Optoelectronică

Curs 5

2023/2024

Disciplina 2023/2024

- 2C/1L Optoelectronică **OPTO**
- **Minim 7 prezente curs + laborator**
- Curs – conf. **Radu Damian**
  - an IV μE
  - Marti 14(**:10**)-16:00, P8
  - E – 70% din nota (50%+20%)
    - **20% test (VP) la curs**, saptamana 4-6?
  - probleme + (2p prez. curs)
  - **toate materialele permise**
- Laborator – **drd. Stefan Stoica**
  - an IV μE
    - Marti 16-20 par
    - Max. 7 prezente
  - L – 30% din nota (+Caiet de laborator)

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)
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- **Dispozitive de captare a energiei solare** (principiu de functionare, utilizare, proiectare)

*** – VP**

Documentatie

RF-OPTO

English | Romana |

Main Courses Master Staff Research Students

Microwave and Optoelectronics Laboratory

We are enlisted in the Telecommunications Department of the Electronics, Telecommunication and Information Technology Faculty (**ETTI**) from the "Gh. Asachi" Technical University (**TUIASI**) in Iasi, Romania

We currently cover inside **ETTI** the fields related to:

- Microwave Circuits and Devices
- Optoelectronics
- Information Technology

Courses

Nr.	Course	Shortcut	Code	Type	Semester	Credits	Weekly	Examination	Link
1	Microwave Devices and Circuits for Radiocommunications	**DCMR**	DOS412T	DOS	7	4	0P,1L,0S,2C	Exam	details
2	Monolithic Microwave Integrated Circuits	**CIMM**	RD.IA.207	DOMS	11	6	1.5L,0S,2C,0P	Exam	details
3	Advanced Techniques in the Design of the Radio-communications Systems	**TAPSR**	RD.IA.103	DIMS	9	6	1.5P,0L,0S,2C	Exam	details
4	Optical Communications	**CO**	DOS409T	DOS	7	5	0P,1L,0S,3C	Colloquium	details
5	Optical Communications	**OC**	EDOS409T	DOS	7	5	0P,1L,0S,3C	Exam	details
6	Satellite Communications	**CS**	RC.IA.104	DIMS	9	6	0L,0S,2C,1.5P	Exam	details
7	Applied Informatics 1	**IA1**	DOF135	DOF	1	4	0P,1L,0S,2C	Verification	details
8	Applied Informatics 1	**AI1**	EDOF135	DOF	1	4	0P,1L,0S,2C	Verification	details
9	Databases, Web Programming and Interfacing	**DWPI**	ITT.IA.601	DIS	11	5	1P,1L,0.25S,1C	Verification	details
10	Web Applications Design	**PAW**	RC.IA.108	DIMS	10	5	1L,0S,1.5C,1P	Exam	details
11	Optoelectronics	**OPTO**	DID405M	DID	8	4	0P,1L,0S,2C	Colloquium	details
12	Microwave Devices and Circuits for Radiocommunications (English)	**MDCR**	EDOS412T	DOS	8	4	0P,1L,0S,2C	Exam	details

Documentatie

- RF-OPTO
  - http://rf-opto.etti.tuiasi.ro
- Fotografie
  - “examen” online
  - necesara la laborator/curs

Bonus (~0.5-4.15)

Disciplina: Optoelectronica, structuri, tehnologii, circuite
An: 2015/2016

Bonus-uri care se aplica la nota de la teza obtinute prin:
- prezenta la curs (0.5p / 3pr)
- 3 miniteste aplicate la curs (max. 3 X 1.5p)
- contributie la site rf-opto (foto <C5=1p, >C5=0.5p)

Nr.	Student	Grupa	Prezente curs	Bonus prezenta	Bonus foto	Bonus T1	Bonus T2	Bonus T3	Total Bonus	Obs.
1	CIOLPAN OCTAVIAN	5306	3	0.5					0.5	-
2	NITA COSTEL-CATALIN	5307	4	0.5	1				1.5	-
3	BARON BOGDAN-IONUT	5405	12	2	1	0.5		0.75	4.25	-

Prezenta

Curs
Laborator

Liste

Studenti care nu pot intra in examen
Bonus-uri acumulate

- **Minim** 7 prezente
- 0.5p/3prez
- 3 teste
- foto <C**7**/<C**9**

Lumina ca undă electromagnetică

Capitolul 2

Cuprins

- **Lumina ca undă electromagnetică** (ecuaţiile lui Maxwell, ecuaţia undelor, parametrii de propagare)
- **Elemente de fotometrie şi radiometrie** (mărimi energetice/luminoase)
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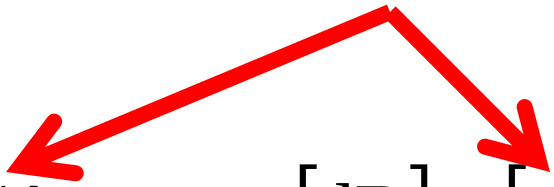
Calculul atenuarii

$$\text{Pierderi} = \frac{P_{out}}{P_{in}} < 1 \qquad \text{Pierderi}[\text{dB}] = 10 \cdot \log_{10}\left(\frac{P_{out}}{P_{in}}\right) < 0$$



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

$$\text{Castig} = \frac{P_{out}}{P_{in}} > 1 \qquad \text{Castig}[\text{dB}] = 10 \cdot \log_{10}\left(\frac{P_{out}}{P_{in}}\right) > 0$$

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

Calculul atenuarii

$$\text{Pierderi/Atenuare} \rightarrow P_{out} < P_{in} \rightarrow P_{out}[\text{dBm}] < P_{in}[\text{dBm}]$$

$$P_{out}[\text{dBm}] = P_{in}[\text{dBm}] - \text{Pierderi/Atenuare}[\text{dB}]$$

$$\text{Castig/Amplificare} \rightarrow P_{out} > P_{in} \rightarrow P_{out}[\text{dBm}] > P_{in}[\text{dBm}]$$

$$P_{out}[\text{dBm}] = P_{in}[\text{dBm}] + \text{Castig/Amplificare}[\text{dB}]$$

Reprezentare logaritmică

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

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

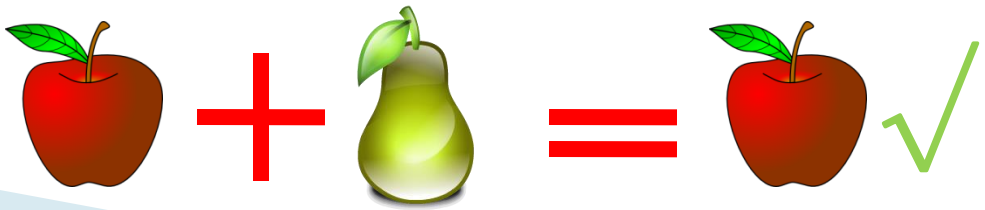
0 dB	= 1
+ 0.1 dB	= 1.023 (+2.3%)
+ 3 dB	= 2
+ 5 dB	= 3
+ 10 dB	= 10
−3 dB	= 0.5
−10 dB	= 0.1
−20 dB	= 0.01
−30 dB	= 0.001

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

[dBm] + [dB] = [dBm]

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

[x] + [dB] = [x]



Fotometrie şi radiometrie

Capitolul 3

Cuprins

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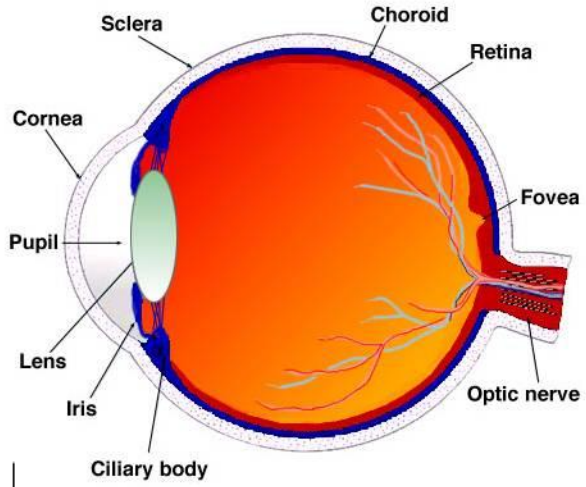
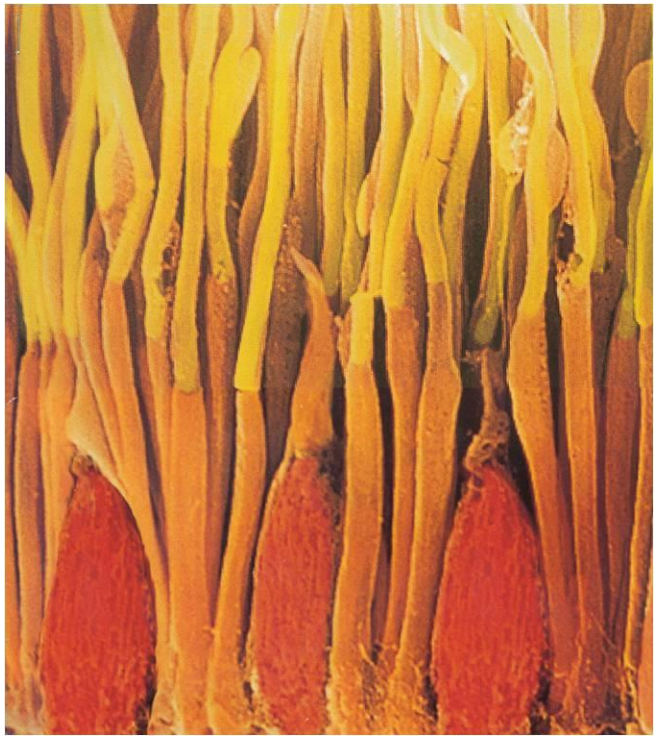
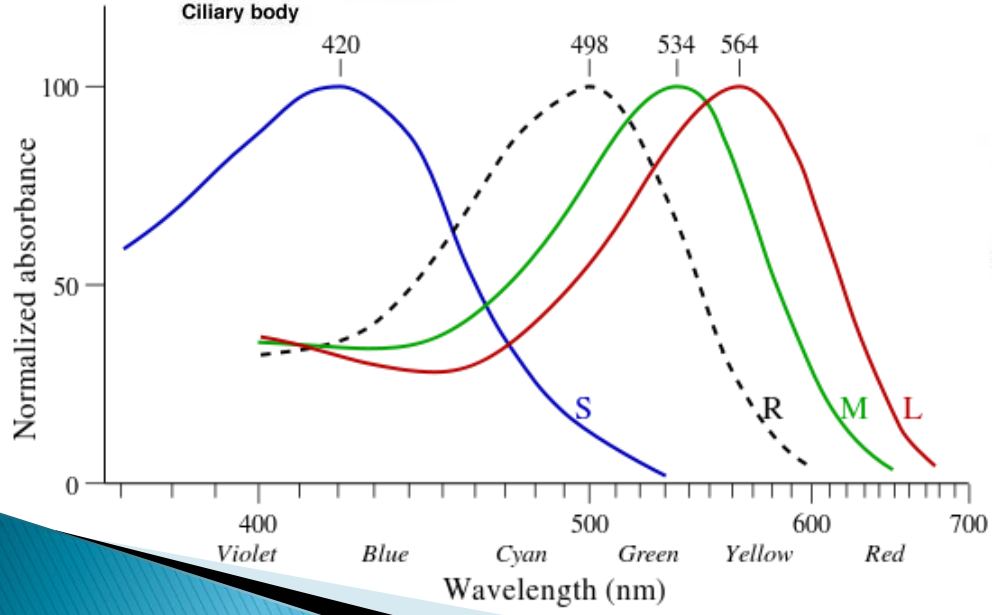
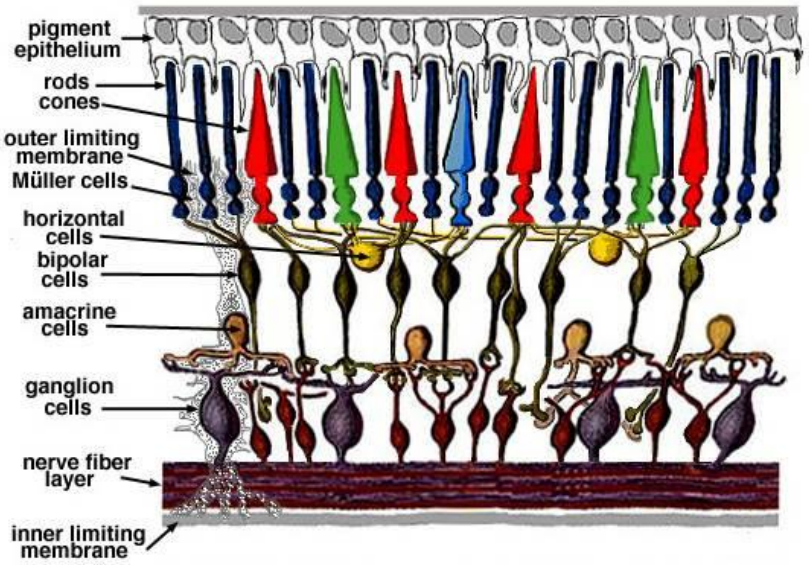
Ochiul uman

