Optoelectronică

Curs 5
2020/2021

Disciplina 2020/2021

- 2C/1L Optoelectronică OPTO
- **Minim** 7 prezente curs + laborator
- Curs – conf. Radu Damian
  - an IV μE
  - Miercuri 11-14, online, Microsoft Teams
  - E - 70% din nota (50+20), online, rf-opto
    - **20% test la curs**, saptamana 4-5?
  - probleme + (**?** 1 subiect teorie) + (2p prez. curs)
  - toate materialele permise
- Laborator – sl. Daniel Matasaru
  - an IV μE
    - Marti 10-14 impar/par
  - L - 30% din nota (+Caiet de laborator)

Orar 2020/2021

▸ Curs
  ◦ Miercuri 11-14, online
  ◦ 2C ⇨ 3C
    • 14*2/3 ≈ 9.33
    • 9÷10 C ≈ 9C + E

Online

- acces la examene necesita parola primita prin email

Online

▶ acces email/parola

Parola

▸ primita prin email

Manual examen online

▸ Aplicatia de examen online utilizata intens la:
  ◦ curs (prezenta)
  ◦ miniteste
  ◦ examen

Materials

Other data

Manual examen on-line (pdf, 2.65 MB, ro, ▮▮)
Simulare Examen (video) (mp4, 65.12 MB, ro, ▮▮)

Microwave Devices and Circuits (Englis

Examen online

- intotdeauna contratimp
  - perioada lunga (prezenta curs/rezultate laborator)
  - perioada scurta (teste: 15min, examen: 2h)

Introducere

Capitolul 1

Aplicatii majore

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

Benzi de lucru in comunicaţiile optice
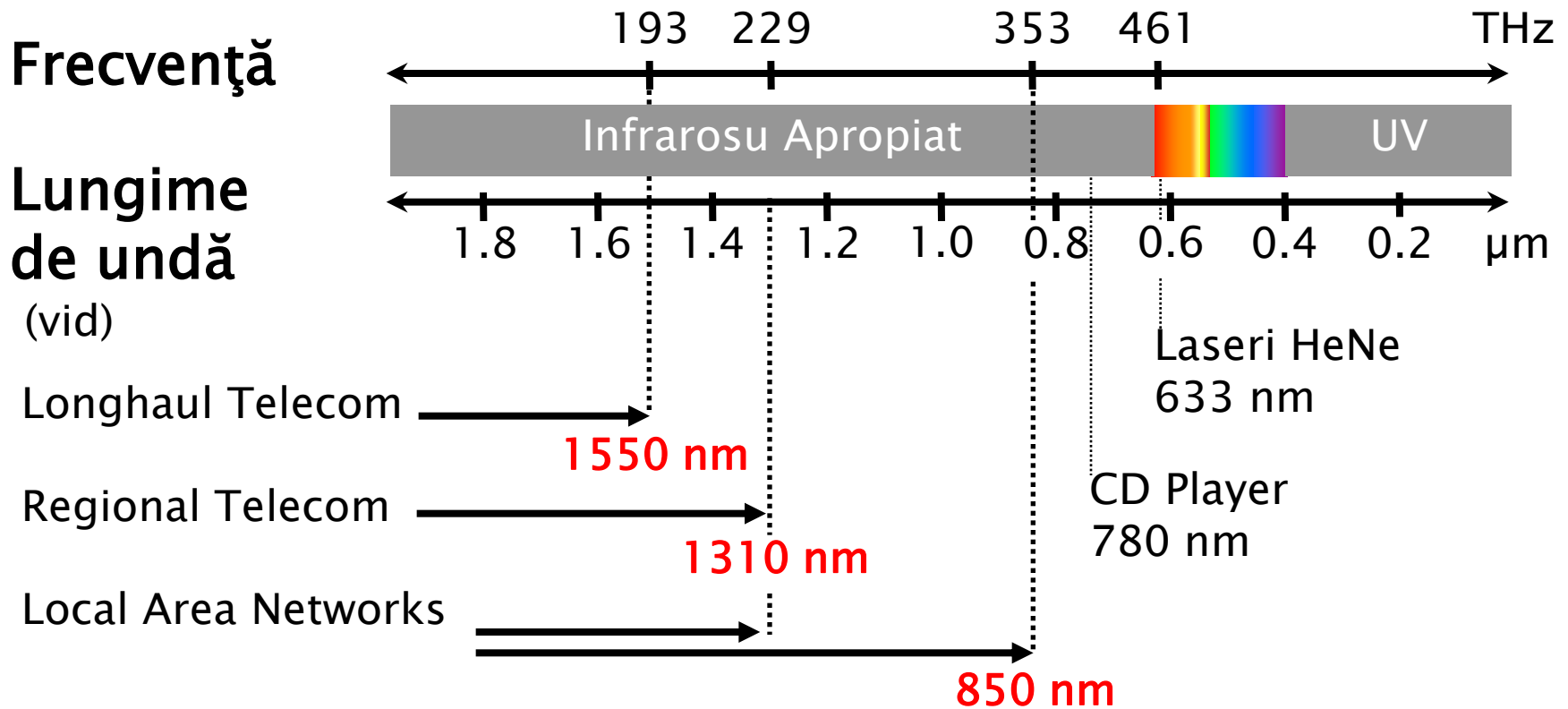
Atenuarea în fibra optică (SiO₂)
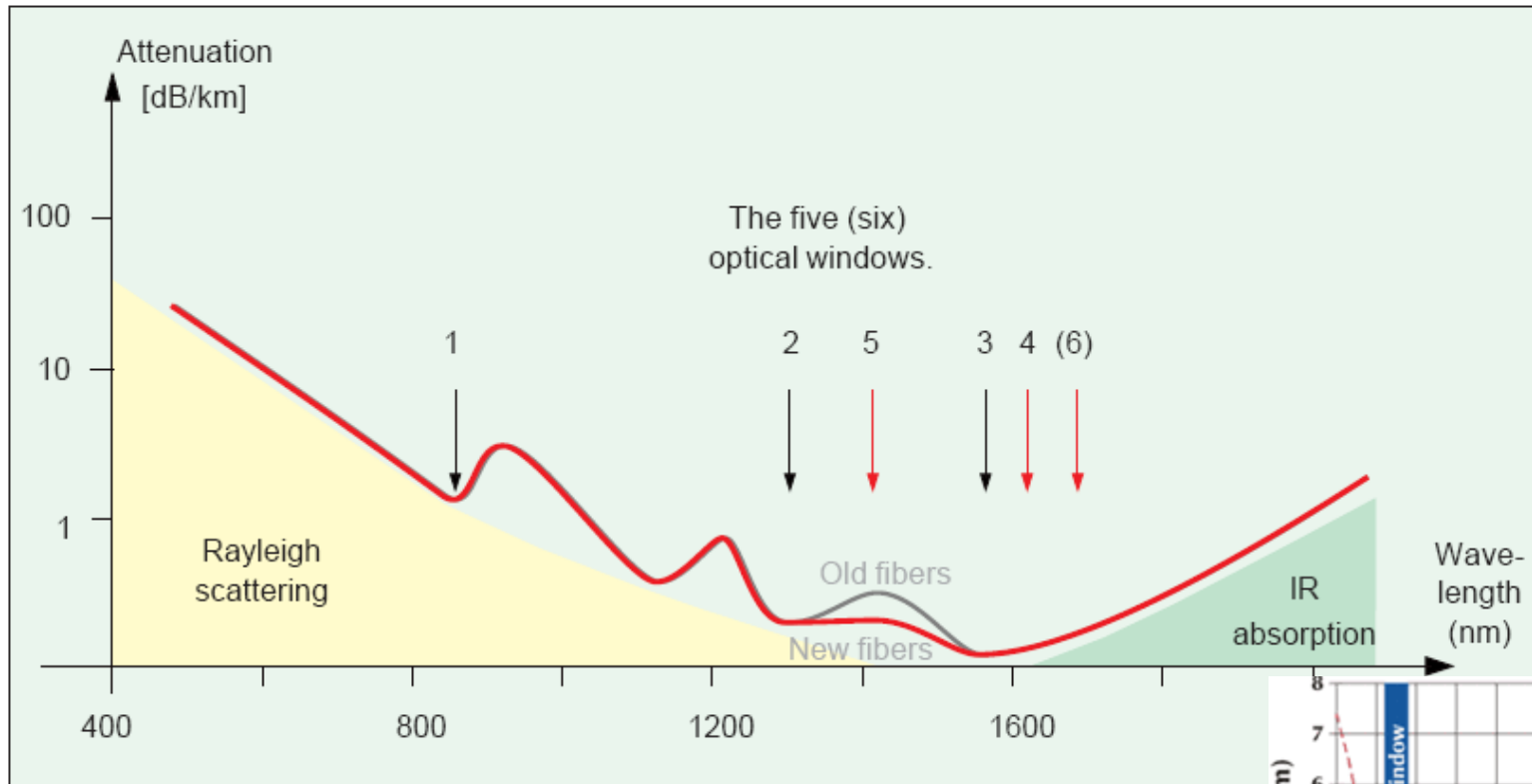
850nm, 1310nm, 1550nm
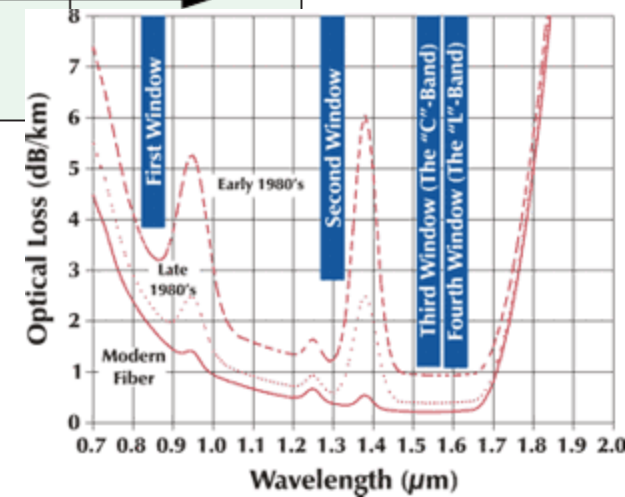
Fibra optică

Capitolul 4

Cuprins

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

Fibra optica

- ## un ghid de unda dielectric
  - miez
  - teaca

Optical fibers

Tube

Strain relief (e.g., Kevlar)

Inner jacket

Sheath

Outer jacket

n_0

n_1

n_2

Normal

i | r

Core
<9 ± 1 μm

Cladding
125 ± 1 μm

Soft acrylate
about 200 μm

Hard acrylate
245 ± 10 μm
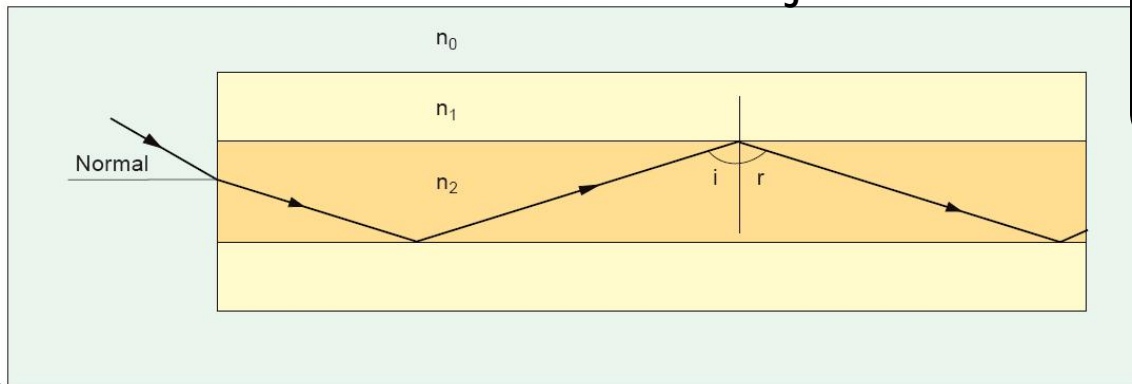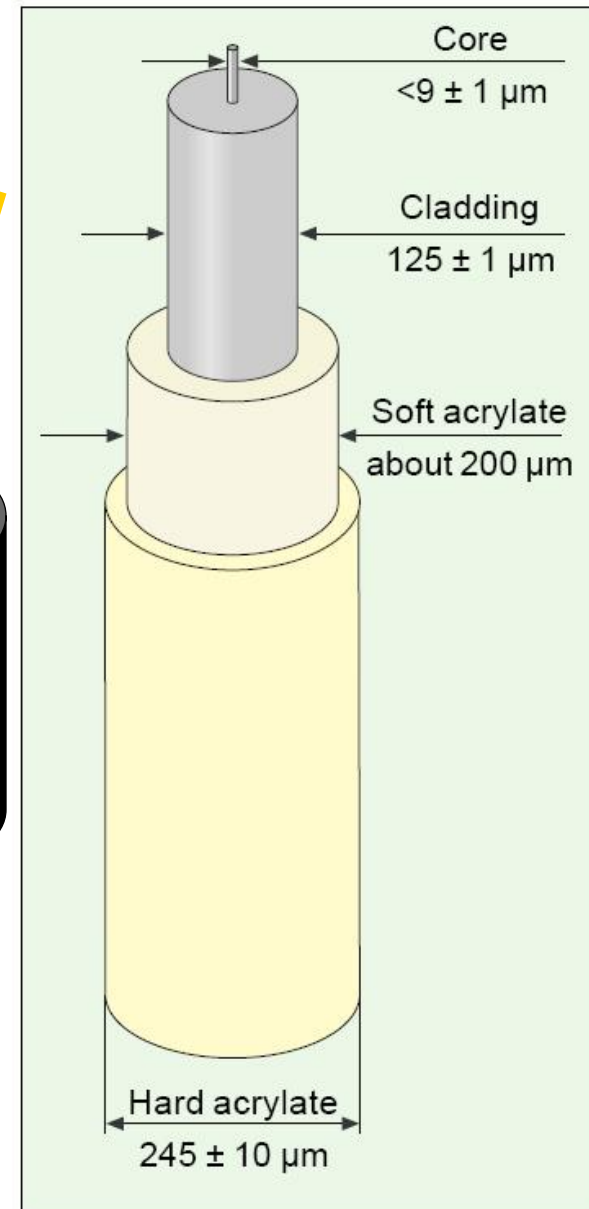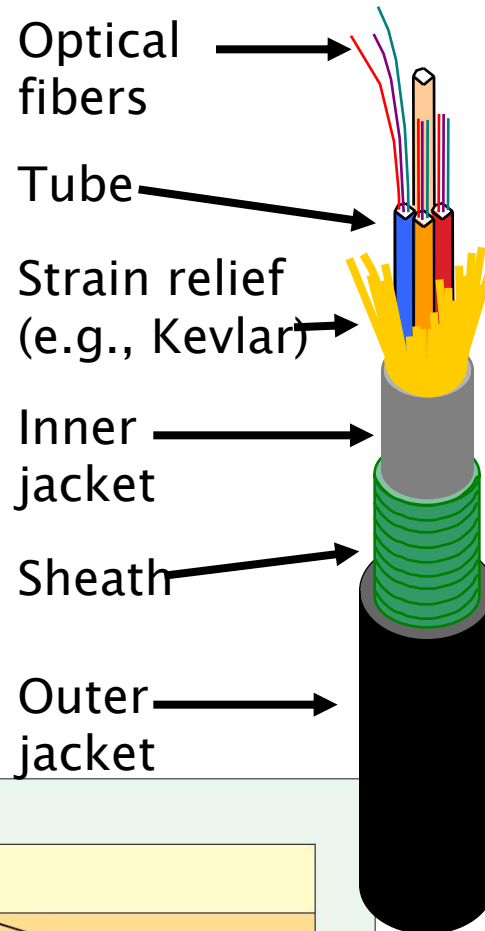
Unghi de acceptanta, apertura numerica

- 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
$n_2 > n_1$!!
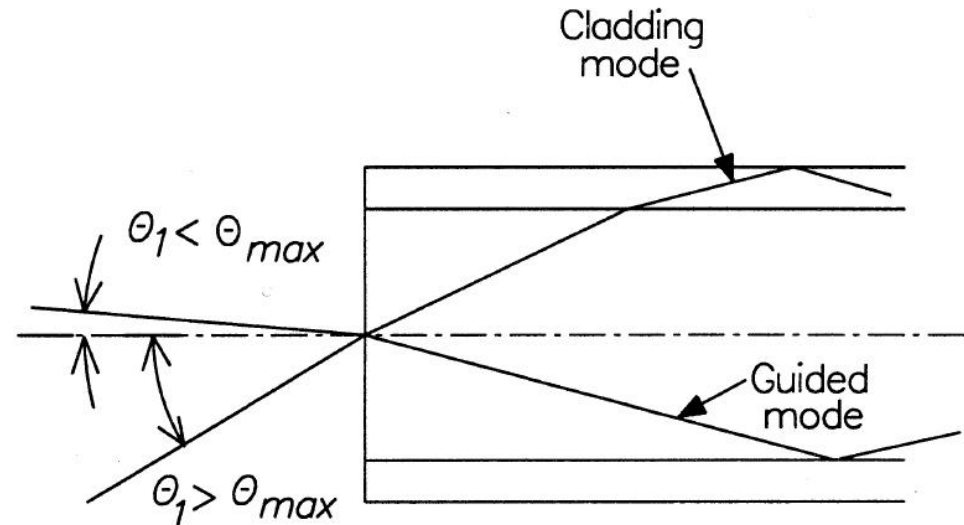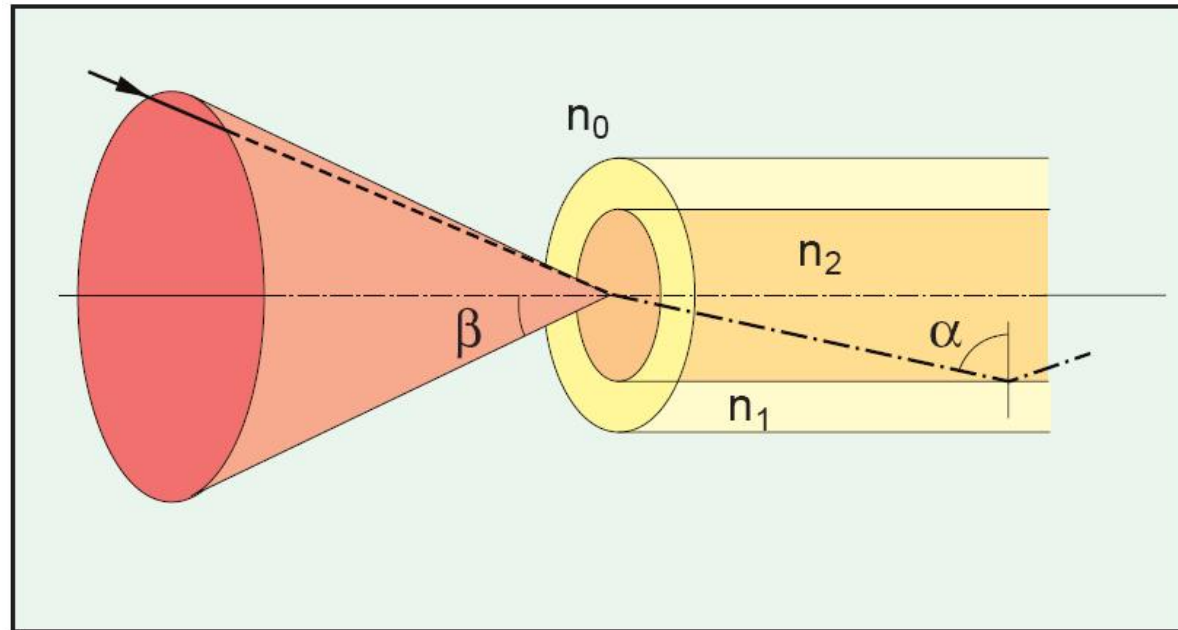
Tipuri de fibra

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

Increasing RI
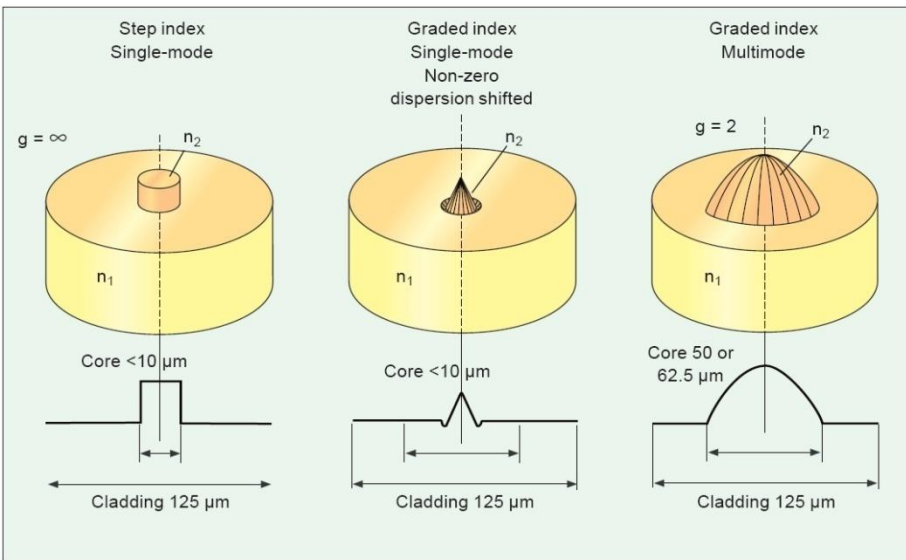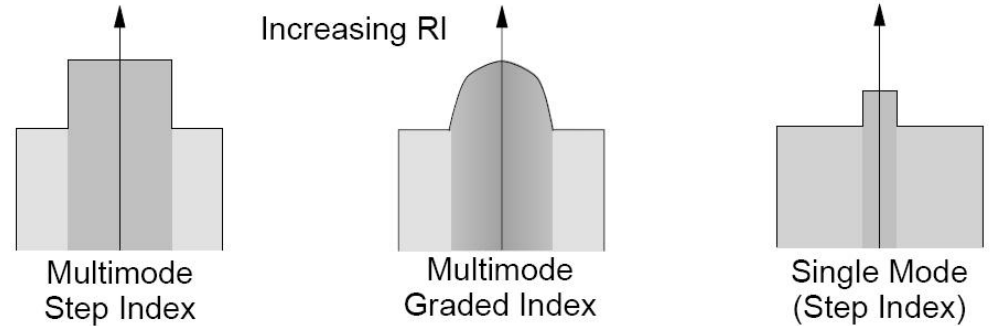
Multimode Step Index

Multimode Graded Index

Single Mode (Step Index)

