

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**
 - $14 * 2/3 \approx 9.33$
 - $9 \div 10 C \approx 9C + E$

Online

- ▶ acces la **examene** necesita **parola** primita prin **email**

The screenshot shows a student profile for POPESCU GOPO ION. The page has a dark blue header with navigation links: Start, Didactic, Master, Colectiv, Cercetare, and Studii. Below the header is a sub-header with links: Note, Lista Studenti, Examene, and Fotografii. The main content area displays the student's name, a placeholder for a photo (labeled 'Fotografia nu exista'), and a table of personal data. A red circle highlights the text 'Acceseaza ca acest student' and a link 'Cere acces la licente'.

English | Romana |

Start Didactic Master Colectiv Cercetare Studii

Note Lista Studenti Examene Fotografii

POPESCU GOPO ION

Fotografia nu exista

Date:

Grupa	5700 (2019/2020)
Specializarea	Inginerie electronica si telecomunicatii
Marca	7000021

Acceseaza ca acest student | [Cere acces la licente](#)

Note obtinute

Inca nu a fost notat.

The screenshot shows a login page titled 'Identificare'. It has a dark blue header with navigation links: Start, Didactic, Master, Colectiv, and Cercetare. Below the header is a sub-header with links: Note, Lista Studenti, Examene, and Fotografii. The main content area contains a form for login. A red arrow points from the 'E-mail/Parola' field to the 'parola' word in the text above. A red circle highlights the 'E-mail/Parola' field.

Start Didactic Master Colectiv Cercetare

Note Lista Studenti Examene Fotografii

Identificare

Introduceti numele si adresa de email utilizata la inscriere

Nume
POPESCU GOPO

E-mail/Parola

Introduceti codul afisat mai jos

4db4457

Trimite

Online

► acces email/parola

Start Didactic Master Colectiv

Note Lista Studenti Examene Fotografii

POPESCU GOPO ION

Fotografia nu exista

Date:

Grupa	5700 (2019/2020)
Specializarea	Inginerie electronica
Marca	7000021

Se acceseaza site-ul [ca acest student!](#)

Start Didactic Master Colectiv

Note Lista Studenti Examene Fotografii

POPESCU GOPO ION

Fotografia nu exista

Date:

Grupa	5700 (2019/2020)
Specializarea	Inginerie electronica s
Marca	7000021

Se acceseaza site-ul [ca acest student \(inclusiv examene\)!](#)

Parola

▶ primita prin email

Important message from RF-OPTO

Inbox x



Radu-Florin Damian

to me, POPESCU

Romanian > English Translate message



Laboratorul de Microunde si Optoelectronica
Facultatea de Electronica, Telecomunicatii si Tehnologia Informatiei
Universitatea Tehnica "Gh. Asachi" Iasi

In atentie: POPESCU GOPO ION

Parola pentru a accesa examenele pe server-ul **rf-opto** este

Parola: [REDACTED]

Identificati-va pe [server](#), cu parola, cat mai rapid, pentru confirmare.

Memorati acest mesaj intr-un loc sigur, pentru utilizare ulterioara

Attention: POPESCU GOPO ION

The password to access the exams on the **rf-opto** server is

Password: [REDACTED]

Login to the [server](#), with this password, as soon as possible, for confirmation.

Save this message in a safe place for later use

Reply

Reply all

Forward

Subject

Correspondents

Important message from RF-OPTO → POPESCU GOPO ION

Validation of MIDCR exam from 02/05/2020

From: Me <rdamian@etti.tuiasi.ro>

Subject: Important message from RF-OPTO

To: [REDACTED]

Cc: Me <rdamian@etti.tuiasi.ro>

Laboratorul de Microunde si Optoelectronica
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Password: [REDACTED]

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Save this message in a safe place for later use

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)

Start Didactic Master Colectiv Cercetare **Studenti**

Note Lista Studenti **Examene** Fotografii

Anunț
17:28 (29/04/2020)

Material suport
17:30 (29/04/2020)

Subiecte
17:32 (29/04/2020)

Rezultate
17:35 (29/04/2020)

Finalizare
17:45 (29/04/2020)

Confirmare
17:45 (30/04/2020)

Urmatorul interval de timp in:
01 m 08 s
[Reincarca acum](#)

Anunț

In acest examen se verifica diverse actiuni ale studentilor pentru examen

Ora pe server

Toate examenele sunt bazate pe fusul orar al server-ului (ar putea sa fie diferit de timpul local). Pentru referinta ora pe server este acum:

29/04/2020 17:28:51

Introducere

Capitolul 1

Aplicatii majore

▶ Comunicatii

- Infrarosu (InGaAsP)

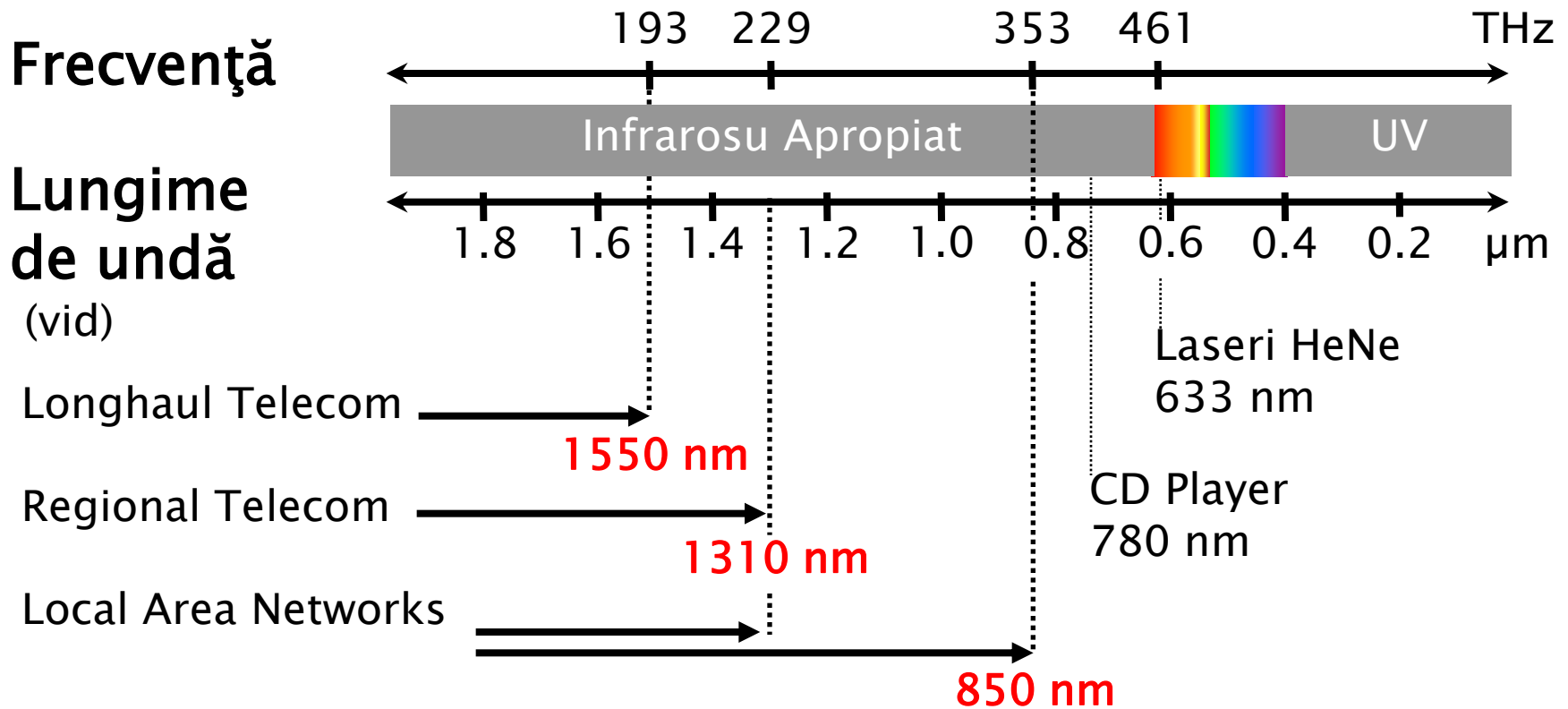
▶ Vizibil

- Spectru vizibil (GaAlAs)

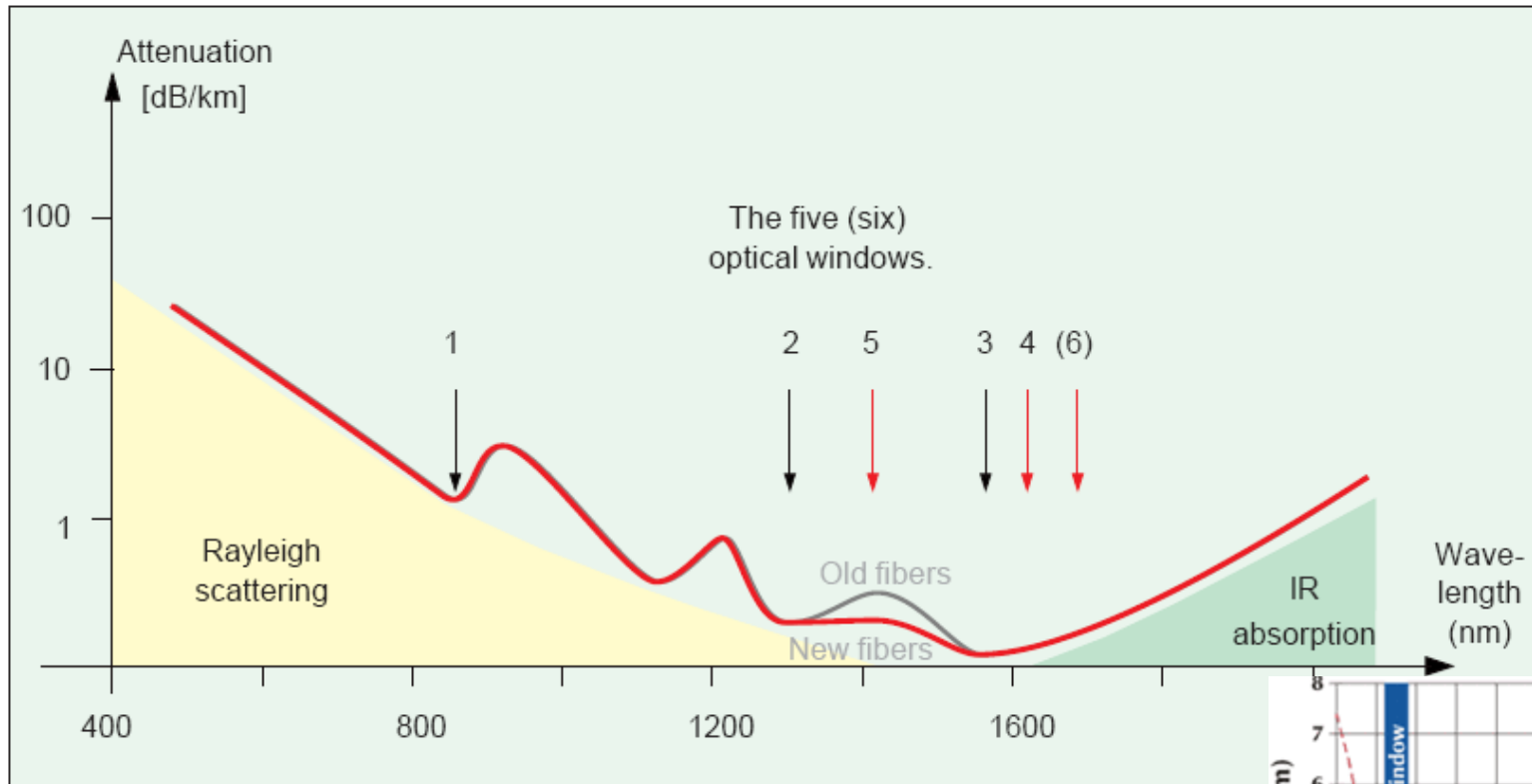
▶ Iluminare

- Putere ridicata, lumina alba (GaInN)

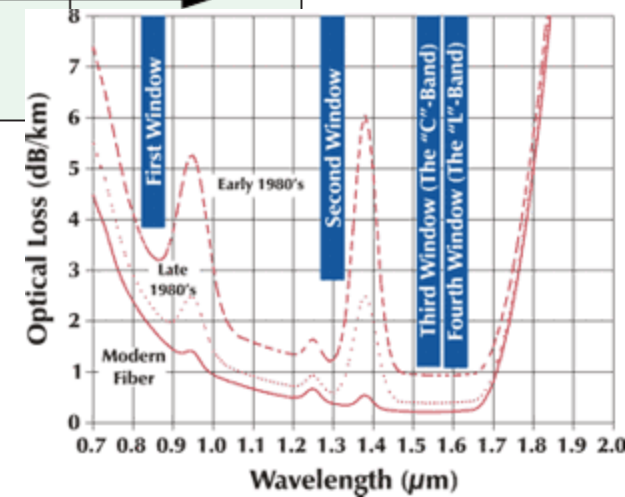
Benzi de lucru in comunicațiile optice



Atenuarea în fibra optică (SiO₂)



850nm, 1310nm, 1550nm



Fibra optică

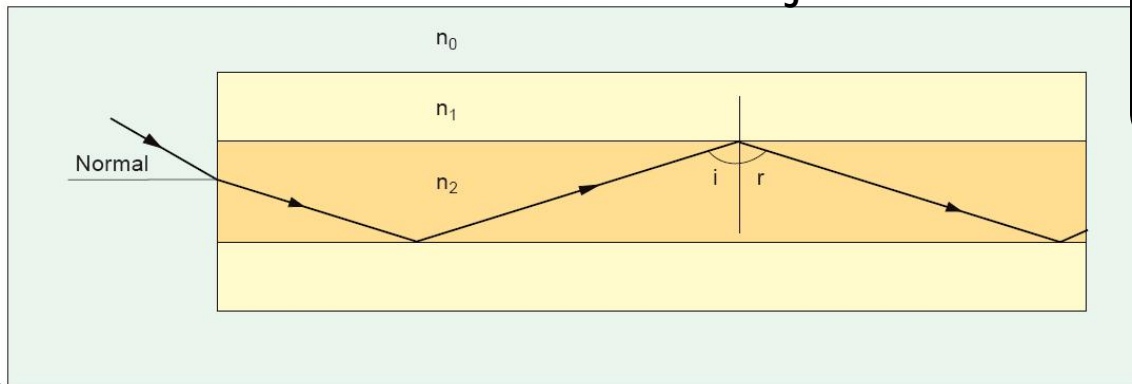
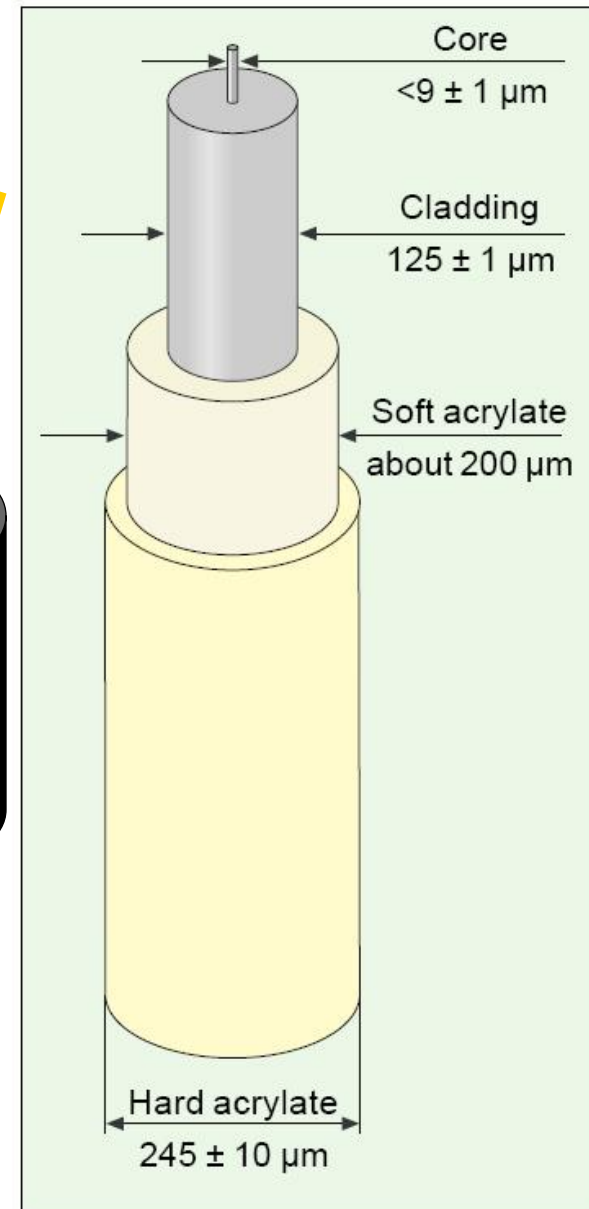
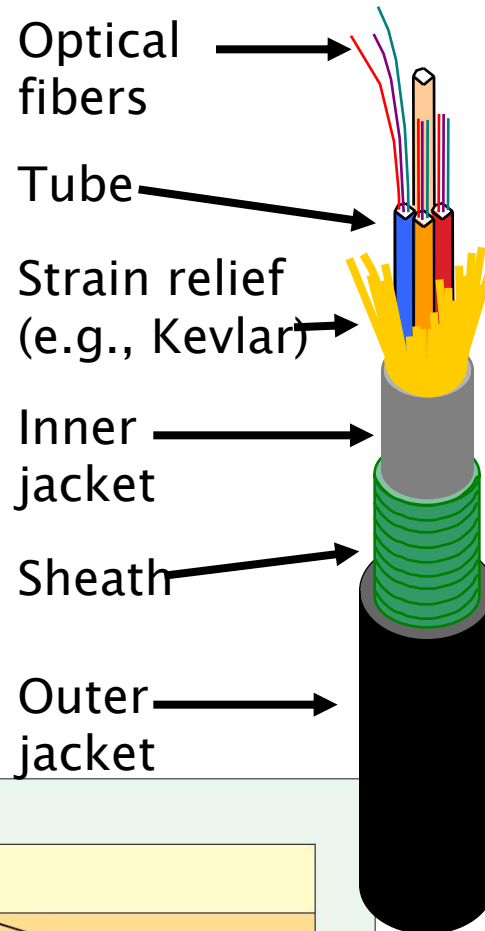
Capitolul 4

Cuprins

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

Fibra optica

- ▶ un ghid de unda dielectric
 - miez
 - teaca



Unghi de acceptanta, apertura numerica

- ▶ Unghi de acceptanta

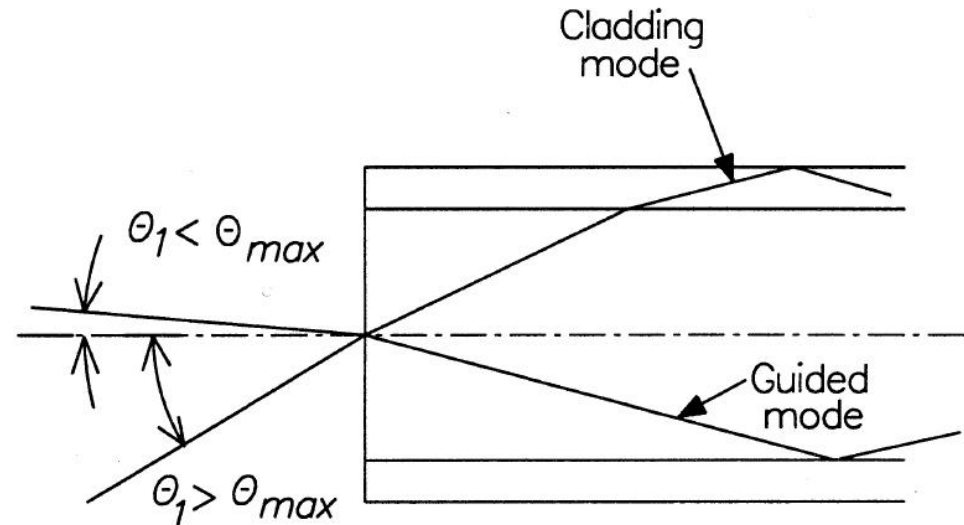
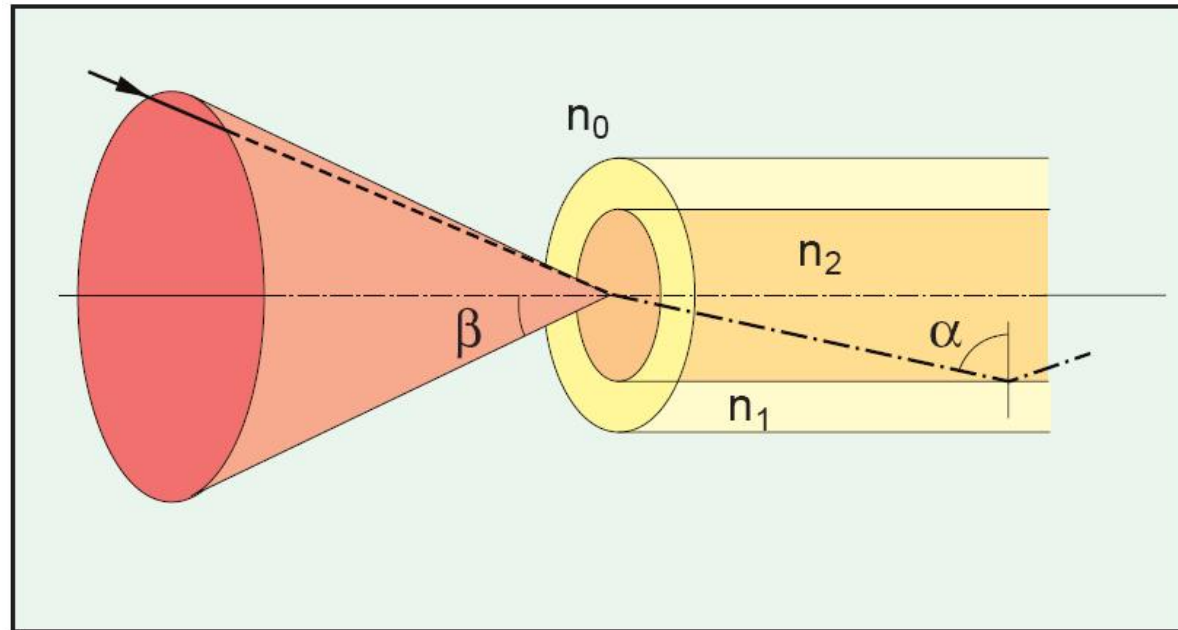
$$n_0 \cdot \sin \theta_{ACC} = n_2 \cdot \sin \phi_c$$

- ▶ **Apertura numerica**

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

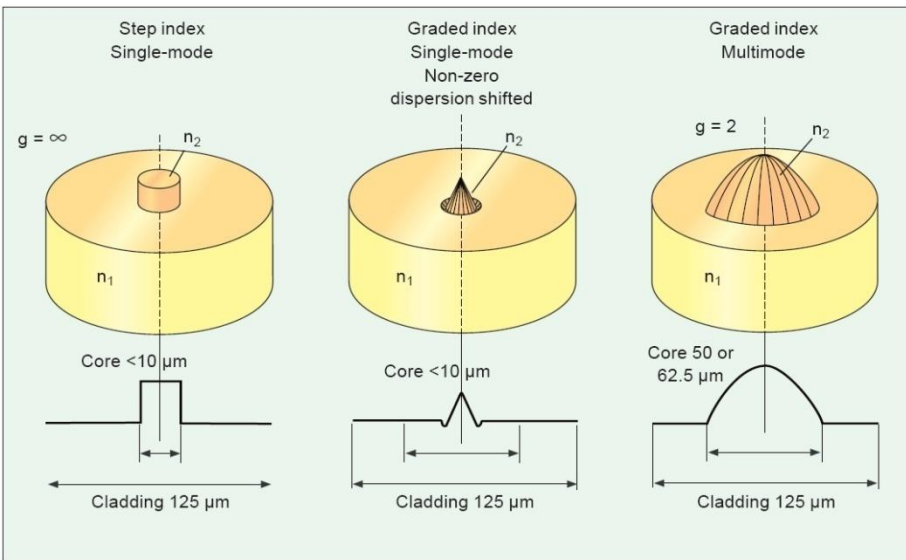
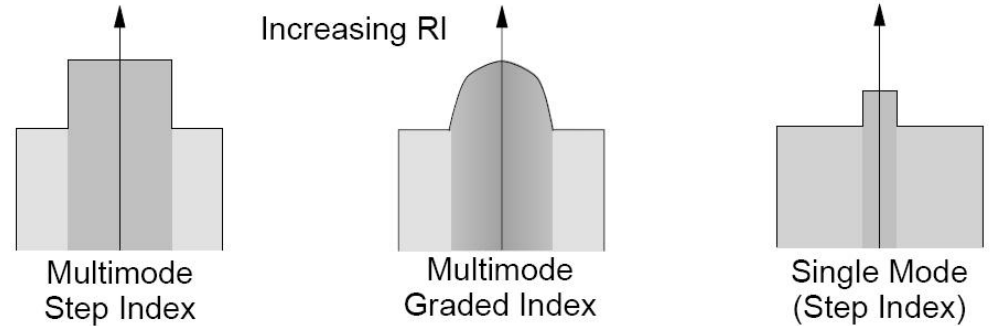
$$NA = n_2 \sqrt{\frac{n_2^2 - n_1^2}{n_2^2}} = \sqrt{n_2^2 - n_1^2}$$

n_2 - miez
 n_1 - teaca
 $n_2 > n_1$!!

