The Optical Fiber

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1. Classification of fibers

Base on refractive index profile

Step Index Fibers

GRIN-Graded Index Fibers

Base on number of modes

SM-Single Mode Fiber

MM-Multi Mode Fiber

One dimension parabolic

Two dimension parabolic

Base on dispersion characteristic

NDSF- Not Dispersion Shifted Fiber

DSF- Dispersion Shifted Fiber

NZDSF- Not Zero Dispersion Shifted Fiber

2. Comparison of fibers

Multi-mode fibers

Core/Cladding size: 50/125 µm, 62.5/125 µm,100/140 µm

Optimum operating window: 850 nm

Advantages:

-LED signal light source can be used

- Large NA
- Inexpensive

Disadvantages:

- Large modal dispersion
- Small bandwidth
- Ideal for short-distance applications

(reach limit -5km)

Single-mode fibers

Core size: 3/125 µm, 9/125 µm

Optimum operating window: 1310 nm or 1550 nm

Advantages:

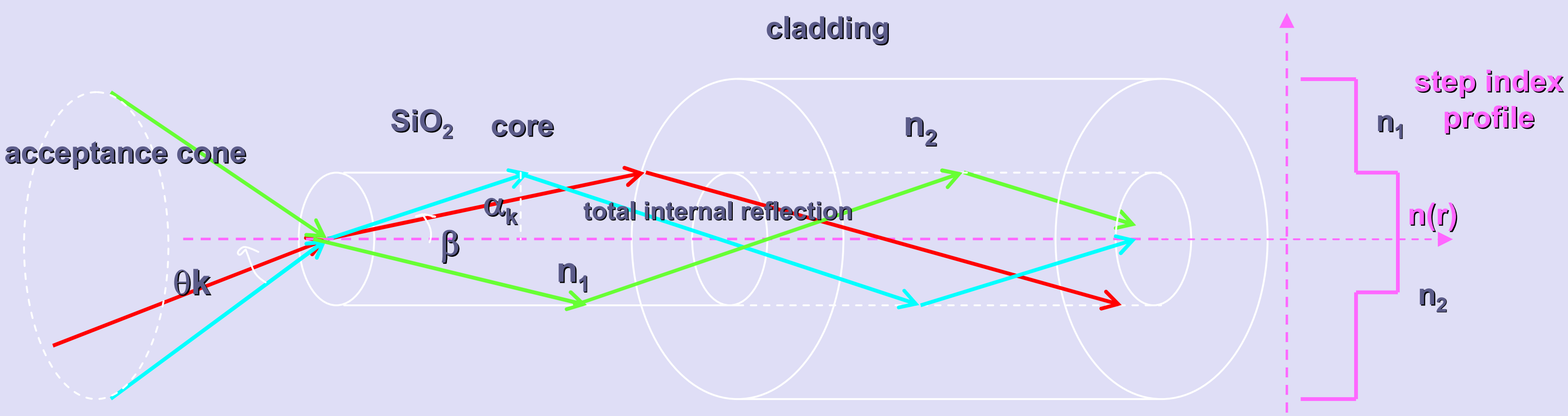
- No modal dispersion
- Large bandwidth
- Ideal for long-distance communication

(reach distance greater than 50 km)

Disadvantages:

- Small NA
- Laser signal light source must be used
- Expensive

3. Propagation of rays in the step index fiber



Numerical aperture results from application of **Snellius-Descartes law** in the input point of the core:

$$\sin\theta_k = n_1 \cdot \sin\beta = n_1 \sin(\pi/2 - \alpha_k) = n1 \cdot \cos\alpha_k = n1 \cdot (1-\sin^2\alpha_k)^{1/2} = n1 \cdot [1-(n_2/n_1)^2]^{1/2} = (n_1^2 - n_2^2)^{1/2}$$

Introduced the relative index difference of core:

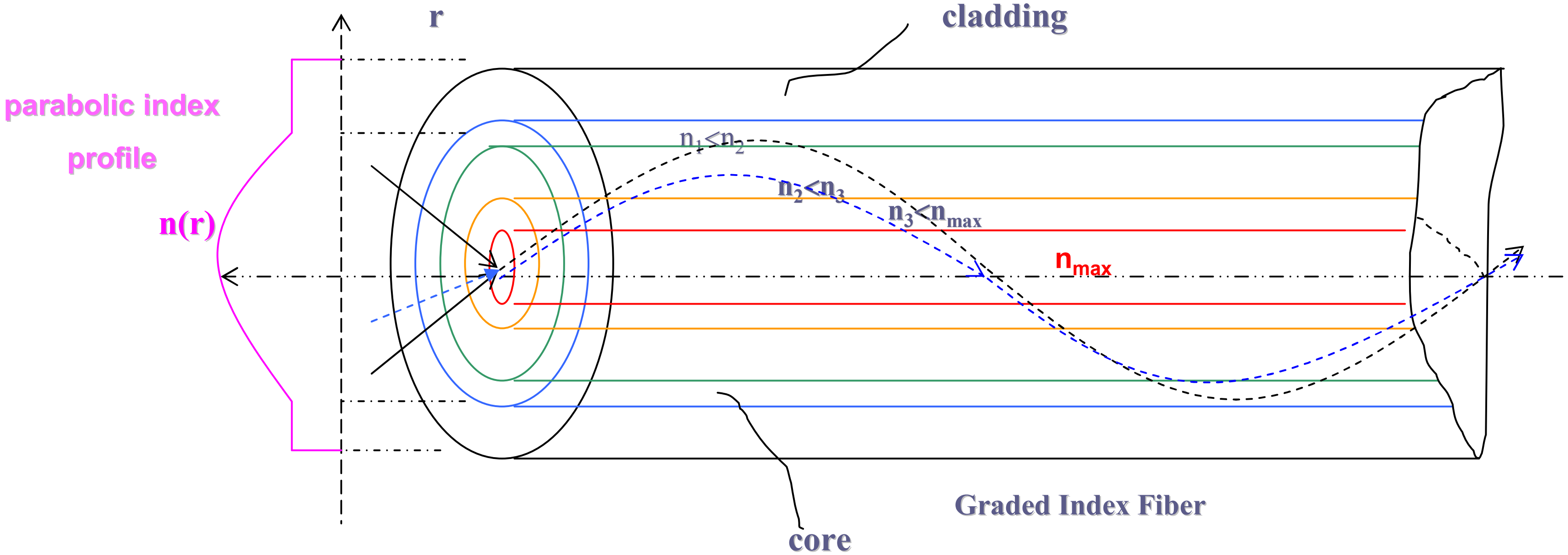
$$\Delta = \frac{n_1^2 - n_2^2}{2 \cdot n_1^2}$$