Step index Single-mode

$g = \infty$

n_2

n_1

Core <10 µm

Cladding 125 µm

Graded index Single-mode Non-zero dispersion shifted

n_2

n_1

Core <10 µm

Cladding 125 µm

Graded index Multimode

$g = 2$

n_2

n_1

Core 50 or 62.5 µm

Cladding 125 µm

Multimode Step Index

125

50/62

Multimode Graded Index

125

50/62

Single Mode

125

9
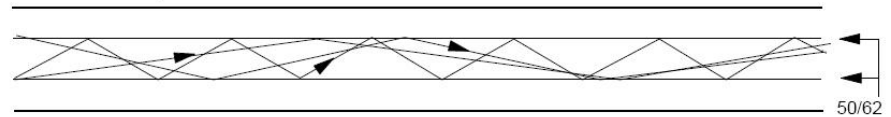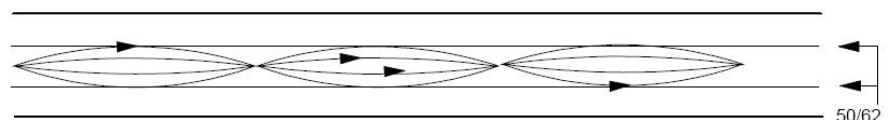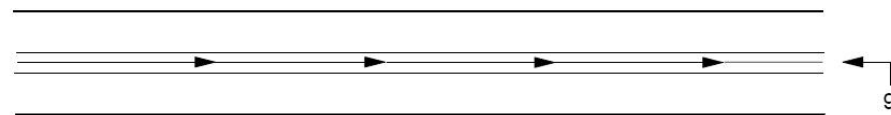
Fibre multimod cu salt de indice

- 50/125 sau 62.5/125 (μm)
- 15–50 MHz·km

Normal

Refractive index of air, $n_0 = 1$

Refractive index of cladding, n_1

90 - α

α

β

Refractive index of core, n_2

$2a = 100$ μm

$D = 140$ μm

n_1

n_2

n_1
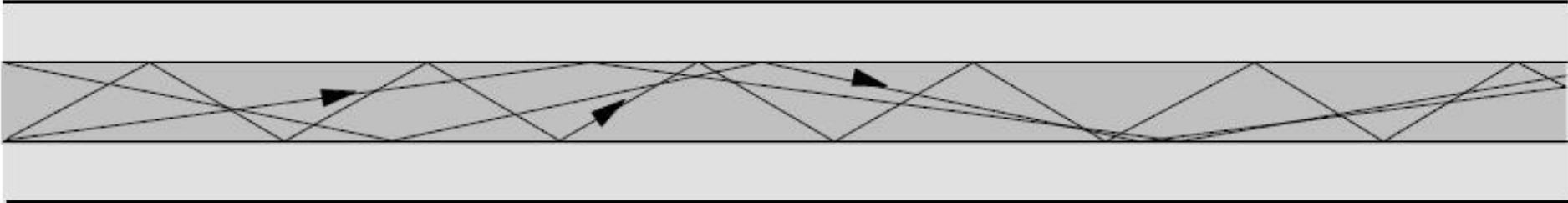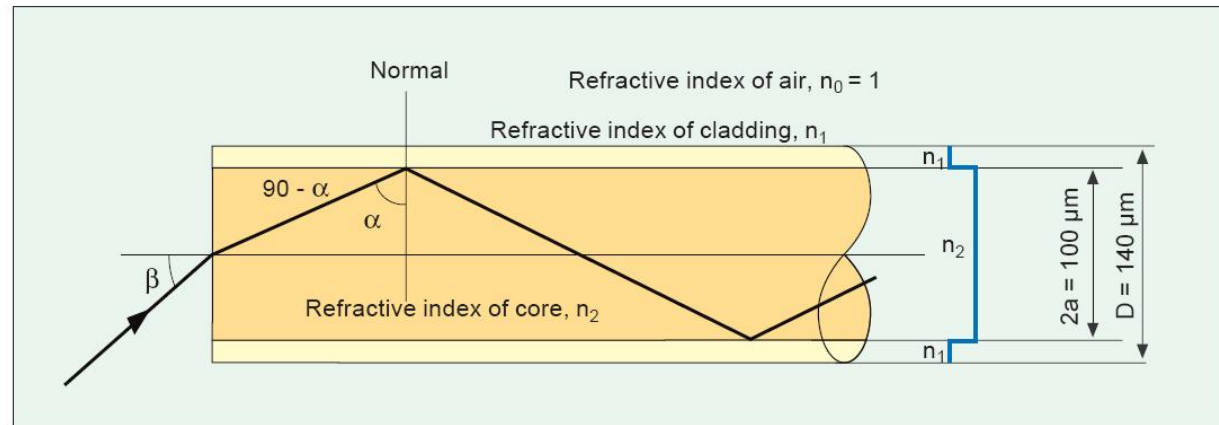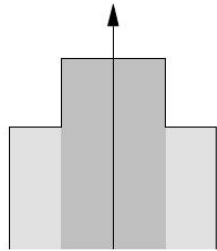
	glass	plastic
core diameter 2a	100 μm	980 μm
cladding diameter D	140 μm	1000 μm
core refractive index n_2	1.48	
cladding refractive index n_1	1.45	

Fibre multimod cu indice gradat
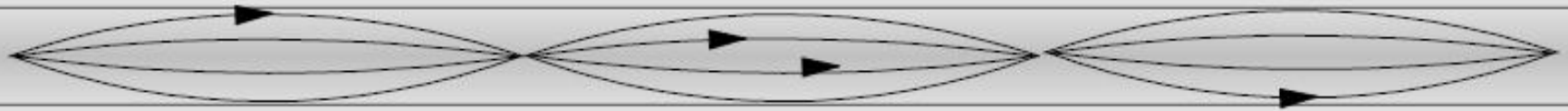
- 50/125 sau 62.5/125 (µm)
- 700–1200 MHz·km
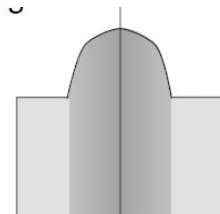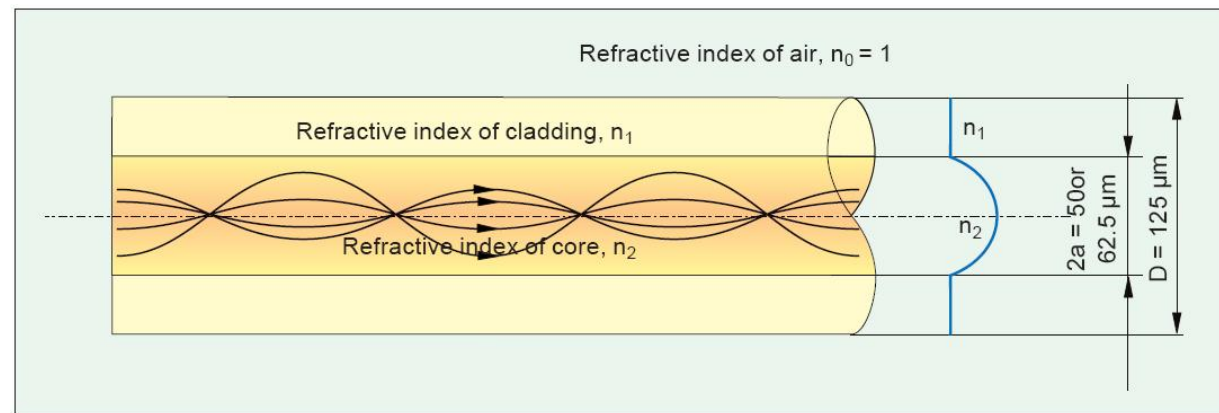
Core diameter 2a	50 or 62.5 µm
Cladding diameter D	125 µm
Maximum refractive index, core	1.46
Relative differential refractive index	0.010

Fata Morgana
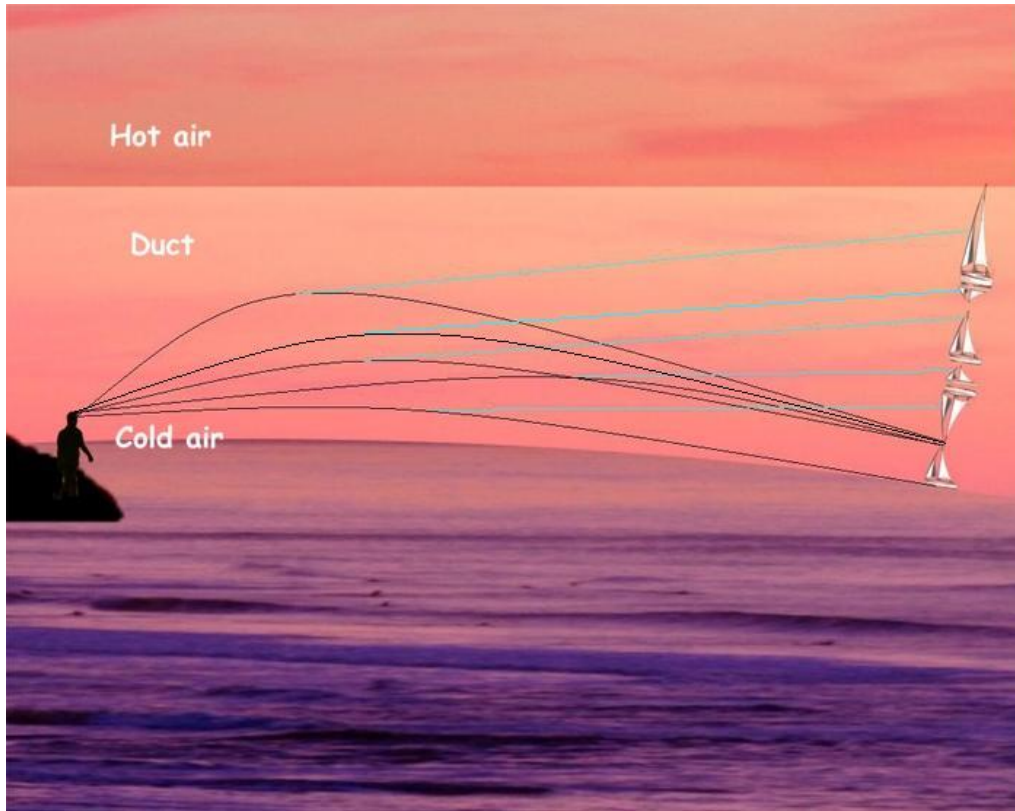
Fibre multimod cu indice gradat
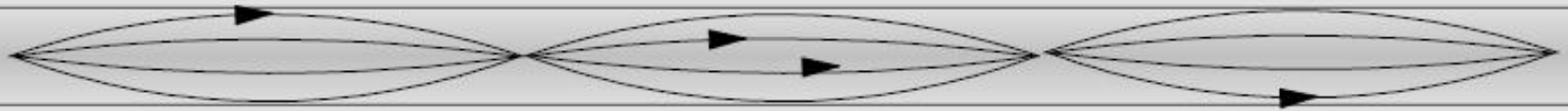
$$n(r)=n_2\left[1-\Delta\left(\frac{r}{a}\right)^{g}\right]$$

$$\Delta = \frac{NA^2}{2n_2^2} = \frac{n_2^2-n_1^2}{2n_2^2} \approx \frac{n_2-n_1}{n_2} \approx \frac{\Delta n}{n} \quad \text{for} \ \Delta \ll 1$$

- $g = 1$ – indice gradat triunghiular
- $g = 2$ – indice gradat parabolic
- $g = \infty$ – salt de indice

Fibre monomod
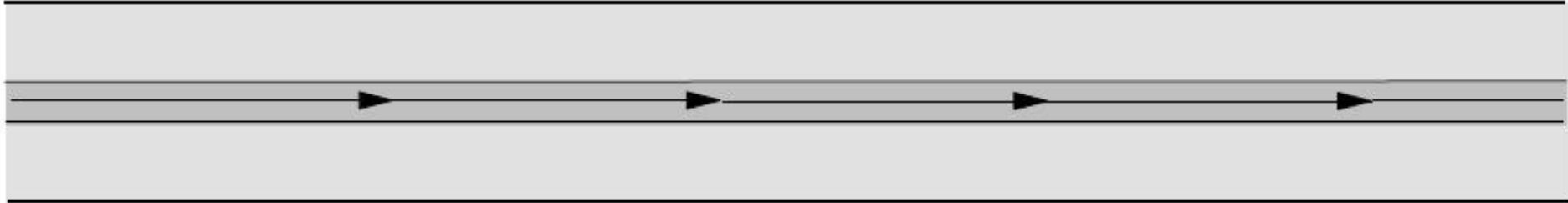
- 6–8/125 (µm)
- MHz·km nerelevant
- MFD – Mode Field Diameter

Refractive index of cladding, n_1

Refractive index of core, n_2

Refractive index of air, $n_0 = 1$

$2a \leq 9.2\ \mu m$
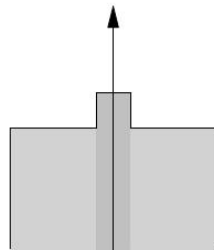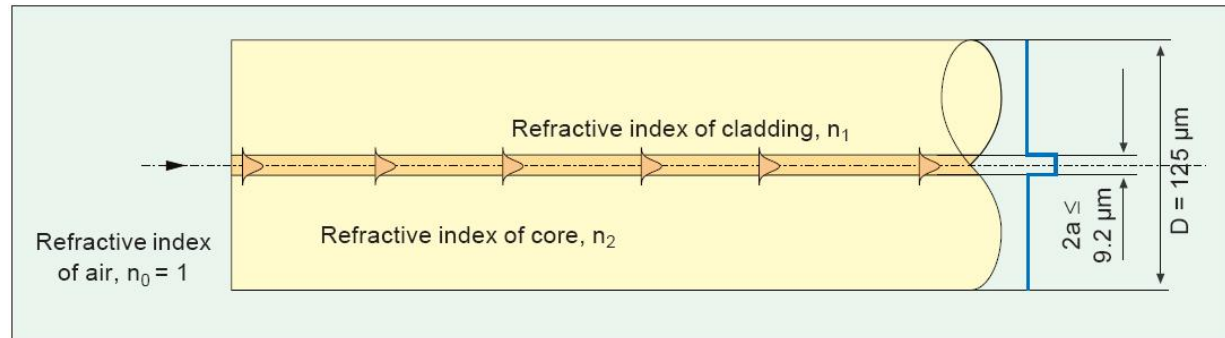
$D = 125\ \mu m$

Cladding diameter D	125 µm
Core refractive index n_2	1.4485
Cladding refractive index n_1	1.4440
Refractive index differential	0.003 = 0.3%

Ghid cilindric dielectric

▸ Ecuatiile lui Maxwell in coordonate cilindrice

$$\frac{\partial^2 U}{\partial r^2} + \frac{1}{r}\frac{\partial U}{\partial r} + \frac{1}{r^2}\frac{\partial^2 U}{\partial \phi^2} + \frac{\partial^2 U}{\partial z^2} + n^2 k_o^2 U = 0$$

a – raza miezului
U – E(r) sau H(r)

$$U(r, \phi, z) = u(r)e^{-jl\phi}e^{-j\beta z}, \qquad l = 0, \pm 1, \pm 2, \ldots$$

$$\frac{d^2 u}{dr^2} + \frac{1}{r}\frac{du}{dr} + \left(n^2(r)k_o^2 - \beta^2 - \frac{l^2}{r^2}\right)u = 0$$

$$\frac{d^2 u}{dr^2} + \frac{1}{r}\frac{du}{dr} + \left(k_T^2 - \frac{l^2}{r^2}\right)u = 0, \qquad r < a$$

$$\frac{d^2 u}{dr^2} + \frac{1}{r}\frac{du}{dr} - \left(\gamma^2 + \frac{l^2}{r^2}\right)u = 0, \qquad r > a$$

Ghid cilindric dielectric

- solutii proportionale cu functii Bessel

$$u(r) \propto \begin{cases} J_l(k_T r), & r < a \quad \text{(core)} \\ K_l(\gamma r), & r > a \quad \text{(cladding)} \end{cases}$$
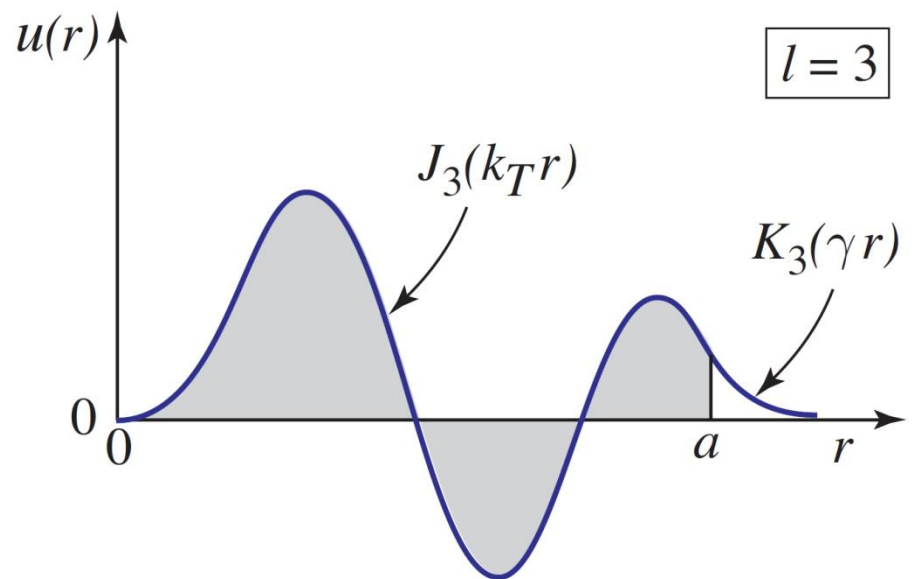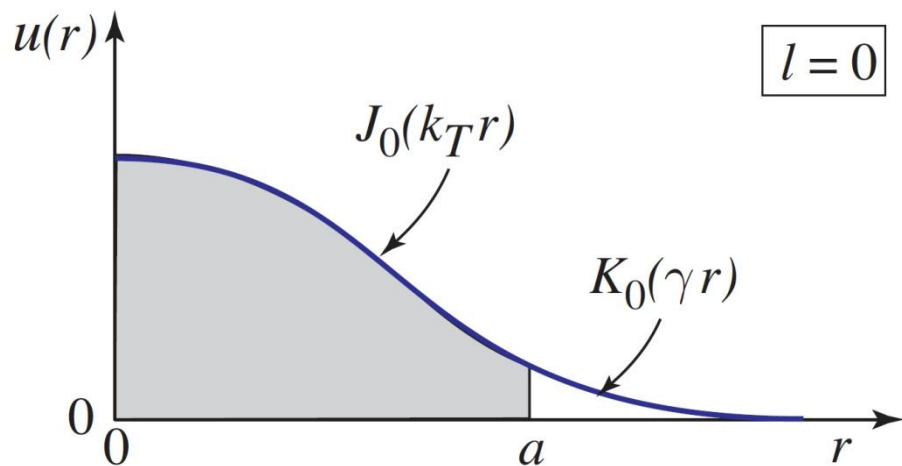
Moduri in fibra

- Moduri in ghid rectangular
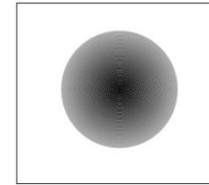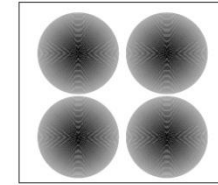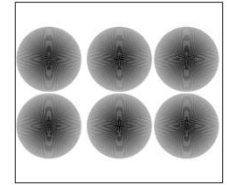
TEM$_{00}$ TEM$_{11}$ TEM$_{21}$

- Moduri linear polarizate in fibra
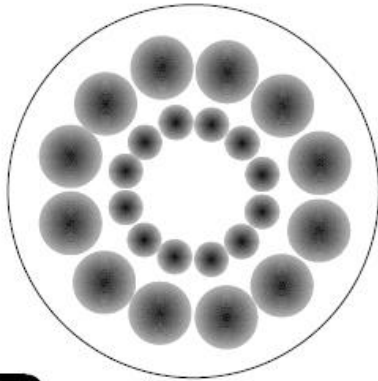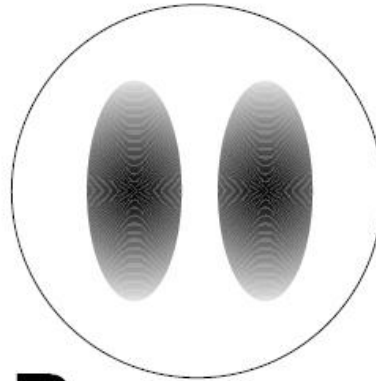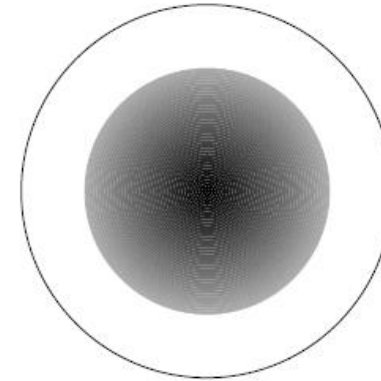
LP$_{62}$ LP$_{11}$ LP$_{01}$

"Sparkle" pattern
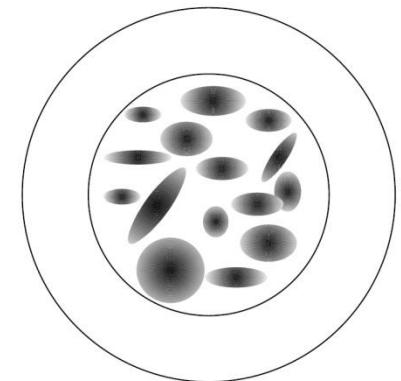
Frecventa normalizata

- Frecventa normalizata

$$V = 2\pi \frac{a}{\lambda} NA = k \cdot a \cdot NA$$ a – raza miezului $$k = \frac{2\pi}{\lambda}$$