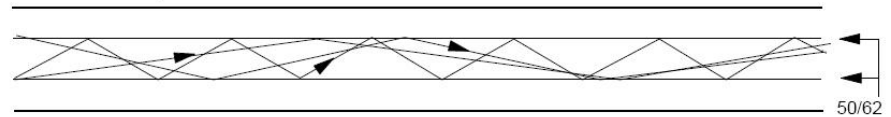


Tipuri de fibra

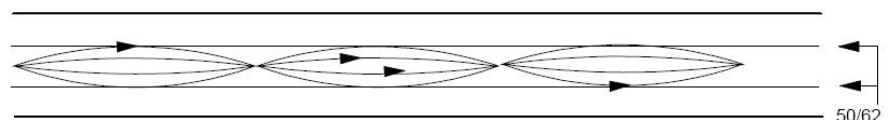
- ▶ Monomod
- ▶ Multimod
 - cu salt de indice
 - cu indice gradat



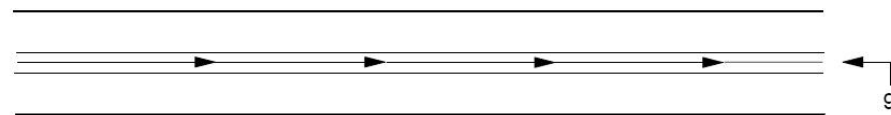
Multimode Step Index



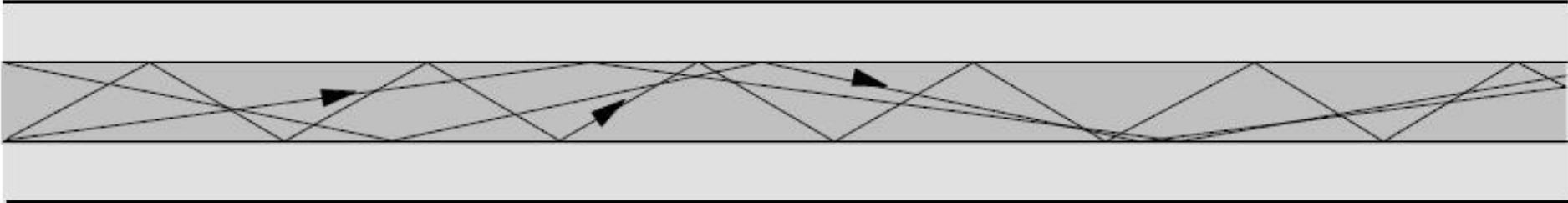
Multimode Graded Index



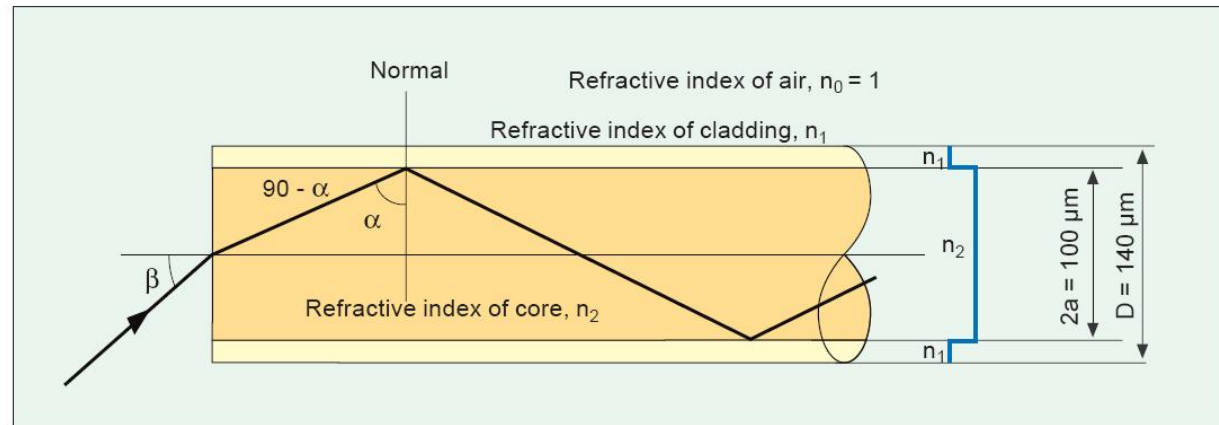
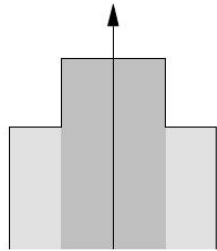
Single Mode



Fibre multimod cu salt de indice

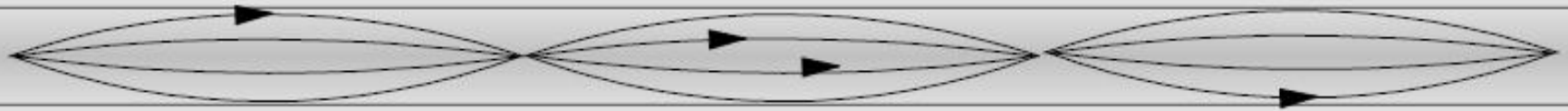


- ▶ 50/125 sau 62.5/125 (μm)
- ▶ 15–50 MHz · km

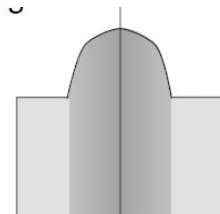
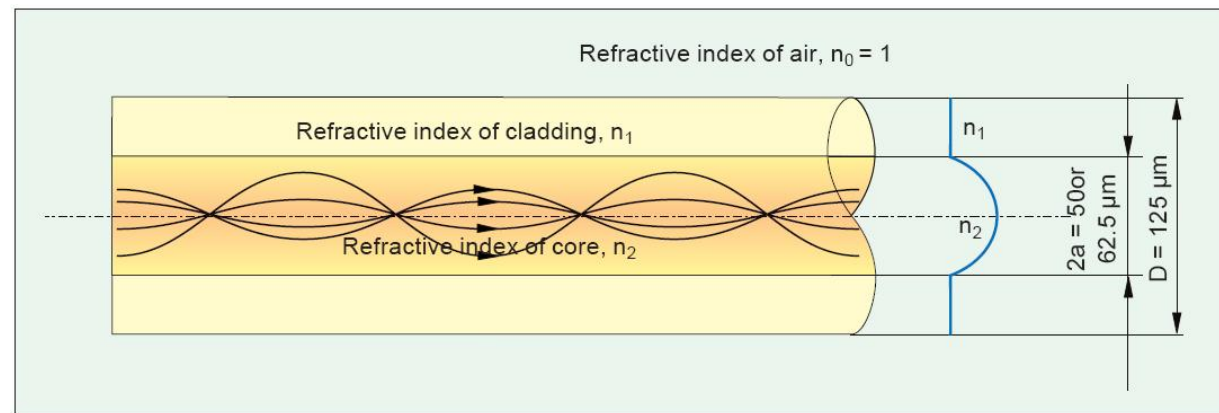


	glass	plastic
core diameter $2a$	100 μm	980 μm
cladding diameter D	140 μm	1000 μm
core refractive index n_2	1.48	
cladding refractive index n_1	1.45	

Fibre multimod cu indice gradat

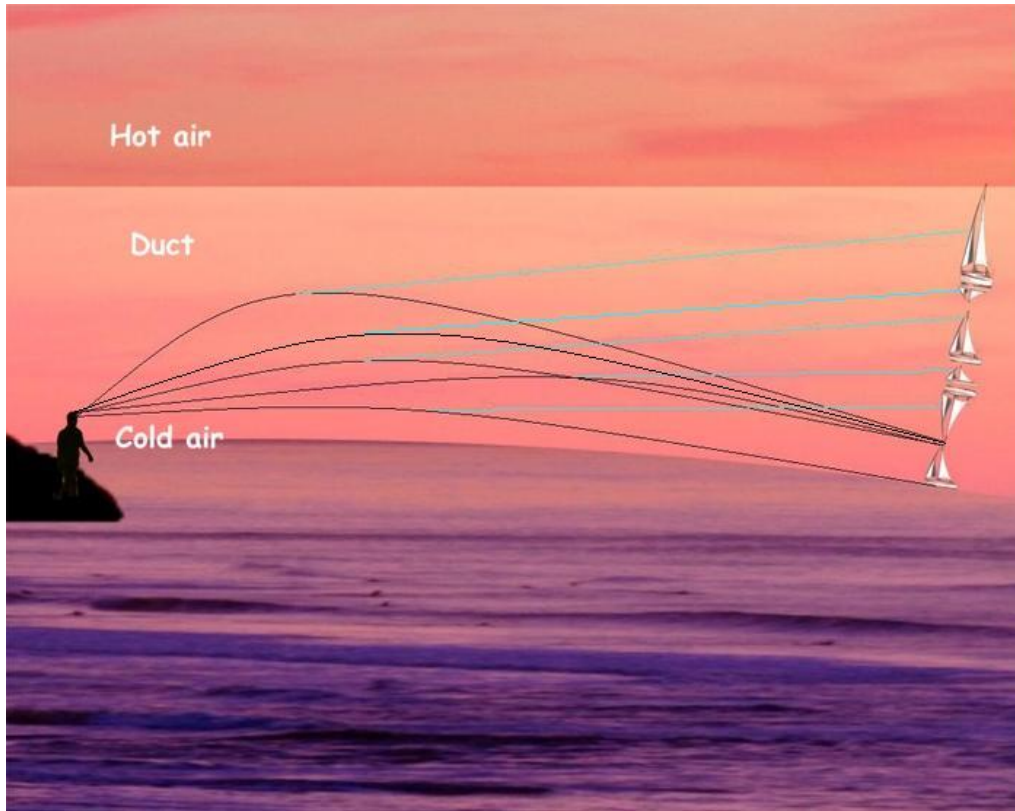


- ▶ 50/125 sau 62.5/125 (μm)
- ▶ 700–1200 MHz · km

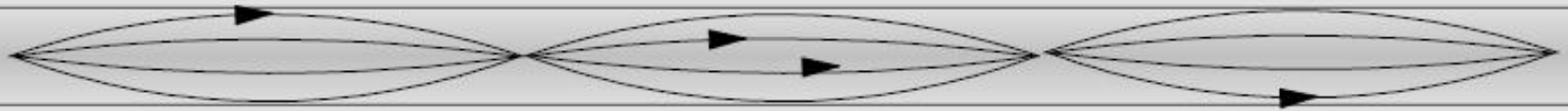


Core diameter $2a$	50 or 62.5 μm
Cladding diameter D	125 μm
Maximum refractive index, core	1.46
Relative differential refractive index	0.010

Fata Morgana



Fibre multimod cu indice gradat

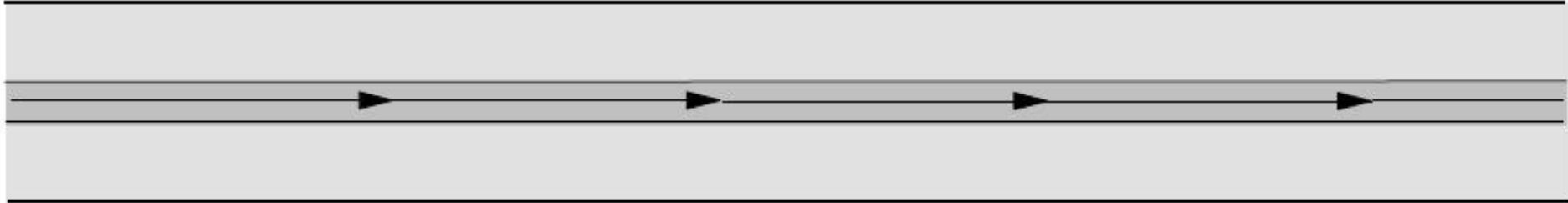


$$n(r) = n_2 \left[1 - \Delta \left(\frac{r}{a} \right)^g \right]$$

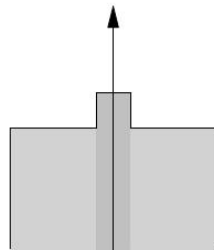
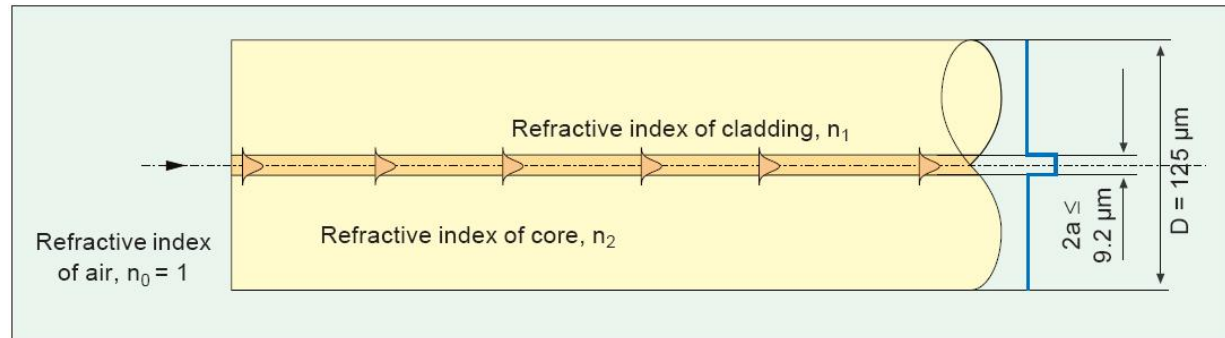
$$\Delta = \frac{NA^2}{2n_2^2} = \frac{n_2^2 - n_1^2}{2n_2^2} \approx \frac{n_2 - n_1}{n_2} \approx \frac{\Delta n}{n} \quad \text{for } \Delta \ll 1$$

- ▶ $g = 1$ - 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



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)

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

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

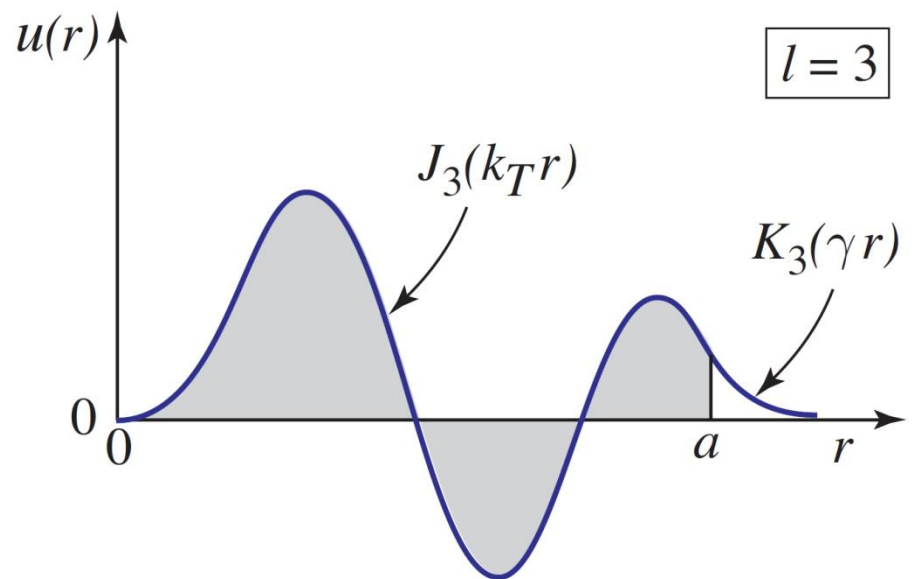
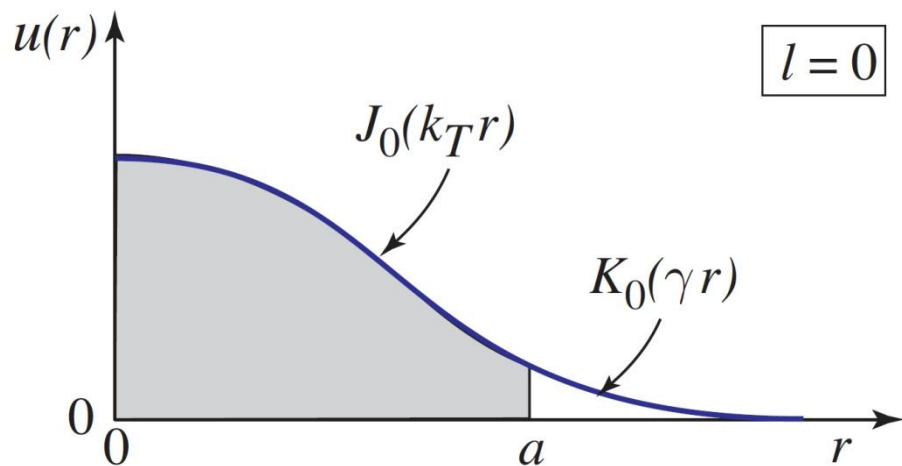
$$\frac{d^2 u}{dr^2} + \frac{1}{r} \frac{du}{dr} + \left(k_T^2 - \frac{l^2}{r^2} \right) u = 0, \quad r < a$$

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

Ghid cilindric dielectric

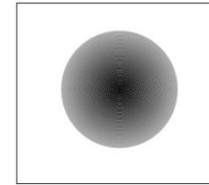
- ▶ solutii proportionale cu functii Bessel