The numerical aperture of core is:

$$NA = \sin\theta_k = \sqrt{n_1^2 - n_2^2} = n_1 \cdot \sqrt{2 \cdot \Delta}$$

Numerical aperture is dependent by relative index difference. Generally Δ<0.01

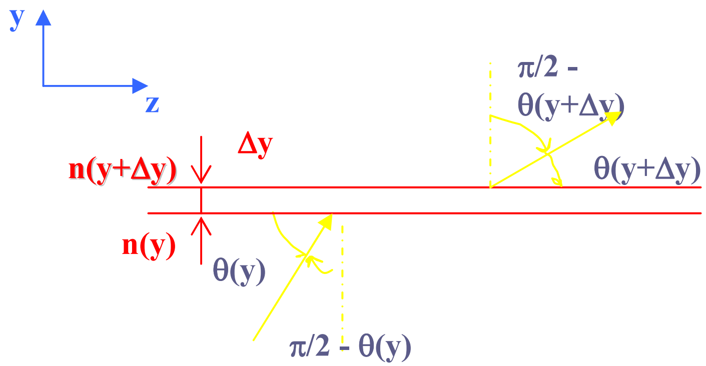
4. Propagation of rays in the graded index fiber



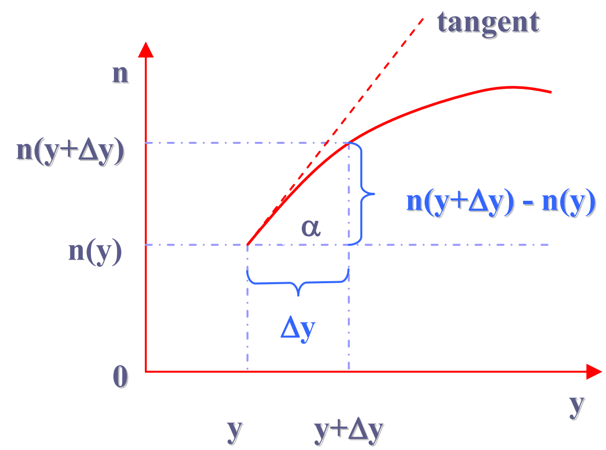
At **GRIN-Graded Index Fibers** the rays accessed under greater angle propagate in the smaller index refraction region of the core, decreasing the modal dispersion in the core.

In the next demonstration we considering that the n-refractive index is the function of only the y-coordinate.

The equation of ray traiectory



Geometry of graded index fiber



Interpretation of differential

From refraction law results:

$$n(y)\cdot\sin(\frac{\pi}{2}-\theta(y)) = n(y+\Delta y)\cdot\sin(\frac{\pi}{2}-\theta(y+\Delta y))$$

$$n(y)\cdot\cos\theta(y) = n(y+\Delta y)\cdot\cos\theta(y+\Delta y) \quad (1)$$

From interpretation of differential we are:

$$tg\alpha = n' = \frac{dn}{dy} = \frac{n(y+\Delta y)-n(y)}{\Delta y}$$

$$\frac{dn}{dy}\cdot\Delta y = n(y+\Delta y)-n(y) \quad \Rightarrow \quad n(y+\Delta y) = n(y)+\frac{dn}{dy}\cdot\Delta y \quad (2)$$

In same mode:

$$(\cos\theta(y))' = \frac{\cos\theta(y+\Delta y)-\cos\theta(y)}{\Delta y} = -\sin\theta(y)\cdot\frac{d\theta}{dy}$$

Which result: $$\cos\theta(y+\Delta y)=\cos\theta(y)-\frac{d\theta}{dy}\cdot\sin\theta(y)\cdot\Delta y \quad (3)$$

Put equation 2 and 3 in first equation result:

$$n(y)\cdot\cos\theta(y)=\left[n(y)+\frac{dn}{dy}\cdot\Delta y\right]\cdot(\cos\theta(y)-\frac{d\theta}{dy}\cdot\sin\theta(y)\cdot\Delta y)$$

After calculation result the following equation:

$$n(y)\cdot\cos\theta(y)=n(y)\cdot(\cos\theta(y)-n(y)\cdot\frac{d\theta}{dy}\cdot\sin\theta(y)\cdot\Delta y)+\frac{dn}{dy}\cdot\Delta y\cdot\cos\theta(y)-\frac{dn}{dy}\cdot\frac{d\theta}{dy}\cdot\Delta y^{2}\cdot\sin\theta(y)$$

Because $\Delta y<<0$ is small , $\Delta^2 y$ is smaller $\Delta^2 y\rightarrow 0$ negligible

$$n(y)\cdot\frac{d\theta}{dy}\cdot\sin\theta(y)=\frac{dn}{dy}\cdot\cos\theta(y) \qquad n(y)\cdot\frac{d\theta}{dy}\cdot tg\theta(y)=\frac{dn}{dy}$$

$$\frac{d\theta}{dy}\cdot tg\theta(y)=\frac{1}{n(y)}\cdot\frac{dn}{dy} \quad (4)$$

