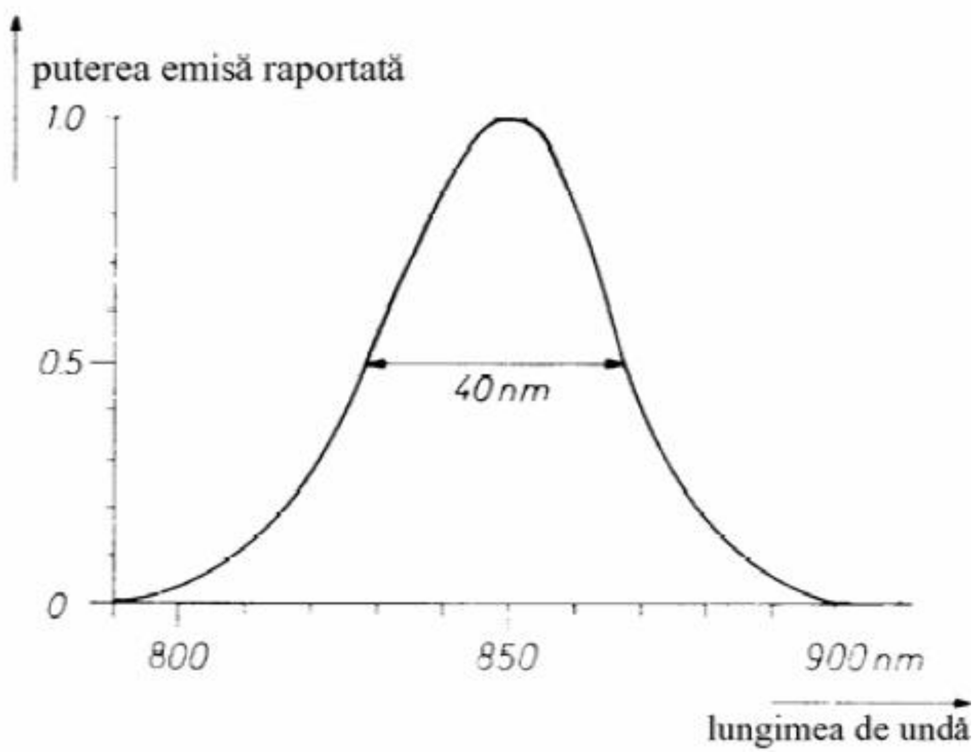
- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- Iluminare
  - Putere ridicata, lumina alba (GaInN)

Calitatea spectrală a emiţătorilor optici



Latimea spectrala a LED-urilor

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



Comportare dinamica a LED

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

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

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

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

  - Banda la 3 dB optic

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

Comportare dinamica a LED

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

Comportare dinamica a LED

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

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

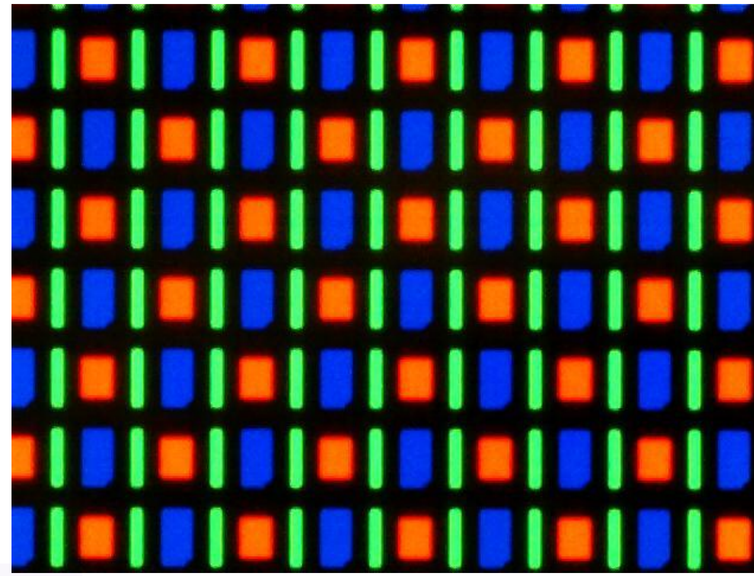
- Capacitatea asociata sarcinilor in regiunea activa: 350÷1000pF
- Produs Putere × Banda

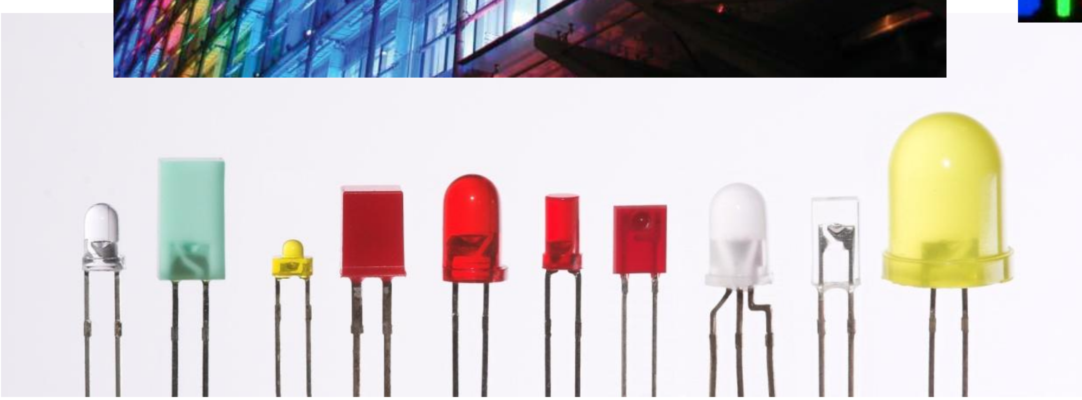
$$P \times \Delta f = \frac{h \cdot c}{2 \cdot \pi \cdot e \cdot \lambda} \cdot \frac{J}{\tau_{lf}}$$