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

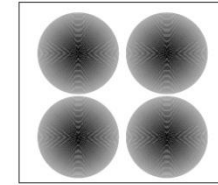


Moduri in fibra

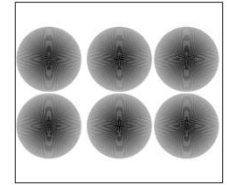
- ▶ Moduri in ghid rectangular



TEM₀₀

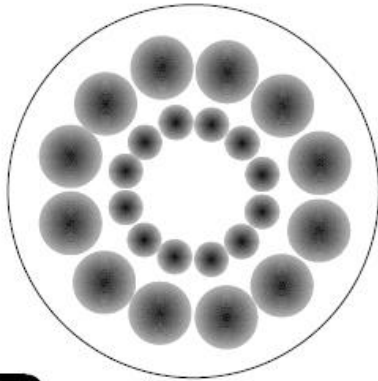


TEM₁₁

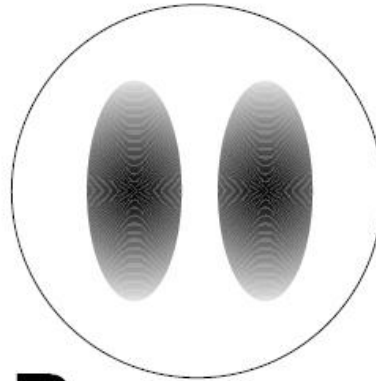


TEM₂₁

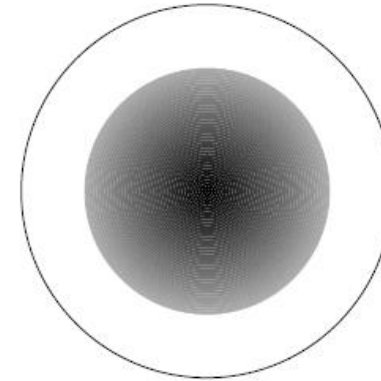
- ▶ Moduri linear polarizate in fibra



LP₆₂

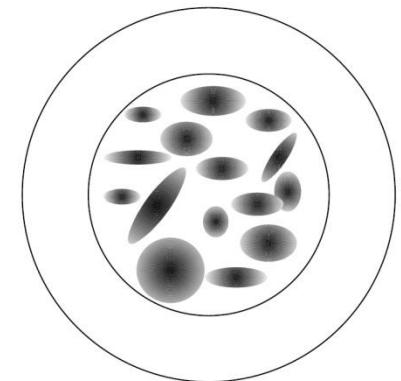


LP₁₁



LP₀₁

“Sparkle” pattern



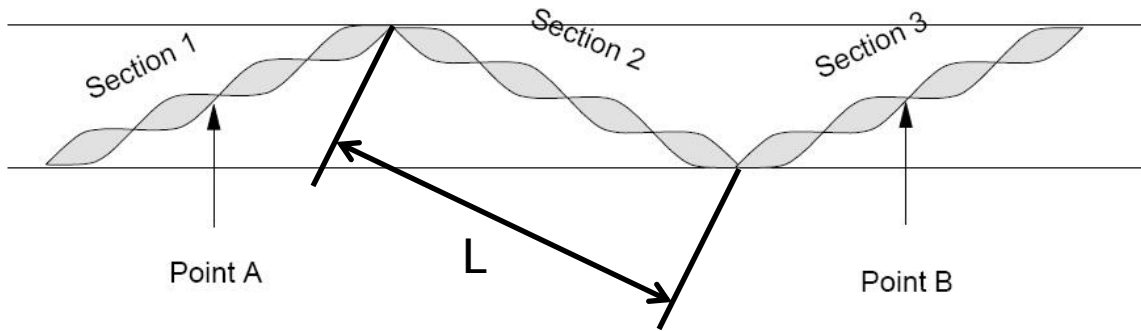
Frecventa normalizata

▶ Frecventa normalizata

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

$$k = \frac{2\pi}{\lambda}$$

▶ Numar de moduri

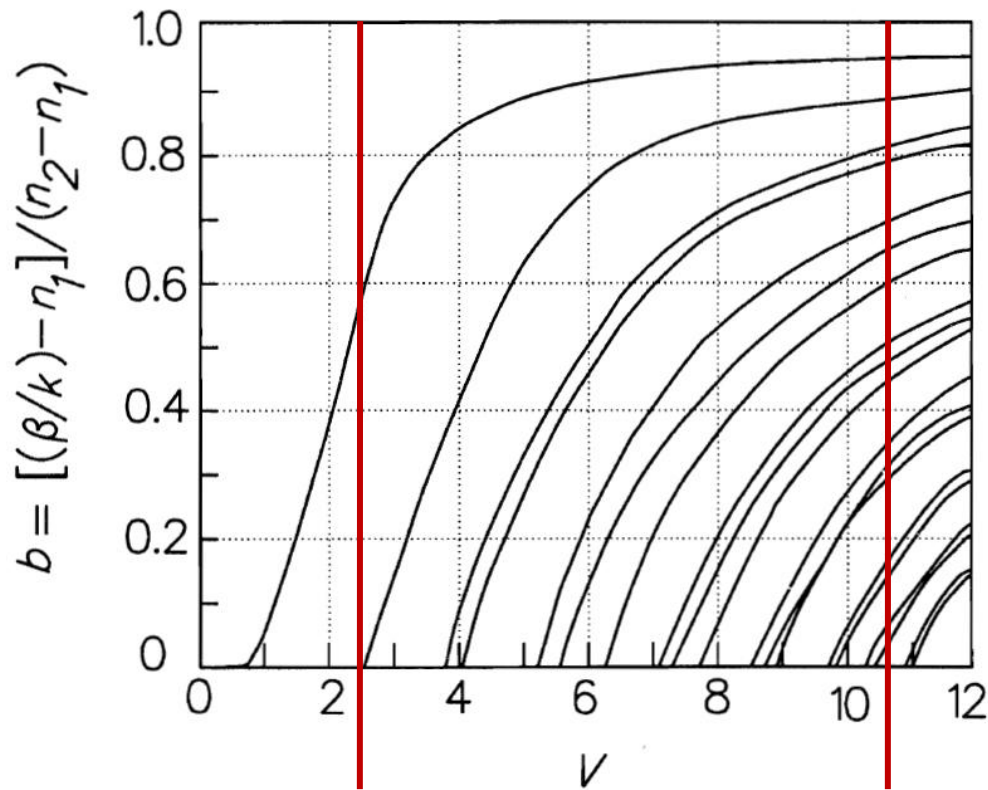


$$L = m \cdot \lambda$$

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

Frecventa normalizata – 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:

$$2a = 8.5 \mu\text{m}$$

$$NA = 0.11$$

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

Frecventa normalizata

- ▶ Numar de moduri
 - Multimod cu salt de indice

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

- Multimod cu indice gradat

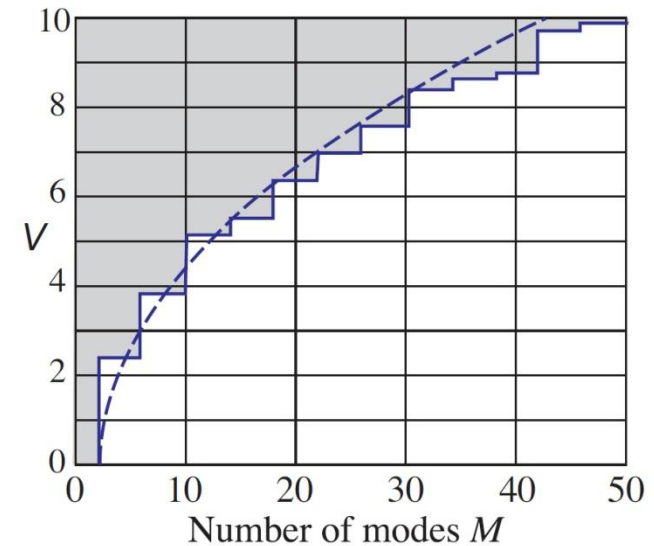
$$g = 2 \Rightarrow N \approx \frac{V^2}{4}$$

- Monomod

$$V \leq V_c = 2.405$$

exista un singur mod (solutii fc. Bessel)

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



Exemplu

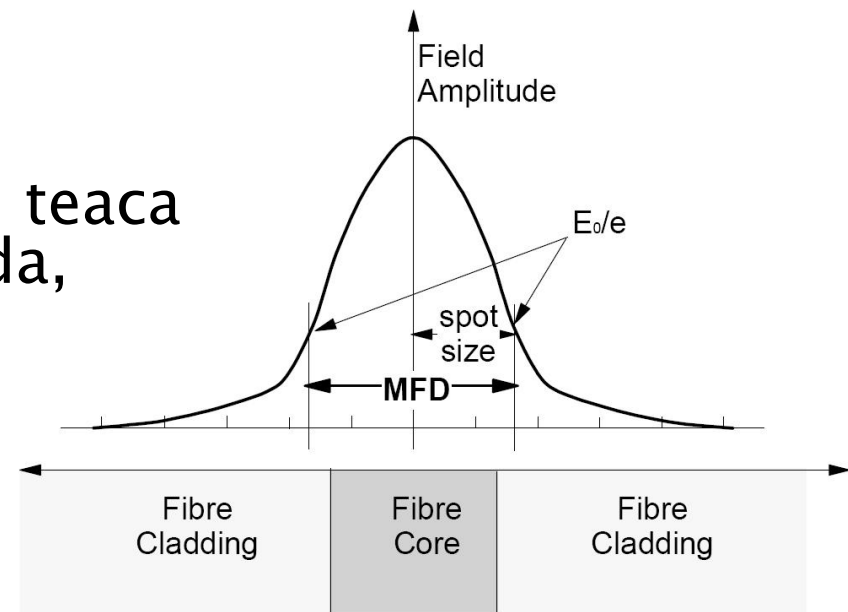
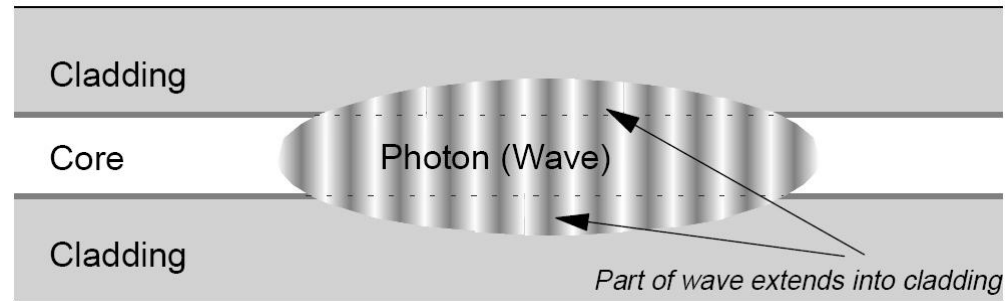
- ▶ fibra tipica multimod
 - $g=2$
 - $2a = 50\mu\text{m} \rightarrow a = 25\mu\text{m}$
 - $NA = 0.2$ la $\lambda = 1\mu\text{m}$

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

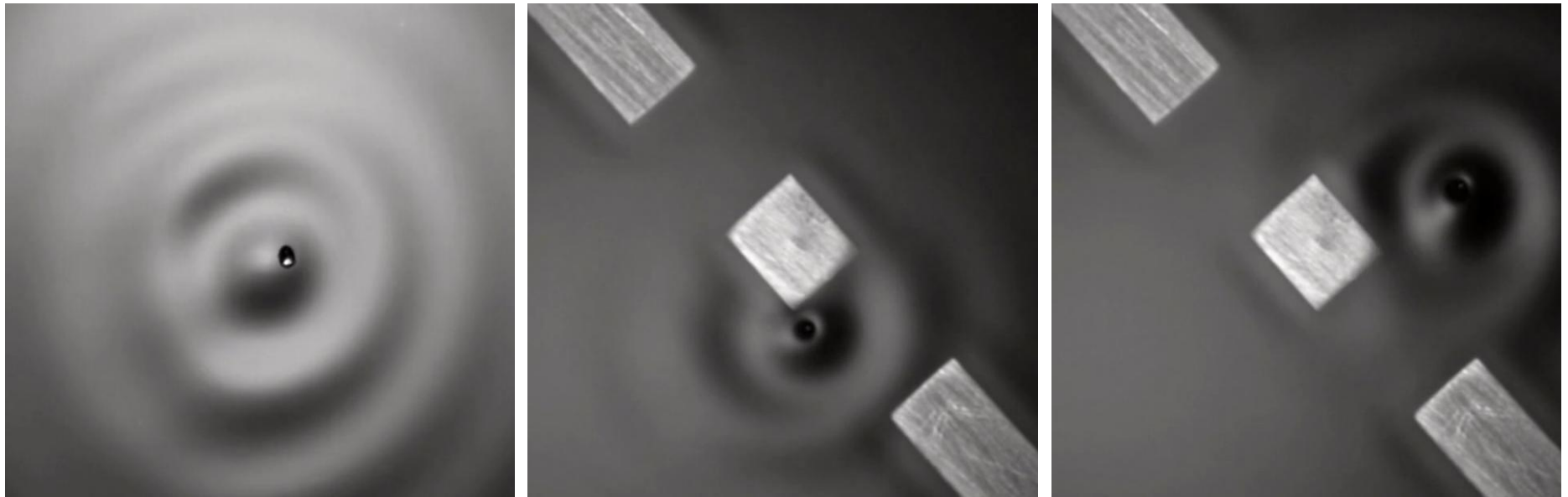
$$g = 2 \Rightarrow N = \frac{V^2}{4} = \frac{31.4^2}{4} = 247$$

Propagarea in fibra monomod

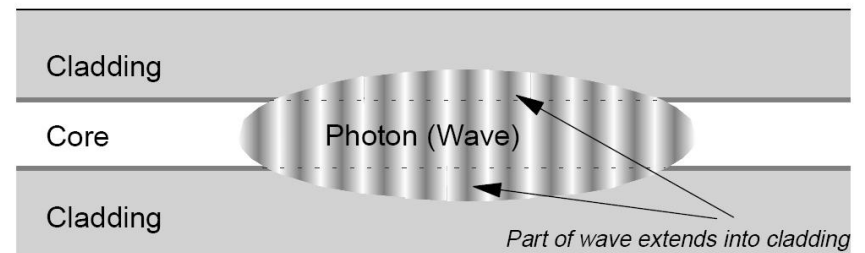
- ▶ Propagarea luminii poate fi explicata doar prin teoria electromagnetica
- ▶ Energia campului se extinde in teaca (diametrul efectiv al spotului luminos – MFD, Mode Field Diameter)
- ▶ $MFD > 2a$
- ▶ Adancimea de patrundere in teaca depinde de lungimea de unda, generand dispersia de ghid



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Calculul atenuarii

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

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

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

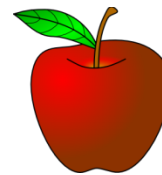
$$\text{Pierderi [dB]} = [-] (P_{out} [\text{dBm}] - P_{in} [\text{dBm}])$$



=



-

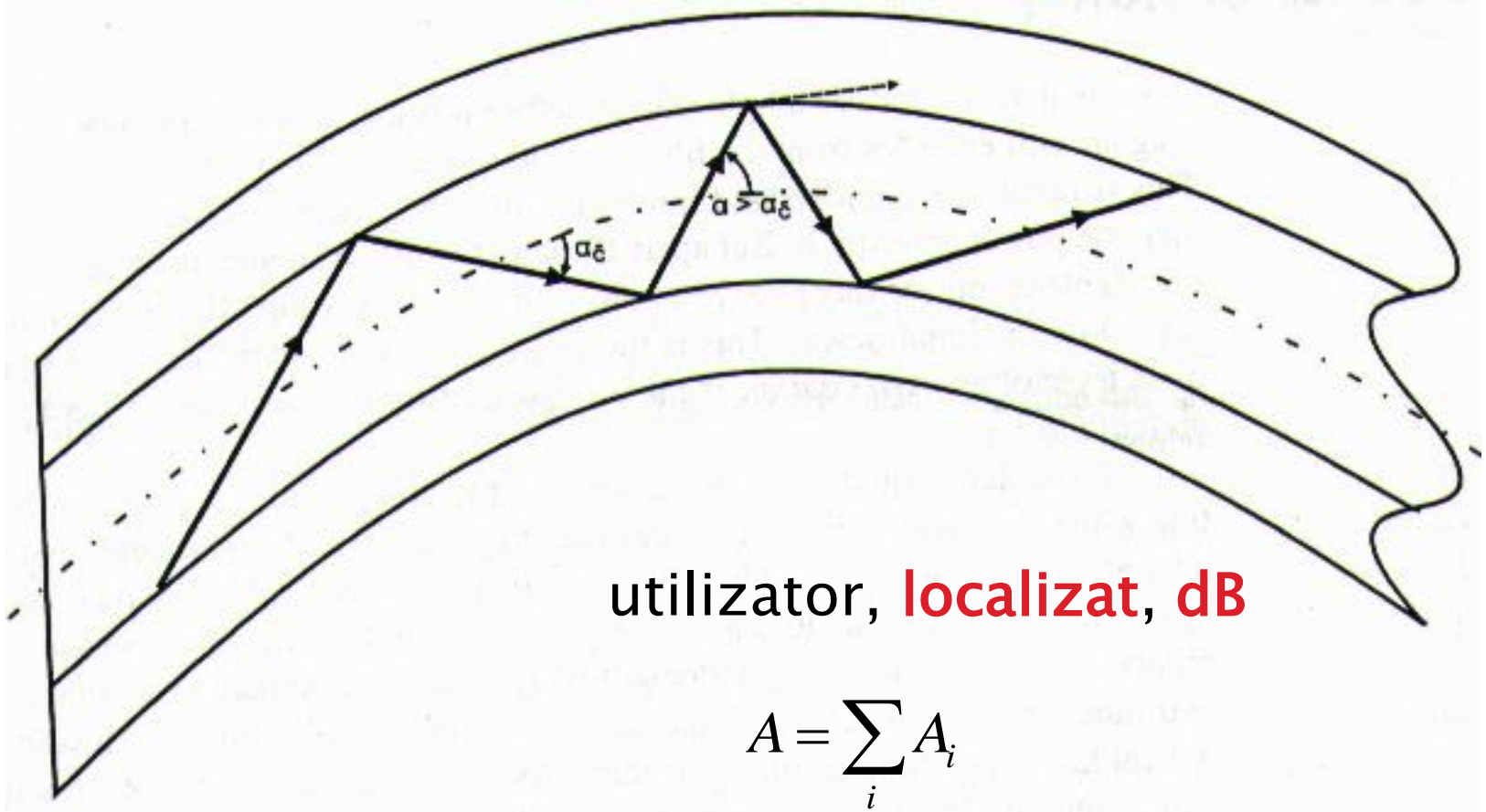


$$\text{Atenuare[dB/km]} = \frac{\text{Pierderi[dB]}}{\text{lungime[km]}}$$

Atenuare

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

Macrocurburi



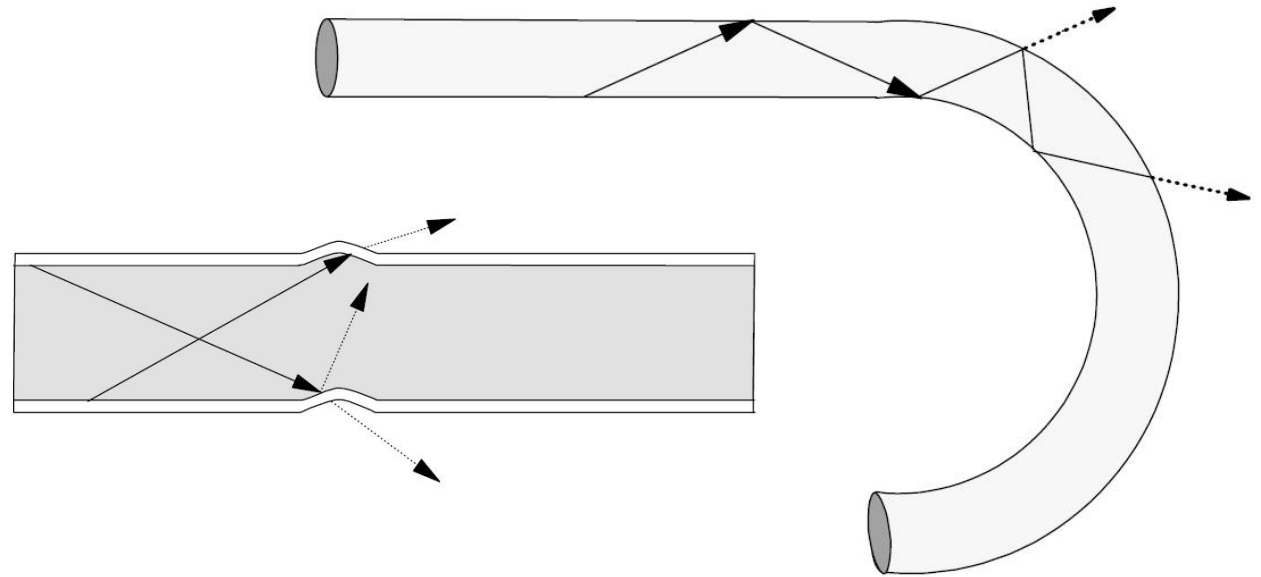
utilizator, **localizat**, dB

$$A = \sum_i A_i$$

$$A = N \cdot A_i$$

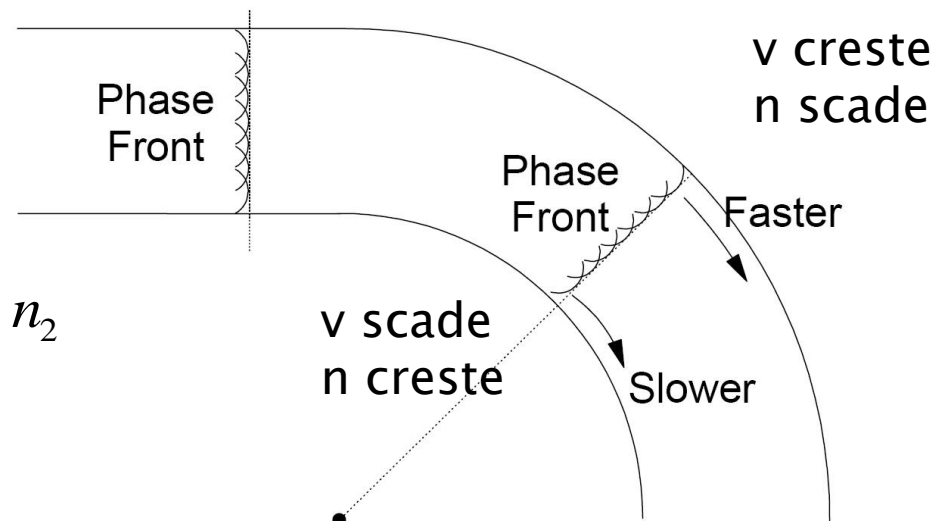
Efectul curburilor

▶ Multimod



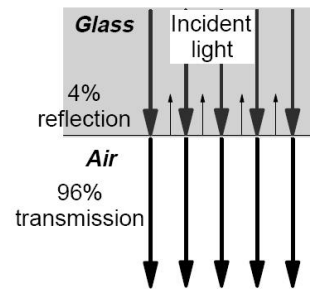
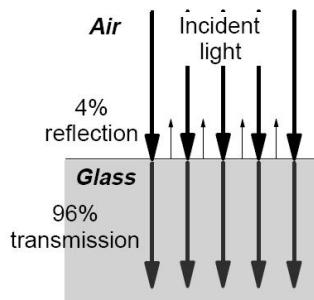
▶ Monomod

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



Discontinuitate in fibra

- ▶ Apare cand nu putem considera fibra un singur ghid dielectric
 - defectiuni
 - conectori

