Ústav fotoniky
a elektroniky

VLASTIMIL MATEJEC

IPE AS CR, v.v.i.

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ūfe Ústav fotoniky a elektroniky

INSTITUTE OF PHOTONICS AND ELECTRONICS ACADEMY OF SCIENCES OF THE CZECH REPUBLIC, PUBLIC RESEARCH INSTITUTION (v.v.i.)

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IPE AS CR, v.v.i. - STATUS, HISTORY

IPE is a **medium-size, non-profit public research institution,** a legal body within the Academy of Sciences of the CR, the Czech largest non-university research organization (54 Institutes).

1954 - The foundation of Institute of Radioengineering and Electronics (IREE) CAS

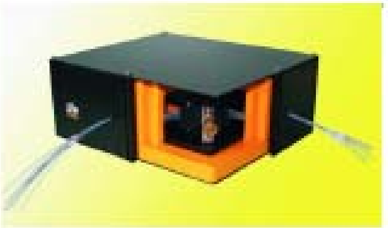
2007 – Institute renamed to IPE and become v.v.i

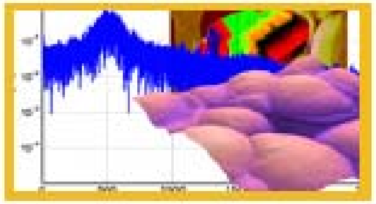
More than 50 years of research activities in areas

Radioengineering, Electronics, Physics, Optoelectronics, Photonics

TODAY IPE MISSION - RESULTS

Prof. Jiří Homola
Head of UFE





FUNDAMENTAL RESEARCH

Optical Biosensors (SPR Homola)

Fiber Lasers and Non-linear Optics (Honzatko)

Nanomaterials (SIMS Lorincik)

Bioelectrodynamics (Cifra)

National Time and Frequency Standard (Kuna)

ÚFE Ústav fotoniky a elektroniky

OPTICAL FIBERS

VLASTIMIL MATĚJEC

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Chaberská 57, 182 51 Prague 8-Kobylisy, Czech Republic

OUTLINE OF COURSE

- Optical fibers – telecommunications
- Fiber-optic lasers
- Fiber-optic sensors
- Novel types of optical fibers - Microstructure fibers, photonic crystal fibers, fibers for energy transfer

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OPTICAL FIBERS
FOR TELECOMMUNICATIONS

OUTLINE

- Optical fibers – basic principles
- Methods for the preparation of optical fibers
- Standard optical fibers for telecommunications - types, characteristics
- Video – MCVD method
- Video - Fiber drawing

WHY OPTICAL FIBERS?

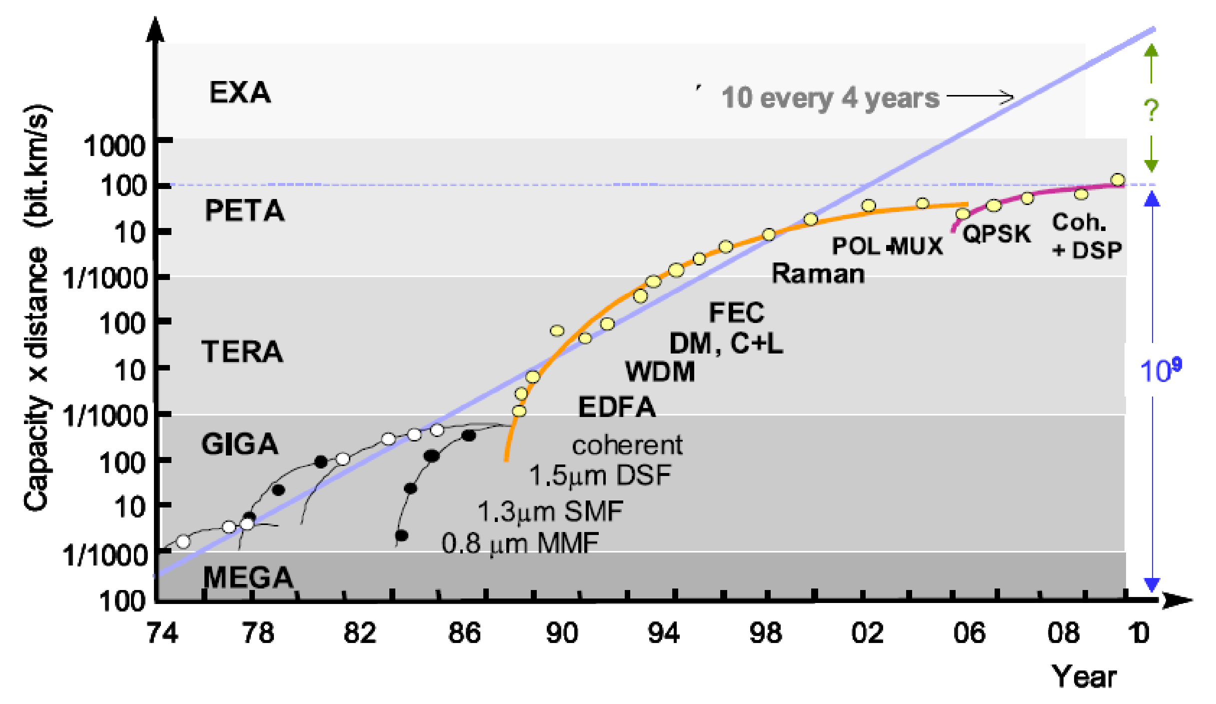
These: Optical fibers offer nearly unlimited performance for telecommunications one of fundamental stones for creating information society.

1. They use the highest speed on Earth – the speed of light ~ 3 10^8 m/s
2. They offer high bandwidths

   e.g. light wave $\lambda=1\ \mu m$ $\nu \sim 10^{14}$ Hz, bandwidth 10^{12} Hz (1%)
3. They are immune to electromagnetic fields
4. They can be prepared in long length with low losses

Today >10^6 km of optical cable lines is installed

TRANSMISSION PERFORMANCE



EDFA – erbium-doped fiber amplifier, WDM – wavelength-division multiplexing, DM – disperion management, FEC – forward error correction, POL-MUX – polarization multiplexing, QPSK-Quadrature-phase-shift keying, DSP-Digital signal processing

E. Desurvire et al., C. R. Physique 12 (2011) 387–416

NOBEL PRIZE IN PHYSICS 2009

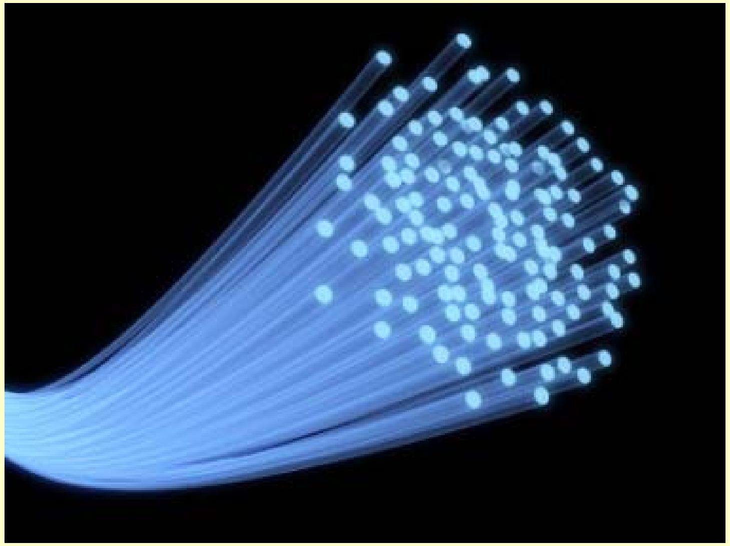
- **Charles K. Kao**
  Standard Telecommunication Laboratories, Harlow, UK, and Chinese University of Hong Kong

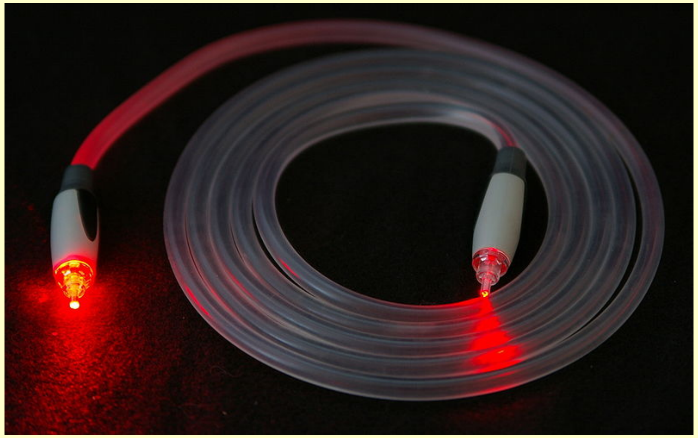
"*for groundbreaking achievements concerning the transmission of light in fibers for optical communication*"

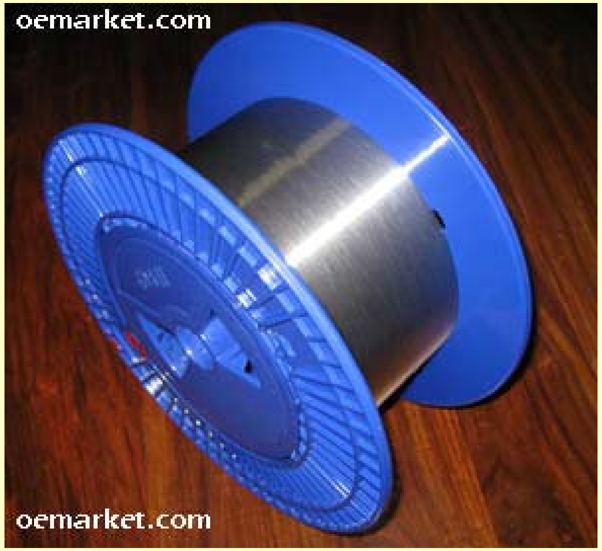
- **Willard S. Boyle and George E. Smith**
  Bell Laboratories, Murray Hill, NJ, USA

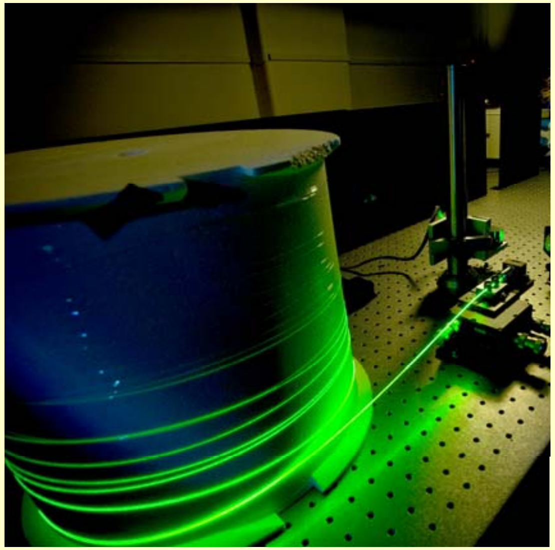
"*for the invention of an imaging semiconductor circuit – the CCD sensor*"

WHAT IS OPTICAL FIBER ?









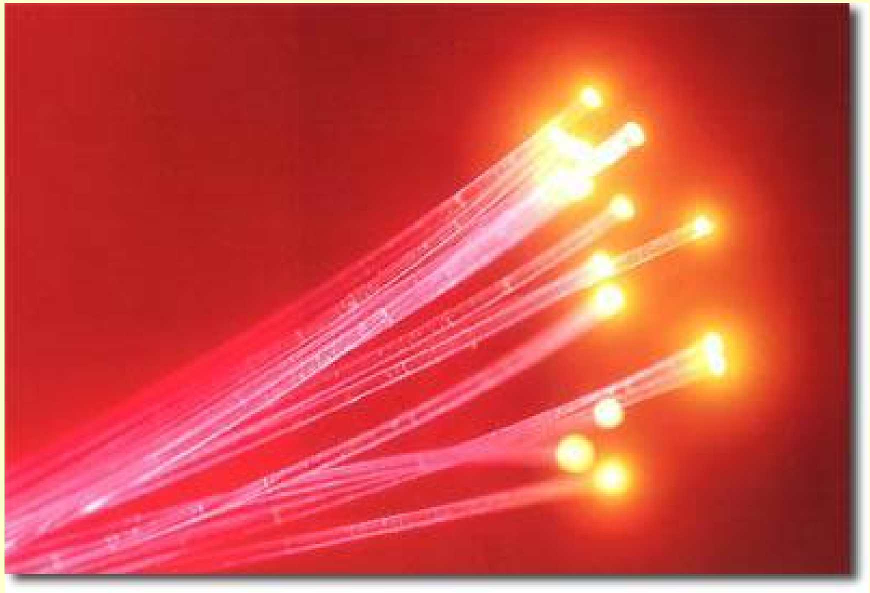
OPTICAL FIBER DEFINITION

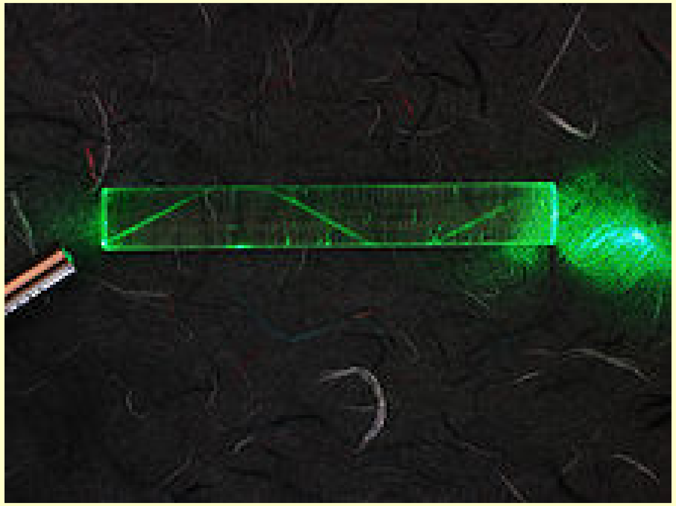
OPTICAL FIBER IS

- structure of dielectric materials (glasses, polymers)
- with transversal (d) << longitudinal dimensions (L) (a long thin cylinder-“thread“)
- enables to confine and guide light waves (UV-IR region) in it.

d ~ mm, L ~ >100 km

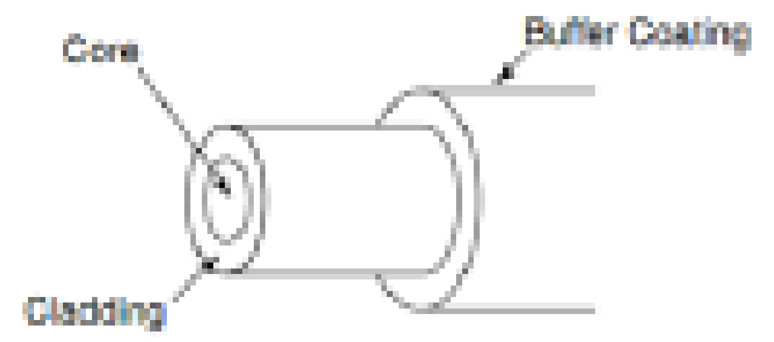
LIGHT CONFINEMENT, GUIDING

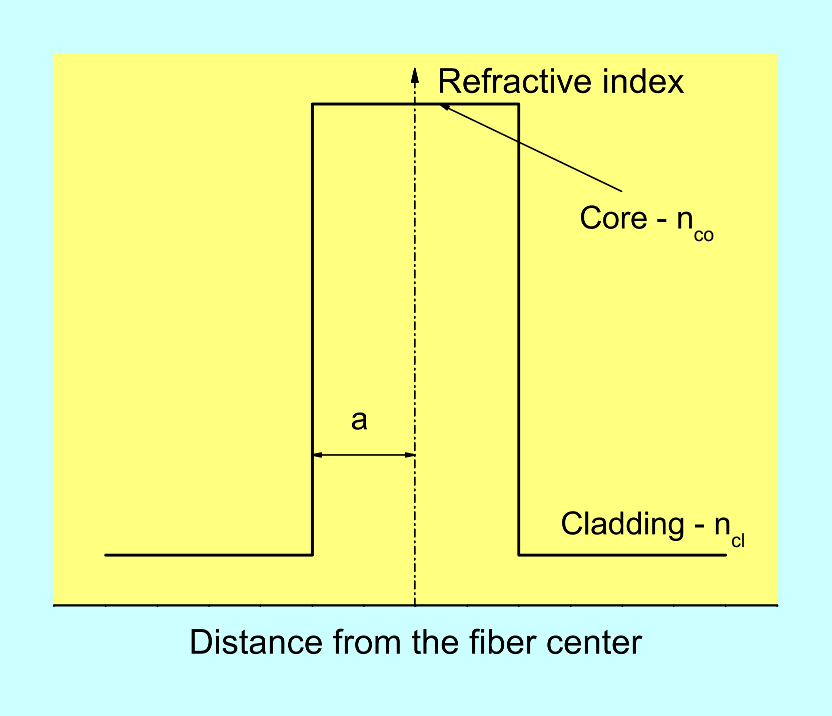




CONDITION OF LIGHT GUIDING

In most cases optical fiber consists of a region of optically dense material - **core** surrounded by an optically less dense material - **cladding**





Buffer protect fiber surface against water → mechanical strength degradation

OPTICAL FIBER PHYSICS

Exact physical description of fiber via

Maxwell's equations

Assumptions

nonmagnetic time-harmonic fields *exp(-i*$\omega\tau$*)*

$$\nabla \times \mathbf{E} = i\sqrt{\left(\frac{\mu_0}{\varepsilon_0}\right)}k\mathbf{H} \qquad \nabla \times \mathbf{H} = \mathbf{J} - i\sqrt{\left(\frac{\varepsilon_0}{\mu_0}\right)}kn^2\mathbf{E}$$

$$\nabla \cdot \left(n^2\mathbf{E}\right) = \frac{\sigma}{\varepsilon_0} \qquad \nabla \cdot \left(\mathbf{H}\right) = 0$$

E,H – intensities of electric and magnetic fields, n - refractive index, $k=2\pi/\lambda=\omega/c$ – wave number, ε_0 and μ_0 – perimtivity and permeability of free space, σ, **J** – total charge and current densities, c – speed of light, i – imaginary unit

SOLUTION OF MAXWELL’ S EQUATIONS

Assumptions

1. Fields without electrical charges and current sources (σ=0, **J=0**).
2. Continuity of **H** and tangential components of **E** on fiber boundaries (core/cladding)
3. Continuity of normal components of $\varepsilon n^2\mathbf{E}$ on fiber boundaries
4. *n* does not change along fiber axis → $n \neq n(z)$

$$\mathbf{E} = \mathbf{e}(r,\varphi)\exp(i\beta z) = (\mathbf{e_t} + e_z\mathbf{z})\exp(i\beta z) \quad \mathbf{H} = \mathbf{h}(r,\varphi)\exp(i\beta z) = (\mathbf{h_t} + h_z\mathbf{z})\exp(i\beta z)$$

e,h – electric and magnetic fields in the fiber cross-section, **$\mathbf{e_t}$, $\mathbf{h_t}$ –** transversal parts of electrical and magnetic fields, e_z ,h_z – z components of the fields, β - propagation constant, **z** – unit vector in axial direction

SOLUTION OF MAXWELL' S EQUATIONS

$$\left(\nabla_t^2 + n^2k^2 - \beta^2\right)\mathbf{e} = -\left(\nabla_t + i\beta\,\mathbf{z}\right)\mathbf{e_t}\cdot\nabla_t \ln n^2$$
$$\left(\nabla_t^2 + n^2k^2 - \beta^2\right)\mathbf{h} = \left(\left(\nabla_t + i\beta\,\mathbf{z}\right)\times\mathbf{h}\right)\times\nabla_t \ln n^2$$

$$\nabla = \nabla_t + \mathbf{z}\frac{\partial}{\partial z},\ \nabla^2\mathbf{A} = \nabla\left(\nabla\cdot\mathbf{A}\right) - \nabla\times\left(\nabla\times\mathbf{A}\right)$$

The set of equation is solved only for e_z and h_z because the transversal components can be calculated from them

$$\mathbf{e_t} = \frac{i}{n^2k^2-\beta^2}\left(\beta\nabla_t e_z - \sqrt{\left(\frac{\mu_0}{\varepsilon_0}\right)}k\mathbf{z}\times\nabla_t h_z\right)$$
$$\mathbf{h_t} = \frac{i}{n^2k^2-\beta^2}\left(\beta\nabla_t h_z - \sqrt{\left(\frac{\varepsilon_0}{\mu_0}\right)}kn^2\mathbf{z}\times\nabla_t e_z\right)$$

If $\Delta=(n_{co}^2 - n_{cl}^2)/n_{co}^2 \ll 1 \rightarrow \nabla_t \ln n^2 \sim 0$ (weakly guiding waveguides)

SWE: $$\left(\nabla_t^2 + n^2k^2 - \beta^2\right)e_z = 0$$

SCALAR WAVE EQUATION (SWE)

SWE for fiber:

$$\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)+\frac{1}{r^{2}}\frac{\partial^{2}}{\partial\varphi^{2}}+k_{rn}^{2}\right)\begin{pmatrix}e_z\\ h_z\end{pmatrix}=0$$

$$k_{rn}^{2} = n(r,\varphi)^{2}\ k^{2} - \beta^{2}$$

r,φ - cylindrical coordinates, $n(r,\varphi)$ - refractive index profile

Boundary condition for e_z (h_z) →
a set of k_m (β) eigenvalues and eigenfunction e_z,(h_z)

SOLUTION OF SWE

$$e_z, (h_z) = F(r, \varphi, \beta)$$

a set of eigenfunctions - optical modes for eigenvalues β

Optical mode is a **spatial distribution** of electric and magnetic fields obtained from SWE for an allowed value of the propagation constant β that is determined from the characteristic scalar equation.