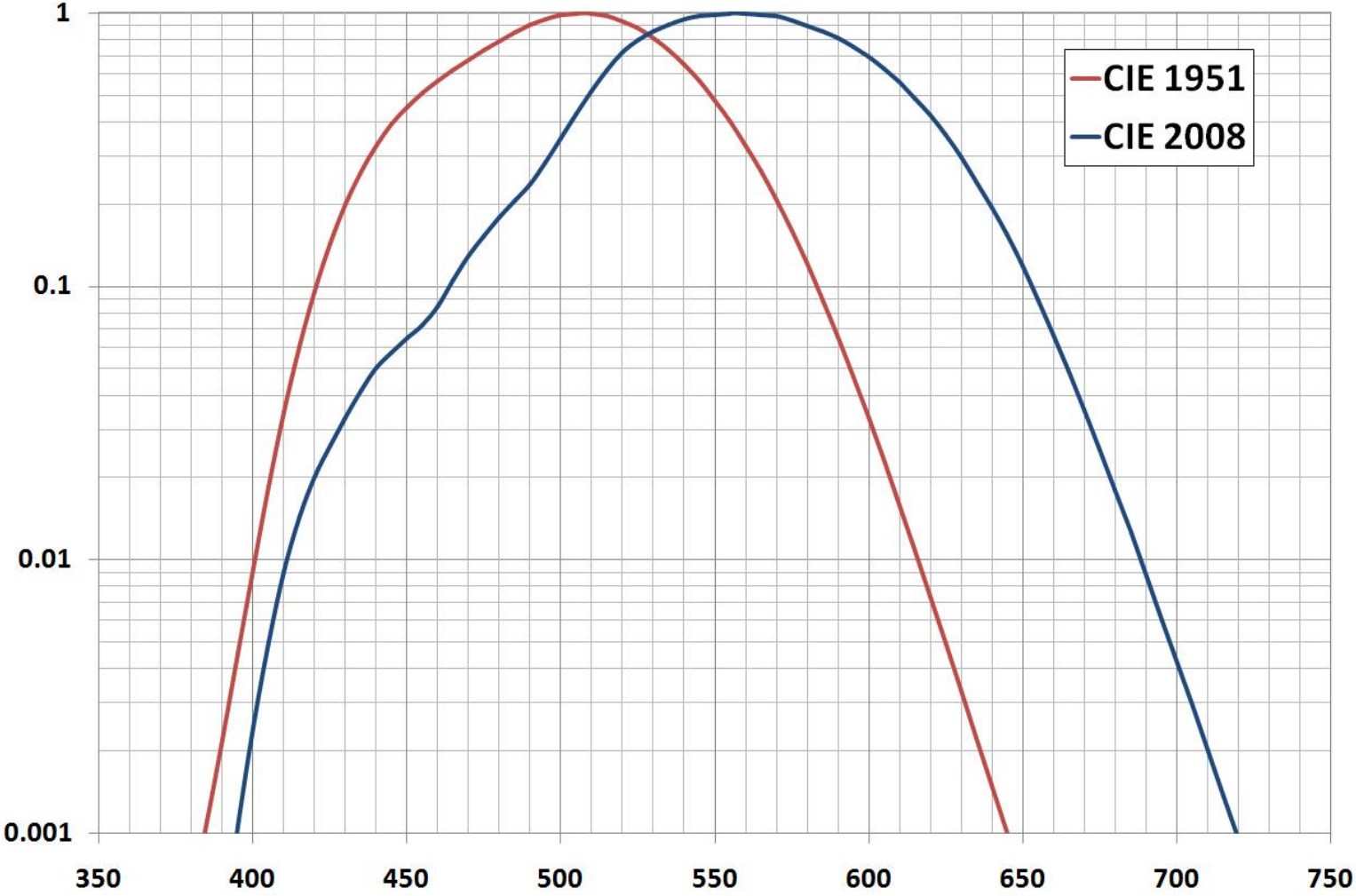

Sclera
Choroid
Retina
Cornea
Fovea
Pupil
Lens
Iris
Optic nerve
Ciliary body



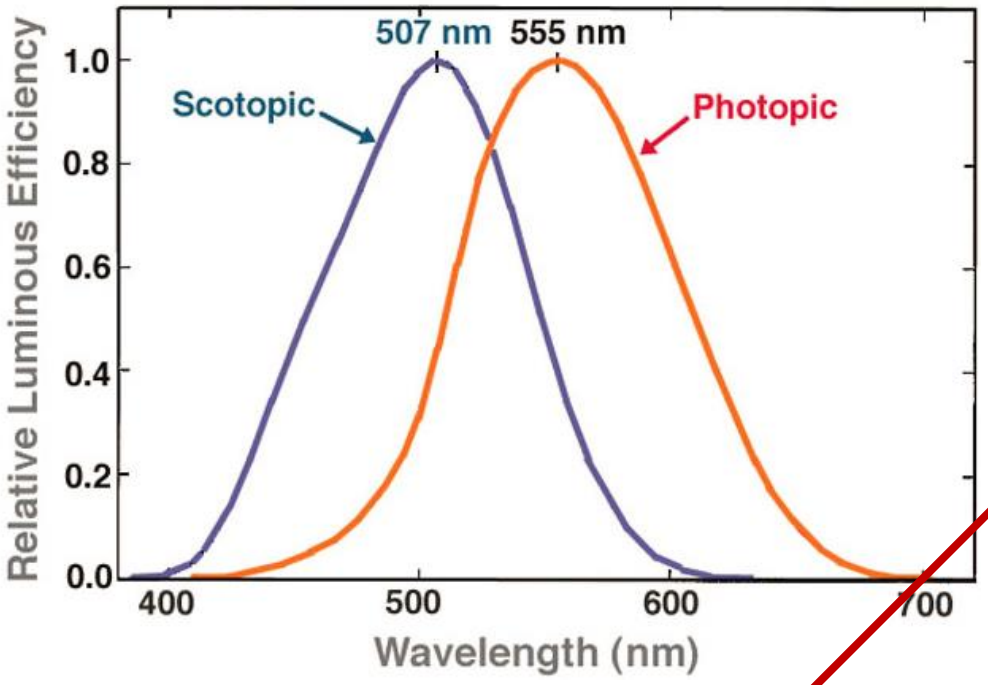

420
498
534
564
100
50
0
Normalized absorbance
S
R
M
L
400
500
600
700
Violet
Blue
Cyan
Green
Yellow
Red
Wavelength (nm)

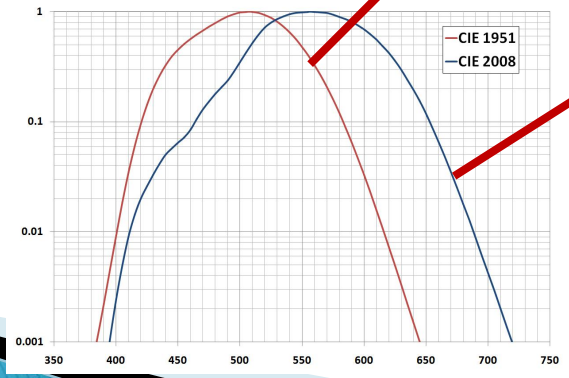

pigment epithelium
rods
cones
outer limiting membrane
Müller cells
horizontal cells
bipolar cells
amacrine cells
ganglion cells
nerve fiber layer
inner limiting membrane