- Numar de moduri

Section 1   Section 2   Section 3

Point A   L   Point B
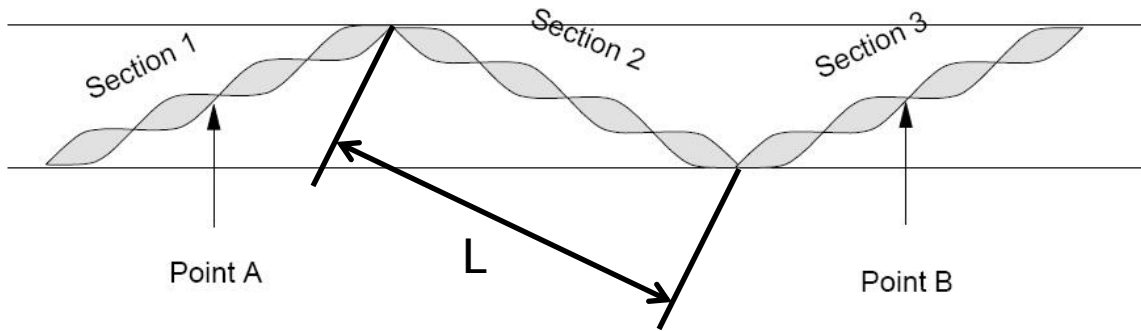
$$L = m \cdot \lambda$$

$$N \approx \frac{V^2}{2} \cdot \frac{g}{g+2}$$

Frecventa normalizata – monomod

▶ Fibre monomod
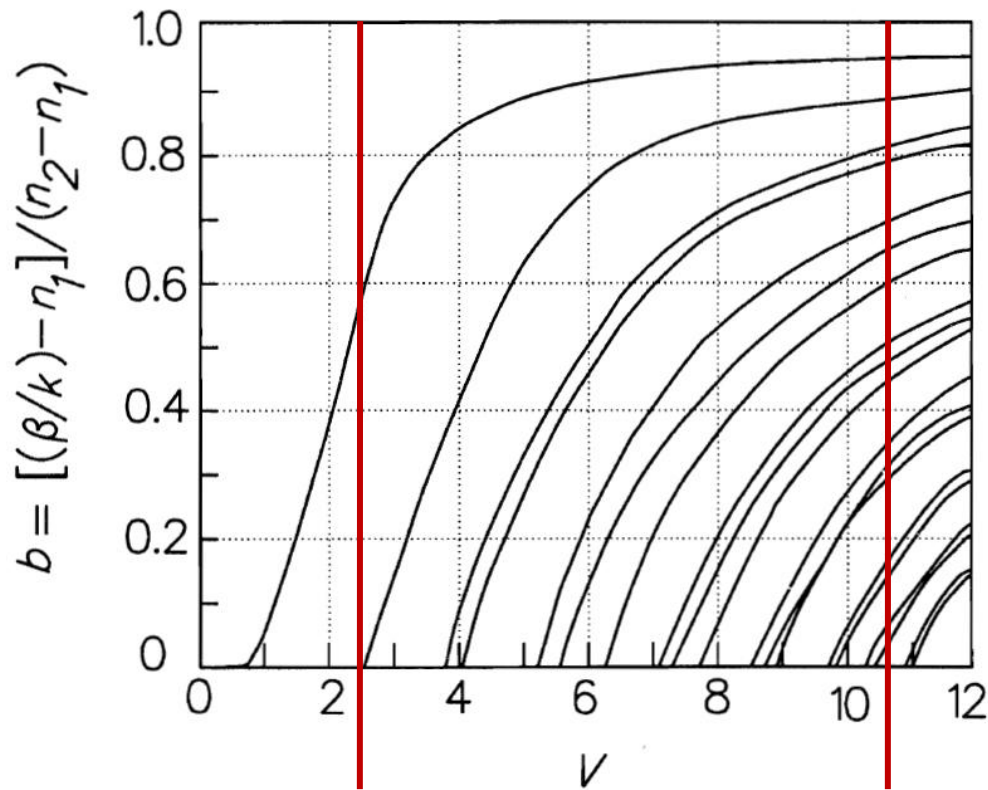
b – coeficient de propagare modal relativ

$$V \leq V_C = 2.405$$

exista un **singur** mod (solutii fc. Bessel)

$$\lambda \geq \lambda_C = \pi \frac{2a}{V_C} NA = \pi \frac{2a}{2.405} NA$$

Exemplu:
2a = 8.5μm
NA = 0.11

$$\lambda_C = \pi \frac{8.5}{2.405} 0.11 = 1210\text{nm}$$

Frecventa normalizata

▶ **Numar de moduri**

$$N \approx \frac{V^2}{2} \cdot \frac{g}{g+2}$$

◦ Multimod cu salt de indice

$$g = \infty \quad \Rightarrow \quad N \approx \frac{V^2}{2}$$

◦ Multimod cu indice gradat

$$g = 2 \quad \Rightarrow \quad N \approx \frac{V^2}{4}$$

◦ Monomod

$$V \leq V_C = 2.405 \qquad \text{exista un singur mod (solutii fc. Bessel)}$$
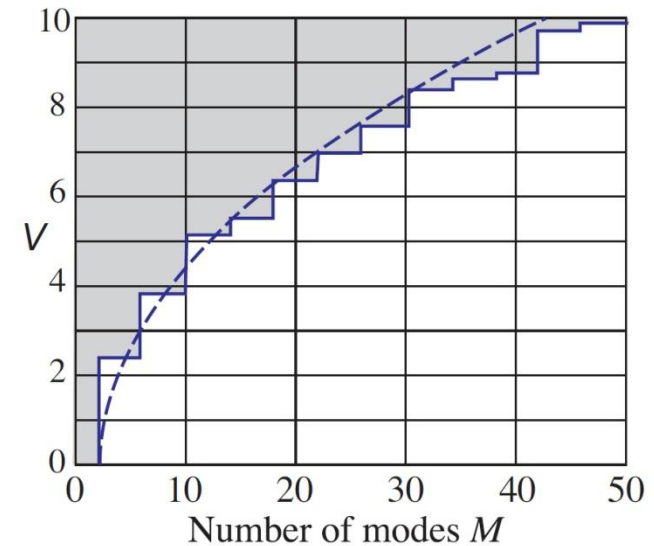
Exemplu

- fibra tipica multimod
  - g=2
  - 2a = 50µm –> a = 25µm
  - NA = 0.2 la λ = 1µm

$$V = 2\pi \frac{a}{\lambda} NA = 2\pi \frac{25}{1} 0.2 = 2 \cdot \pi \cdot 5 \approx 31.4$$

$$g = 2 \quad \Rightarrow \quad N = \frac{V^2}{4} = \frac{31.4^2}{4} = 247$$

Propagarea in fibra monomod

▸ Propagarea luminii poate fi explicata doar prin teoria electromagnetica

▸ Energia campului se extinde in teaca (diametrul efectiv al spotului luminos – MFD, Mode Field Diameter)

▸ MFD > 2a

▸ Adancimea de patrundere in teaca depinde de lungimea de unda, generand dispersia de ghid
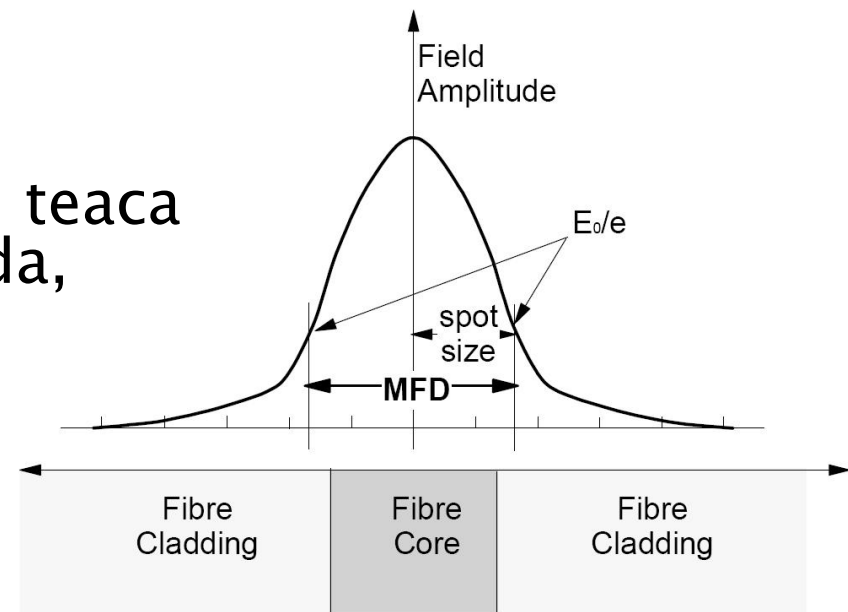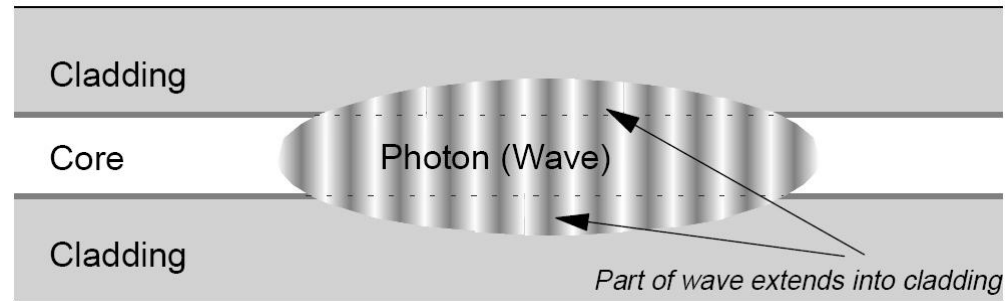
Modelare
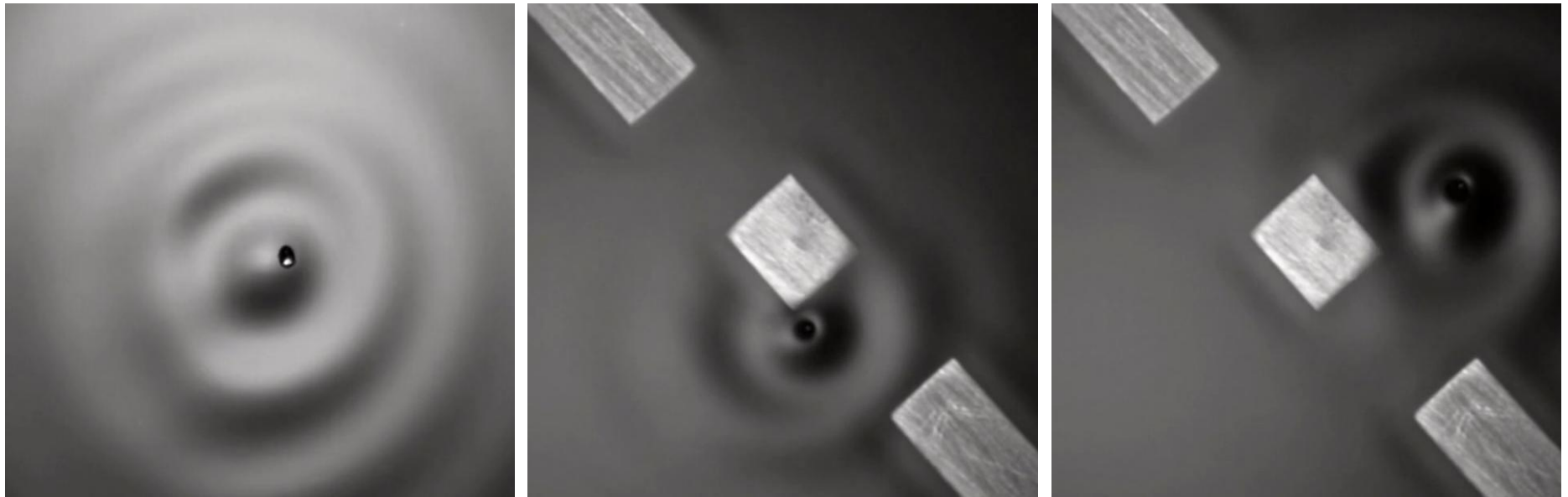
Through the Wormhole
S02E07 How Does the Universe Work
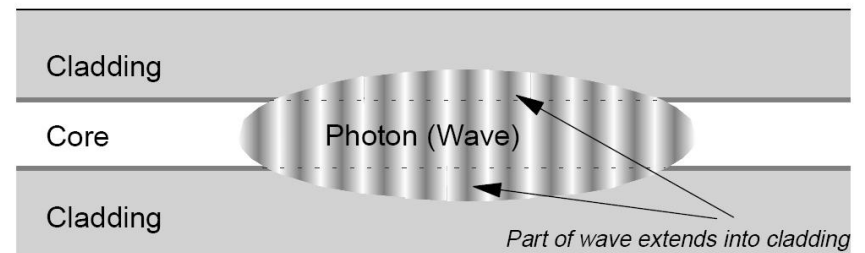
Fenomene de interes

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

Reprezentare logaritmică

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

$$P[\text{dBm}] = 10 \cdot \log_{10}\left(\frac{P}{P_0}\right) = 10 \cdot \log_{10}\left(\frac{P}{1mW}\right)$$

dB	= 10 · $\log_{10}$ (P_2 / P_1)

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

dBm = 10 · $\log_{10}$ (P / 1 mW)

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]

Calculul atenuarii

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

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

$$\text{Pierderi}[\text{dB}] = [-]10 \cdot \log_{10}\left(\frac{P_{out}}{P_0} \cdot \frac{P_0}{P_{in}}\right) = [-]10 \cdot \left[\log_{10}\left(\frac{P_{out}}{P_0}\right) - \log_{10}\left(\frac{P_{in}}{P_0}\right)\right]$$

$$\text{Pierderi}[\text{dB}] = [-]\left(P_{out}[\text{dBm}] - P_{in}[\text{dBm}]\right)$$
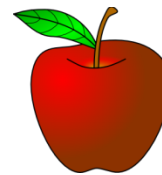
$$\text{Atenuare}[\text{dB/km}] = \frac{\text{Pierderi}[\text{d B}]}{\text{lungime}[\text{km}]}$$

Atenuare

- Macrocurburi
  - utilizator, **localizat**, dB
- Discontinuitate in fibra
  - utilizator, **localizat**, dB
- Microcurburi
  - **distribuit**, tehnologie, dB/km
- Imprastiere
  - **distribuit**, tehnologie, dB/km
- Absorbtie
  - **distribuit**, material, dB/km

Macrocurburi
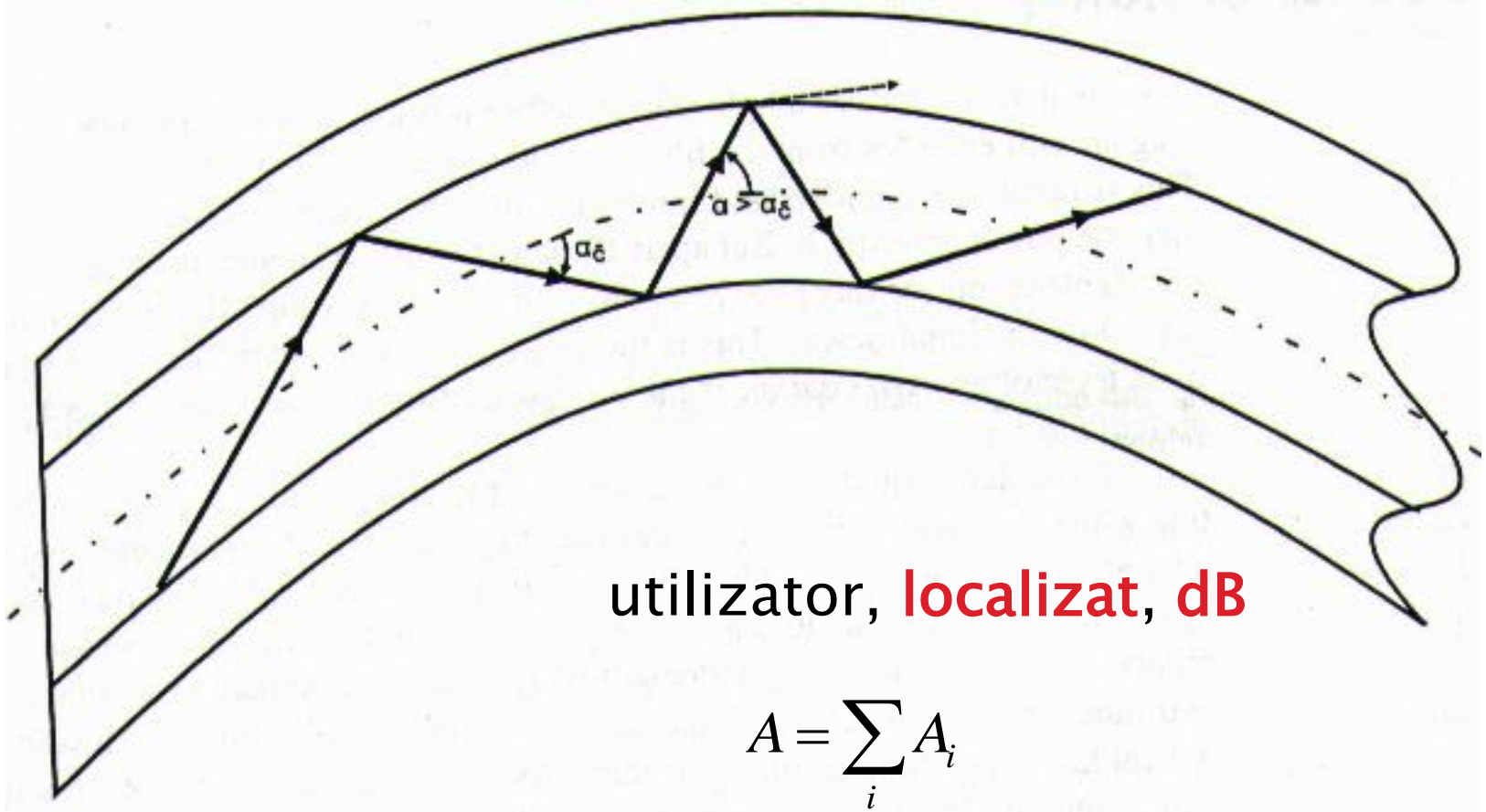
utilizator, localizat, dB

$$A = \sum_i A_i$$

$$A = N \cdot A_i$$

Efectul curburilor

▸ **Multimod**

▸ **Monomod**

$$R > R_C \quad \Rightarrow \quad n_{1,ext} > n_2$$

Phase Front

Phase Front

v creste
n scade

Faster

v scade
n creste

Slower
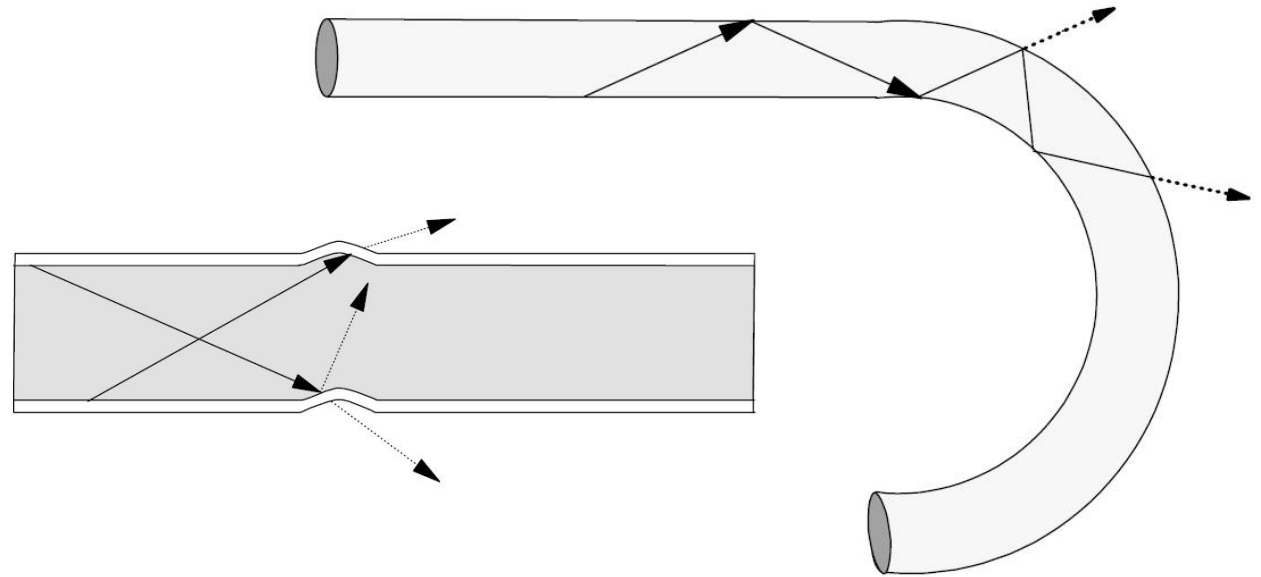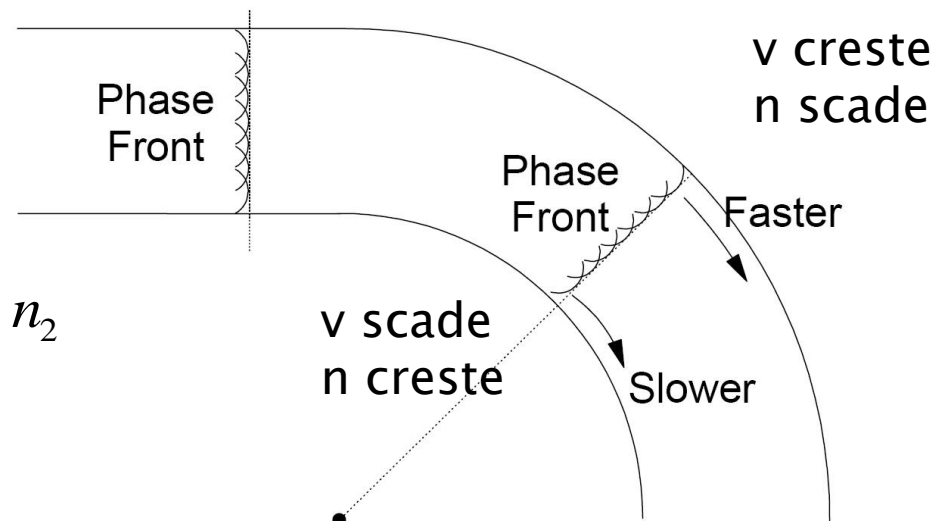
Discontinuitate in fibra