I. $n_{cl}\,k < \beta \leq n_{co}\,k$

II. **A limited number of β is allowed**

STEP - INDEX FIBER PROFILE

$$\text{Core}\quad e_z = A\frac{J_l(UR)}{J_l(U)}f_l(\varphi)\quad h_z = B\frac{J_l(UR)}{J_l(U)}g_l(\varphi)$$

$$\text{Cladding}\quad e_z = A\frac{K_l(WR)}{K_l(W)}f_l(\varphi)\quad h_z = B\frac{K_l(WR)}{K_l(W)}g_l(\varphi)$$

$$f_l(\varphi)=\begin{pmatrix}\cos(l\varphi)\\ \sin(l\varphi)\end{pmatrix}, g_\nu(\varphi)=\begin{pmatrix}-\sin(l\varphi)\\ \cos(l\varphi)\end{pmatrix}\quad \begin{matrix}\textit{sude}\\ \textit{liche}\end{matrix}$$

J_ν, K_ν - Bessel functions of the first and second kind, R=r/a

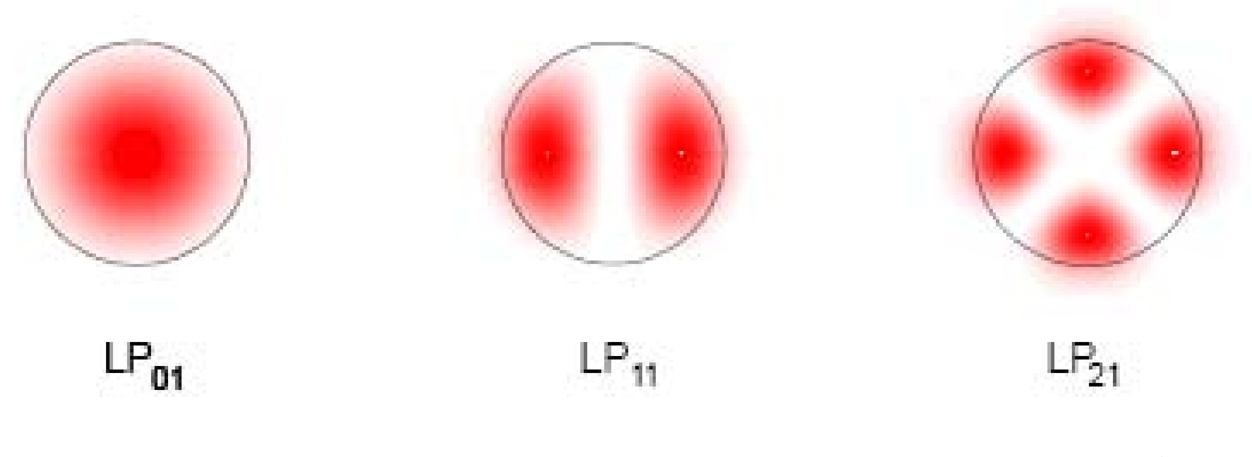
$U=a(k^2n_{co}^2 - \beta^2)^{0.5}$; $W = a(\beta^2 - k^2n_{cl}^2)^{0,5}$, $U^2 + W^2 = V^2 = k^2a^2(n_{co}^2 - n_{cl}^2)$

V – normalized frequency

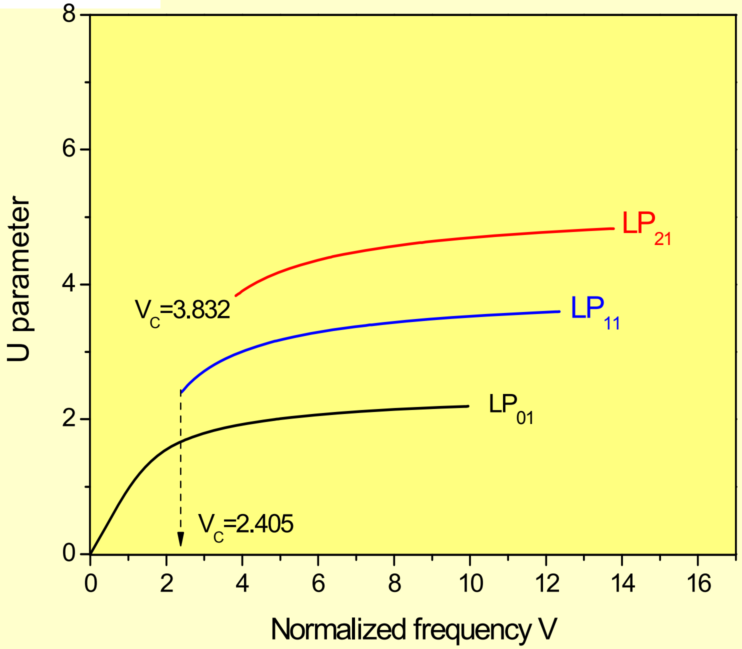
Characteristic Equation

$$U\frac{J_{l+1}(U)}{J_l(U)} = W\frac{K_{l+1}(W)}{K_l(W)}$$

STEP-INDEX PROFILE – MODES-SPATIAL PROFILES, PROPAGATION CONSTANTS



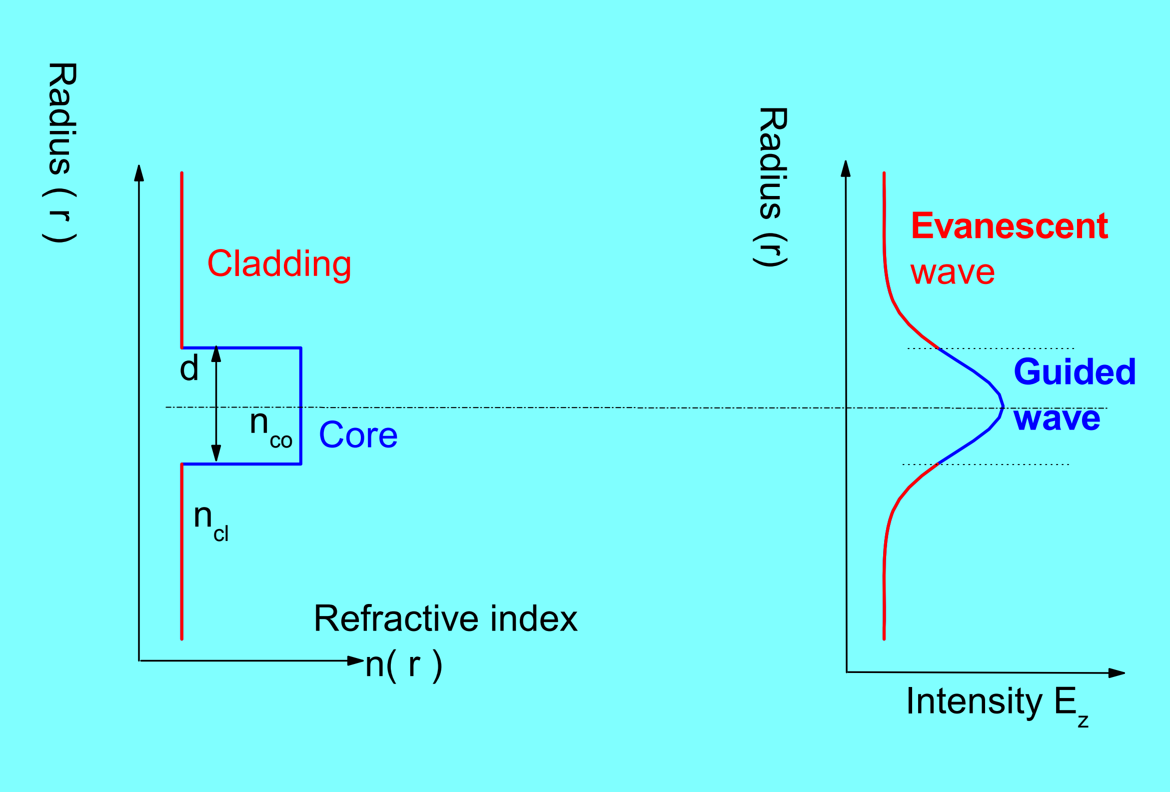
Cut-off conditions V_c



$$V = \frac{2\pi a}{\lambda}\sqrt{n_{co}^2 - n_{cl}^2}$$

V describes the profile and determines which optical modes can be guided in the core

FIELD DISTRIBUTION OF LP$_{01}$ MODE



Nearly Gaussian distribution of electric (magnetic) field.

Evanescent wave – a part of the field distribution in the cladding; exponential decrease of the amplitude from the core/cladding boundary on micrometer scale

STEP-INDEX FIBER NUMBER OF OPTICAL MODES

$$N_g \approx \frac{V^2}{2} = \frac{k^2 a^2}{2} NA^2 = \frac{\left(\frac{2\pi}{\lambda}\right)^2 a^2}{2} (n_1^2 - n_2^2)$$

a - core radius, *NA* - numerical aperture,
e.g. a=25 µm, *NA*=0.21, λ=1 µm, $N_g \approx 2200$.

N_g >1 - Multimode fibers

N_g =1 – Single mode fibers

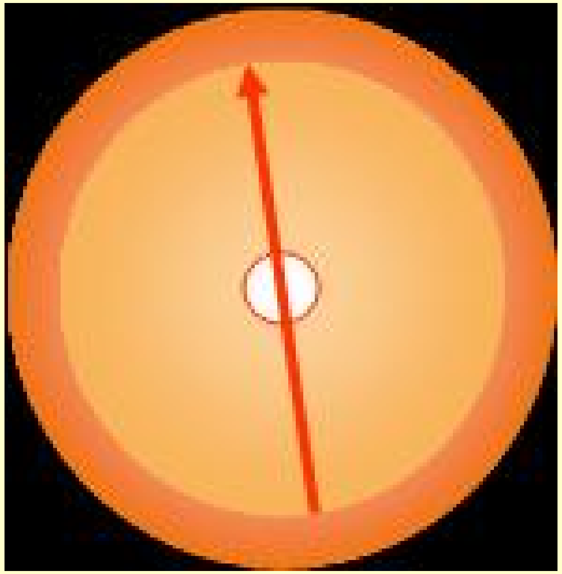
RAY OPTICS MODEL

- For N_g >>1 and a>>1 E_z *(an optical mode)* can be approximated by a plane uniform wave which can be represented by an optical ray.
- In ray optics light guiding in optical fibers is described by **total reflection of light** on the core/cladding boundary

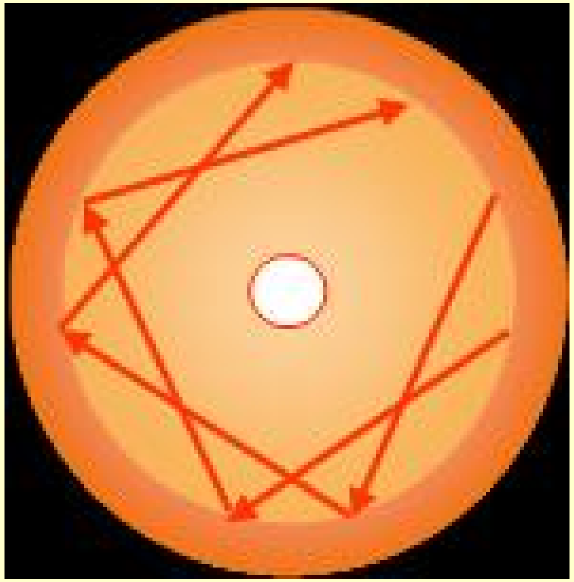
TYPES OF OPTICAL RAYS

- Two types of optical rays – meridional and skew

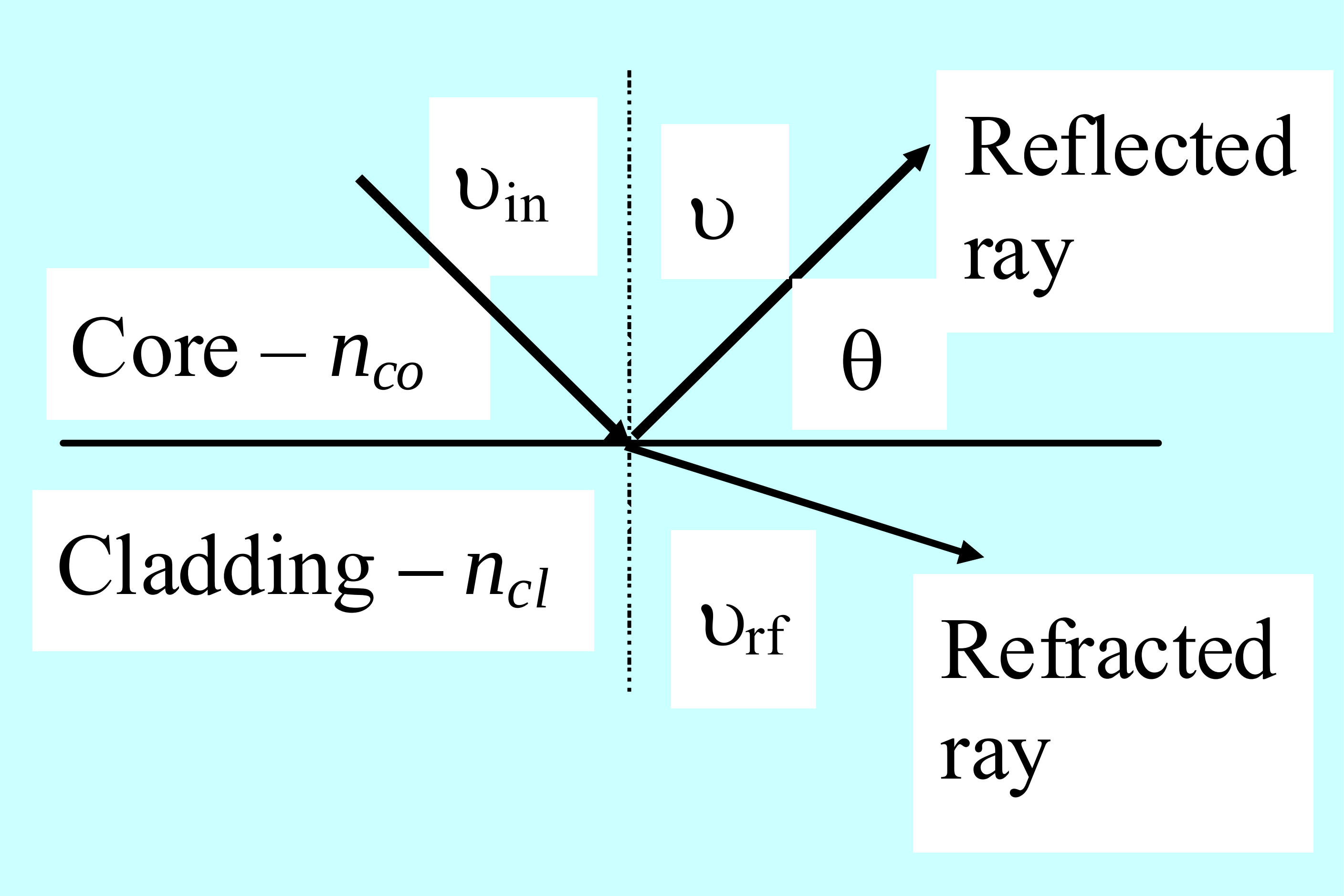
Meridional through centre



Skew outside centre



REFLECTION AND REFRACTION OF LIGHT



$\theta = 90 - \upsilon$ – axial angle

EQUATIONS OF RAY OPTICS

- *Snell's laws*
- Reflection: $\upsilon_{in} = \upsilon$
- Refraction: $n_{co} \sin \upsilon_{in} = n_{cl} \sin \upsilon_{rf}$

$$\beta = n_{co} \sin \upsilon_{in} = n_{co} \cos \theta_{in}$$

- *A limit of the total reflection*

$$\upsilon_{rf} = 90\,° \Rightarrow \upsilon_{in} = \upsilon_{c}$$

- Distribution of the optical power into the reflected and refracted rays determines the <u>power reflection coefficient R - reflectivity</u>

REFLECTION FROM BOUNDARY- FRESNEL FORMULAS

$$\Gamma^{(TE)} = \frac{\sqrt{1-\sin^2\theta} - \sqrt{1-\sin^2\theta\,\frac{\varepsilon_1\mu_1}{\varepsilon_2\mu_2}}\sqrt{\frac{\varepsilon_2\mu_1}{\varepsilon_1\mu_2}}}{\sqrt{1-\sin^2\theta} + \sqrt{1-\sin^2\theta\,\frac{\varepsilon_1\mu_1}{\varepsilon_2\mu_2}}\sqrt{\frac{\varepsilon_2\mu_1}{\varepsilon_1\mu_2}}}$$

$$\Gamma^{(TM)} = \frac{\sqrt{1-\sin^2\theta} - \sqrt{1-\sin^2\theta\,\frac{\varepsilon_1\mu_1}{\varepsilon_2\mu_2}}\sqrt{\frac{\varepsilon_1\mu_2}{\varepsilon_2\mu_1}}}{\sqrt{1-\sin^2\theta} + \sqrt{1-\sin^2\theta\,\frac{\varepsilon_1\mu_1}{\varepsilon_2\mu_2}}\sqrt{\frac{\varepsilon_1\mu_2}{\varepsilon_2\mu_1}}}$$

$\mu_1 = \mu_2$,- magnetic permeability , ε - electric permitivity

$n^2 = \varepsilon\mu$

Γ - intenzity reflection coefficient (complex number)

$R = |\Gamma|^2$

TE polarization – intenzity of electric field paralel with the boundary,

TM-polarization – intenzity of magnetic field paralel with the boundary. Unpolarized light:

$$R = \frac{1}{2}\left(R^{TE} + R^{TM}\right)$$

MATERIALS WITH OPTICAL LOSSES

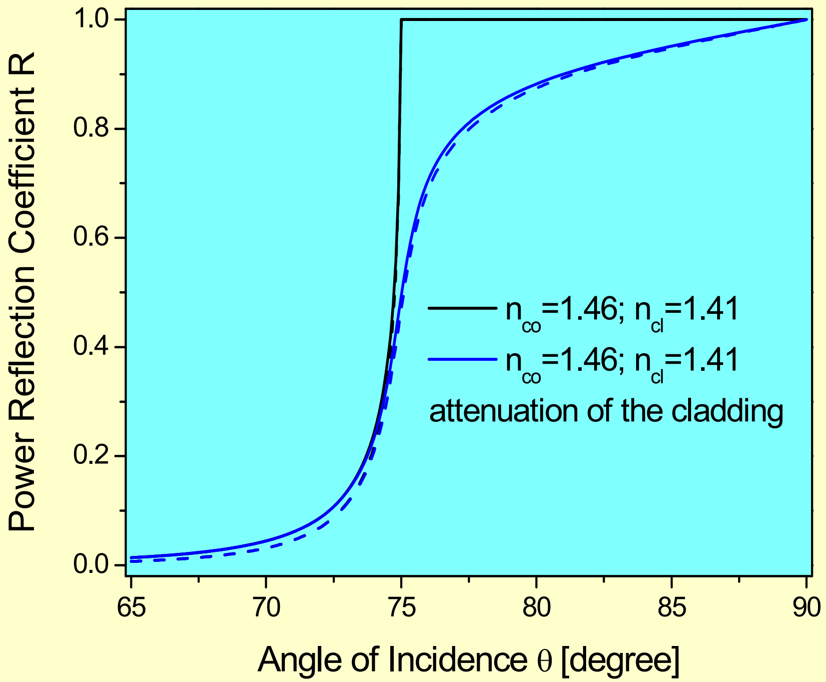
Material with optical losses characterized by a complex refractive index

$$n=n_r + i\, n_i$$

n_r – real part of the refractive index;
i – $(-1)^{0.5}$
n_i – immaginary part of the refractive index related to optical losses γ

$$\gamma = \frac{4\pi}{\lambda} n_i$$

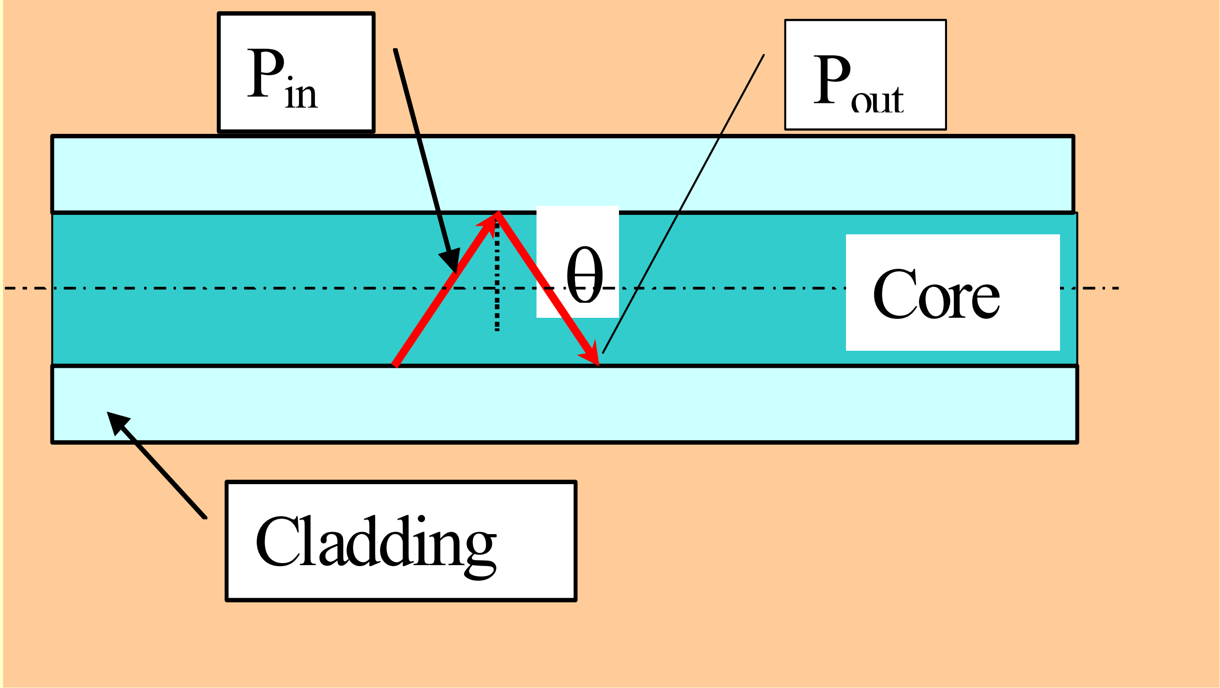
POWER REFLECTION COEFFICIENT- REFLECTIVITY



$$R = \frac{P_{refl}}{P_{in}} = F\left(n_{co}, n_{cl}.\theta\right)$$

R≤1 for totally reflected rays (guided rays)

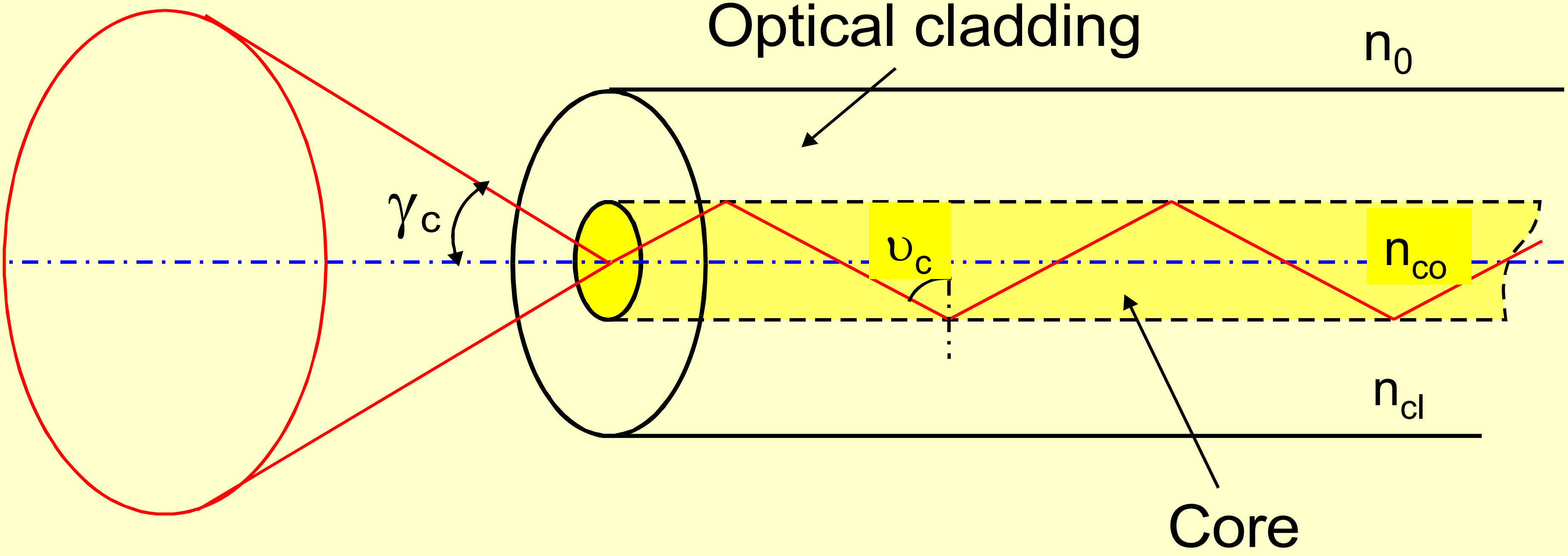
LIGHT TRANSMISSION IN FIBERS VIA TOTAL REFLECTION



$$\mathbf{P_{out} = P_{in}\, R}$$

$$R \leq 1 \rightarrow P_{out} \leq P_{in}$$

NUMERICAL APERTURE NA



$$NA = n_0 \sin \gamma_c = \sqrt{n_{co}^2 - n_{cl}^2}$$

NA determines a maximum spatial angle γ_c at which it is possible to launch a ray into the core and guided it