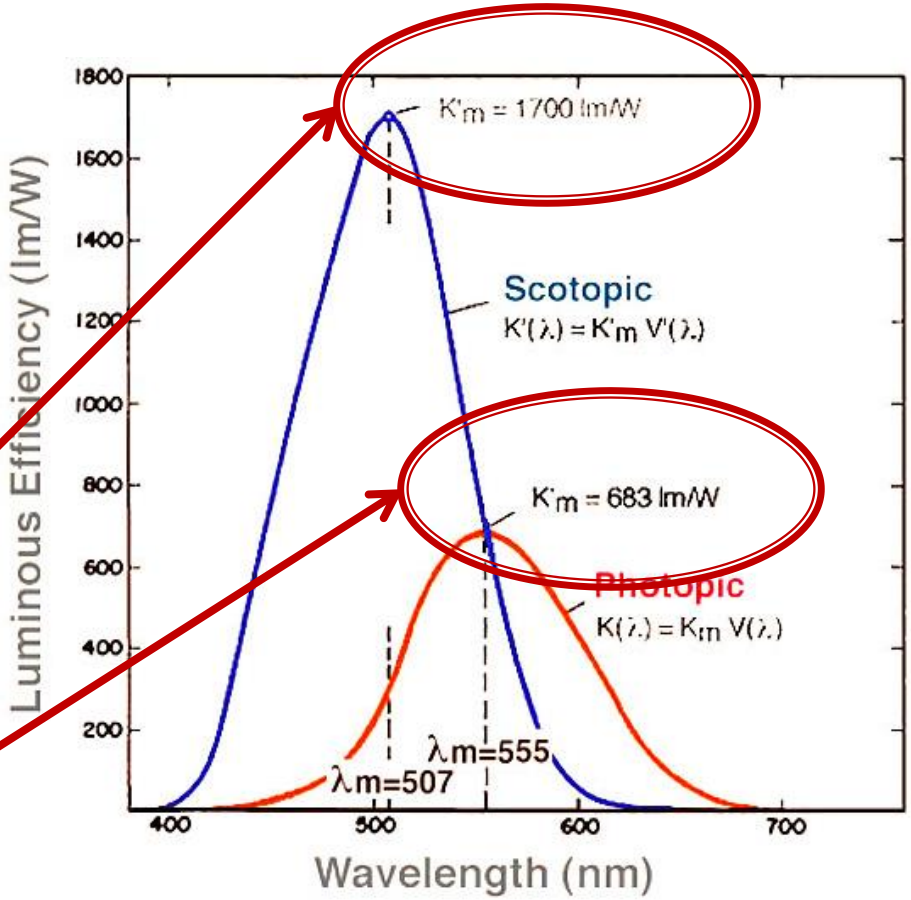
CIE V(λ) fotopic / scotopic



Relatie radiometrie/fotometrie

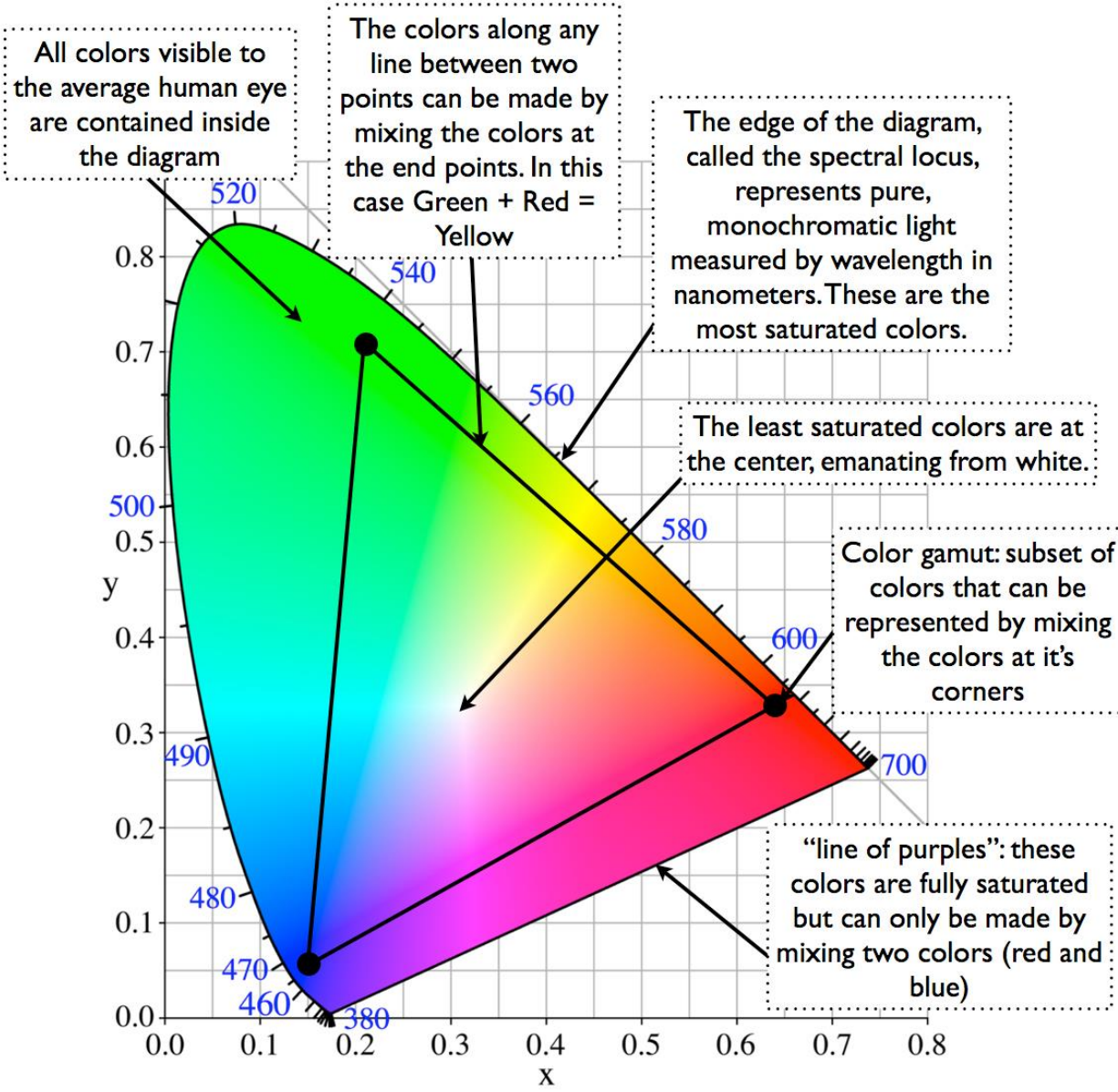






CIE xy 1931

- utilizare



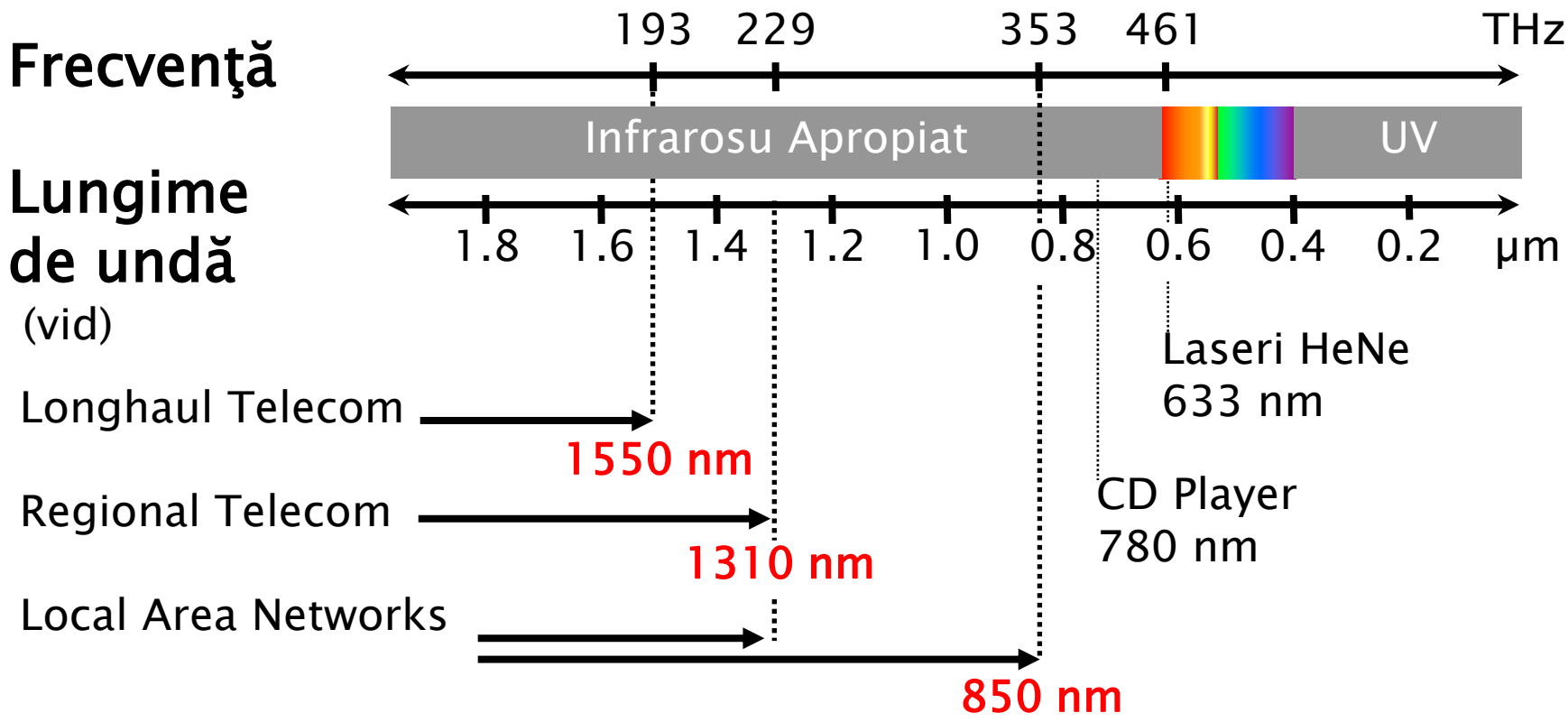
Fibra optică

Capitolul 4

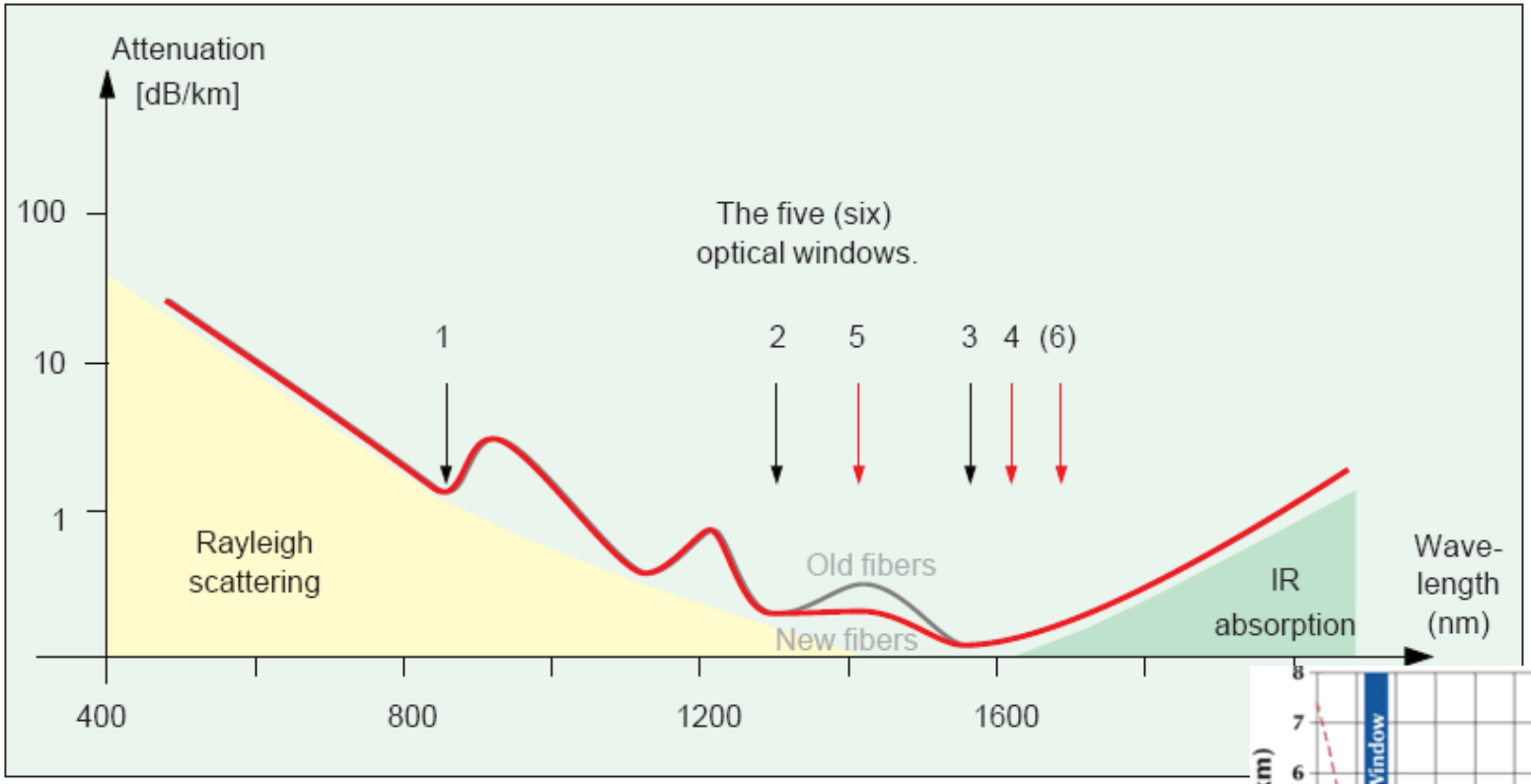
Aplicatii majore

- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- Iluminare
  - Putere ridicata, lumina alba (GaInN)
- Energie solara
  - Efect fotovoltaic (Si)

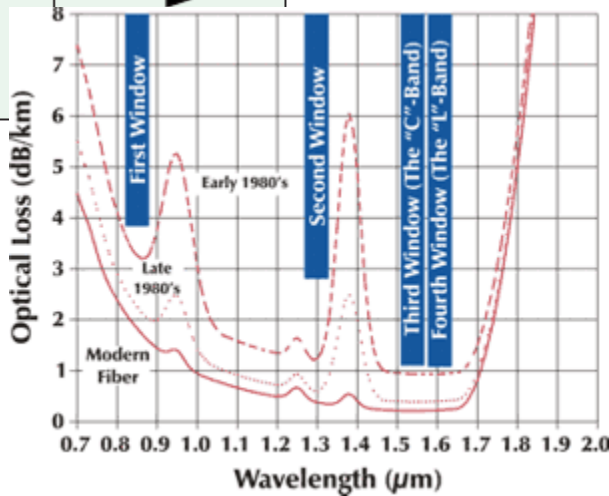
Benzi de lucru in comunicaţiile optice



Atenuarea în fibra optică (SiO_2)



850nm, 1310nm, 1550nm



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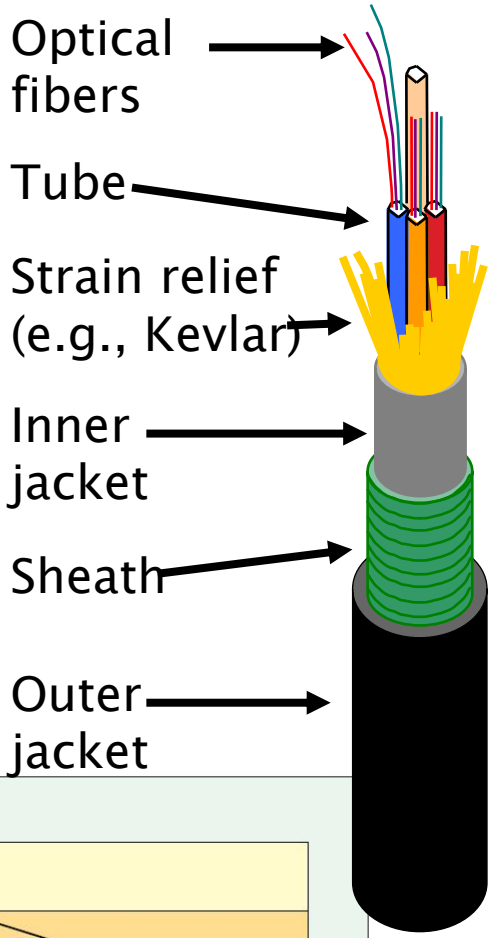
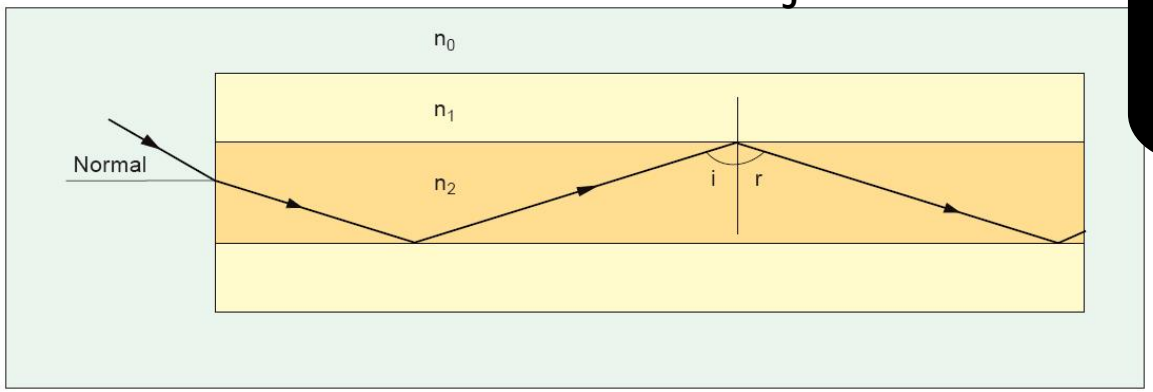
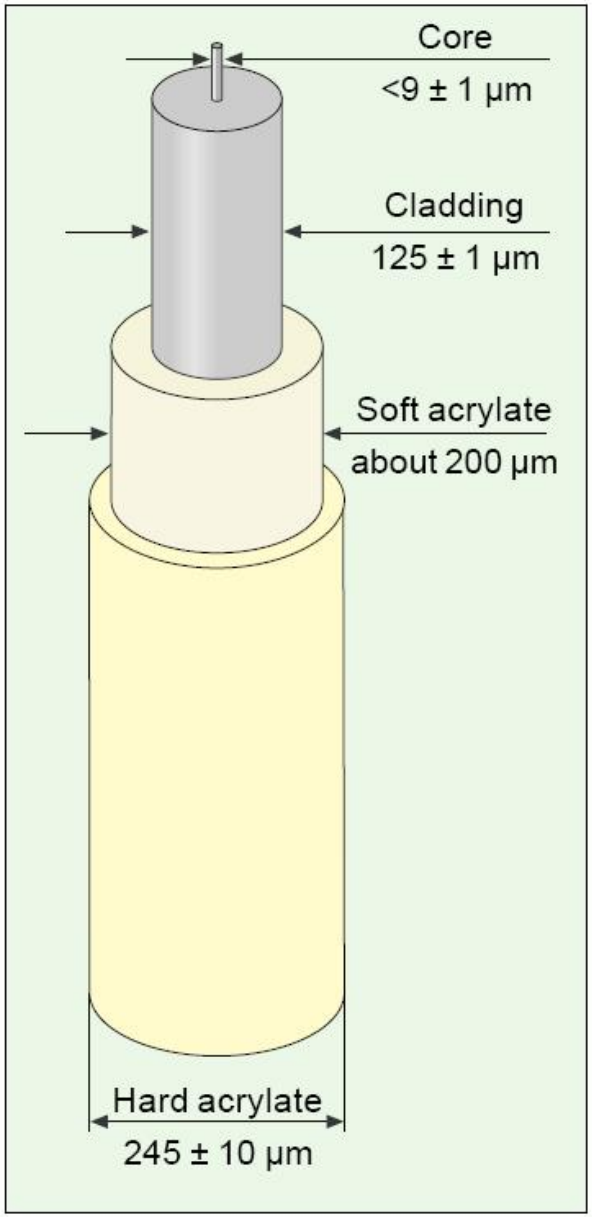
Fibra optica