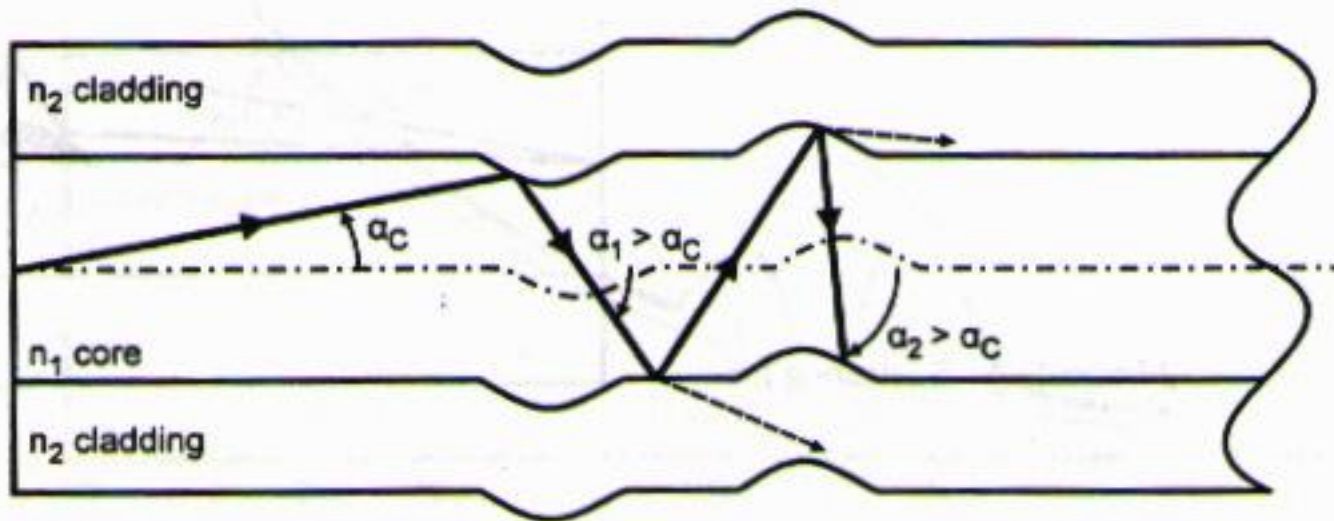


utilizator, **localizat**, dB

$$A = \sum_i A_i$$

$$A = N \cdot A_i$$

Microcurburi

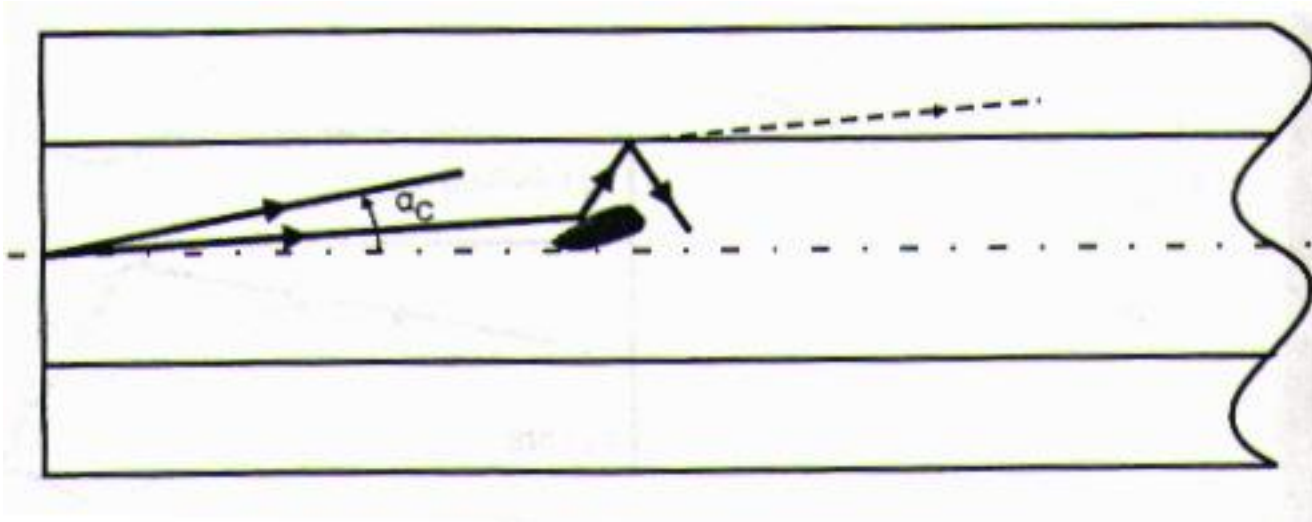


distribuit, tehnologie, **dB/km**

$$A = A_i \cdot L$$

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

Imprastiere

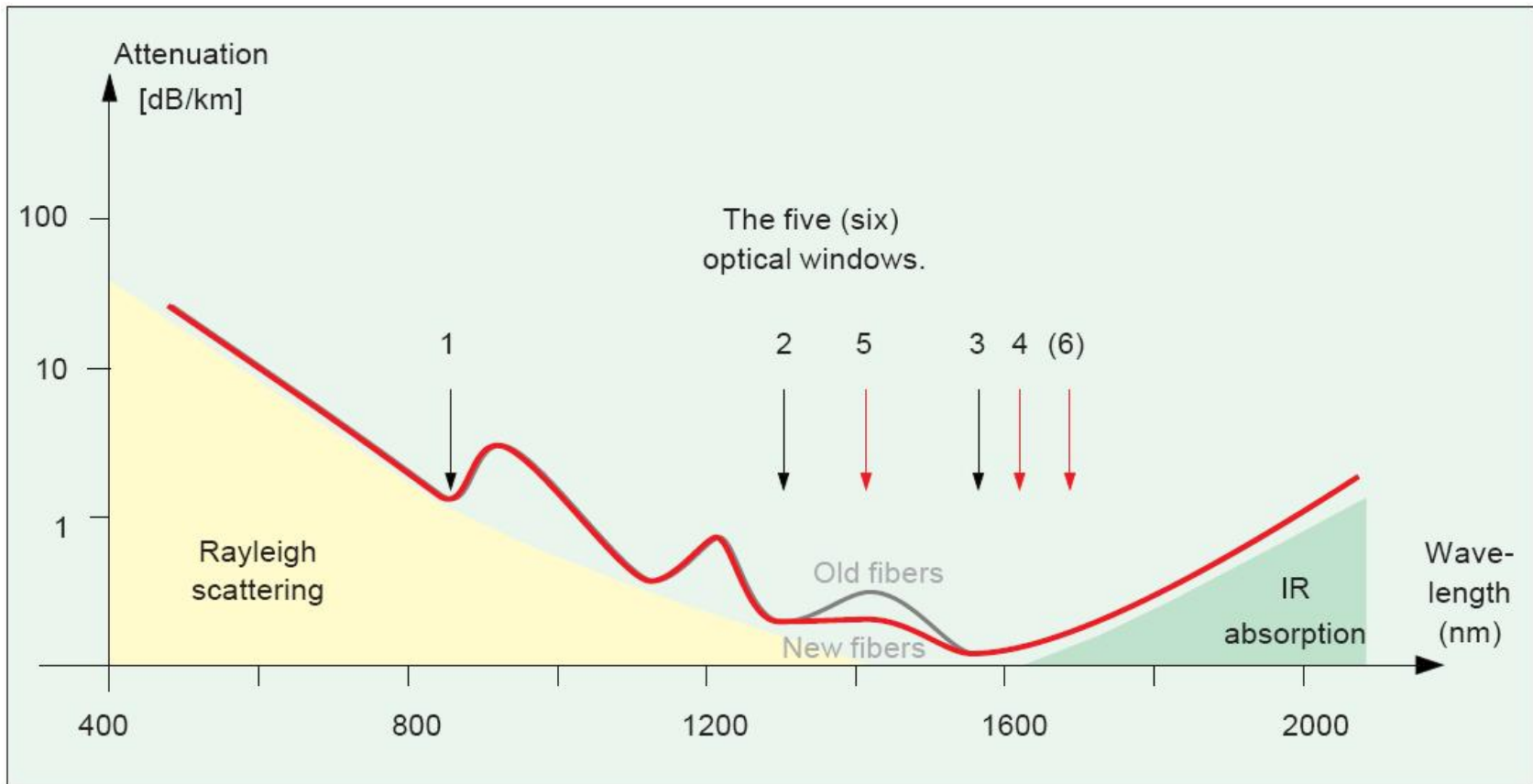


distribuit, tehnologie, **dB/km**

$$A = A_i \cdot L$$

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

Absorbtie

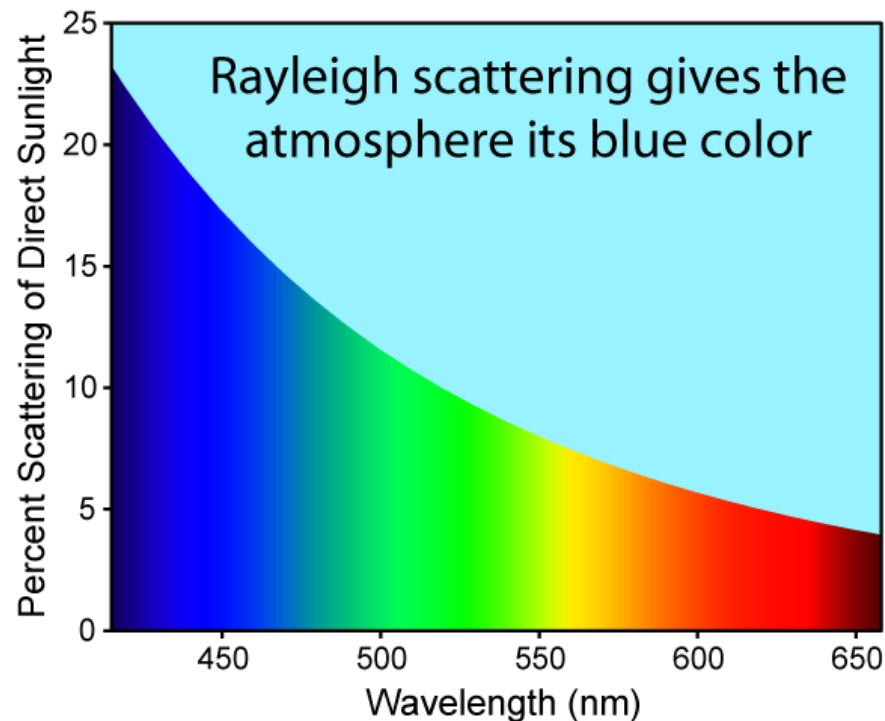


distribuit, material, dB/km

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

Difractie Rayleighgh

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



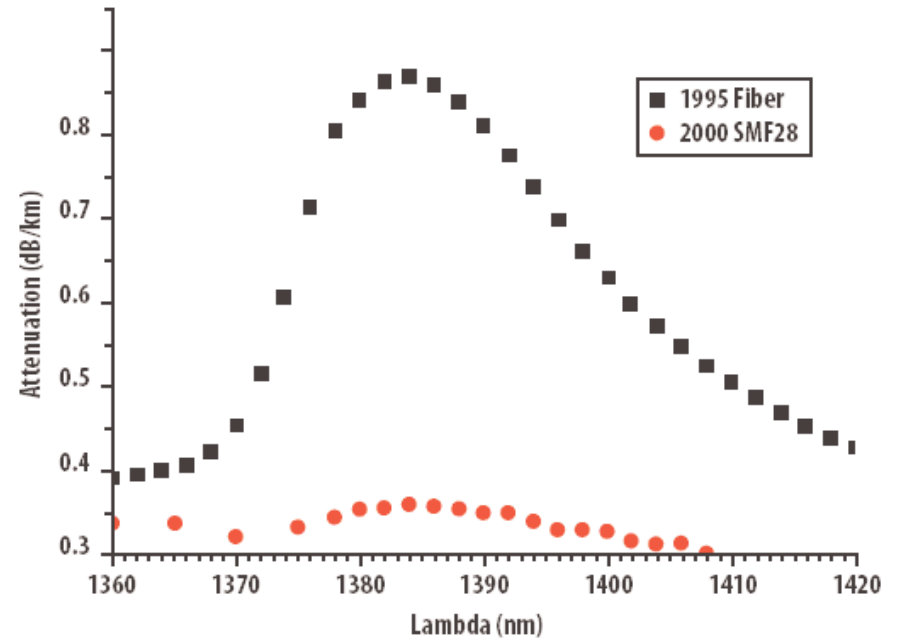
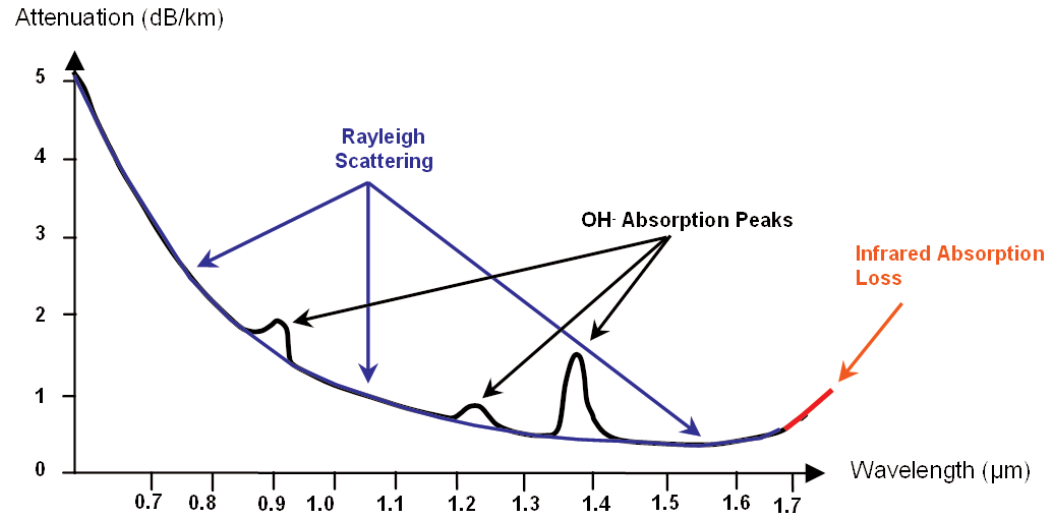
$$A \sim \frac{1}{\lambda^4}$$

Absorbentie OH

▶ Absorbentie

- 950nm
- 1244nm
- 1383nm

▶ Apa!



Fiber Attenuation Comparison

Atenuare

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

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

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

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

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

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

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

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

Calculul atenuarii

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

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

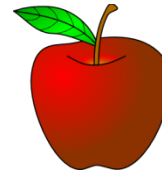
$$\text{Pierderi [dB]} = [-] (P_{out} [\text{dBm}] - P_{in} [\text{dBm}])$$



=



-

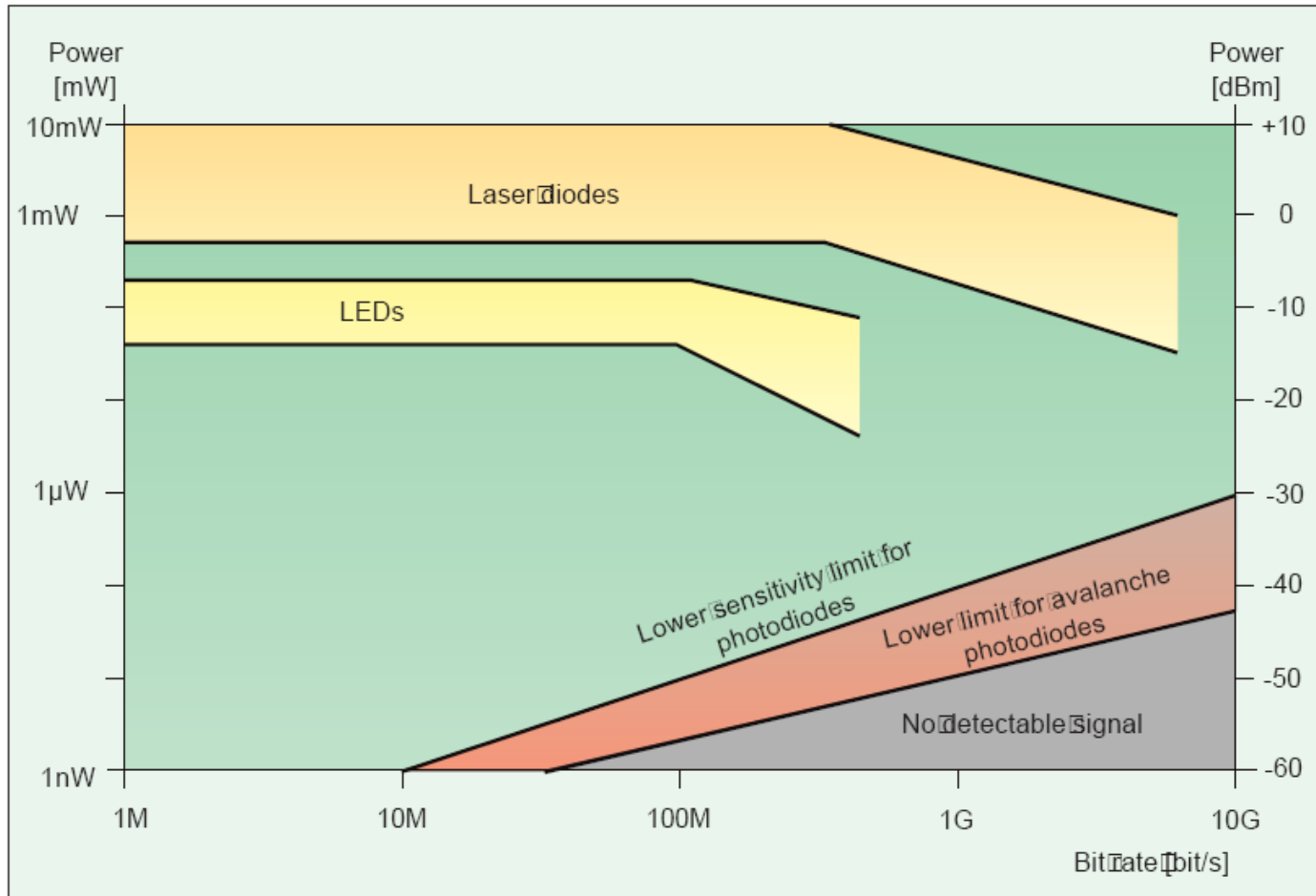


$$\text{Atenuare[dB/km]} = \frac{\text{Pierderi[dB]}}{\text{lungime[km]}}$$

Efecte neliniare in fibra

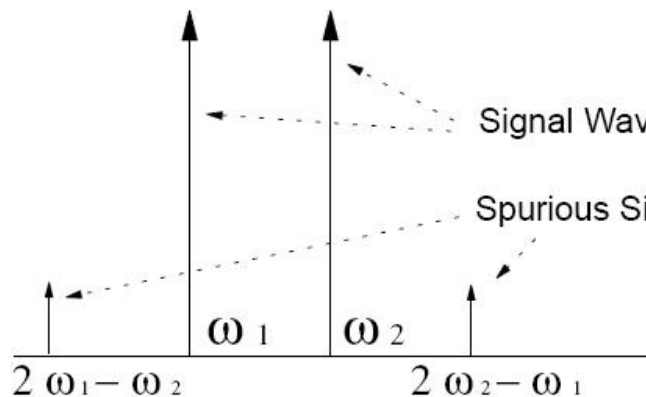
- ▶ **Stimulated Brillouin Scattering, SBC**
 - difractia luminii inspre emitator datorita undelor mecano-acustice generate in fibra
 - 6–10 dBm
- ▶ **Stimulated Raman Scattering, SRS**
 - interactiunea luminii cu vibratiile moleculare
 - 27 dBm (~1W)
- ▶ **Self Phase Modulation, SPM**
 - Frontiera impulsului 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