OPTICAL POWER TRANSMITTED BY RAY

$$P_{iout} = P_{i0} R(\theta_i, n, \alpha)^{N_i}$$

P_{iout} - optical power transmitted by i-th ray

P_{i0} - optical power launched into i-th ray

n - n_{co}, n_{cl} refractive indices on the core/cladding boundary

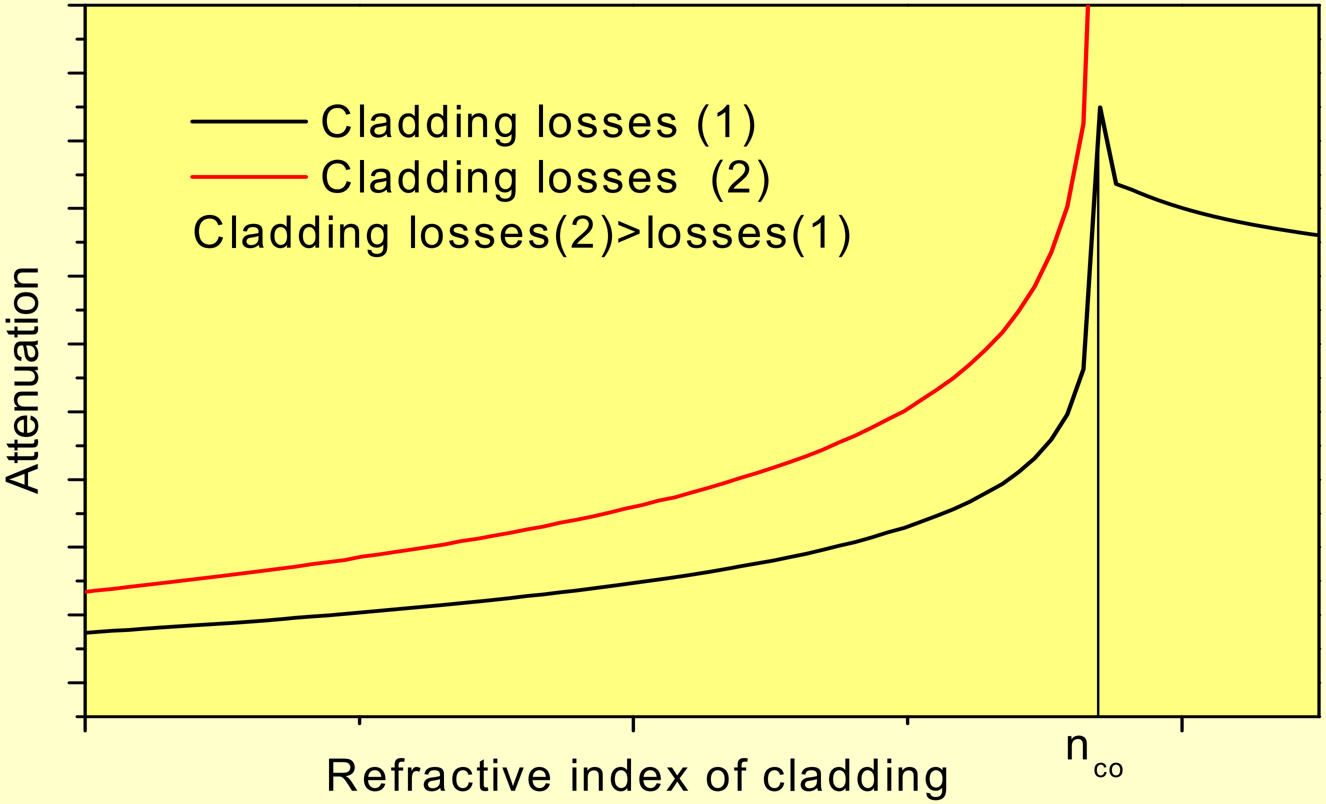
α - bulk absorption coefficient of the cladding

N_i - number of reflection of i-th ray

$$N_i = \frac{L}{2a} tg(\theta_i)$$

a=25 μm, θ_i=5 °C, N_i = 1749 1/m; R=0.999, T~ 17% (1m)

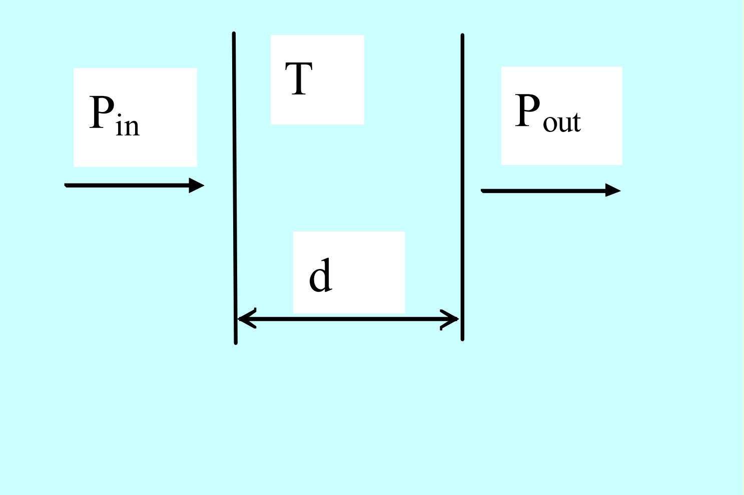
OPTICAL LOSSES - MULTIMODE FIBER



Optical losses [dB/km]= Attenuation ↑ ↔ Transmitted power ↓

MATERIALS-CHARACTERISTICS

- Transmission T [%]

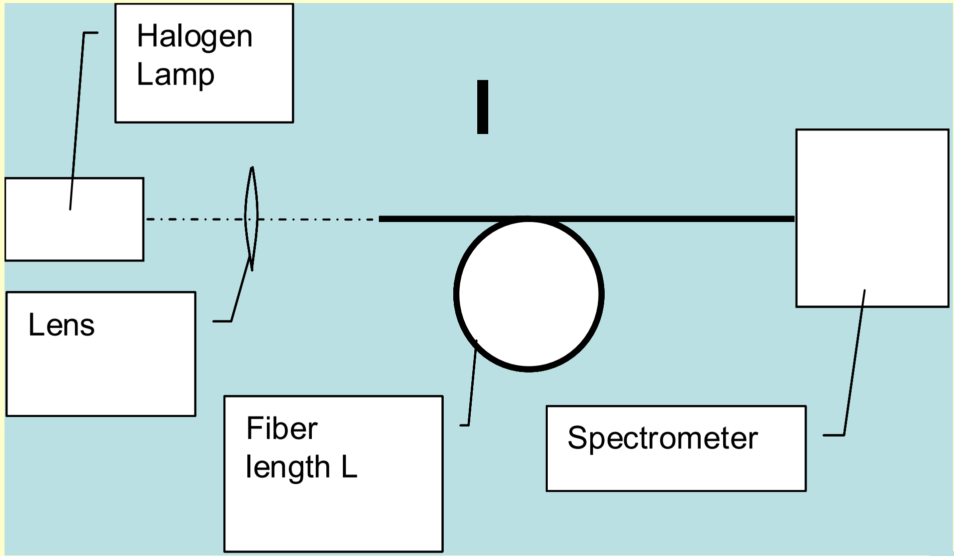


$$T = 100\left(\frac{P_{out}}{P_{in}}\right) \quad [\%]$$

Measured on bulk samples with parallel rays (spectrometers)

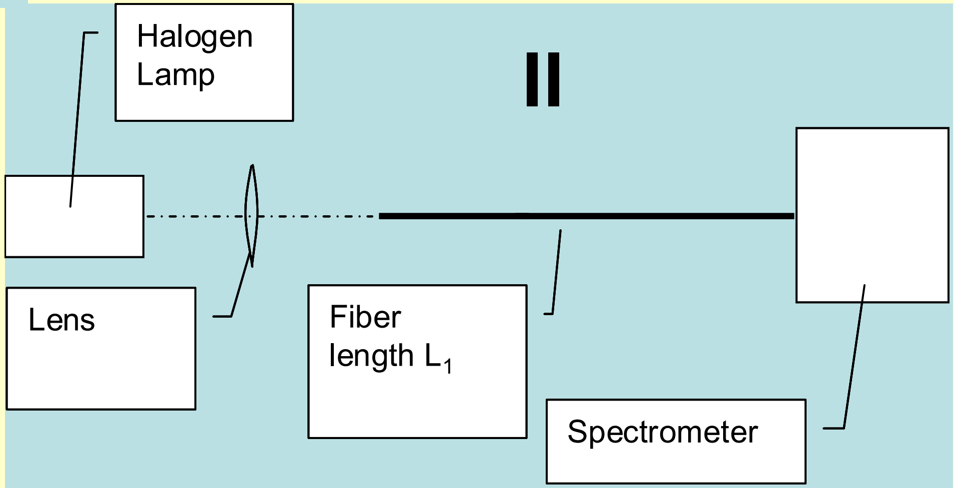
MATERIALS - CHARACTERISTICS

- Optical losses α [dB] – cut back method

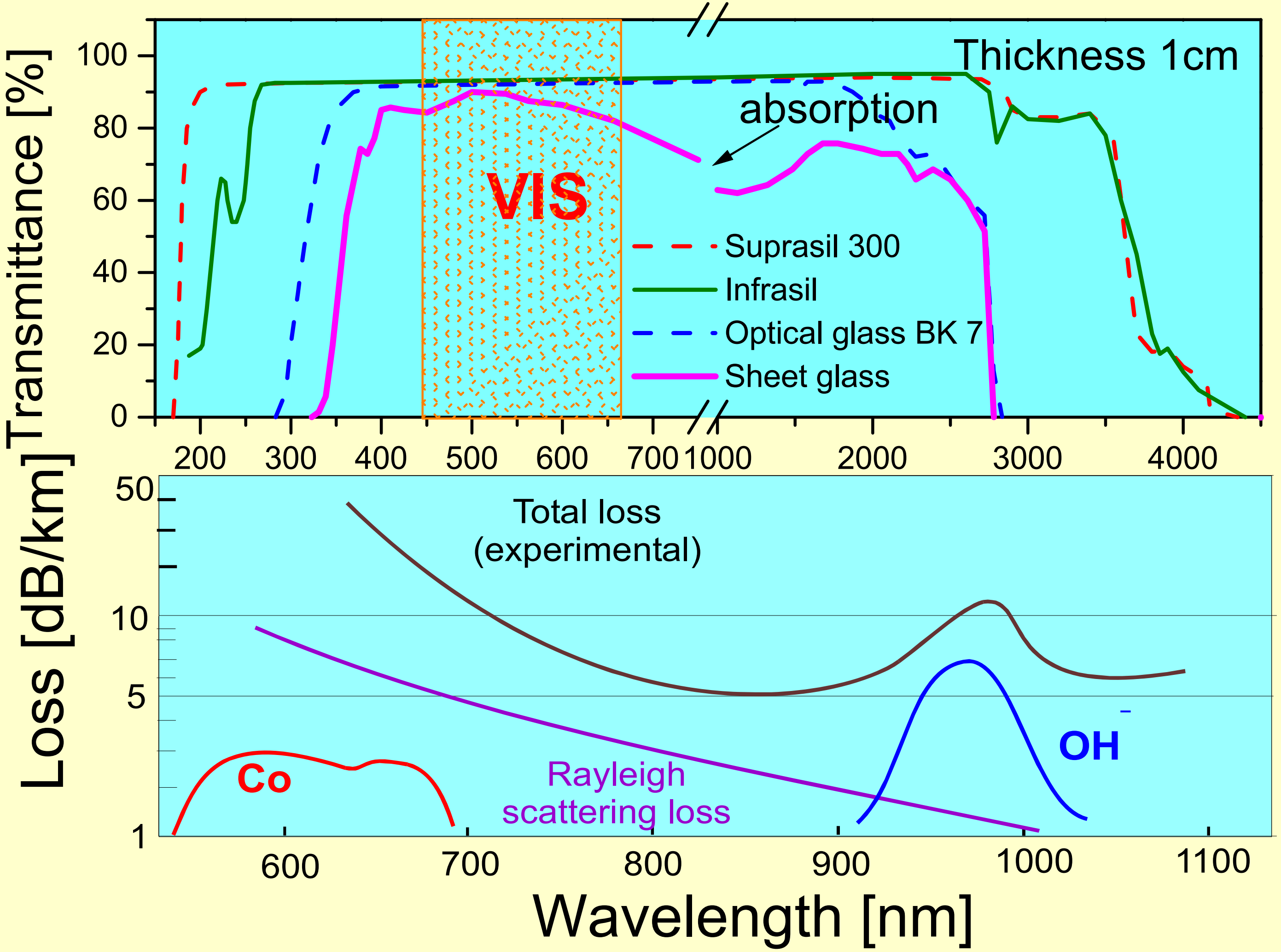


$$\alpha = \frac{10}{L - L_1}\log\left(\frac{P_{ref}}{P_1}\right) \quad [dB/km]$$

L_1 ~ 2m, the same mode distribution at the end as a long fiber

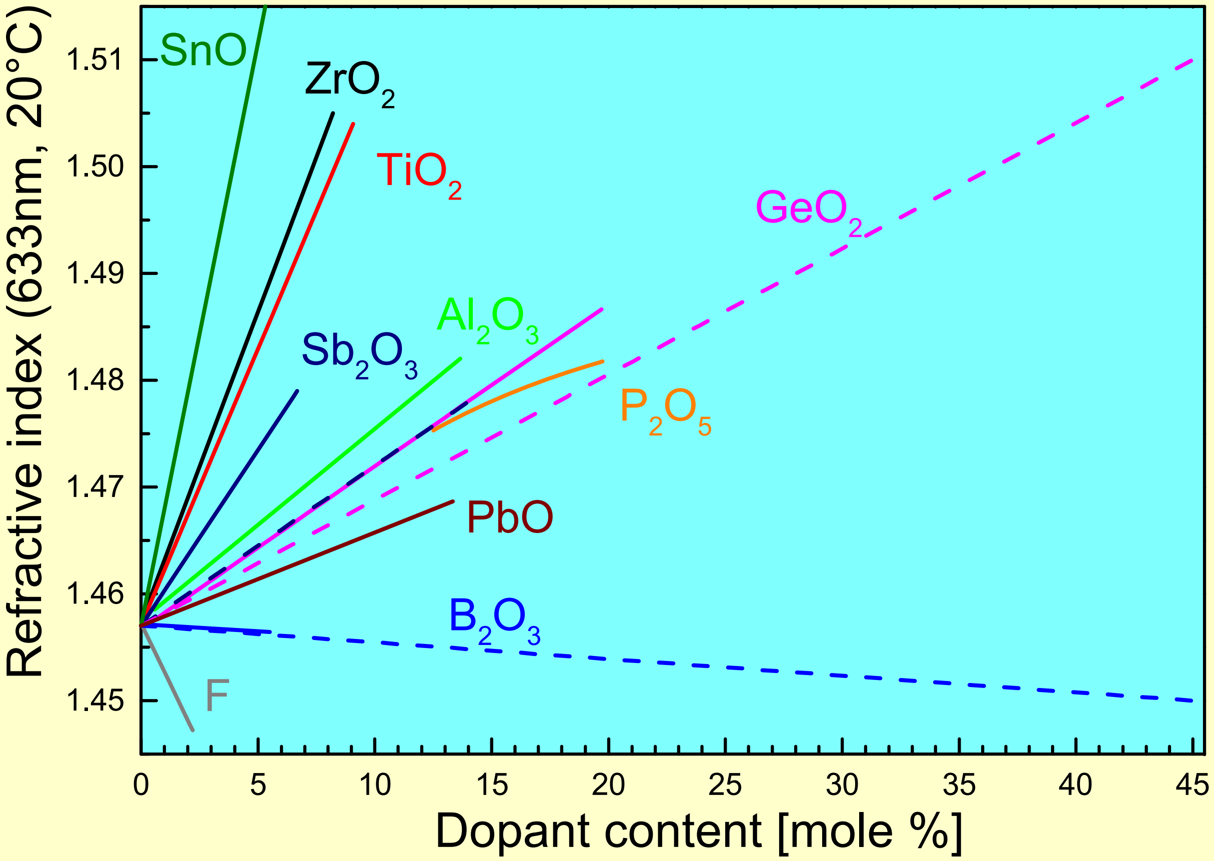


TRANSMISSION AND ATTENUATION



T=90% (1cm) ↔ 45 dB/m > > fiber losses

REFRACTIVE INDEX – DOPED SILICA

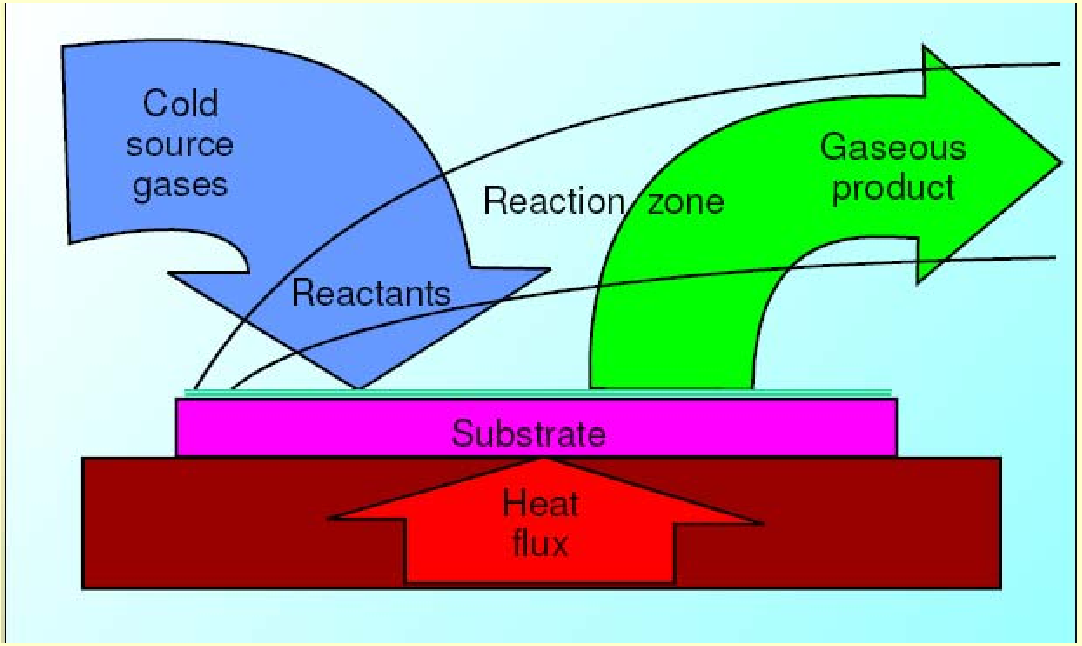


OXIDE GLASSES

- **1960** fibers from silica glasses α~ 1 dB/m
  prepared by melting of oxide powders
  First fibers for a distance 30 m
- **1966** K.C. Kao, C.A. Hockham predicted that advanced methods allow decrease impurities and achieve losses 0.02 dB/m
- **1970** - α = 0.020 dB/m (vapour deposition)
  Doped quartz (silica) glass
- **From 1974** - rapid progress related to

CHEMICAL VAPOUR DEPOSITION - CVD

CVD=production and deposition of material in solid state from starting materials in gaseous state through a chemical reaction: **A (g) + B(g) = AB (s)**



FIBER PREFORMS-VAPOUR DEPOSITION METHODS

- Input chemicals in gaseous phase ($SiCl_4$, $GeCl_4$, BBr_3, $POCl_3$, SF_6, Freons)
- Chemical reactions of the chemicals ⇒ formation of aerosol particles
- Deposition of aerosol particles on a substrate (layers, bulks)
- Sintering porous deposit ⇒ glass layers, glass bulks ⇒ **preforms**

PREFORMS AND FIBERS

Vapour Deposition Methods enable reduce the content of impurities in glass (metal ions) to the ppb level (1 ion in 10^9 glass units)

$$\alpha = 2\text{x}10^{-4}\ \text{dB/m}$$

Fibers are prepared by elongation (<u>fiber drawing -pulling</u>) of glass preforms

VAPOUR AXIAL DEPOSITION (VAD)

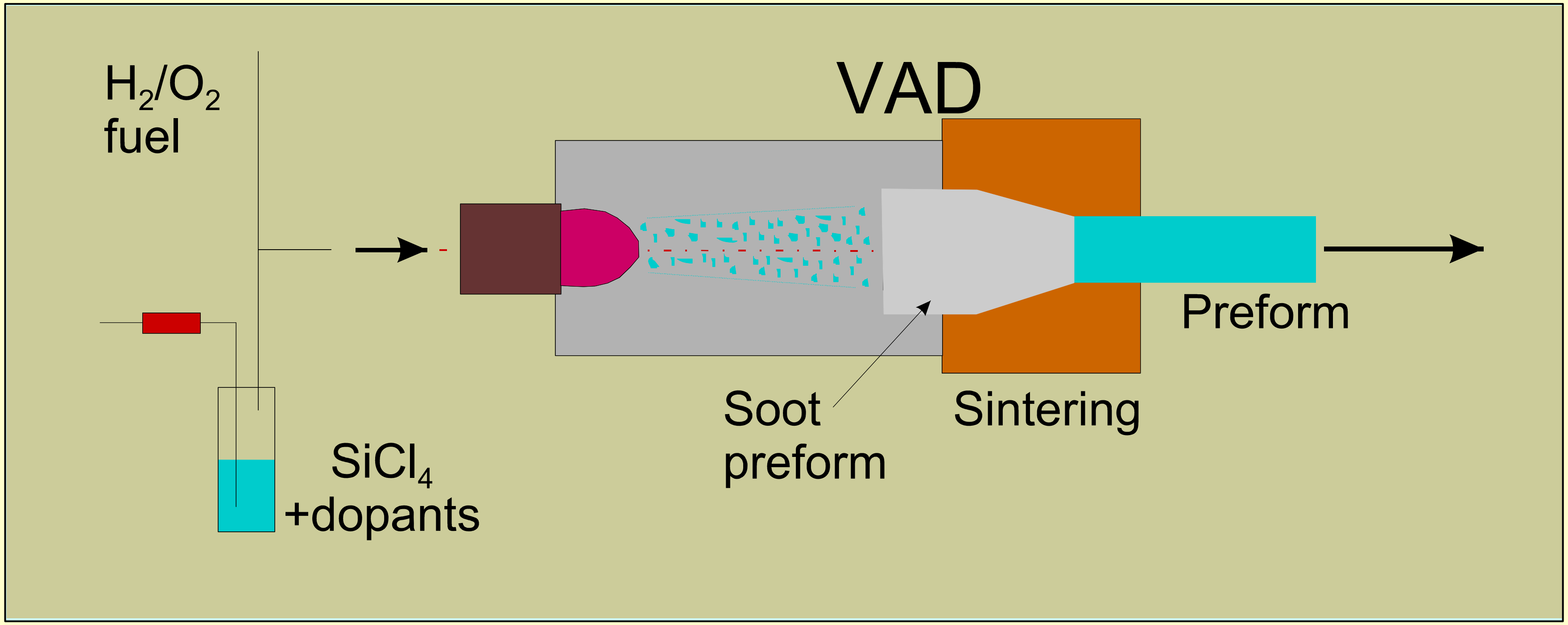
Main features

- Reaction in a burner

$SiCl_4(g) + 2H_2(g) + O_2(g) = SiO_2(s) + 4HCl(g)$

- Deposition onto a slowly translating substrate
- Sintering of the porous bulk in a flow of $SOCl_2$ (removing –OH groups)