- un ghid de unda dielectric
  - miez
  - teaca







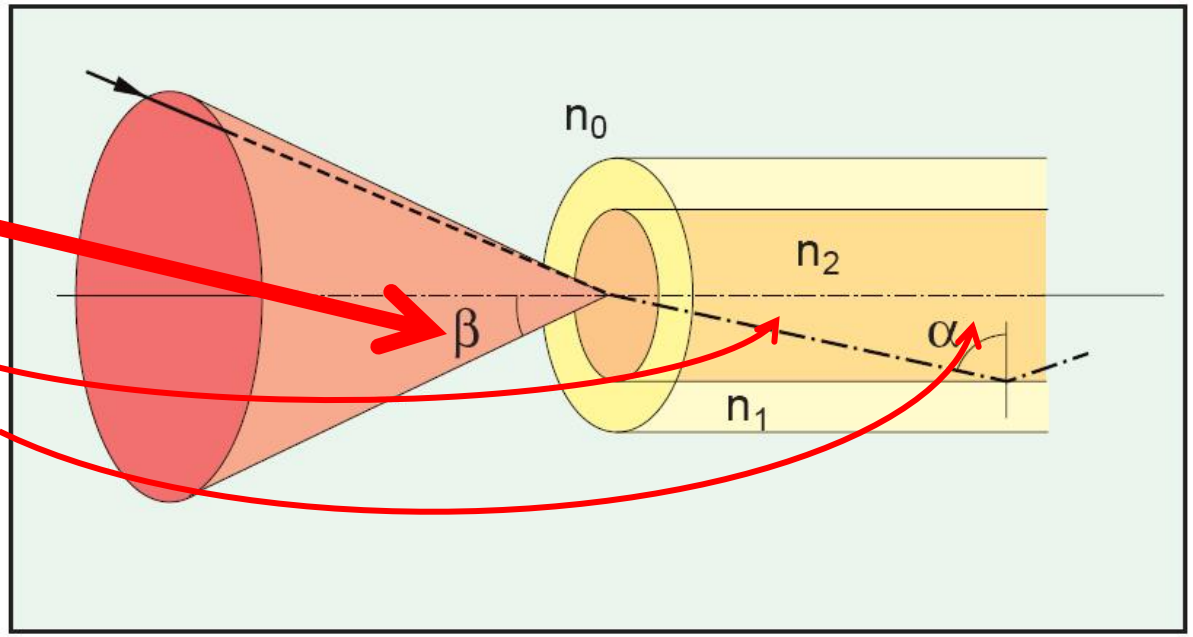
Unghi de acceptanta, apertura numerica

- Unghi de acceptanta

$$n_0 \cdot \sin\theta_{ACC} = n_2 \cdot \sin\phi_2$$

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

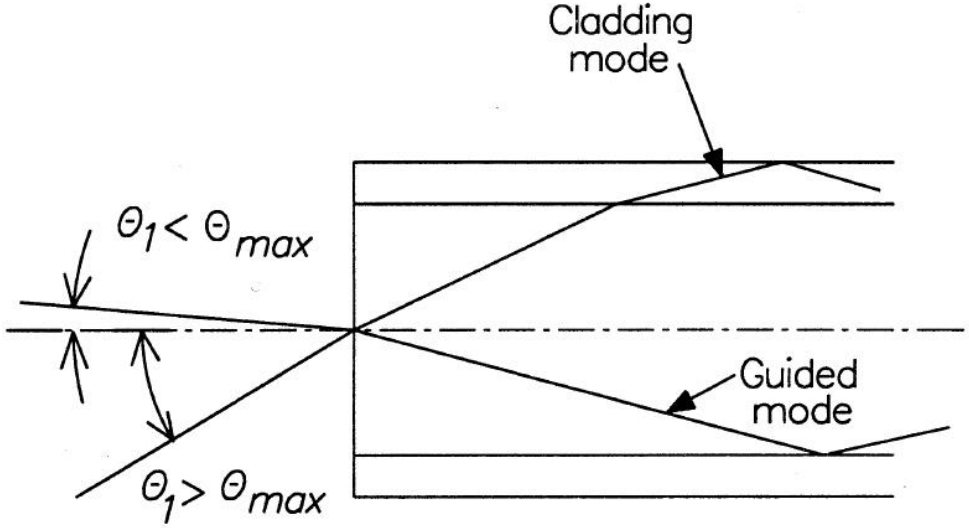
- **Apertura numerica**



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

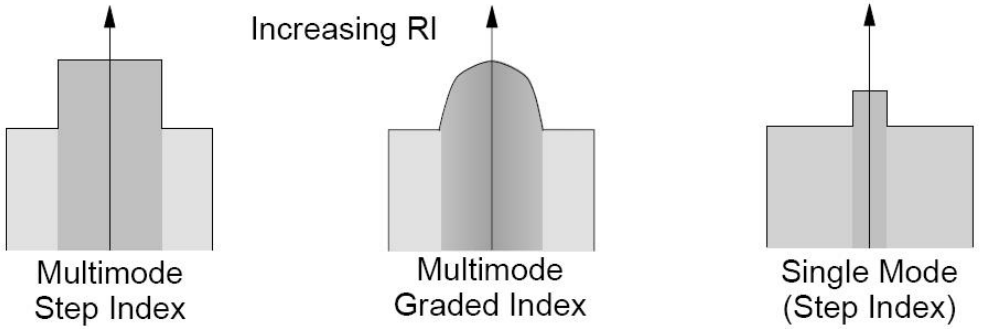
$$NA = n_2\sqrt{\frac{n_2^2 - n_1^2}{n_2^2}} = \sqrt{n_2^2 - n_1^2}$$

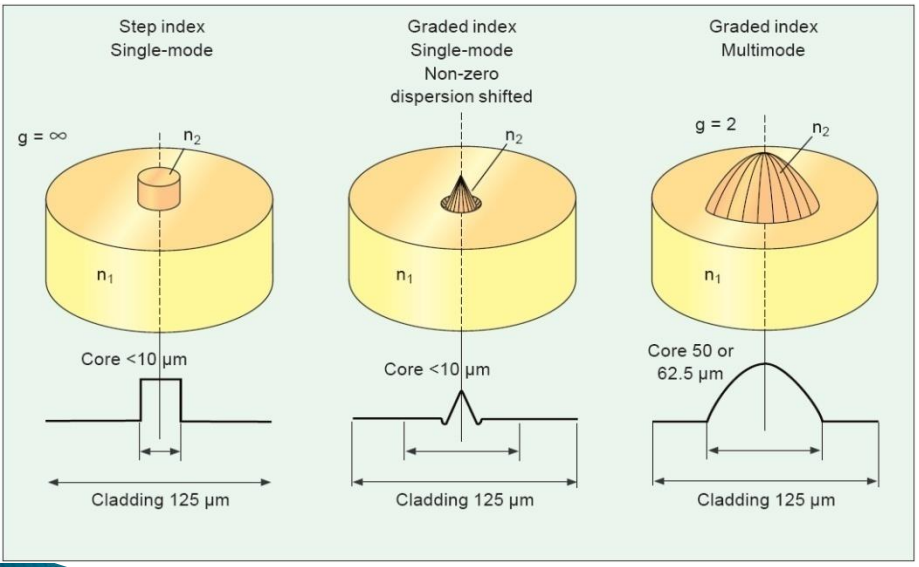
n_2 – miez
n_1 – teaca
$n_2 > n_1$!!

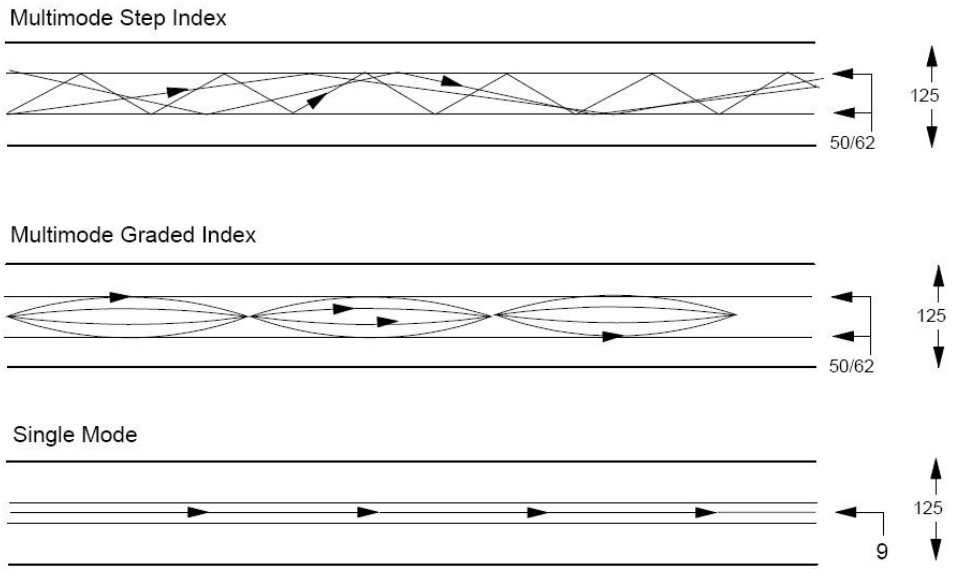


Tipuri de fibra

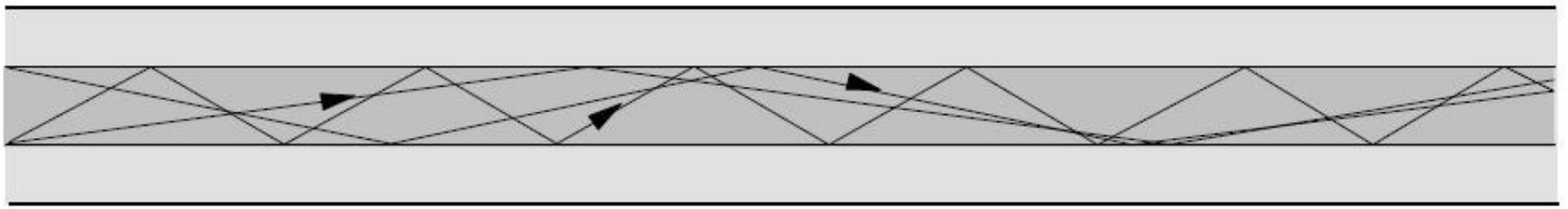
- Monomod
- Multimod
  - cu salt de indice
  - cu indice gradat



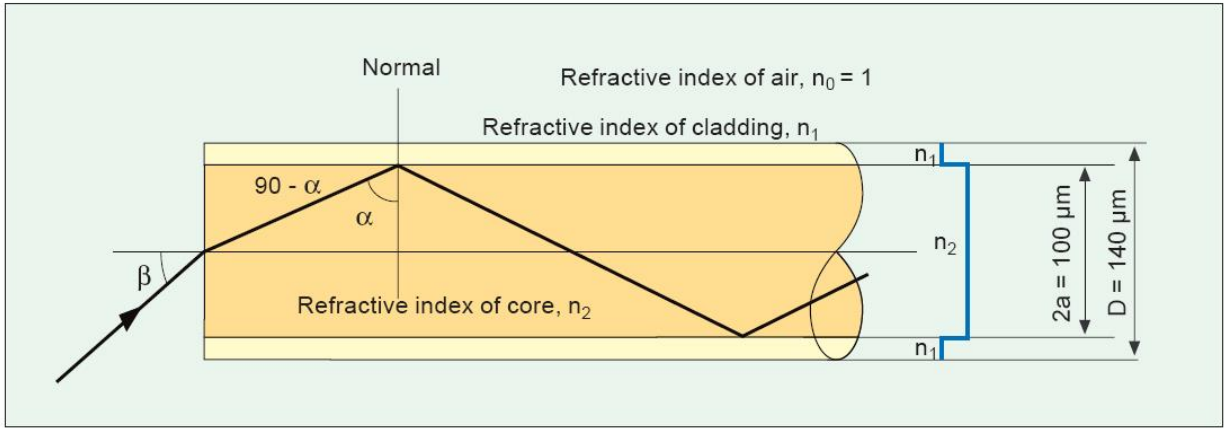


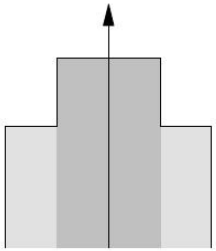


Fibre multimod cu salt de indice



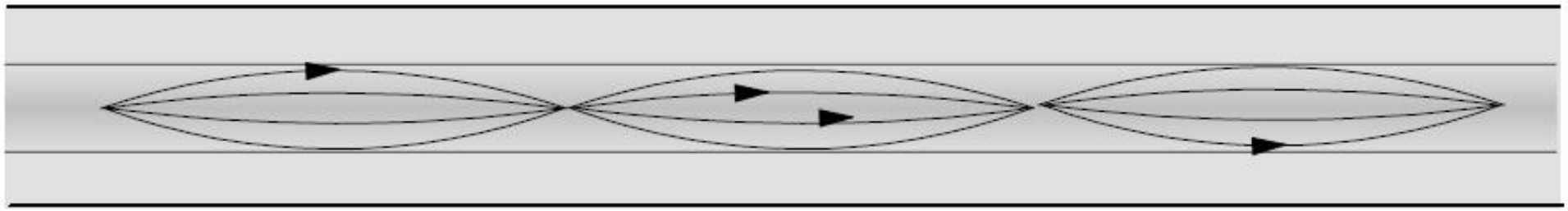
- 50/125 sau 62.5/125 (µm)
- 15–50 MHz · km



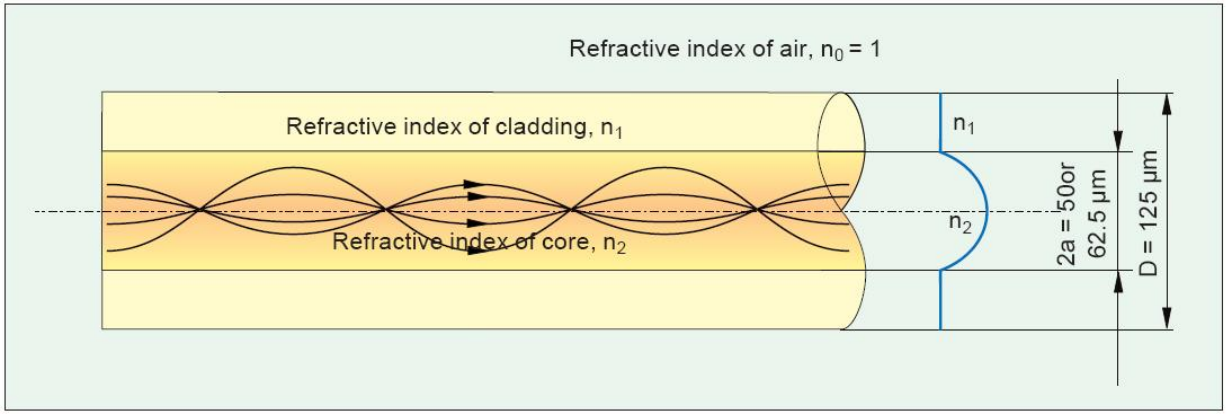


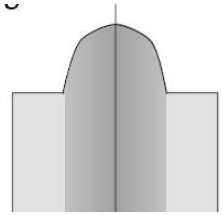
		glass	plastic
core diameter 2a	62.5	~~100~~ µm	980 µm
cladding diameter D	125	~~140~~ µm	1000 µm
core refractive index n_2		1.48	
cladding refractive index n_1		1.45	

Fibre multimod cu indice gradat



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

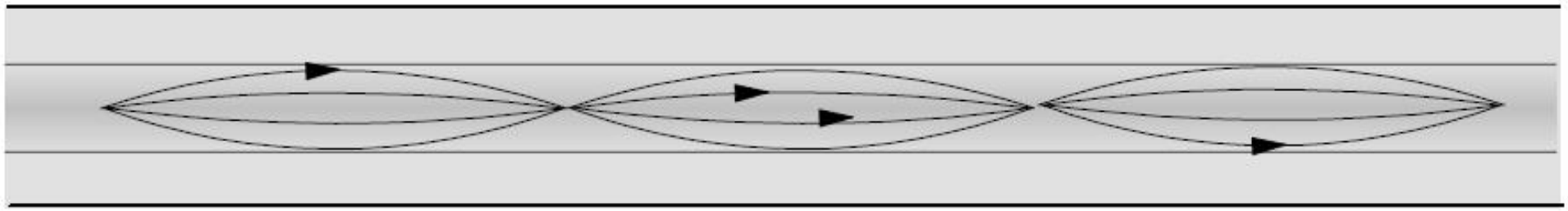




Core diameter 2a	50 or 62.5 µm
Cladding diameter D	125 µm
Maximum refractive index, core	1.46
Relative differential refractive index	0.010