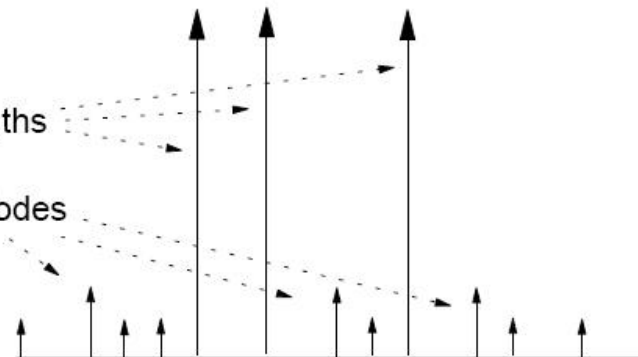


Four-Wave Mixing, FWM

Two Channels



Three Channels

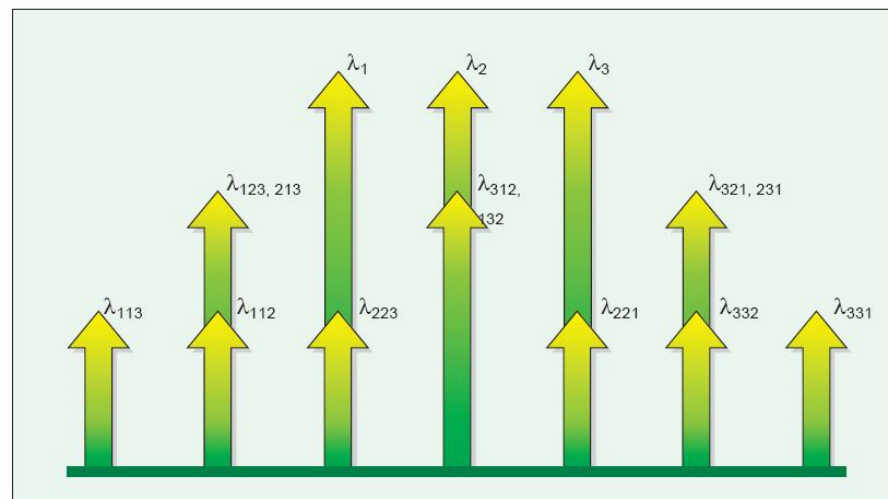


$$NL = \frac{1}{2}(N^3 - N^2)$$

$$N = 2, NL = 4$$

$$N = 3, NL = 9$$

$$N = 16, NL = 1920$$

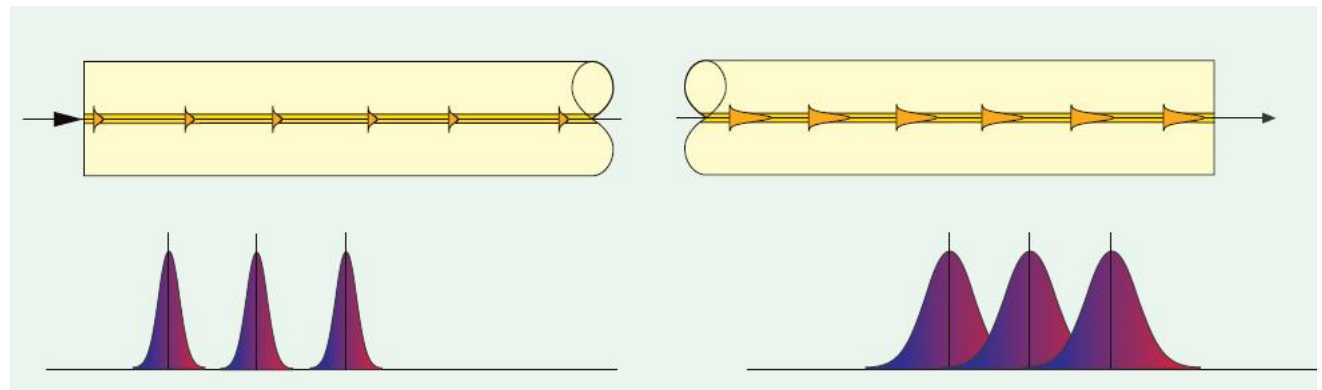


Fenomene de interes

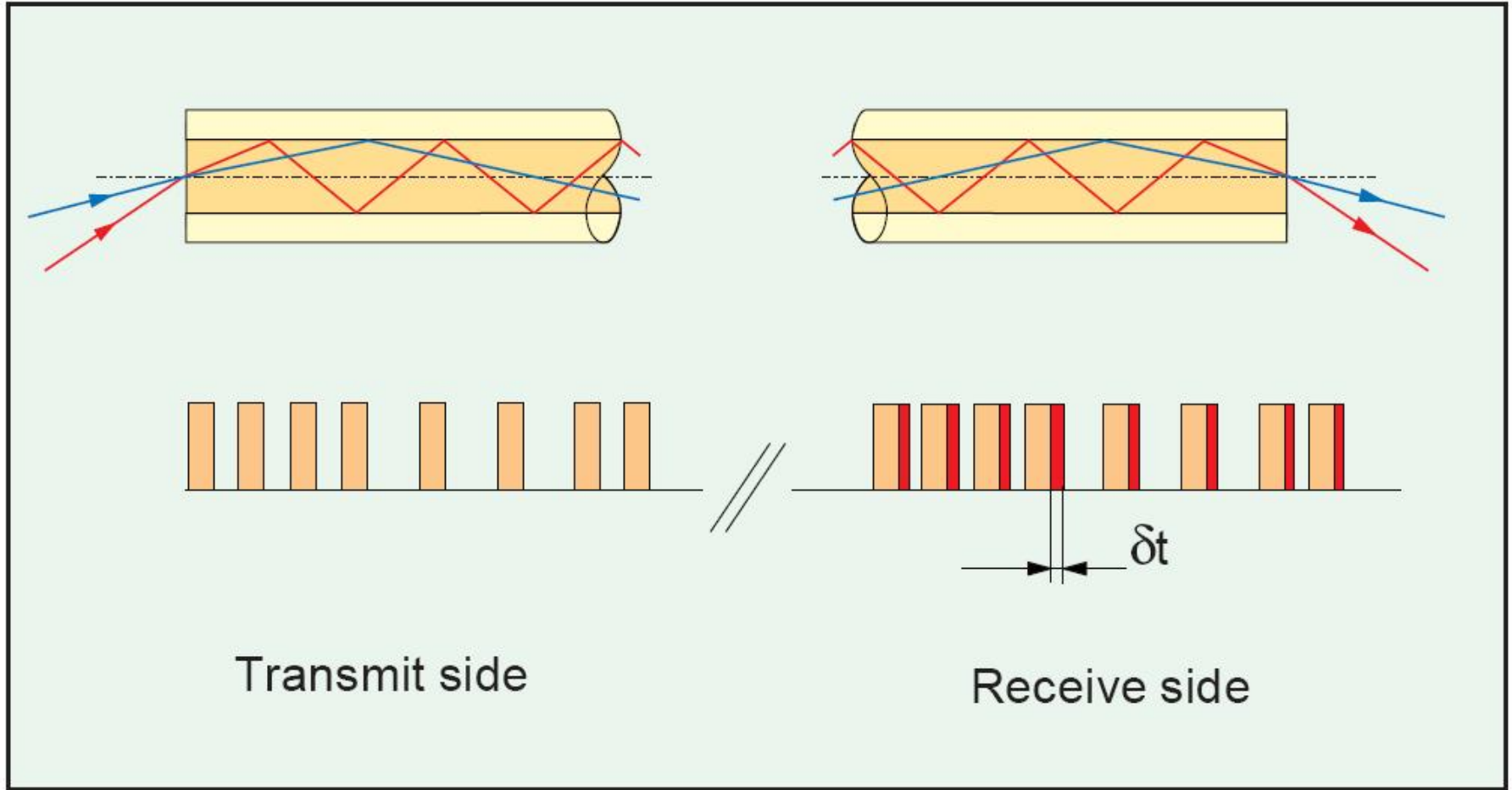
- ▶ Cat de departe pot transmite semnalul luminos pe fibra
 - atenuare
- ▶ Cat de rapid pot transmite informația
 - **dispersie**

Dispersia

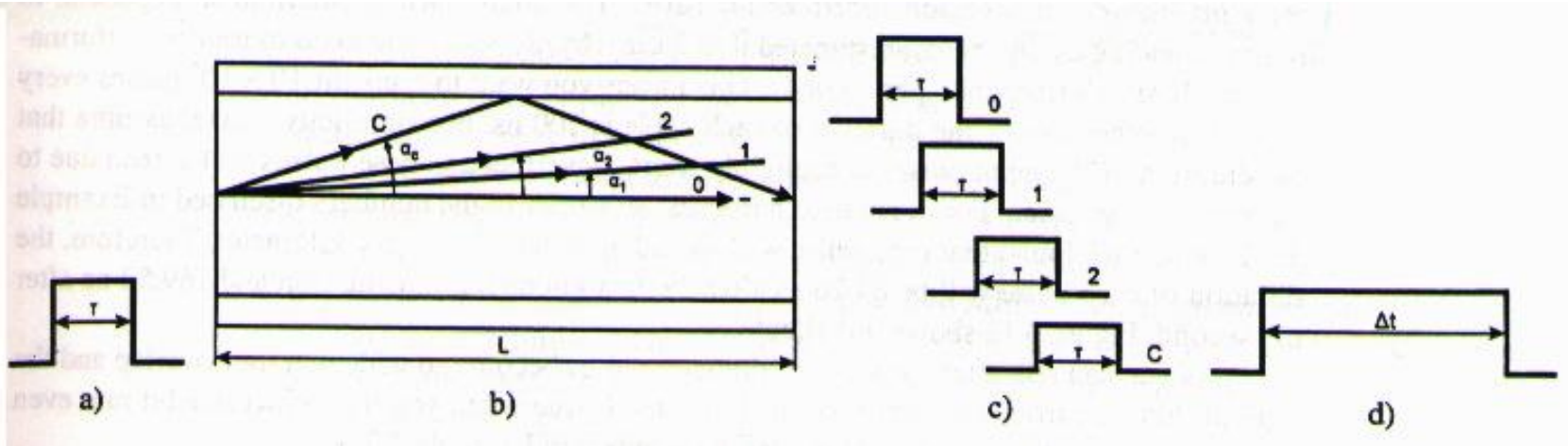
- ▶ Propagarea cu viteze diferite a radiatiilor cu trasee/lungimi de unda diferite
 - intermodala (**modala** – depinde de prezenta modurilor)
 - intramodala (**cromatica** – depinde de lungimea de unda)
 - de material
 - de ghid



Dispersia modala



Dispersia modala



$$t_0 = \frac{L}{v}$$

$$t_c = \frac{L}{v \cdot \cos \alpha_c}$$

$$v = \frac{c}{n_2}$$

$$\cos \alpha_c = NA$$

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

$$\Delta t_{SI} = t_c - t_0 = \frac{L \cdot n_2}{c} \cdot \Delta$$

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

$$\Delta t_{SI} = t_c - t_0 \approx \frac{L}{2 \cdot c \cdot n_2} \cdot (NA)^2$$

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

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

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

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

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

▶ indice gradat

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

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

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

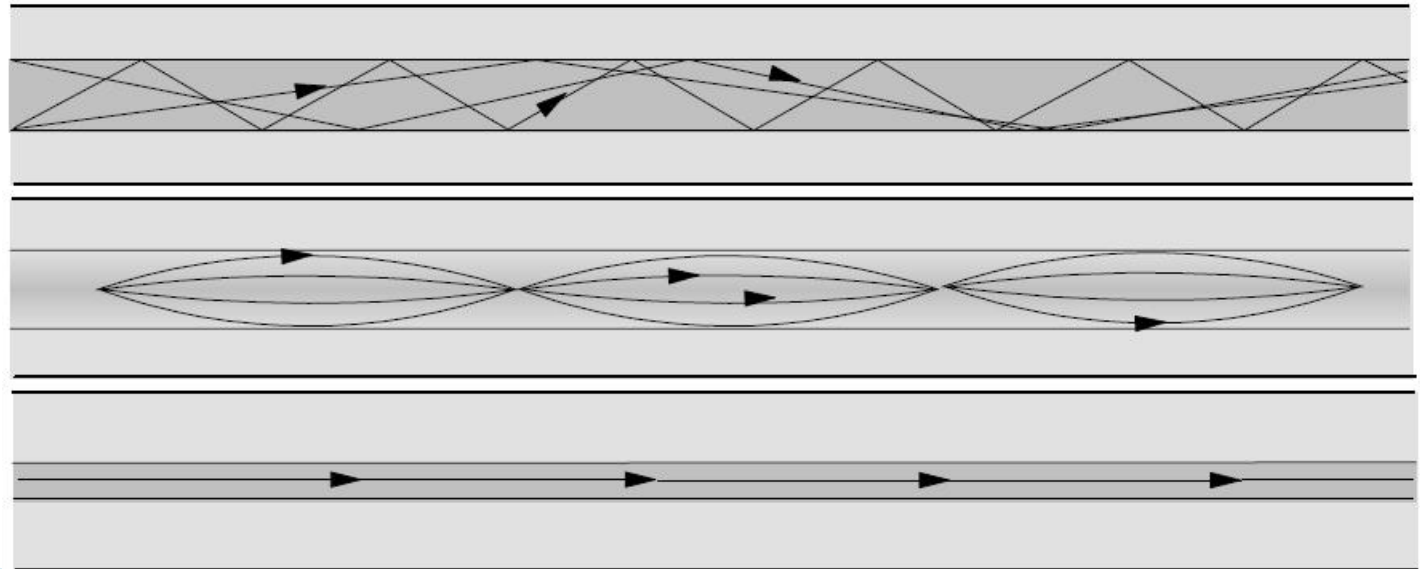
n_2 - miez

n_1 - teaca

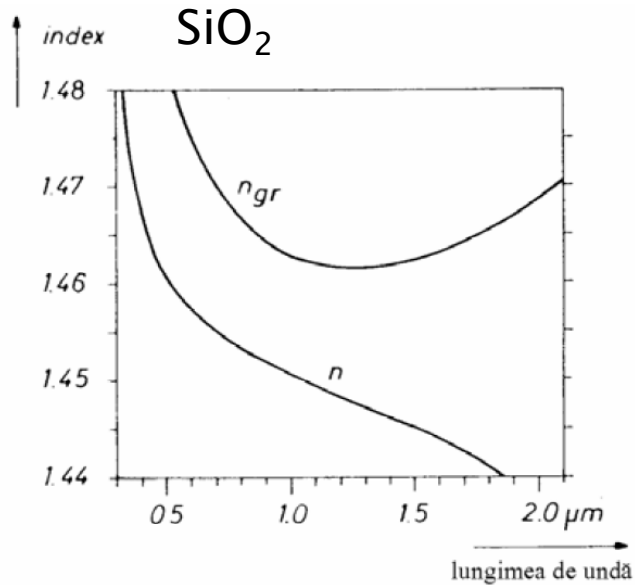
$n_2 > n_1$!!

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

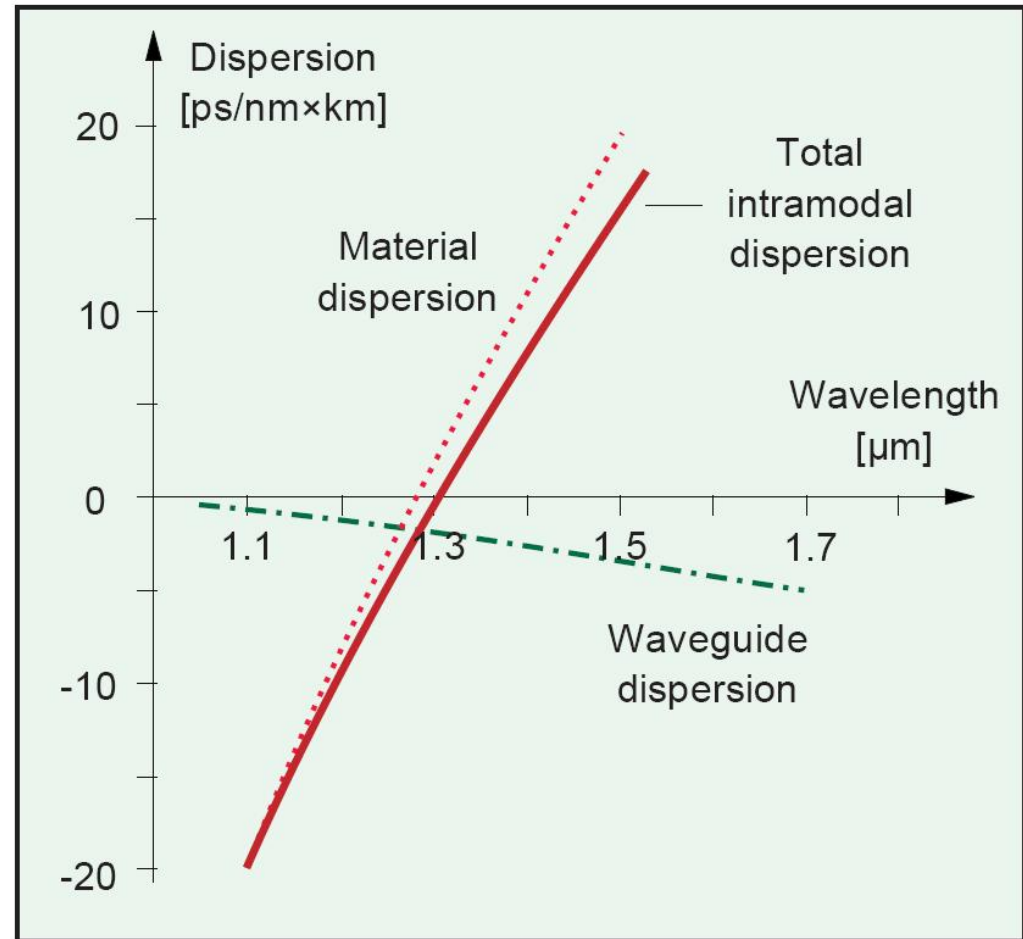


Dispersia de material



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

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

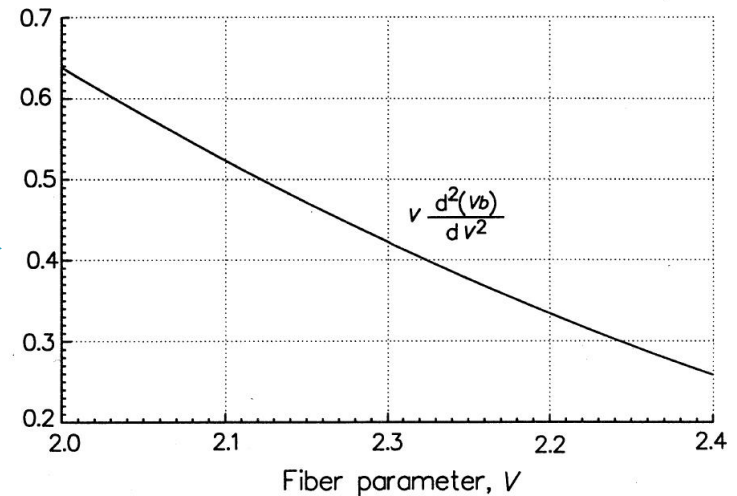
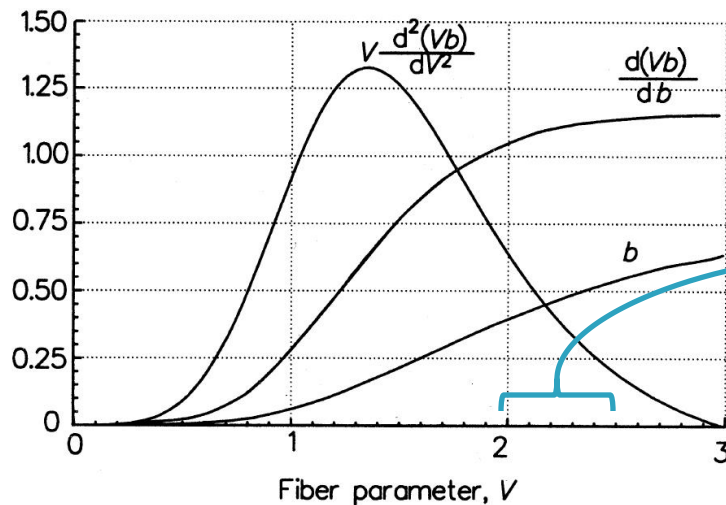


Dispersia de ghid

- ▶ Neglijabila in fibrele multimod fata de dispersia modala

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

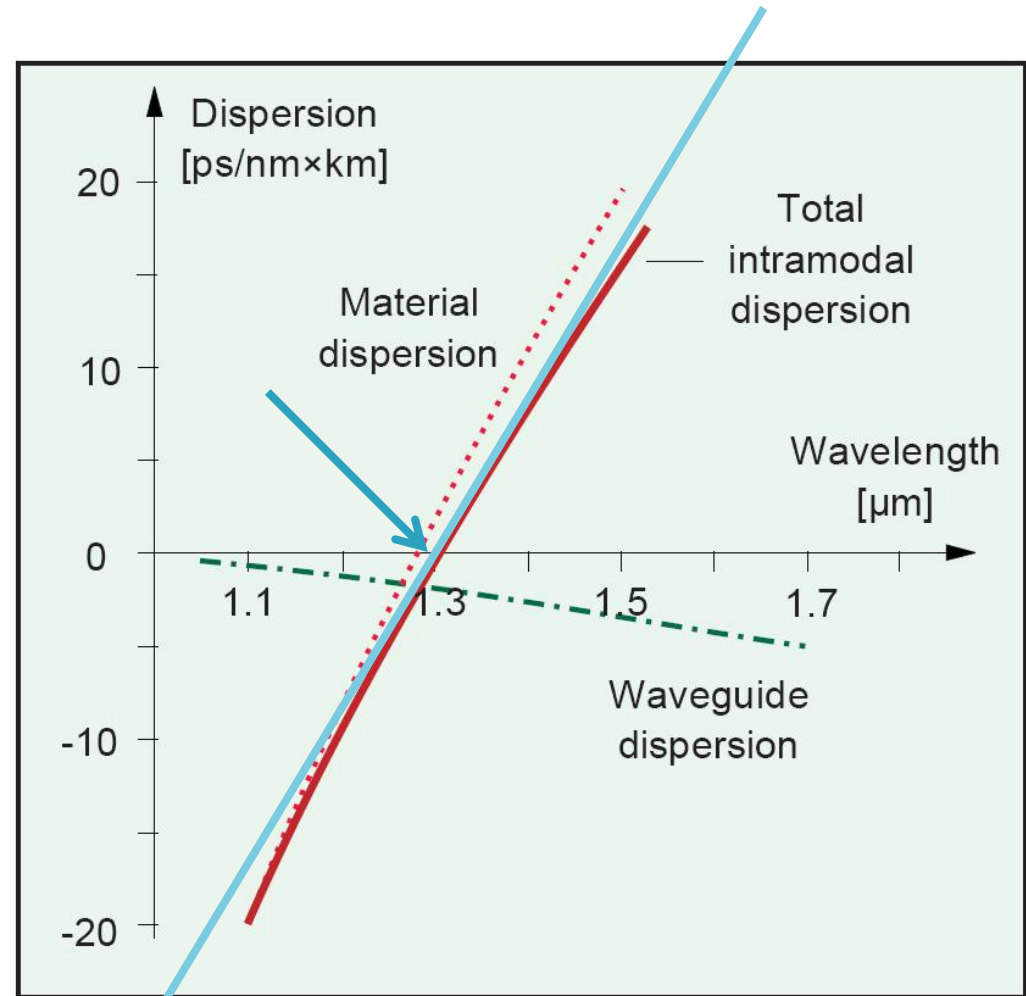
b – constanta de propagare normalizata



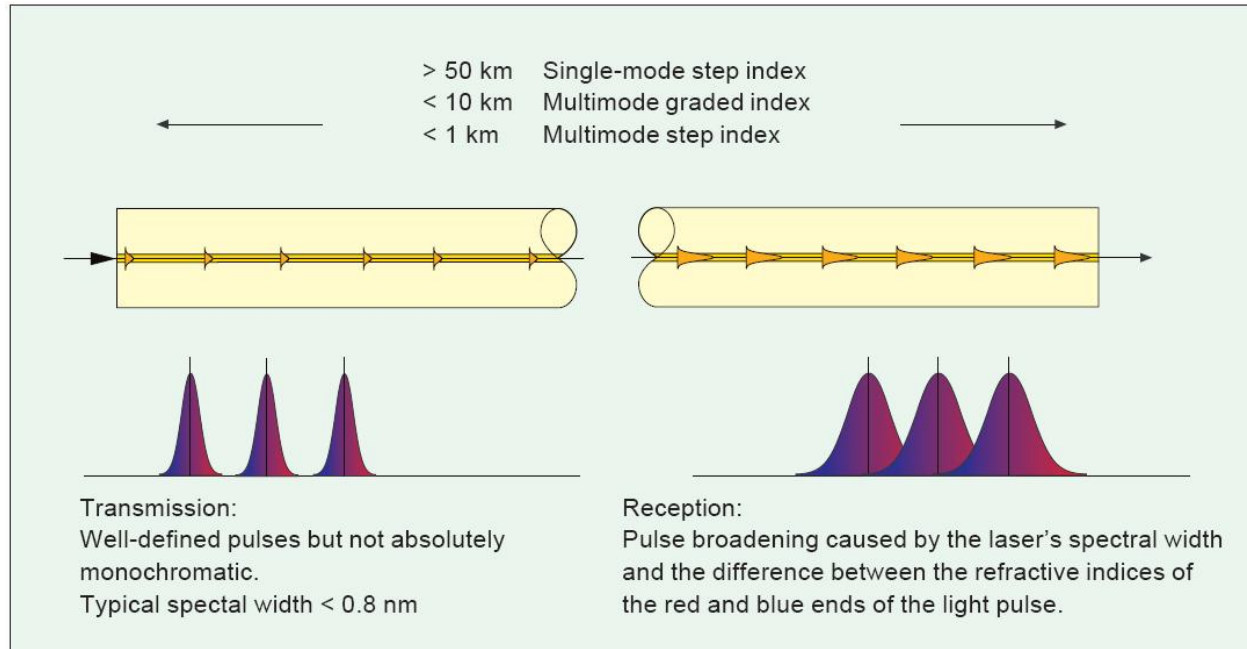
$$V \leq V_C = 2.405$$

Dispersia cromatica (gh+mat)

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



Dispersia cromatica (gh+mat)



