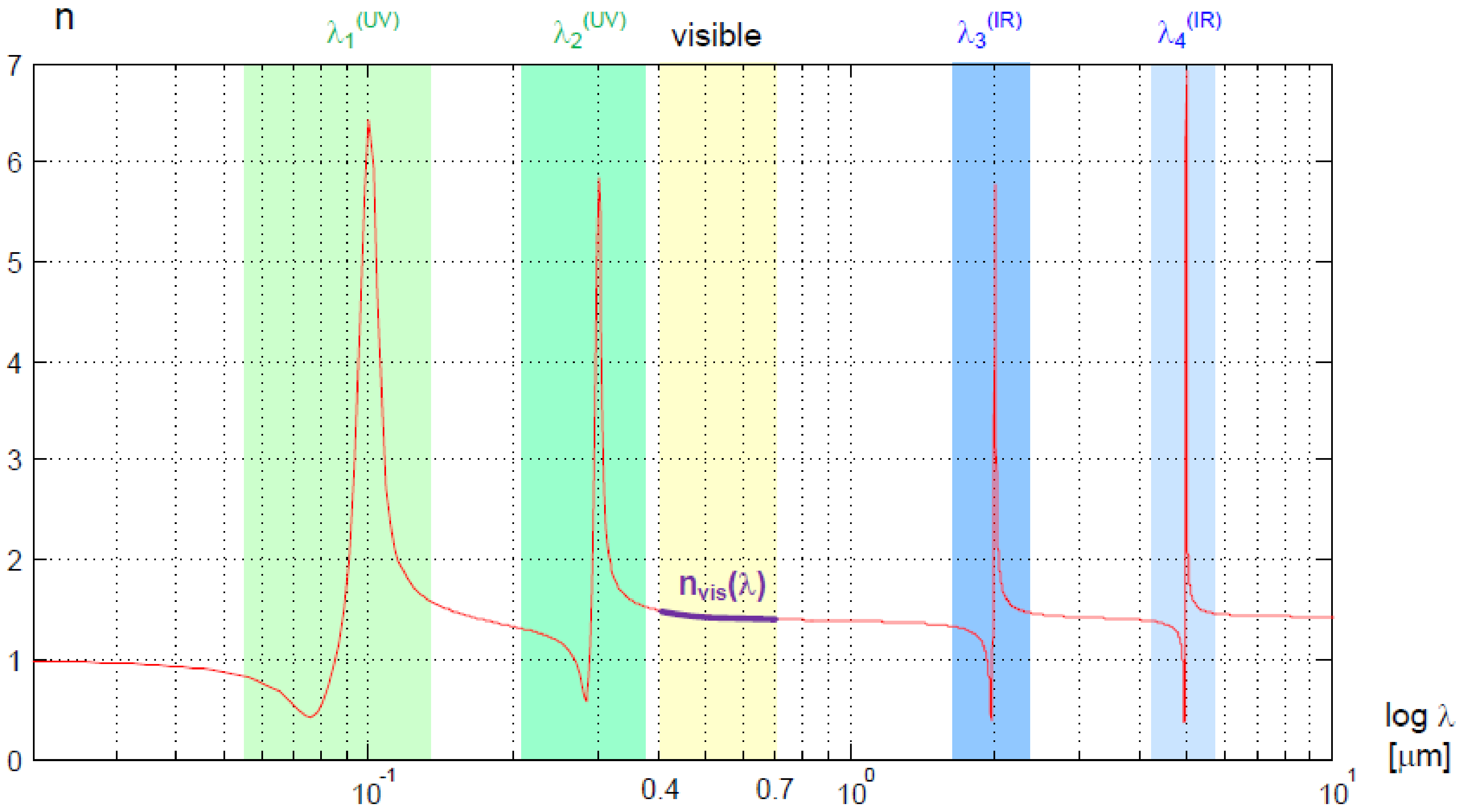
2.4 Optical glasses



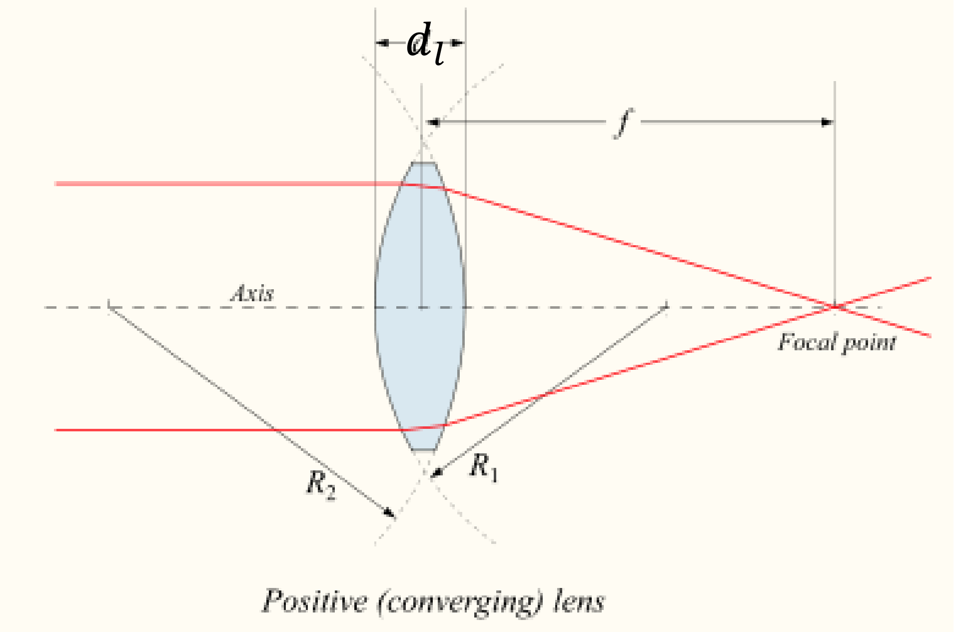
Refractive index of glasses (transparency window in the vis and NIR)

