Optoelectronică, structuri şi tehnologii
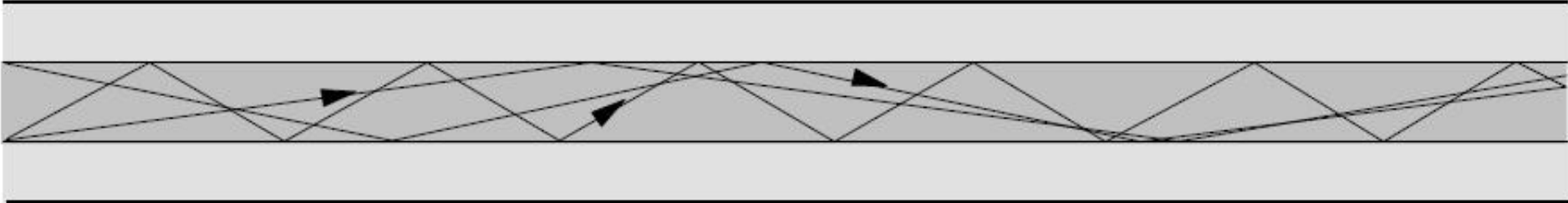
Curs 5
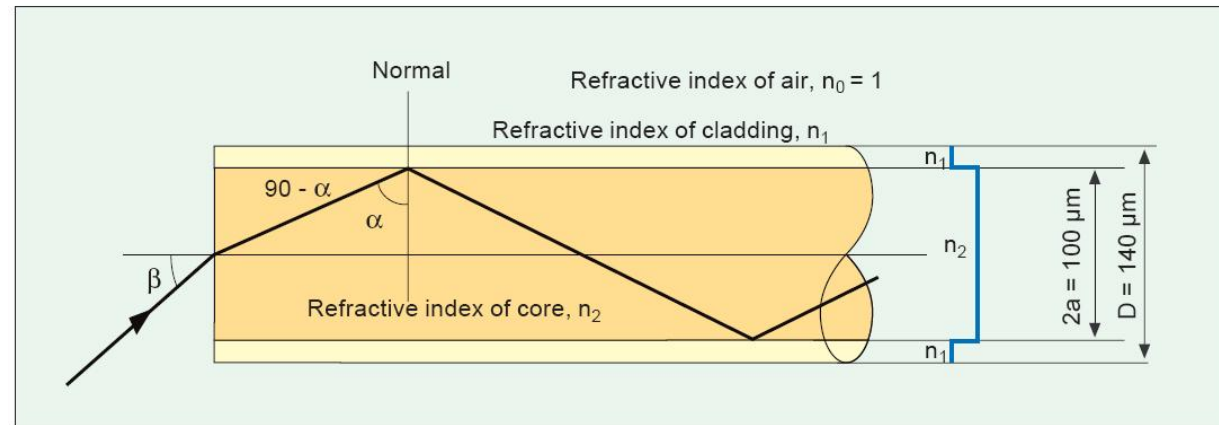## 2011/2012

Fibra optică

Capitolul 5

Fibre multimod cu salt de indice
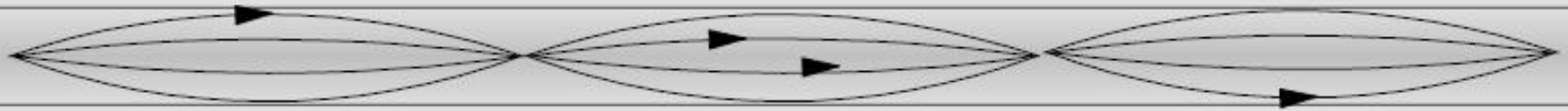

- 50/125 sau 62.5/125 (µm)
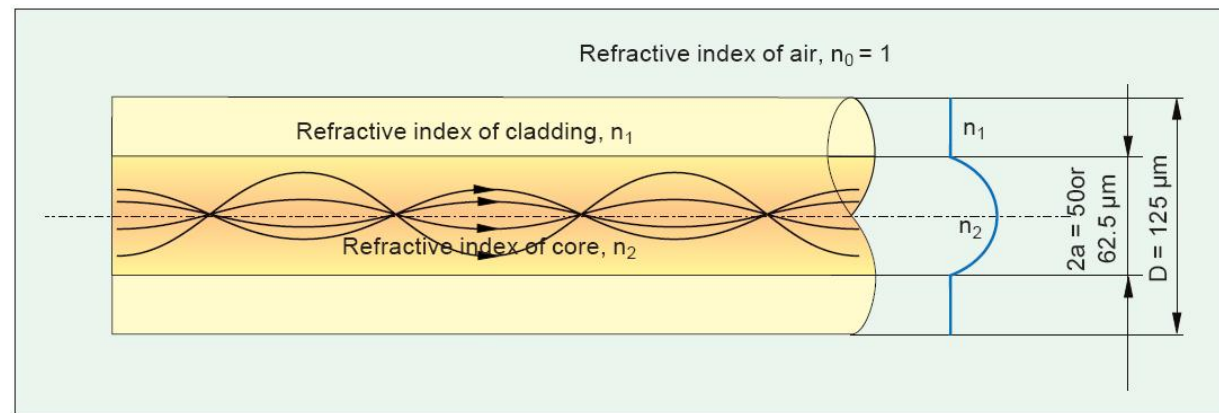- 15–50 MHz km

	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

Refractive index of air, $n_0 = 1$

Refractive index of cladding, n_1

Refractive index of core, n_2

n_1

n_2

$2a = 50$ or 62.5 μm

$D = 125$ μm

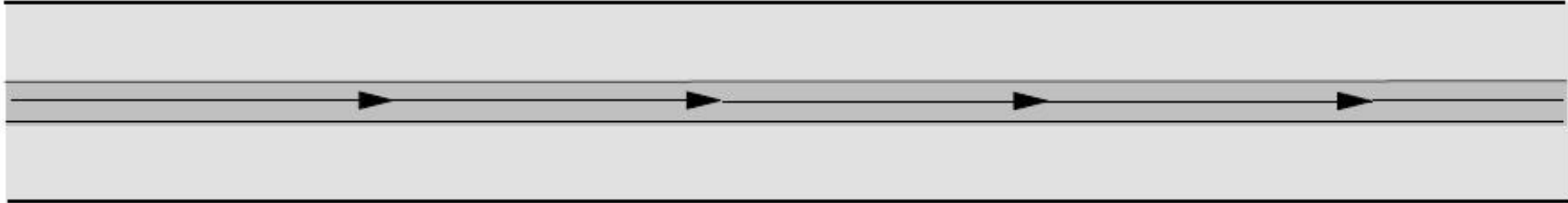|	
Core diameter 2a	50 or 62.5 μm
Cladding diameter D	125 μm
Maximum refractive index, core	1.46
Relative differential refractive index	0.010

Fibre multimod cu indice gradat

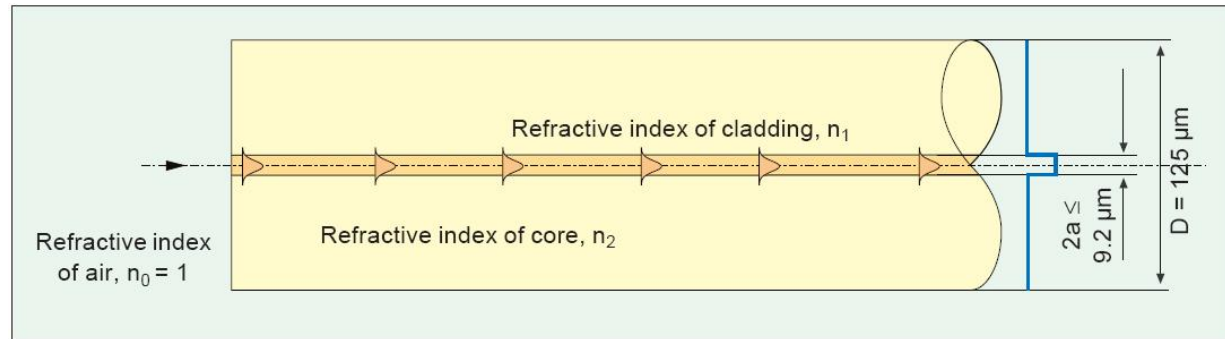$$n(r) = n_2 \left[1 - \Delta \left(\frac{r}{a} \right)^g \right]$$

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

- g = 1 – indice gradat triunghiular
- g = 2 – indice gradat parabolic
- g = ∞ – 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, $n_0 = 1$

$2a \leq 9.2$ μm

$D = 125$ μm

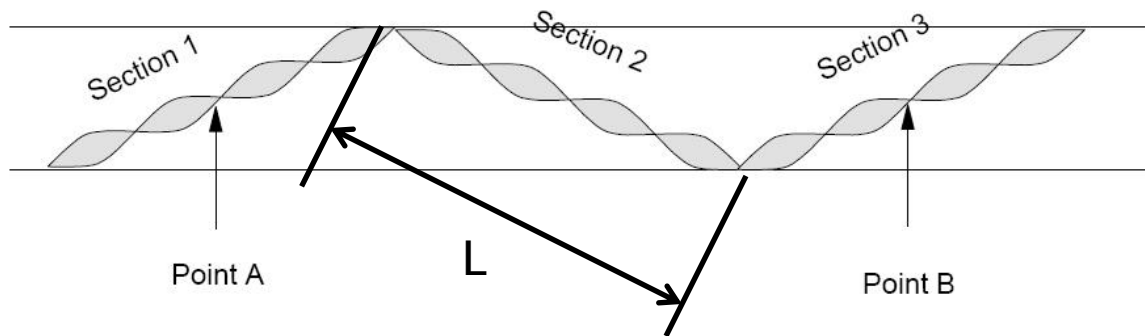|	
Cladding diameter D	125 μm
Core refractive index n_2	1.4485
Cladding refractive index n_1	1.4440
Refractive index differential	0.003 = 0.3%

Frecventa normalizata

- ## Frecventa normalizata

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

- ## Numar de moduri

$$L = m \cdot \lambda$$

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

Frecventa normalizata

- Numar de moduri
  - Multimod cu salt de indice

  $$g = 1 \quad \Rightarrow \quad N \approx \frac{V^2}{2}$$

  - 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

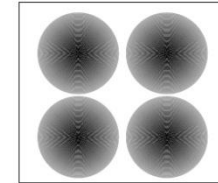$$V = 2\pi \frac{a}{\lambda} NA = 2\pi \frac{25}{1} 0.2 = 2 \cdot \pi \cdot 5 \approx 31.4$$

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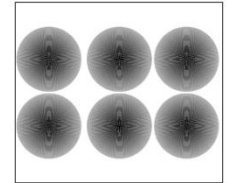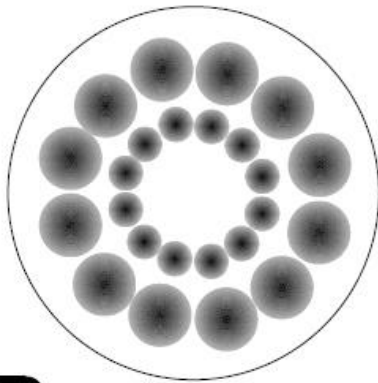
Moduri in fibra

- Moduri in ghid rectangular

TEM$_{00}$ TEM$_{11}$ TEM$_{21}$

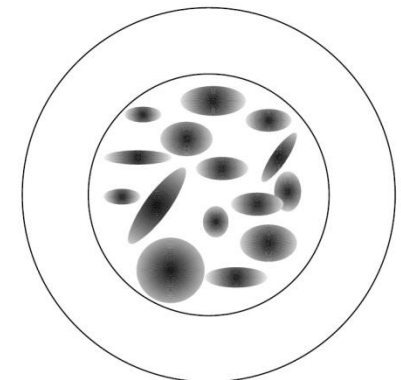- Moduri linear polarizate in fibra
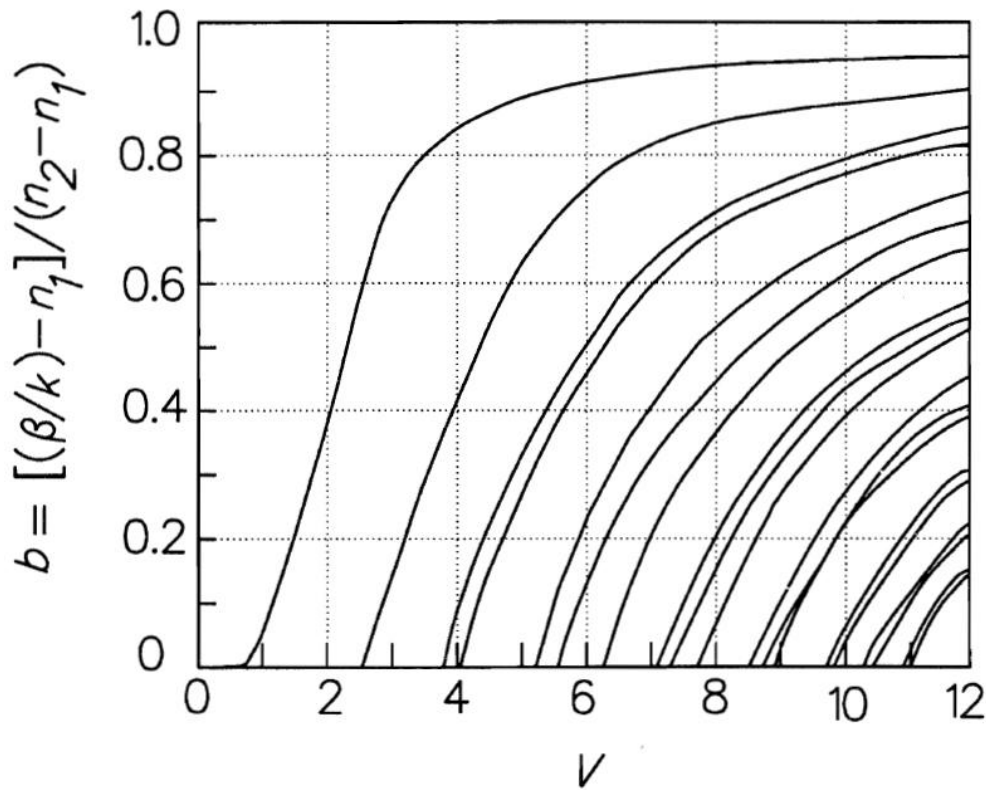