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

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

S_0 panta dispersiei - ps/nm²/km

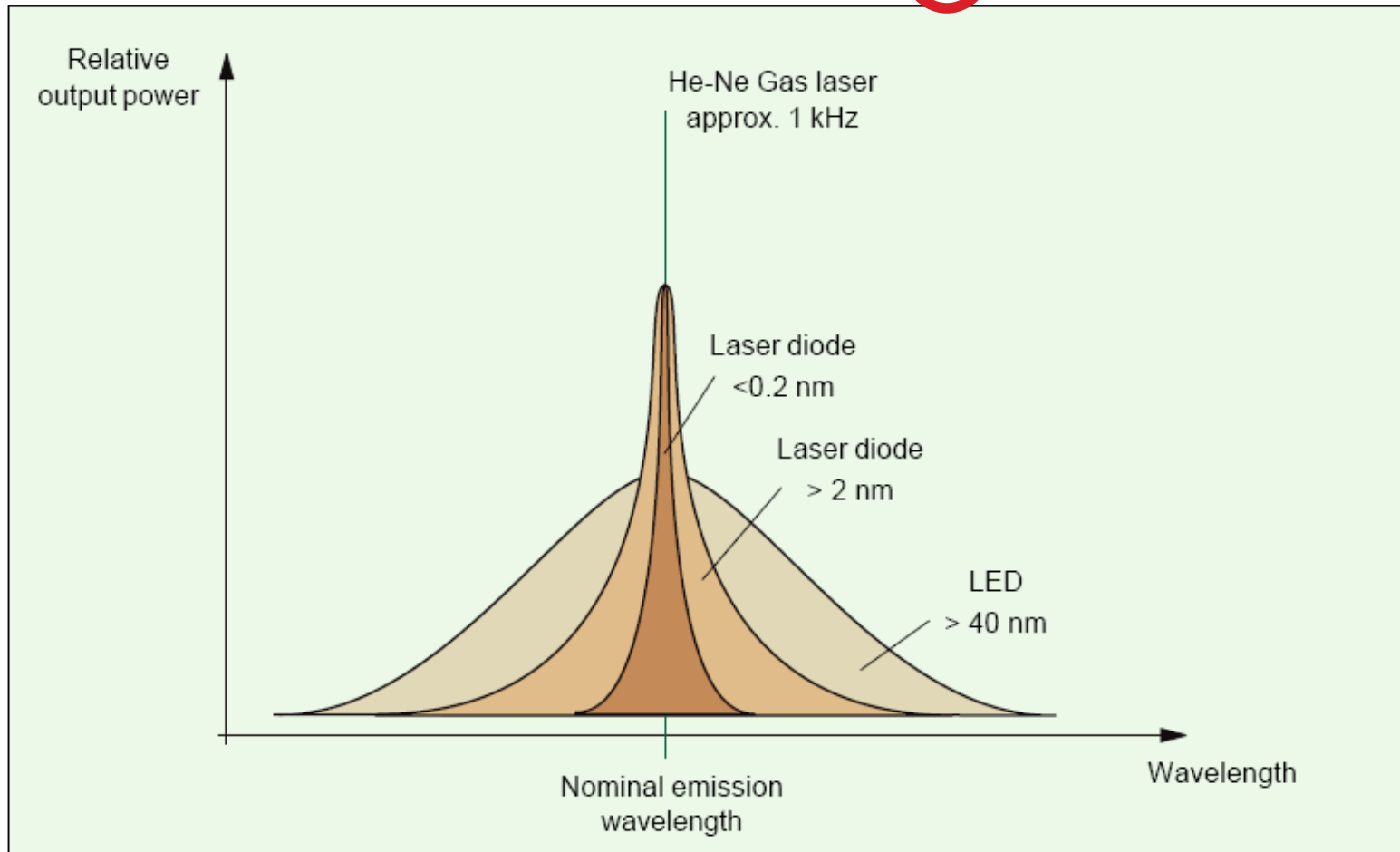
$$D(\lambda_0) = 0$$

- ▶ $D(\lambda) \approx 100 + 0.4 (850 - \lambda)$ [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

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

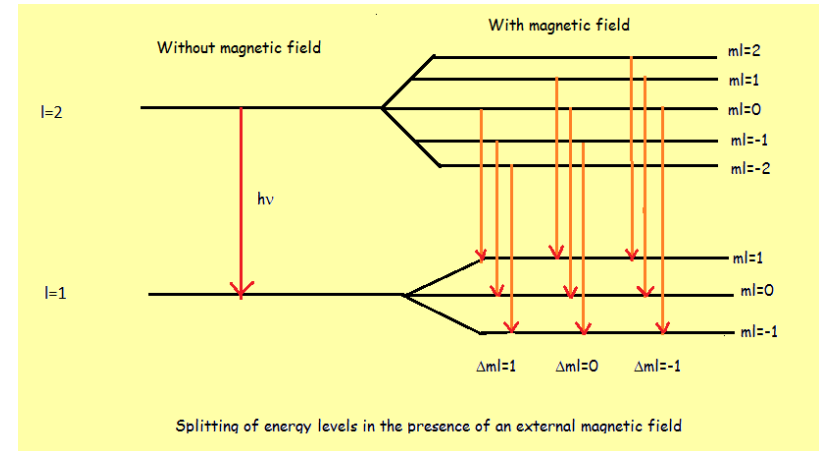
Calitatea spectrală a emițătorilor optici

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

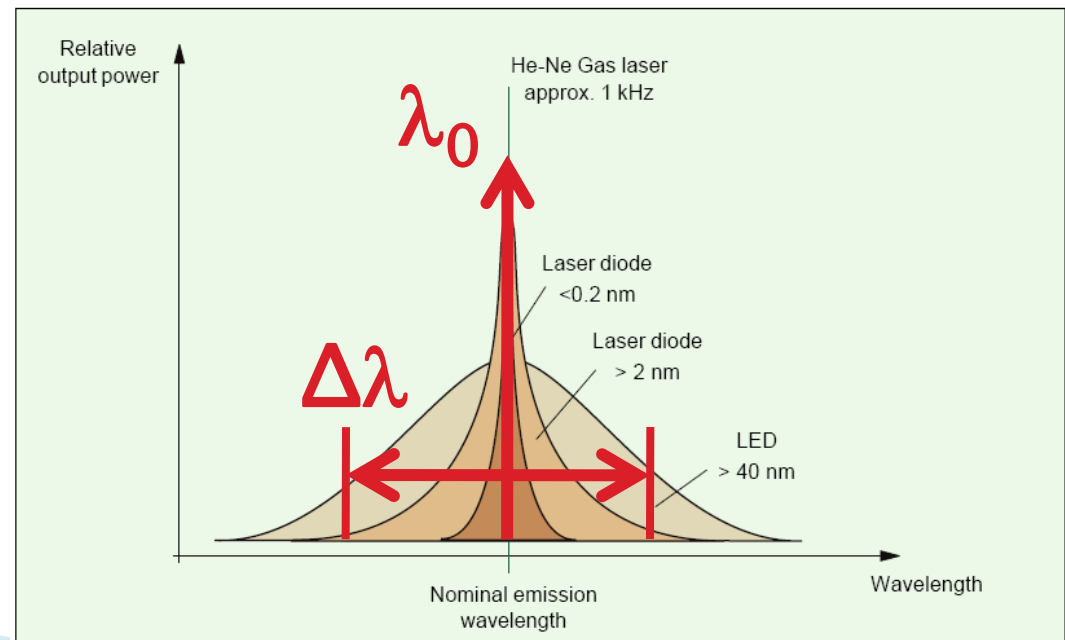


Calitatea spectrală a emițătorilor optici

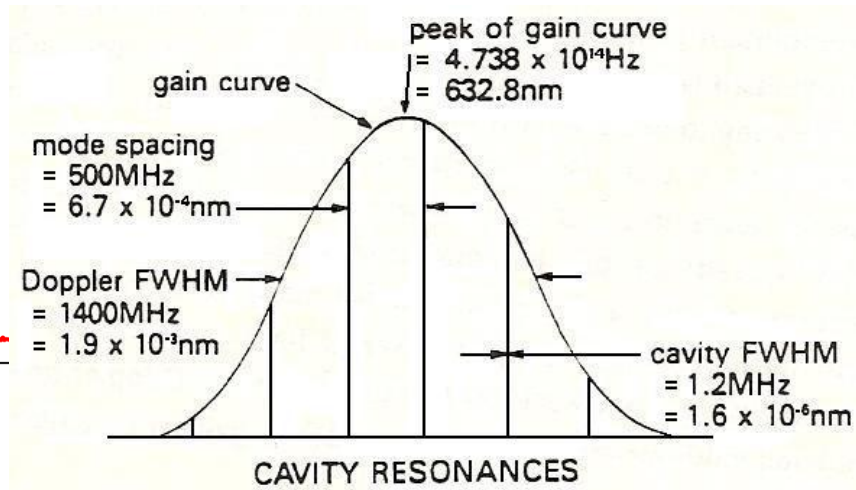
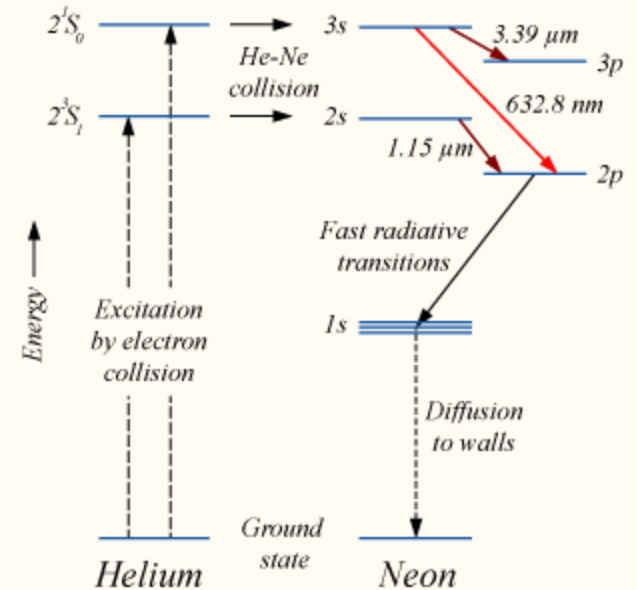
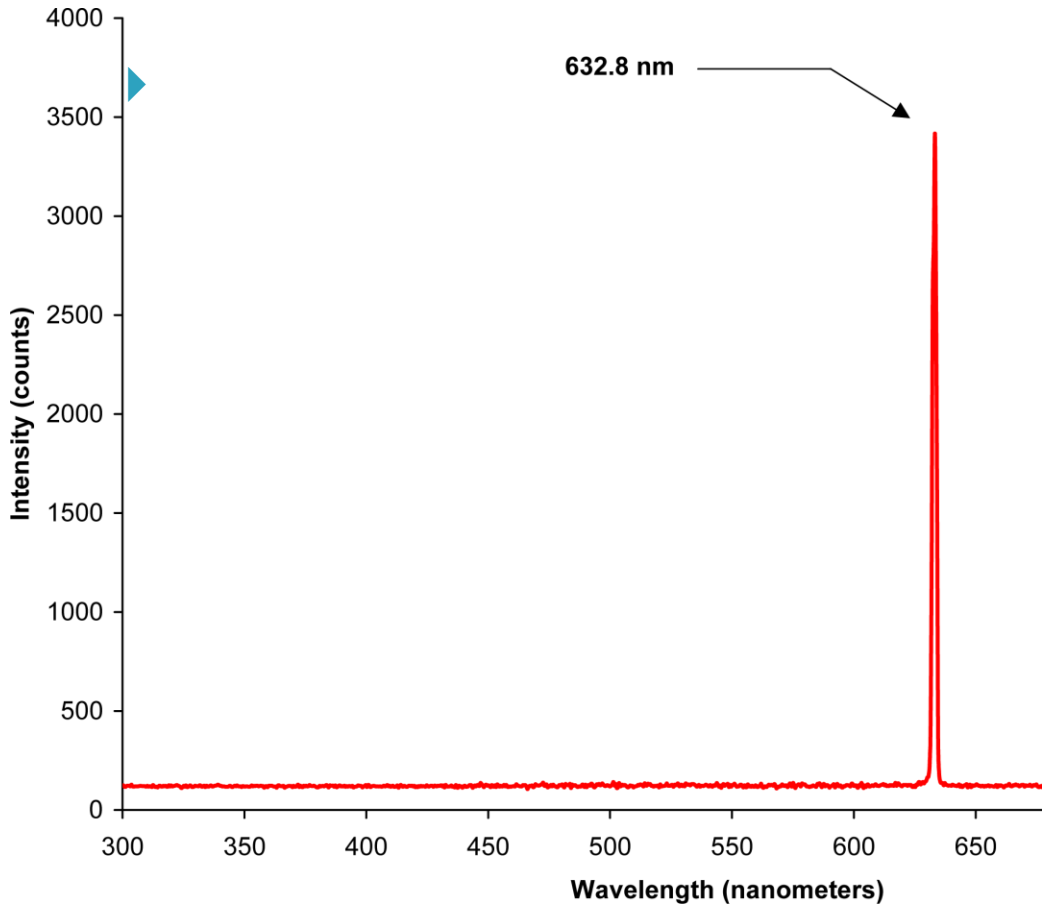
- ▶ degenerarea nivelelor energetice duce la aparitia benzilor energetice
- ▶ Multitudinea de tranzitii posibile intre cate doua nivele situate in benzi energetice diferite duce la largirea caracteristicii spectrale a surselor



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

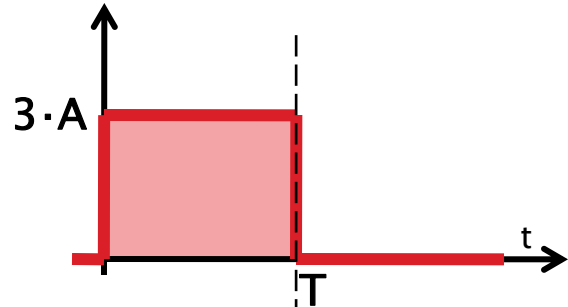


He-Ne Laser

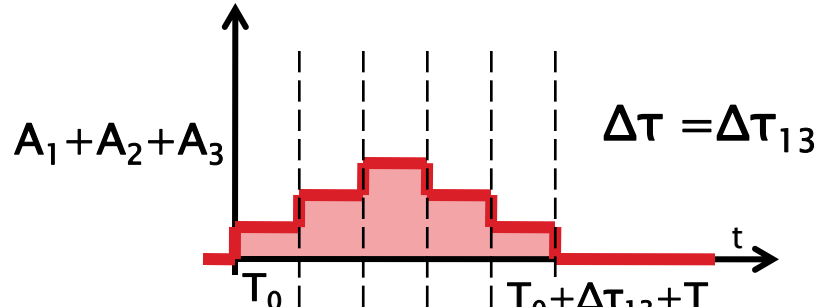
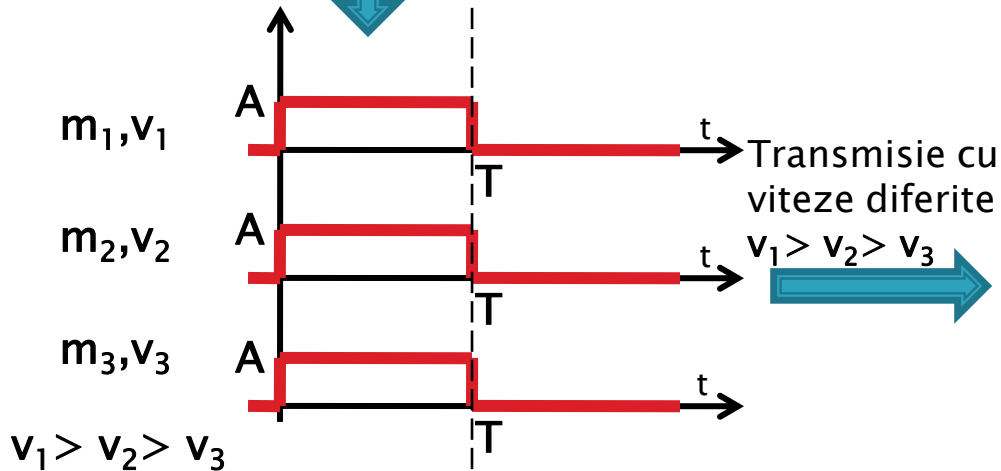


$$\Delta\lambda = 0.002 \text{ nm}$$

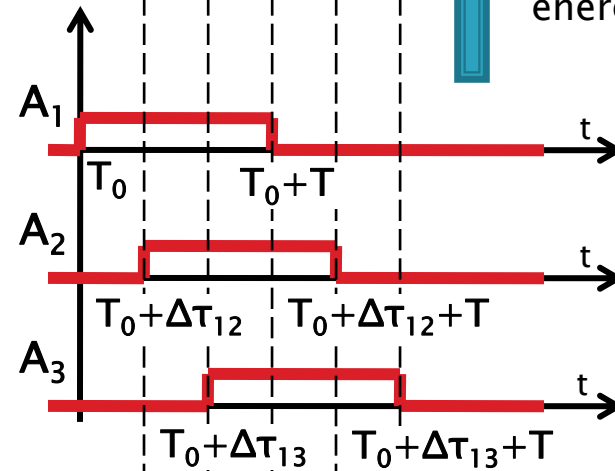
Dispersia modala



Impartire energie pe moduri

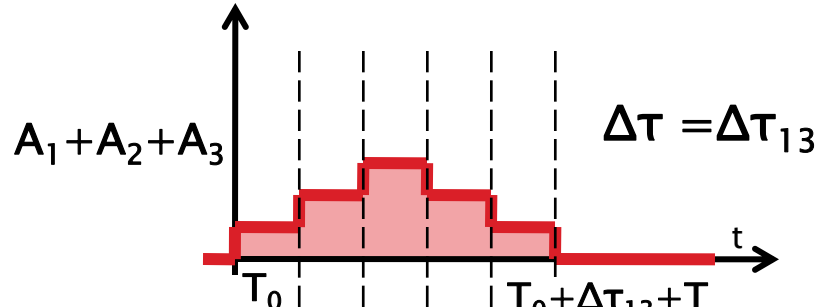
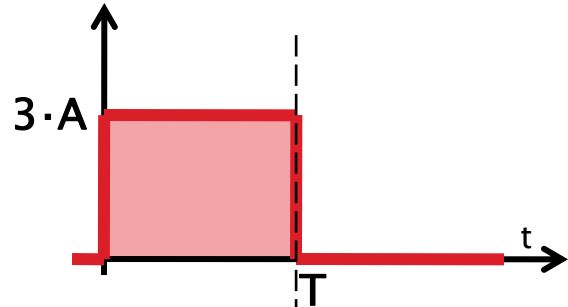


Recombinarea energiei modurilor

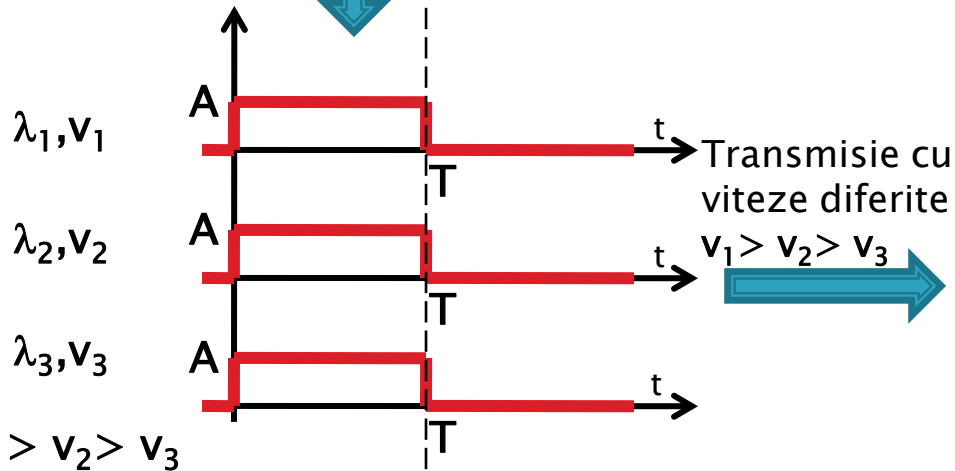


Conceptual $\rightarrow f(t) = \int_{-\infty}^{\infty} g(\omega) \cdot e^{j\omega t} d\omega$

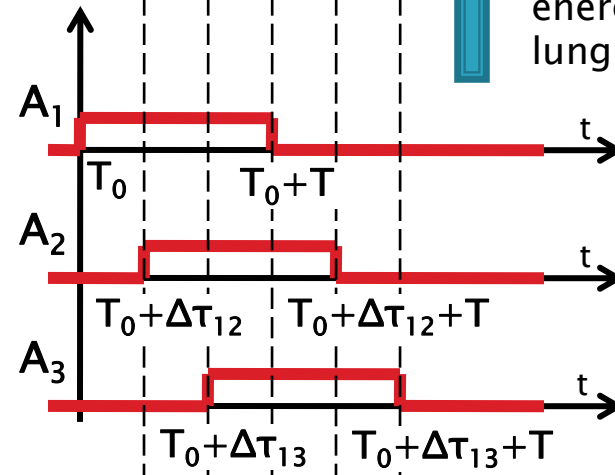
Dispersia cromatica (gh+mat)