▸ Apare cand nu putem considera fibra un singur ghid dielectric
  ◦ defectiuni
  ◦ conectori
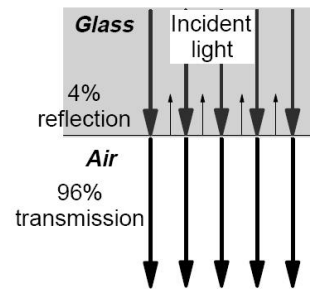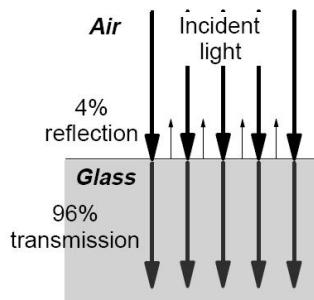
utilizator, **localizat**, **dB**

$$A = \sum_i A_i$$

$$A = N \cdot A_i$$

Microcurburi
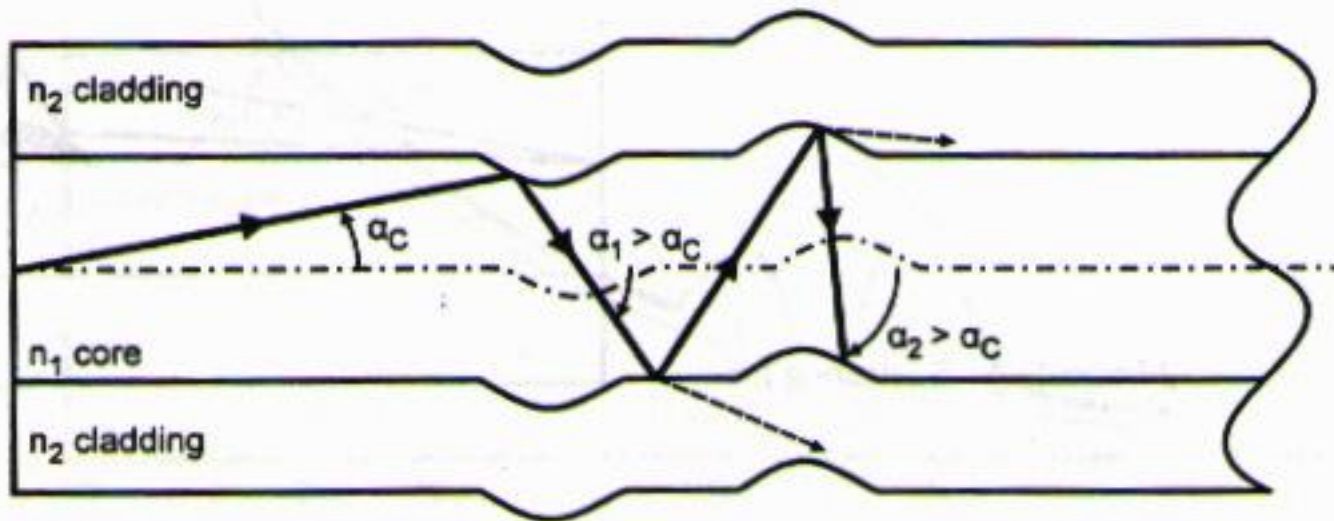
distribuit, tehnologie, dB/km

$$A = A_i \cdot L$$

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

Imprastiere
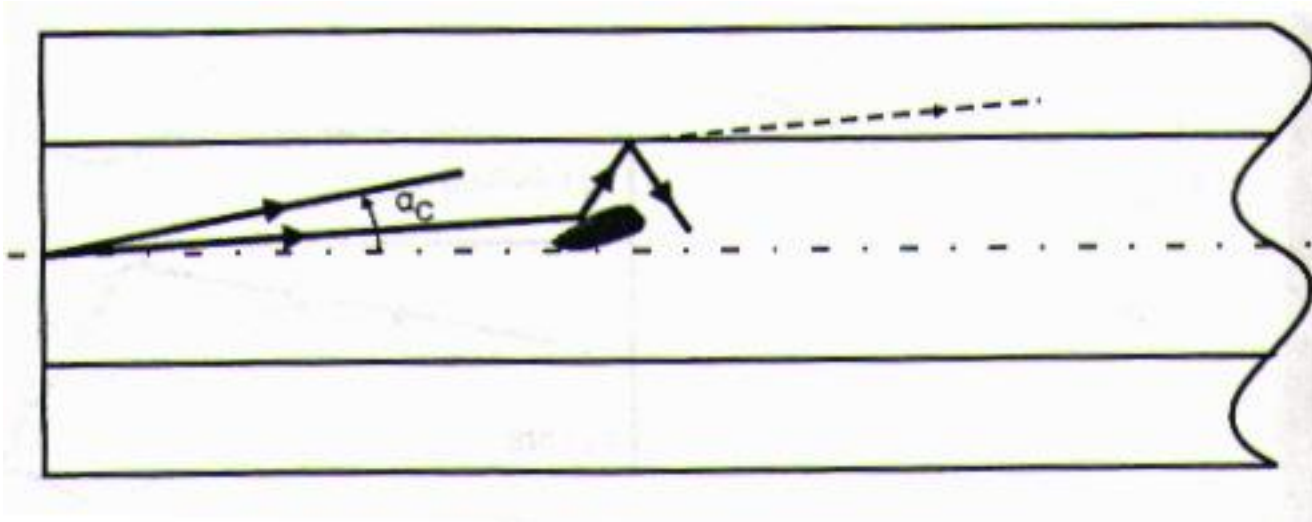
distribuit, tehnologie, **dB/km**

$$A = A_i \cdot L$$

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

Absorbtie
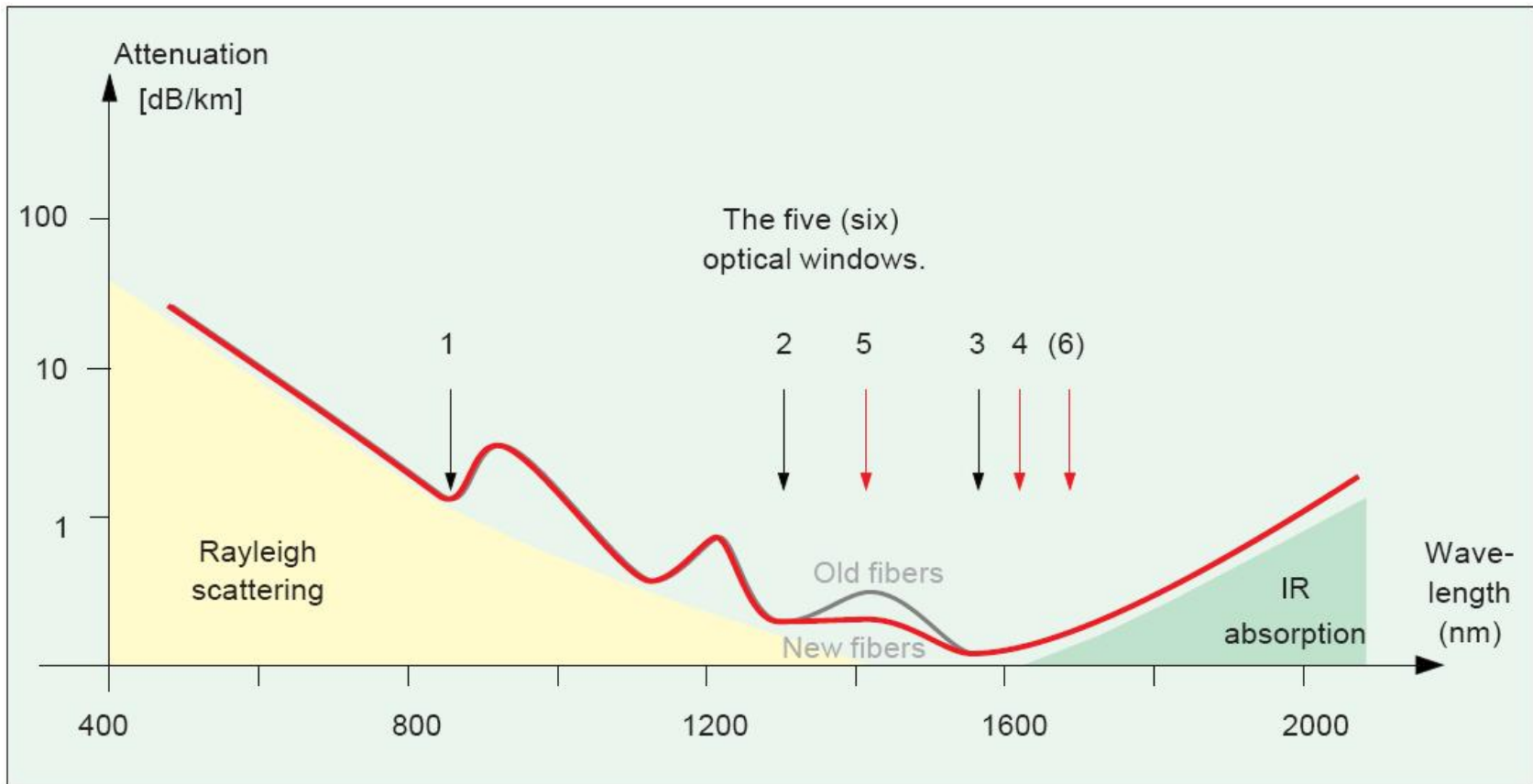
distribuit, material, dB/km

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

Difractie Rayleygh

- imprastierea luminii (si a altor radiatii electromagnetice) de particule (molecule) mult mai mici decat lungimea de unda

$$A \sim \frac{1}{\lambda^4}$$
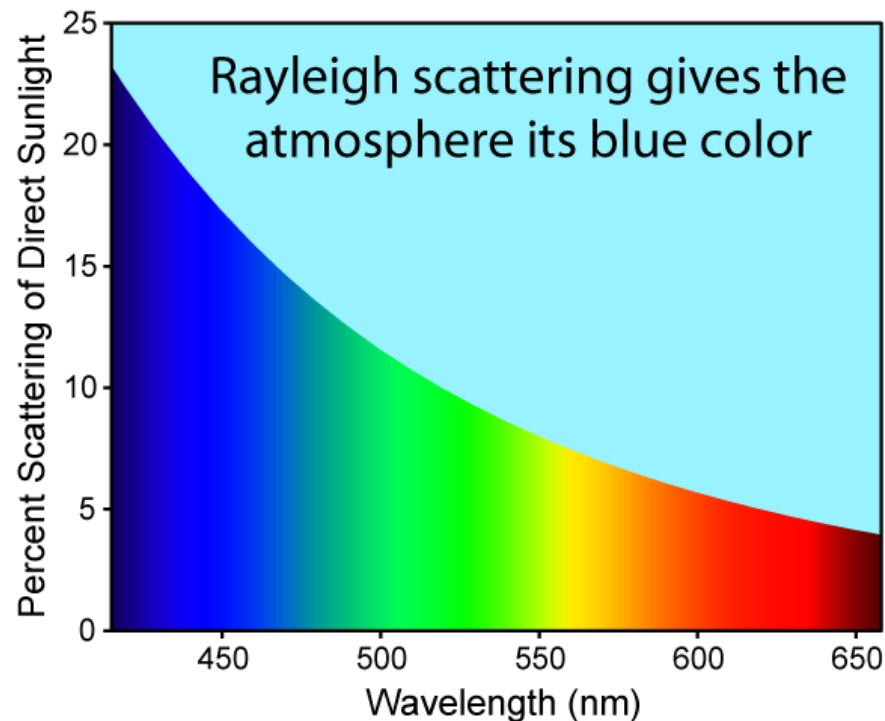
Absorbtie OH

- Absorbtie
  - 950nm
  - 1244nm
  - 1383nm
- Apa!
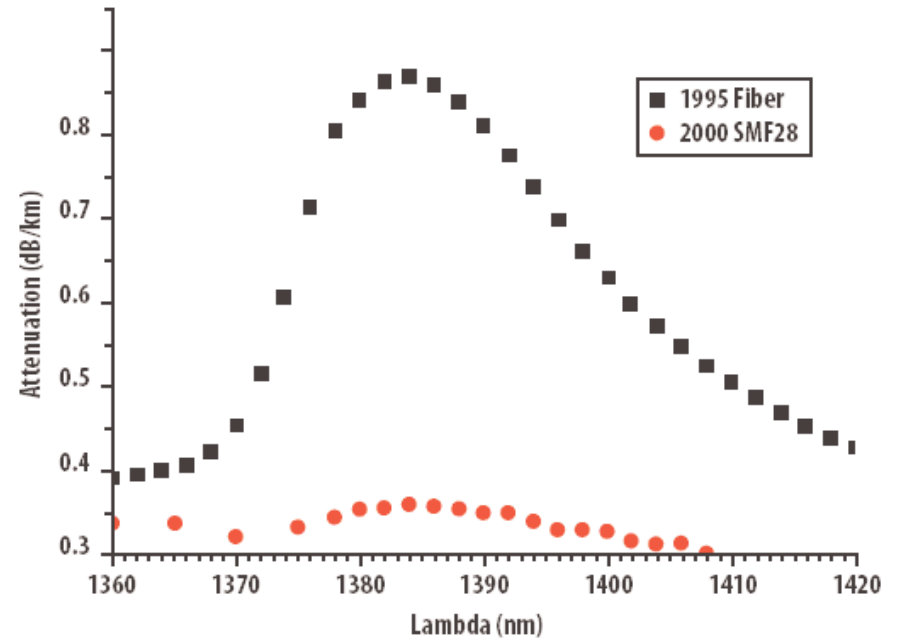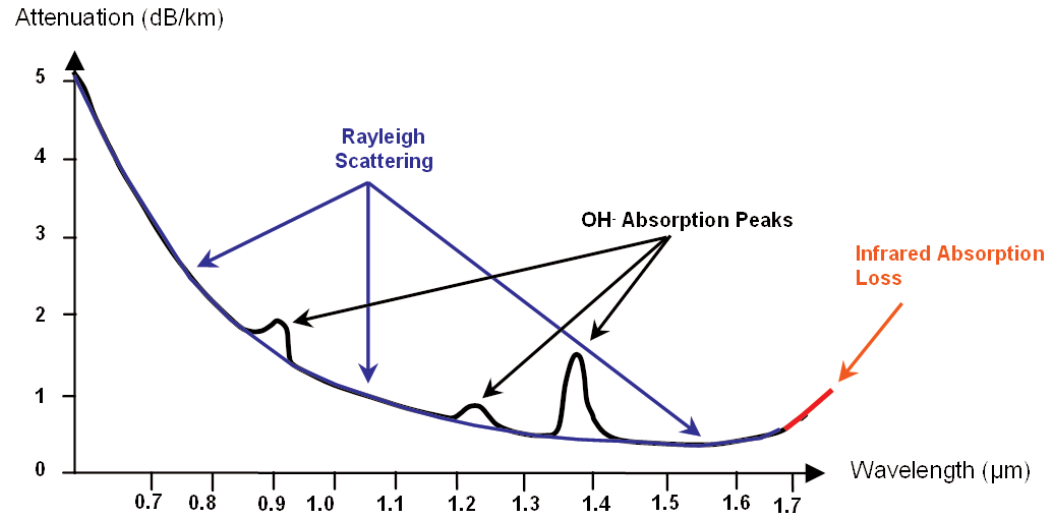
Fiber Attenuation Comparison

Atenuare

$$E_y(z_1) = Ct \cdot e^{-\alpha \cdot z_1} \cdot e^{j(\omega \cdot t - \beta \cdot z_1)} \qquad\qquad E_y(z_2) = Ct \cdot e^{-\alpha \cdot z_2} \cdot e^{j(\omega \cdot t - \beta \cdot z_2)}$$

$$W, P \sim \int E^2$$

$$A = \frac{P_2}{P_1} = \frac{Ct^2 \cdot e^{-2\alpha \cdot z_2}}{Ct^2 \cdot e^{-2\alpha \cdot z_1}} = e^{-2\alpha \cdot (z_2 - z_1)}$$

$$A[dB] = 10\log_{10}\frac{P_2}{P_1} = 10\log_{10}\left[e^{-2\alpha \cdot (z_2 - z_1)}\right]$$

$$A[dB] = -20 \cdot \alpha \cdot (z_2 - z_1)\log_{10} e = -8.686 \cdot \alpha \cdot (z_2 - z_1)$$

$$A/L[dB/km] = -8.686 \cdot \alpha < 0$$

- Atenuarea se exprima de obicei in **dB/km**
  - de obicei valori pozitive
  - semnul = **implicit**

Calculul atenuarii

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

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

$$\text{Pierderi}\,[\text{dB}] = [-]\left(P_{out}[\text{dBm}] - P_{in}[\text{dBm}]\right)$$
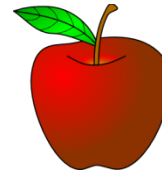
$$\text{Atenuare[dB/km]} = \frac{\text{Pierderi[d B]}}{\text{lungime[km]}}$$

Efecte neliniare in fibra

- Stimulated Brillouin Scattering, SBC
  - difractia luminii inspre emitator datorita undelor mecano-acustice generate in fibra
  - 6-10 dBm
- Stimulated Raman Scattering, SRS
  - interactiunea luminii cu vibratiile moleculare
  - 27 dBm (~1W)
- Self Phase Modulation, SPM
  - Frontiera impulsului implica indice de refractie variabil in timp moduland faza impulsului
  - 5 dBm
  - Cross Phase Modulation, CPM
- Four-Wave Mixing, FWM
  - 0 dBm

Limite putere/bandă a dispozitivelor optoelectronice
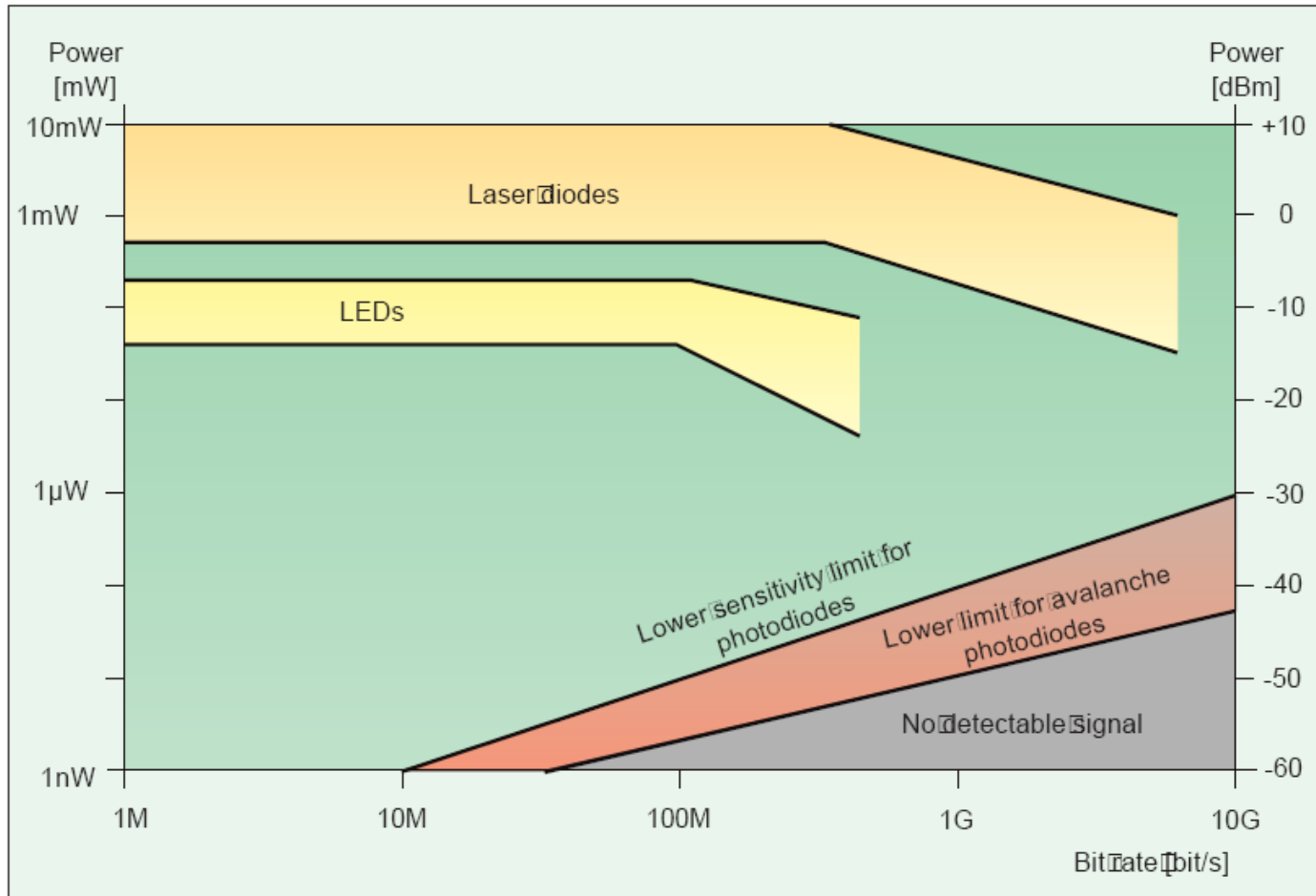
Four-Wave Mixing, FWM

Two Channels

Three Channels

Signal Wavelengths

Spurious Side Modes

ω_1 ω_2

$2\omega_1 - \omega_2$ $2\omega_2 - \omega_1$
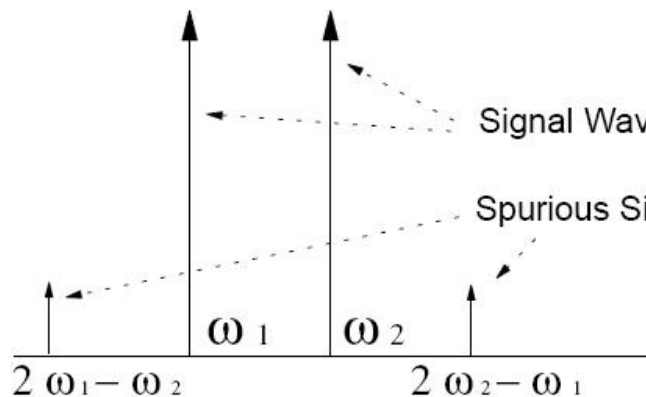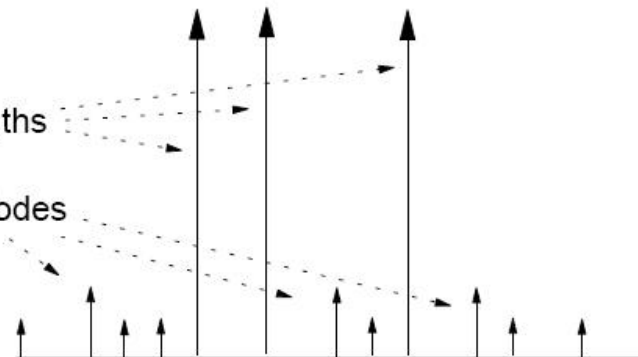
$$NL = \frac{1}{2}\left(N^3 - N^2\right)$$

N = 2, NL = 4
N = 3, NL = 9
N = 16, NL = 1920
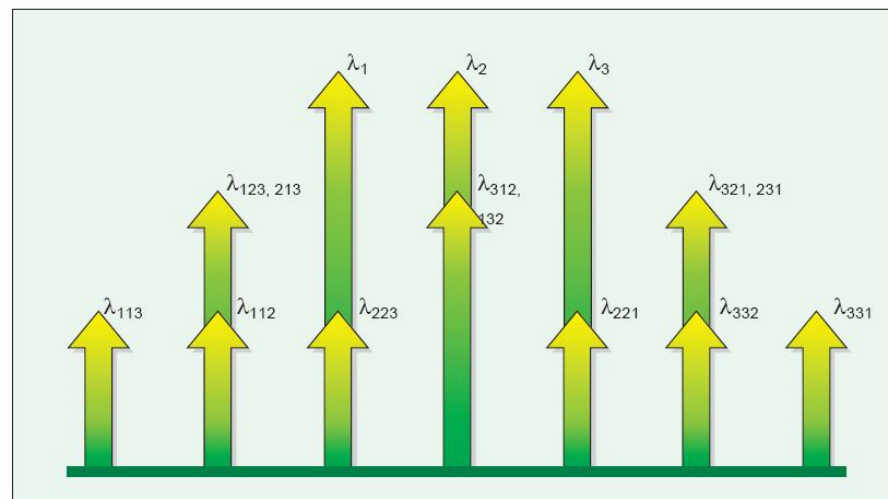
λ_1 λ_2 λ_3

$\lambda_{123, 213}$ $\lambda_{312, 132}$ $\lambda_{321, 231}$

λ_{113} λ_{112} λ_{223} λ_{221} λ_{332} λ_{331}

Fenomene de interes

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

Dispersia

- Propagarea cu viteze diferite a radiatiilor cu trasee/lungimi de unda diferite
  - ◦ intermodala (**modala** – depinde de prezenta modurilor)
  - ◦ intramodala (**cromatica** – depinde de lungimea de unda)
    - • de material
    - • de ghid