VAD SCHEME



Used mainly in Japan

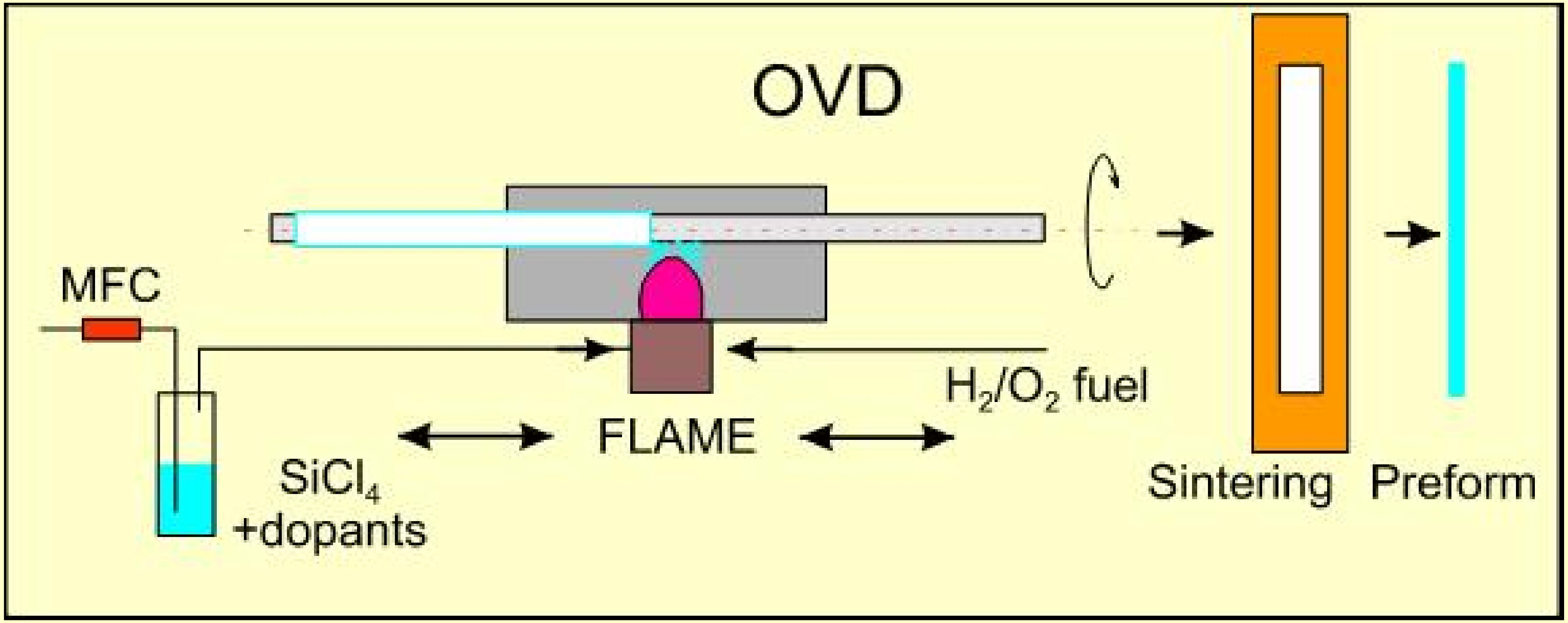
OUTER VAPOUR DEPOSITION (OVD)

- Reaction in a burner

$SiCl_4(g) + 2H_2(g) + O_2(g) = SiO_2(s) + 4HCl(g)$

- Deposition onto rotating substrate (mandrel)
- Removing the mandrel; sintering the porous bulk into a composite glass tube
- Viscous collapse of the tube into a glass rod – a preform

OVD SCHEME



France – Alcatel, USA

MODIFIED CHEMICAL VAPOUR DEPOSITION (MCVD)

IPE

- Reaction in a rotating substrate silica tube

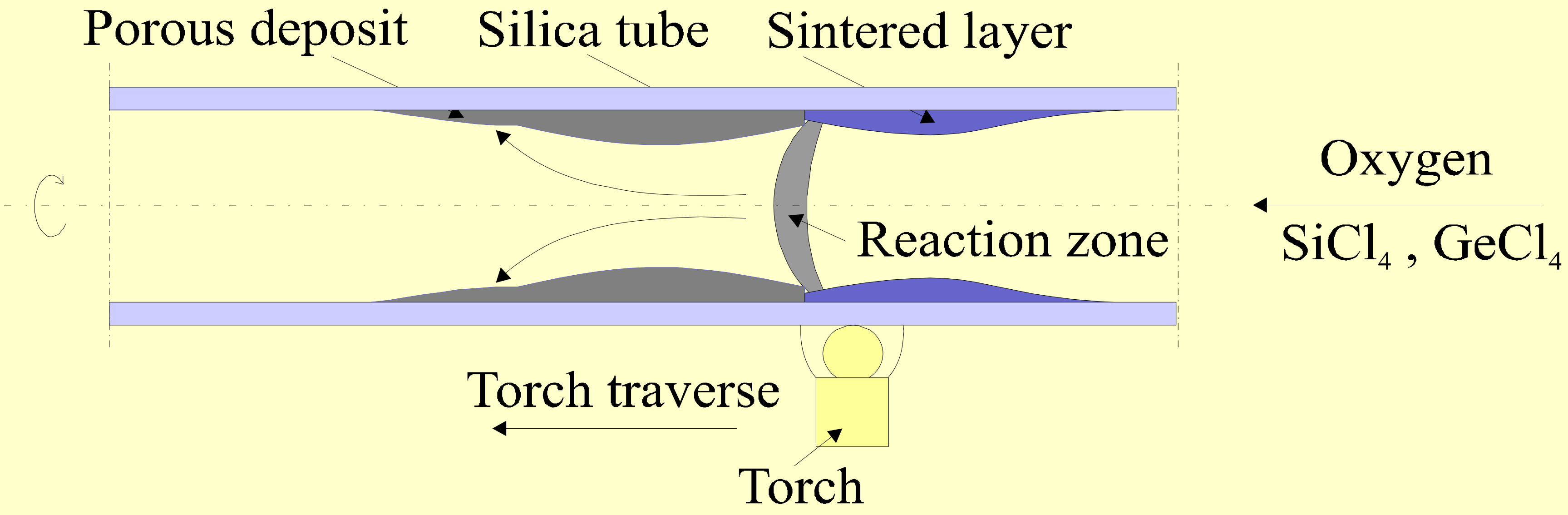
$SiCl_4(g) + O_2(g) = SiO_2(s) + 2Cl_2(g)$

- Deposition of porous layers onto the inner surface of the tube **(thermophoresis)**
- Sintering the porous layers into glass layers
- Viscous collapse of the tube with layers into a glass rod – a preform

PREPARATION OF PREFORMS - DEPOSITION

DEPOSITION OF THIN GLASS LAYERS

t = 1400 - 1700 °C



MCVD DEPOSITION – EXTENTS (YIELDS)

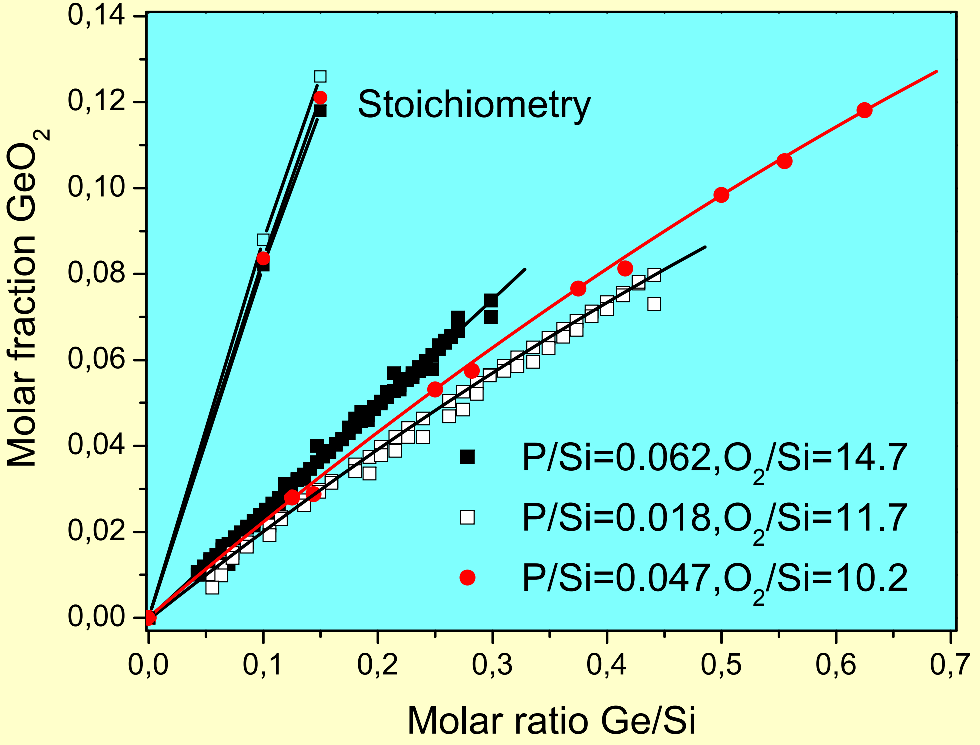
- 10-60 glassy layers deposited (a thickness 5-20 μm)
- Some of MCVD chemical reactions are thermodynamically controlled

Essential chemical equilibria in the MCVD process

P_4O_{10} (g) = 4 $PO_{2.5}$ (gl)	K≈0.3
$GeCl_4$ (g)+O_2 (g) = GeO_2 (gl)+2 Cl_2 (g)	K≈0.1-0.13
SiF_4 (g)+3 SiO_2 (gl) = 4 $SiO_{1.5}F$ (gl)	$K \approx 5.10^{-6}$
$3SiF_4$ (g)+SiO_2 (gl)+$2Cl_2$ (g) = $4SiF_3Cl$ (g)+O_2 (g)	K≈0.5

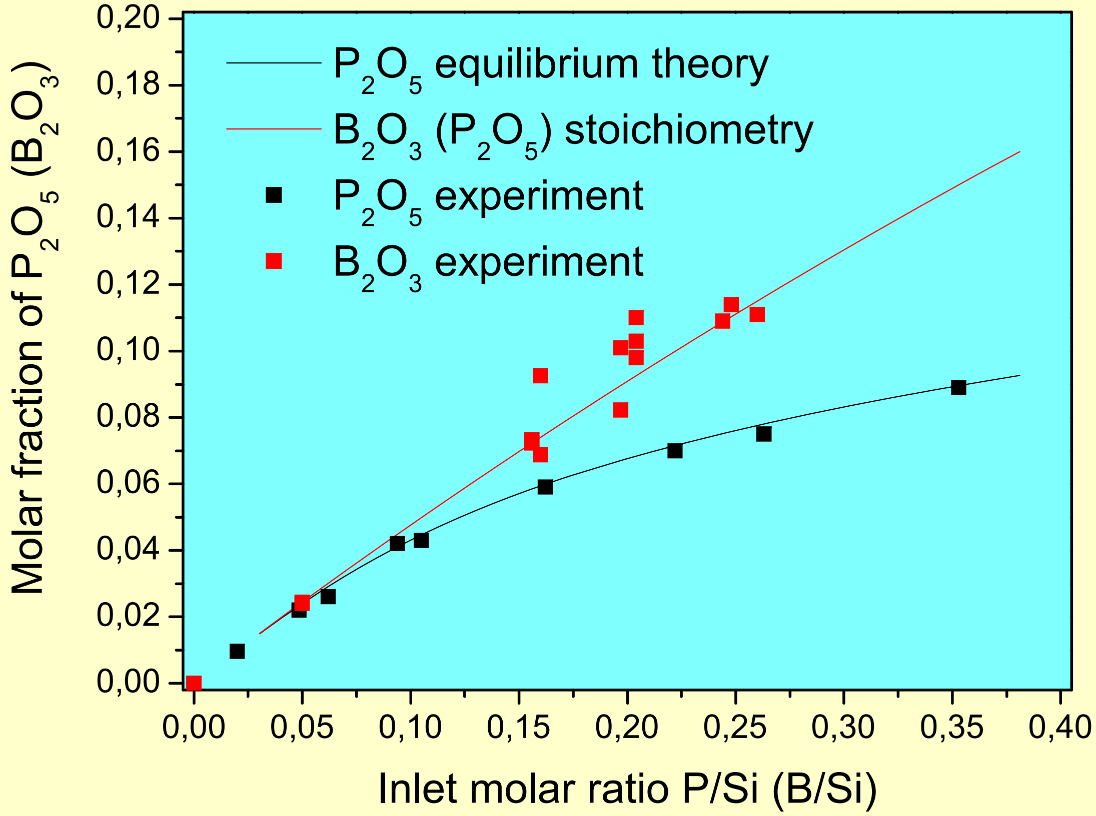
Equilibrium constants K for the other MCVD reactions, e.g. $SiCl_4$, are high enough to achieve 100% reaction extent

GeO_2 DEPOSITION



The reaction extent is ~ 20%, depends on P content

B_2O_3 AND P_2O_5 DEPOSITION



BBr_3 reacts completely, $POCl_3$ does not

V. Matějec et al., SPIE Optics Optoelectronics, 15.4.2013, hotel Clarion, Praha

DOPING WITH FLUORINE

Raw material	Input molar ratios			Content of F [wgt.%]		
	F/Si	P/Si	O/Si	Theory	Experiment	Stoichiometry
SF_6	0.632 1.446	0.0445 0.0434	9.8 9.5	0.48 0.61	0.5 0.6	72.7 85.9
$C_2Cl_3F_3$	0.065 1.796 0.450 0.900	0.0266 0.0000 0.0200 0.0000	5.4 5.3 7.2 7.0	0.32 0.76 0.50 0.62	0.25 0.72 0.47 0.66	21.7 88.5 65.7 79.4

F raw materials do not react completely due to SiF_4 formation

THERMOPHORETIC DEPOSITION

- Driving force

$$T_{\text{reaction}} - T_{\text{Eq.Wall}}$$

drives hot particles to cold wall where they are deposited.

$T_{\text{Eq.Wall}}$ - temperature of the wall in thermal equilibrium with gases flowing in the tube (300 – 500 °C). It can be decreased by water cooling the tube

EFFICIENCY OF THERMOPHORESIS

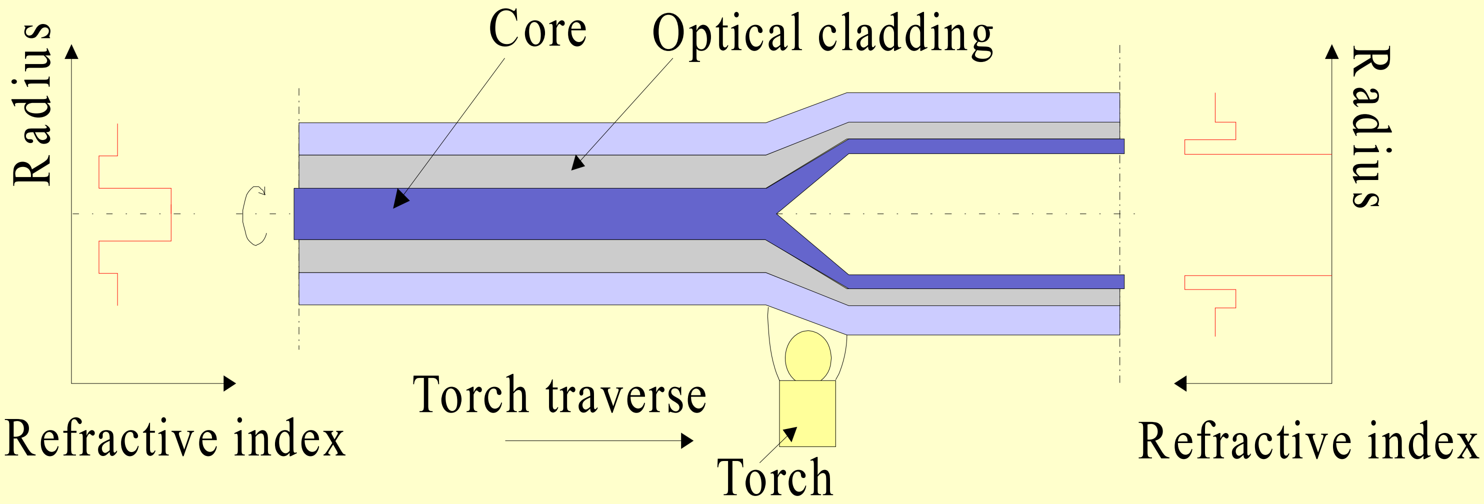
- Deposition Efficiency E_T depends on the temperature profile. Estimation

$$E_T = 0.8\left(1 - \frac{T_{Eq.Wall}}{T_{react.}}\right)$$

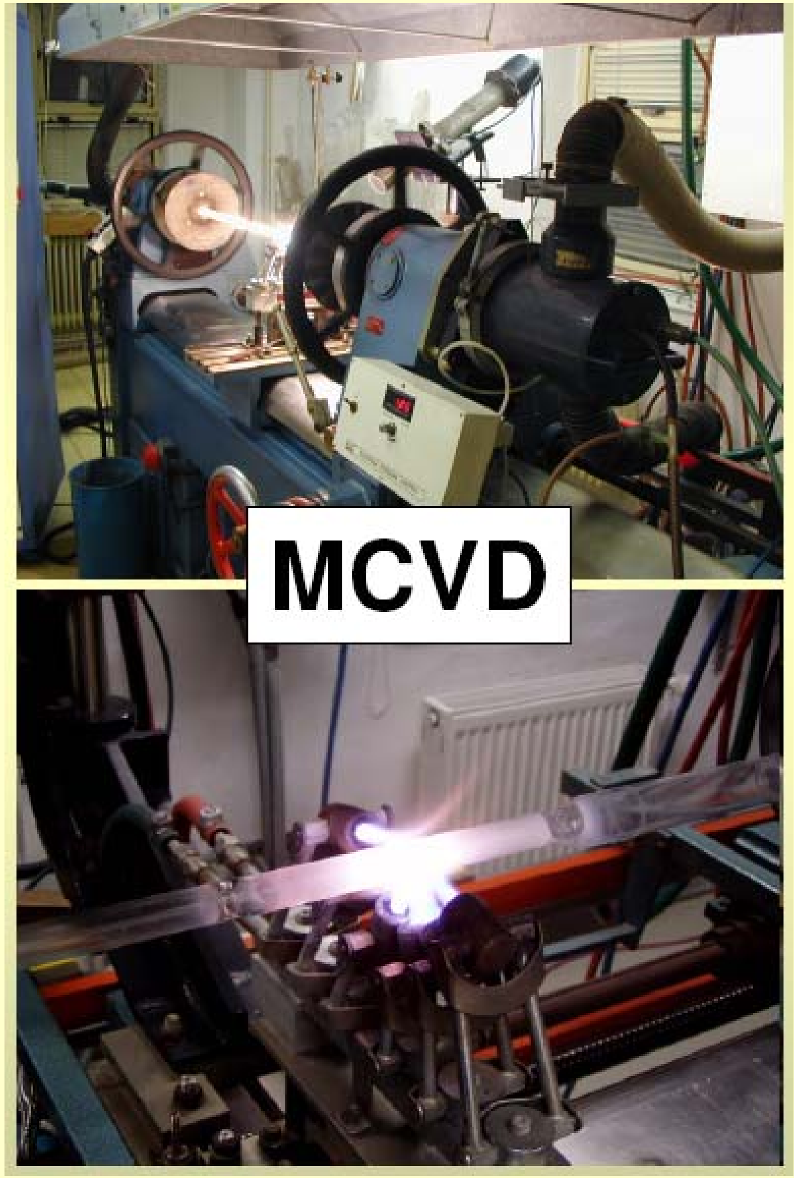
$E_T \sim 0.4 – 0.6$ can be achieved in standard MCVD

VISCOUS COLLAPSE OF THE TUBE

- **Temperatures 1900-2000 °C**
- Viscous flow driven by surface tension

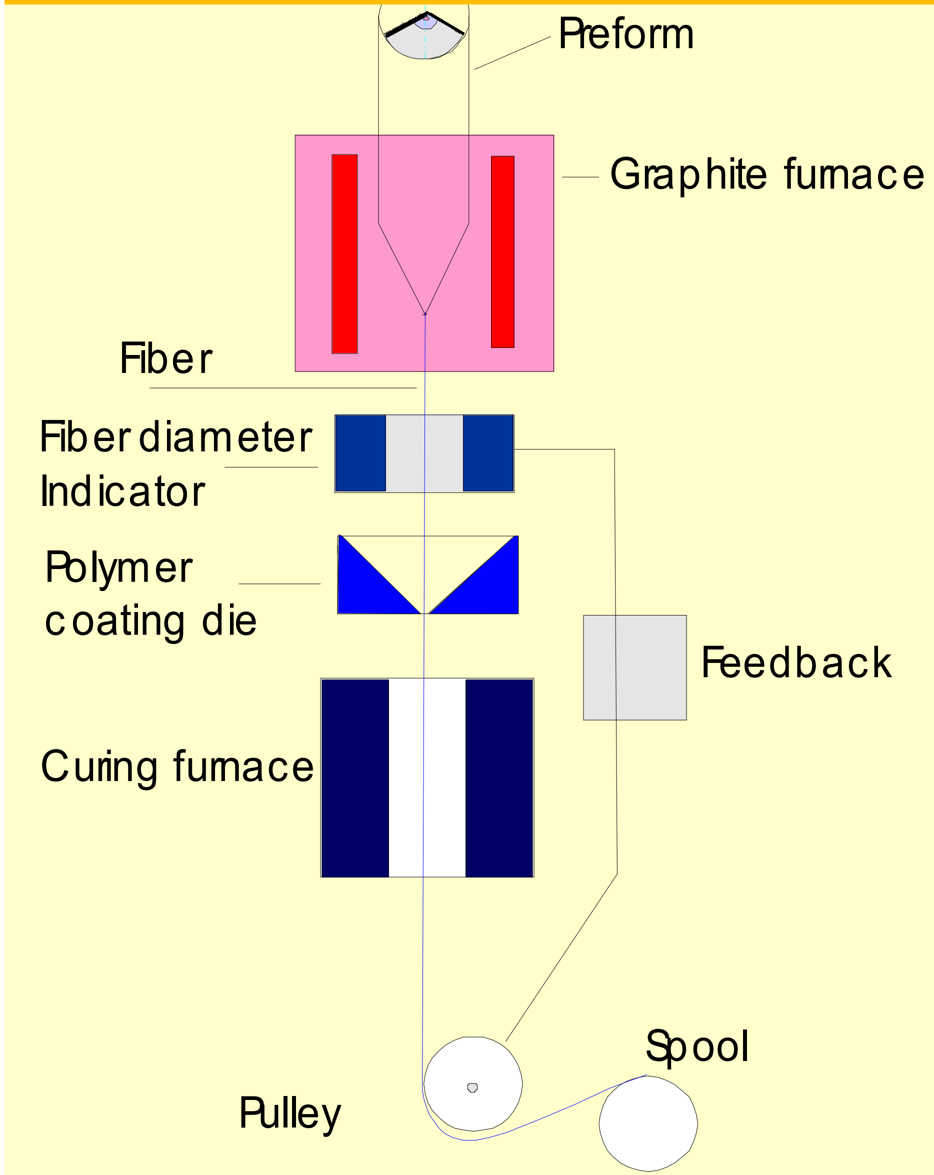


MCVD DEVICE – GLASS WORKING LATHE



Traversing
hydrogen/oxygen burner

FIBER PULLING (DRAWING)



Fiber diameter
50-5000 μm

<u>Standard 125 μm</u>

Temperatures in a hot zone 1900-2200 °C

Protective polymeric coatings against water (UV-curable acrylates, siloxanes)

FIBER DRAWING

- Effect of water on silica surface:

  $Si\text{-}O\text{-}Si + H_2O = 2\ Si\text{-}OH$

  induces decrease of mechanical strength of the fiber especially under the tension ⇒ fibers have to be protected by the application of polymeric jackets
- Drawing velocity (6-100 m/min) controlled on the basis of diameter measurements (feedback)

IPE- FIBER DRAWING

DRAWING TOWER

DRAWING FURNACE

Video

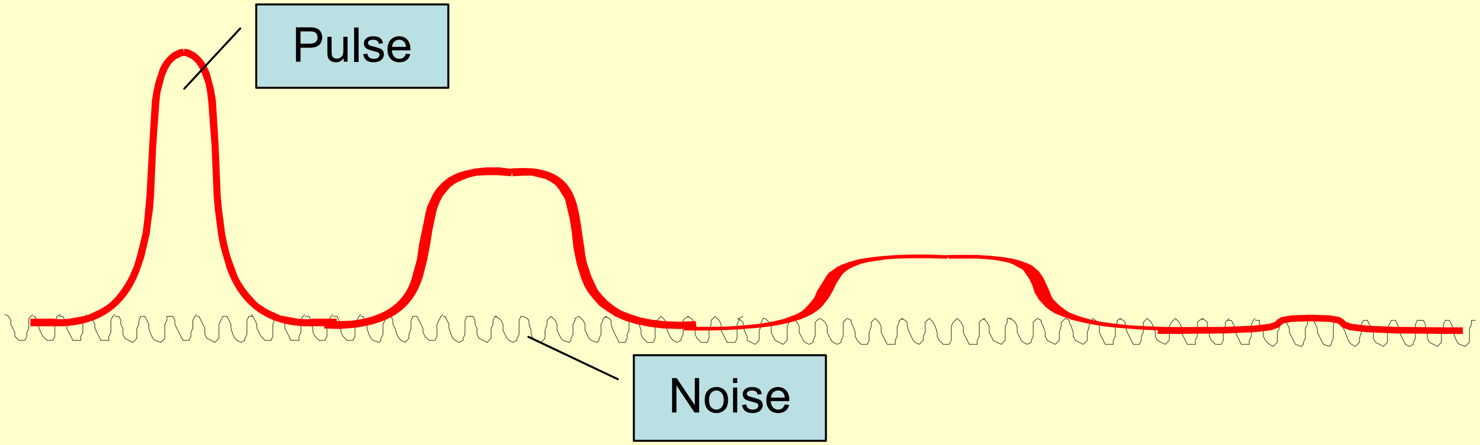
OPTICAL FIBERS - APPLICATIONS

- Fibers for telecommunications

  (Polymer clad silica fibers, graded-index fibers, single-mode fibers, microstructure fibers)
- Fibers for special purpose (fiber lasers and amplifiers, sensors, energy transmission,…)