LP$_{62}$ LP$_{11}$ LP$_{01}$

"Sparkle" pattern

Frecventa normalizata – monomod

▶ Fibre monomod

b – coeficient de propagare modal relativ

$$V \leq V_C = 2.405$$

exista un singur mod (solutii fc. Bessel)

$$\lambda \geq \lambda_C = \pi \frac{2a}{V_C} NA = \pi \frac{2a}{2.405} NA$$
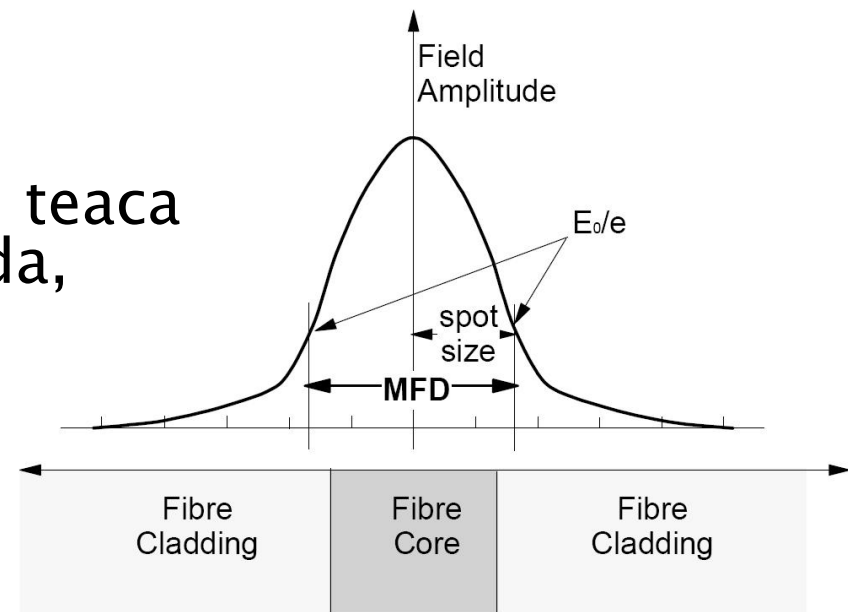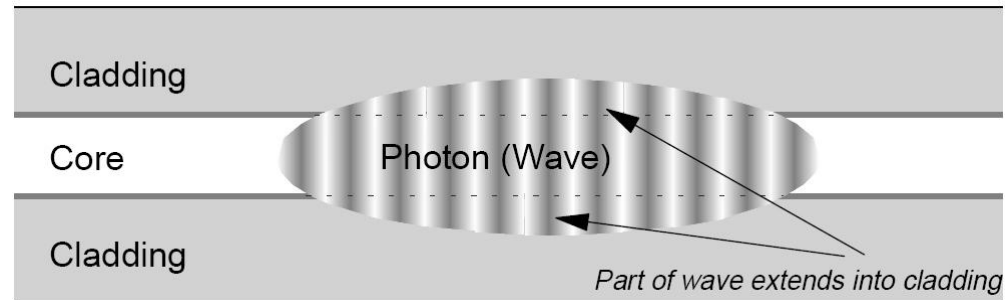
Exemplu:
2a = 8.5µm
NA = 0.11

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

Propagarea in fibra monomod
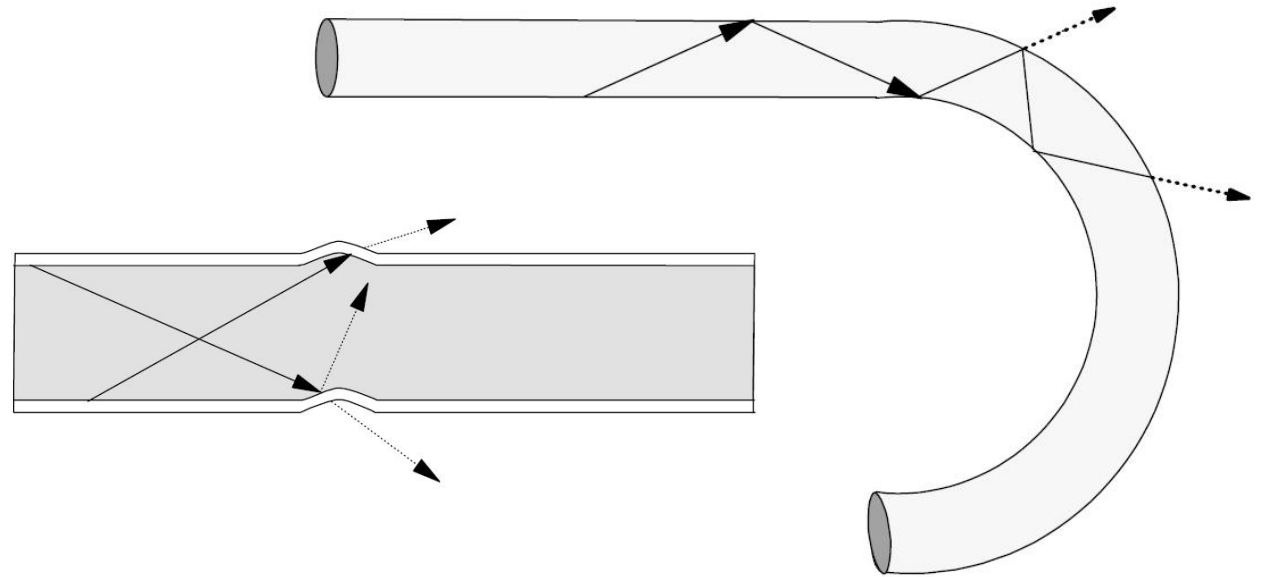
- Propagarea luminii poate fi explicata doar prin teoria electromagnetica