Dispersia modala

Transmit side

Receive side
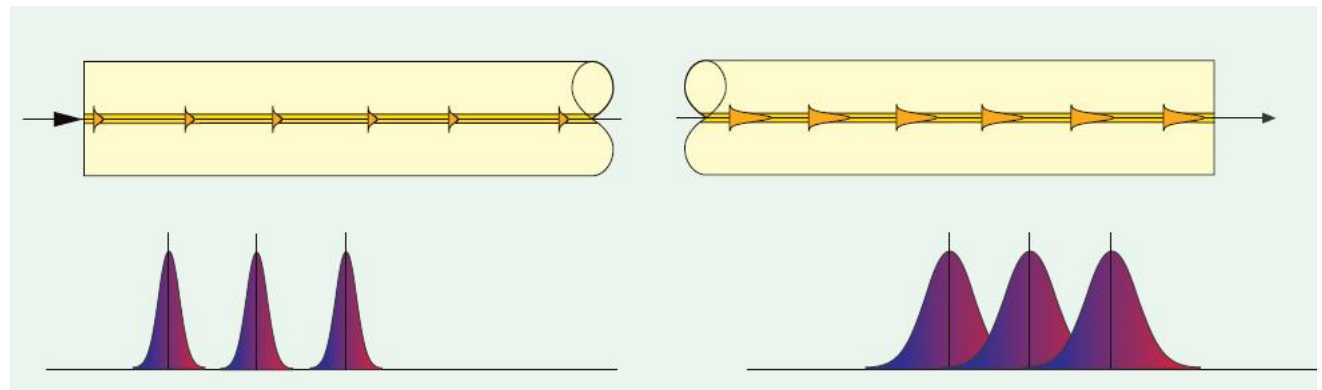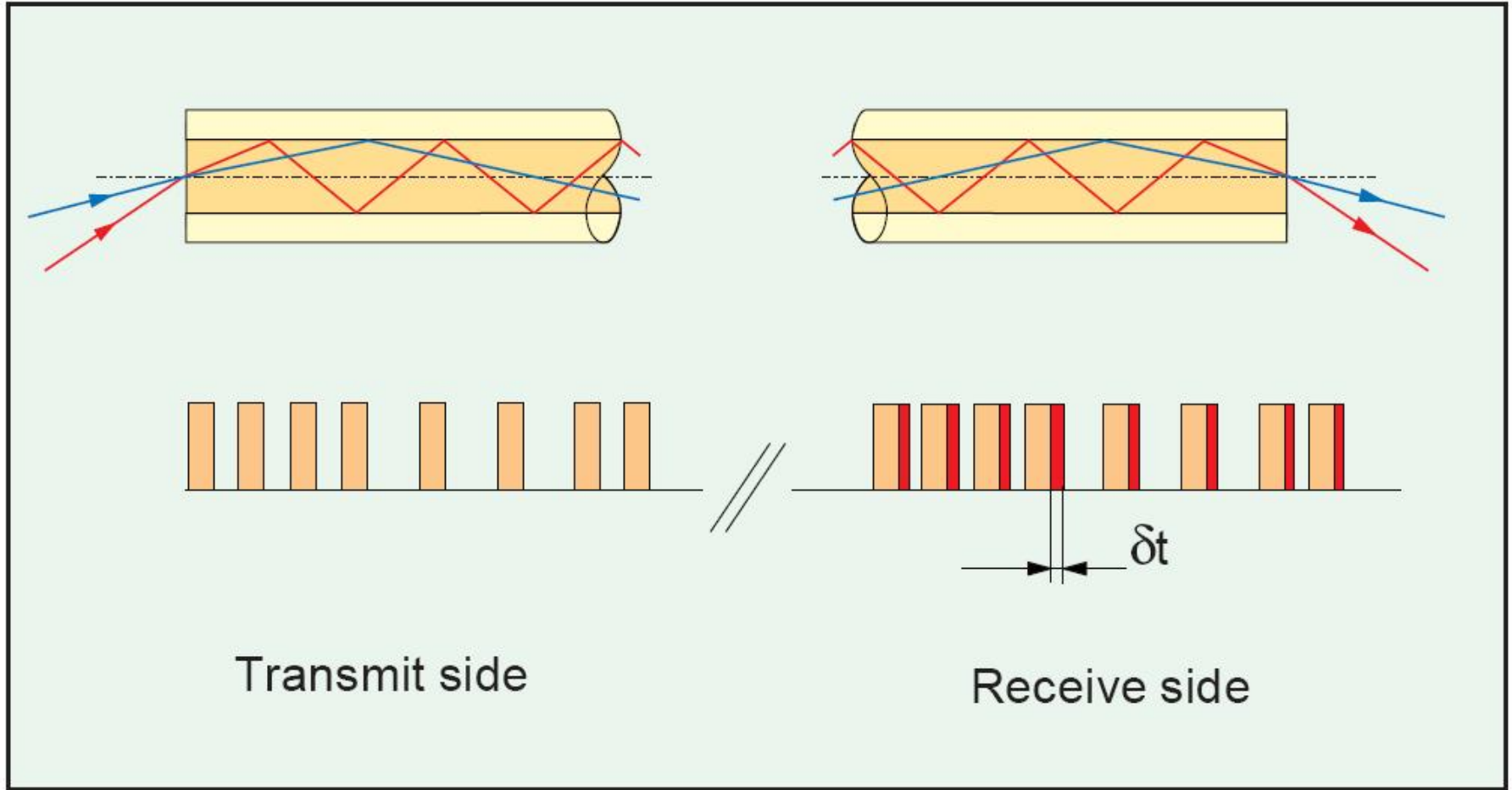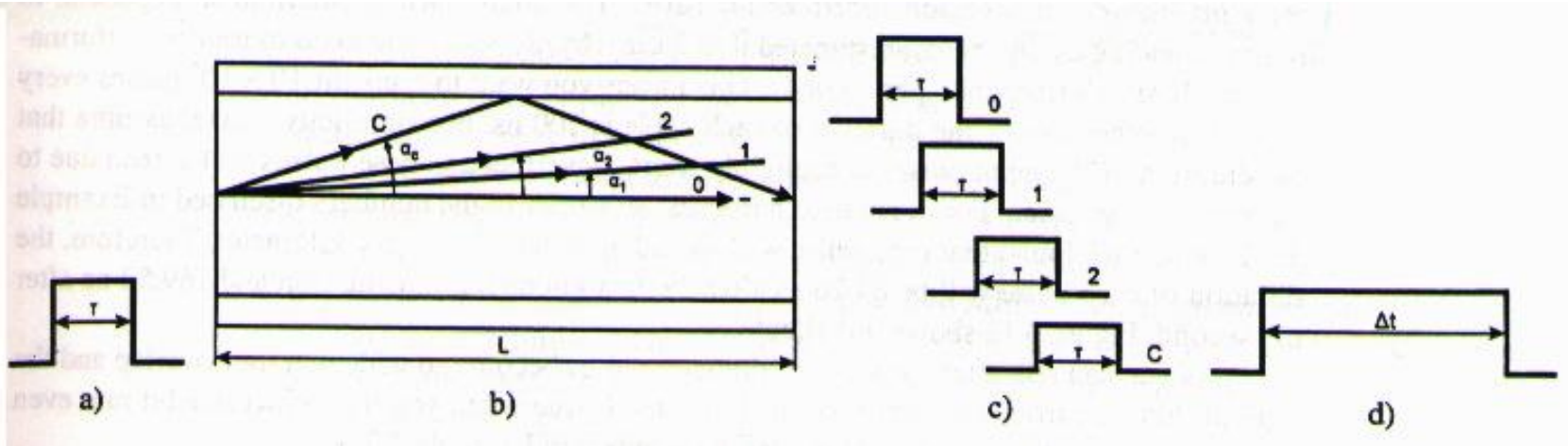
Dispersia modala

$$t_0 = \frac{L}{v} \qquad t_C = \frac{L}{v \cdot \cos\alpha_C} \qquad v = \frac{c}{n_2} \qquad \cos\alpha_C = NA$$

$$\Delta t_{SI} = t_C - t_0 = \frac{L \cdot n_2}{c} \cdot \left(\frac{n_2 - n_1}{n_2} \right) \qquad \Delta t_{SI} = t_C - t_0 = \frac{L \cdot n_2}{c} \cdot \Delta$$

$$\Delta = \frac{n_2 - n_1}{n_1} << 1 \qquad \Delta t_{SI} = t_C - t_0 \approx \frac{L}{2 \cdot c \cdot n_2} \cdot (NA)^2$$

$$\Delta t_{SI} \rightarrow dt$$

Dispersia modala

- salt de indice

$$dt = \frac{L \cdot n_2^2}{c \cdot n_1}\left(\frac{n_2 - n_1}{n_2}\right) \approx \frac{L \cdot NA^2}{2 \cdot c \cdot n_2}$$

intarzierea intre moduri cand

$$\Delta = \frac{n_2 - n_1}{n_1} << 1$$

$$\Delta \tau_{\text{mod}}^2 = \frac{1}{3}\left(\frac{dt}{2}\right)^2$$

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

- indice gradat

$$dt = \frac{L \cdot n_2 \cdot \Delta^2}{2c} \approx \frac{L \cdot NA^4}{8 \cdot c \cdot n_2^3}$$

$$\Delta \tau_{\text{mod}} \cong \frac{L \cdot n_2 \cdot \Delta^2}{4\sqrt{3} \cdot c}$$
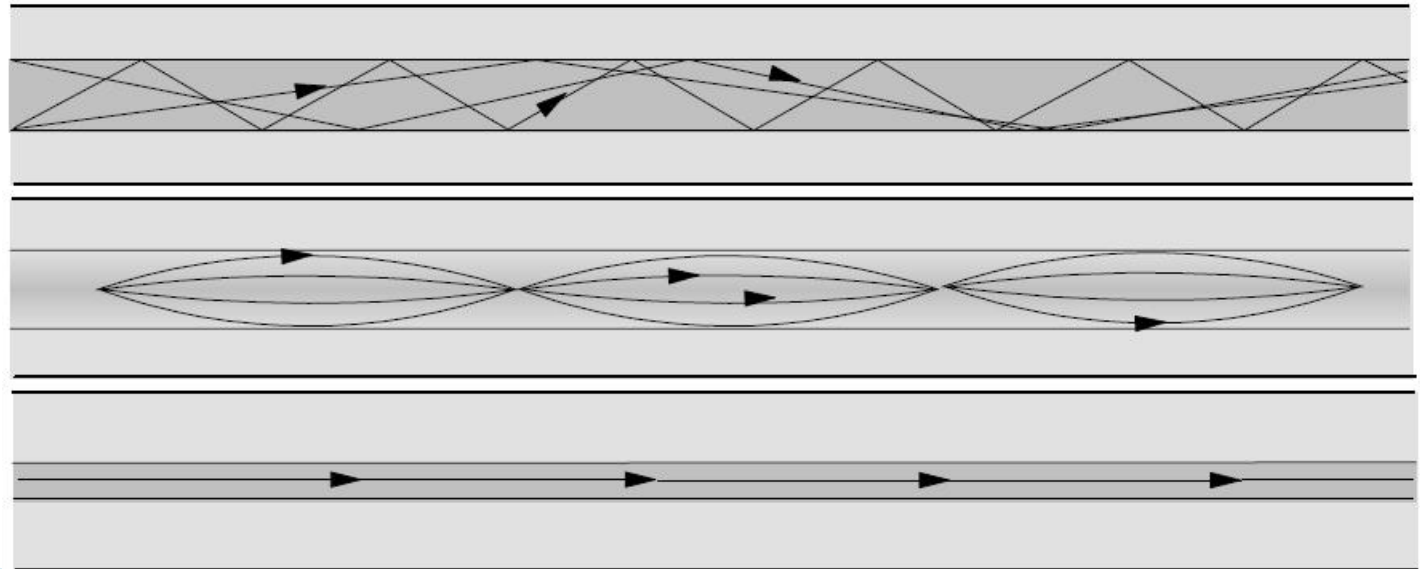
$$NA = 0.1 \div 0.2 < 1$$

n_2 – miez
n_1 – teaca
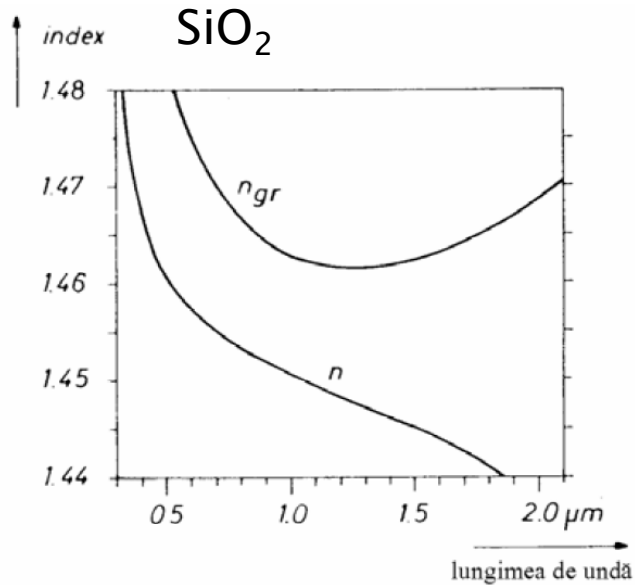$n_2 > n_1$!!

Dispersia modala

- Mai mare la fibre multimod cu salt de indice
- Mai mica la fibre multimod cu indice gradat
  - traseele mai lungi trec prin zone cu indice mai mic
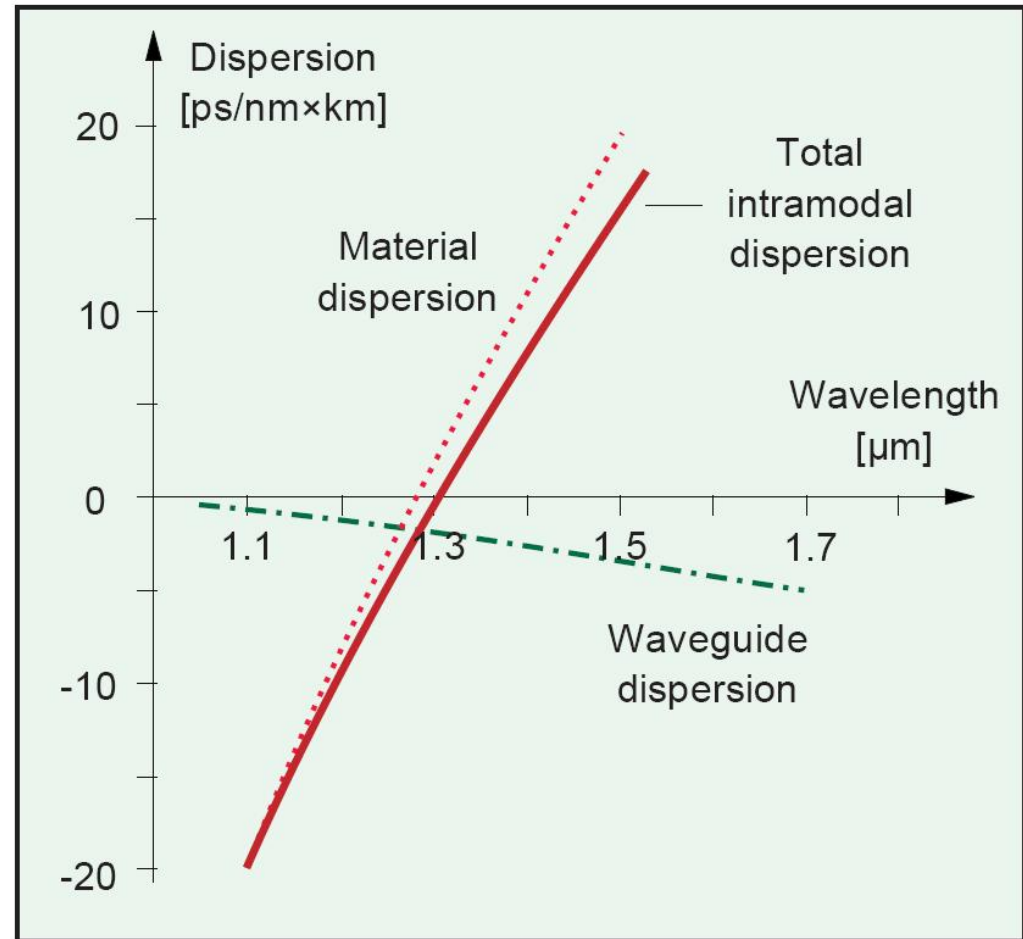- Inexistenta la fibrele monomod

Dispersia de material

SiO$_2$

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

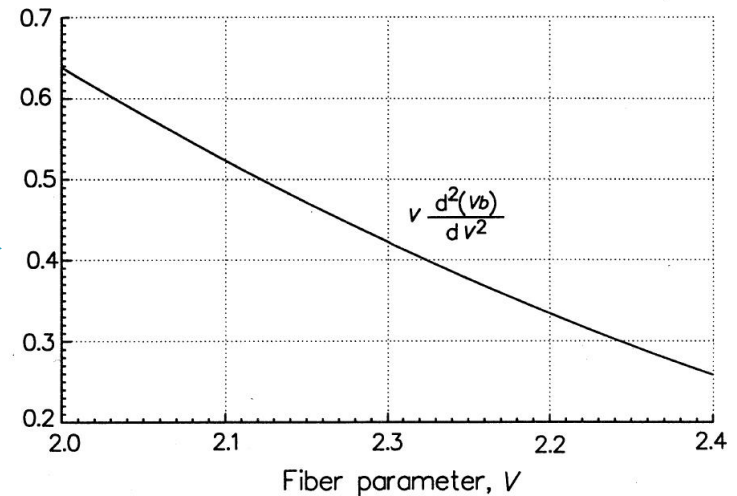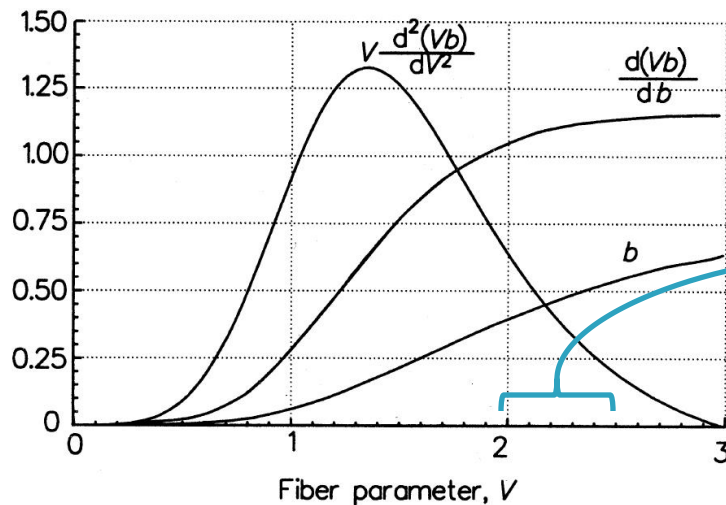$$\Delta\tau_{mat} = \frac{L \cdot \lambda \cdot \Delta\lambda}{c} \cdot \frac{d^2 n}{d\lambda^2}$$

Dispersia de ghid

▸ Neglijabila in fibrele multimod fata de dispersia modala

$$\Delta\tau_{gh} = \frac{n \cdot L \cdot \Delta}{c} \cdot \frac{\Delta\lambda}{\lambda} \cdot \left(V \frac{d^2(Vb)}{dV^2} \right)$$
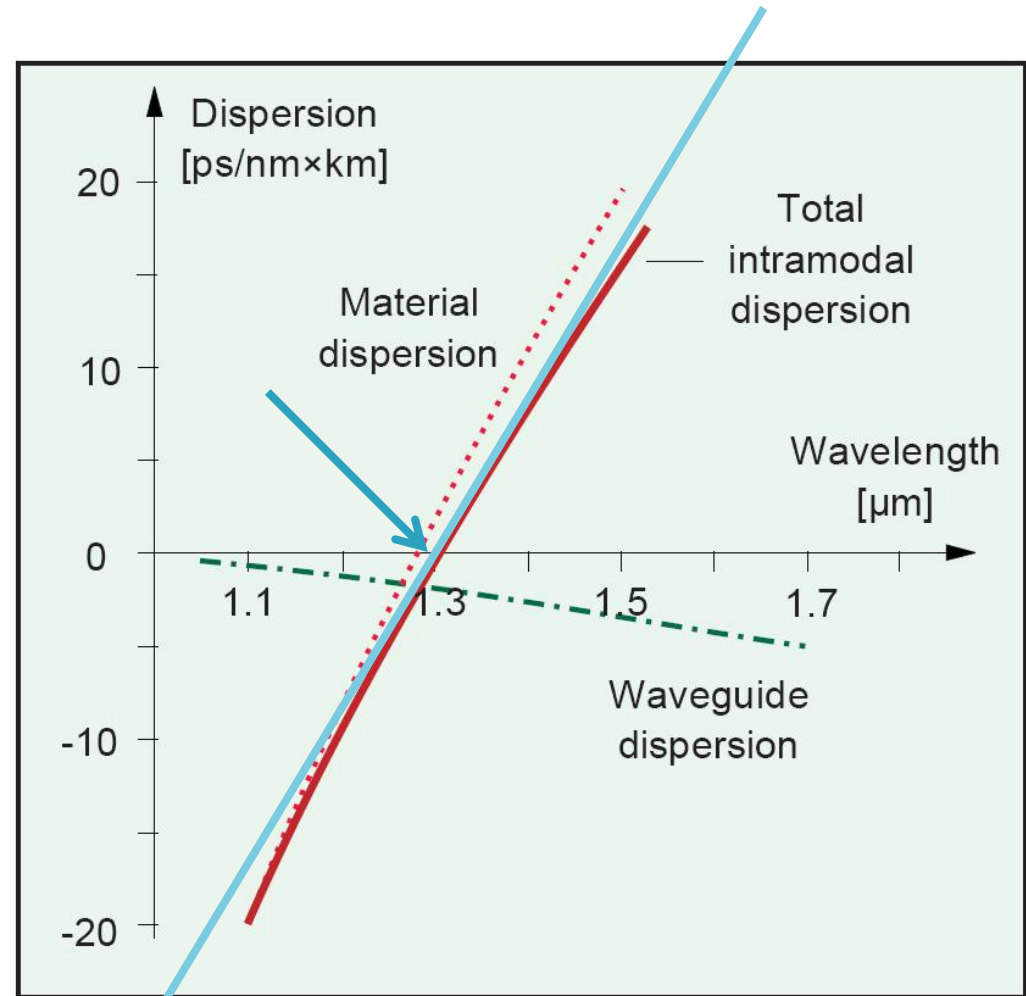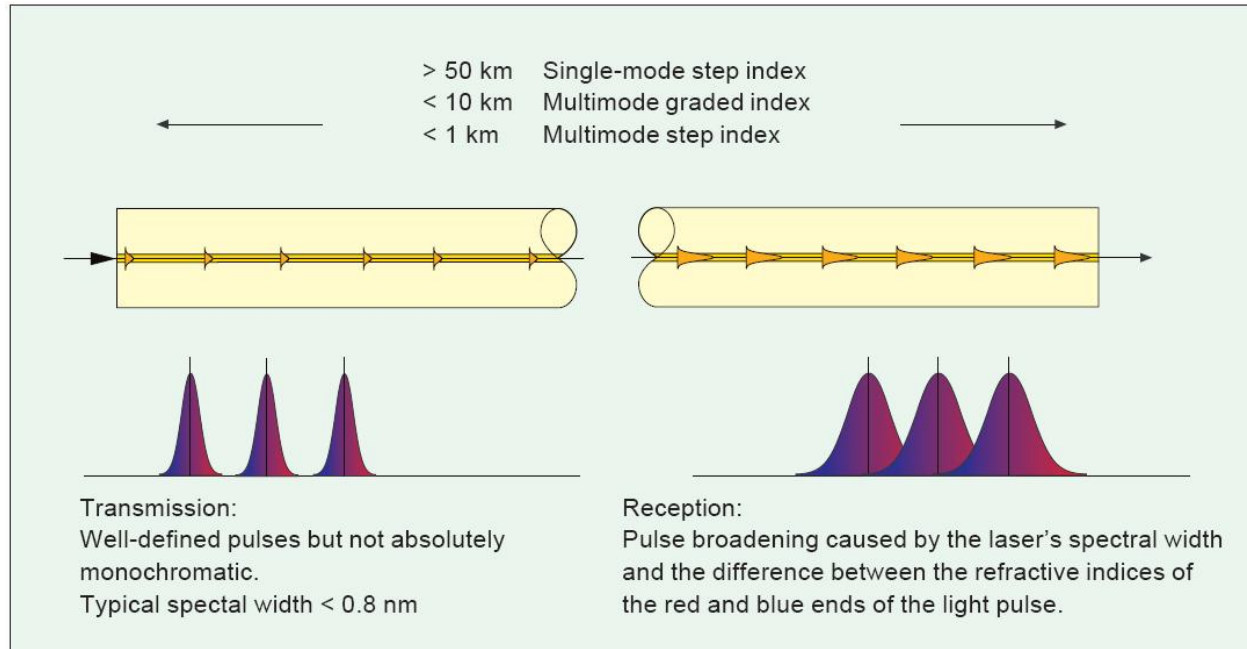
b – constanta de propagare normalizata

$$V \leq V_C = 2.405$$

Dispersia cromatica (gh+mat)

- Variatie aproximativ liniara
- Caracterizata de panta si punctul de trecere prin 0

Dispersia cromatica (gh+mat)

> 50 km Single-mode step index
< 10 km Multimode graded index
< 1 km Multimode step index

Transmission:
Well-defined pulses but not absolutely monochromatic.
Typical spectal width < 0.8 nm

Reception:
Pulse broadening caused by the laser's spectral width and the difference between the refractive indices of the red and blue ends of the light pulse.