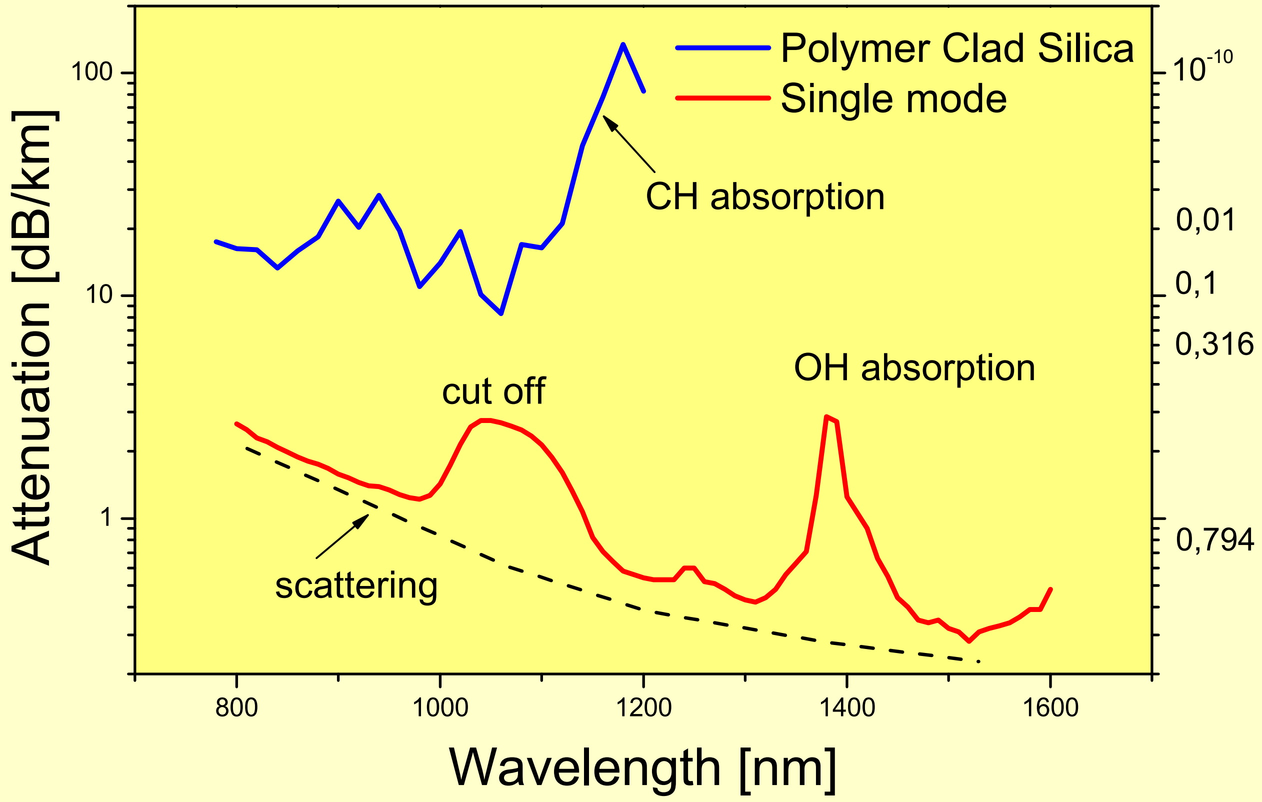
FIBERS FOR TELECOMMUNICATIONS

- Optical telecommunications are based on sending optical pulses into lines (1/0 code)
- In the lines the pulse suffers from decrease (effect of attenuation) and broadening (effect of dispersion)

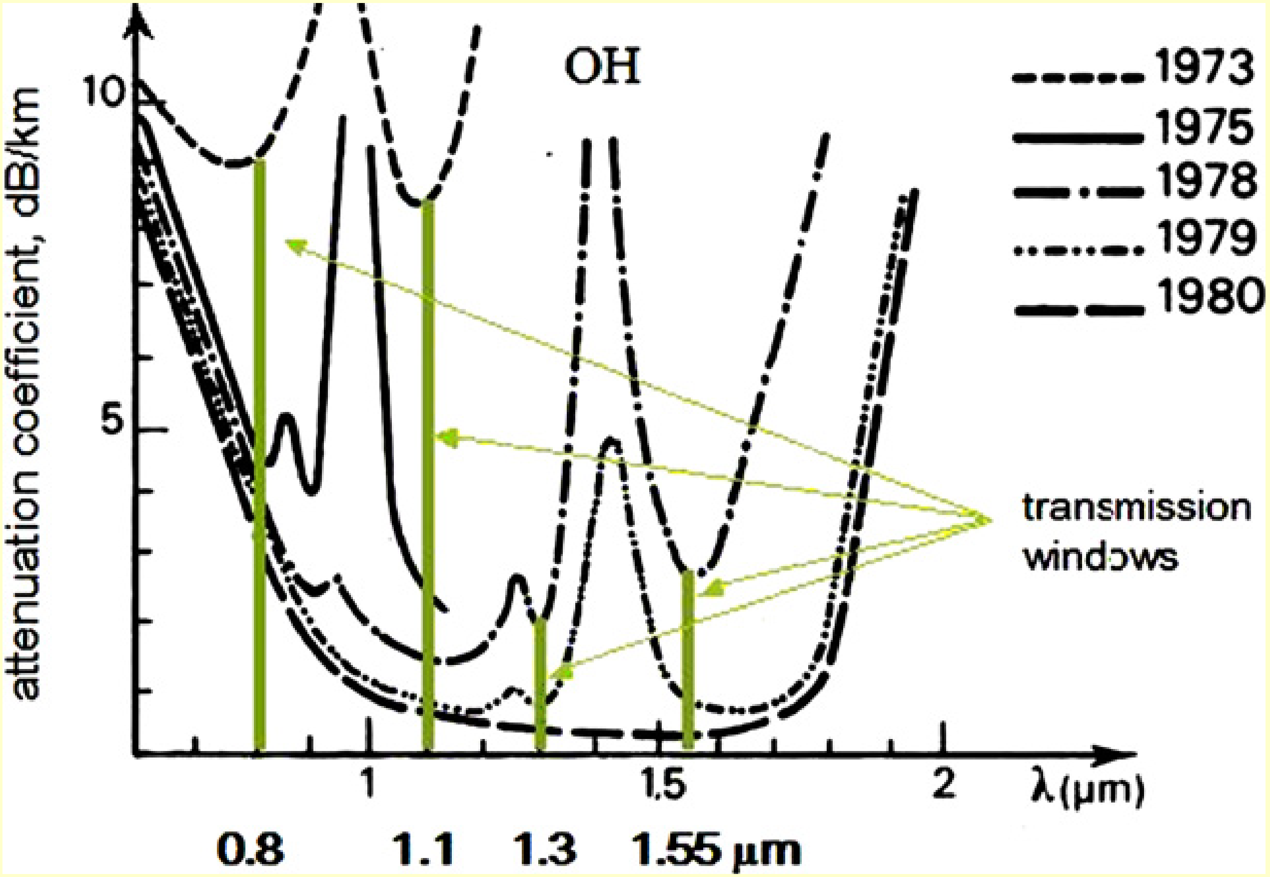


FIBER LOSSES (ATTENUATION)

Sources: impurities (- OH groups), scattering, UV and IR edges, cut off losses



DECREASE OF FIBER ATTENUATION



Telecommunication windows: 850, 1300, 1550 nm (1100 nm) ↔ Available light sources

DISPERSION

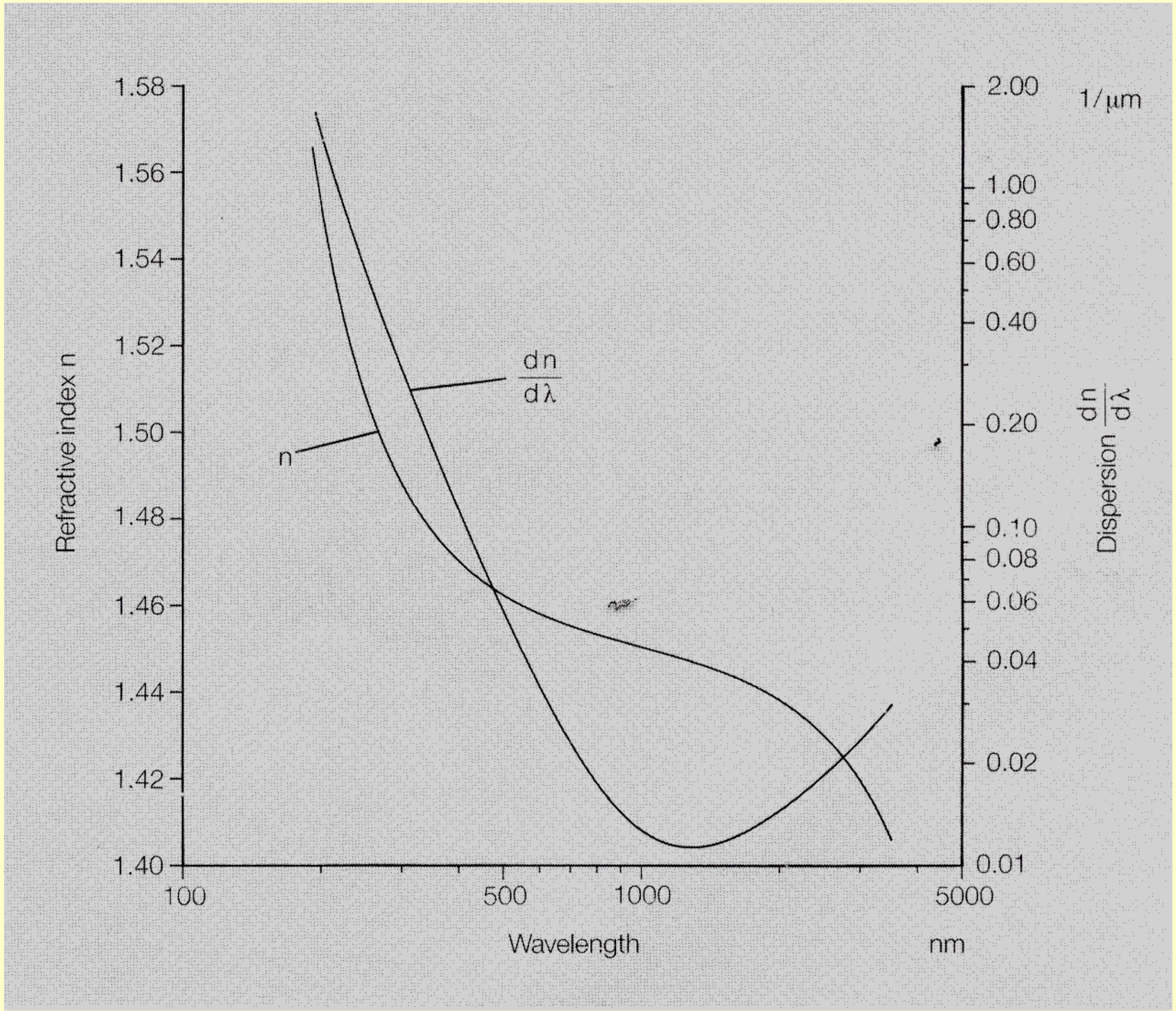
Broadening of light pulses due to frequence dependence of refractive indexes and propagation constants β

1. Material dispersion D_m
2. Intermodal dispersion D_i
3. Chromatic dispersion D_c
4. Polarization dispersion D_p

$$D = D_m + D_i + D_c + D_p$$

$$D_m = -\left(\frac{\lambda}{c}\right)\frac{d^2 n}{d\lambda^2} \qquad D_C = -\left(\frac{\omega}{c}\right)\frac{d^2 \beta}{d\omega^2}$$

REFRACTIVE INDEX OF SILICA



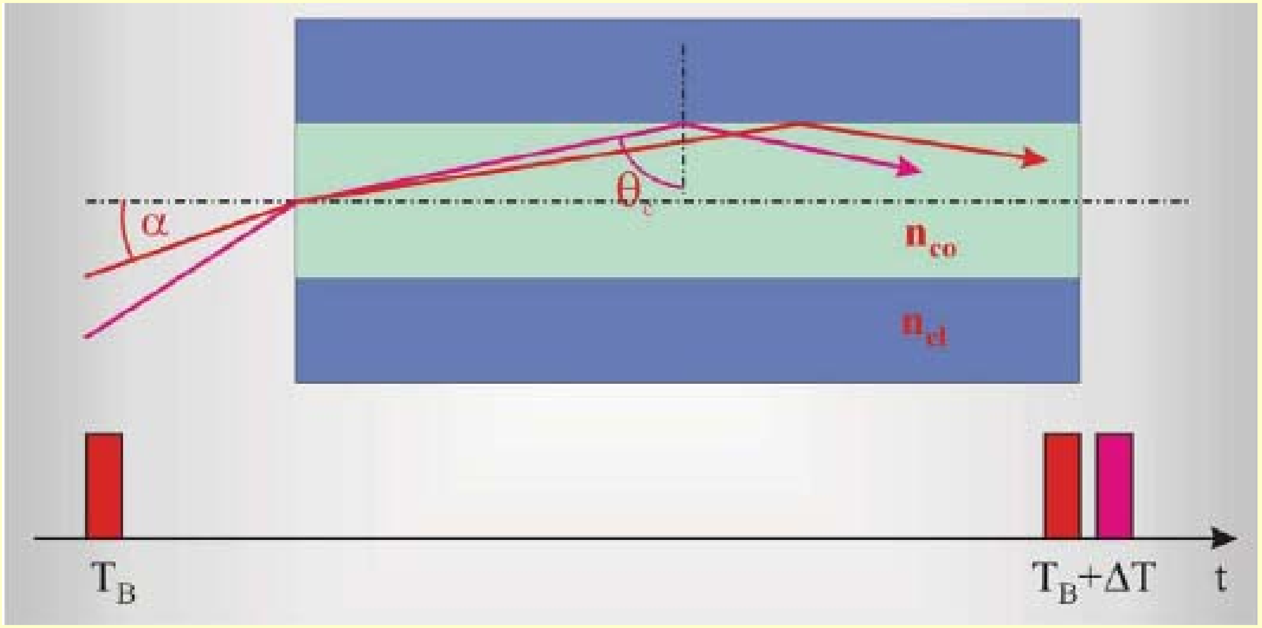
λ<1300 nm

D_m >0

λ=1300 nm

D_m = 0 ps/nm/km

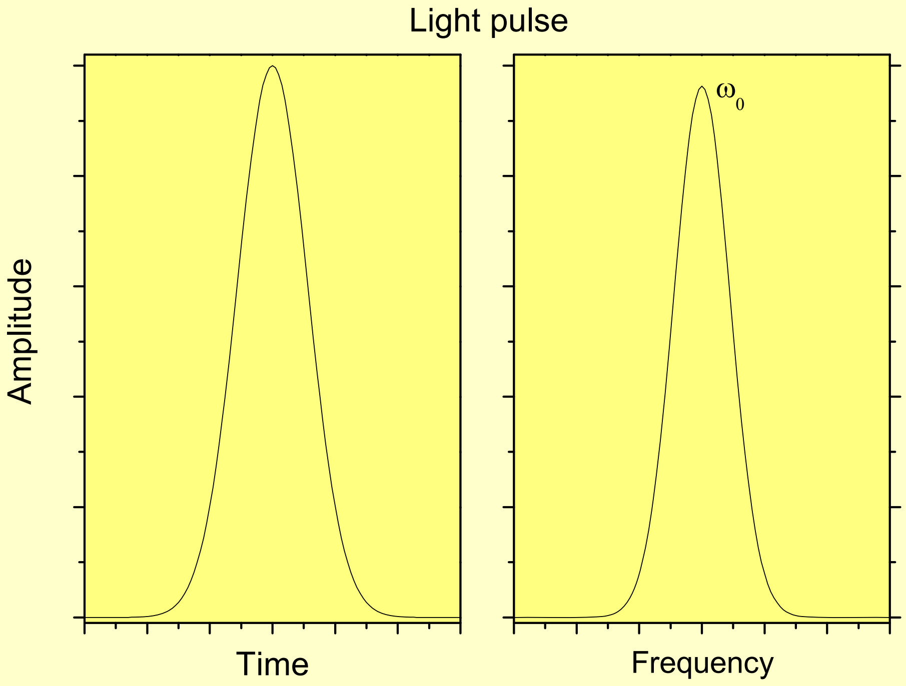
INTERMODAL DISPERSION



Input pulse transmitted by modes with different β (by different rays) which achieve the fiber output at different times.

Intermodal dispersion [MHz.km], can be decreased by using graded-index fibers

CHROMATIC DISPERSION



Monochromatic pulse with a finite duration transmits at different frequencies → different β

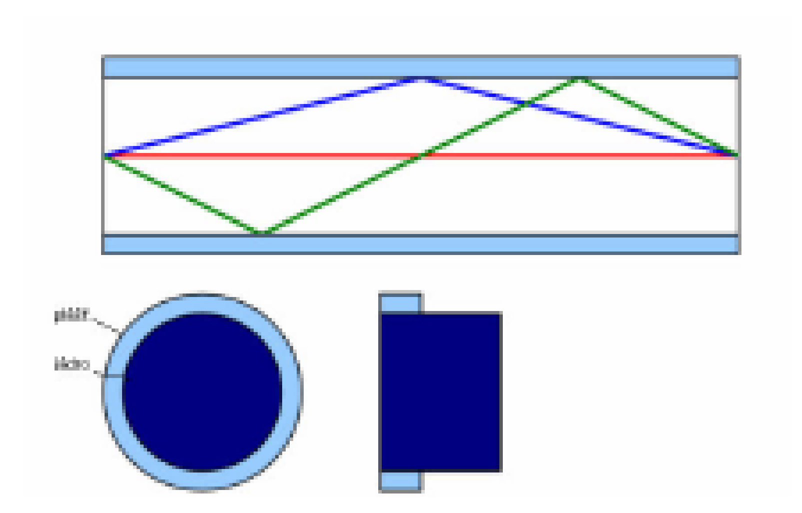
Broad in time domain ↔ Narrow in frequency domain

FIBERS FOR TELECOMMUNICATION LINES

- Polymer Clad Silica (PCS) fibers
- Graded-Index (GI)fibers
- Single Mode (SM) fibers
- Fibers with special refractive-index profiles for dispersion control (DC)

PCS FIBERS

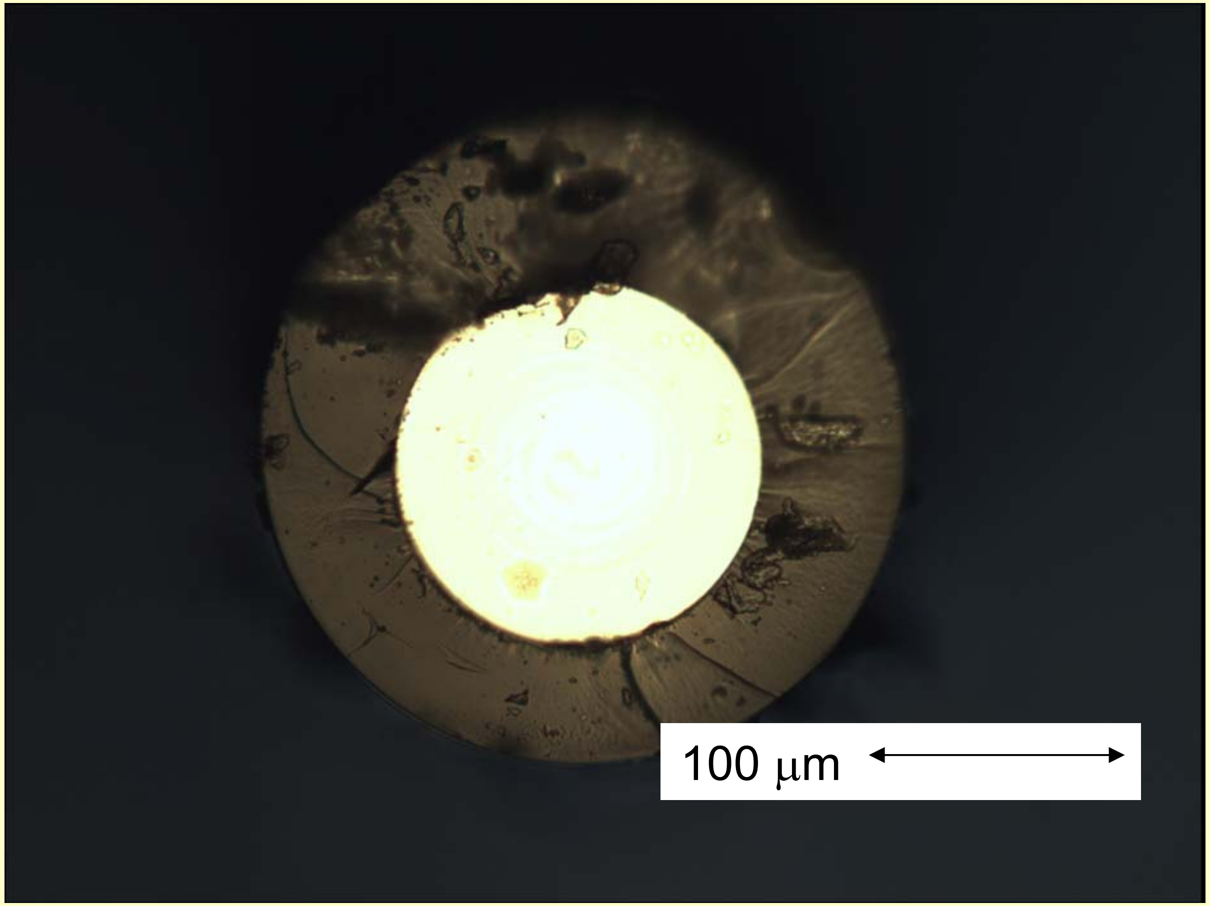
- Step-index profile – multimode fibers
- n_{co} =1.46 (silica core); n_{cl} =1.41 (siloxane or fluoroacrylate polymer); NA~0.35