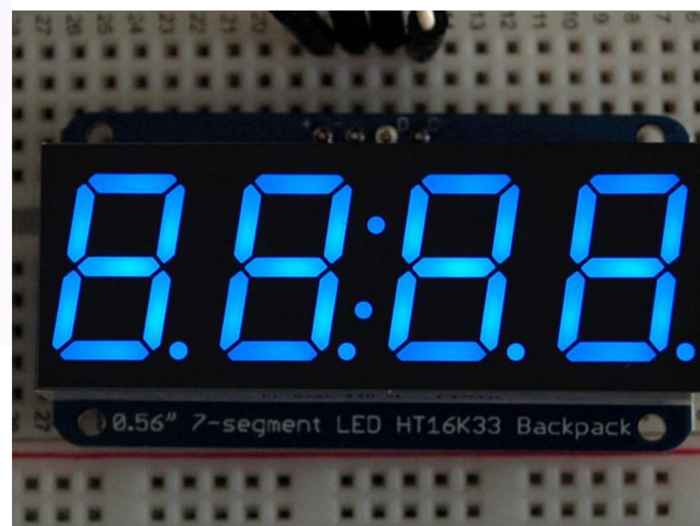
Aplicatii majore LED

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

Aplicatii in spectru vizibil

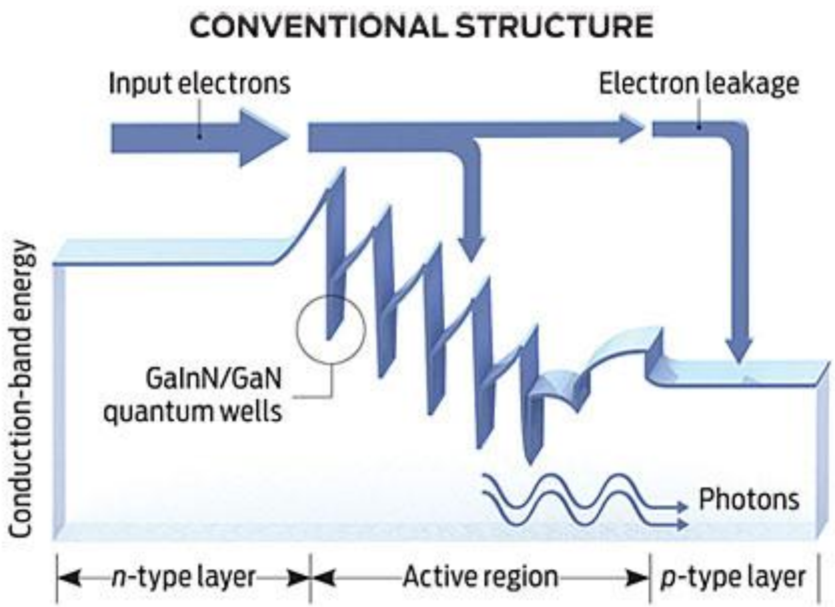


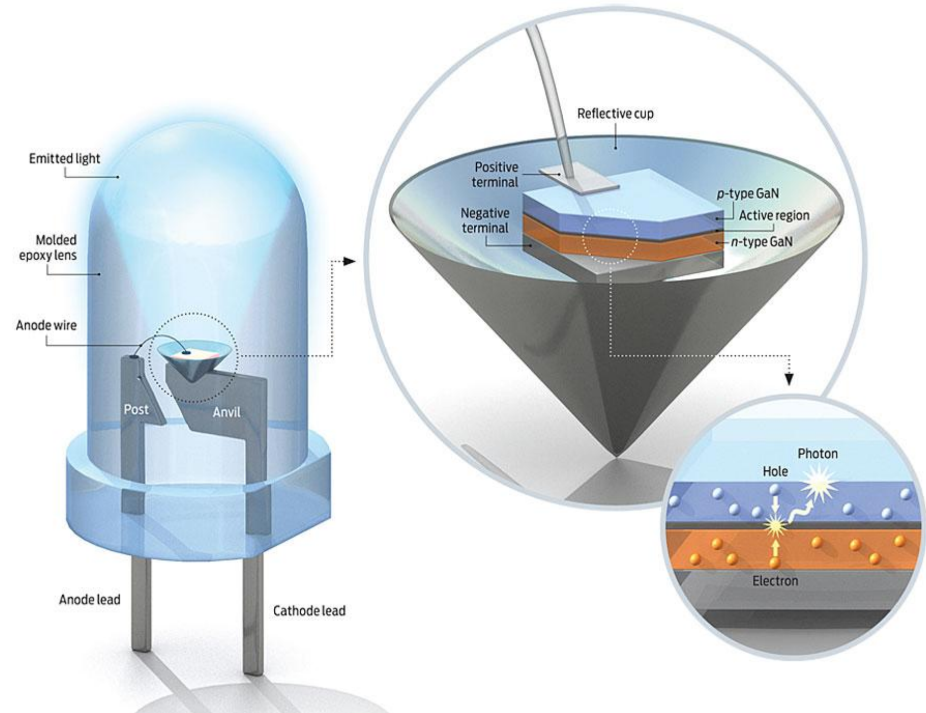




LED albastru

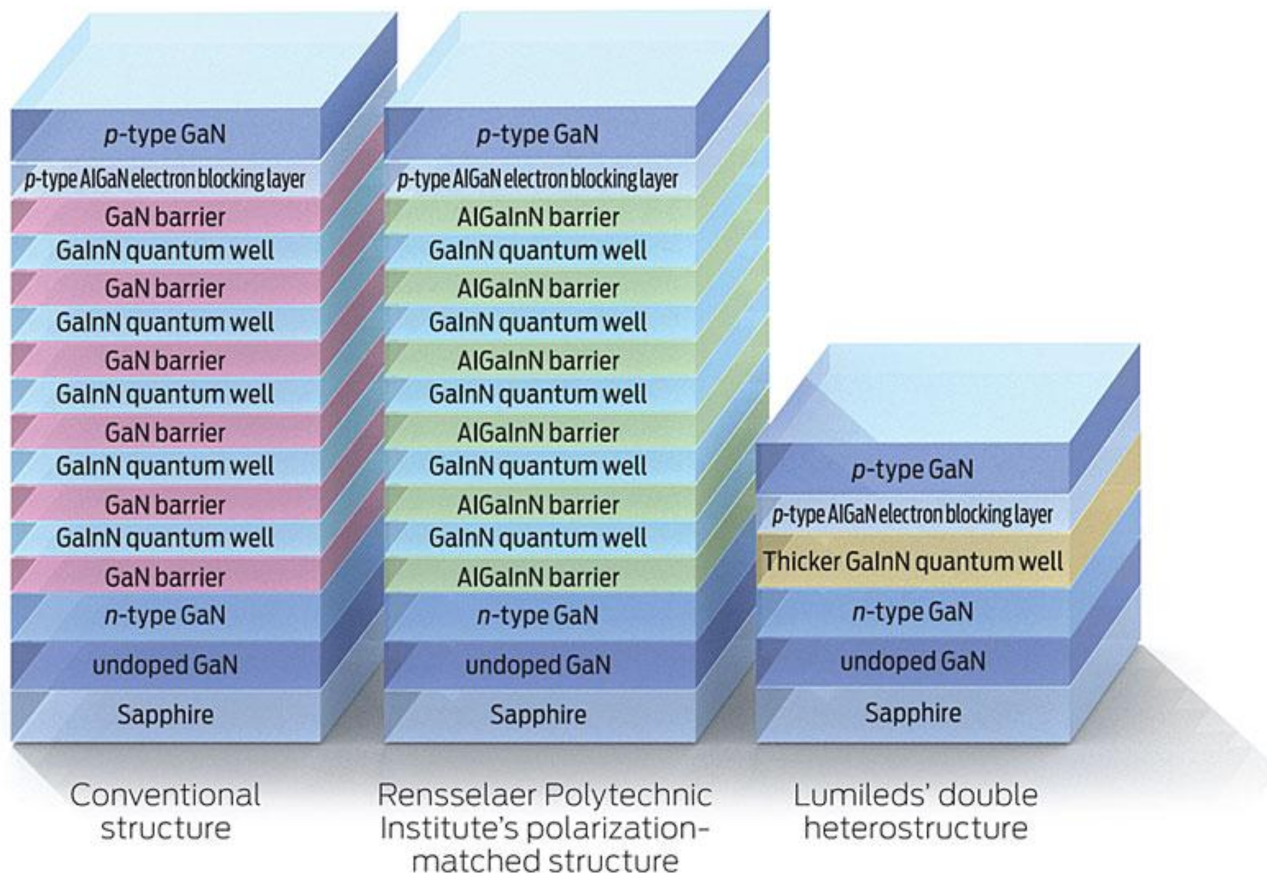
- bazat pe GaInN
- dezvoltare tardiva (GaN)