Fata Morgana

Fibre multimod cu indice gradat

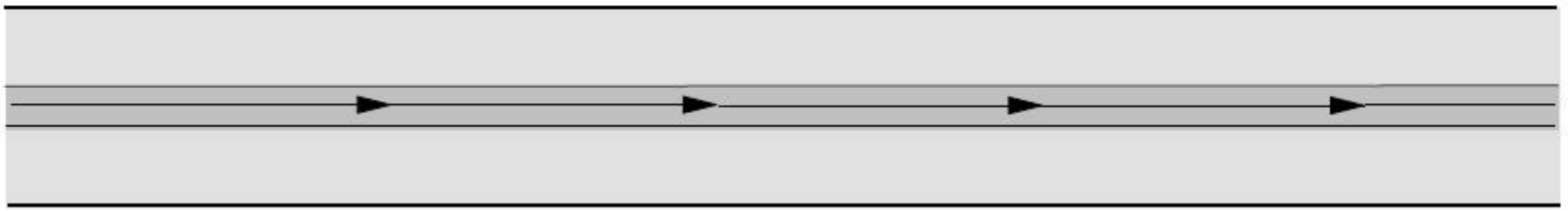


$$n(r) = n_2\left[1 - \Delta\left(\frac{r}{a}\right)^g\right]$$

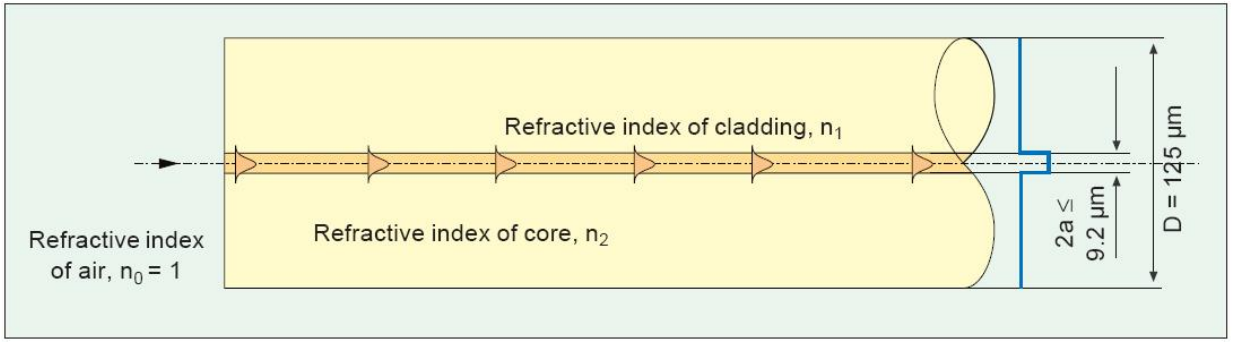
$$\Delta = \frac{NA^2}{2n_2^2} = \frac{n_2^2 - n_1^2}{2n_2^2} \approx \frac{n_2 - n_1}{n_2} \approx \frac{\Delta n}{n} \quad \text{for } \Delta << 1$$

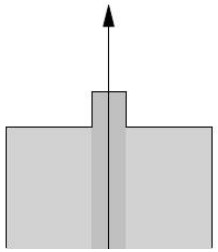
- g = 1 – indice gradat triunghiular
- g = 2 – indice gradat parabolic
- g = ∞ – salt de indice

Fibre monomod



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





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)

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

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

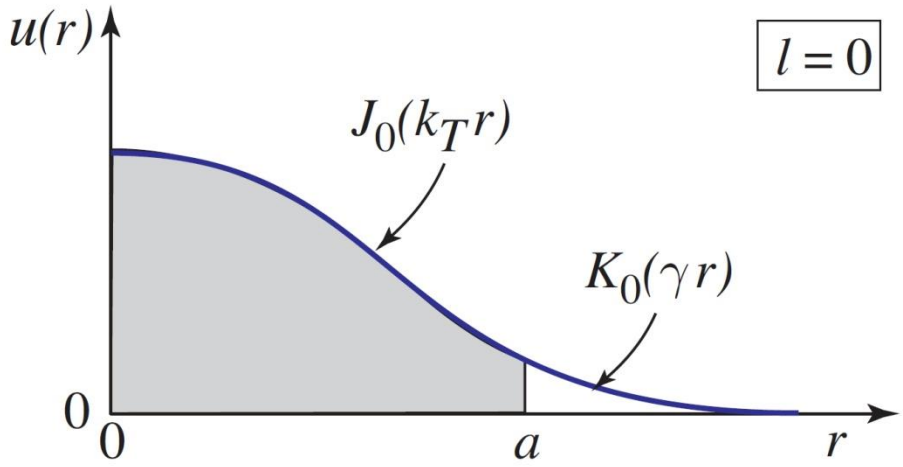
$$\frac{d^2 u}{dr^2} + \frac{1}{r}\frac{du}{dr} + \left(k_T^2 - \frac{l^2}{r^2}\right)u = 0, \qquad r < a$$

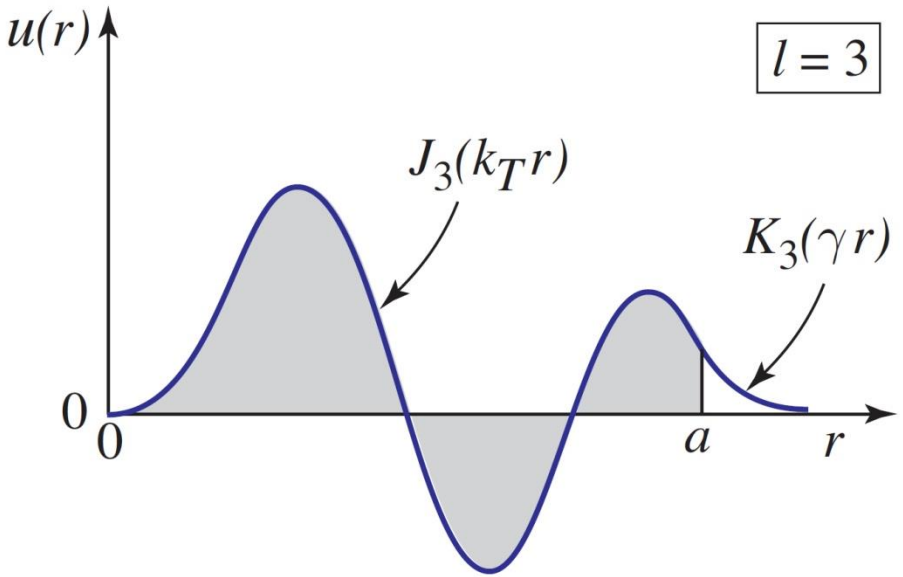
$$\frac{d^2 u}{dr^2} + \frac{1}{r}\frac{du}{dr} - \left(\gamma^2 + \frac{l^2}{r^2}\right)u = 0, \qquad r > a$$

Ghid cilindric dielectric

- solutii proportionale cu functii Bessel

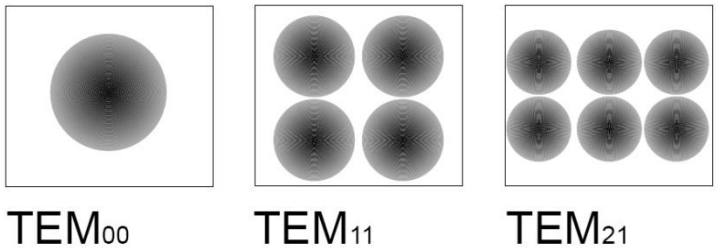
$$u(r) \propto \begin{cases} J_l(k_T r), & r < a \quad \text{(core)} \\ K_l(\gamma r), & r > a \quad \text{(cladding)} \end{cases}$$



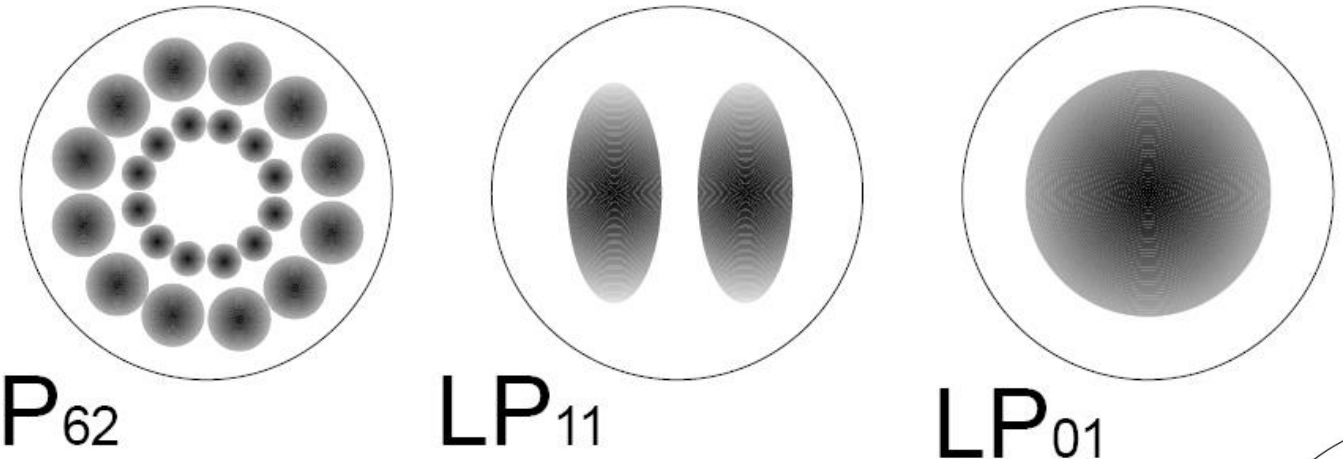


Moduri in fibra

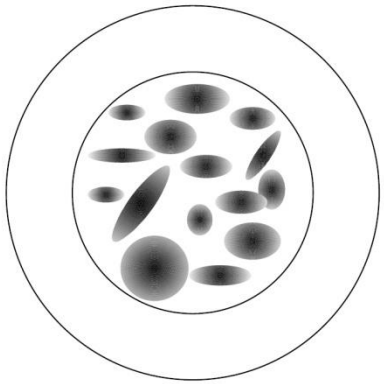
- Moduri in ghid rectangular



- Moduri linear polarizate in fibra



"Sparkle" pattern



Frecventa normalizata

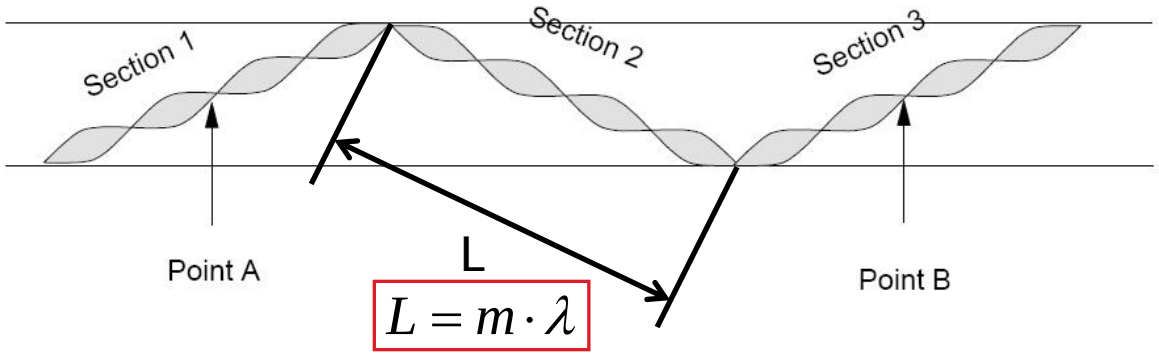
- Frecventa normalizata

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

a – **raza** miezului

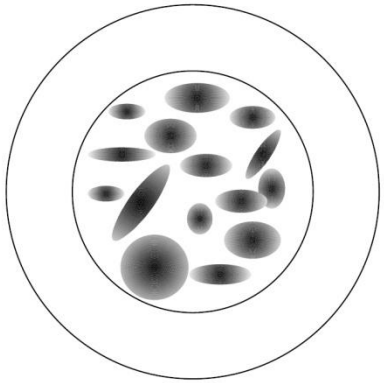
$$k = \frac{2\pi}{\lambda}$$

- Numar de moduri



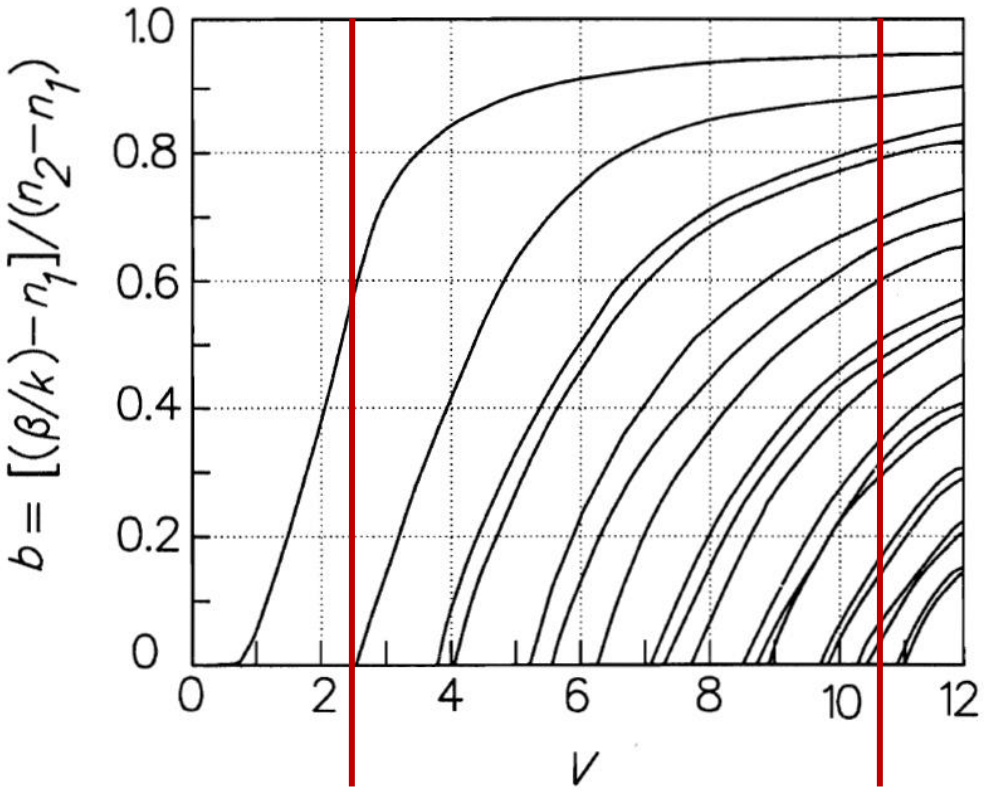
$$L = m \cdot \lambda$$

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



Frecventa normalizata – monomod

- Fibre monomod



b – coeficient de propagare modal relativ

$$V \le V_C = 2.405$$

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

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

Exemplu:

$2a = 8.5\mu m$

$NA = 0.11$

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

Frecventa normalizata

- Numar de moduri
  - Multimod cu salt de indice

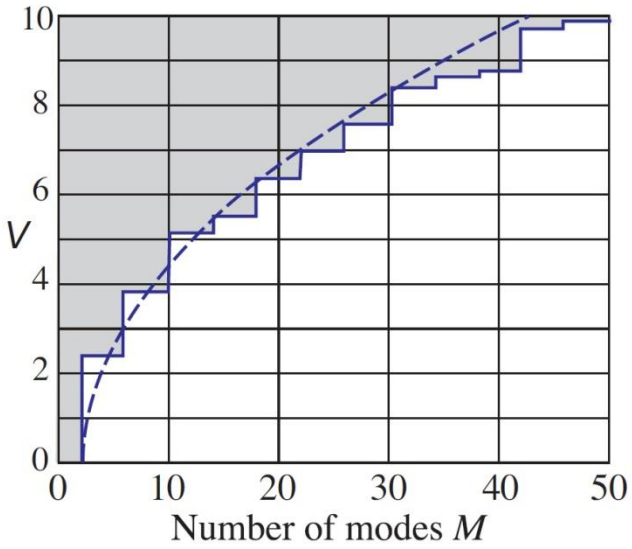
$$g = \infty \quad \Rightarrow \quad N \approx \frac{V^2}{2}$$

  - Multimod cu indice gradat

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

  - Monomod

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



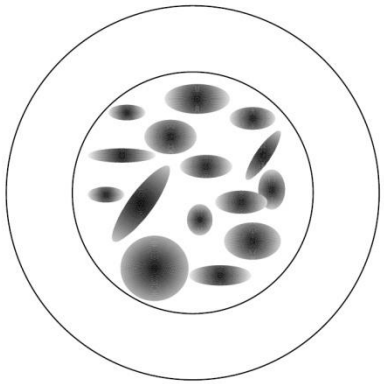
$V \le V_C = 2.405$ exista un singur mod (solutii fc. Bessel)

Exemplu

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

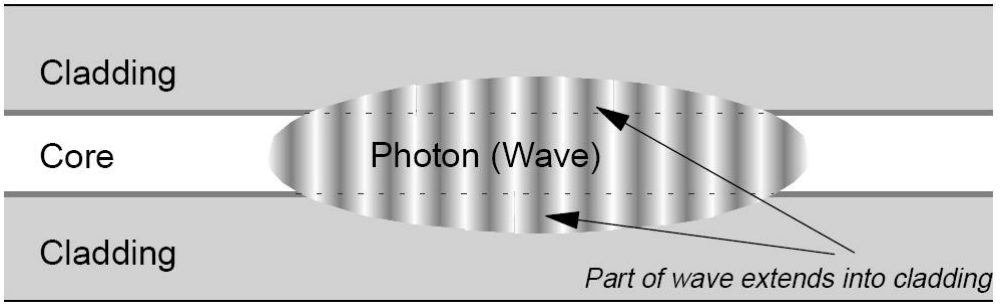
$$V = 2\pi \frac{a}{\lambda} NA = 2\pi \frac{25}{1} 0.2 = 2 \cdot \pi \cdot 5 \approx 31.4$$

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

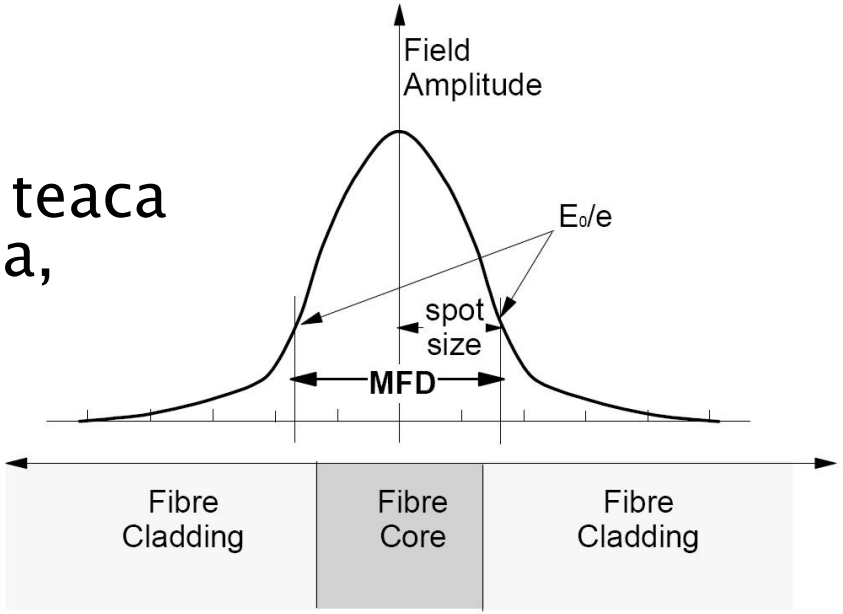


Propagarea in fibra monomod

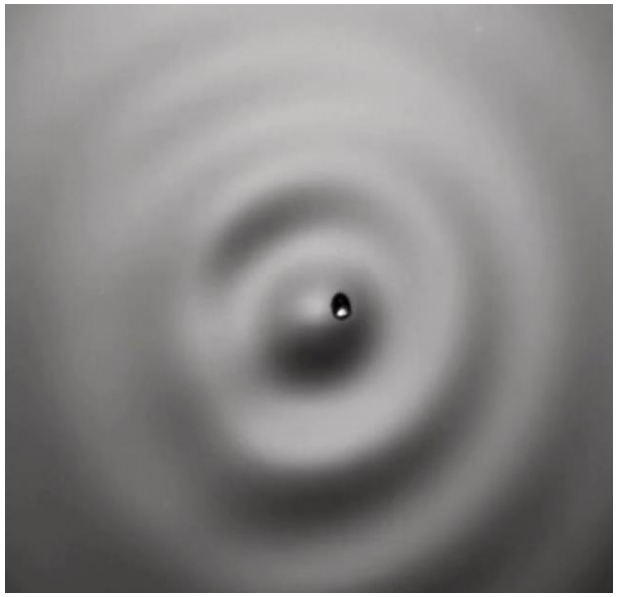
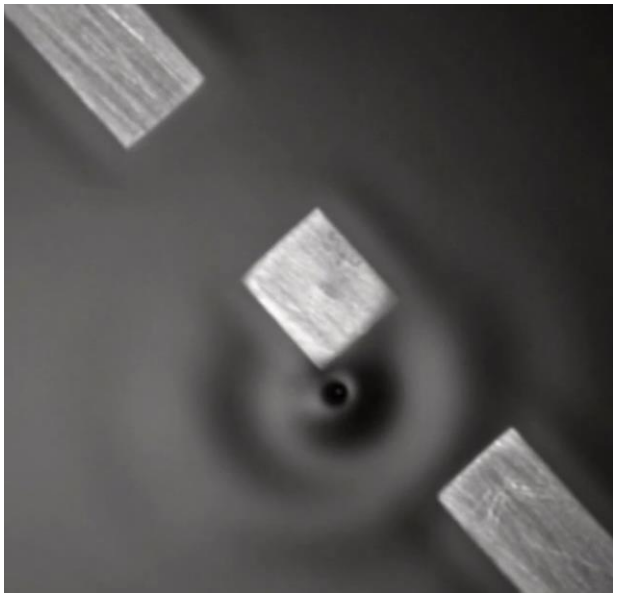
- Propagarea luminii poate fi explicata doar prin teoria electromagnetica



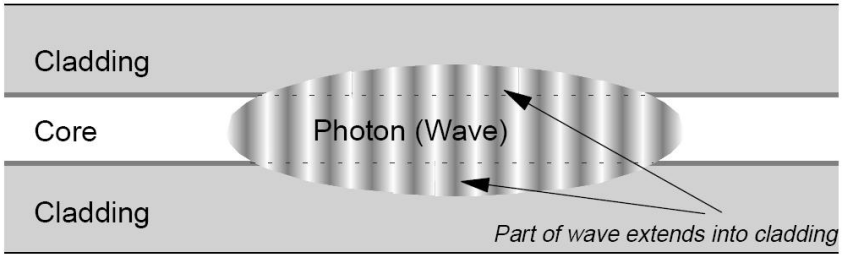
- Energia campului se extinde in teaca (diametrul efectiv al spotului luminos – MFD, Mode Field Diameter)
- MFD > 2a
- Adancimea de patrundere in teaca depinde de lungimea de unda, generand dispersia de ghid



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

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

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

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

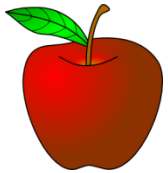
$$\text{Pierderi} = \frac{P_{out}}{P_{in}}$$

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

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

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



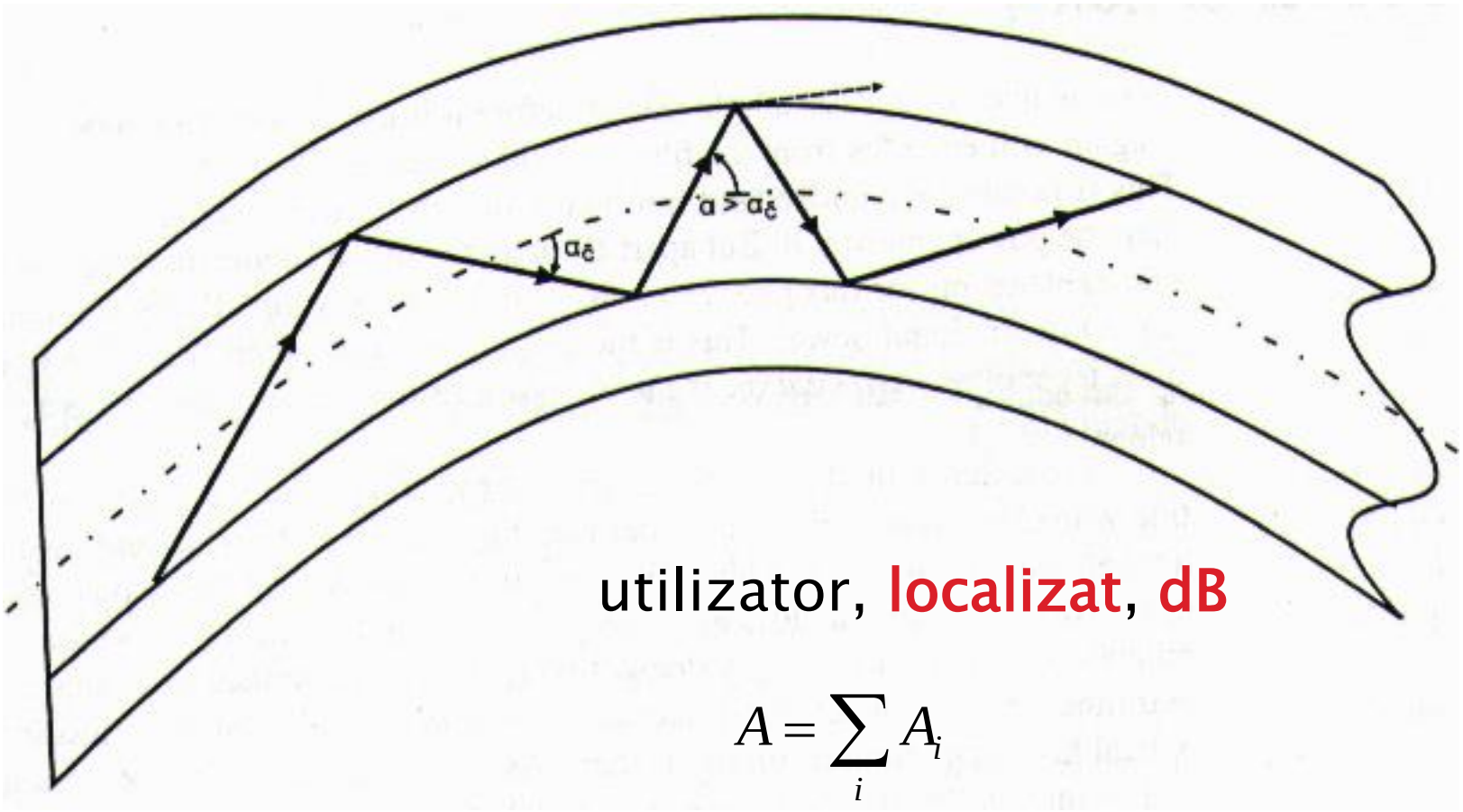


$$\text{Atenuare}[\text{dB/km}] = \frac{\text{Pierderi}[\text{dB}]}{\text{lungime}[\text{km}]}$$