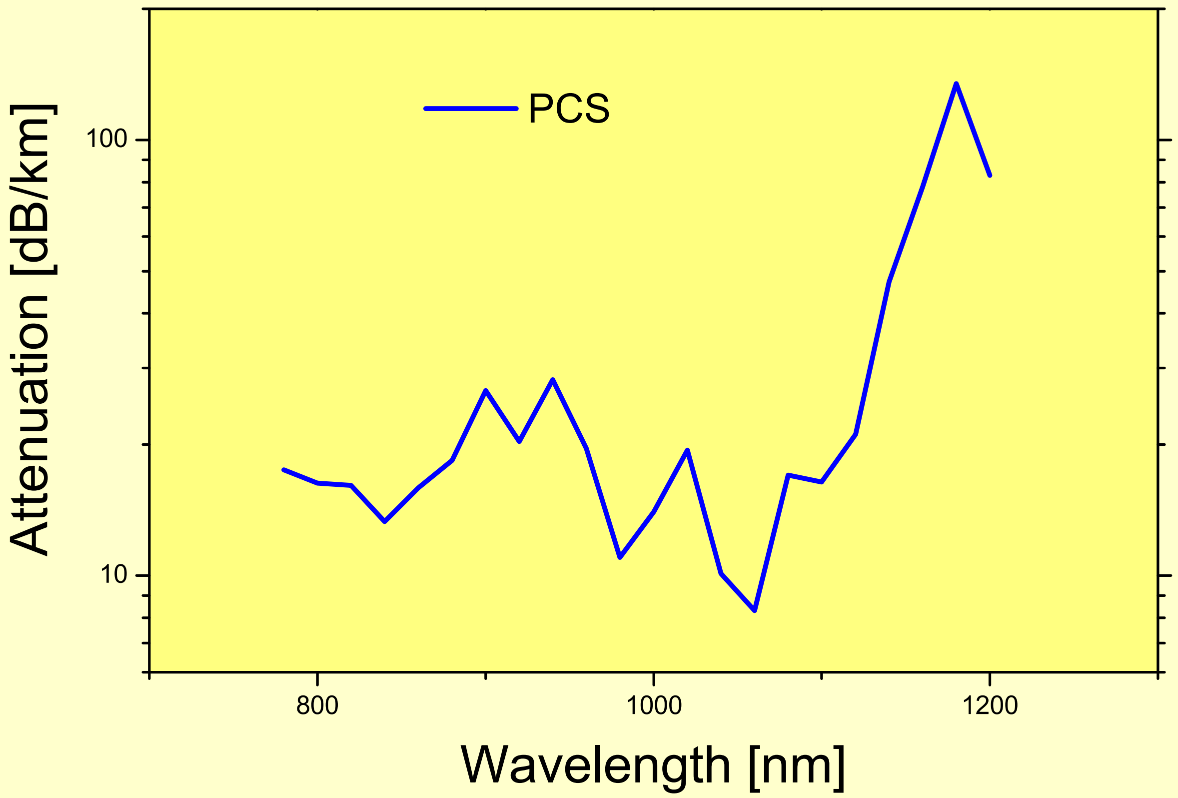
Fiber dimensions

100-800 μm – core

PCS FIBER – CROSS SECTION



PCS FIBERS - ATTENUATION



PCS FIBERS - APPLICATIONS

- Short telecommunication lines (≈ 300 m) power stations, computer networks Bandwidth 5-10 MHz.km – high intermodal dispersion
- **Fiber-optic chemical sensors, energy transfer in medicine**
- IPE technological research finished in 1985 – results transferred into a pilot plan production in Teplice, CR

REFRACTIVE-INDEX PROFILE OF GI FIBERS

- Graded refractive-index profile in multimode fibers enables to increase the fiber bandwidth due to decrease of <u>intermodal dispersion</u>

$$n(r) = n_{Max}\left(1 - \Delta\left[\frac{r}{a}\right]\right)^{\varepsilon}$$

n_{Max} *- maximum refractive index in the profile*

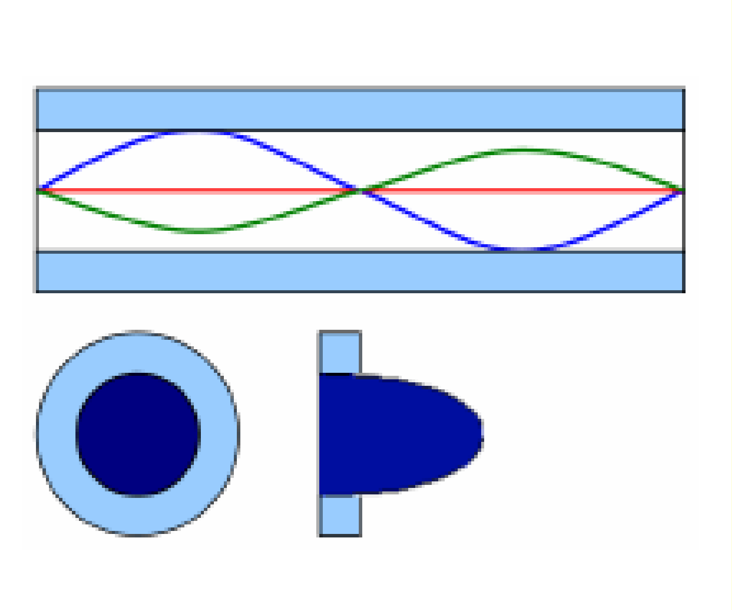
Δ *- refractive-index difference core/cladding*

a *- the fiber-core radius*

ε *- coefficient (close to 2)*

TRAJECTORIES IN GI FIBERS

- Different rays have the same path lengths in the core → D_i ~ 0 ps/nm/km



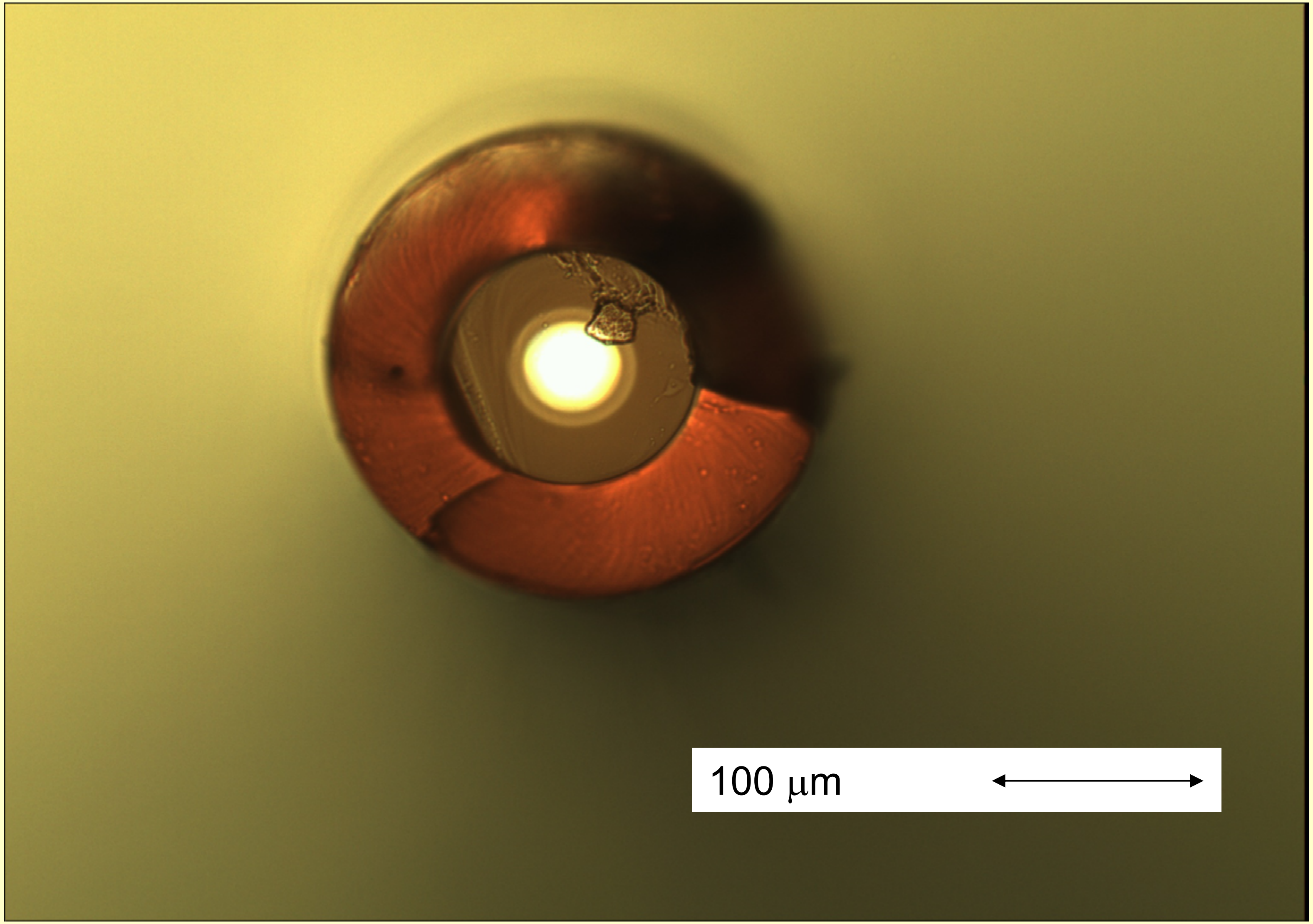
<u>Fiber dimensions</u>

50 (62.5)μm – core

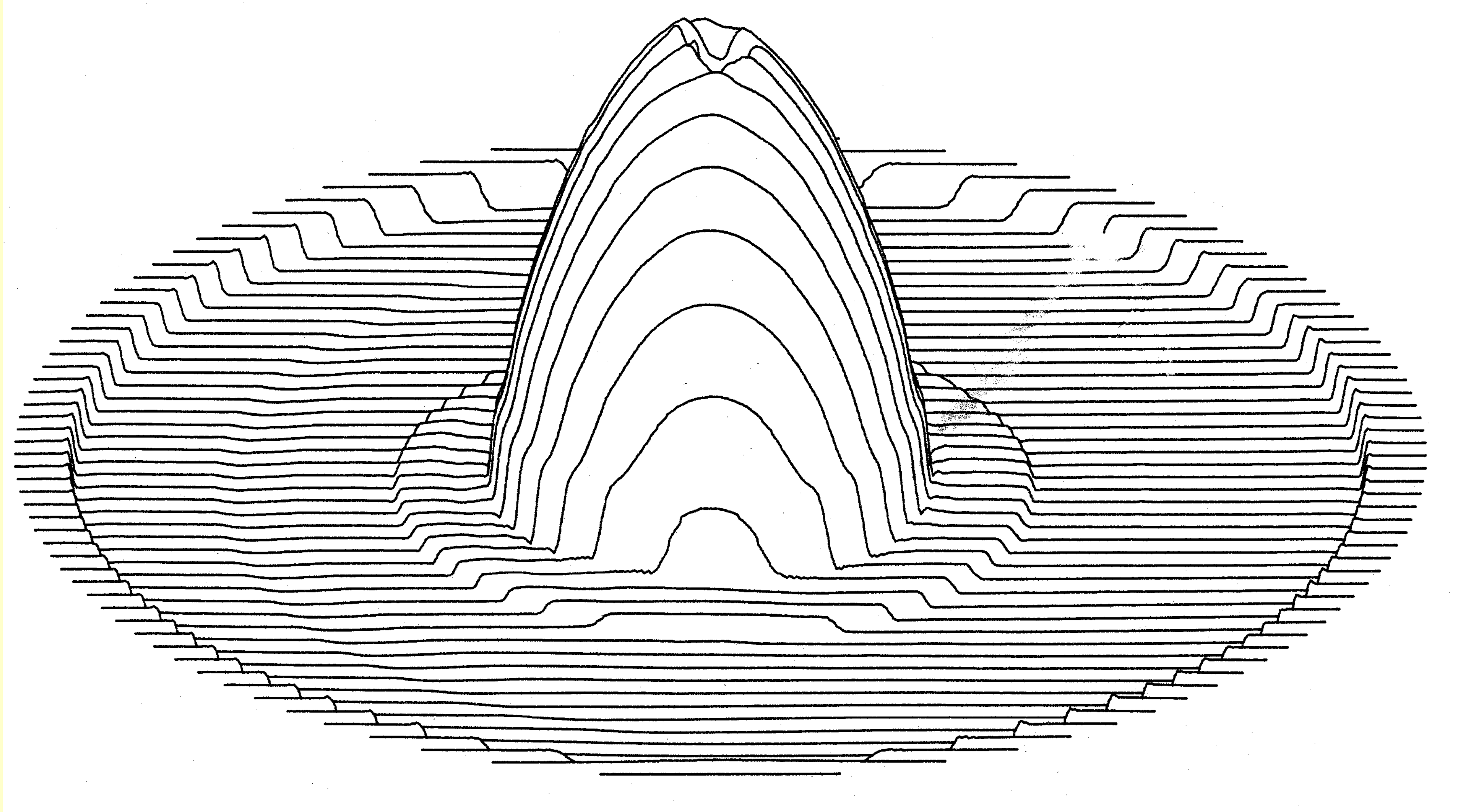
125 μm – cladding

<u>Jacket</u> – UV curable acrylate

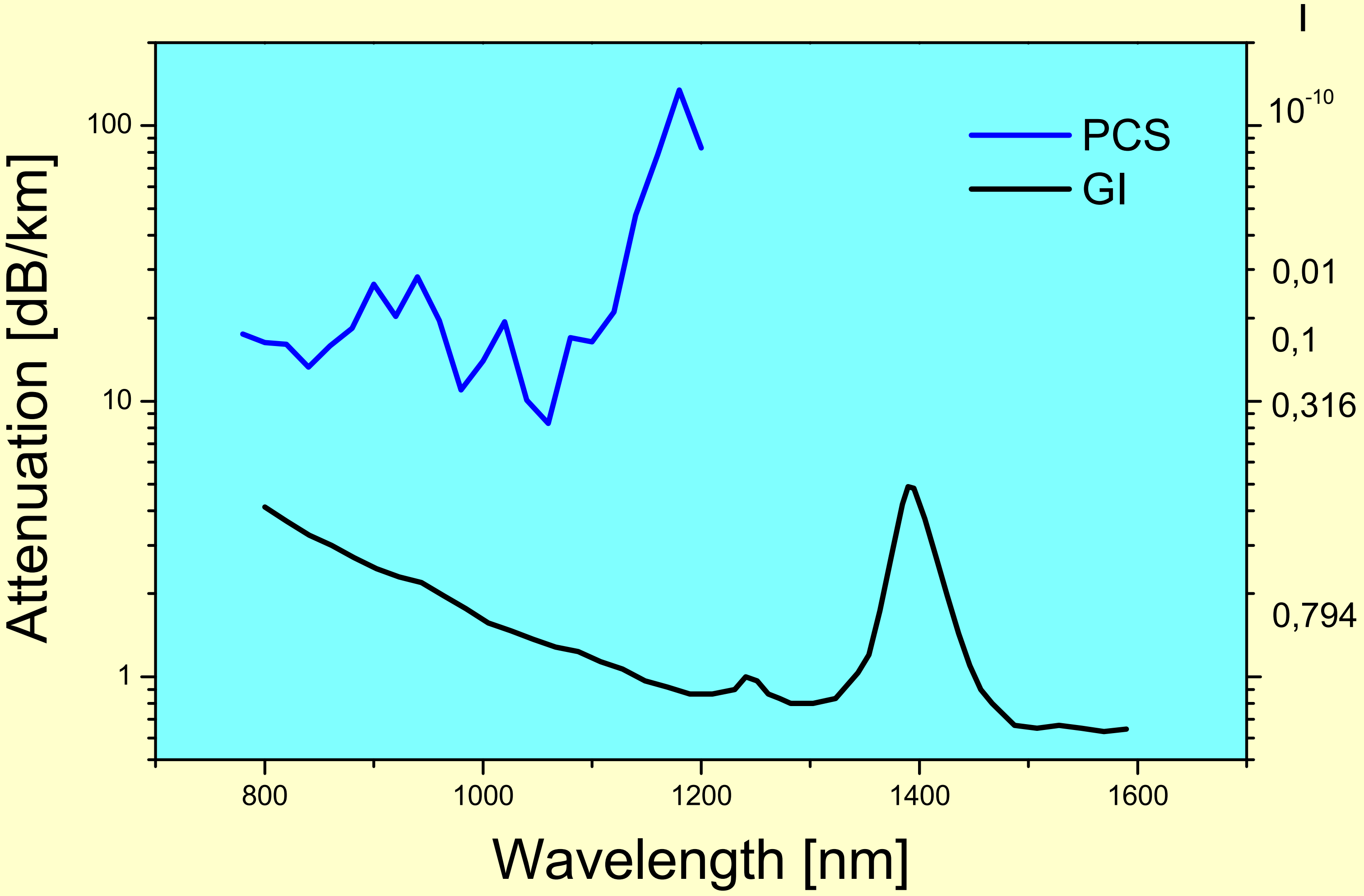
GI FIBER – CROSS SECTION



GI FIBER – SPATIAL REFRACTIVE-INDEX PROFILE



GI FIBER - ATTENUATION



GI FIBERS - APPLICATIONS

- Short lines ~ 10 km (local area networks)
- IPE- Technological research 1984 – 1987

  Operating wavelength – 850 nm,
  Bandwidth 1 GHz. km
- *The fibers tested in short telecommunication lines in Prague together with Japanese cables*

SM FIBERS

- Small fiber core supports the transmission of one optical mode

  <u>Nearly zero chromatic dispersion</u> (a bandwidth of THz.km) can be achieved

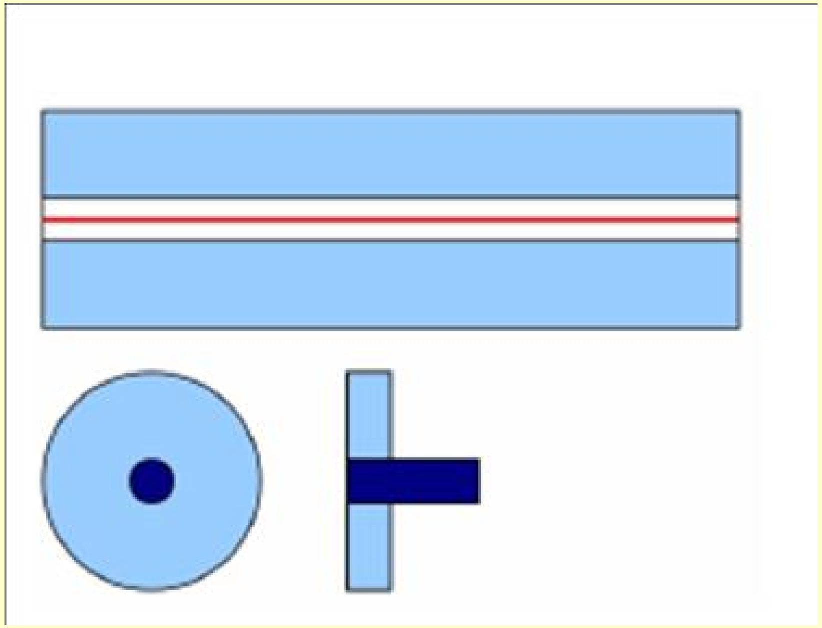
<u>1300 nm</u> – standard SM fibers

<u>1550 nm</u> – SM fibers with special refractive index profiles (Dispersion shifted SM fibers)

<u>1300-1550 nm</u> - SM fibers with special refractive index profiles (Dispersion flattened SM fibers)