Cladding
Core — Photon (Wave)
Cladding
Part of wave extends into cladding

- 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

Field Amplitude

E_0/e
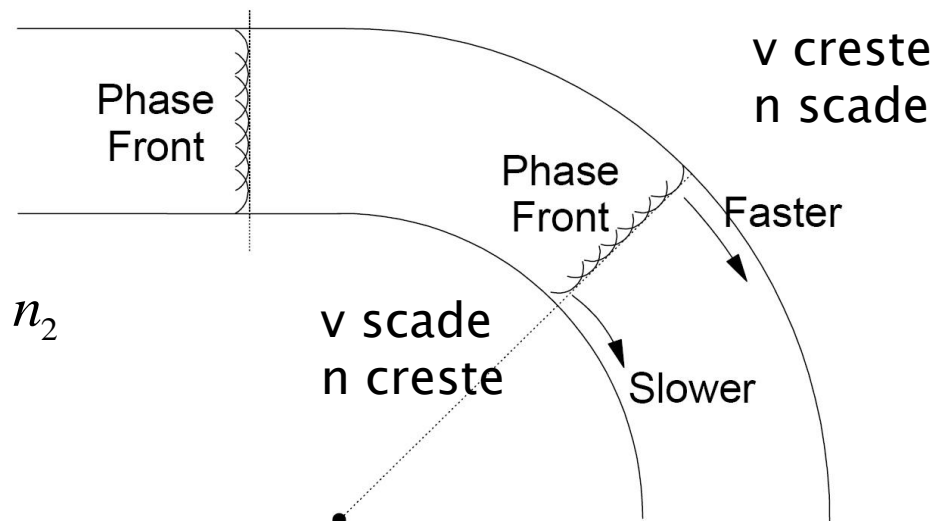
spot size

MFD

Fibre Cladding | Fibre Core | Fibre Cladding

Efectul curburilor

▸ **Multimod**

▸ **Monomod**

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

Phase Front

Phase Front
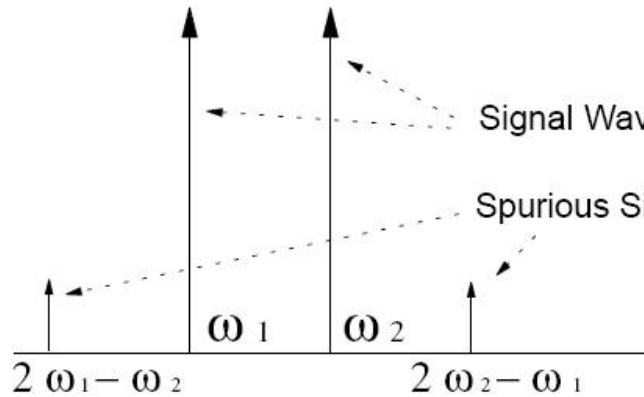
Faster

Slower

v creste
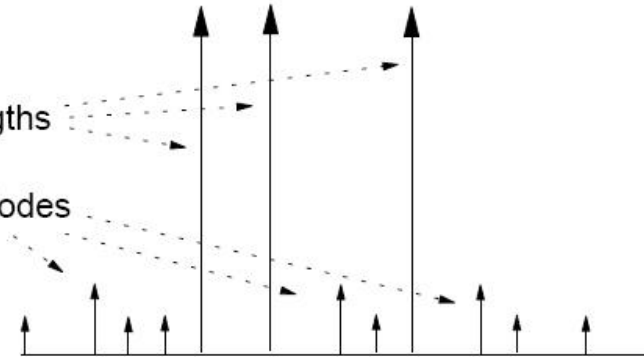n scade

v scade
n creste

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

Four-Wave Mixing, FWM
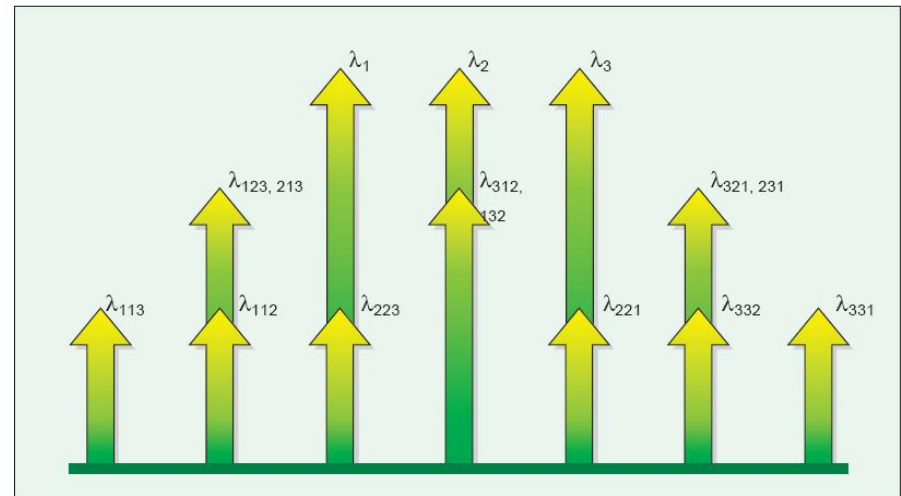

Two Channels

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}
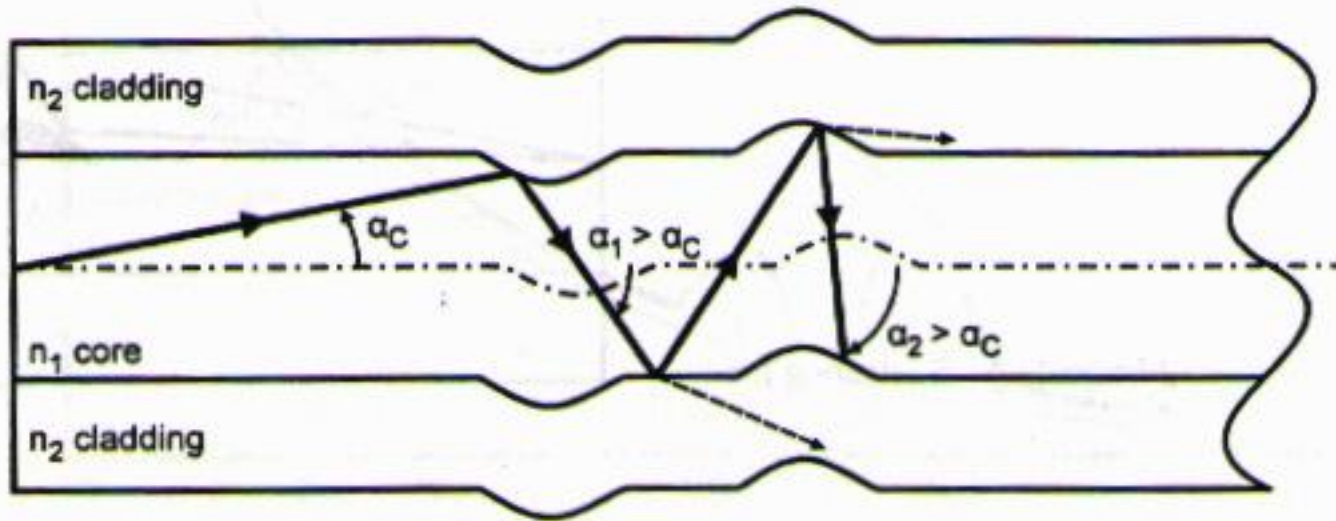
ATENUAREA
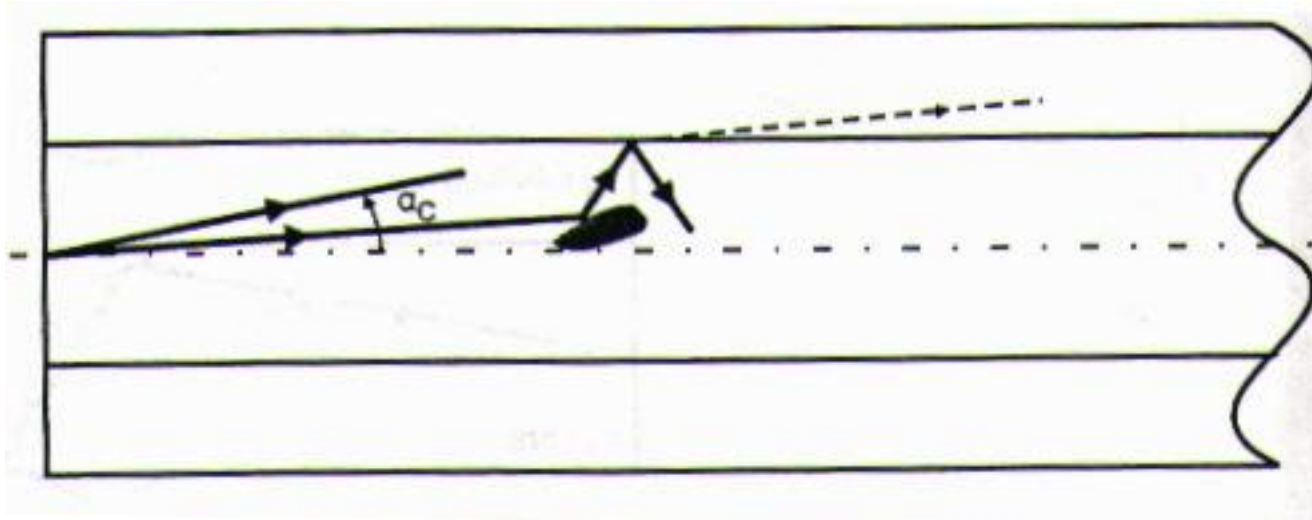
- Macrocurburi
- Microcurburi
- Imprastiere
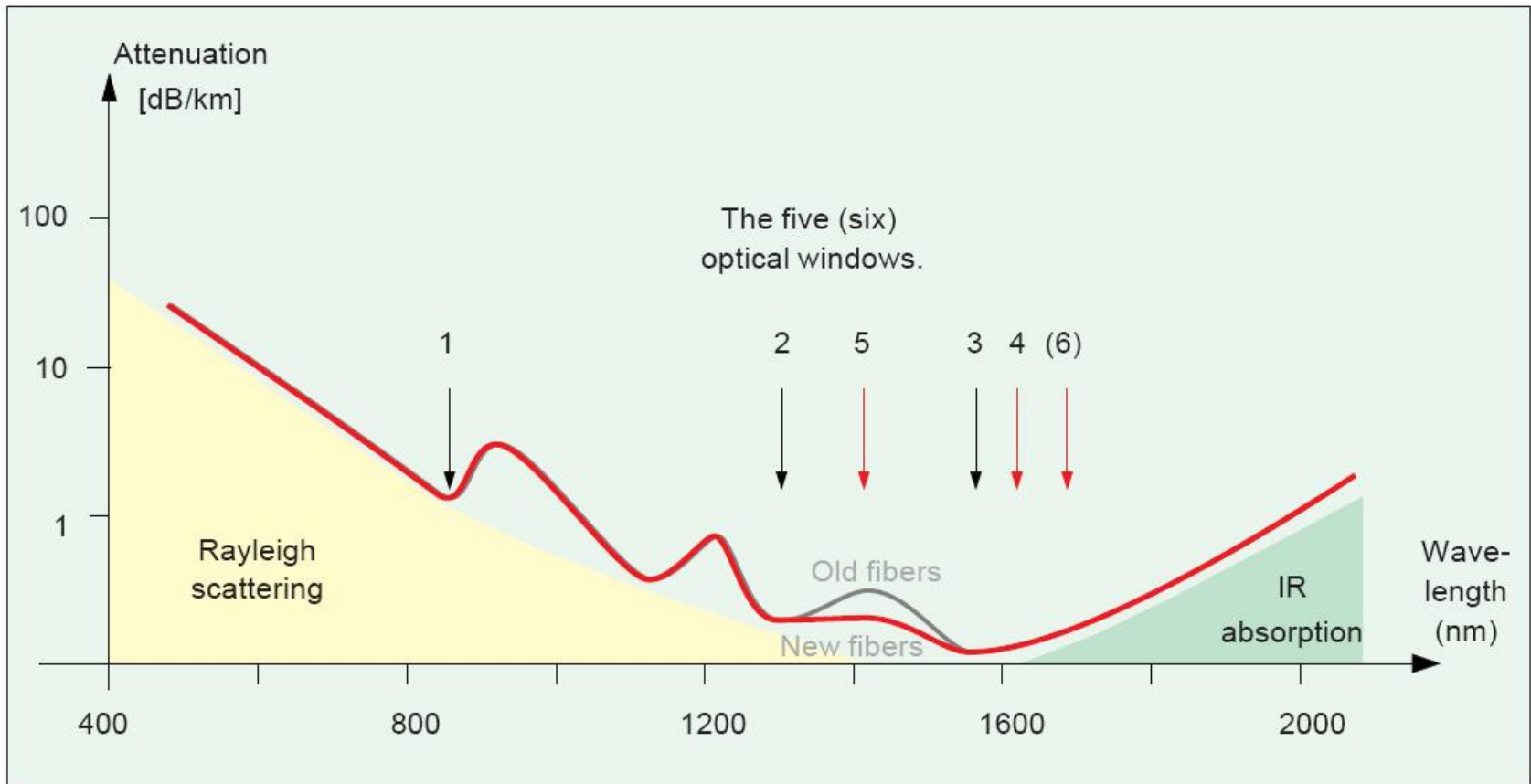- Absorbtie

Macrocurburi

Microcurburi

Imprastiere

Absorbtie

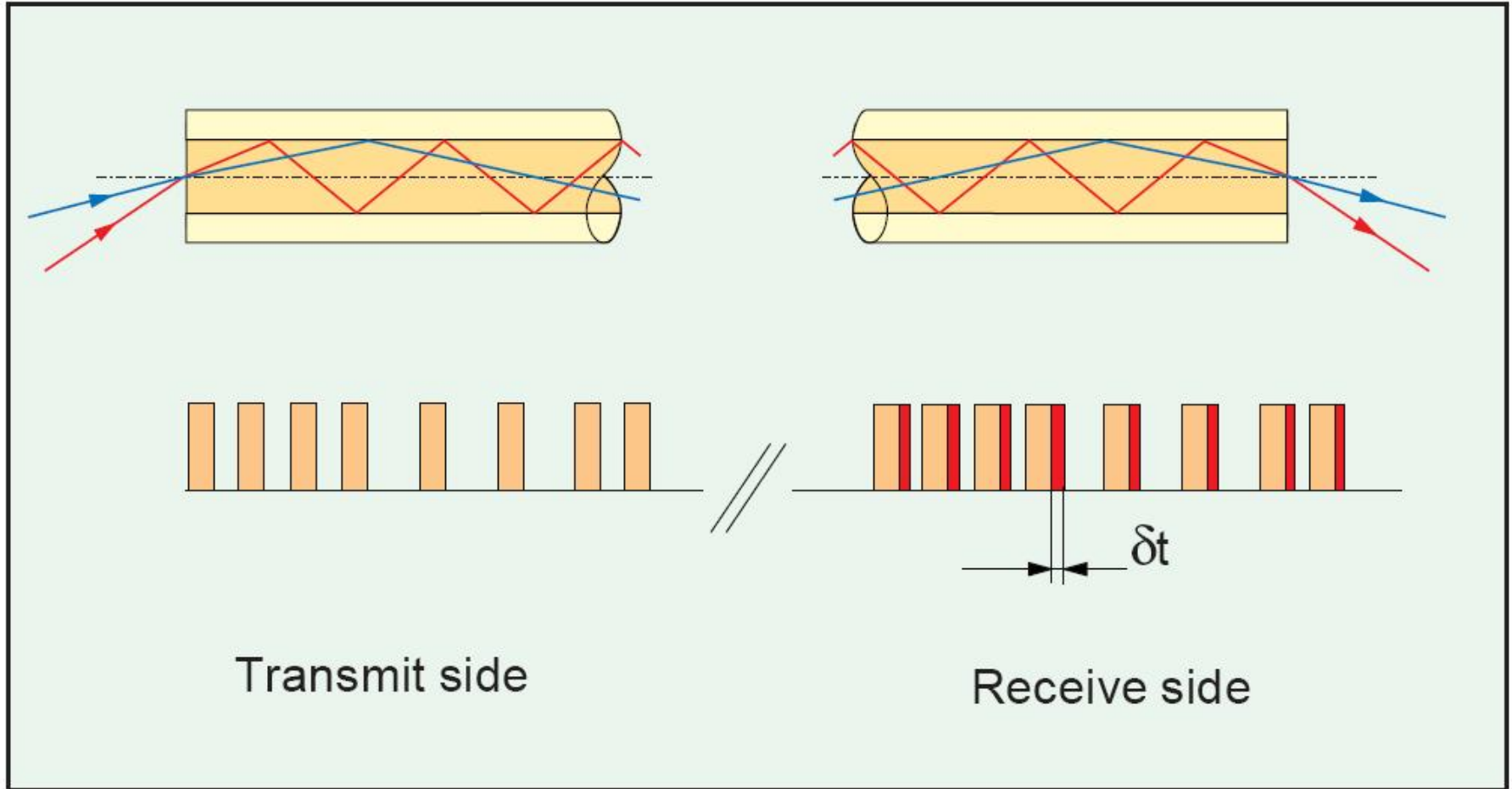# Calculul atenuarii

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

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

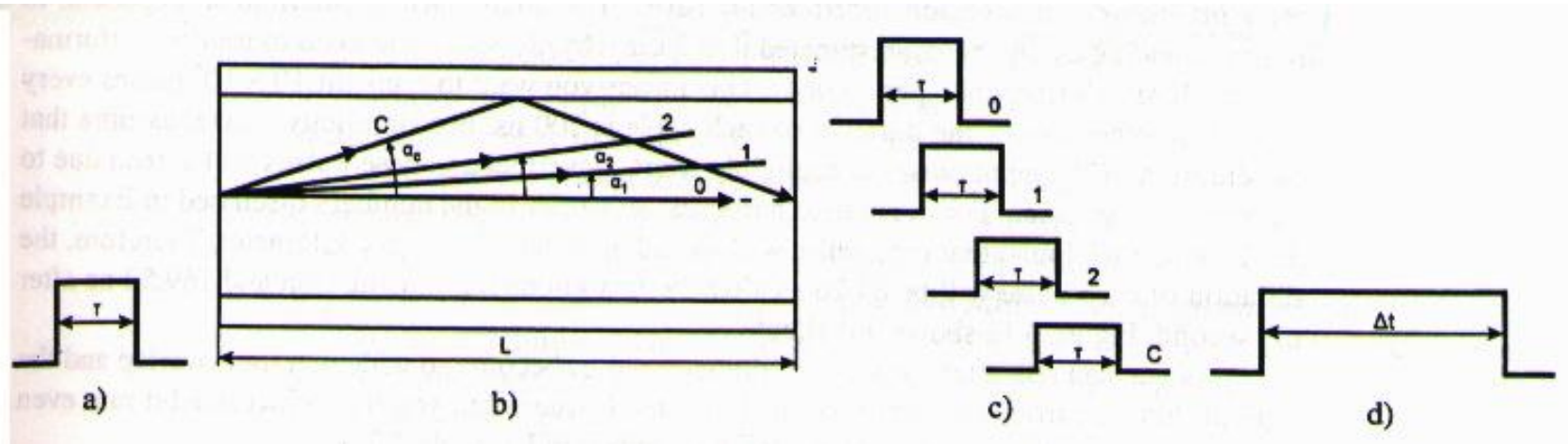$$\text{Atenuare}[\text{dB/km}] = \frac{\text{Pierderi}[\text{dB}]}{\text{lungime}[\text{km}]}$$