After <u>Gauss approximation</u> (paraxial aproximation) results:

$$tg\theta(y)=\theta(z)=\frac{dy}{dz} \quad (5)$$

Put equation 5 in equation 4 result the ray trajectory in the glass fiber:

$$\frac{1}{n(y)}\frac{dn}{dy} = \frac{d\theta}{dy}\cdot\frac{dy}{dz} = \frac{d}{dy}\left(\frac{dy}{dz}\right)\cdot\frac{dy}{dz} = \frac{d^2y}{dz^2} \qquad \frac{1}{n(y)}\cdot\frac{dn}{dy} = \frac{d^2y}{dz^2} \quad (6)$$

One dimension parabolic refraction index-profile: $n^2(y) = n_0^2\cdot(1-a^2\cdot y^2)$

where the a is very small and $a^2y^2 \ll 1$.

$$n(y) = \sqrt{n_0^2\cdot(1-a^2\cdot y^2)} \approx n_0\cdot(1-\frac{a^2\cdot y^2}{2}) \approx n_0$$

because a is small $a^2 \rightarrow 0$

$$(1-\frac{a^2\cdot y^2}{2})^2 = 1-2\frac{a^2\cdot y^2}{2}+\frac{a^4\cdot y^4}{4} \approx 1-a^2\cdot y^2$$

because a is small $a^4 \rightarrow 0$

The refraction index is: $n(y) = n_0$

Derivate of refraction index : $n' = \frac{dn(y)}{dy} = \frac{d}{dy}\left(n_0\cdot(1-\frac{a^2y^2}{2})\right) = -n_0\cdot a^2\cdot\frac{2y}{2} = -n_0\cdot a^2\cdot y$

Substituing in ray equation:

$$\frac{1}{n(y)} \cdot \frac{dn}{dy} = \frac{d^2 y}{d z^2}$$

result

$$\frac{1}{n_0} \cdot (-n_0 a^2 y) = \frac{d^2 y}{d z^2}$$

$$\frac{d^2 y}{d z^2} = -a^2 \cdot y$$

Parabolic differential equation

With following substitution

$$\frac{dy}{dz} = p(y)$$

result

$$\frac{d^2 y}{d z^2} = \frac{dp(y)}{dz} = \frac{dp}{dy} \cdot \frac{dy}{dz} = \frac{dp}{dy} \cdot p$$

$$\frac{dp}{dy} \cdot p = -a^2 \cdot y \qquad dp \cdot p = -a^2 \cdot y \cdot dy$$

$$\frac{p^2}{2} = -\frac{a^2 \cdot y^2}{2} \Rightarrow p^2 = -a^2 \cdot y^2 \qquad p_{12} = \pm i \cdot ay$$

$$y(z) = C_1 \cdot \cos(az) + C_2 \cdot \sin(az)$$

Determination of constants:

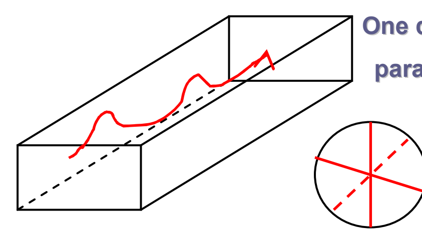
For z=0 $y(0) = C_1 \cdot \cos(0) + C_2 \cdot \sin(0) = C_1 \cdot 1 = C_1 \Rightarrow C_1 = y(0)$

$$\theta(z) = \frac{dy}{dz} \qquad \theta(z) = \frac{dy}{dz} = -a \cdot C_1 \cdot \sin(az) + a \cdot C_2 \cdot \cos(az)$$

For z=0 $\theta(0) = y'(0) = -a \cdot C_1 \cdot \sin(0) + a \cdot C_2 \cdot \cos(0) = -a \cdot C_1 \cdot 0 + a \cdot C_2 \cdot 1 = a \cdot C_2 \qquad C_2 = \frac{\theta(0)}{a}$

Solutions of equation:

$$\begin{cases} y(z) = y(0) \cdot \cos(az) + \frac{\theta(0)}{a} \cdot \sin(az) \\ \theta(z) = -ay(0) \cdot \cos(az) + \theta(0) \cdot \sin(az) \end{cases}$$