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



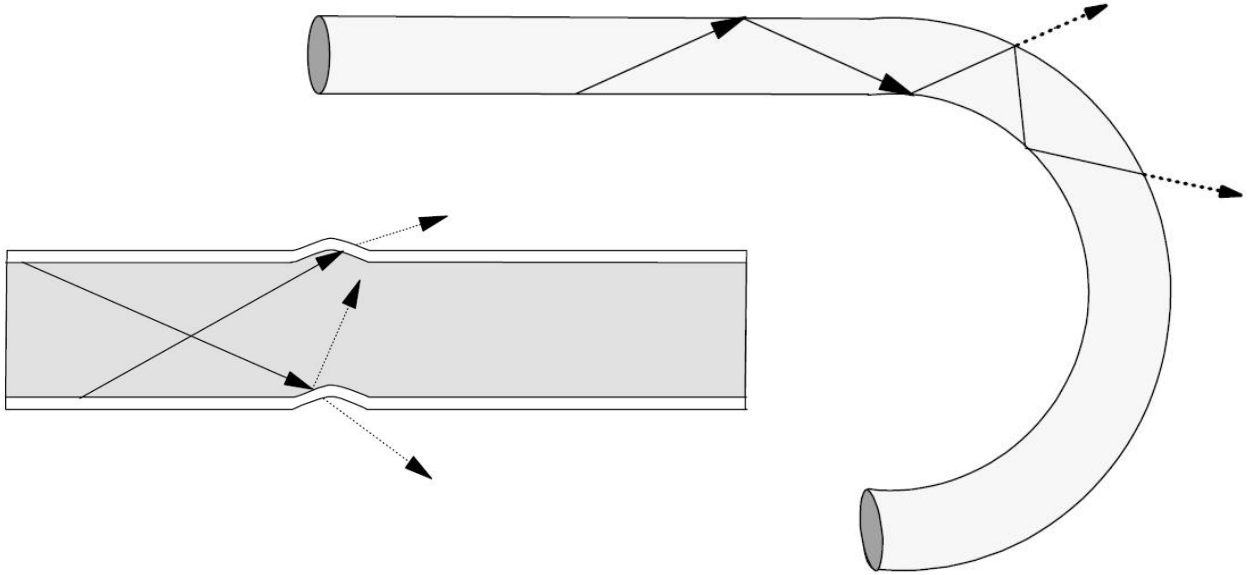
utilizator, localizat, dB

$$A = \sum_i A_i$$

$$A = N \cdot A_i$$

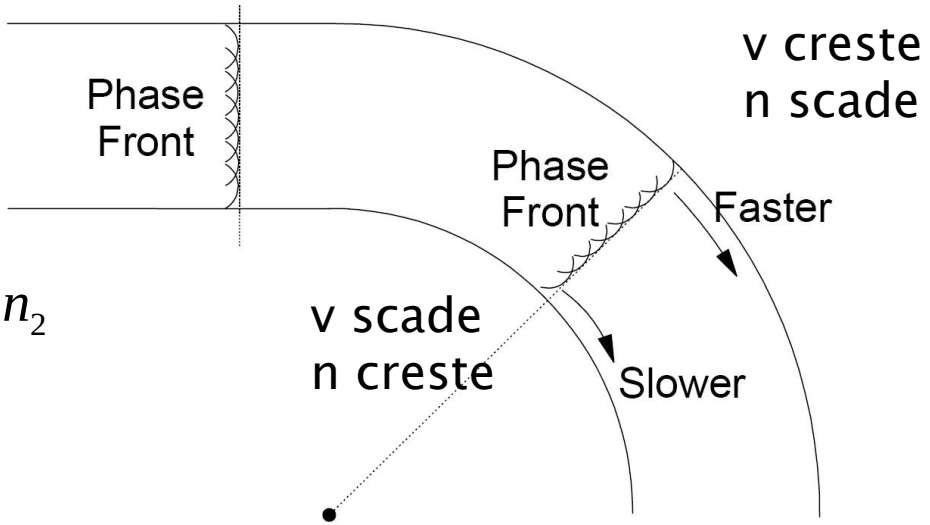
Efectul curburilor

- Multimod



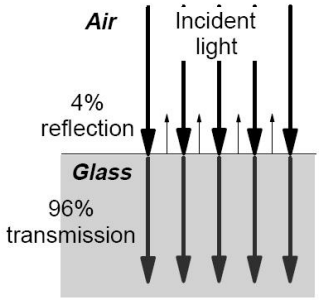
- Monomod

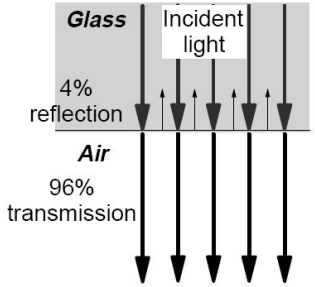
$$R > R_C \quad \Rightarrow \quad n_{1,ext} > n_2$$