Dispersia

- 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

$$t_0 = L/v \qquad\qquad t_C = L/(v\cos\alpha_C)$$

$$\Delta t_{SI} = t_C - t_0 = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right)$$

$$\Delta t_{SI} = t_C - t_0 = (Ln_1/c)\Delta \qquad\qquad \Delta t_{SI} = t_C - t_0 \approx \frac{L}{2cn_1}(NA)^2$$

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

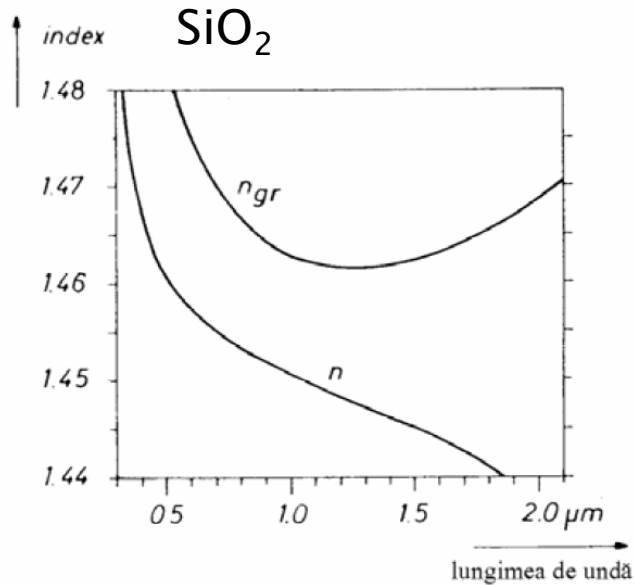$$\Delta\tau_{\mathrm{mod}}^2 = \frac{1}{3}\left(\frac{dt}{2}\right)^2$$

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

- indice gradat

$$dt = \frac{L \cdot n_2 \cdot \Delta^2}{2c} \approx \frac{L \cdot NA^4}{8 \cdot c \cdot n_2^3}$$
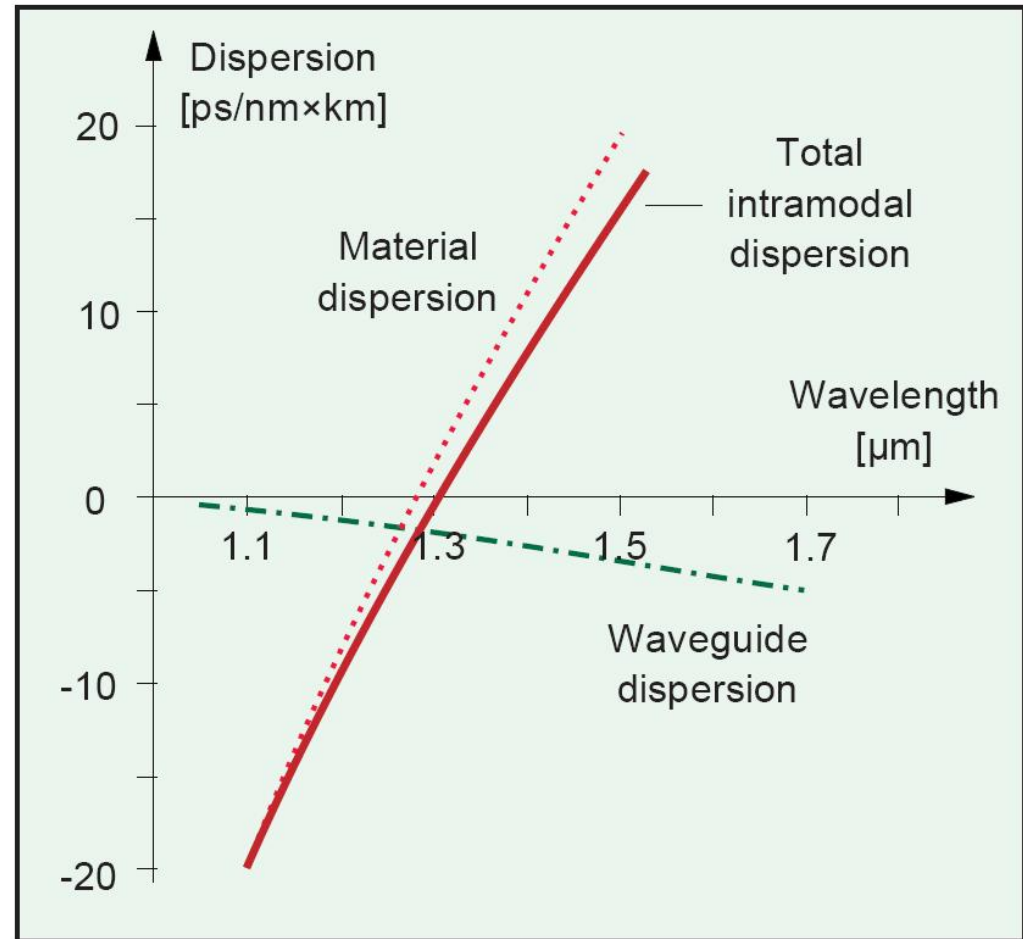
$$\Delta\tau_{\mathrm{mod}} \cong \frac{L \cdot n_2 \cdot \Delta^2}{4\sqrt{3} \cdot c}$$

Dispersia de material

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

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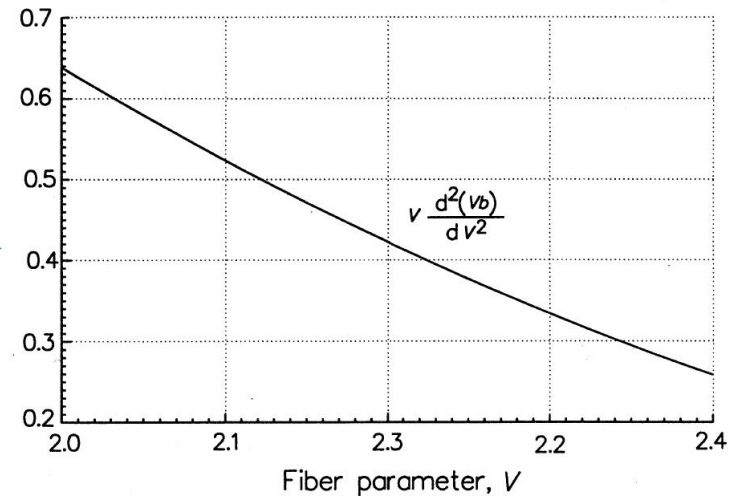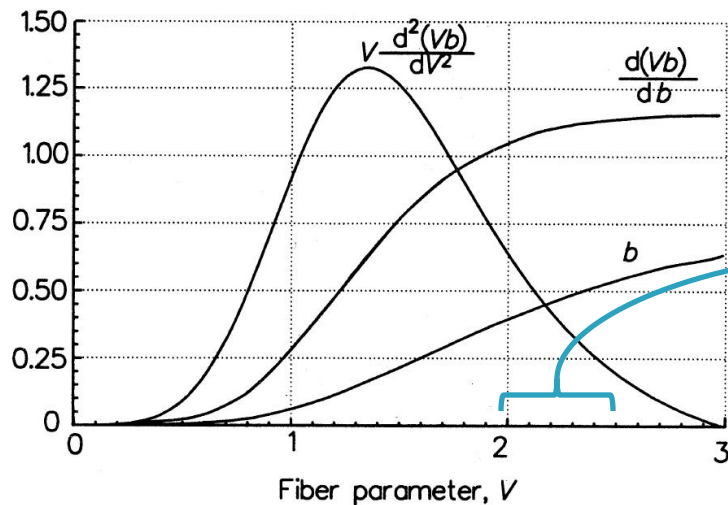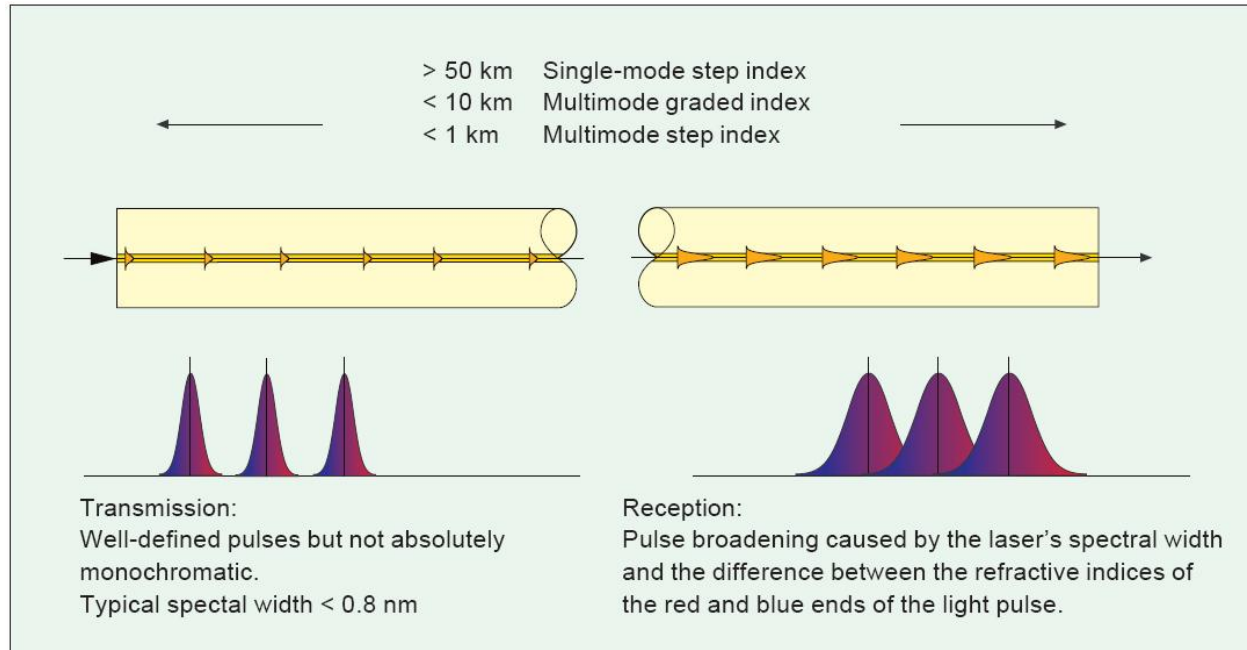
Dispersia de ghid

▸ Neglijabila in fibrele multimod fata de dispersia modala

$$\Delta\tau_{mat} = \frac{n \cdot L \cdot \Delta}{c} \cdot \frac{\Delta\lambda}{\lambda} \cdot \left(V \frac{d^2(Vb)}{dV^2} \right)$$

b – constanta de propagare normalizata

Dispersia cromatica

> 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 – $ps/nm^2/km$

- $D(\lambda) \approx 100 + 0.4\,(850 - \lambda)\ [ps/nm/km]$ pentru $800 < \lambda < 900$ nm
- $D(\lambda) \leq 3{,}5\ ps/nm/km$ pentru $1285 < \lambda < 1330$ nm $D(\lambda) = \frac{S_0}{4}\cdot\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right)$
- $D(\lambda) \leq 17\ ps/nm/km$ pentru $1525 < \lambda < 1575$ nm

Banda

- ## Dispersia totala

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

- ## Banda

$$B_{opt} = \frac{0.44}{\Delta\tau_{tot}[ns]} \quad [GHz] \qquad\qquad B_{opt} = \sqrt{2}B_{el}$$