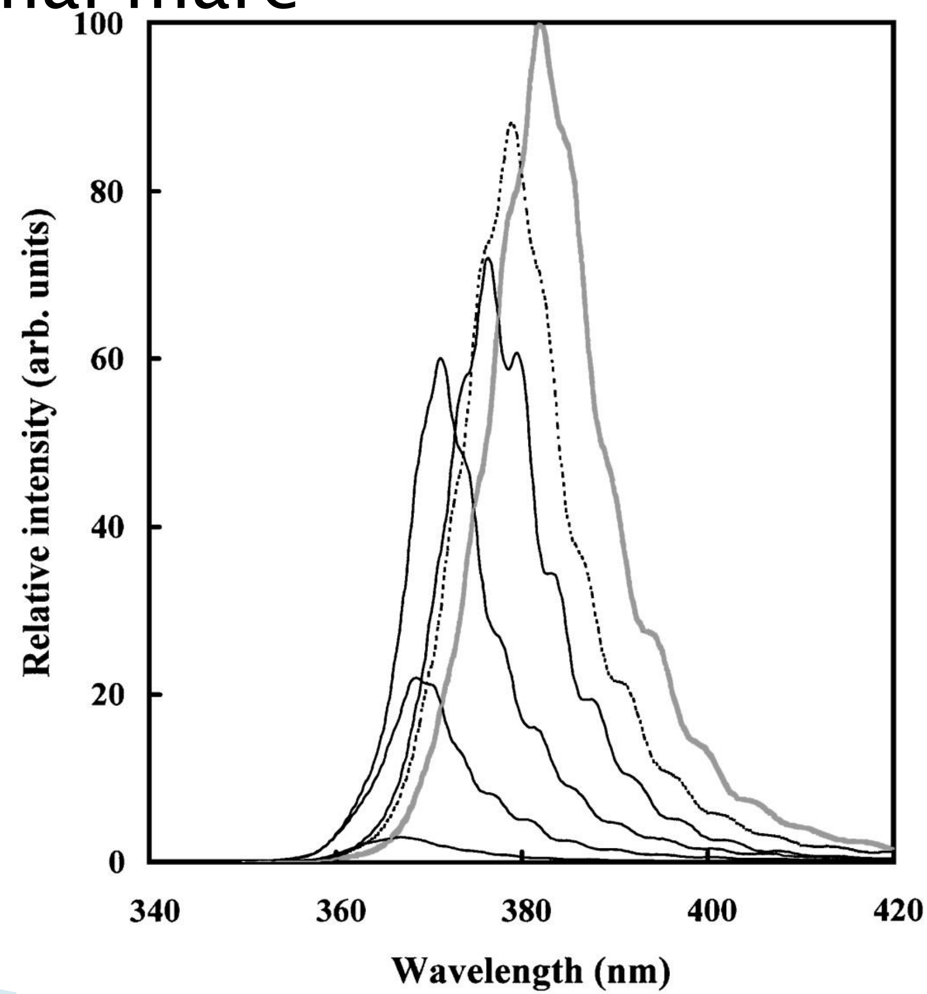
LED albastru

- realizare: GaInN Quantum Well/GaN

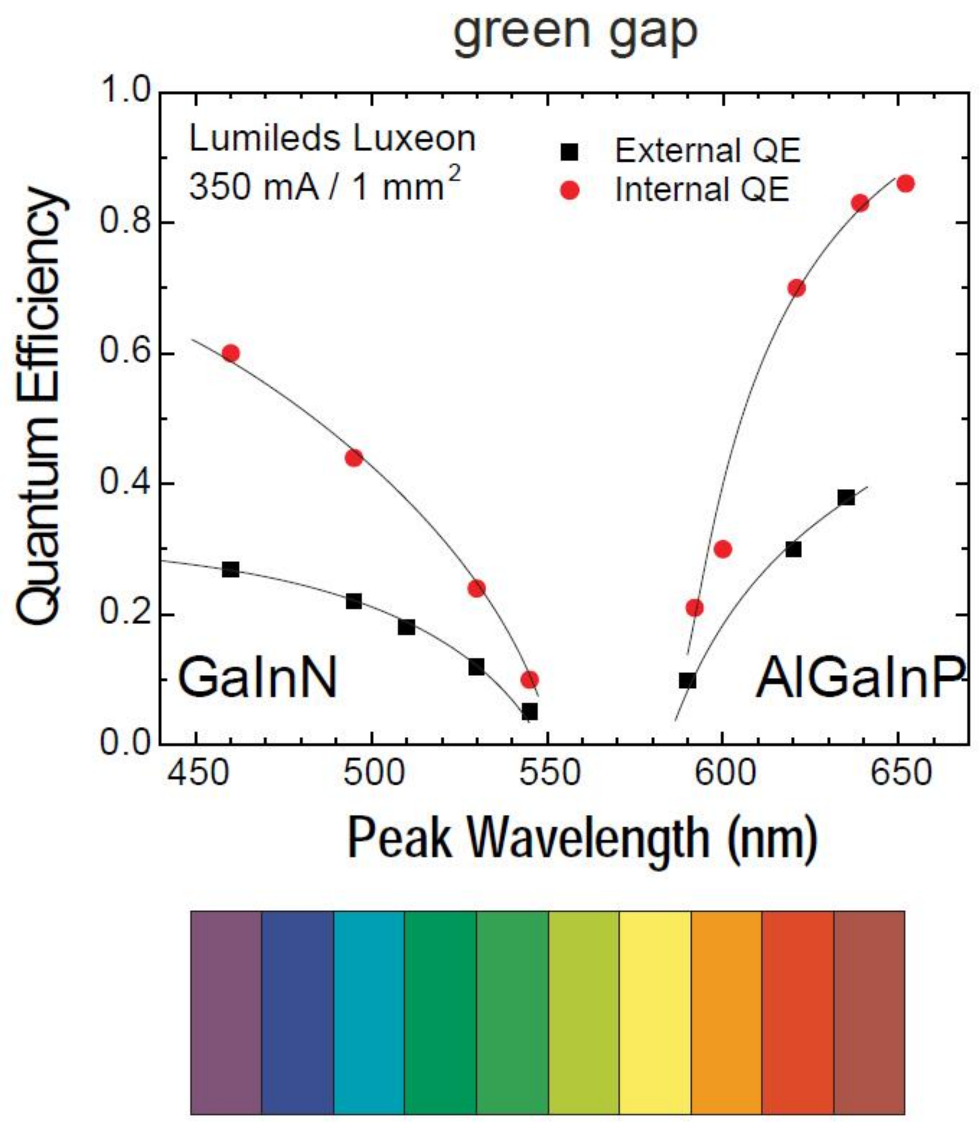


Spectru LED albastru

- Δλ relativ la λ mai mare