Discontinuitate in fibra

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



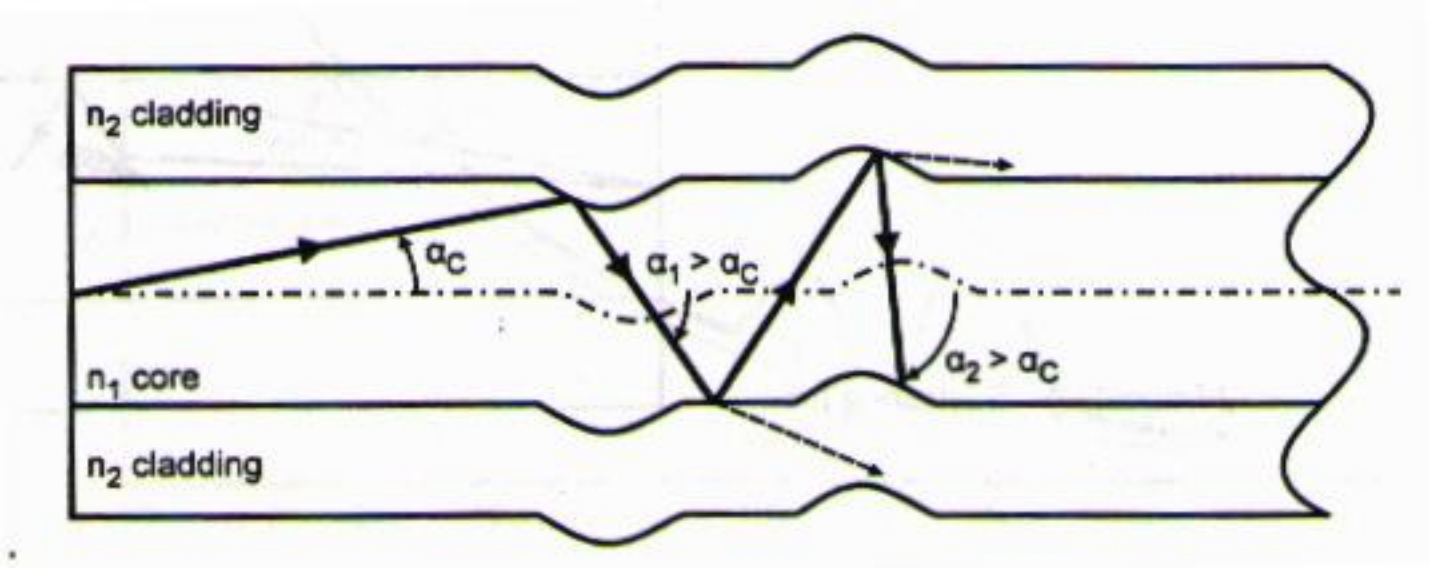


utilizator, localizat, dB

$$A = \sum_i A_i$$

$$A = N \cdot A_i$$

Microcurburi

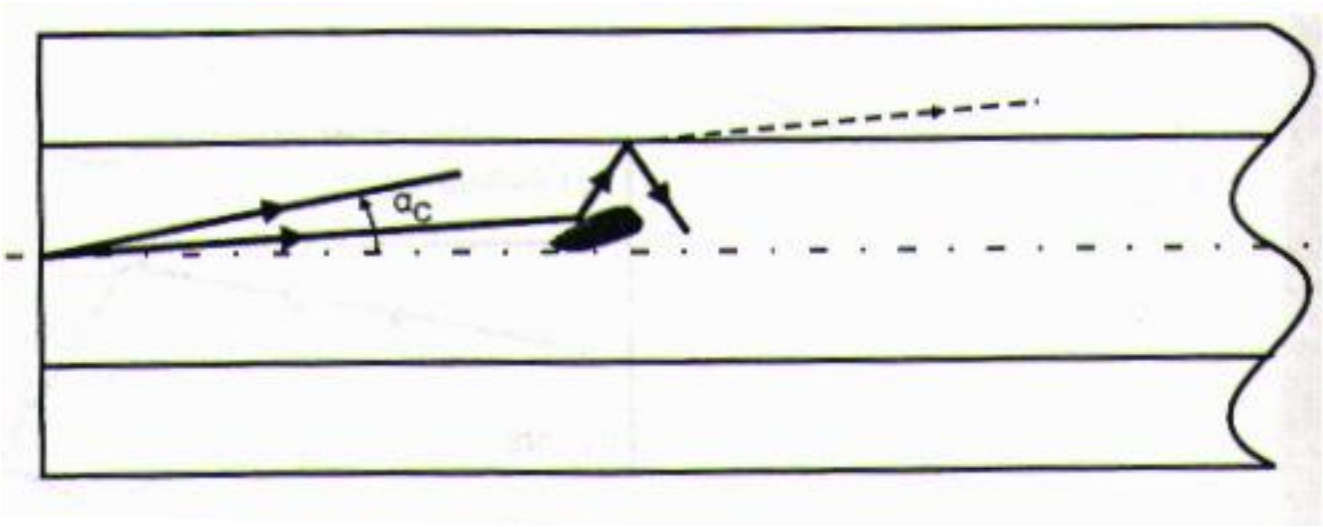


distribuit, tehnologie, **dB/km**

$$A = A_i \cdot L$$

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

Imprastiere

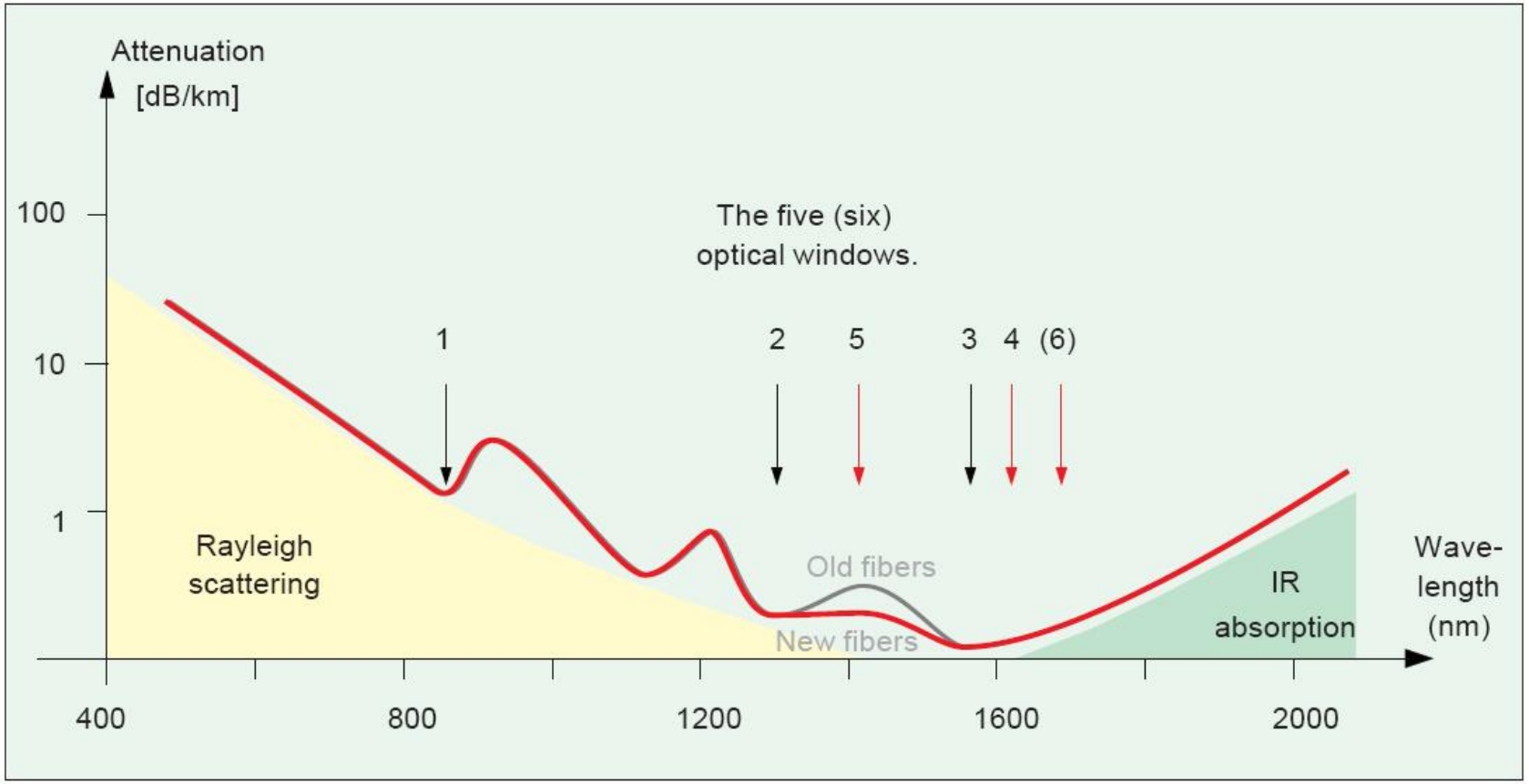


distribuit, tehnologie, **dB/km**

$$A = A_i \cdot L$$

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

Absorbtie

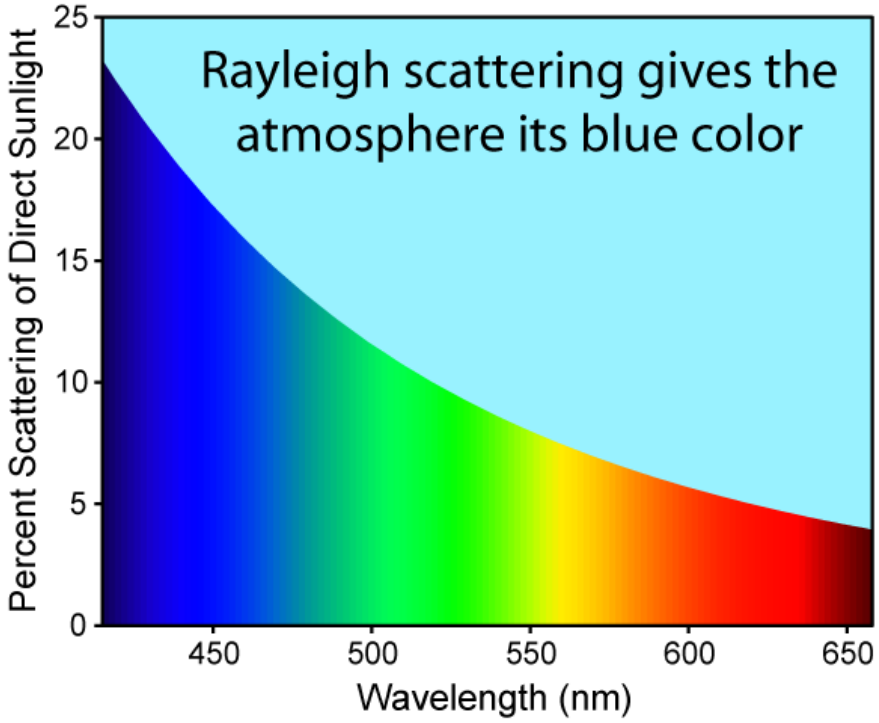


distribuit, material, **dB/km**

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

Difractie Rayleygh

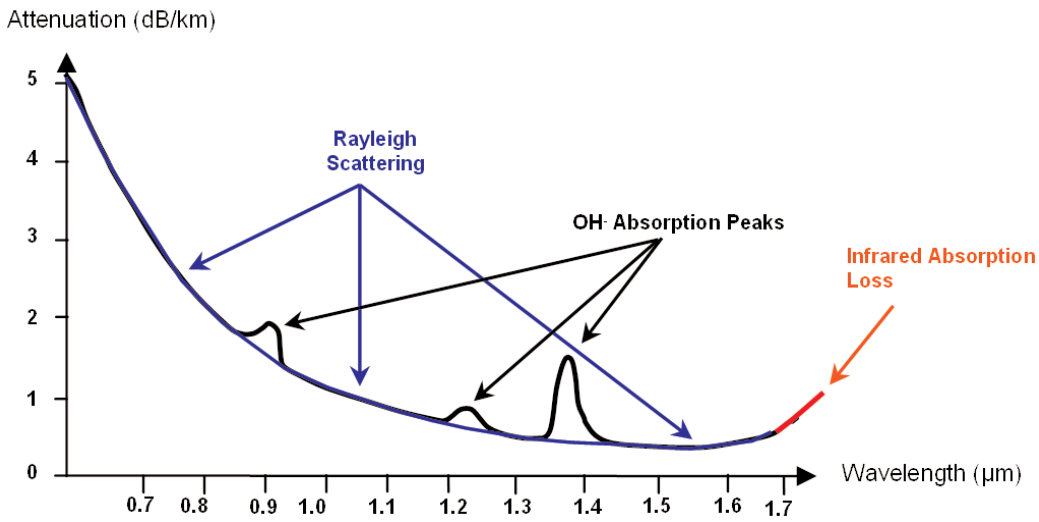
- imprastierea luminii (si a altor radiatii electromagnetice) de particule (molecule) mult mai mici decat lungimea de unda

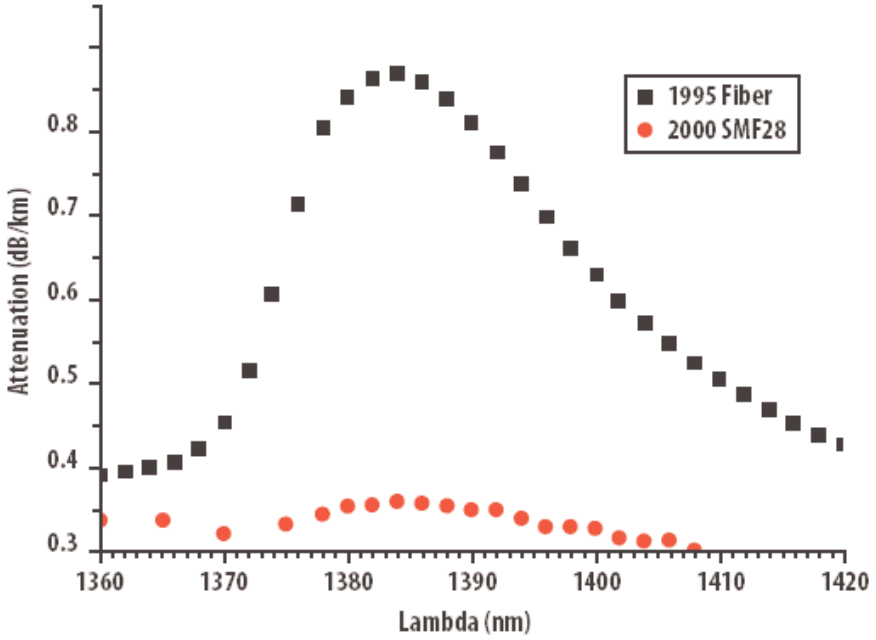


$$A \sim \frac{1}{\lambda^4}$$

Absorbtie OH

- Absorbtie
  - 950nm
  - 1244nm
  - 1383nm
- Apa!





Fiber Attenuation Comparison

Atenuare

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

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

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

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

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

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

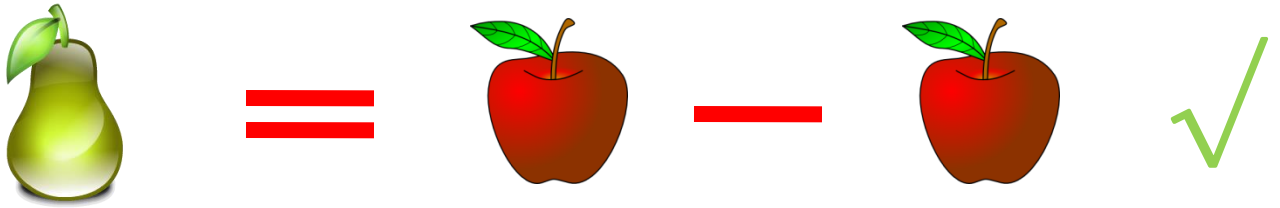
- Atenuarea se exprima de obicei in **dB/km**
  - de obicei valori pozitive
  - semnul = **implicit**

Calculul atenuarii

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

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

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

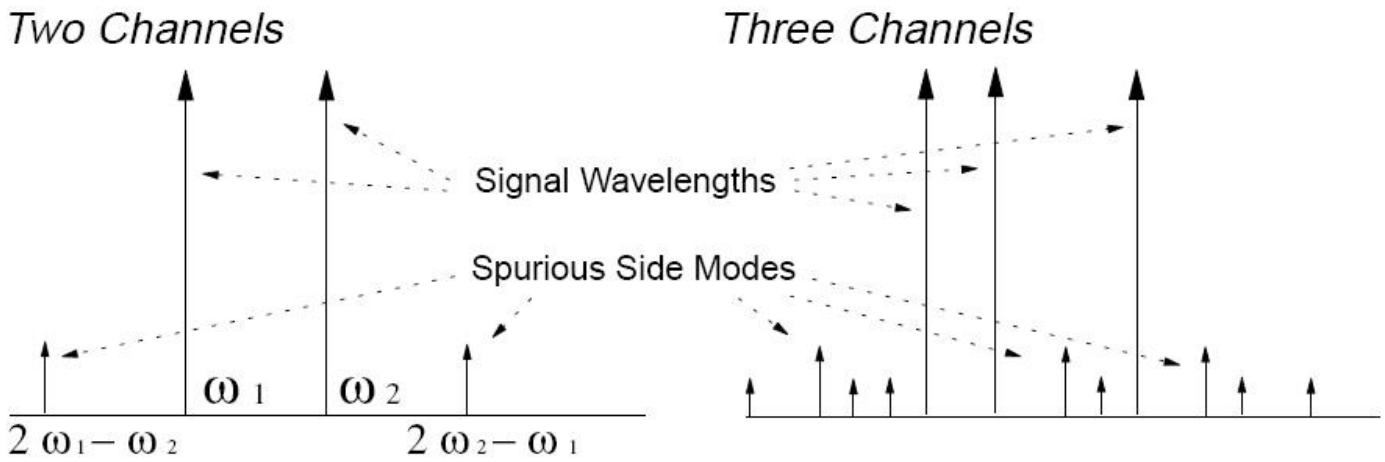


$$\text{Atenuare}[\text{dB/km}] = \frac{\text{Pierderi}[\text{dB}]}{\text{lungime}[\text{km}]}$$

Efecte neliniare in fibra

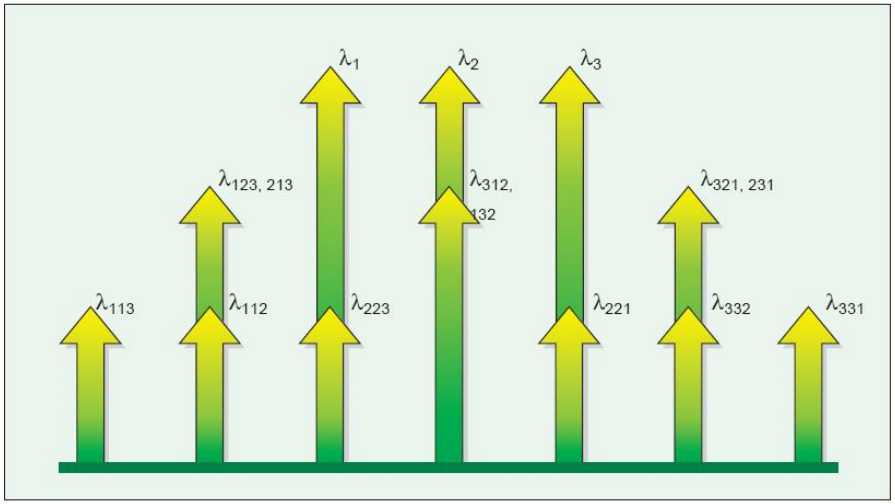
- Stimulated Brillouin Scattering, SBC
  - difractia luminii inspre emitator datorita undelor mecano-acustice generate in fibra
  - 6-10 dBm
- Stimulated Raman Scattering, SRS
  - interactiunea luminii cu vibratiile moleculare
  - 27 dBm (~1W)
- Self Phase Modulation, SPM
  - Frontiera impulsului implica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

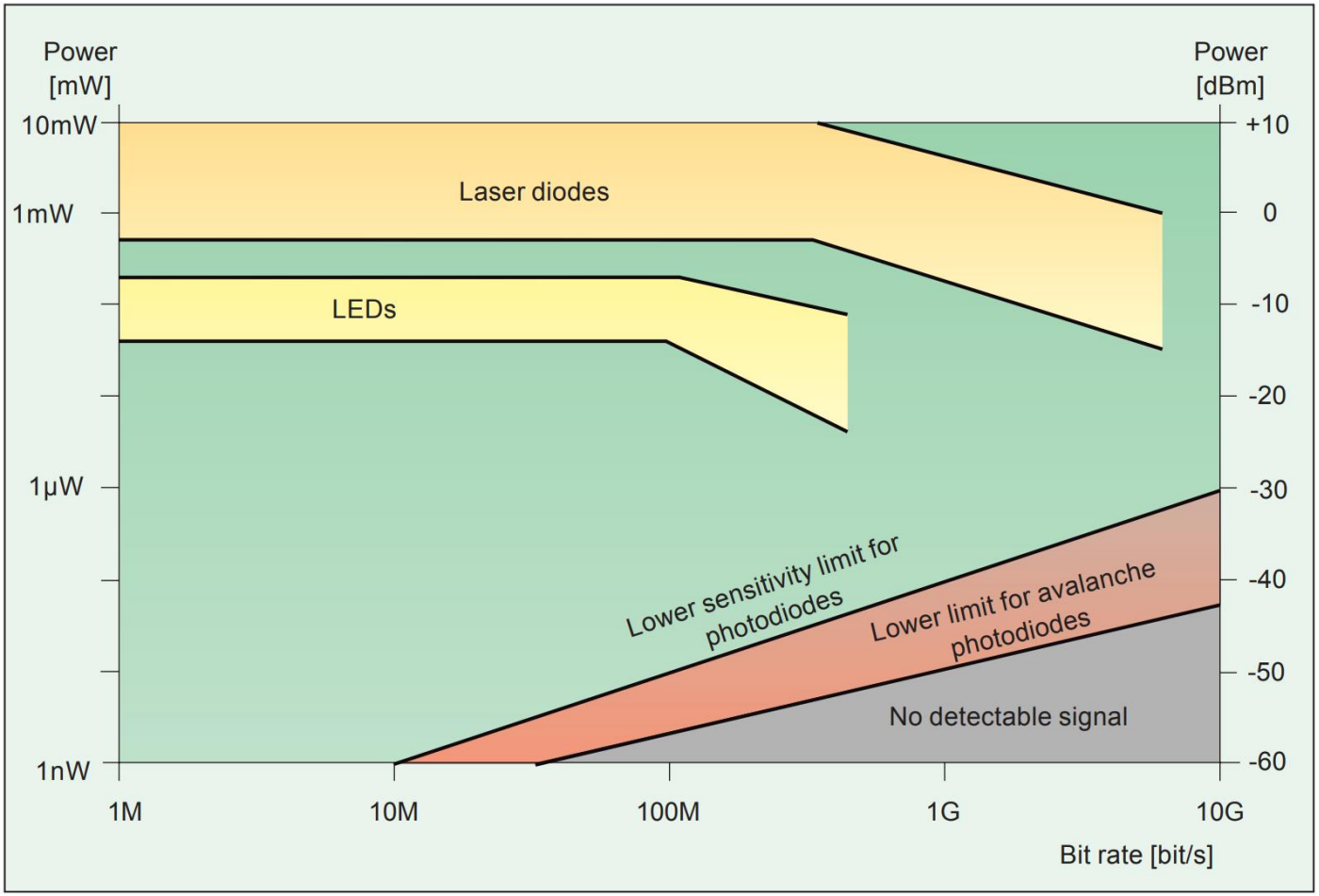


$$NL = \frac{1}{2}\left(N^3 - N^2\right)$$

N = 2, NL = 4
N = 3, NL = 9
N = 16, NL = 1920



Limite putere/bandă a dispozitivelor optoelectronice



Contact

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