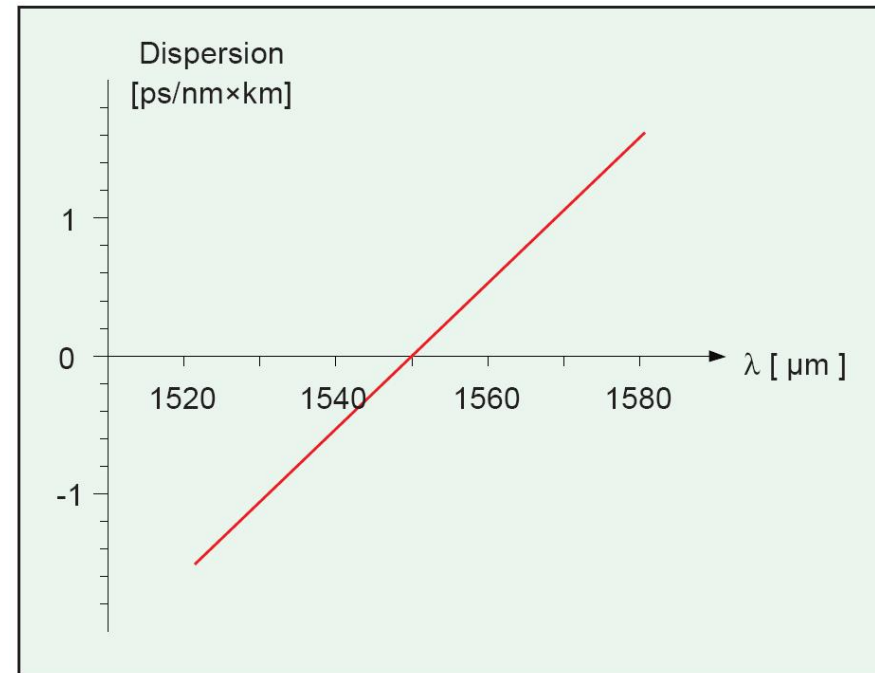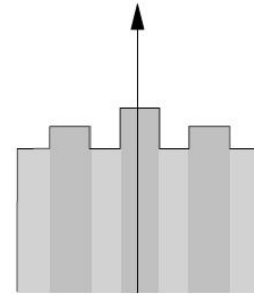- ## Banda optica la 3 dB corespunde unei benzi electrice la 6 dB
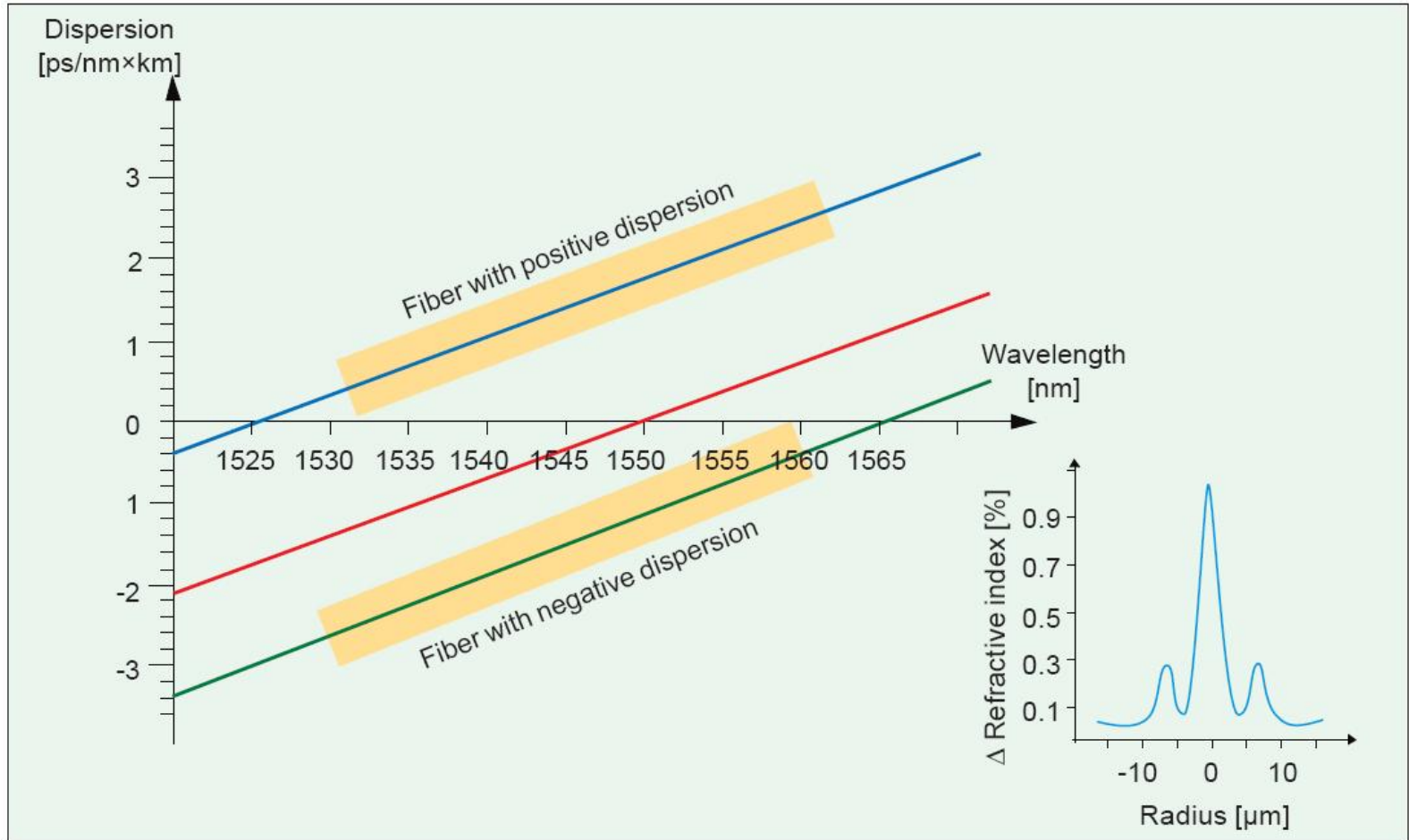
  ◦ $P_{opt} \sim I; \quad P_{el} \sim I^2$

- ## Viteza legaturii
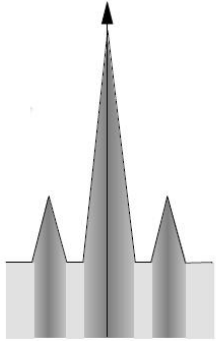
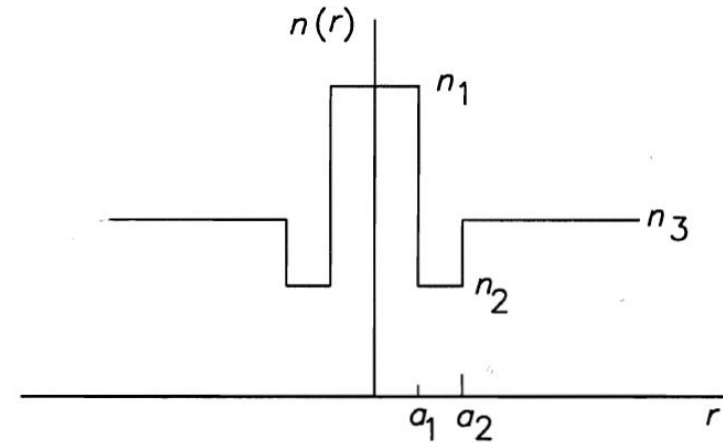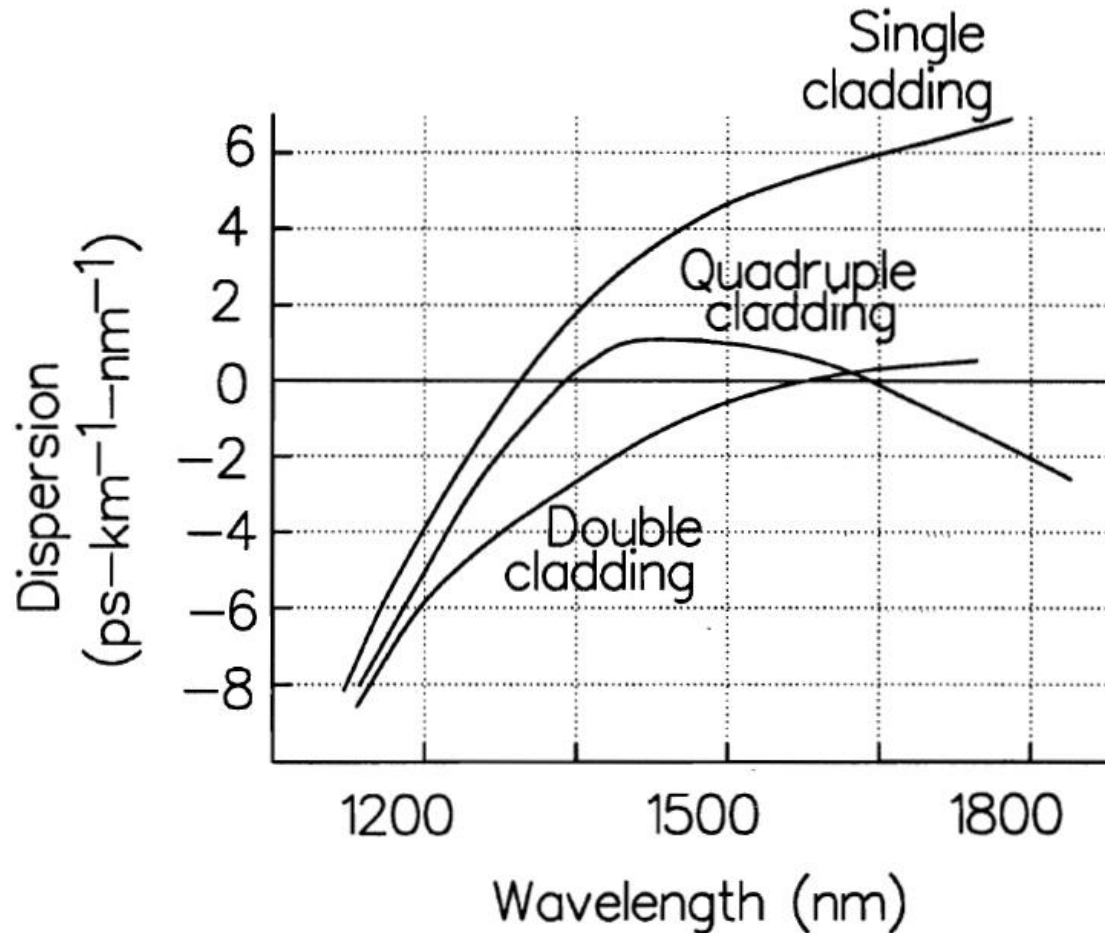$$V[Gb/s] \cong \frac{1}{2}B_{el}$$

Dispersion shifted fibers

- Atenuarea e mai mica la 1550 nm
- EDFA (Erbium doped fibre amplifiers) opereaza in banda aceasta
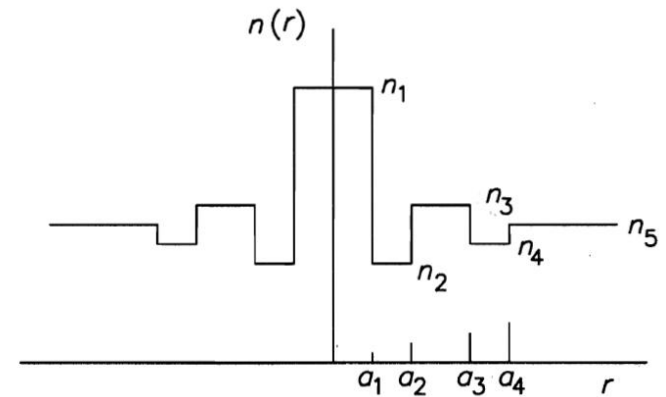- Sistemele WDM (Wavelength division Multiplexing) necestia banda larga amplificata

Dispersion [ps/nm×km]

λ [μm]