SM FIBERS - DIMENSIONS

- Ray optics can’ be used for description of light propagation in SM fibers



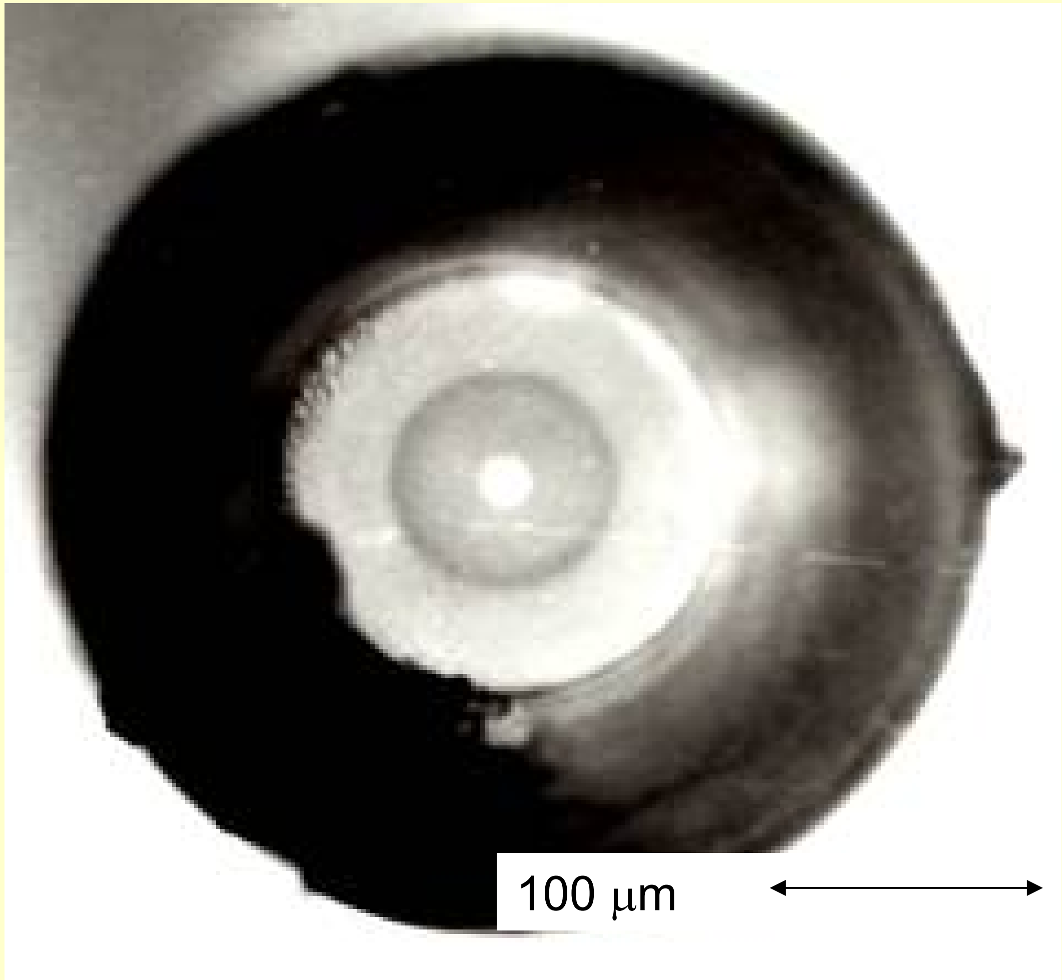
Fiber dimensions

<10 μm – core

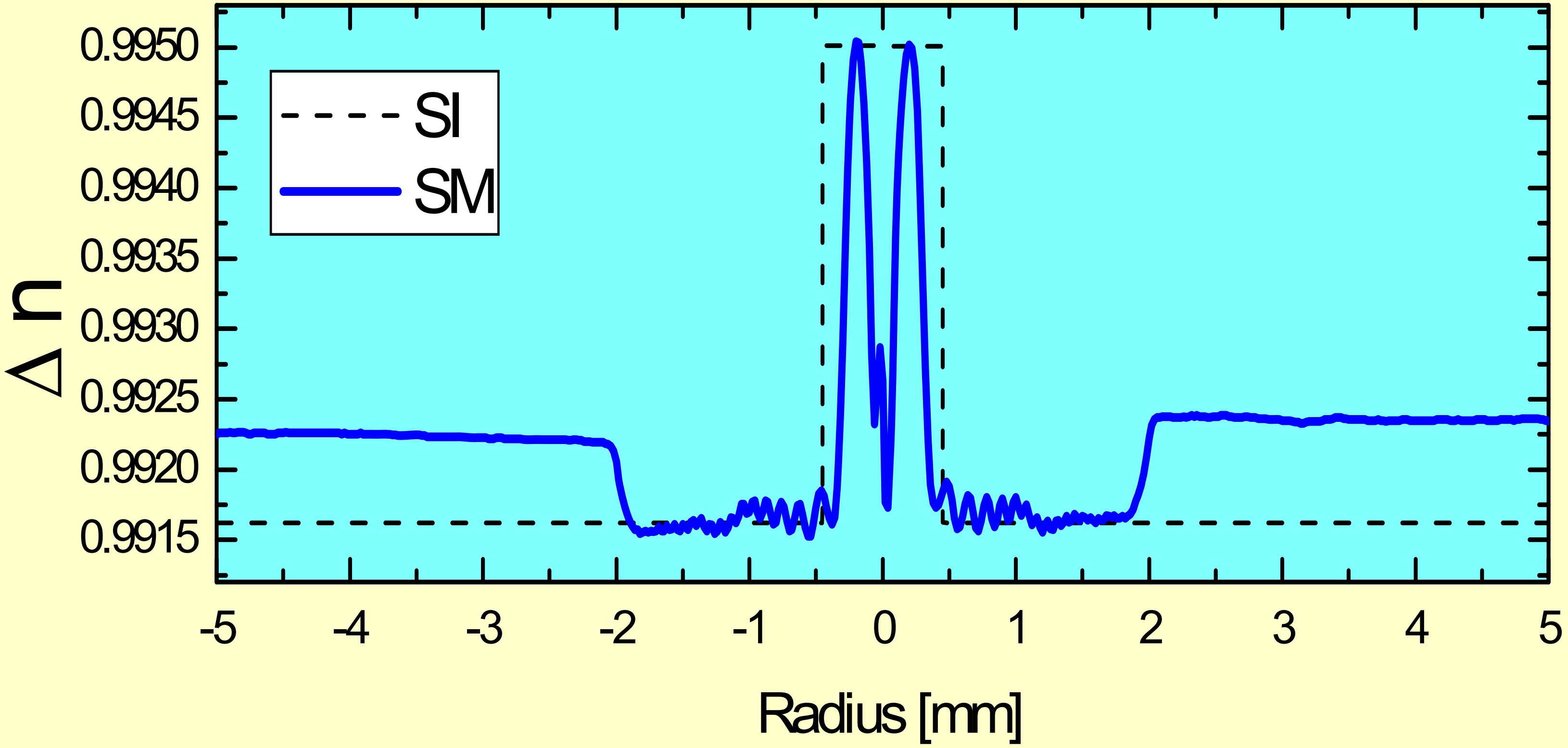
125 μm – cladding

Jacket – UV curable acrylate

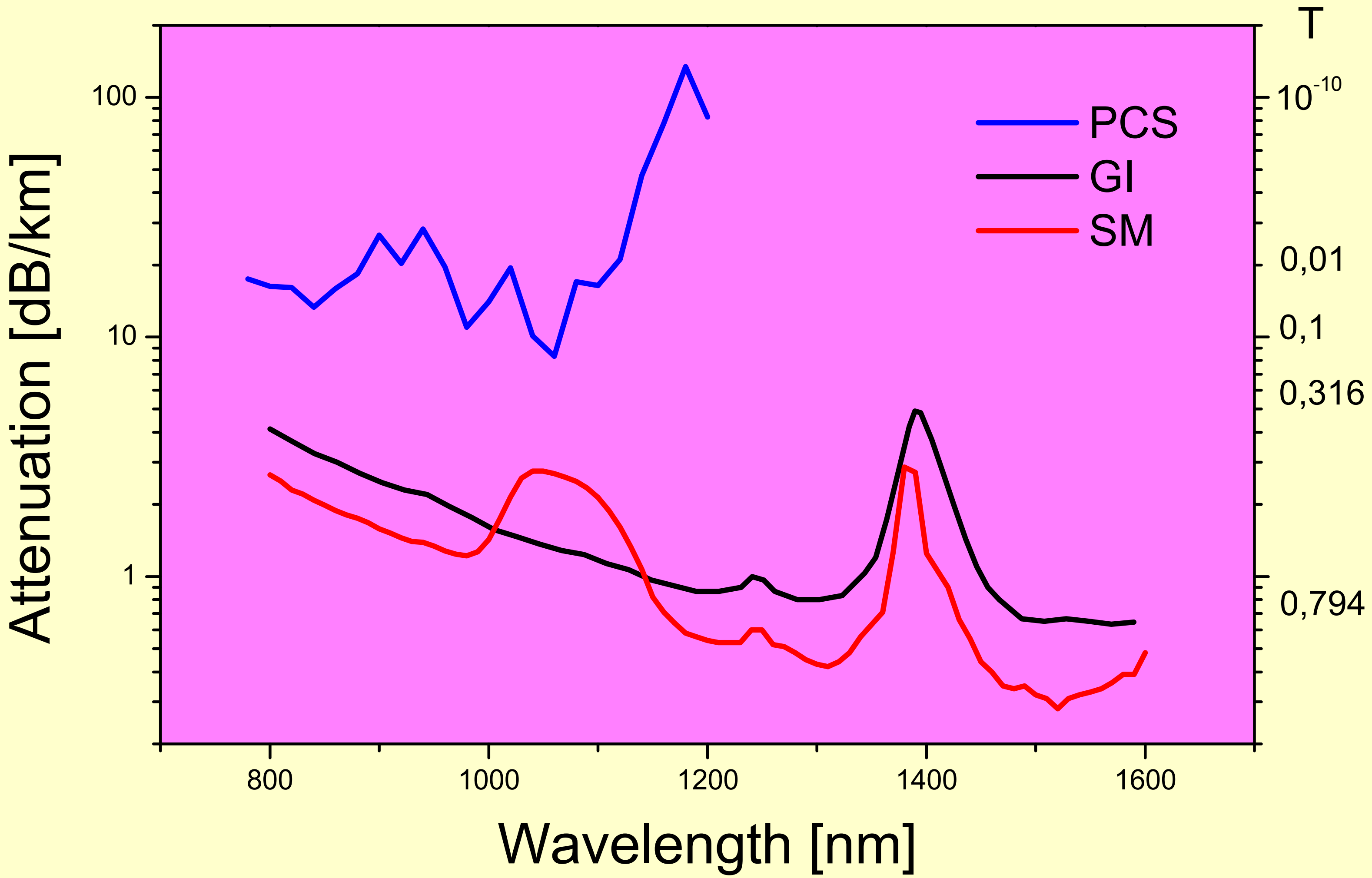
SM FIBER – CROSS SECTION



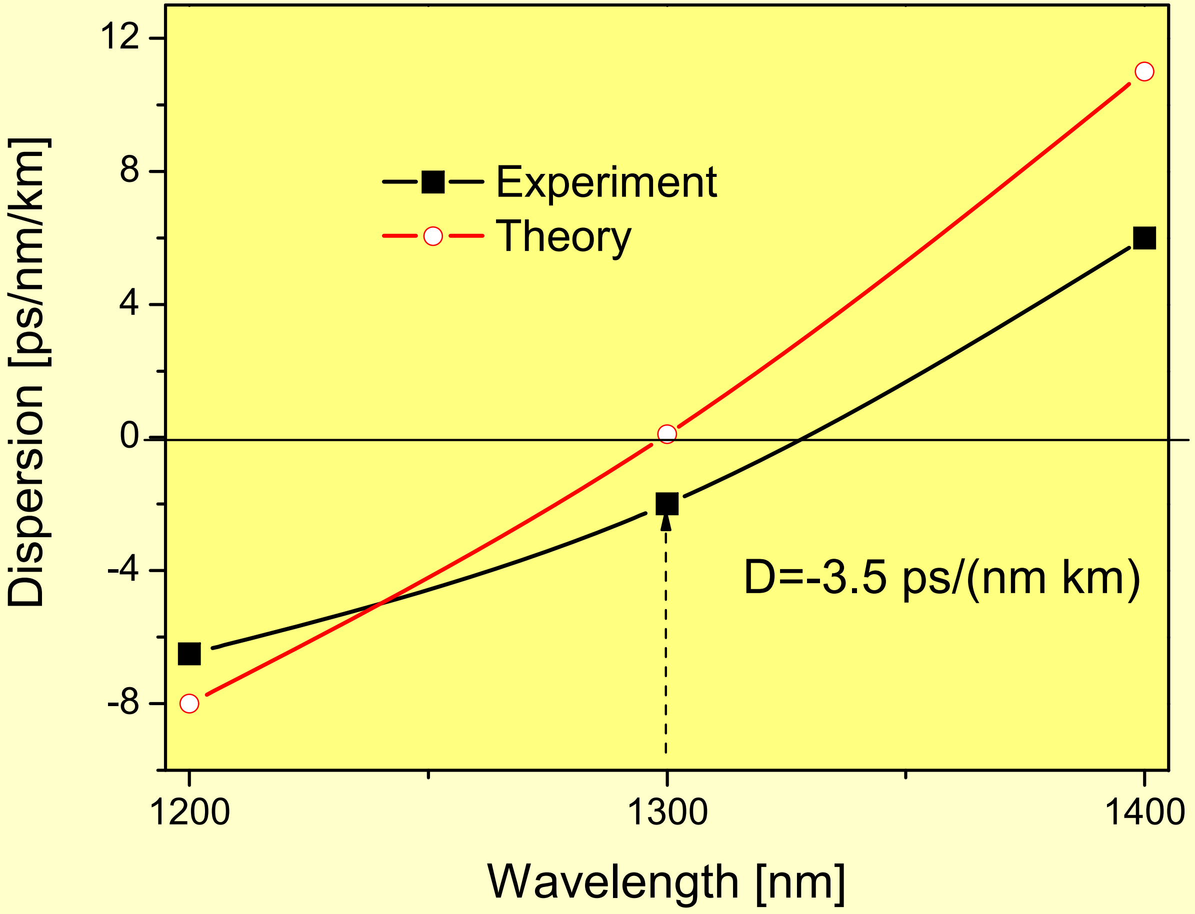
SM FIBERS – REFRACTIVE-INDEX PROFILE



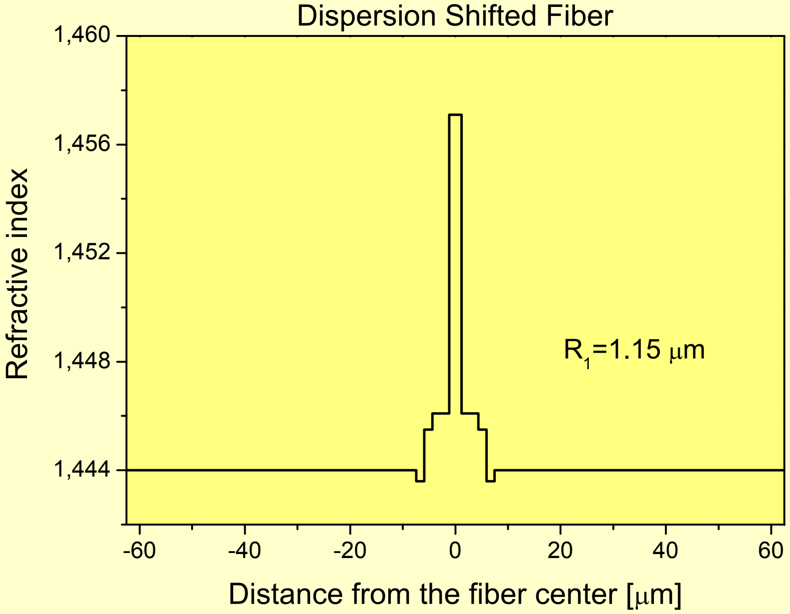
SM FIBERS - ATTENUATION

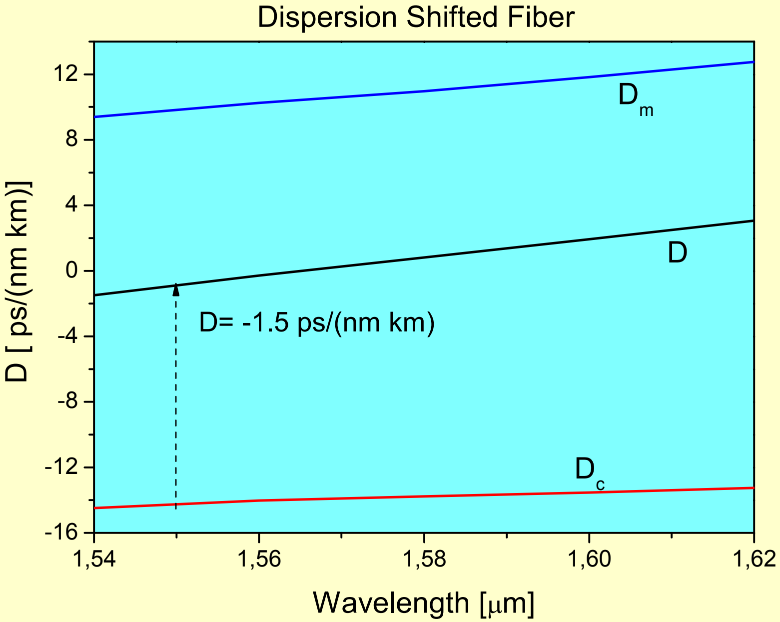


SM FIBERS IPE - DISPERSION



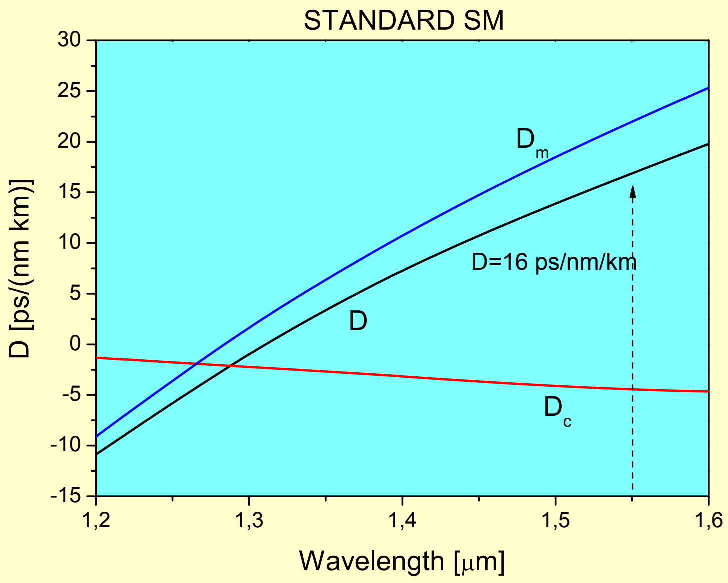
DISPERSION SHIFTED FIBERS





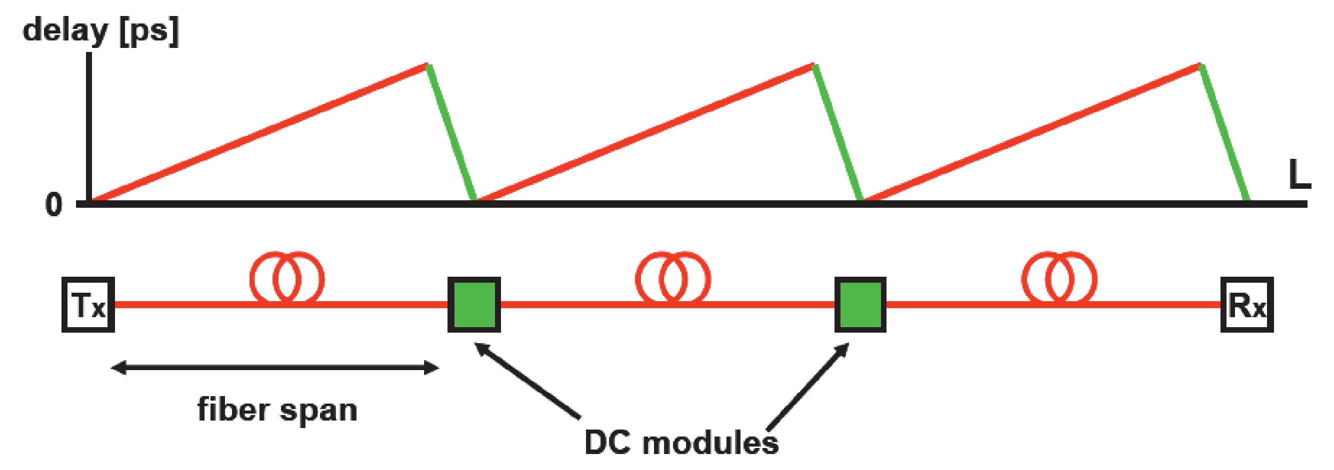
Commercially available (Corning)

DISPERSION COMPENSATION

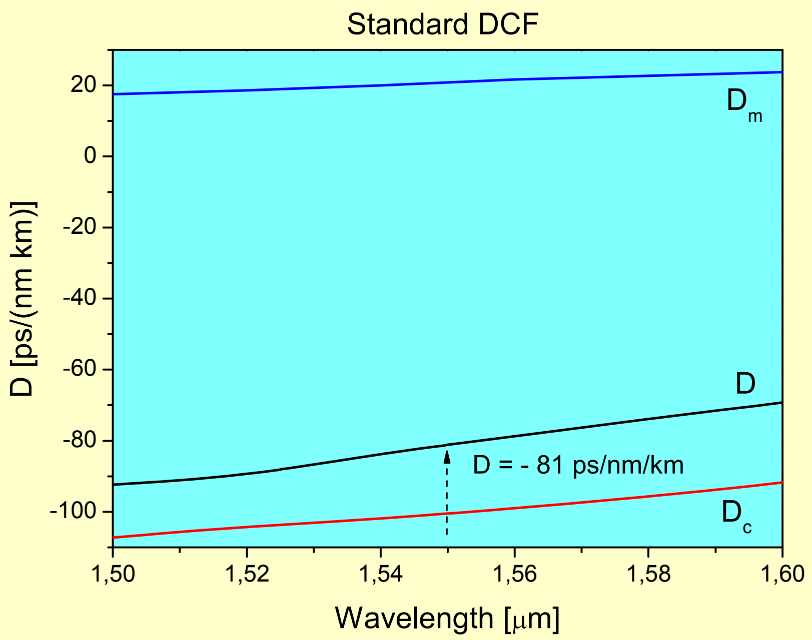


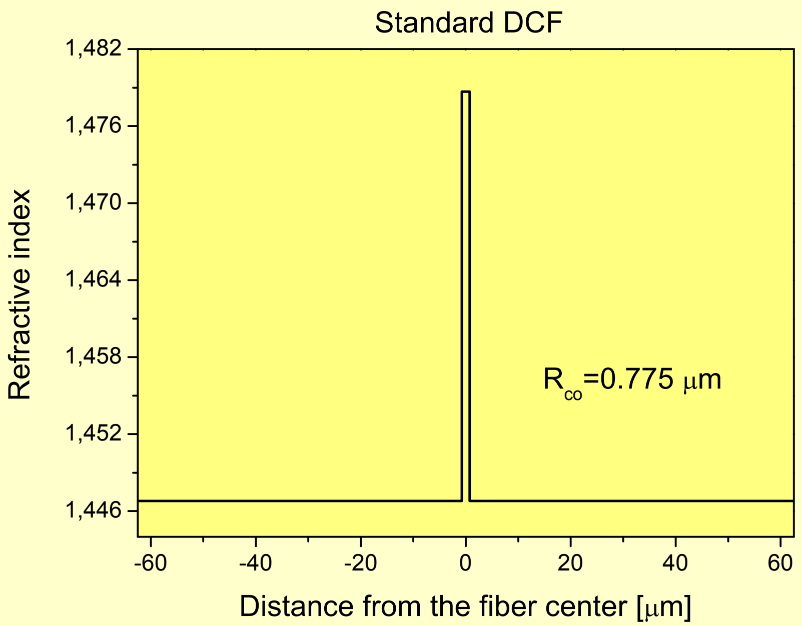
Splice standard SM to a proper length of a fiber with a negative D

$D_+ L_+ + D_- L_- = 0$



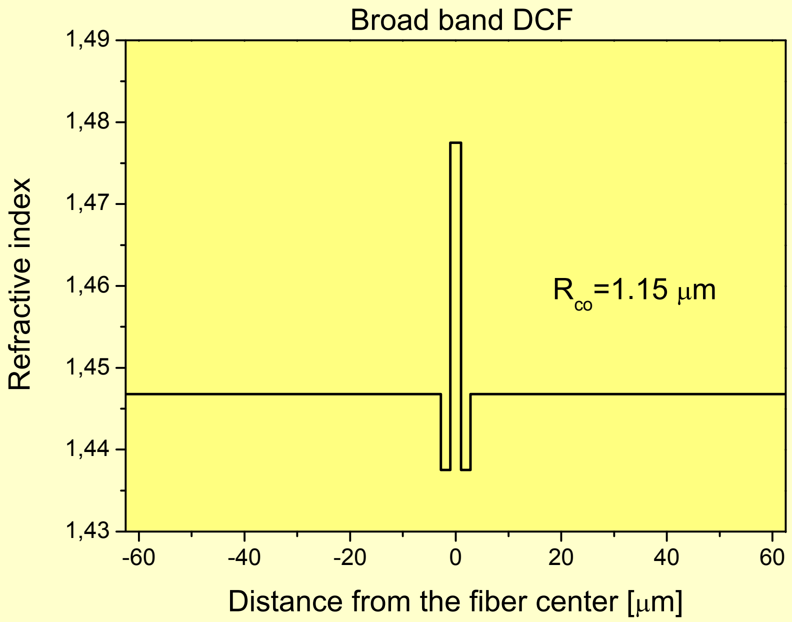
DISPERSION COMPENSATING FIBER - DCF

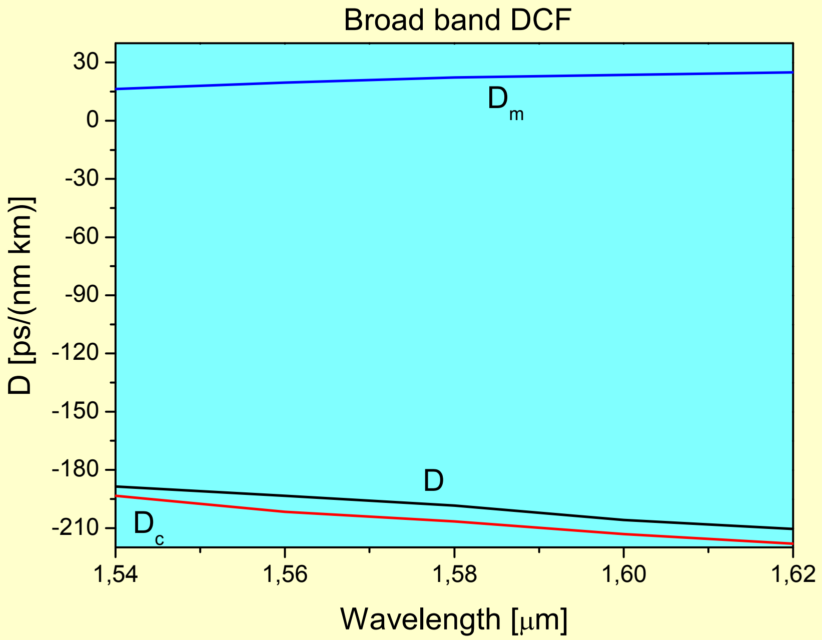




More expensive than SM, but used in shorter lengths

DISPERSION COMPENSATING FIBER





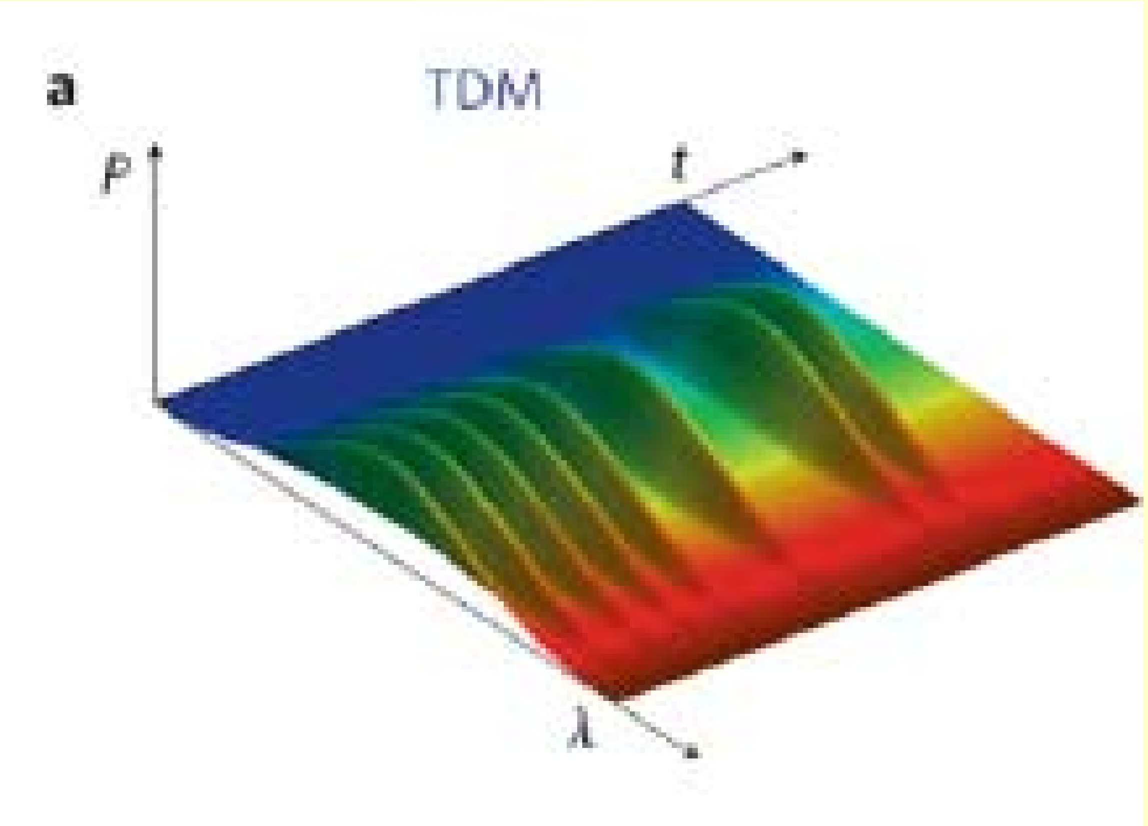
D in a range -189 to -210 ps/nm/km between 1540-1620 nm