Impartire energie pe lungimi de unda



Recombinarea energiei la diferite lungimi de unda

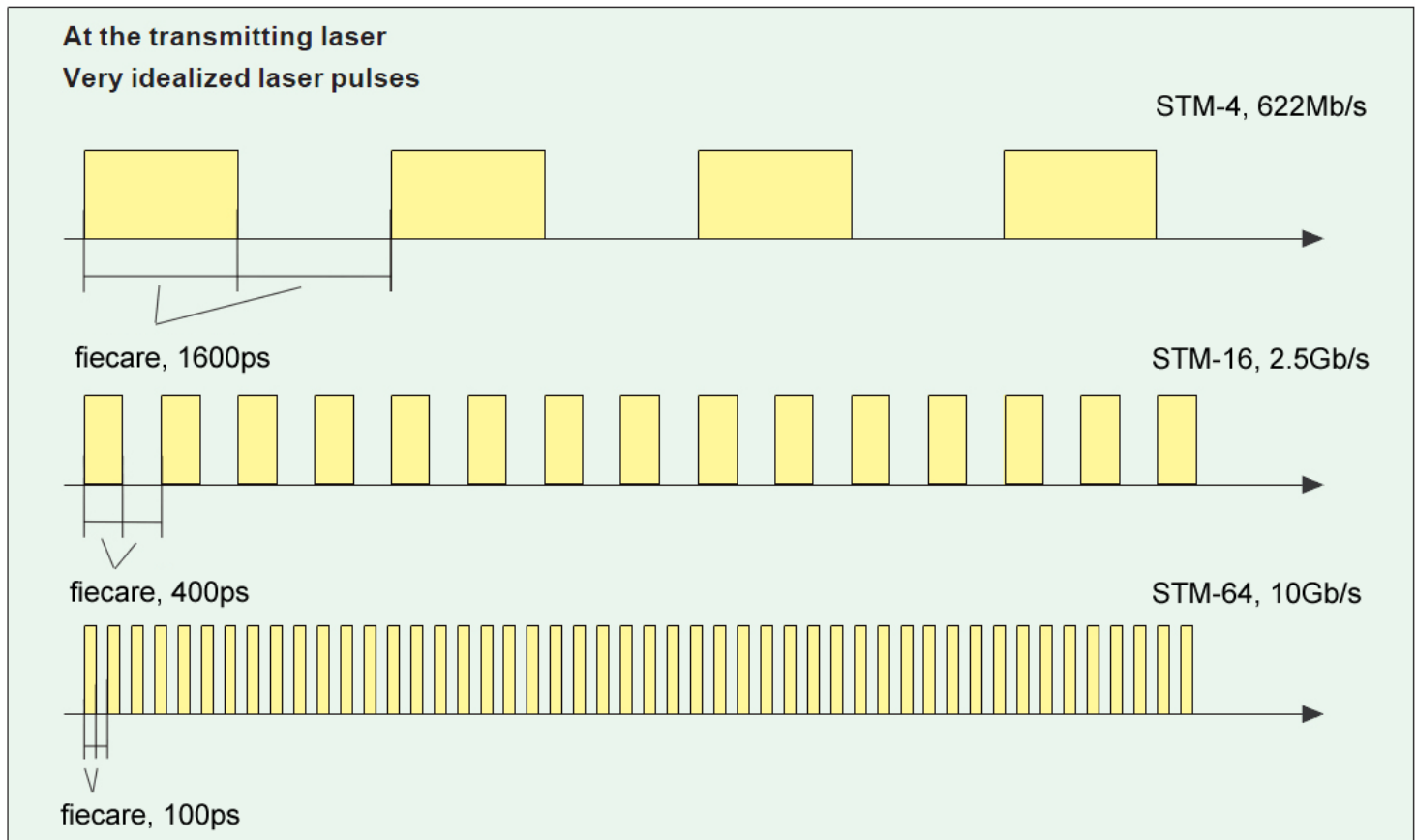


Efectiv $\rightarrow f(t) = \int_{-\infty}^{\infty} g(\omega) \cdot e^{j\omega t} d\omega$

Dispersie exemplu - 1

- ▶ transmisii cu viteze diferite

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



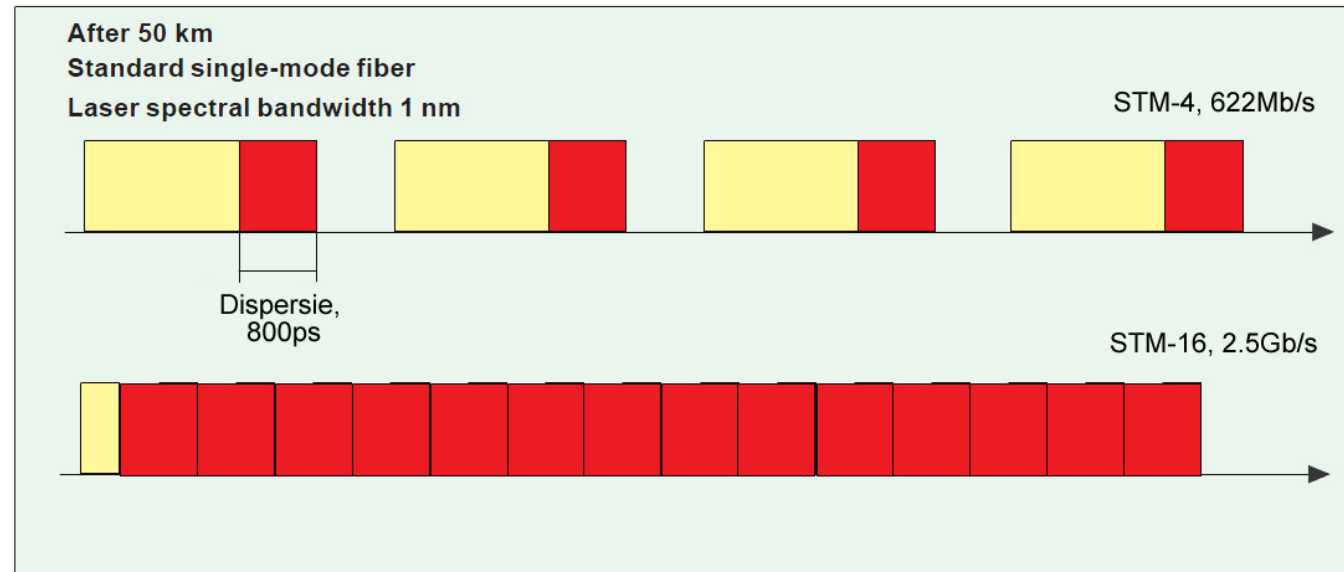
Dispersie exemplu - 2

▶ 1550nm

▶ Efectul sursei

- fibra monomod cu dispersia 16ps/nm/km@1550
- latimea spectrala a sursei $\Delta\lambda=1$ nm
- 50km

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



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

$$\Delta\tau_{cr} = 16 \cdot 1 \cdot 50 \text{ ps} = 800 \text{ ps}$$

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

$$100 < 400 < 800 < 1600$$

Dispersie exemplu – 3

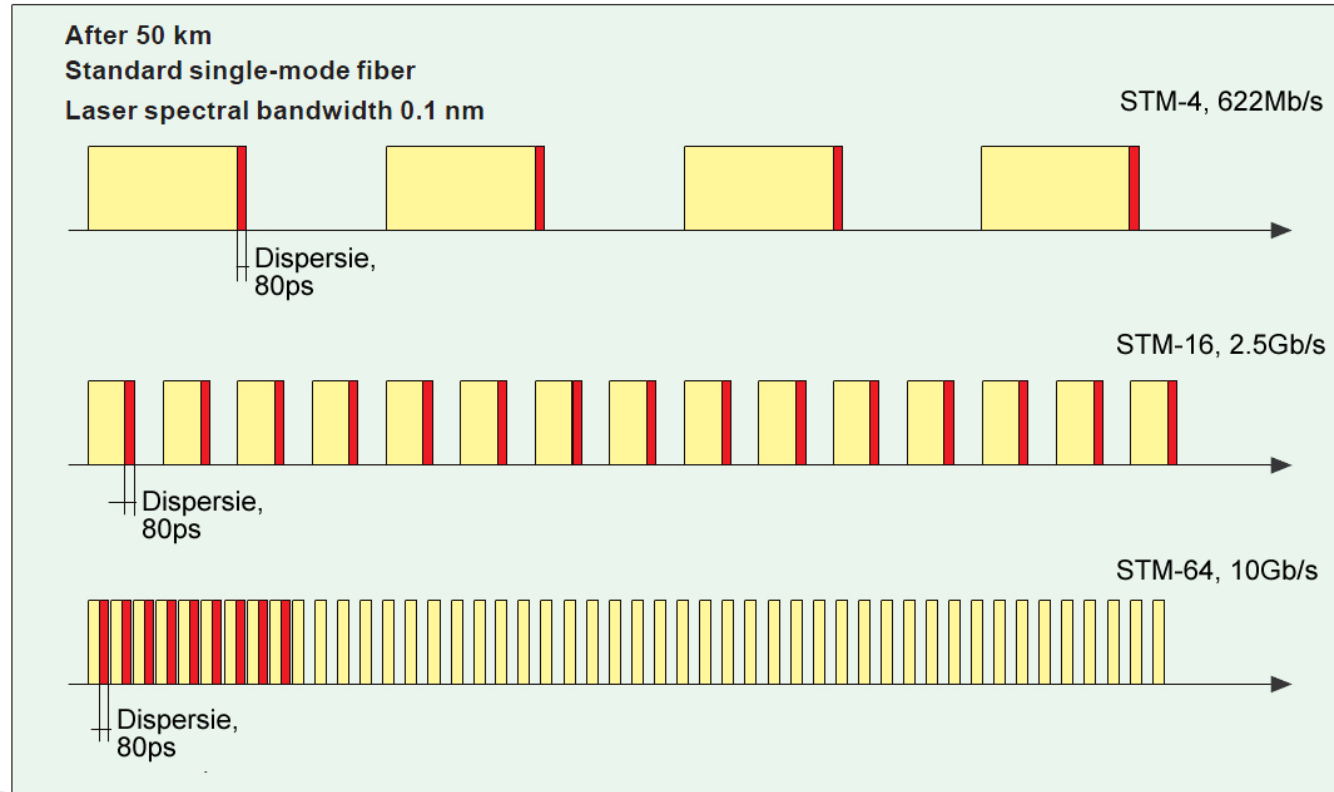
- ▶ 1550nm
- ▶ Efectul sursei
 - fibra monomod cu dispersia 16ps/nm/km@1550
 - latimea spectrala a sursei $\Delta\lambda=0.1\text{ nm}$
 - 50km

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

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

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

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



$$100 \approx 80 < 400 < 1600$$

Dispersie exemplu - 4

▶ Efectul fibrei

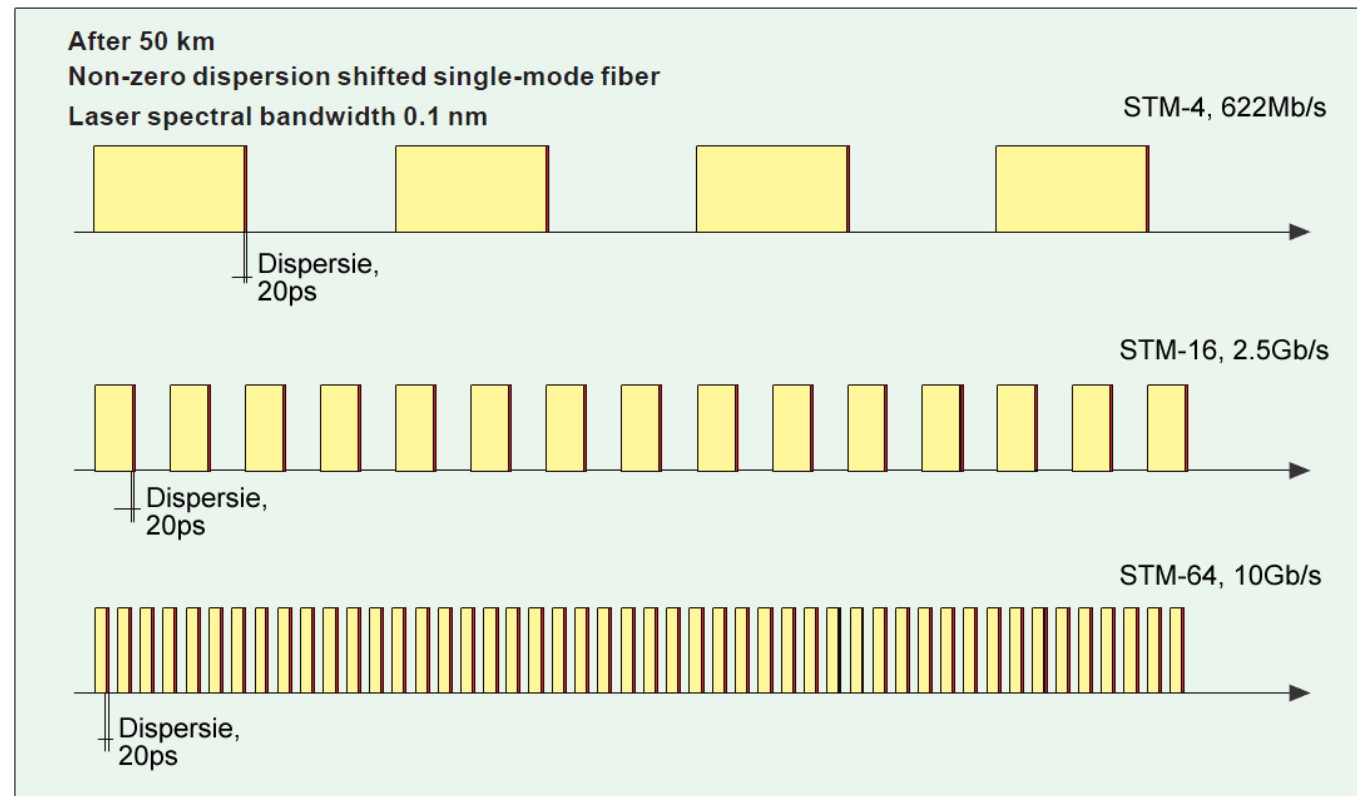
- fibra cu dispersie deplasata: **4ps/nm/km@1550**
- latimea spectrala a sursei $\Delta\lambda=0.1\text{ nm}$
- 50km

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

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

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

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



20 < 100 < 400 < 1600

Dispersie exemplu – 5

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

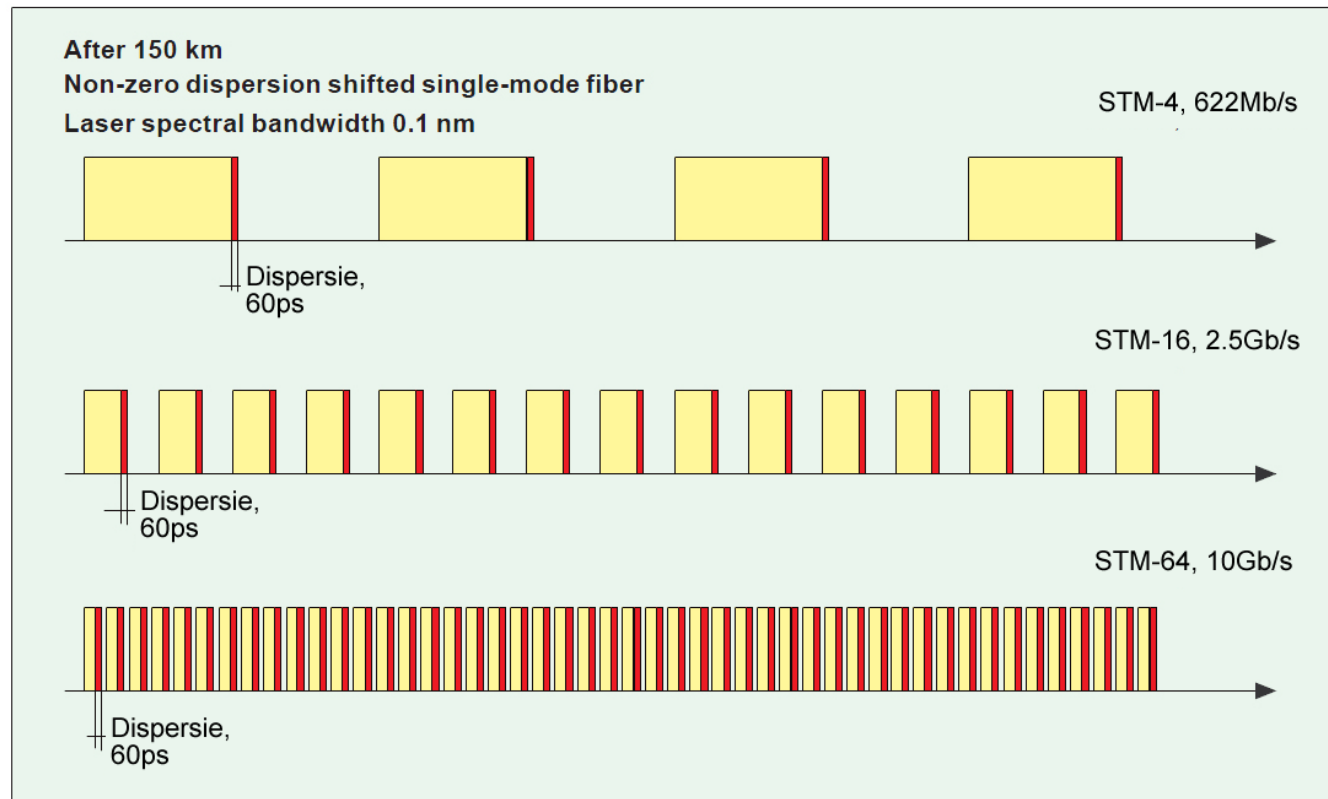
▶ Efectul fibrei

- fibra cu dispersie deplasata: 4ps/nm/km@1550
- latimea spectrala a sursei $\Delta\lambda=0.1$ nm
- **150km**

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

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

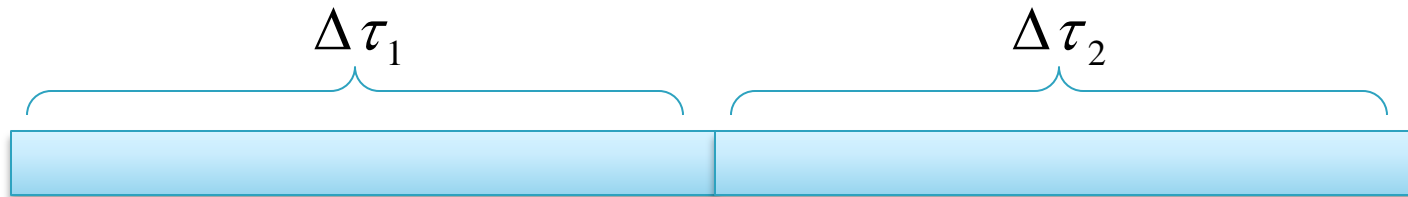
$$[\Delta\tau_{cr}] = \frac{\text{ps}}{\text{nm} \cdot \text{km}} \cdot \text{nm} \cdot \text{km} = \text{ps}$$



$$60 < 100 < 400 < 1600$$

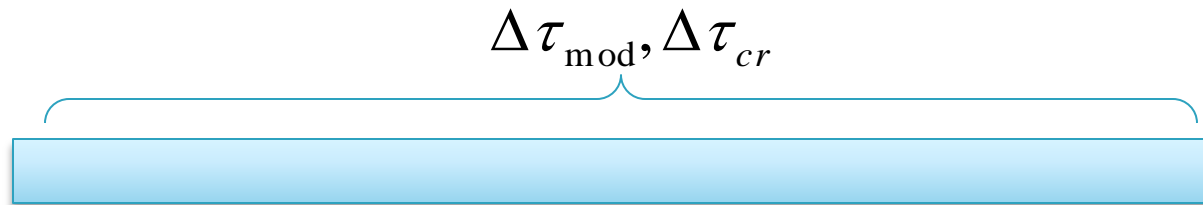
Sumarea efectelor

- ▶ efecte **succesive** se adună liniar



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

- ▶ efecte **simultane** se adună pătratic



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

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

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

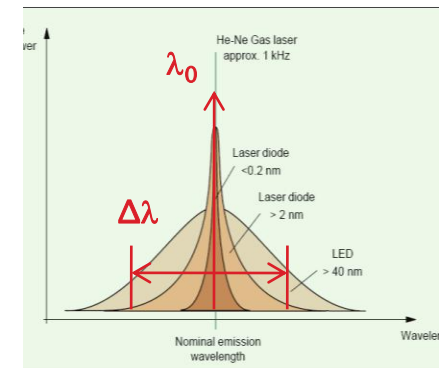
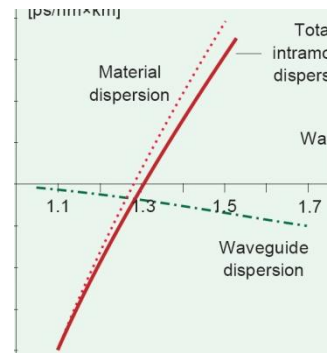
$$\Delta = 0.01 \div 0.02 \ll 1$$

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

▶ Dispersia cromatica

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

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



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

Banda

- ▶ Dispersia totala

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

- ▶ Banda

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

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

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

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

- ▶ Viteza legaturii

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

Produs Banda · Distanta

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

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

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

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

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

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

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

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

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

Produs Banda X Distanta

$$\Delta\tau_{\text{mod}} \sim L$$

$$\Delta\tau_{\text{cr}} \sim L$$

$$\Delta\tau_{\text{tot}} \sim L$$

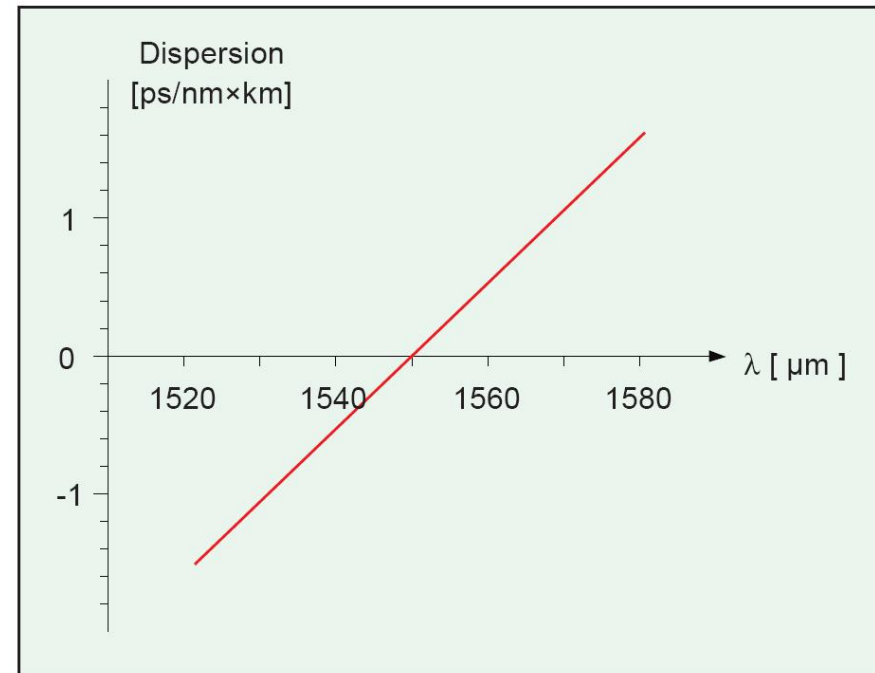
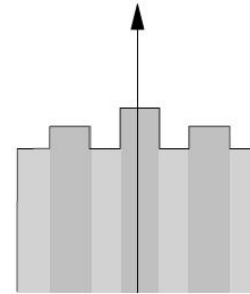
$$V[\text{Gb/s}] \sim B_{\text{el}}[\text{GHz}] \sim \frac{1}{\Delta\tau_{\text{tot}}} \sim \frac{1}{L[\text{km}]}$$