Non-zero Dispersion shifted fibers

Dispersion shifted fibers
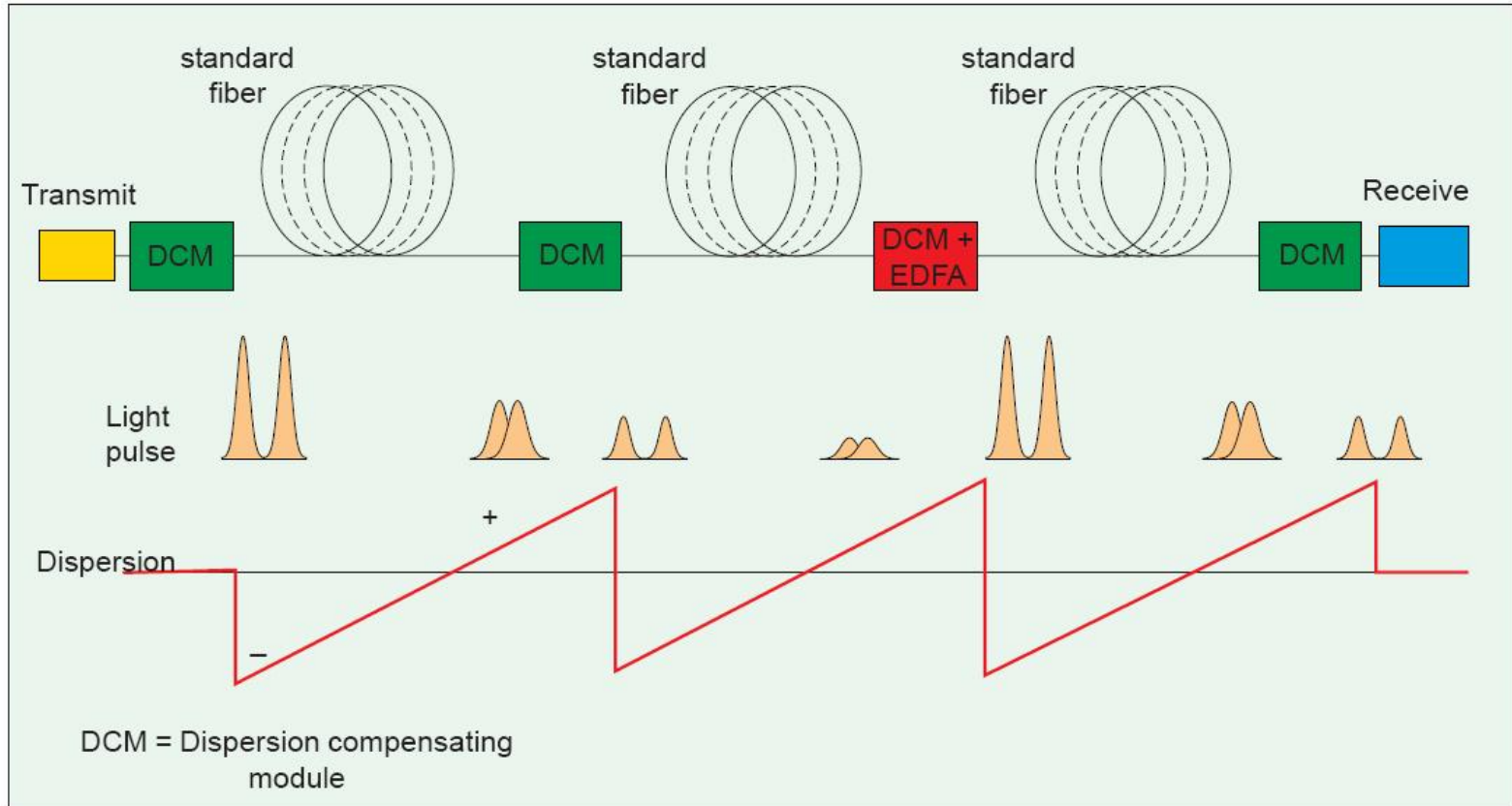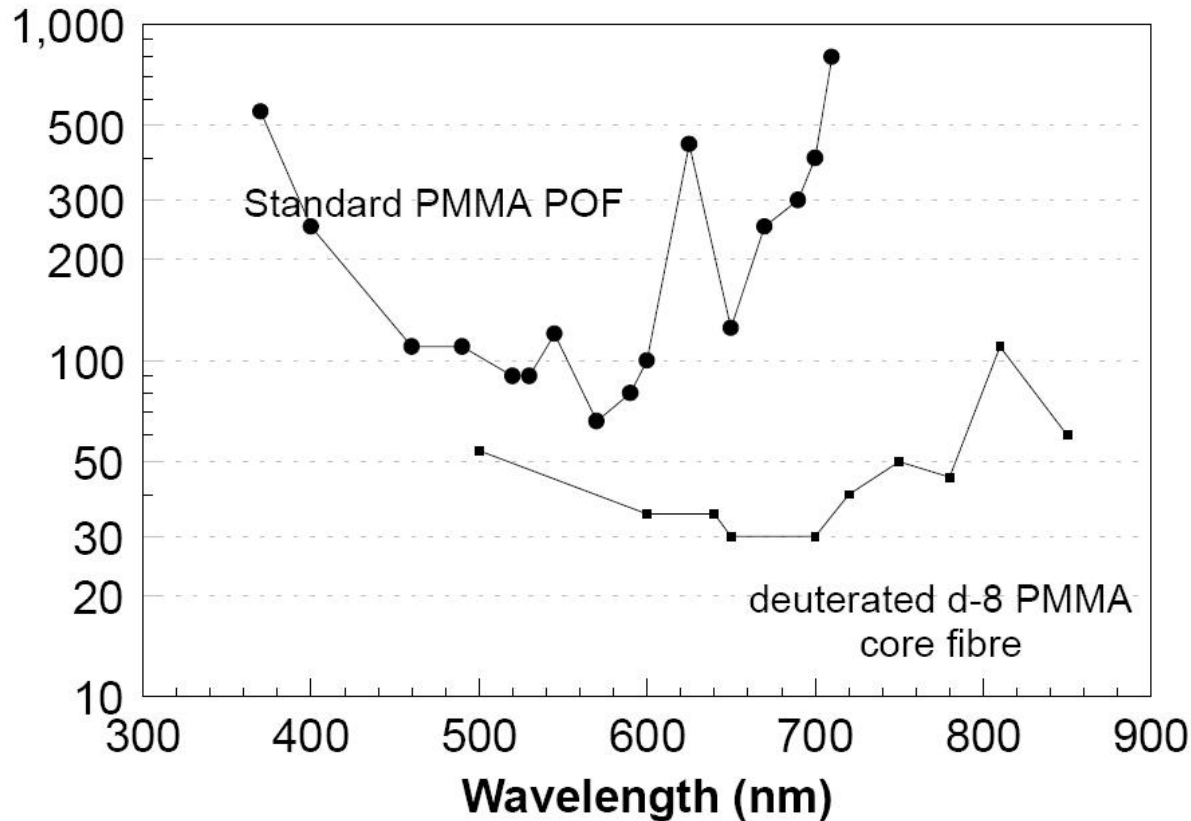
Fibra pentru compensarea dispersiei

- Dispersie −100 ps/nm/km
- Atenuare 0.5 dB/km

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/nm²/km
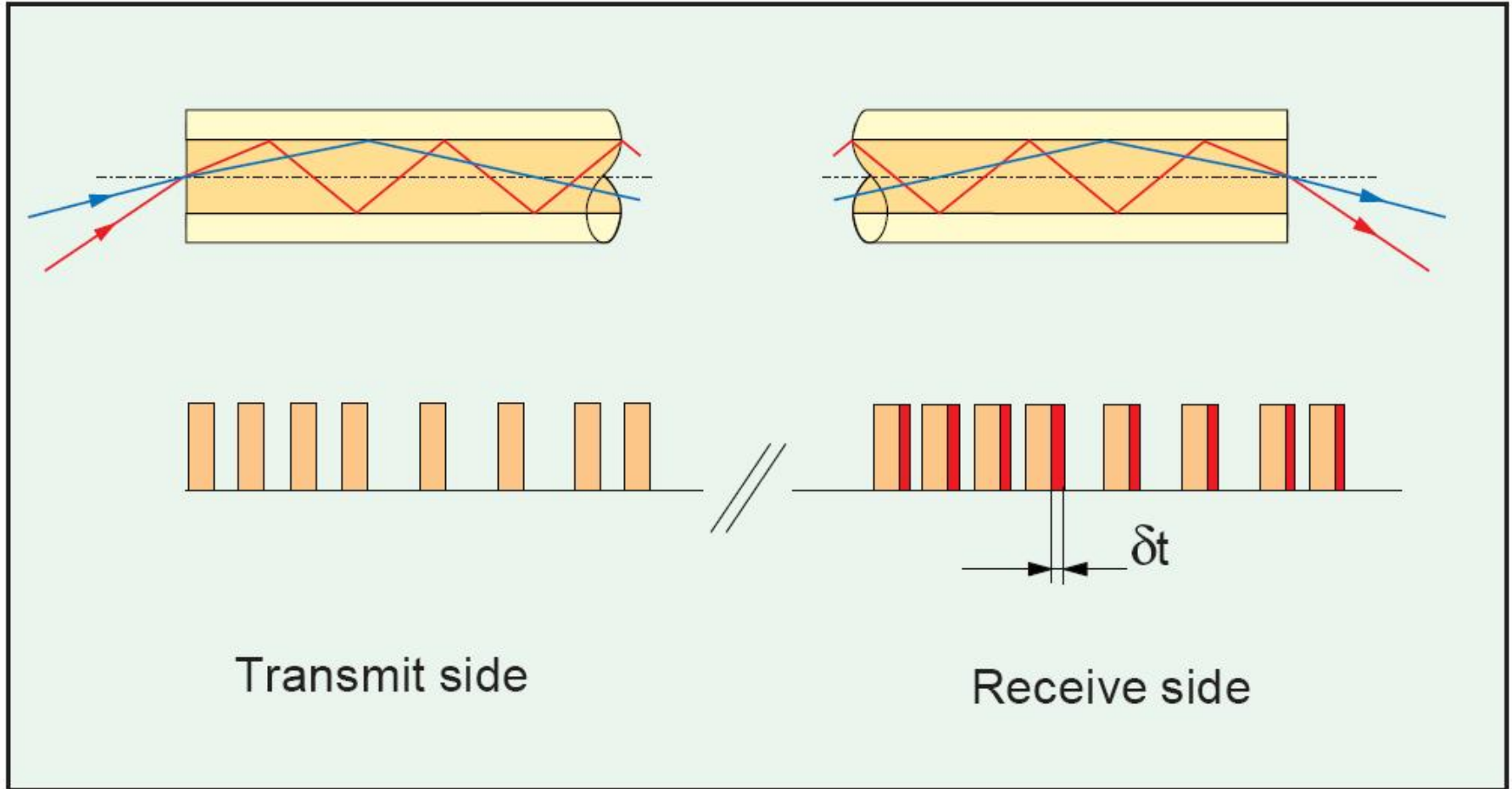
Fibra optica din plastic (POF)

Attenuation dB/Km

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

Dispersia

- 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

- ## 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 $\Delta = \dfrac{n_2 - n_1}{n_1} << 1$

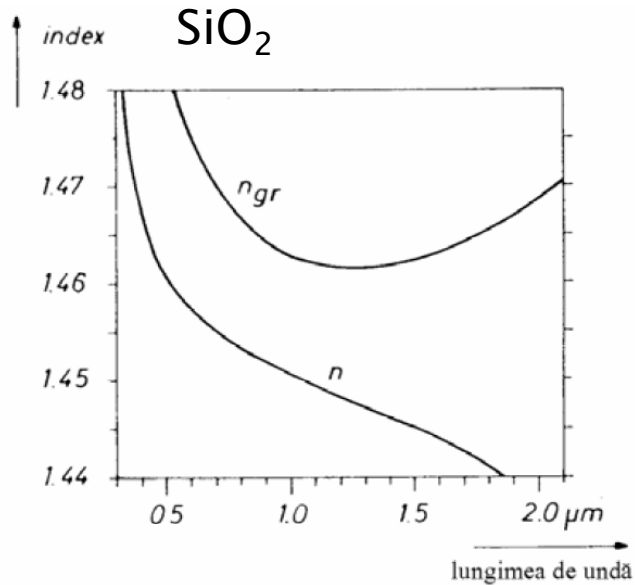$$\Delta\tau_{mod}^2 = \frac{1}{3}\left(\frac{dt}{2}\right)^2$$

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

- ## indice gradat

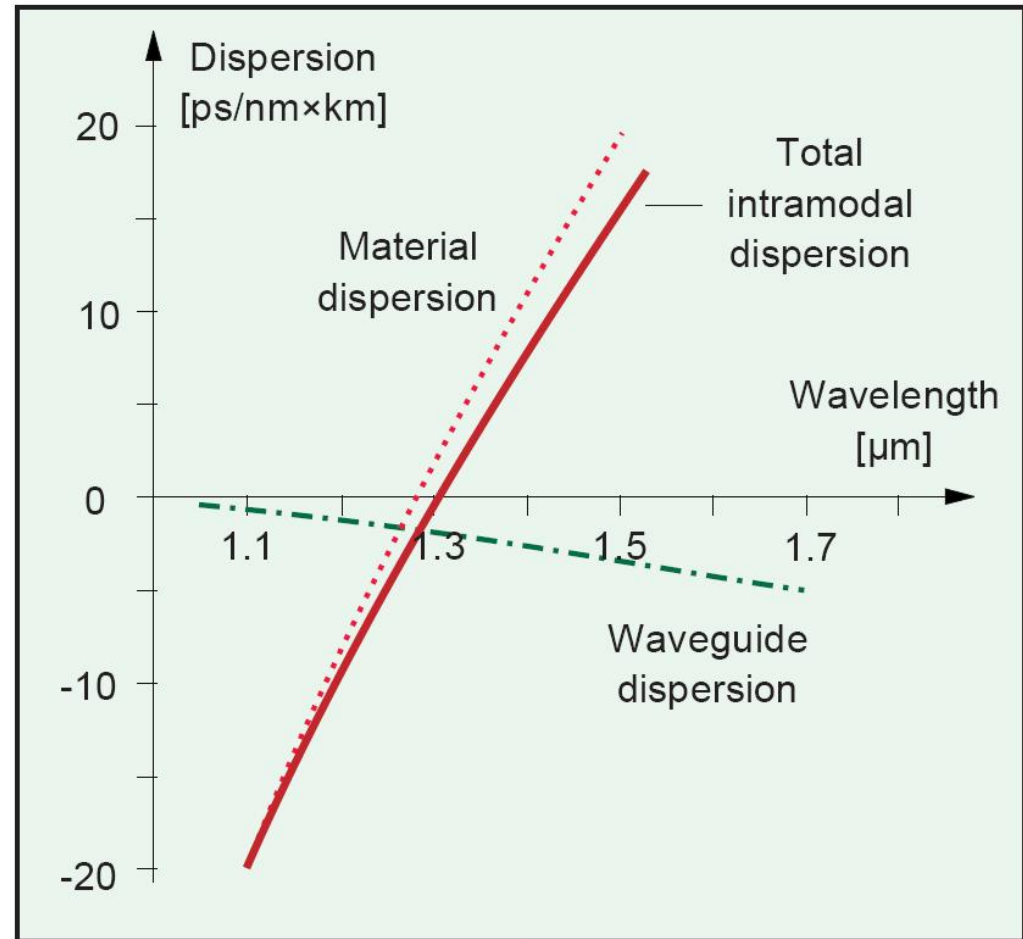$$dt = \frac{L \cdot n_2 \cdot \Delta^2}{2c} \approx \frac{L \cdot NA^4}{8 \cdot c \cdot n_2^3}$$