Eficienta 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

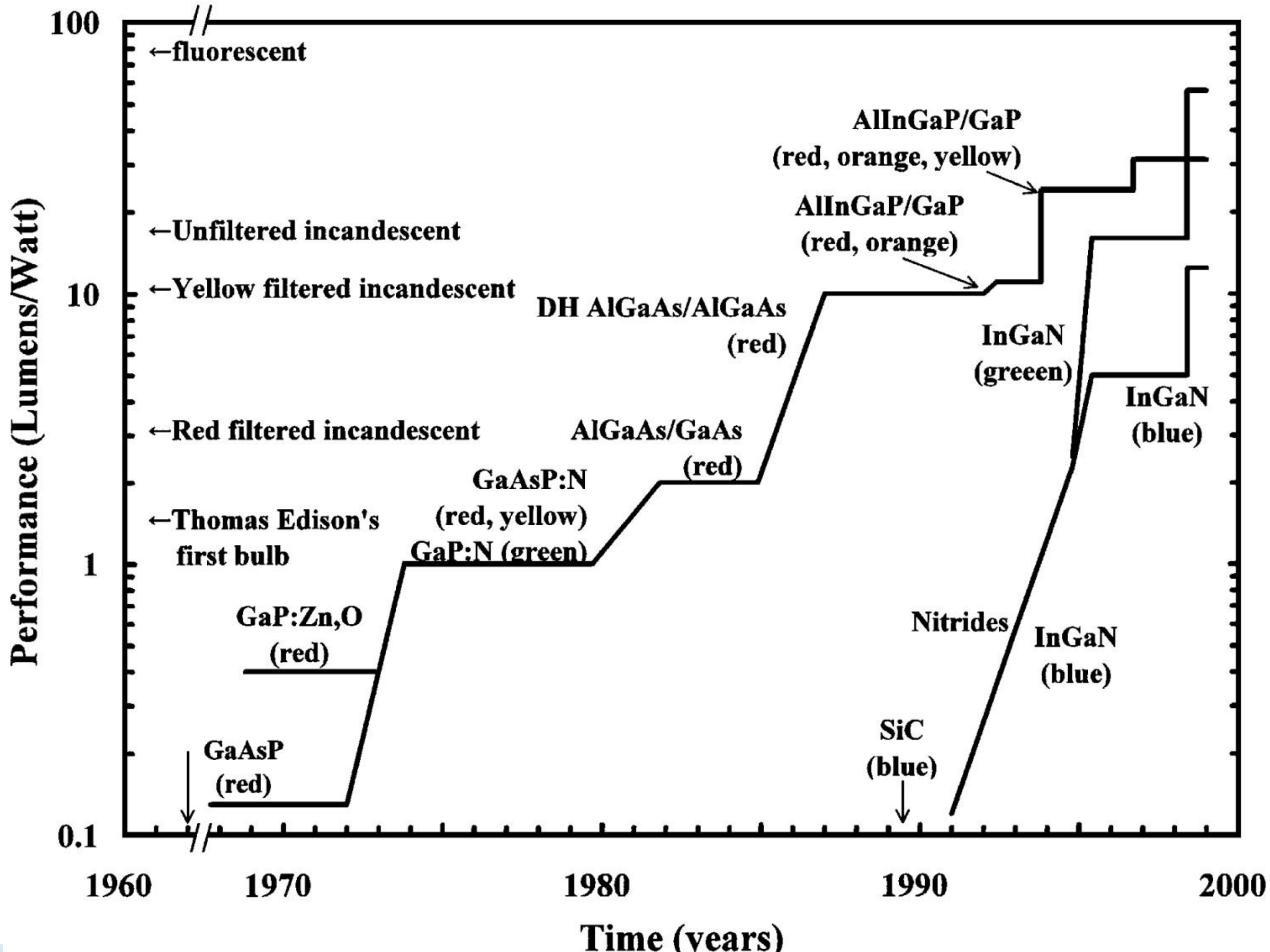
- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- **Iluminare**
  - Putere ridicata, lumina alba (GaInN)