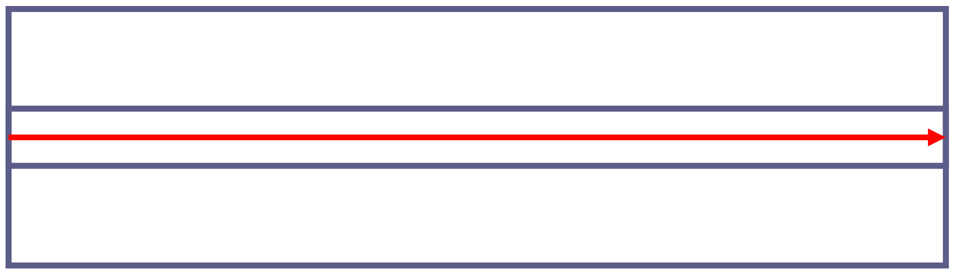


One dimension parabolic ray

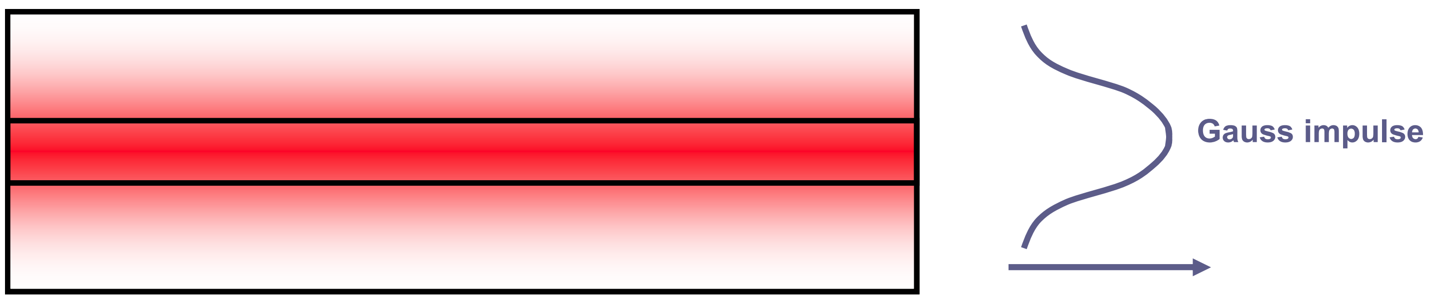
The ray propagate in the perpendicular plane of the fibre core.

Propagation of ray in single mode fiber

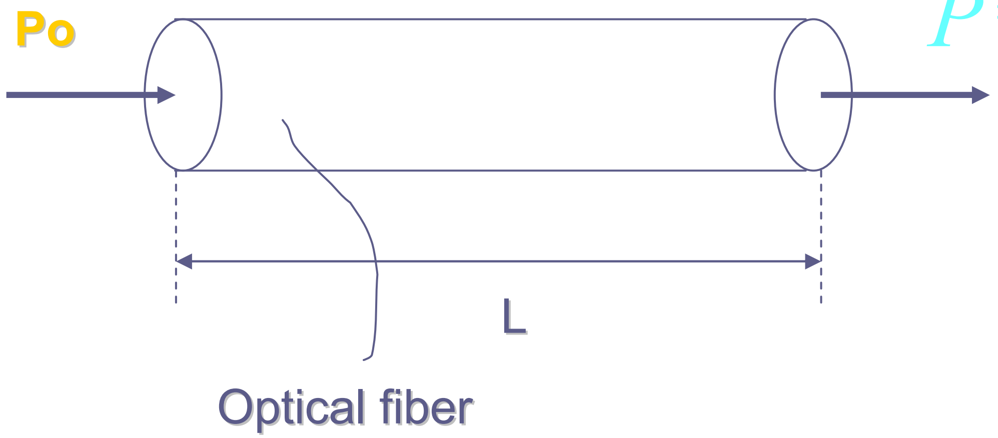
Single-mode fiber



Single-mode fiber – Gaussian model



5. The optical power loss



$$P = P_o \cdot 10^{-\alpha \cdot L}$$

The optical power decreased exponential at end of fiber.

α - is the attenuation of fiber in dB/km

6. The optical attenuation

The optical power loss is: $P = P_0 \cdot 10^{-\alpha \cdot L}$

$P / Po = 10^{-\alpha \cdot L}$ $\qquad \lg \frac{P}{Po} = -\alpha L \cdot \lg 10 = -\alpha \cdot L \cdot 1 = -\alpha \cdot L$

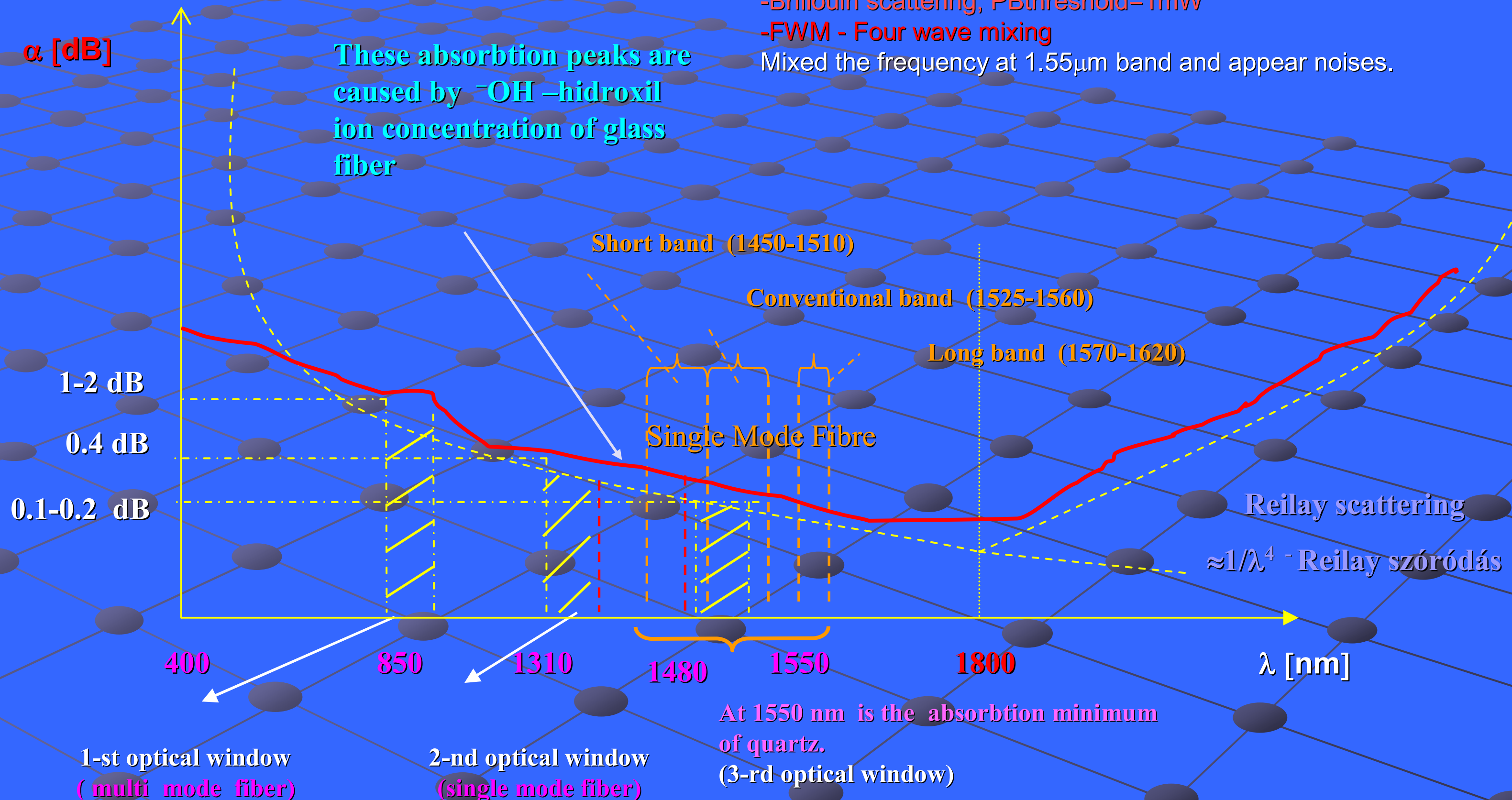
$$\alpha = -\frac{1}{L} \cdot \lg \frac{P}{P_o}$$