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

$$D(\lambda) = \frac{S_0}{4}\cdot\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right)$$
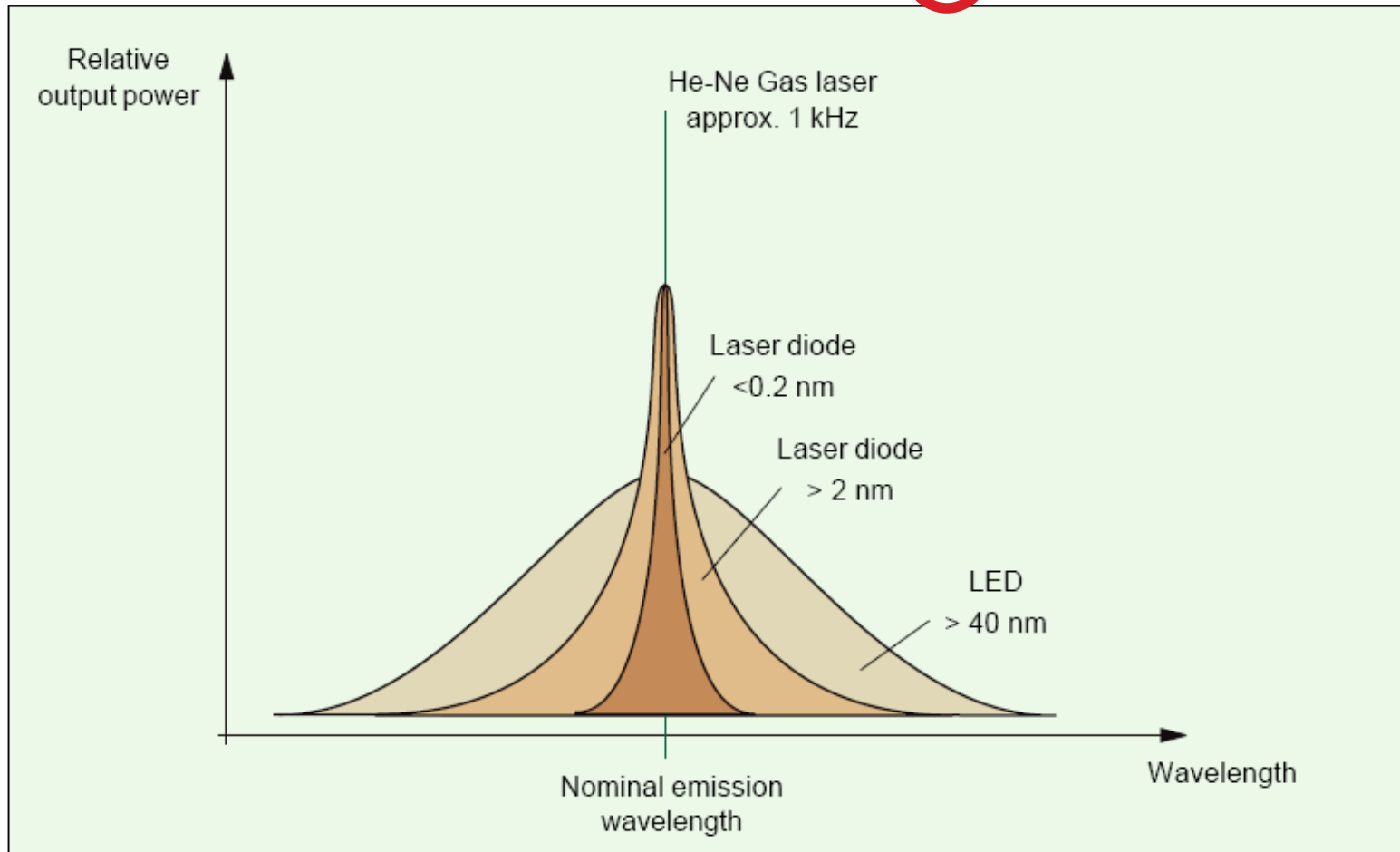
S_0 panta dispersiei – ps/nm²/km

$$D(\lambda_0) = 0$$

- $D(\lambda) \approx 100 + 0.4\,(850 - \lambda)$ [ps/nm/km] pentru $800 < \lambda < 900$ nm
- $D(\lambda) \leq 3{,}5$ ps/nm/km pentru $1285 < \lambda < 1330$ nm
- $D(\lambda) \leq 17$ ps/nm/km pentru $1525 < \lambda < 1575$ nm

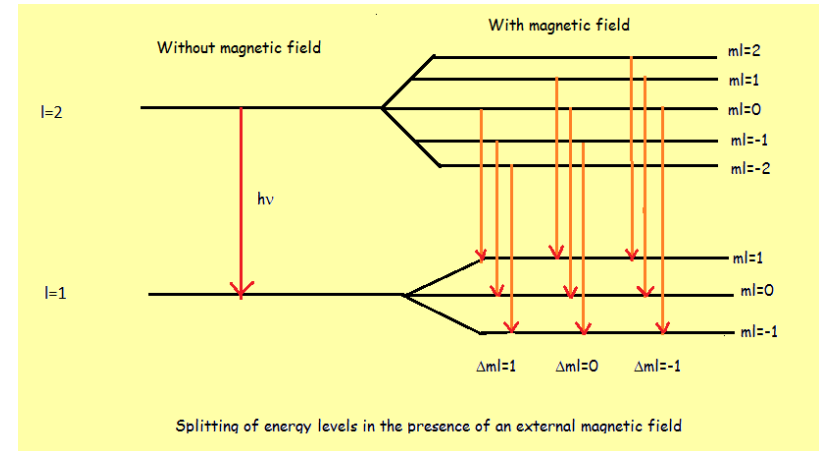$$D(\lambda) = \frac{S_0}{4}\cdot\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right)$$

Calitatea spectrală a emiţătorilor optici
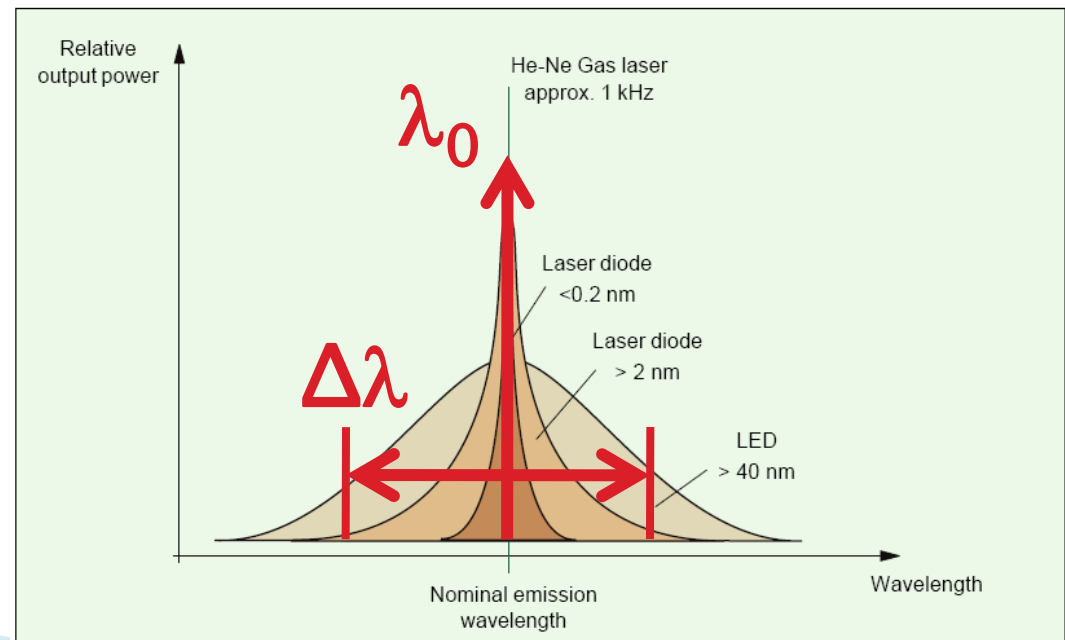
$$\Delta\tau_{cr} = D(\lambda)\,\Delta\lambda\,L$$
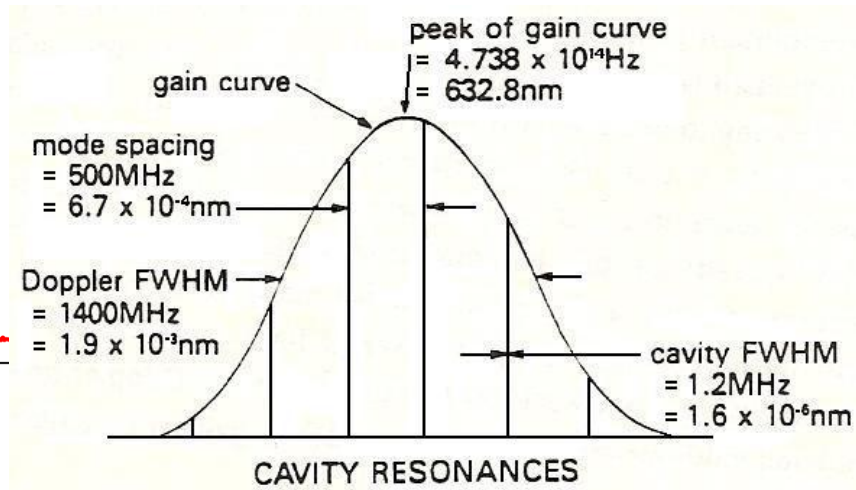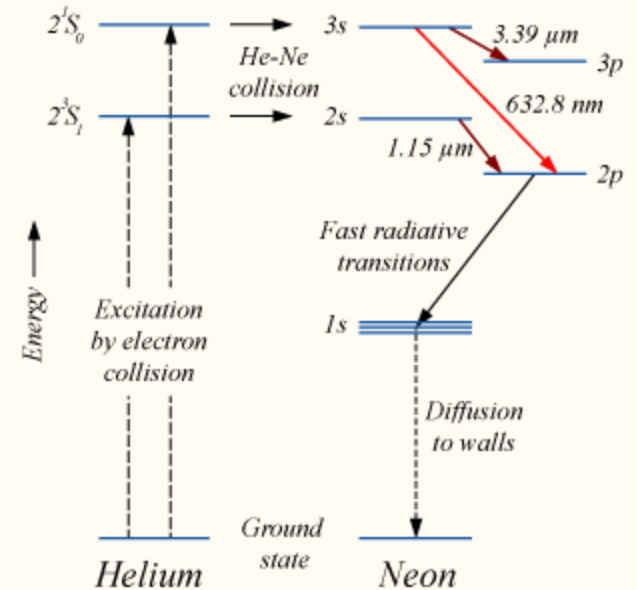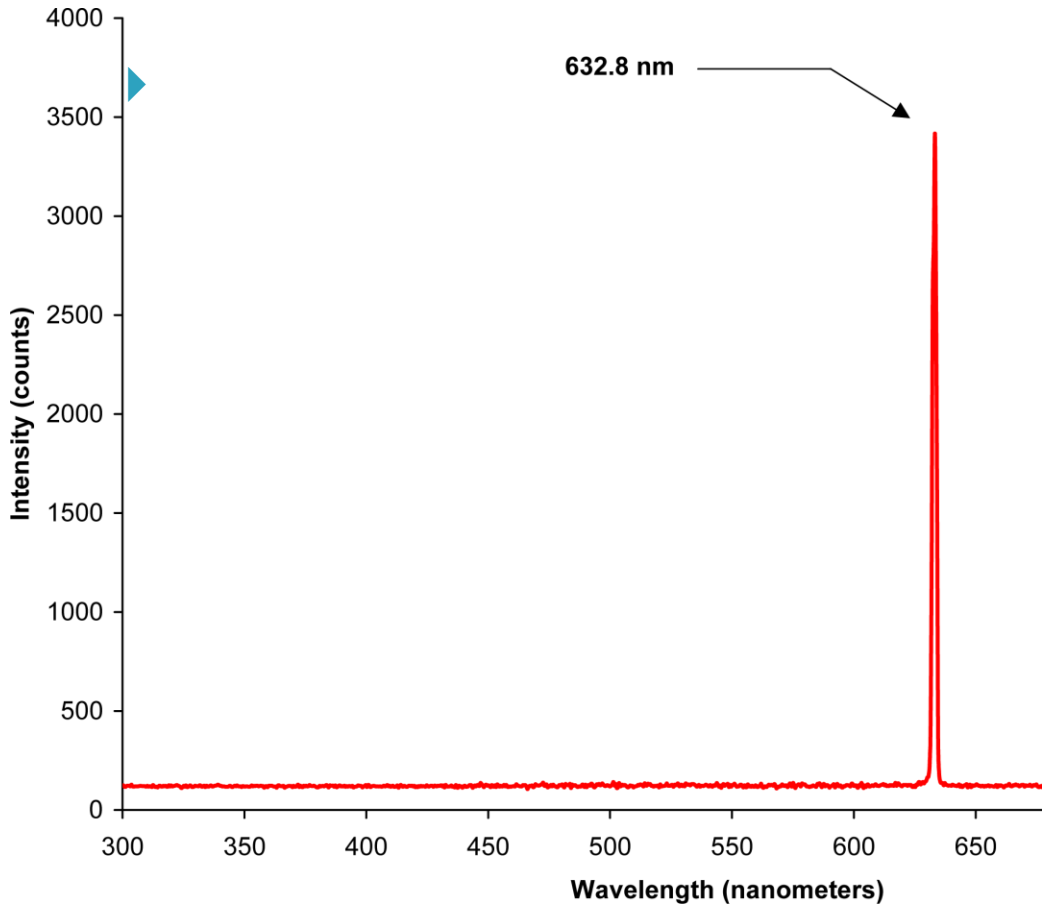
Calitatea spectrală a emiţătorilor optici

- 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

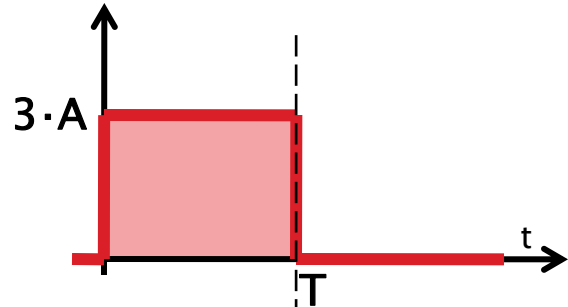$$\lambda_0 \rightarrow \left[\lambda_0 - \frac{\Delta\lambda}{2}, \lambda_0 + \frac{\Delta\lambda}{2} \right]$$
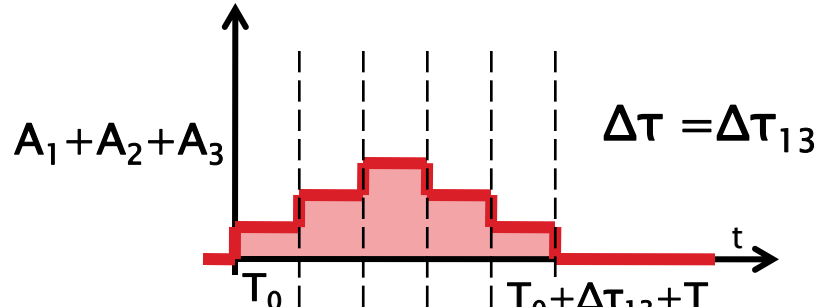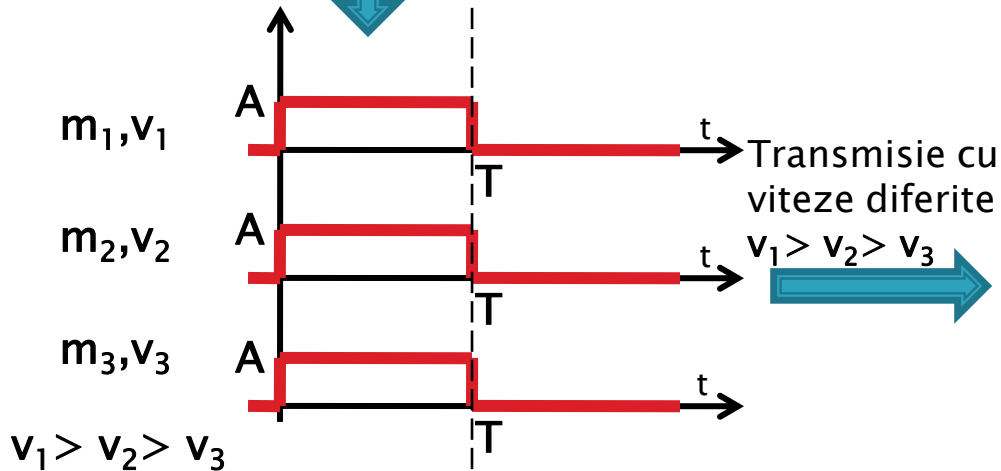

Splitting of energy levels in the presence of an external magnetic field

He–Ne Laser

$$\Delta\lambda = 0.002 \ nm$$

Dispersia modala

$3 \cdot A$

T

Impartire energie pe moduri

A

m_1, v_1

T

A

m_2, v_2

T

A

m_3, v_3

T

$v_1 > v_2 > v_3$

Transmisie cu viteze diferite
$v_1 > v_2 > v_3$

$A_1 + A_2 + A_3$

$\Delta\tau = \Delta\tau_{13}$

T_0

$T_0 + \Delta\tau_{13} + T$

Recombinarea energiei modurilor

A_1

T_0

$T_0 + T$

A_2

$T_0 + \Delta\tau_{12}$

$T_0 + \Delta\tau_{12} + T$

A_3

$T_0 + \Delta\tau_{13}$

$T_0 + \Delta\tau_{13} + T$
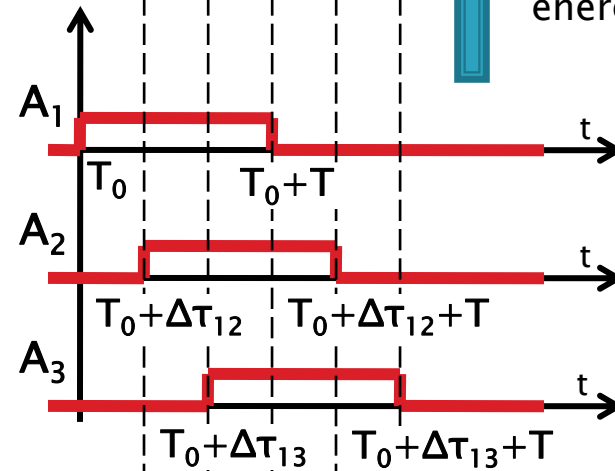
Conceptual→ $f(t) = \int_{-\infty}^{\infty} g(\omega) \cdot e^{j\omega t} d\omega$

Dispersia cromatica (gh+mat)

$3 \cdot A$

T

$A_1 + A_2 + A_3$

$\Delta\tau = \Delta\tau_{13}$

T_0 $T_0 + \Delta\tau_{13} + T$
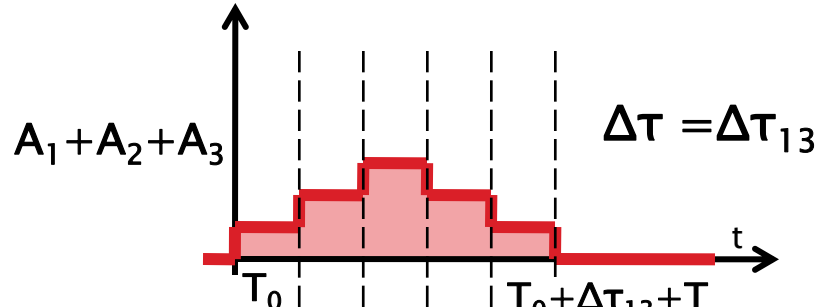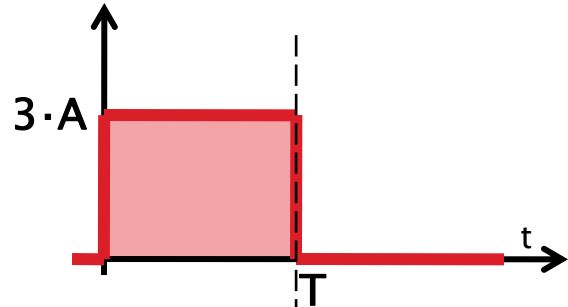
Impartire energie pe lungimi de unda
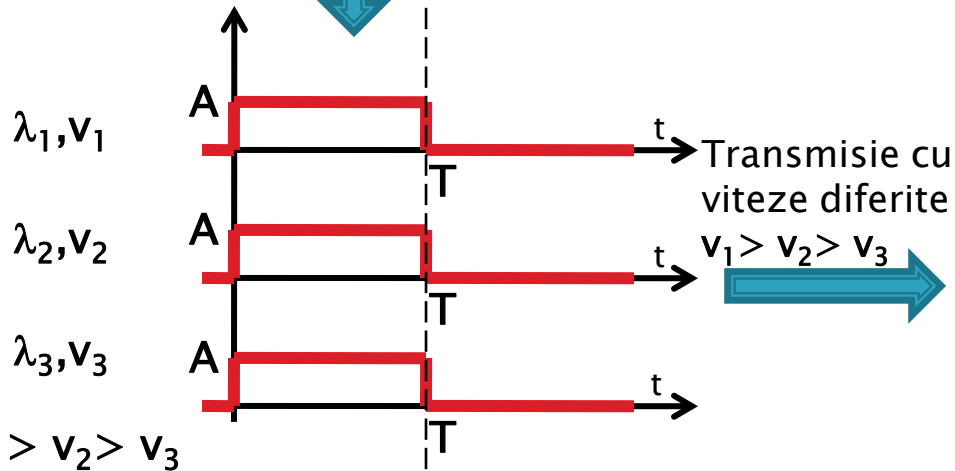
Recombinarea energiei la diferite lungimi de unda