Premiul Nobel, Fizica, 2014

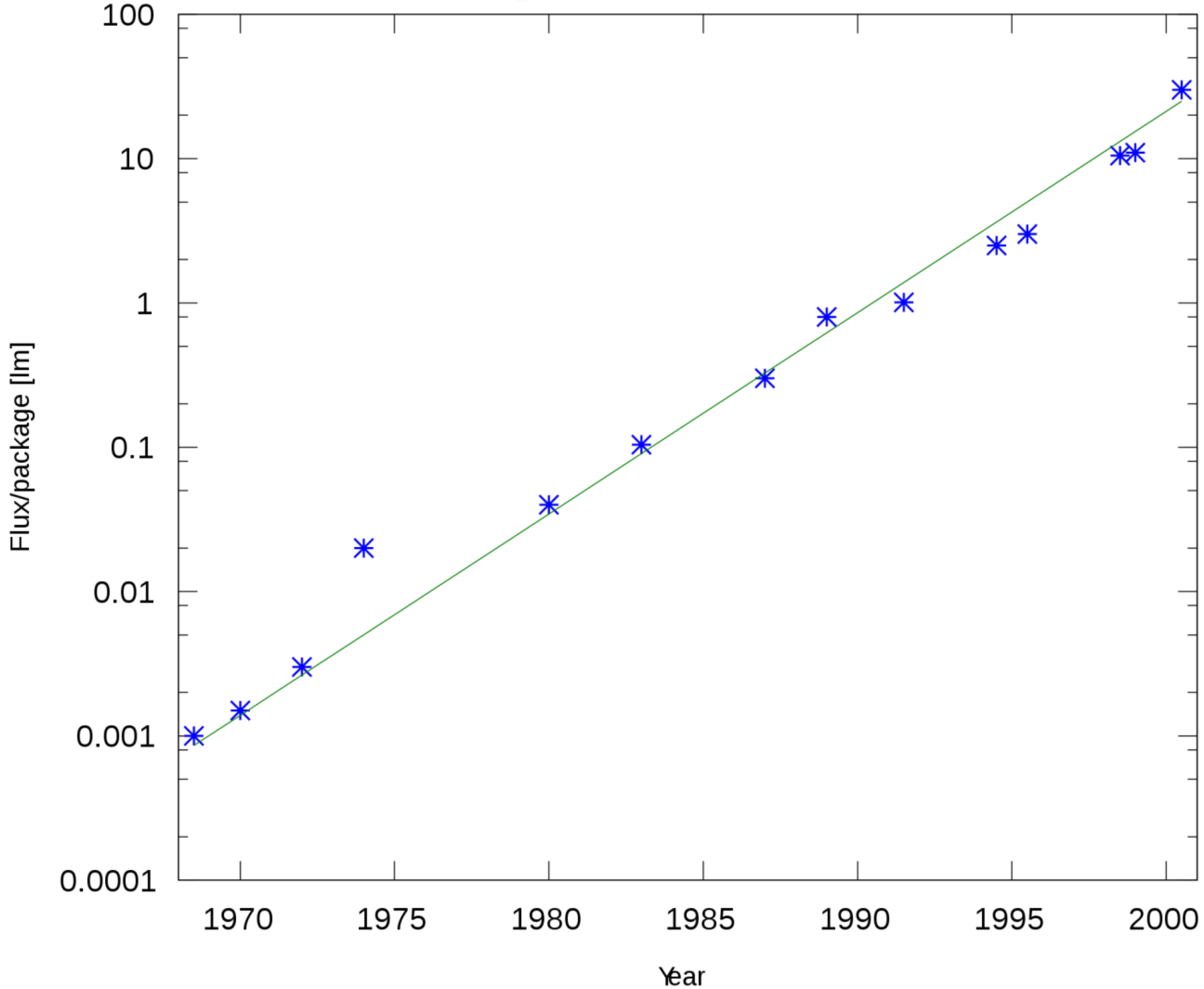
Eficienta

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

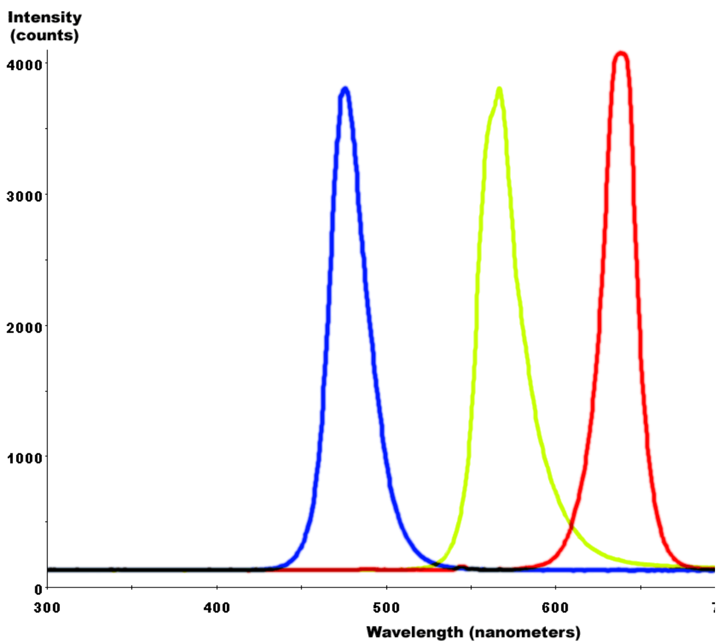
Eficienta in timp

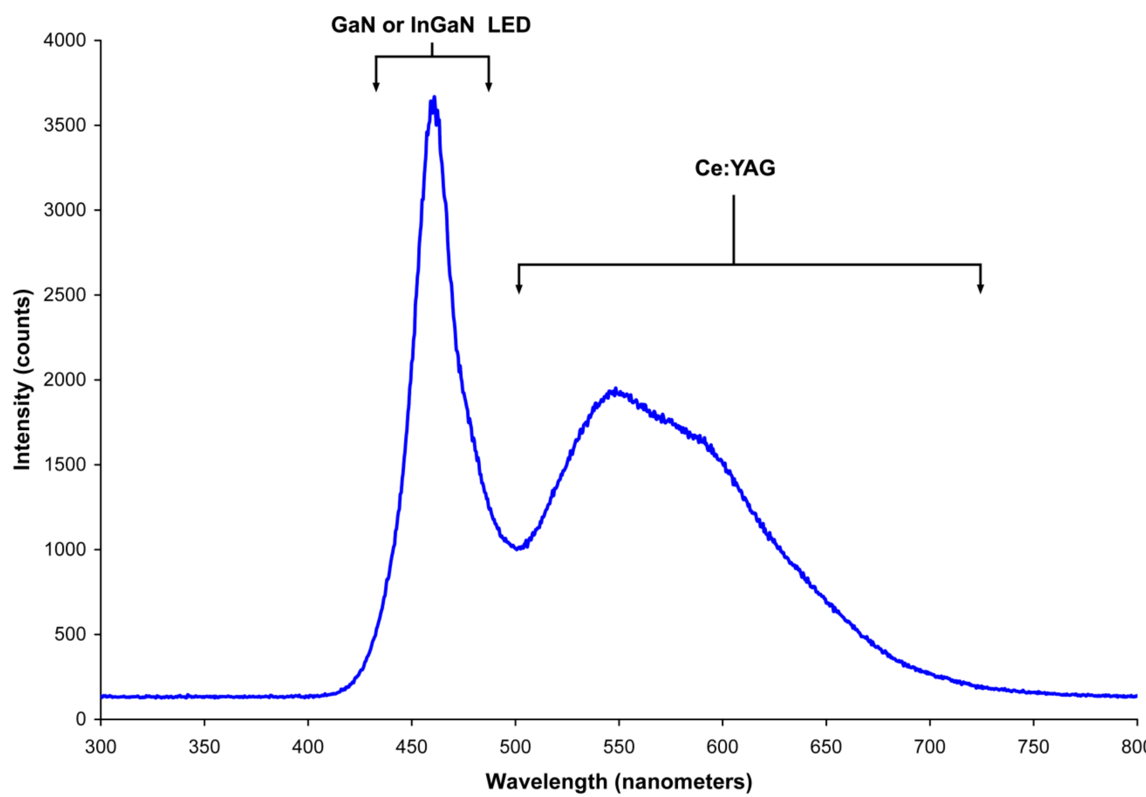


Eficienta in timp

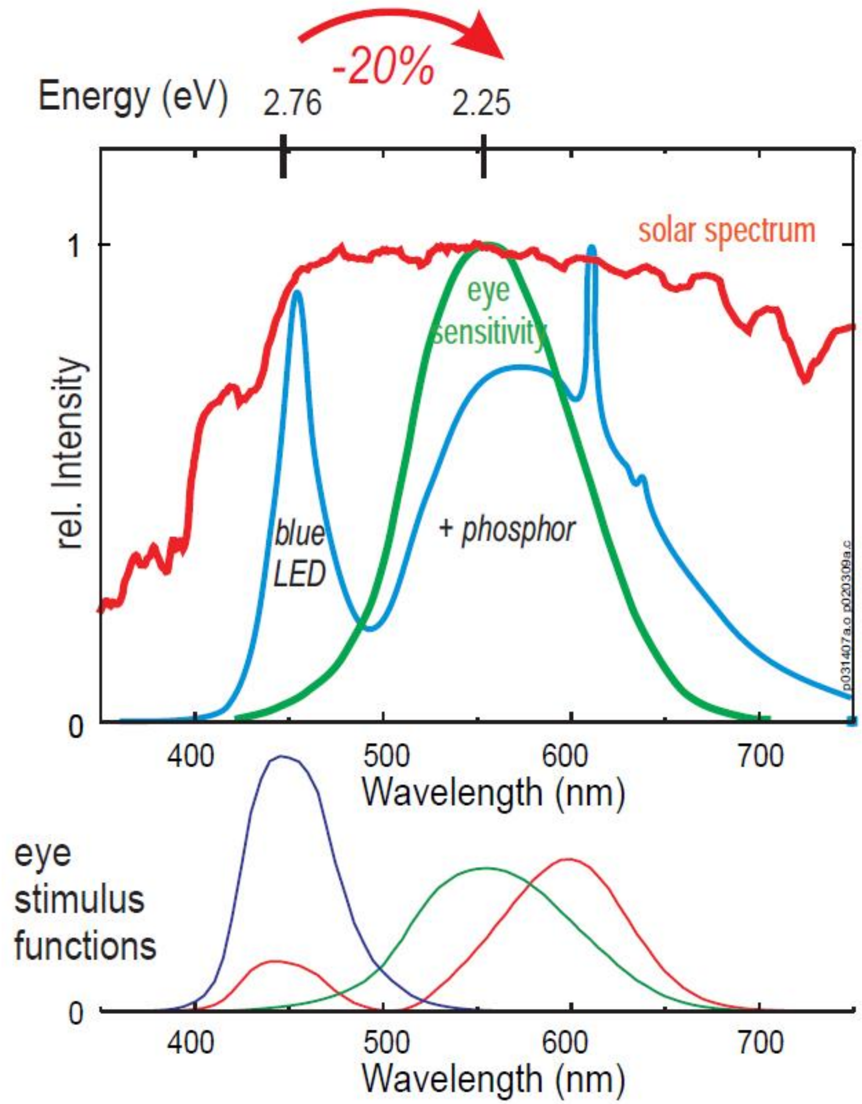


Culoare alba