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

Dispersia de material

SiO$_2$

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

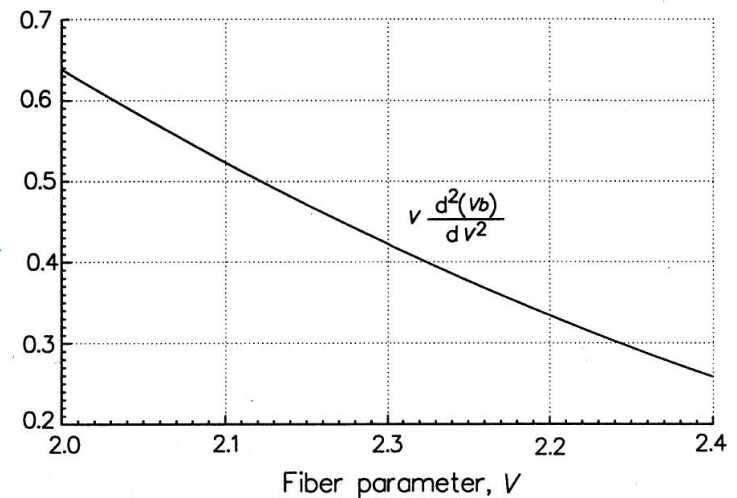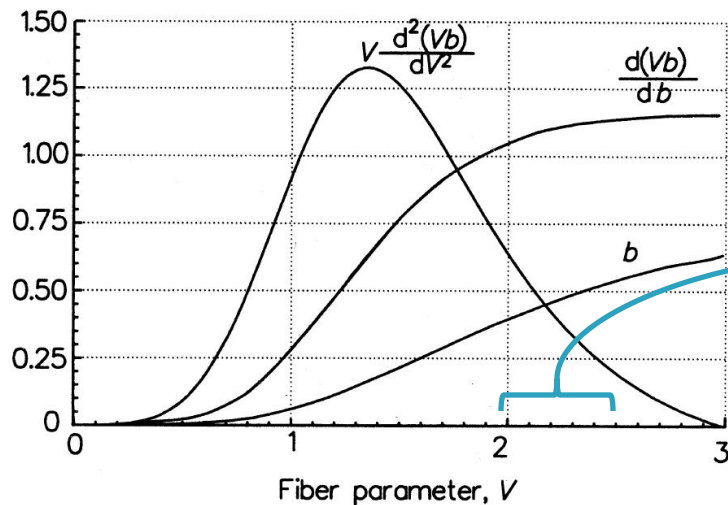$$\Delta\tau_{mat} = \frac{L \cdot \lambda \cdot \Delta\lambda}{c} \cdot \frac{d^2 n}{d\lambda^2}$$
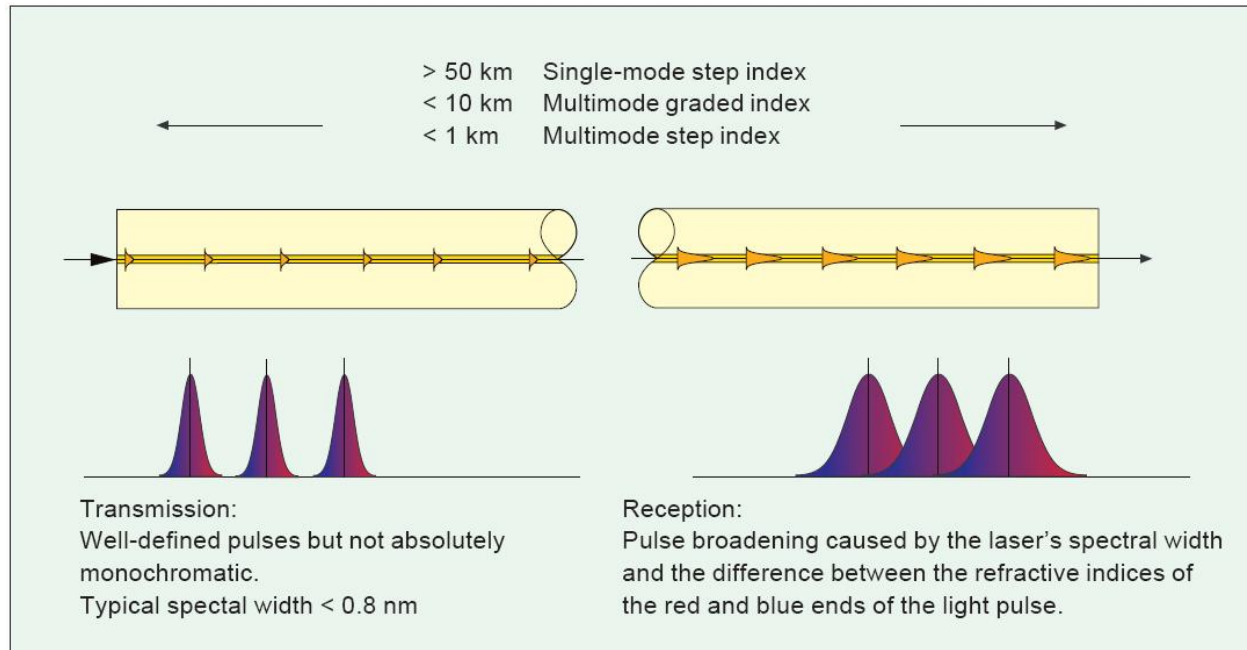
Dispersia de ghid

- Neglijabila in fibrele multimod fata de dispersia modala

$$\Delta\tau_{mat} = \frac{n \cdot L \cdot \Delta}{c} \cdot \frac{\Delta\lambda}{\lambda} \cdot \left(V \frac{d^2(Vb)}{dV^2} \right)$$

b – constanta de propagare normalizata

Dispersia cromatica

> 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(λ) ≈ 100 + 0.4 (850 − λ) [ps/nm/km] pentru 800 < λ < 900 nm
- D(λ) ≤ 3,5 ps/nm/km pentru 1285 < λ < 1330 nm
- D(λ) ≤ 17 ps/nm/km pentru 1525 < λ < 1575 nm

Banda

- Dispersia totala

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

- Banda

$$B_{opt} = \frac{0.44}{\Delta\tau_{tot}[ns]} \quad [GHz] \qquad B_{opt} = \sqrt{2}B_{el}$$

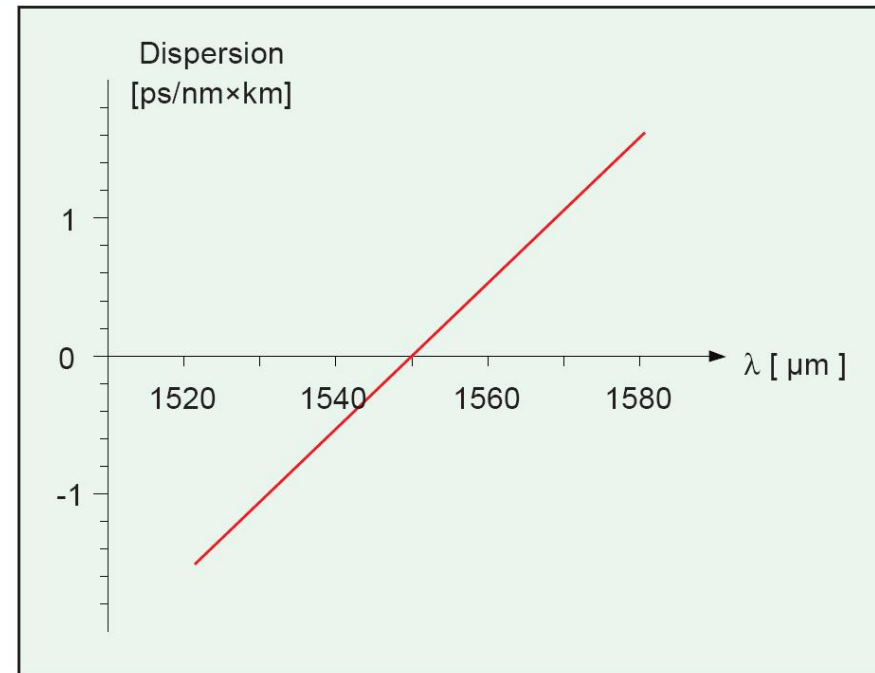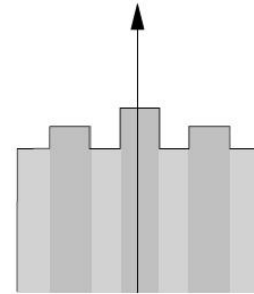- Banda optica la 3 dB corespunde unei benzi electrice la 6 dB

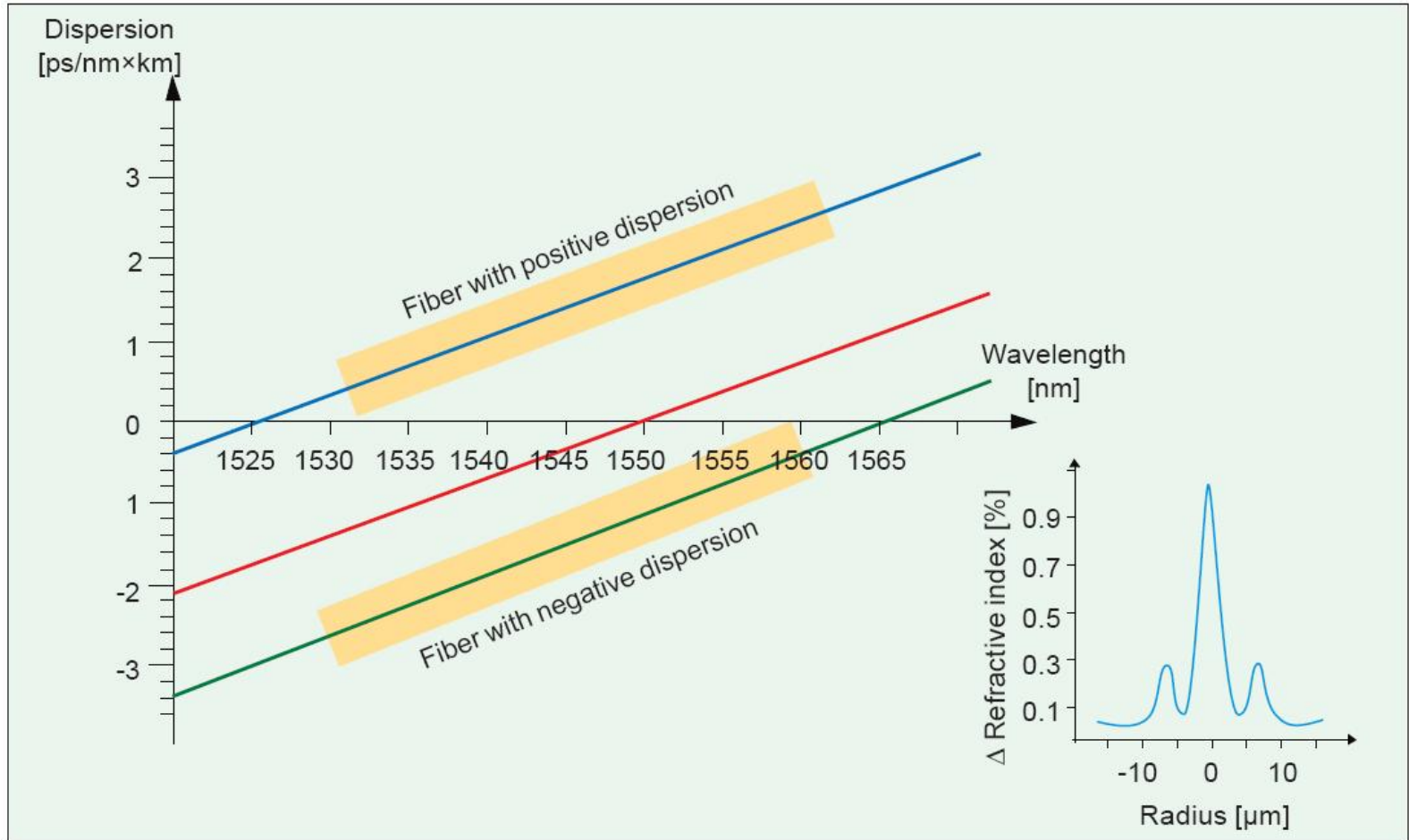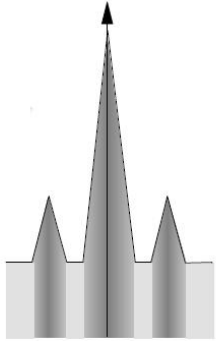 ◦ $P_{opt} \sim I; \quad P_{el} \sim I^2$