λ_1, v_1 A

T

Transmisie cu viteze diferite

$v_1 > v_2 > v_3$

A_1

T_0 $T_0 + T$

λ_2, v_2 A

T

A_2

$T_0 + \Delta\tau_{12}$ $T_0 + \Delta\tau_{12} + T$

λ_3, v_3 A

T

A_3

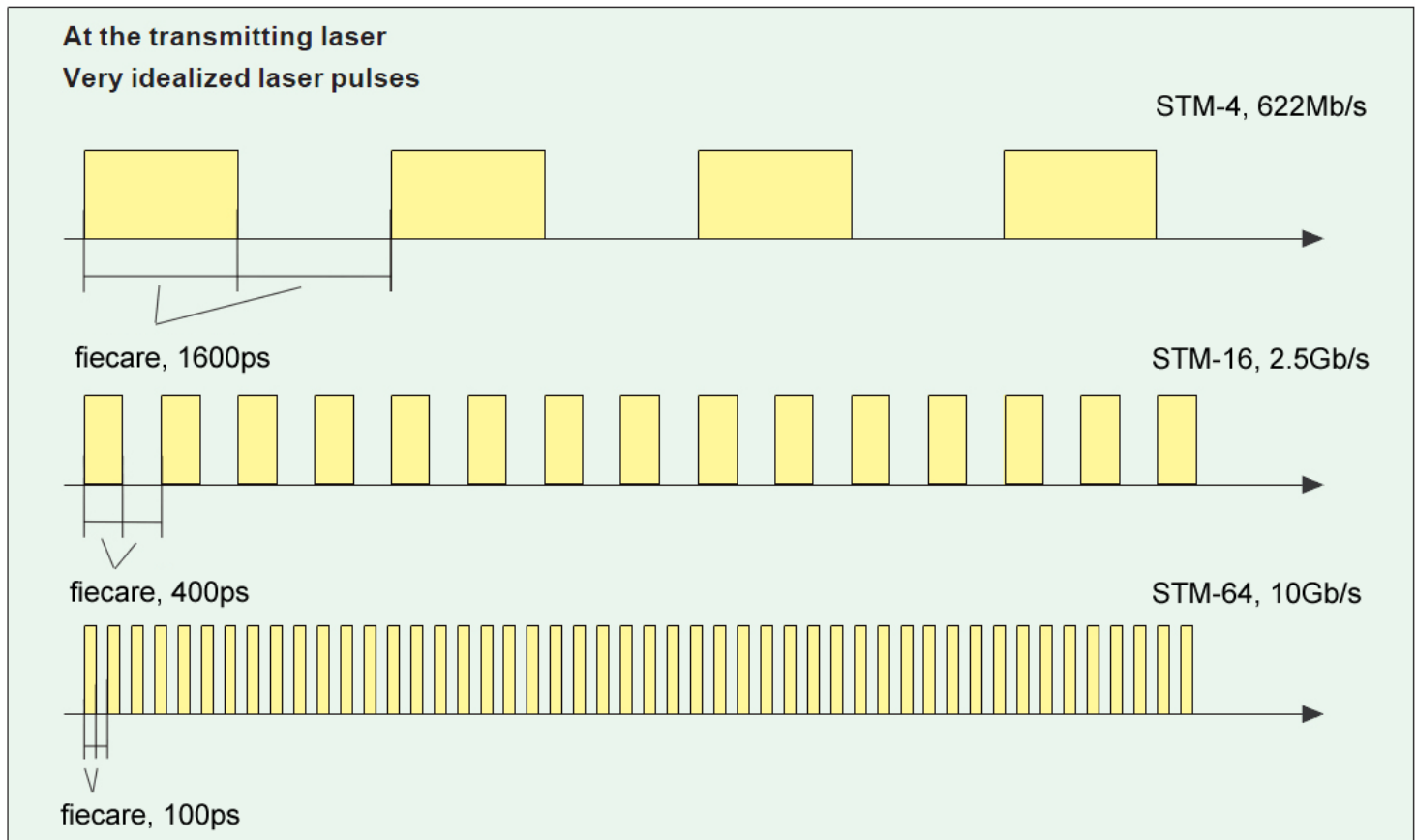$T_0 + \Delta\tau_{13}$ $T_0 + \Delta\tau_{13} + T$

$v_1 > v_2 > v_3$
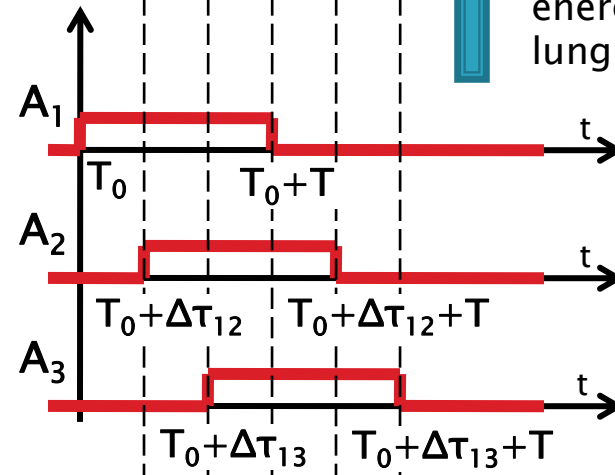
Efectiv→ $f(t) = \int_{-\infty}^{\infty} g(\omega) \cdot e^{j\omega t} d\omega$

Dispersie exemplu – 1

- transmisii cu viteze diferite
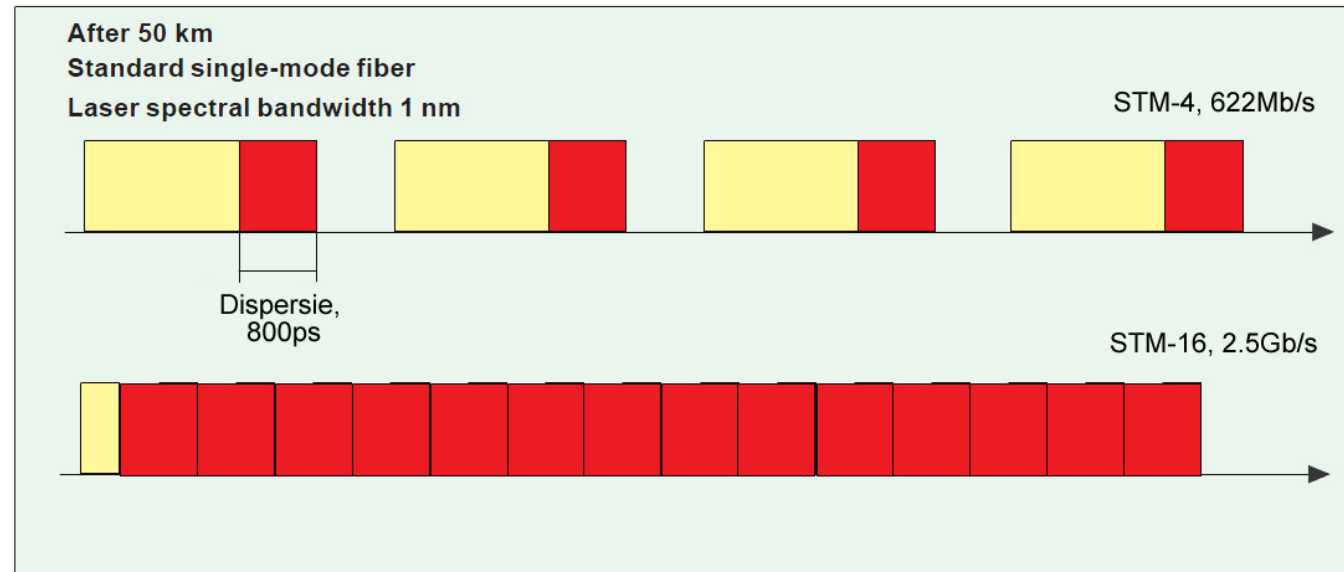
$$\Delta\tau_{cr} = D(\lambda)\cdot\Delta\lambda\cdot L$$

At the transmitting laser
Very idealized laser pulses

STM-4, 622Mb/s

fiecare, 1600ps

STM-16, 2.5Gb/s

fiecare, 400ps

STM-64, 10Gb/s

fiecare, 100ps

Dispersie exemplu – 2
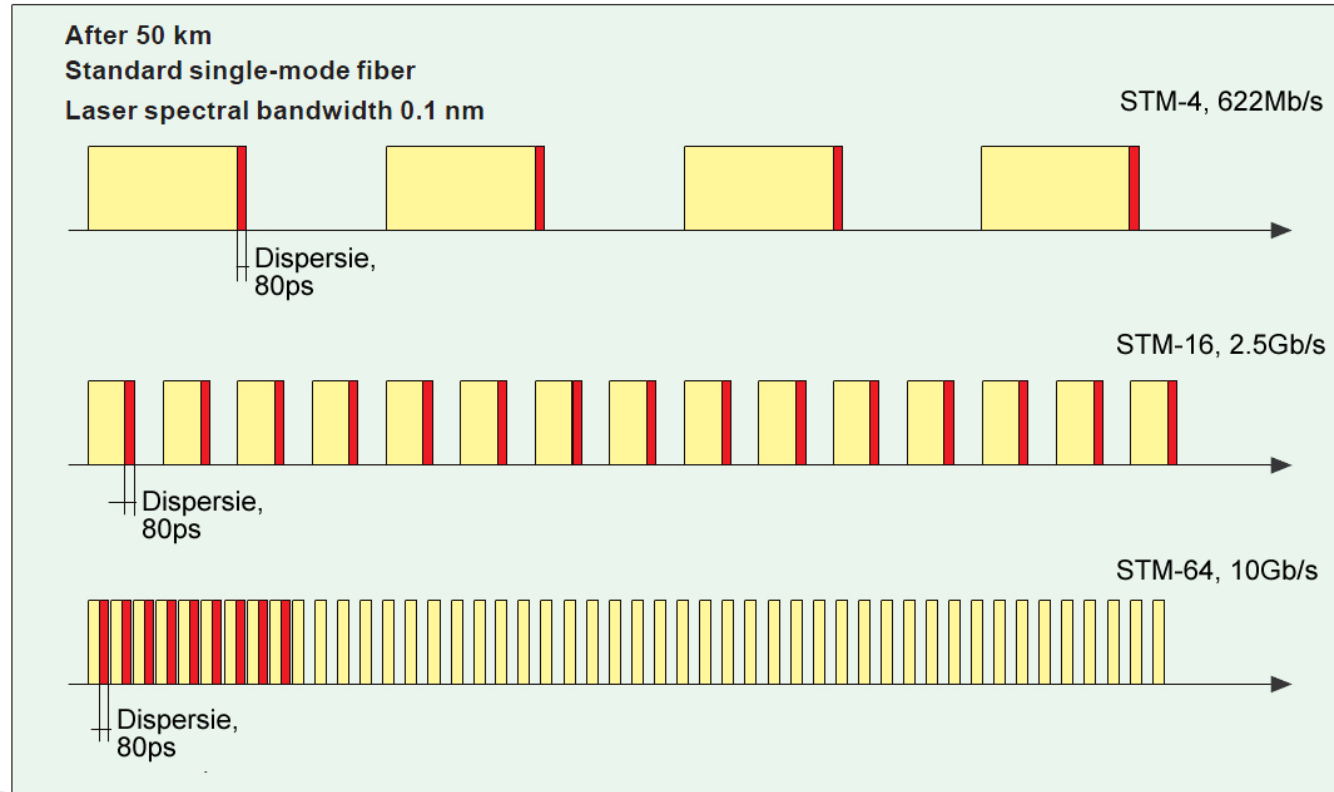
- 1550nm
- Efectul **sursei**
  - ◦ fibra monomod cu dispersia 16ps/nm/km@1550
  - ◦ latimea spectrala a sursei Δλ=1nm
  - ◦ 50km

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

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

$$\Delta\tau_{cr} = 16\cdot1\cdot50\ ps = 800\ ps$$

$$[\Delta\tau_{cr}] = \frac{ps}{nm\cdot km}\cdot nm\cdot km = ps$$

After 50 km
Standard single-mode fiber
Laser spectral bandwidth 1 nm

STM-4, 622Mb/s

Dispersie, 800ps

STM-16, 2.5Gb/s

$100<400<\textbf{800}<1600$

Dispersie exemplu – 3

- ▸ 1550nm
- ▸ Efectul sursei
  - ◦ fibra monomod cu dispersia 16ps/nm/km@1550
  - ◦ latimea spectrala a sursei Δλ=0.1nm
  - ◦ 50km

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

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

$$\Delta\tau_{cr} = 16\cdot 0.1\cdot 50\,ps = 80\,ps$$

$$[\Delta\tau_{cr}] = \frac{ps}{nm\cdot km}\cdot nm\cdot km = ps$$

After 50 km
Standard single-mode fiber
Laser spectral bandwidth 0.1 nm

STM-4, 622Mb/s

Dispersie, 80ps

STM-16, 2.5Gb/s

Dispersie, 80ps

STM-64, 10Gb/s

Dispersie, 80ps
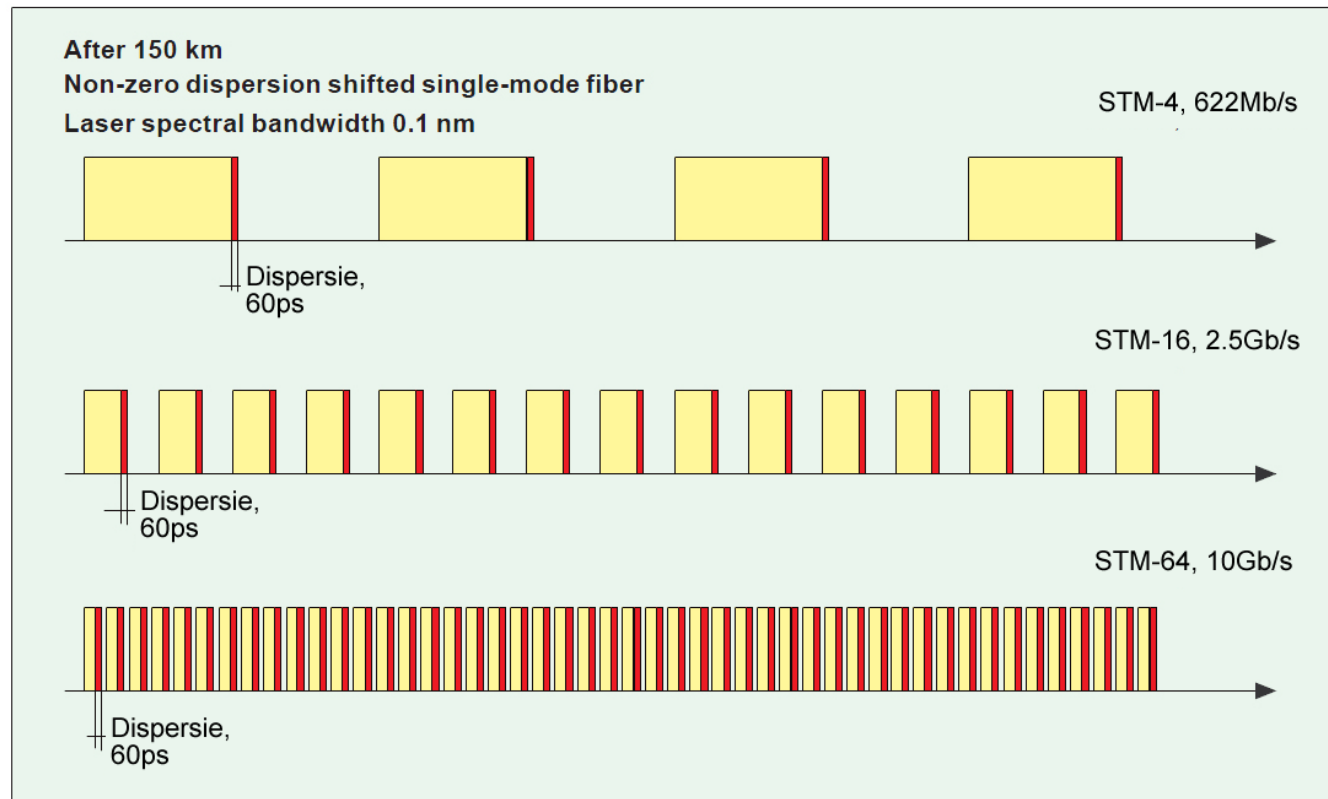
$$100 \approx 80 < 400 < 1600$$

Dispersie exemplu – 4

▸ **Efectul fibrei**
  ◦ fibra cu dipersie deplasata: **4ps**/nm/km@1550
  ◦ latimea spectrala a sursei Δλ=0.1nm
  ◦ 50km

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

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

$$\Delta\tau_{cr} = 4 \cdot 0.1 \cdot 50 \, ps = 20 \, ps$$

$$[\Delta\tau_{cr}] = \frac{ps}{nm \cdot km} \cdot nm \cdot km = ps$$

After 50 km
Non-zero dispersion shifted single-mode fiber
Laser spectral bandwidth 0.1 nm

STM-4, 622Mb/s

Dispersie, 20ps

STM-16, 2.5Gb/s

Dispersie, 20ps

STM-64, 10Gb/s
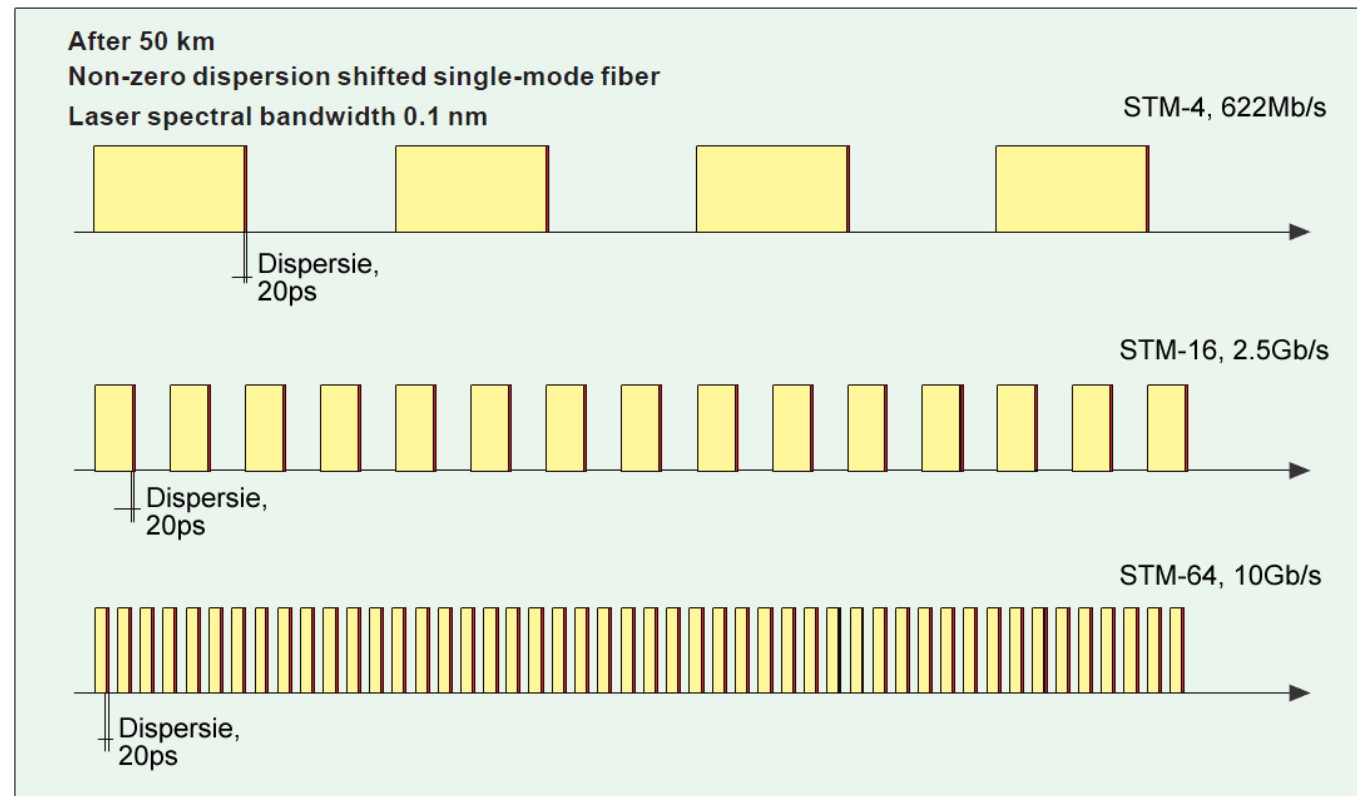
Dispersie, 20ps

$20 < 100 < 400 < 1600$

Dispersie exemplu – 5

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

▸ Efectul **fibrei**
  ◦ fibra cu dipersie deplasata: 4ps/nm/km@1550
  ◦ latimea spectrala a sursei Δλ=0.1nm
  ◦ 150km

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

$$\Delta\tau_{cr} = 4\cdot 0.1\cdot 150\, ps = 60\, ps$$

$$[\Delta\tau_{cr}] = \frac{ps}{nm\cdot km}\cdot nm\cdot km = ps$$

After 150 km
Non-zero dispersion shifted single-mode fiber
Laser spectral bandwidth 0.1 nm

STM-4, 622Mb/s

Dispersie, 60ps

STM-16, 2.5Gb/s

Dispersie, 60ps

STM-64, 10Gb/s

Dispersie, 60ps

$60 < 100 < 400 < 1600$

Sumarea efectelor

- efecte **succesive** se adună liniar

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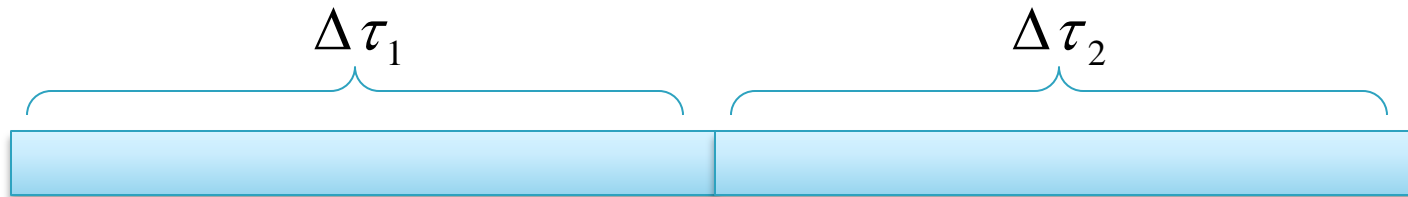
$$\Delta\tau_{tot} = \Delta\tau_1 + \Delta\tau_2$$

- efecte **simultane** se adună pătratic

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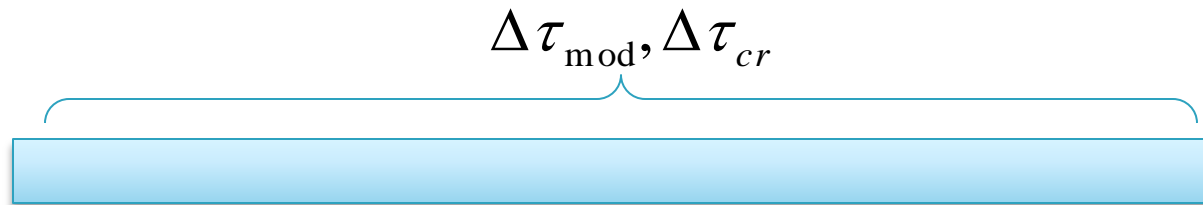
$$\Delta\tau_{tot} = \sqrt{\Delta\tau_{cr}^2 + \Delta\tau_{\mathrm{mod}}^2}$$