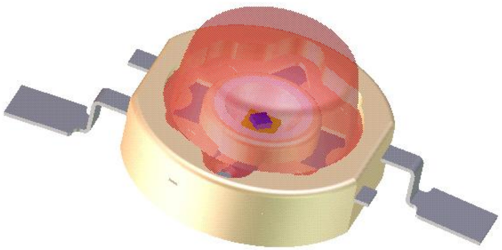


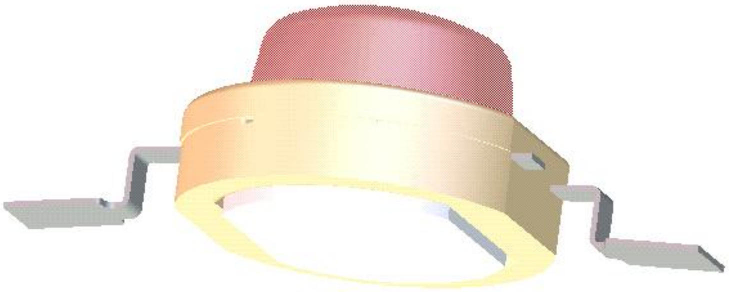


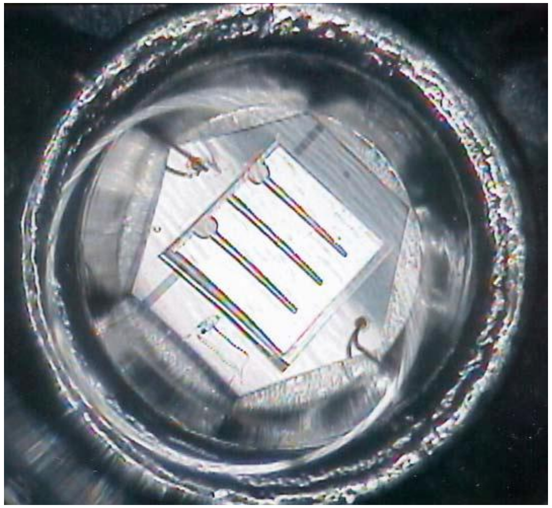
Fosfor activat de LED albastru/UV



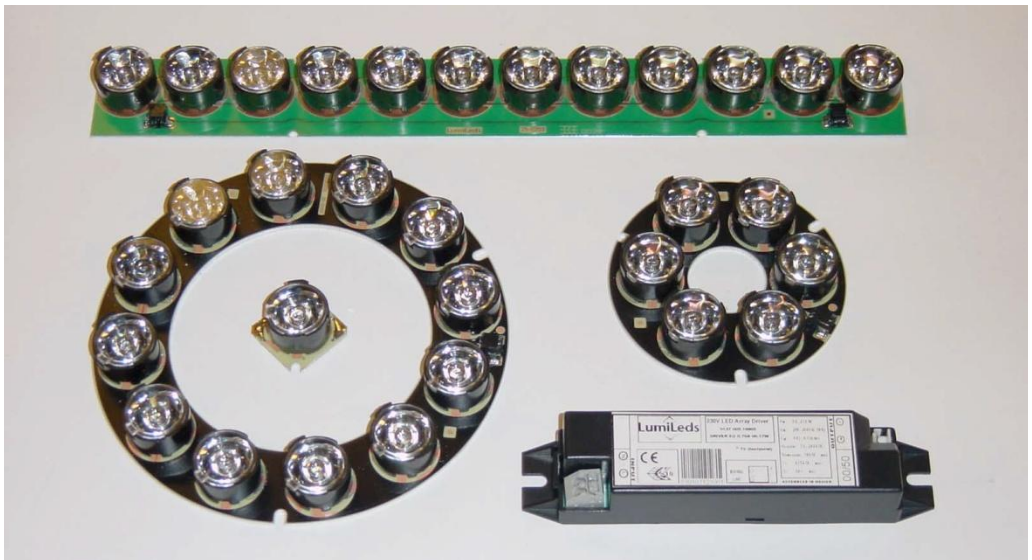
Realizare LED de putere

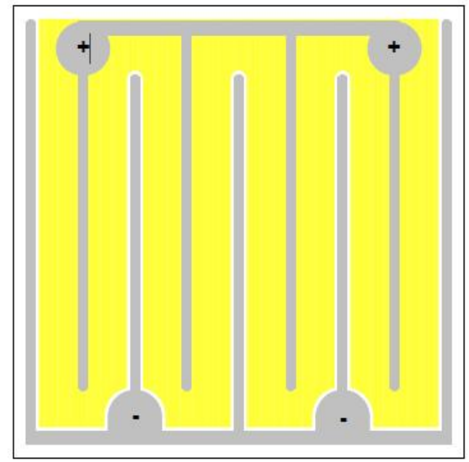




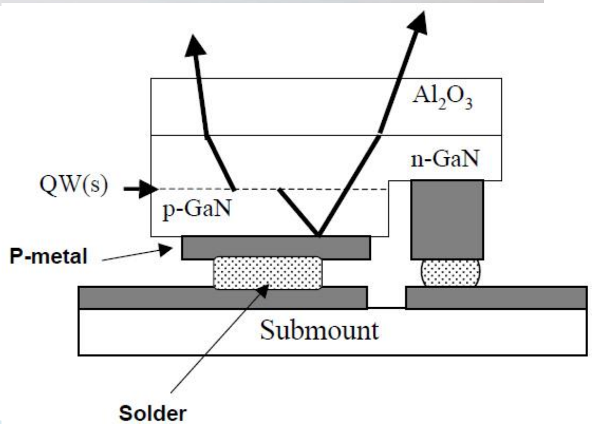