If L=1km , the attenuation is:

$\alpha = -\lg \frac{P}{P_0} \; [Bell/km]$ $\qquad \alpha = -10 \cdot \lg \frac{P}{P_0} \; [dB/km]$

7. Transfer characteristic

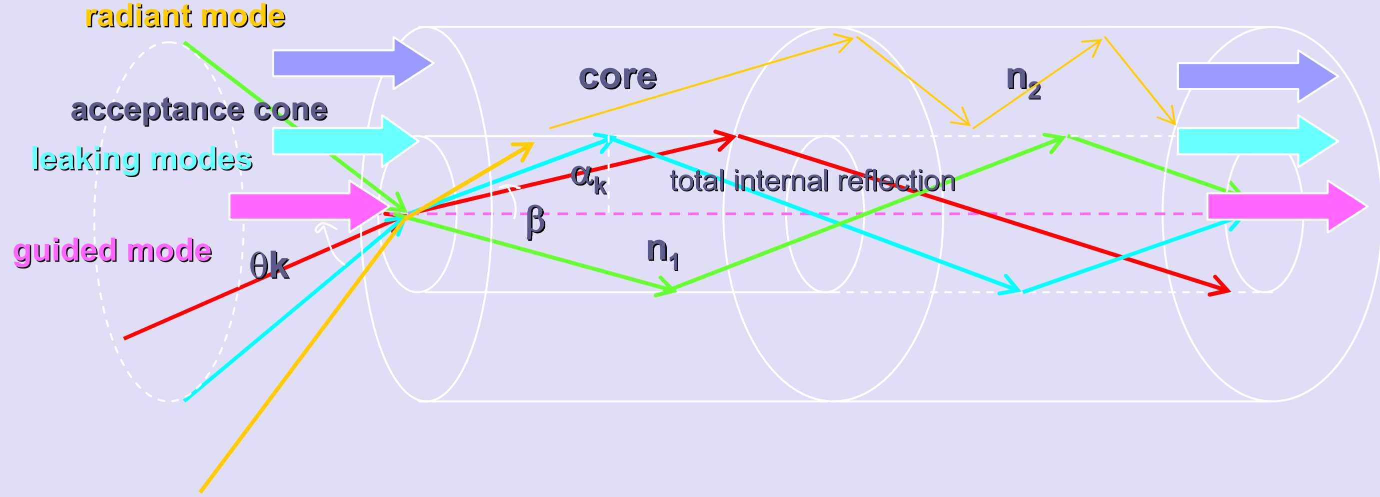
After 1800 nm appears the nonlinear effect. The refractive index is deppending of the optical power from core n=n(P).
-Raman scattering PRthreshold=570mW=0.57W ≈1W
-Brillouin scattering, PBthreshold=1mW
-FWM - Four wave mixing
Mixed the frequency at 1.55µm band and appear noises.



Generaly all optical networks working at <u>second optical window</u> at 1310 nm wavelength.

The greater absorbtion peaks are between 1300 nm and 1480 nm.

8. Propagation modes



$N_{modes}=V^2/2$ V-is the normalized frequency

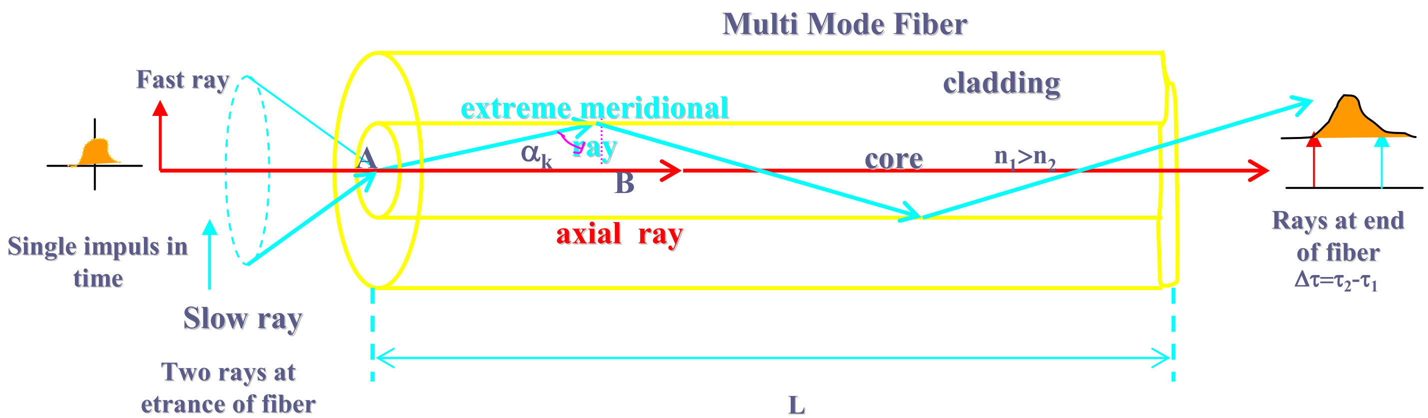
V=2.405 is the limit of single mode operation

Radiant mode (lesugárzó módus): From the outside of allowable acceptance angle ingoing light generated mode.