APPROACHES FOR INCREASING LINE CAPACITY

A high bandwidth of SM optical fibers (THz.km) and small bandwidths of light sources (MHz) require novel approaches for employment the performance of optical fibers

- Time division multiplexing – sending narrow pulses with high frequency
- Wavelength division multiplexing (WDM, DWDM) sending pulses from several laser sources operating at different wavelength

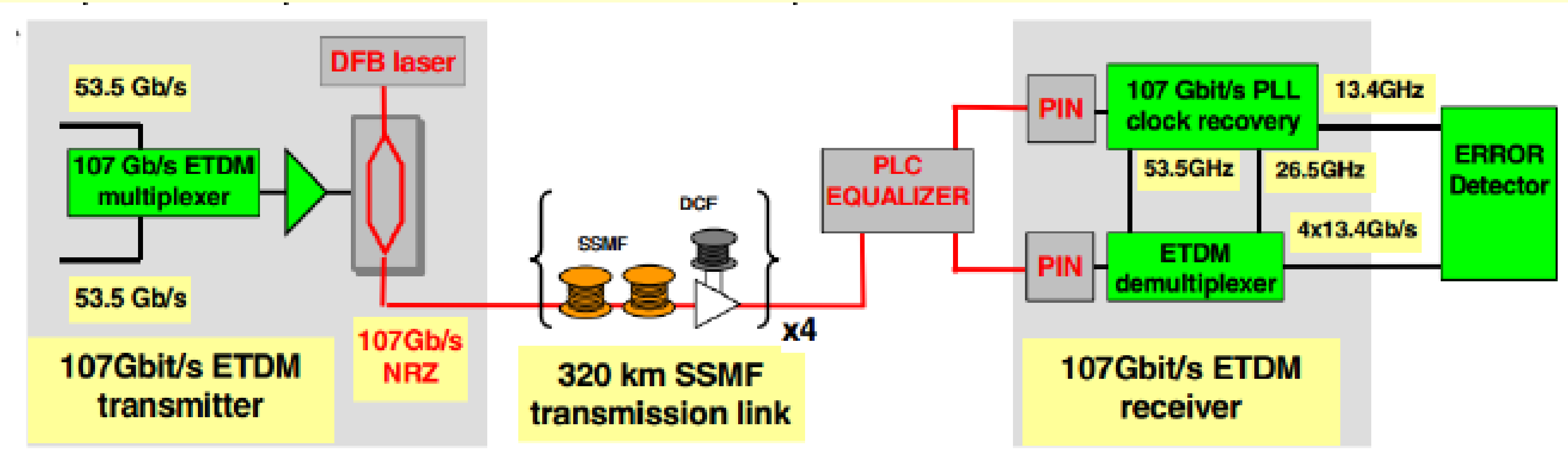
TIME DIVISION MULTIPLEXING (TDM)



Serial signal transmission, high transmission speeds 100 GBit/s Ethernet

Short pulses ↔ Broad spectrum, dispersion effects

TDM REALISATION



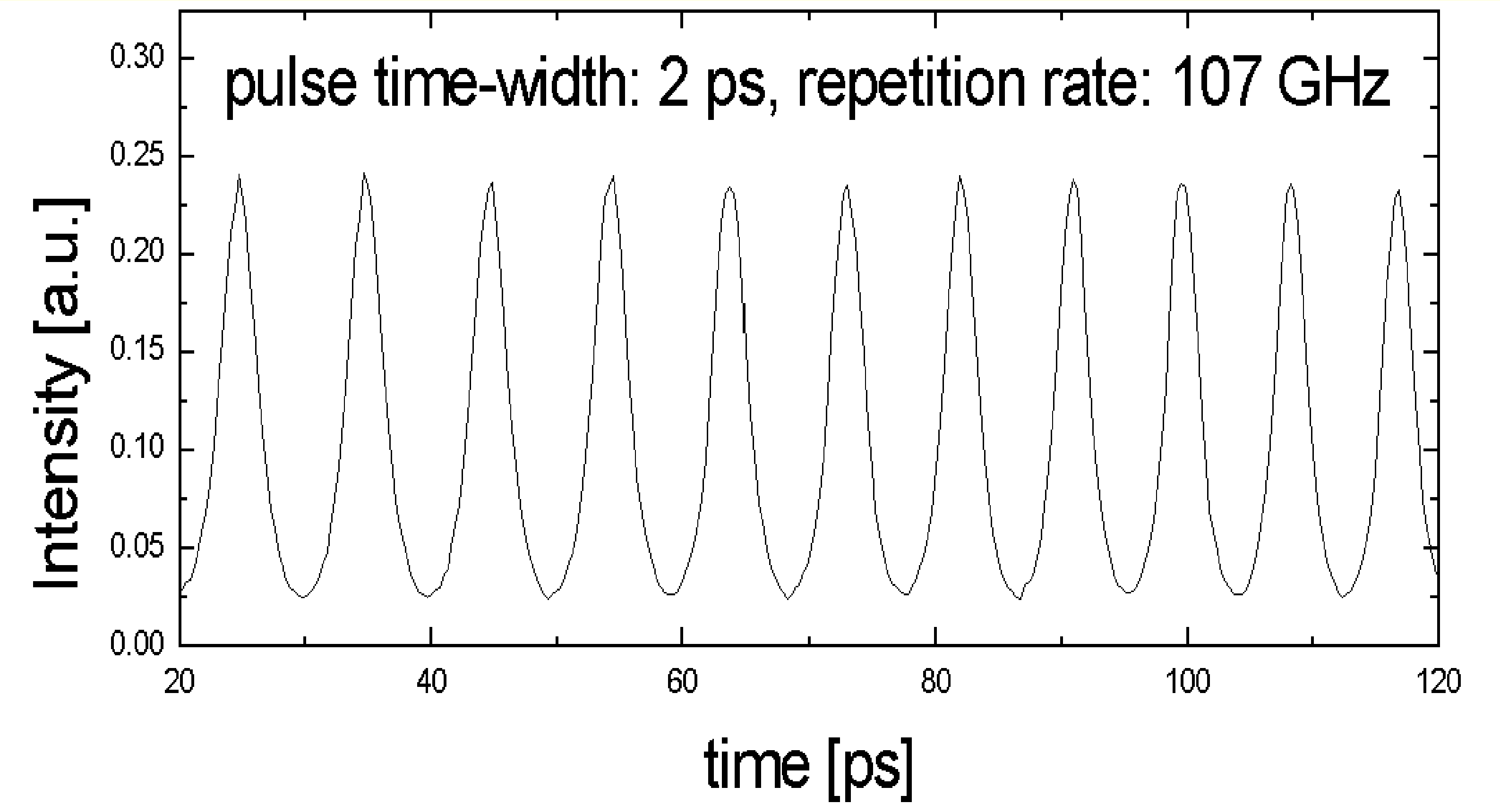
Integrated eTDM receiver 107 Gb/s, Fraunhofer Institute, Berlin, Fiber 480 km Dispersion compensation,

C. Schubert et al., J. of Lightwave Technol. 25, 122-130 (2007).

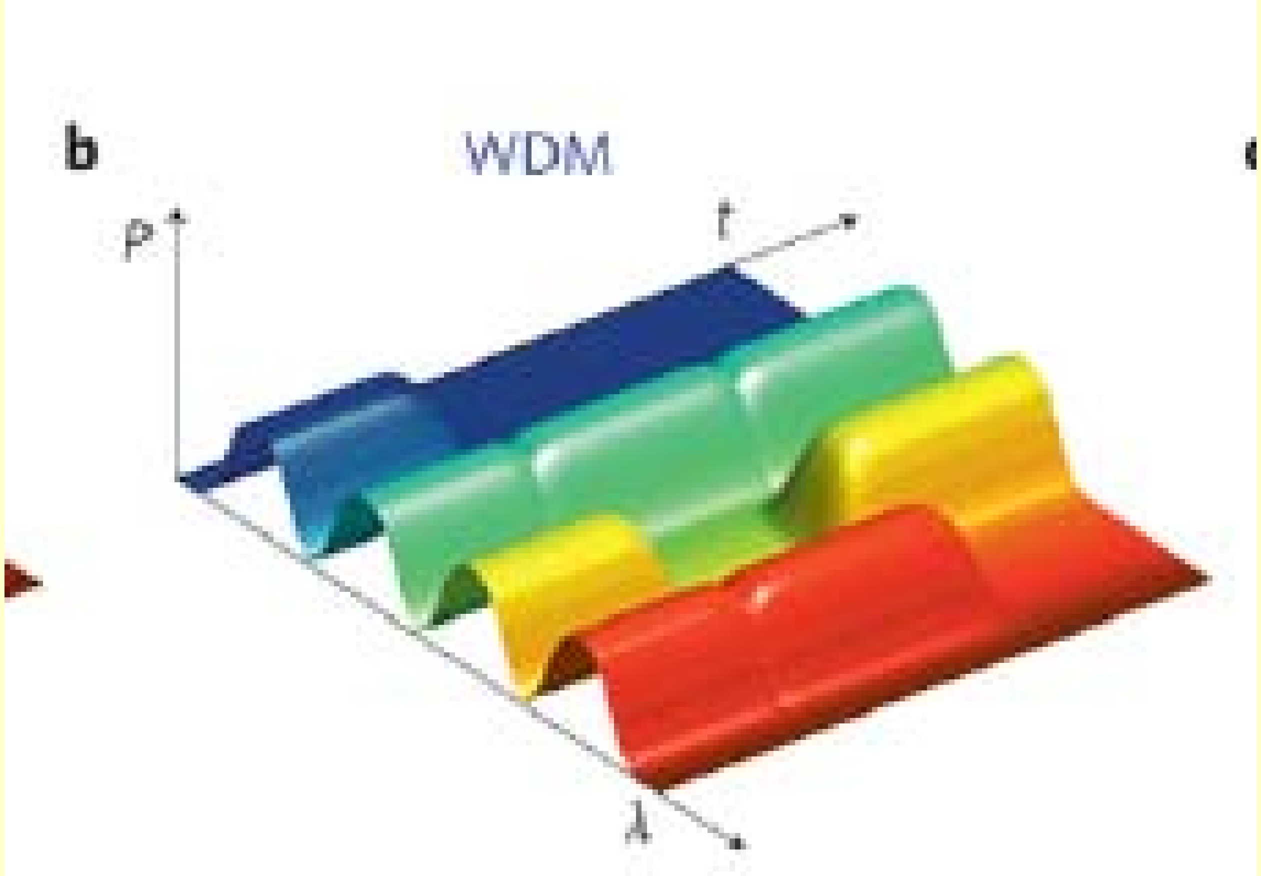
TRAIN OF OPTICAL SOLITONS IPE FIBER LASER

Time Division Multiplexing

very narrow pulses – optical solitons ⇒novel laser sources



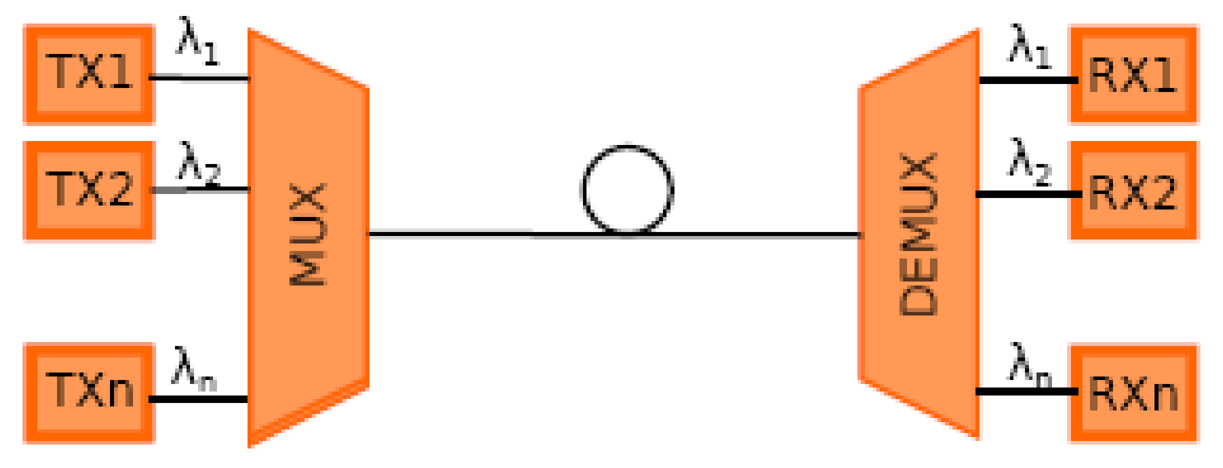
WAVELENGTH DIVISION MULTIPLEXING (WDM)



Transmission in several channels without mutual interference

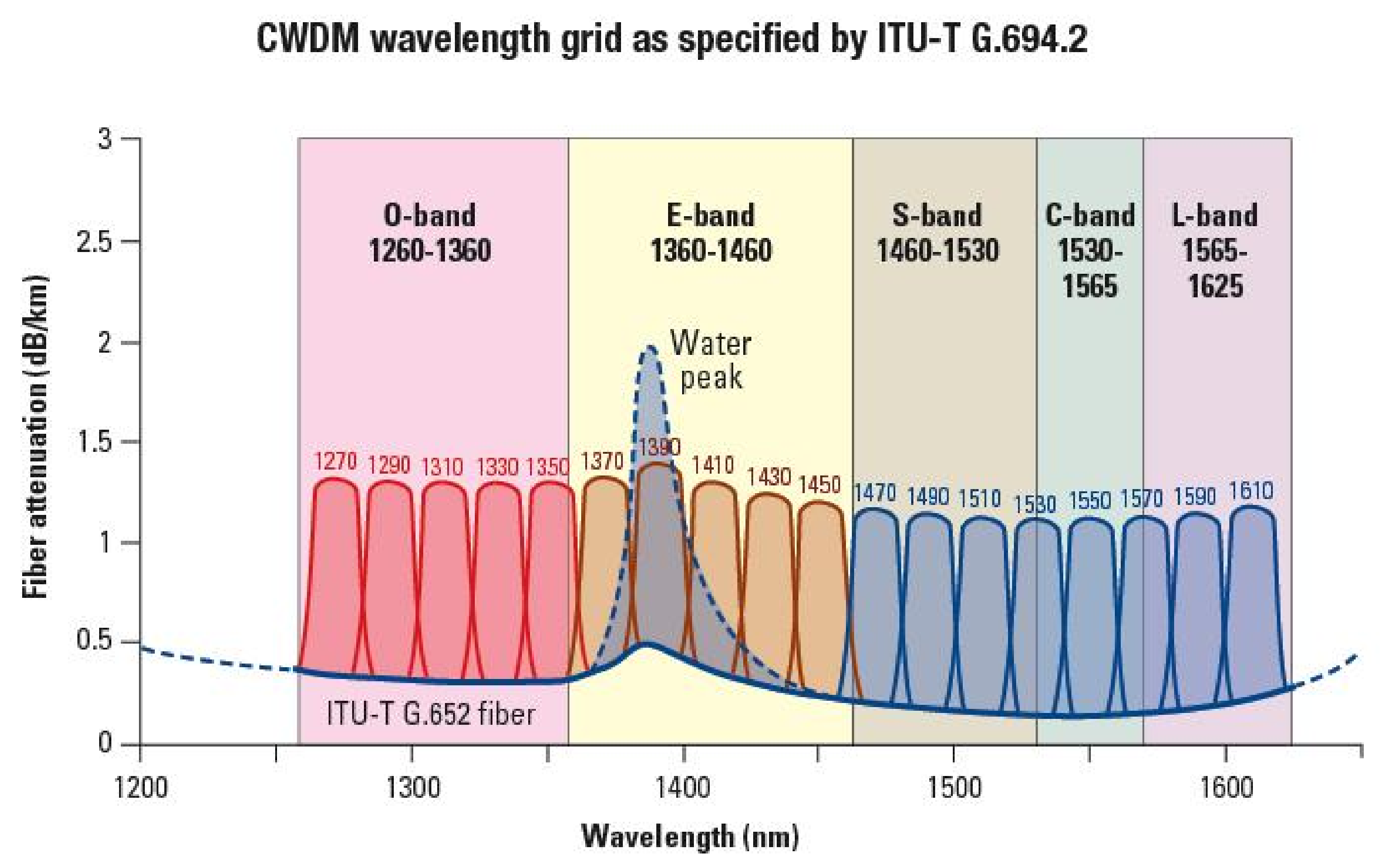
Standard: ITU scale

WAVELENGTH DIVISION MULTIPLEXING



Tunable laser sources

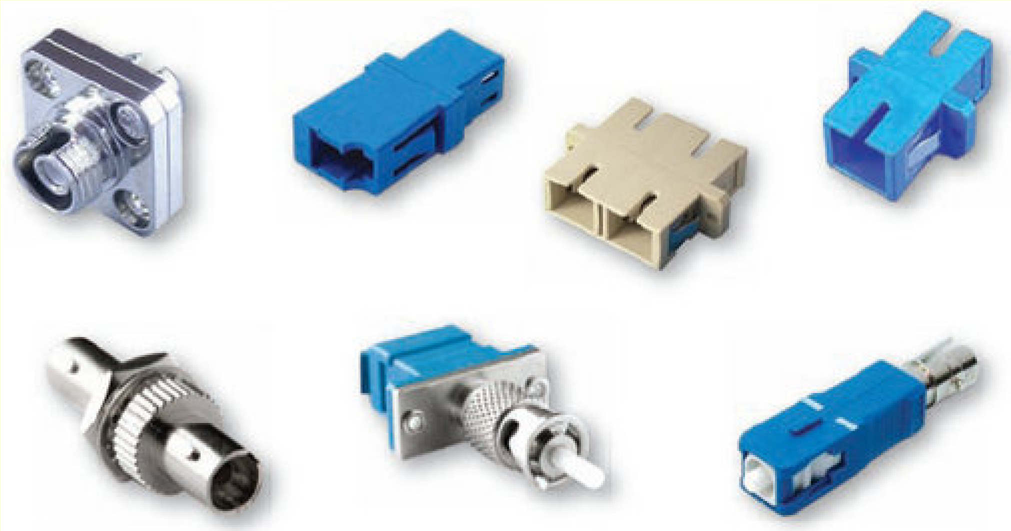
WAVELENGTH DIVISION MULTIPLEXING

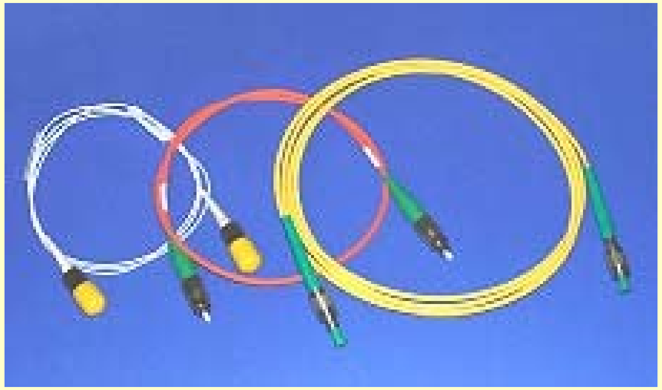


S-L Band: Frequencies 196-186 THz, Channel distance 10 GHz

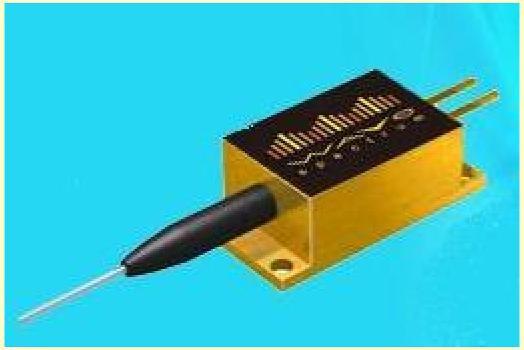
FIBER-OPTIC ACCESSORIES

Connectors, connectored fibers





Fiber excitation: **pigtailed, LED, LD**



LIGHT SOURCES

High transmission rates, WDM systems → novel light sources and detectors

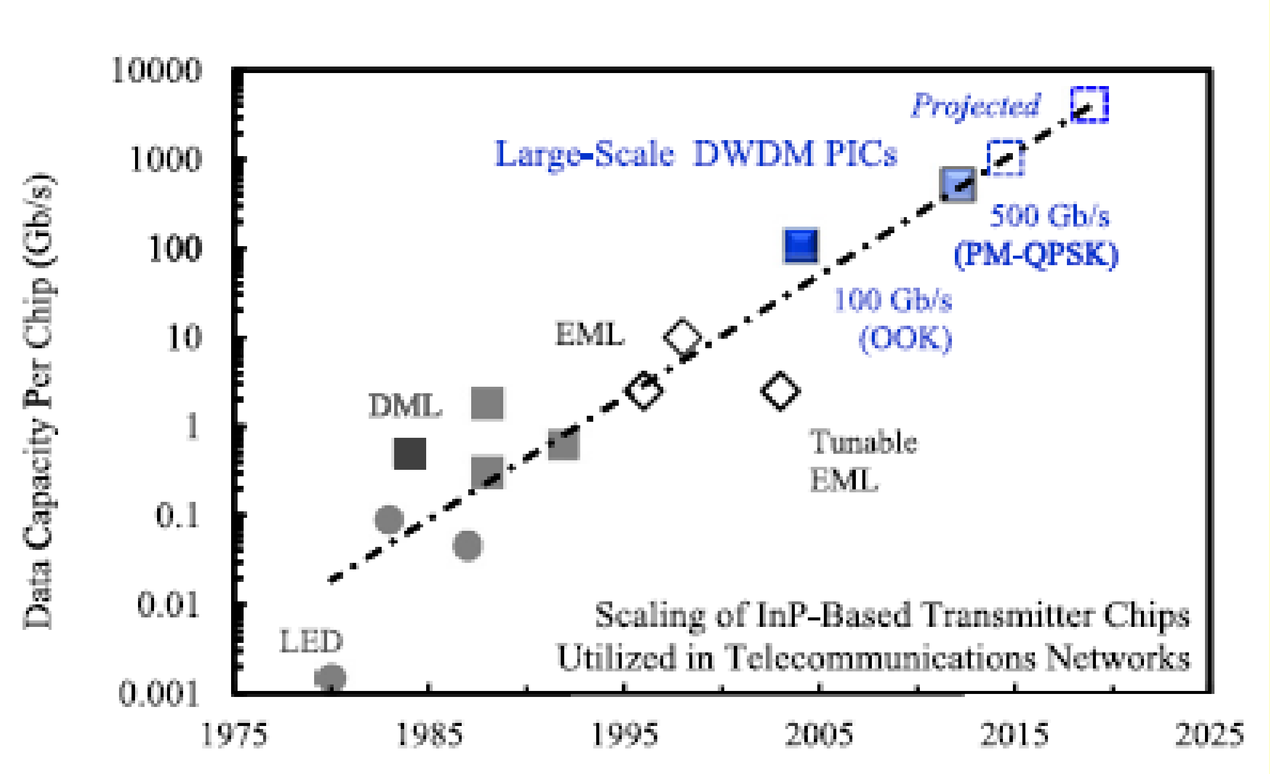
- Distributed feed-back lasers (DFB) – 10 GBit/s
- Lasers with external modulation – 80-100 GBit/s

Novel directions

Quantum Dots lasers, Quantum Cascade Lasers

LIGHT DETECTORS

Photodiodes, avalanche diodes based on InP



See Review: E. Desurvire et al., C. R. Physique 12 (2011) 387–416

NOVEL DIRECTIONS

- Telecommunication fibers for MIR region
- Novel preparational techniques (e.g. sol-gel method) for making tubes for overcladding preforms
- Telecommunications employing only optics (all-optical telecommunications, all-optical switching)
- Using fibers in computers, measuring devices etc.