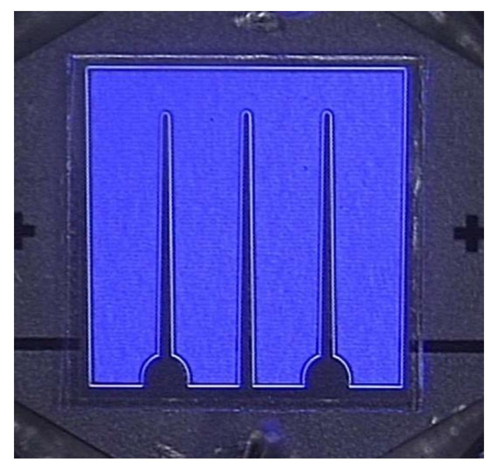
Realizare LED de putere



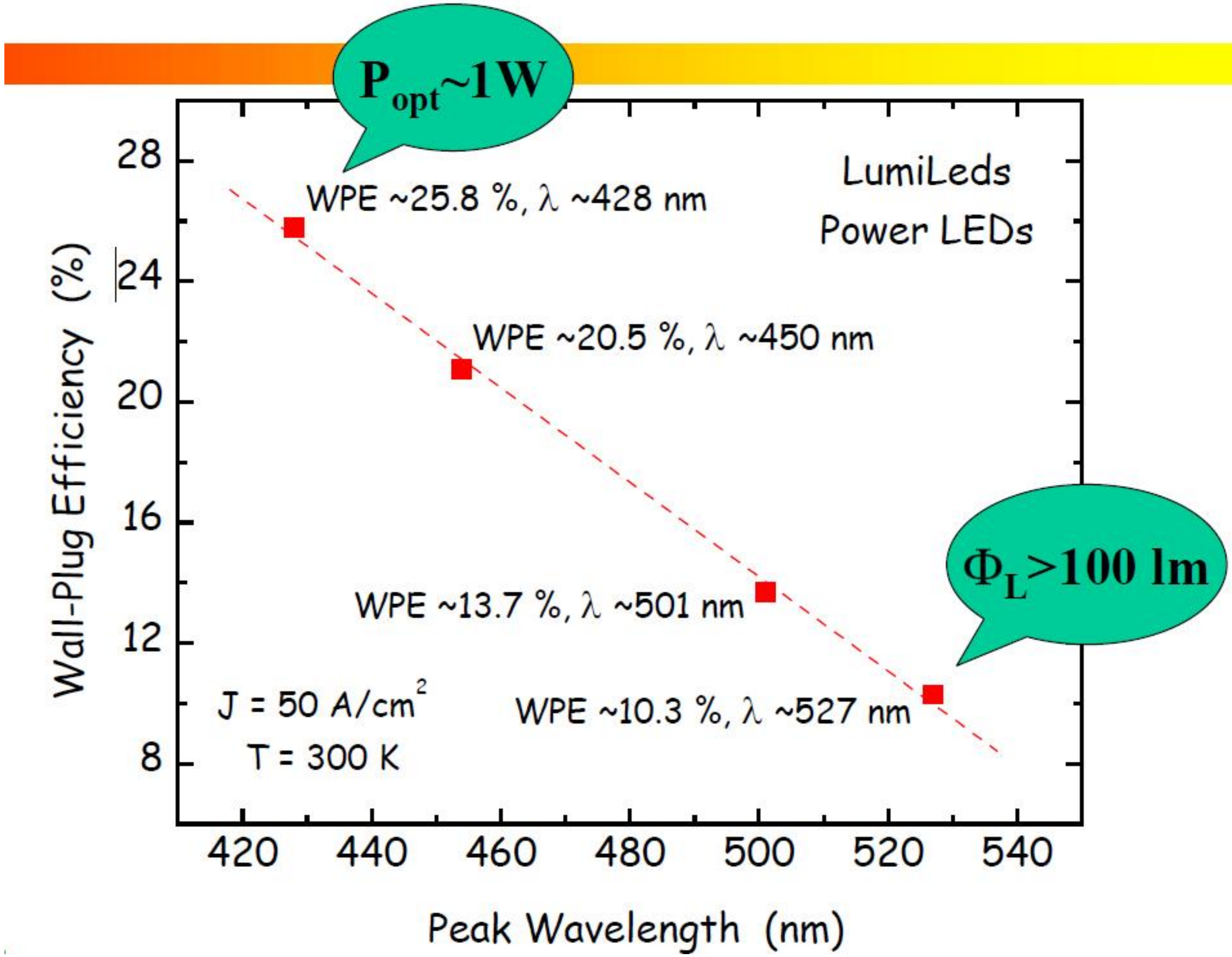


$A_{chip} \sim 1 \times 1\ mm^2$; $N = 4$





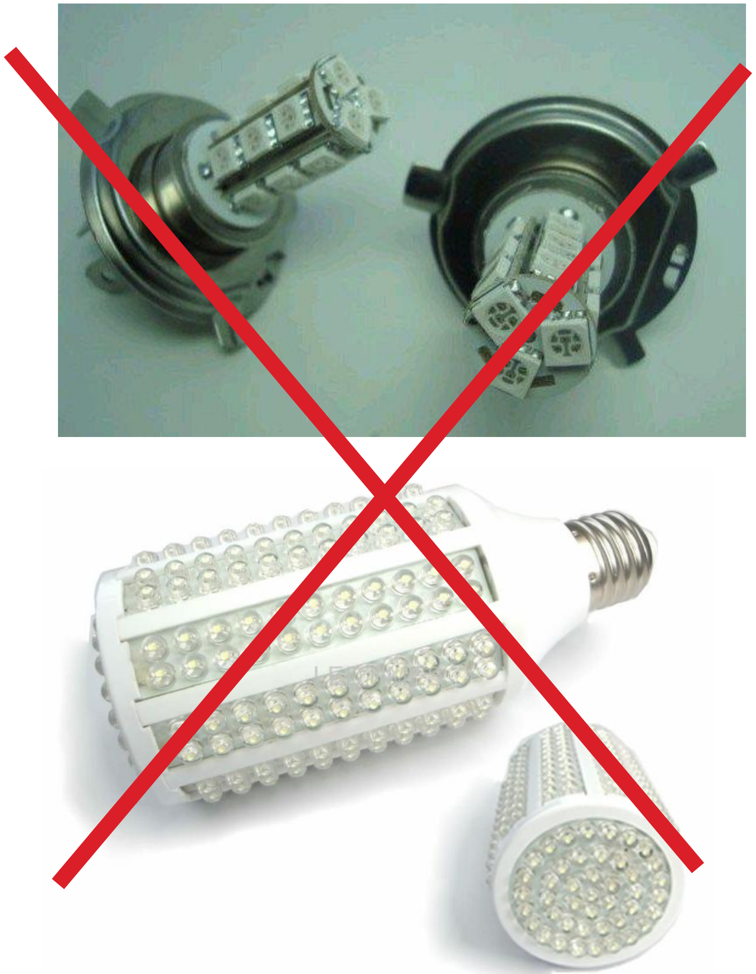
Performanta

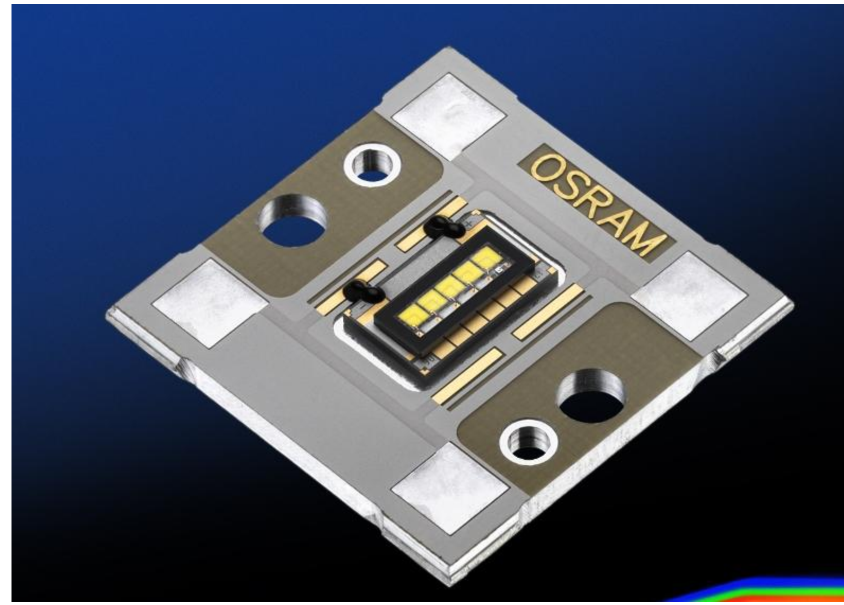


Aplicatii

- 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)