Dispersia

Dispersia modala

salt de indice

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

indice gradat

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

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

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

Dispersia cromatica

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

$$D(\lambda) = \frac{S_0}{4} \cdot \left(\lambda - \frac{\lambda_0^4}{\lambda^3} \right)$$
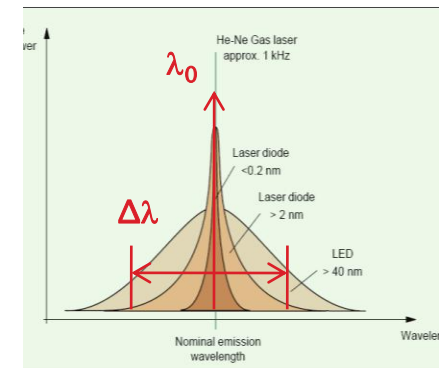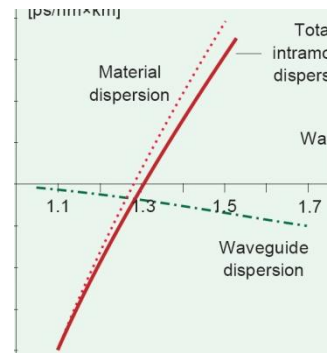
$$\Delta\tau_{tot} = \sqrt{\Delta\tau_{cr}^2 + \Delta\tau_{\mathrm{mod}}^2}$$

Banda

▸ **Dispersia totala**

$$\Delta\tau_{tot} = \sqrt{\Delta\tau_{cr}^2 + \Delta\tau_{\text{mod}}^2} \quad \text{sau} \quad \Delta\tau_{tot} = \Delta\tau_1 + \Delta\tau_2$$

▸ **Banda**

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

▸ **Banda optica la 3 dB corespunde unei benzi electrice la 6 dB**

◦ $P_{opt} \sim I; \quad P_{el} \sim I^2 \qquad\qquad B_{opt} = \sqrt{2}B_{el}$

▸ **Viteza legaturii**

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

Produs Banda · Distanta

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

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

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

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

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

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

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

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

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

Produs Banda X Distanta

$$\Delta\tau_{\mathrm{mod}} \sim L \qquad\qquad \Delta\tau_{cr} \sim L \qquad\qquad \Delta\tau_{tot} \sim L$$

$$V[Gb/s] \sim B_{el}[GHz] \sim \frac{1}{\Delta\tau_{tot}} \sim \frac{1}{L[km]}$$

$$V[Gb/s] \times L[km] = \mathrm{ct.}$$

$$B_{el}[MHz] \times L[km] = \mathrm{ct.}$$

Dispersion shifted fibers

- Sticla are (nativ) dispersie cromatica 0 la 1310nm
- Atenuarea e mai mica la 1550 nm
- EDFAÿ(Erbium doped fibre amplifiers) opereaza in banda 1550nm
- Sistemele WDM (Wavelength division Multiplexing) necestia banda larga amplificata

Dispersion
[ps/nm×km]

1

0

-1

1520   1540   1560   1580

λ [μm]
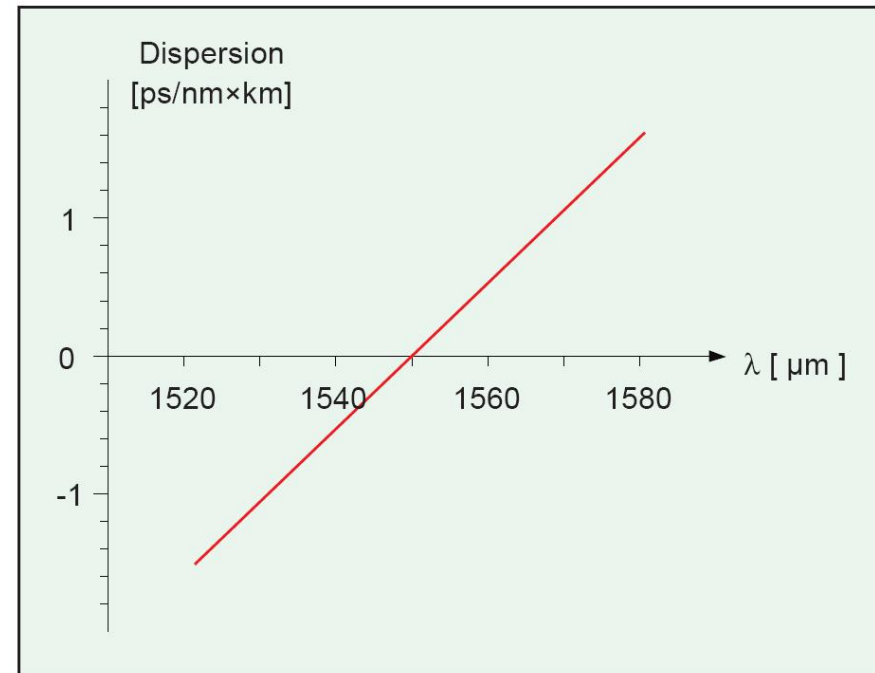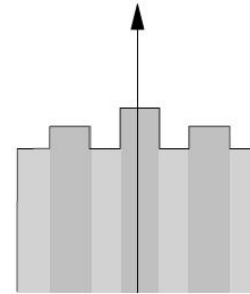
Non-zero Dispersion shifted fibers
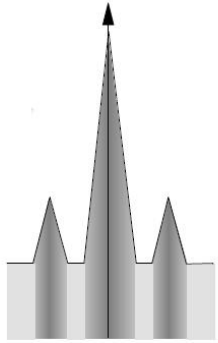
FWM
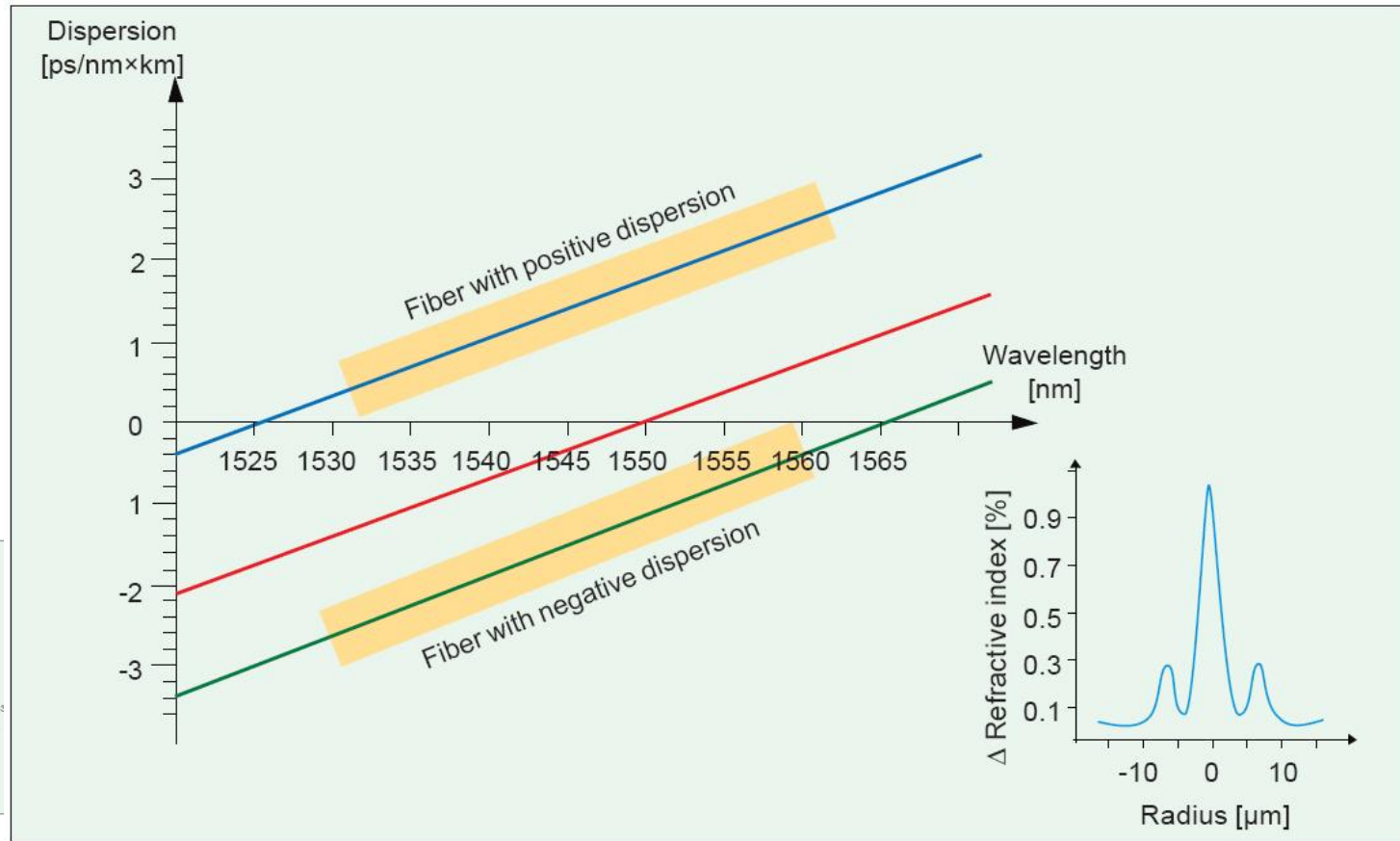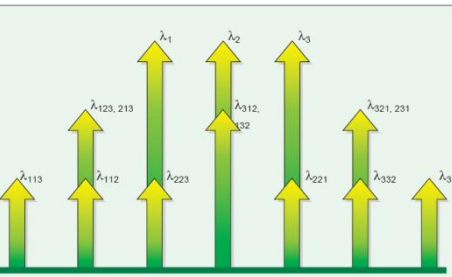
Dispersion shifted fibers
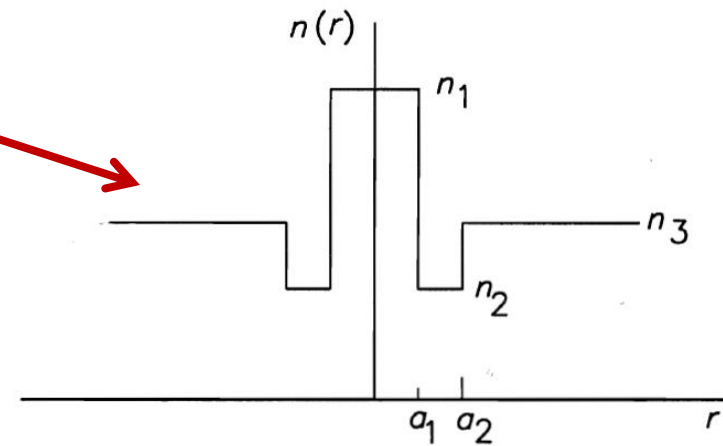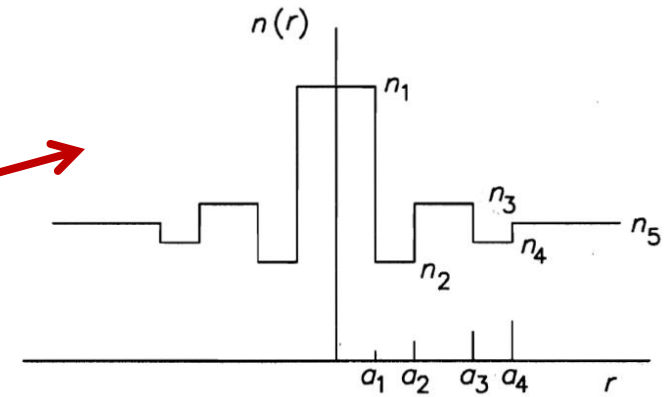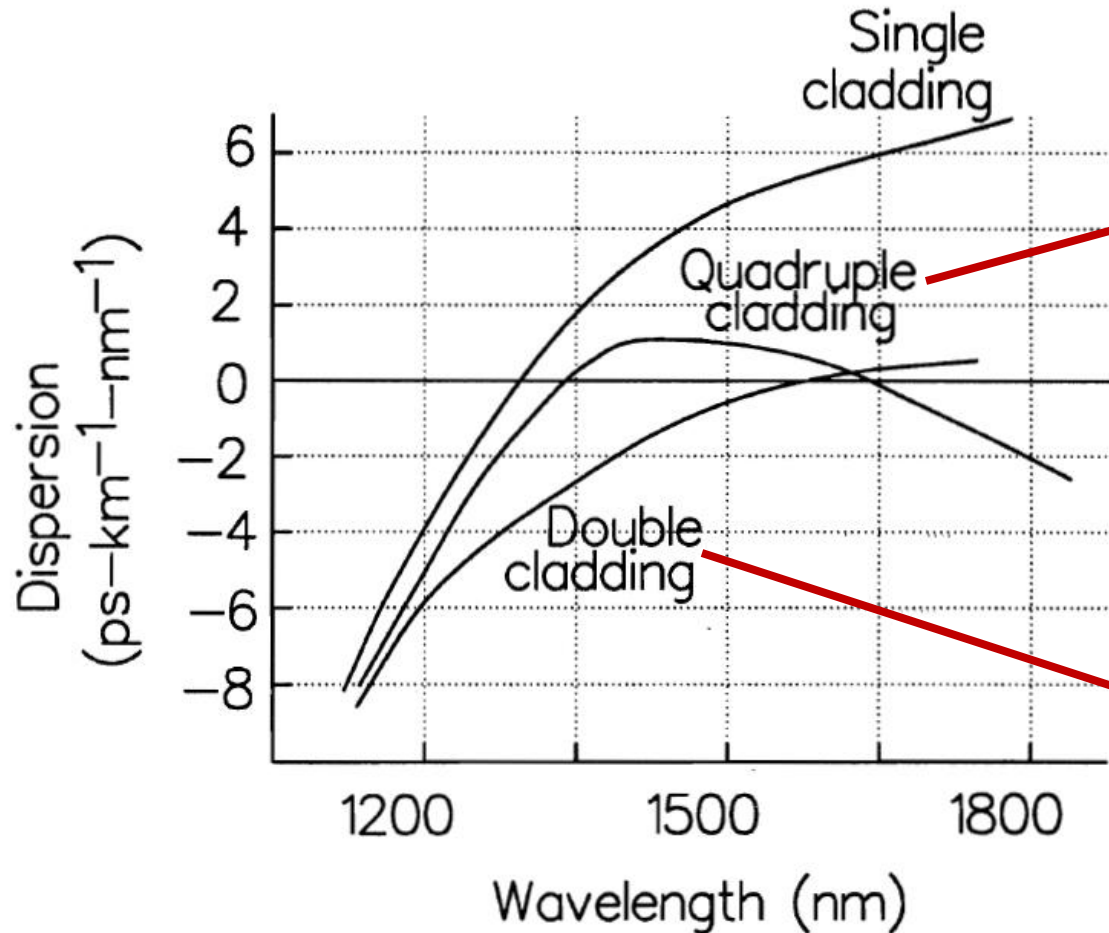
Fibra pentru compensarea dispersiei
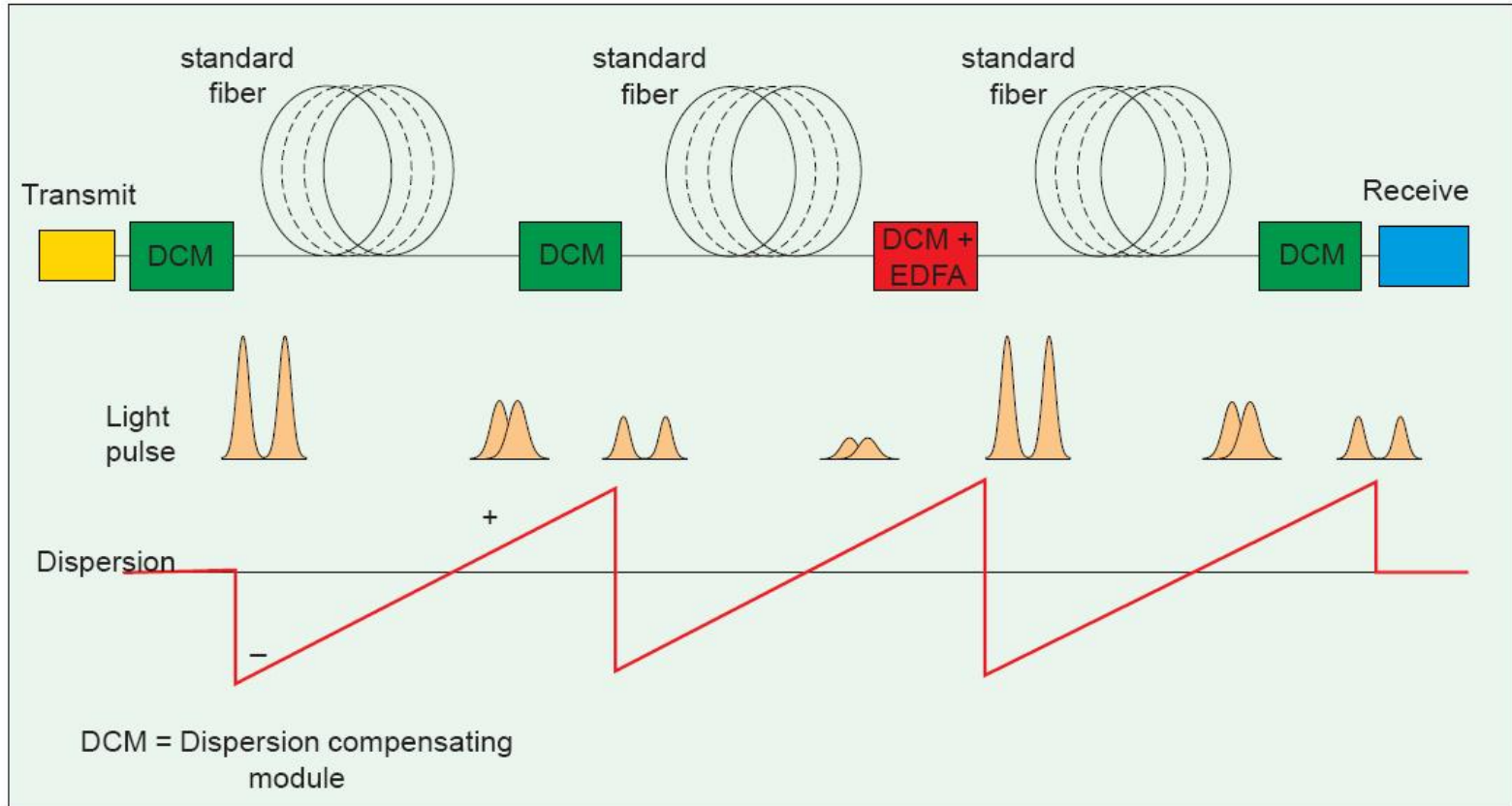
▸ Dispersie: −100 ps/nm/km
▸ Atenuare 0.5 dB/km

Catalog – monomod

$$D(\lambda) = \frac{S_0}{4} \cdot \left(\lambda - \frac{\lambda_0^4}{\lambda^3} \right)$$

Catalog – multimod

Bandwidth

$$D(\lambda) = \frac{S_0}{4} \cdot \left(\lambda - \frac{\lambda_0^4}{\lambda^3} \right)$$

+

| Standard Bandwidth Cells |
| --- |
| 850/1300 nm (MHz•km) |
| 400/400 |
| 400/600 |
| 400/1200 |
| 500/500 |
| 600/600 |
| 600/1000 |

Other bandwidth cells available upon request.

Fibra standard ITU G.652

- Diametru teaca = 125 µm
- MFD = 9÷10 µm la 1300 nm
- λ_C = 1100÷1280 nm
- Pierderi de curbura (la 1550 nm) mai mici de 1 dB pentru 100 spire de fibra rulata pe un mosor cu 7.5 cm diametru
- Dispersia in banda 1300 nm (1285–1330 nm) mai mica de 3.5 ps/nm/km. La 1550 nm dispersia trebuie sa fie mai mica de 20 ps/nm/km
- Viteza de variatie a dispersiei (panta dispersiei S_0) mai mica de 0.095 ps/nm^2/km

ITU (International Telecommunication Union) is the United Nations specialized agency for information and communication technologies – ICTs

Fibra optica din plastic (POF)

Attenuation dB/Km
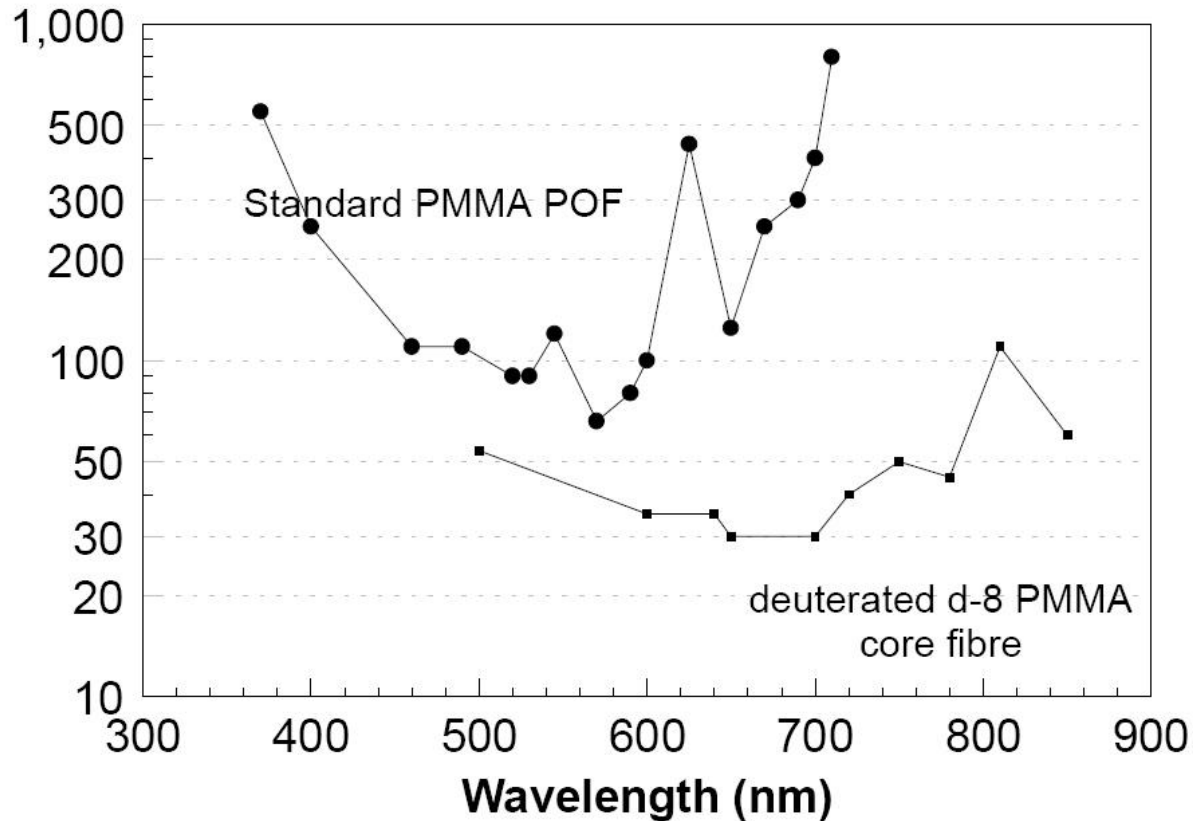
- Atenuare 180 dB/km
- NA = 0.3
- Diametru 1 mm
- Banda 125MHz (100m)

Contact

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