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

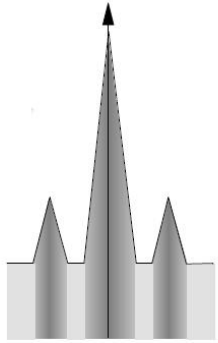
$$B_{\text{el}}[\text{MHz}] \times L[\text{km}] = \text{ct.}$$

Dispersion shifted fibers

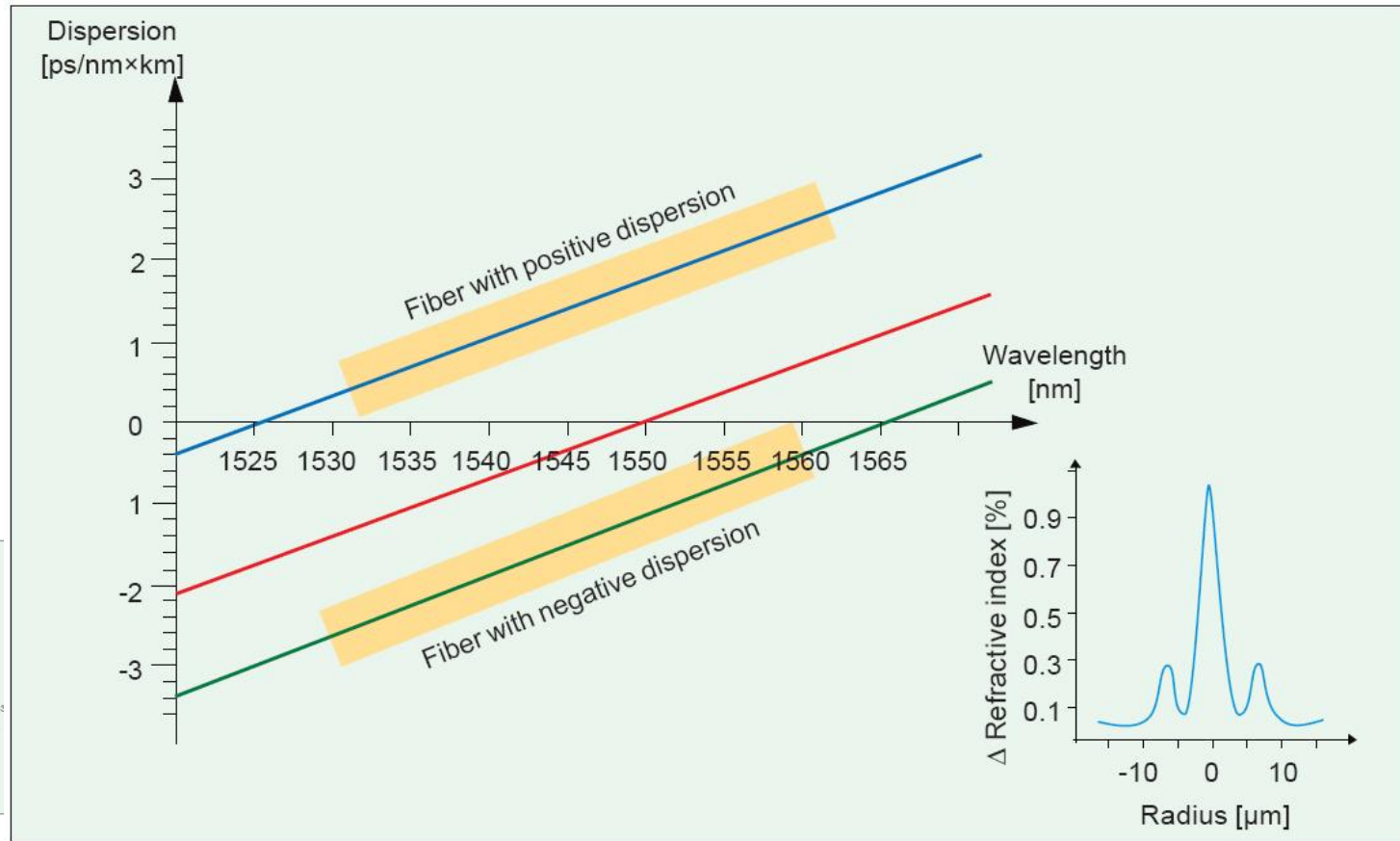
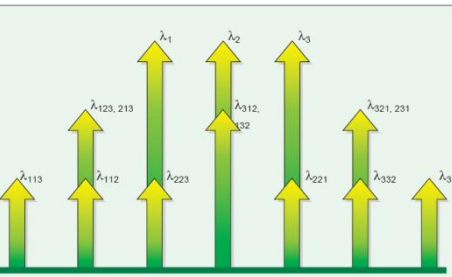
- ▶ Sticla are (nativ) dispersie cromatica 0 la 1310nm
- ▶ Atenuarea e mai mica la 1550 nm
- ▶ EDFA (Erbium doped fibre amplifiers) opereaza in banda 1550nm
- ▶ Sistemele WDM (Wavelength division Multiplexing) necesita banda larga amplificata



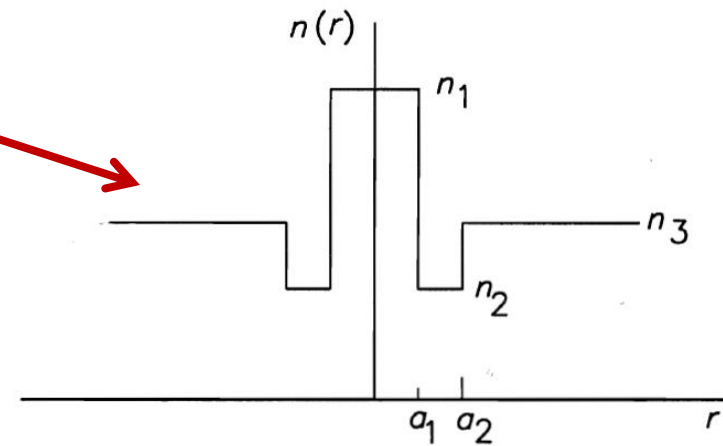
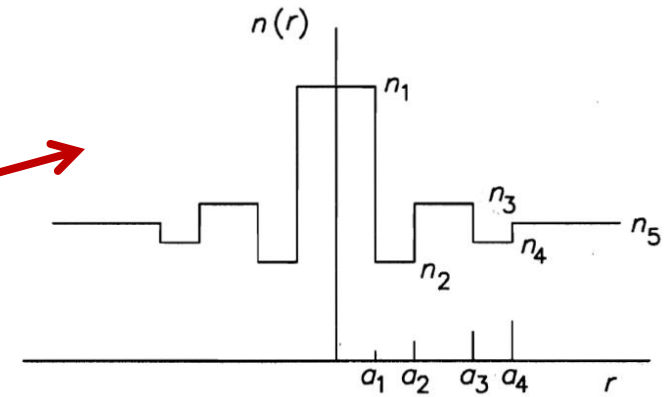
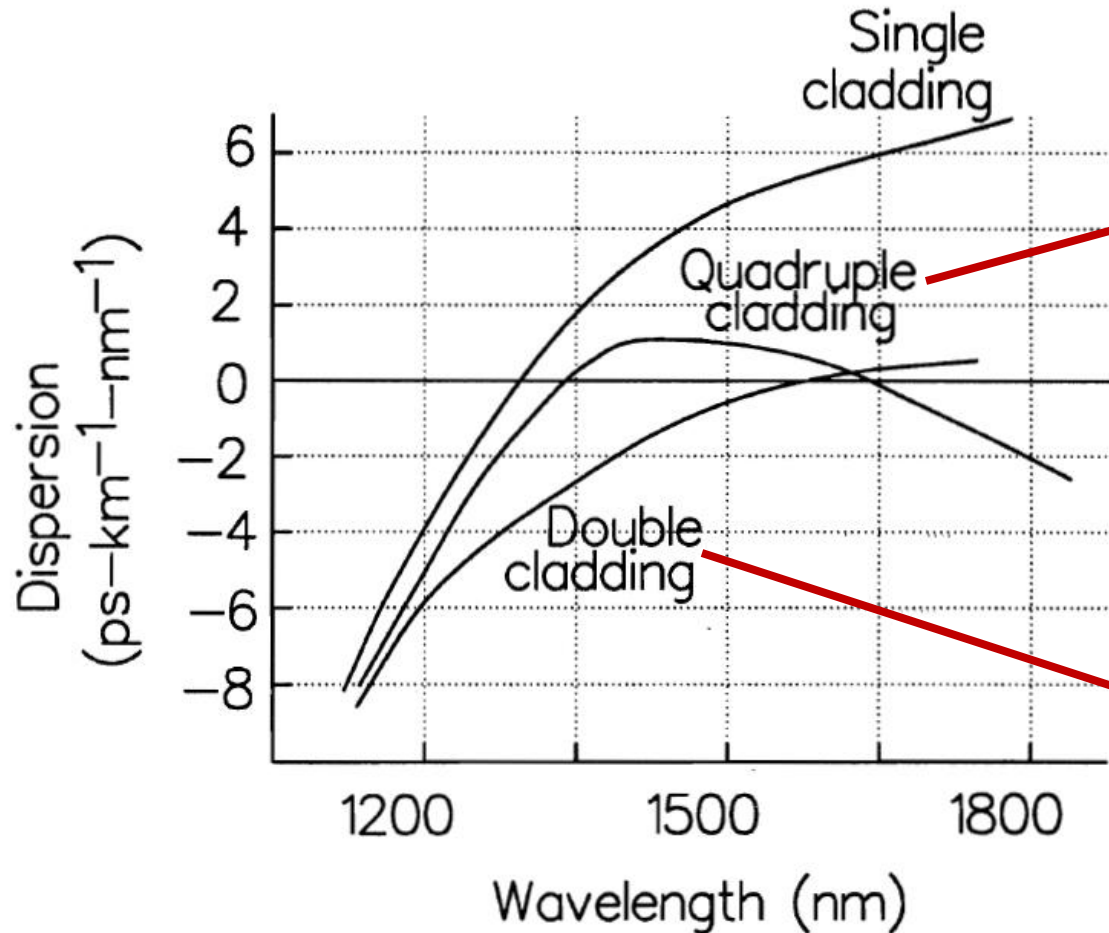
Non-zero Dispersion shifted fibers



FWM



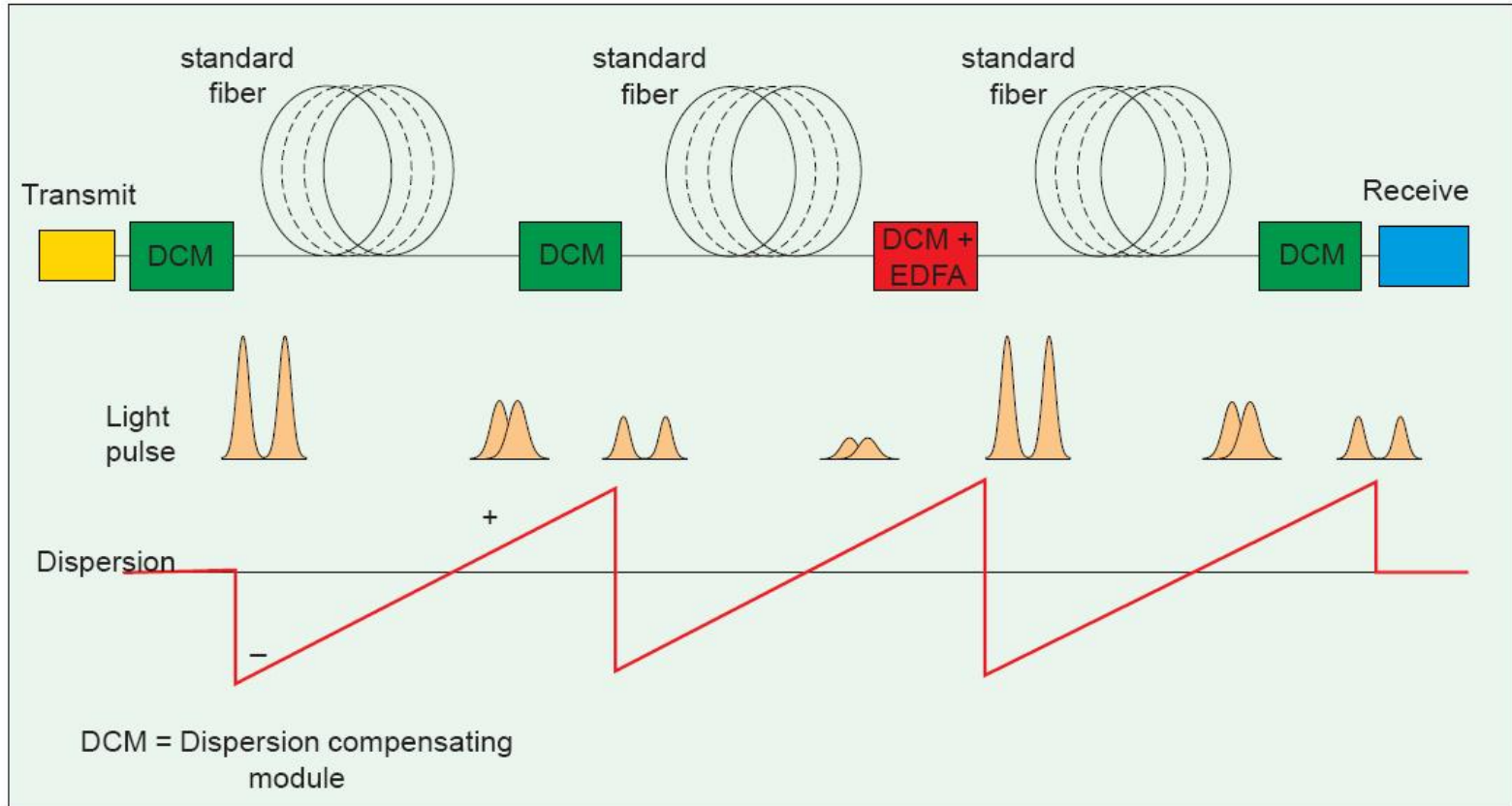
Dispersion shifted fibers



(a)

(b)

Fibra pentru compensarea dispersiei



- ▶ Dispersie: -100 ps/nm/km
- ▶ Atenuare 0.5 dB/km

Catalog – monomod

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

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 optical lengths available.

Performance Characterizations

Characterized parameters are typical values.

Core Diameter	8.2 μ m
Numerical Aperture	0.14 <i>NA is measured as the one percent power level of a one-dimensional intensity profile at 1310 nm.</i>
Zero Dispersion Wavelength (λ_0)	1317 nm
Zero Dispersion Slope (S_0)	0.088 ps/(nm ² ·km)
Effective Group Index at Wavelength (N_e)	1310 nm: 1.4670 1550 nm: 1.4675
Fatigue Resistance Parameter (N_f)	20
Coating Strip Force	Dry: 0.6 lbs. (3N) Wet, 14-day room temperature: 0.6 lbs. (3N)
Rayleigh Backscatter Coefficient (for 1 μ m Pulse Width)	1310 nm: -77 dB 1550 nm: -82 dB
Stimulated Brillouin Scattering Threshold	20 dBm ⁰

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, NextCor fiber offers a 3 dB improvement over standard single-mode fiber independent of these variables.

Formulas

Dispersion

$$\text{Dispersion} = D(\lambda) = -\frac{S_0}{4} \left[\lambda - \frac{\lambda_0^4}{\lambda^3} \right] \text{ ps/(nm}^2\text{·km)}$$

for 1200 nm \leq λ \leq 1625 nm
 λ = Operating Wavelength

Cladding Non-Circularity

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

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: opticalfibres@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: 800-525-5724 (U.S. and Canada)
607-786-8125 (International)
Fax: 800-539-3632 (U.S. and Canada)
607-786-8344 (International)
Email: corning@corning.com

Europe
Ph: 00 800 6620 6621 (U.K., Ireland, France, Germany, The Netherlands, Spain and Sweden)
+1 607 248 4377 (All Other Countries)
Fax: 00 44 1244 287 4377
Email: 786 8344

Asia Pacific
Australia
Ph: 1-800-148-690
Fax: 1-800-148-568

Indonesia
Ph: 001-800-015-721-1261
Fax: 001-800-015-721-1262

Malaysia
Ph: 1-800-80-3156
Fax: 1-800-80-3155

Philippines
Ph: 1-800-1-116-0338
Fax: 1-800-1-116-0339

Singapore
Ph: 800-1300-955
Fax: 800-1300-956

Thailand
Ph: 001-800-1-1-721-1261
Fax: 001-800-1-1-721-1264

Latin America
Brazil
Ph: 000817-762-4732
Fax: 000817-762-4996

Mexico
Ph: 001-800-235-1719
Fax: 001-800-339-1472

Venezuela
Ph: 800-1-4418
Fax: 800-1-4419

Greater China
Email: CCCofic@corning.com

Beijing
Ph: (86) 10-6505-5066
Fax: (86) 10-6505-5077

Hong Kong
Ph: (852) 2807-2723
Fax: (852) 2807-2152

Shanghai
Ph: (86) 21-3222-4608
Fax: (86) 21-6288-1575

Taiwan
Ph: (886) 2-2716-0338
Fax: (886) 2-2716-0339

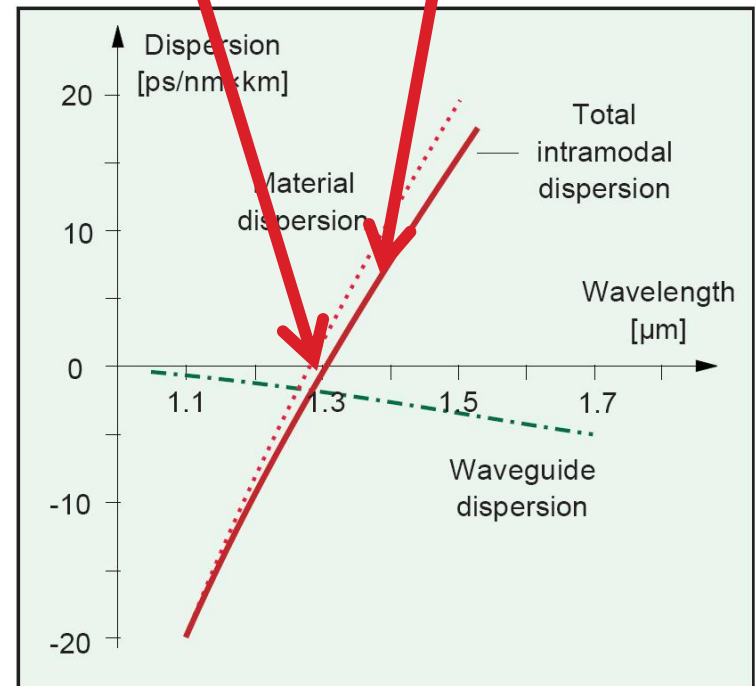
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Any warranty of any nature relating to any Corning optical fiber is only contained in the written agreements between Corning Incorporated and the direct purchaser of such fiber.

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jar-jveia scan at 1510 nm

Zero Dispersion Wavelength (λ_0)	1317 nm
Zero Dispersion Slope (S_0)	0.088 ps/(nm ² ·km)
Effective Group Index at Wavelength (N_e)	1310 nm: 1.4670 1550 nm: 1.4675



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.

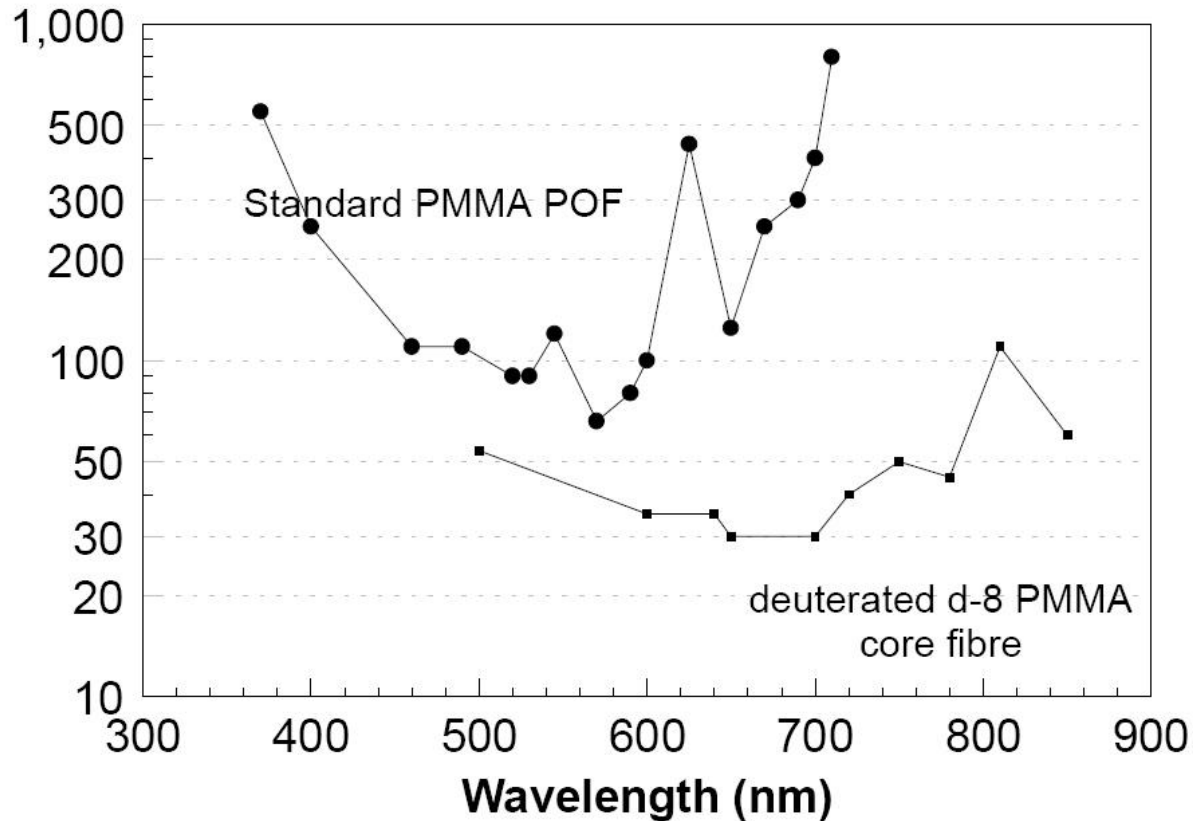
Fibra standard ITU G.652

- ▶ Diametru teaca = 125 μm
- ▶ MFD = 9÷10 μm la 1300 nm
- ▶ $\lambda_C = 1100\div 1280$ 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

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

- ▶ Laboratorul de microunde si optoelectronica
- ▶ <http://rf-opto.etti.tuiasi.ro>
- ▶ rdamian@etti.tuiasi.ro