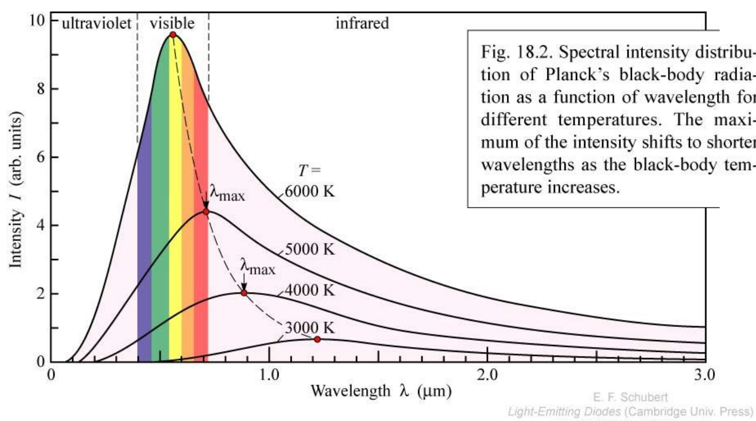
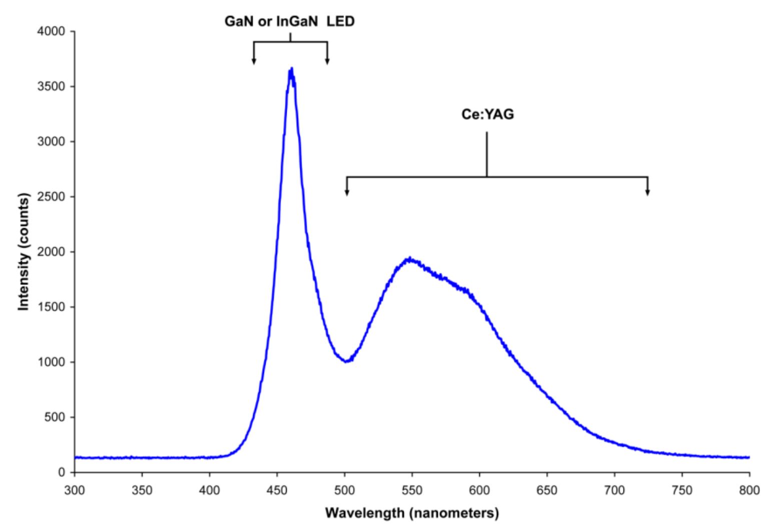
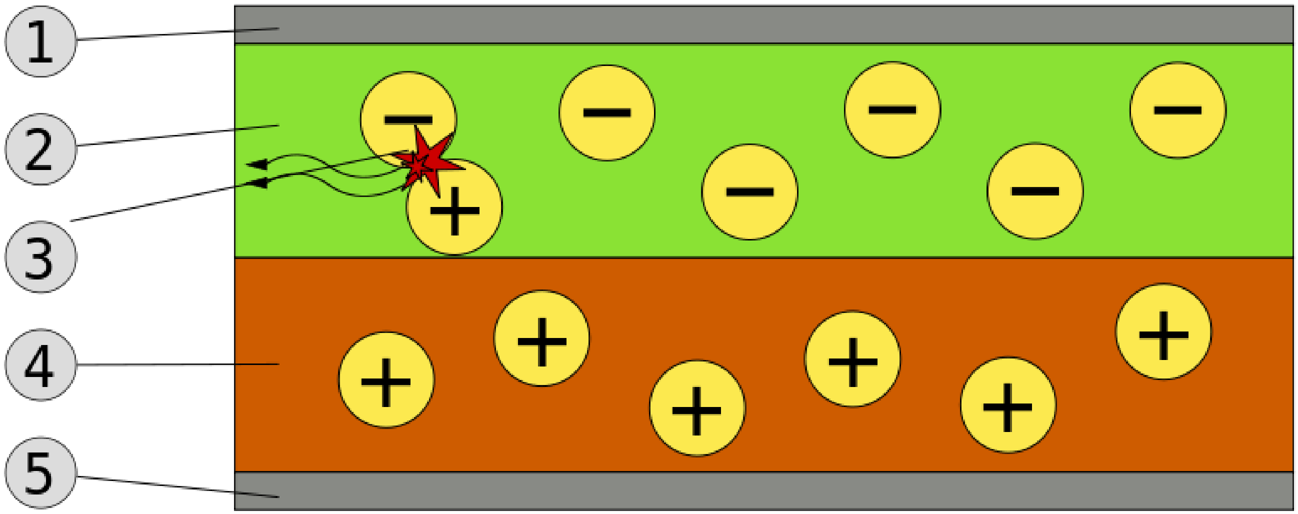
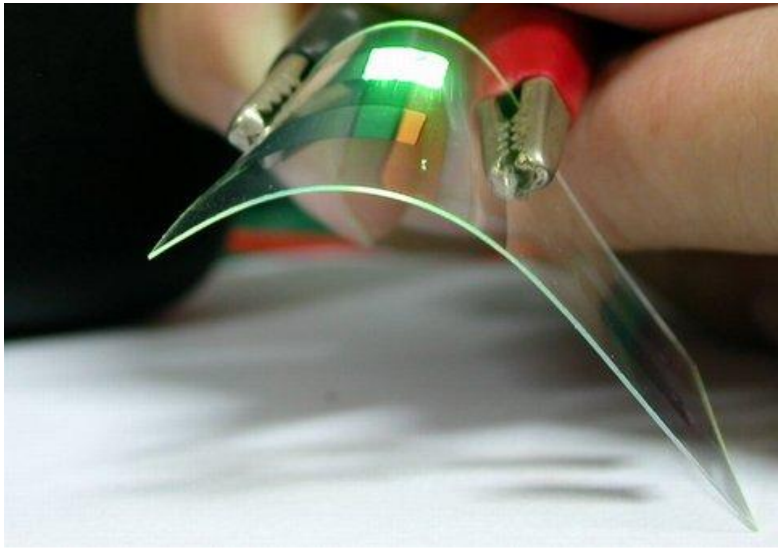


Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

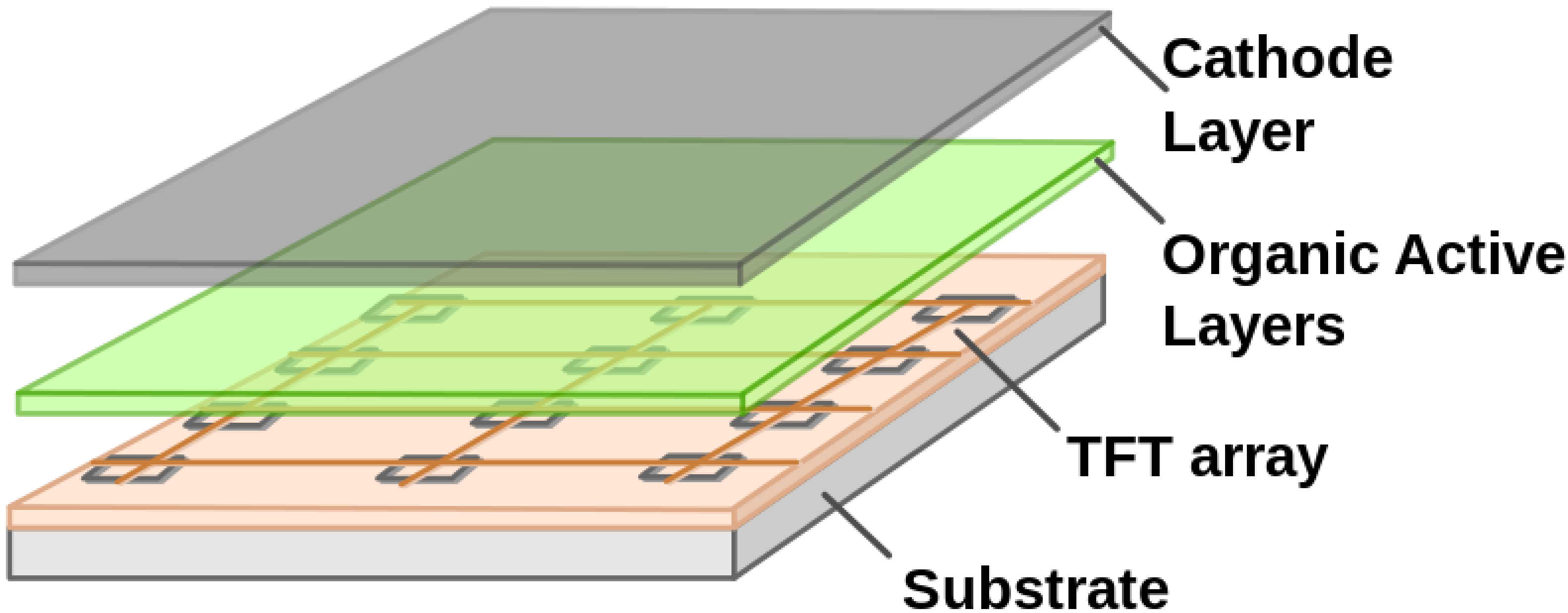


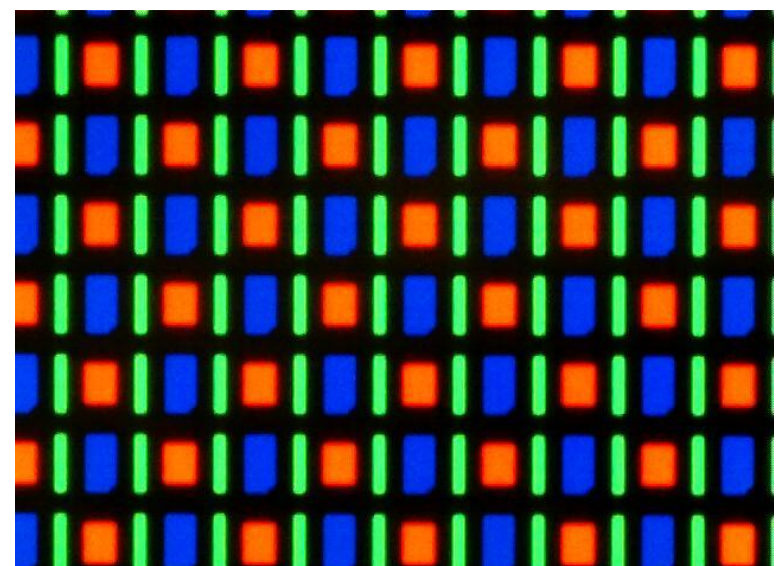
OLED





AMOLED





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