Leaking mode :Propagate on the core-cladding interface.

Guided mode :Given moment and length in the core of fiber located mode.

9. Dispersion



Ilustration of dispersion

From different delays the received pulse will be wider as transmitted pulse, this is so called dispersion.

The dispersion is characterized by $\Delta\tau=\tau_{max}-\tau_{min}=\tau_2-\tau_1$ **maximal time delay difference.**

The sinus of critical angle α_k $\sin\alpha_k = \frac{AB}{AC}$ **from this result** $\frac{AC}{AB} = \frac{1}{\sin\alpha_k} = \frac{1}{\frac{n_2}{n_1}} = \frac{n_1}{n_2}$

$$\Delta\tau = \tau_2 - \tau_1 = \frac{L}{v1}\cdot\left(\frac{AC}{AB}-1\right) = \frac{L\cdot n_1}{c}\cdot\frac{n_1}{n_2} - \frac{L\cdot n_1}{c} = \frac{L\cdot n_1}{c}\cdot\left(\frac{n_1}{n_2}-1\right) = \frac{L\cdot n_1}{c}\cdot\left(\frac{n_1-n_2}{n_2}\right) \approx \frac{L\cdot n_1}{c}\cdot\Delta$$

For multimode fibers the maximum time delay difference is: $$\Delta\tau = \frac{L\cdot n_1}{c}\cdot\Delta$$

10. Type of dispersion

Dm - Modal Dispersion

Derived of that, in the multimode fibers trough numerous possible light way one of the photons arrive sooner to end of core which the other which to smart total internal reflection in several times on the wall.

Dw-Waveguide Dispersion

Derived of that, in near of core the cladding also guided the light in case of single mode fibers.

Chromatic Dispersion (Material Dispersion)

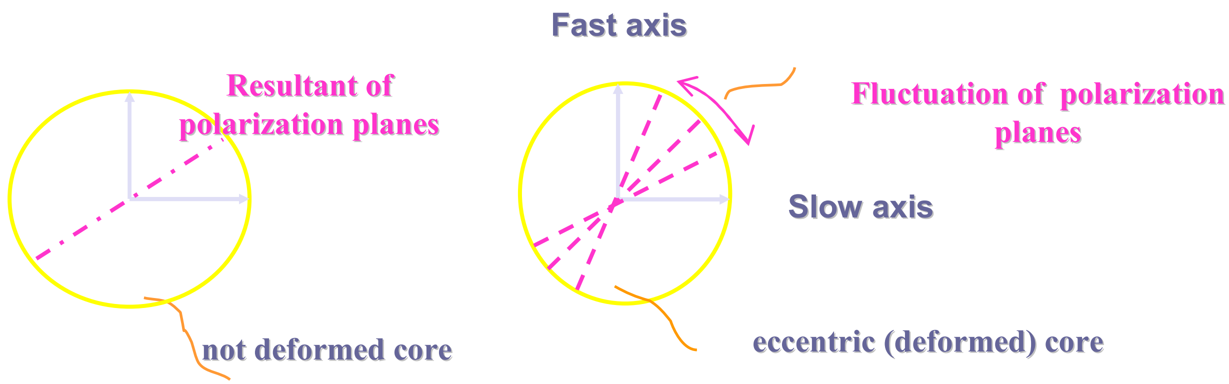
Derived of that, the light rays with different wavelength propagate with different velocity in fibre core.

Ussually at fibers customery give the wide of zero dispersion window and the chromatic dispersion variation in out off the window.

Example:

zero dispersion wavelength- $\lambda o \approx 1300$ nm -1332 nm, zero dispersion slope-So$\leq$0.092 ps/nm2·km

11. PMD-Polarization Mode Dispersion



Cross section of optical fiber

In case of deformed core the resultant polarization planes fluctuate in the fluctuation range, because the light propagate with different velocity in different planes and that's why at end of core the outgoing optical power resulted pulsating.

$$\langle \Delta_{PMD} \rangle \approx D_{PMD} \cdot \sqrt{L}$$

Δ_{PMD} – medium delay time

D_{PMD} - polarization coefficient

$$D_{PMD} \; 0.1 \div 1 \, ps / \sqrt{km}$$

at 1 dB attenuation:

$$D_{PMD} \cdot \sqrt{L} \leq 0.1 \cdot T = 0.1 \cdot \frac{1}{B_r}$$

$$B_r \cdot D_{PMD} \cdot \sqrt{L} \leq 0.1$$

where T is the bit period and Br is the bit velocity

12. Compensation of dispersion

Solutions

Standard fiber

Dispersion Shifted Fiber

D=±3.5 ps/nm·km

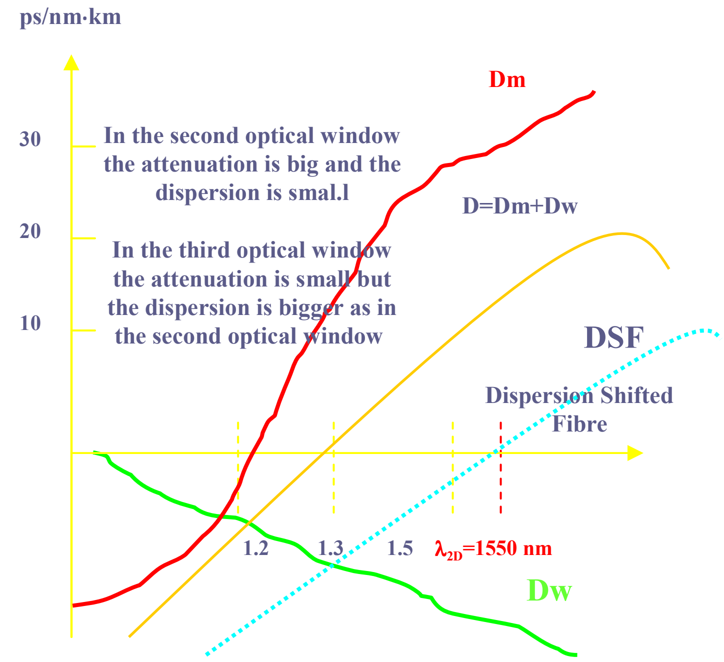
Dispersion compensation with negative dispersion fiber

Soliton transfer

The solitons are light pulses which contains more wavelength.
The bigness of different wavelength belonging amplitudes as that the indirect Kerr effect compensate the dispersion.

Standard fiber	Dispersion compensated fiber
D=17 ps/nm·km	D_c=-85 ps/nm·km
L=100 km	L_c=20 km
D·L=1700 ps/nm	$D_c \cdot L_c$=-1700 ps/nm

D·L+ $D_c \cdot L_c$=1700ps/nm -1700 ps/nm=0 ps/nm



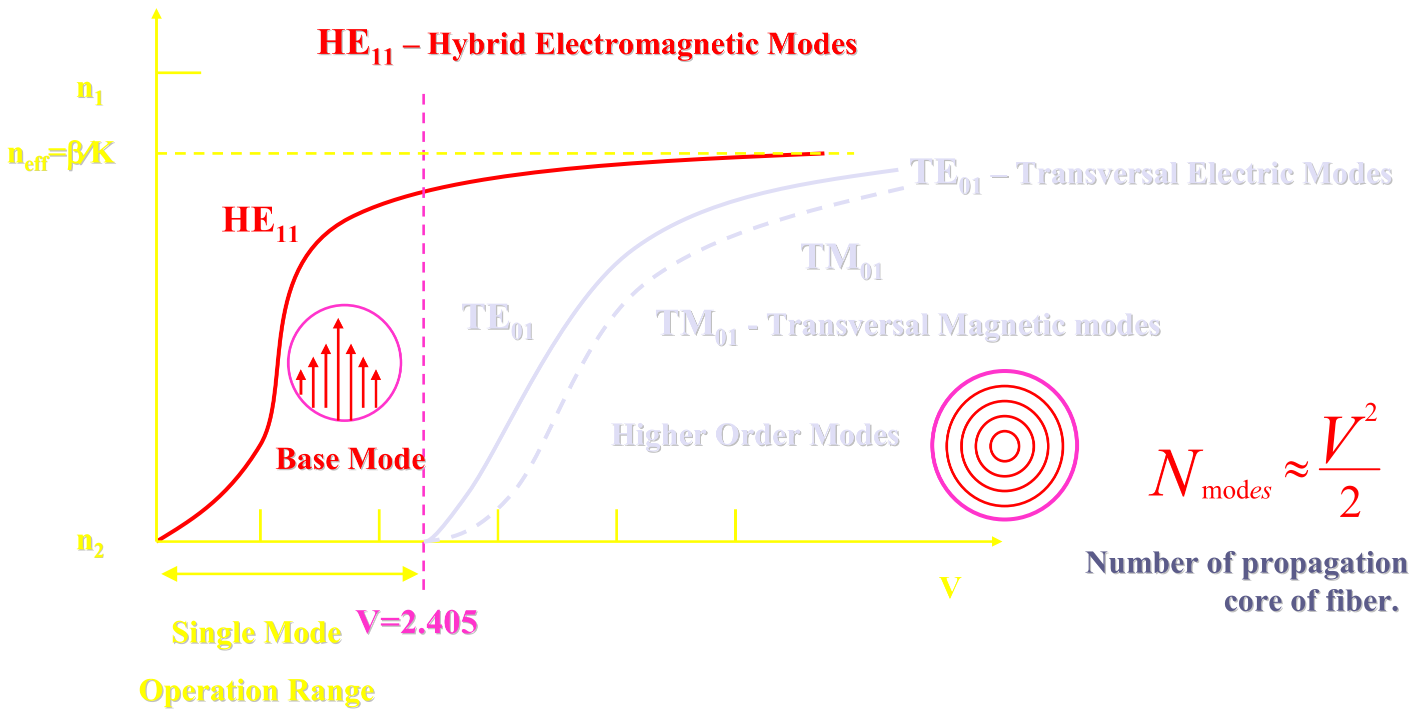
13. Normalized frequency

$$V = \frac{2\pi a}{\lambda} \cdot \sqrt{n_1^2 - n_2^2} = \frac{2\pi a}{\lambda} \cdot NA \leq 2.405$$

The V=2.405 value is the limit value of single mode operation.

The higher modes we can eliminate that so must give the a-<u>radius of core</u> that the V- <u>normalized frequency</u>

V≤ 2.405 (will be minor as 2.405) . (The normalized frequency is the <u>result of wavguide optic discussion</u>.)



$$N_{modes} \approx \frac{V^2}{2}$$

Number of propagation modes in core of fiber.