- Viteza legaturii

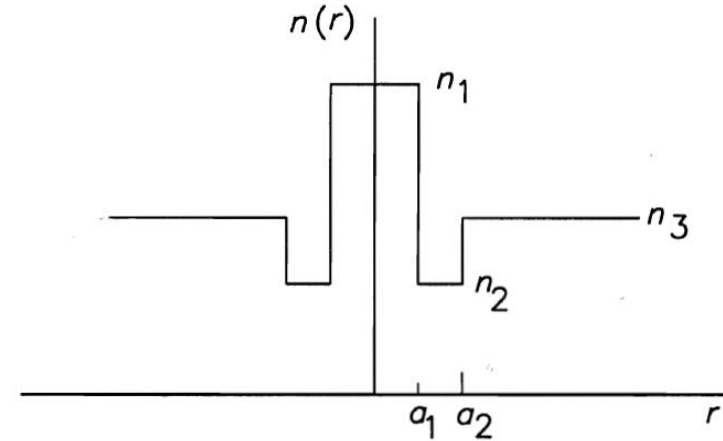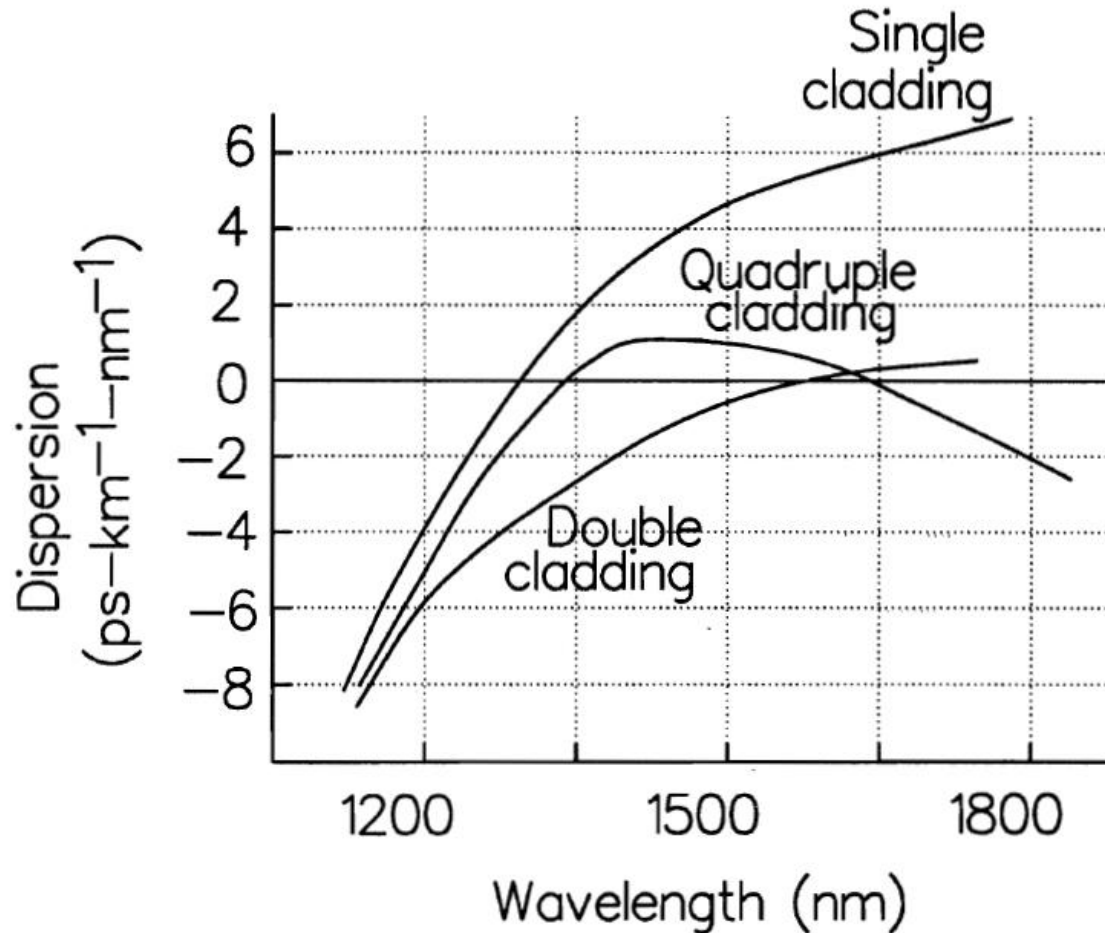$$V[Gb/s] \cong \frac{1}{2}B_{el}$$

Dispersion shifted fibers

▸ Atenuarea e mai mica la 1550 nm

▸ EDFA (Erbium doped fibre amplifiers) opereaza in banda aceasta

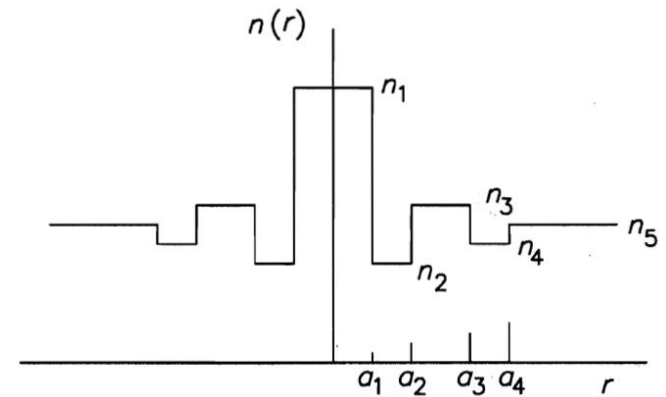▸ Sistemele WDM (Wavelength division Multiplexing) necestia banda larga amplificata

Non-zero Dispersion shifted fibers
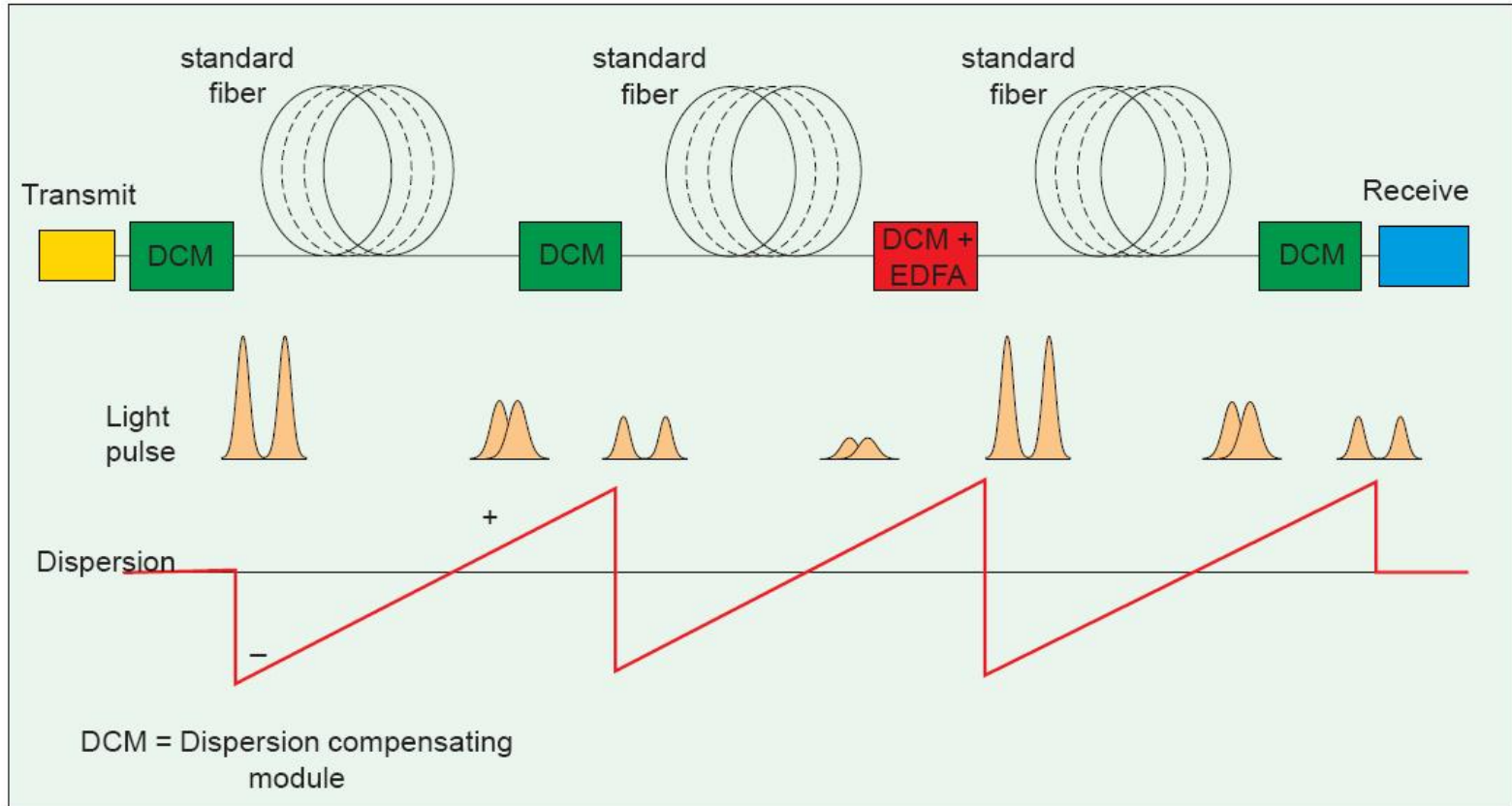
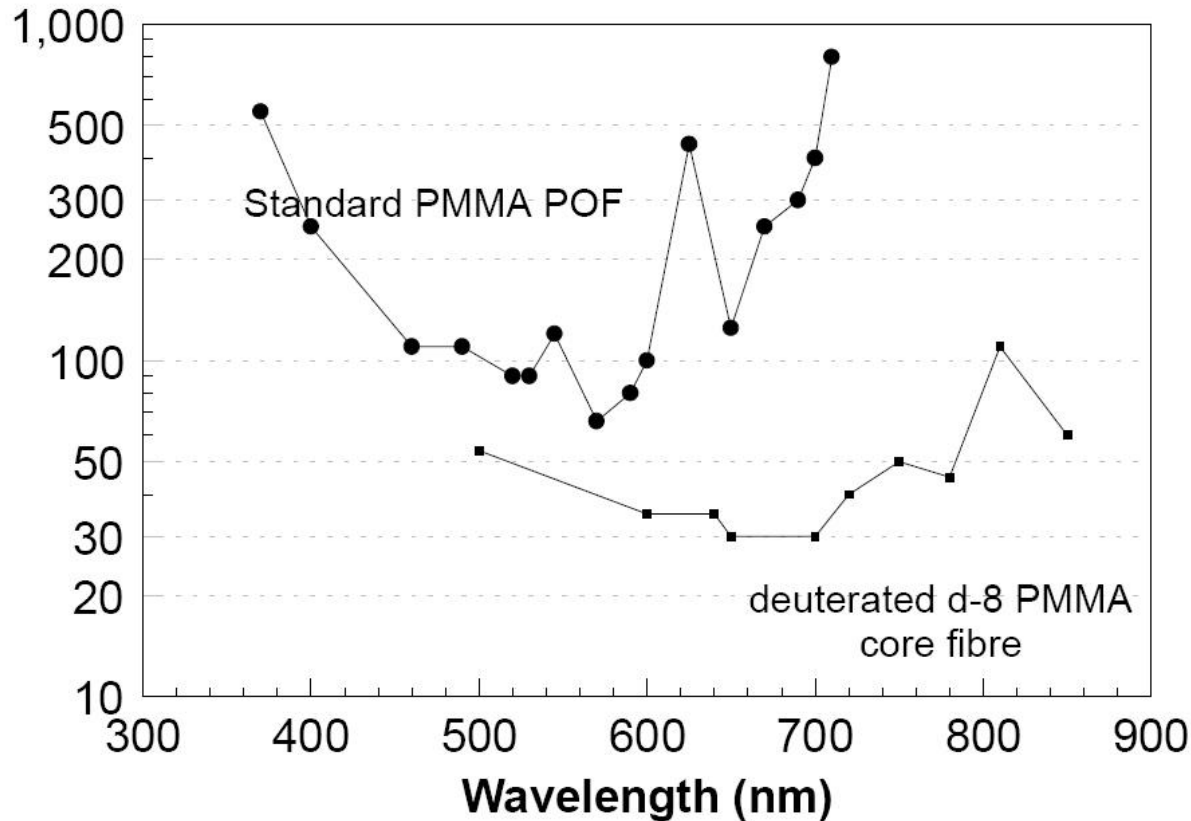# Dispersion shifted fibers

Fibra pentru compensarea dispersiei

- Dispersie −100 ps/nm/km
- Atenuare 0.5 dB/km

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) mai mica de 0.095 ps/nm²/km

Fibra optica din plastic (POF)

Attenuation dB/Km

Standard PMMA POF

deuterated d-8 PMMA core fibre

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

Contact

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