14. Bend radius

In multimode fibers the number of propagation modes is reduced as a function of bend radius according to the following description:

$$M(R) = Mo \cdot (1 - D_F \cdot n_2^2 / R \cdot NA^2)$$

Mo= number of propagation modes without bending

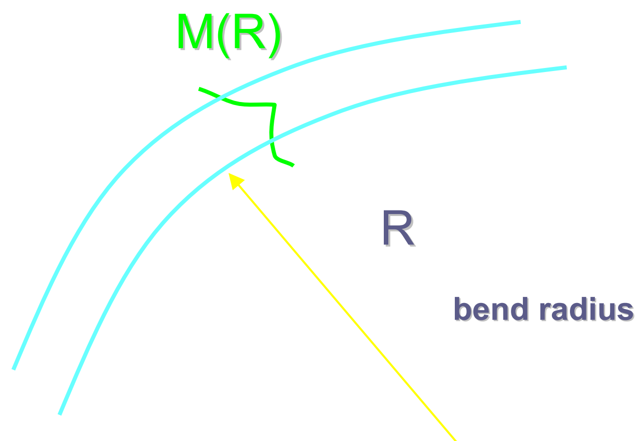
M(R)= number of propagation modes with bending

R – bend radius

DF- fiber diameter

n_2-clad refractive index

NA – numerical aperture



The critical bend radius is:

$$R_{critic} = 3n_2 \cdot \lambda / 4\pi \cdot NA^3 = a / NA^2$$

Generally the R is 20 time more than cladding diameter.

15. Characteristic of optical fibres

Fiber Type: SM 332

1. Attenuation (Csillapítás)

Wavelength (nm)	Attenuation (dB/km)
λ=1320	≤ 0.235
λ= 1550	≤ 0.21

2. Point Discontinuity (Pontszerű anyaghibák)

Point discontinuity is not greater than 0.05 dB at either 1310 nm and 1550 nm.

3. Water Peak (Hidroxil ion –OH tartalom)

Water peak is not greater than 1 dB/km at 1383 ± 3 nm.

4. Mode Field Diameter (Módus tartomány átmérő)

9.2 ± 0.5 µm at 1310 nm

10.4 ± 1.0 µm at 1550 nm

5. Cable Cutoff Wavelength (Levágási hullámhossz)

$\lambda_{cc} \leq 1260$ nm

6. Chromatic Dispersion (Kromatikus diszperzió)

Zero dispersion wavelength λ_o=1300 – 1322 nm

Zero dispersion slope: ≤0.092 ps/nm^{2}km

7. Polarization Mode Dispersion

(Polarizációs módus diszperzió)

Individual Fiber: ≤0.2 ps/(km)$^{1/2}$

PMD Link Value: ≤0.1 ps/(km)$^{1/2}$

8. Dispersion

(Diszperzió)

$$D(\lambda) = \frac{S_o}{4} \cdot \left[\lambda - \frac{\lambda_o^2}{\lambda^3} \right]$$

1200 nm ≤ λ ≤ 1600 nm

λ-operating wavelength

9. Glass Geometries

(Üvegszál geometriája)

9a. Cladding Diameter: 125.0 ± 1 μm

9b. Core concentricity Error: ≤ 0.5 μm

9c. Cladding Noncircularity: ≤1%

Defined as:

$$Cladnoncirc. = \left[1 - \frac{Min.\ \ cladding\ \ diameter}{Max.\ \ cladding\ \ diameter} \right] \times 100$$

10. Environmental Characteristics

(Környezeti jellemzők)

Temperature Dependence: -60ºC -+85 ºC ≤0.1 dB/km at 1310 nm

Water Immersion: +23ºC ± 2ºC ≤0.05 dB/km at 1310 nm

11. Mechanical Characteristic

(Mechanikai jellemző)

Tensile Proof Test: 0.69 GPa (at 100 kpsi)

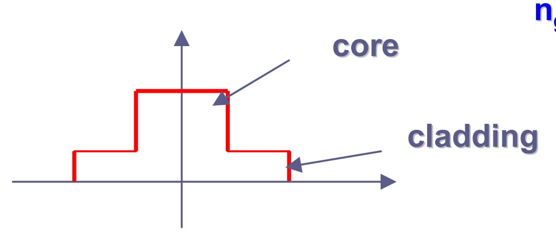
12. Technical Characterizations

(Technikai jellemzők)

12a. Refractive Index Difference: Δ =0.36

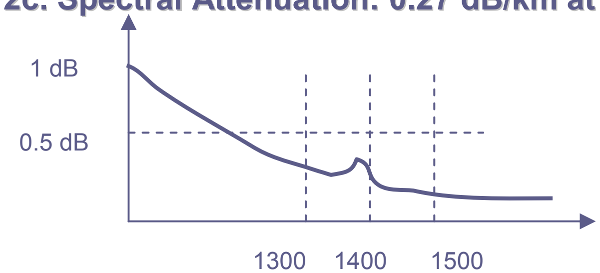
12b. Group Refractive Index: n_g =1.468 at 1310 nm

n_g =1.469 at 1550 nm



$$\Delta \approx \frac{n_1 - n_2}{n_1}$$

12c. Spectral Attenuation: 0.27 dB/km at 1380 nm



16. Connectors and patch cords

LC duplex to LC duplex

LC duplex to LC simplex

LC duplex to ST

LC simplex and LC duplex connectors

LC duplex and SC duplex connectors

l a n d L C d

MTRJ multi mode connector

MTRJ single mode connector

The principal characteristic of connectors

1. Maximal investiture attenuation: 0.5-1.0 dB
2. Minimal attenuation in back direction: 23-30 dB
3. Minimal number of connectors in the network: minimum 1000 connectors
4. Temperature range: -20-+70 Cº