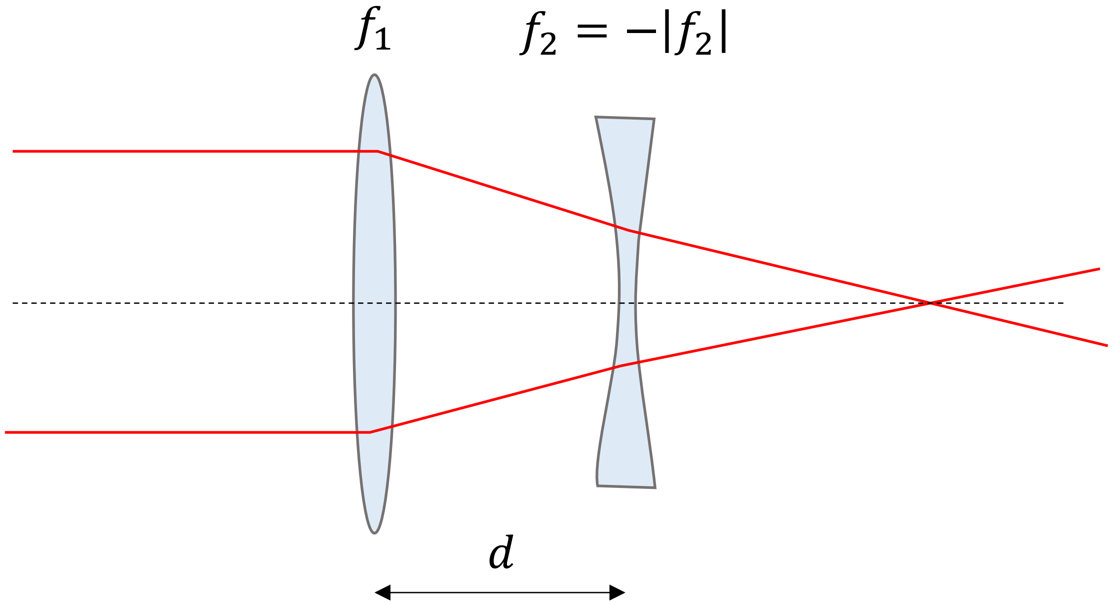
Empirical description of the refractive index dispersion:

- ❑ Cauchy
- ❑ Sellmeier
- ❑ Schott
- ❑ Bausch-Lomb
- ❑ Herzberger
- ❑ Hartmann

etc.

Geometrical optics





Focal power (refractive power etc.) of a lens

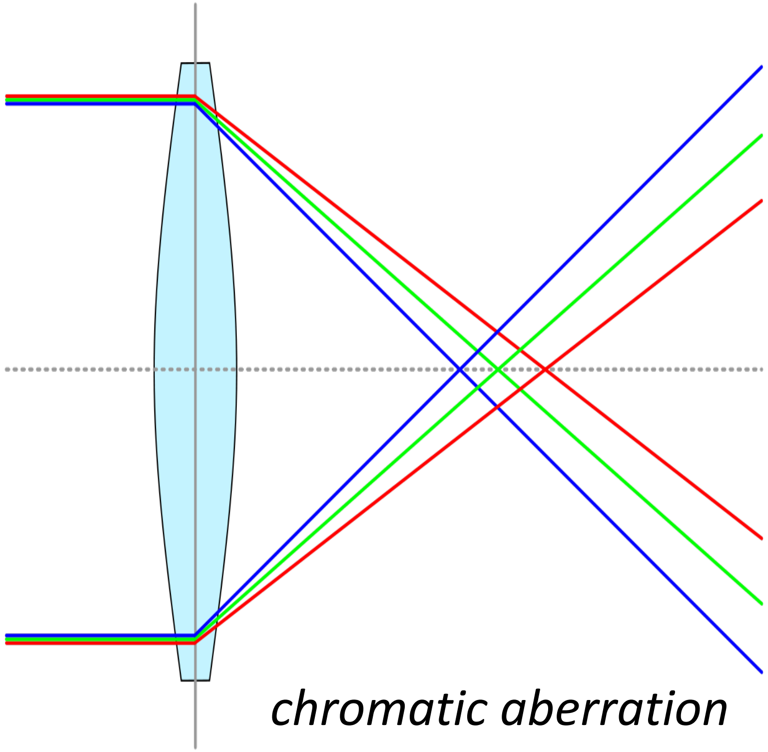
$$\frac{1}{f} = (n_l - 1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n_l - 1)d_l}{n_l R_1 R_2}\right]$$

Focal power of the lens system

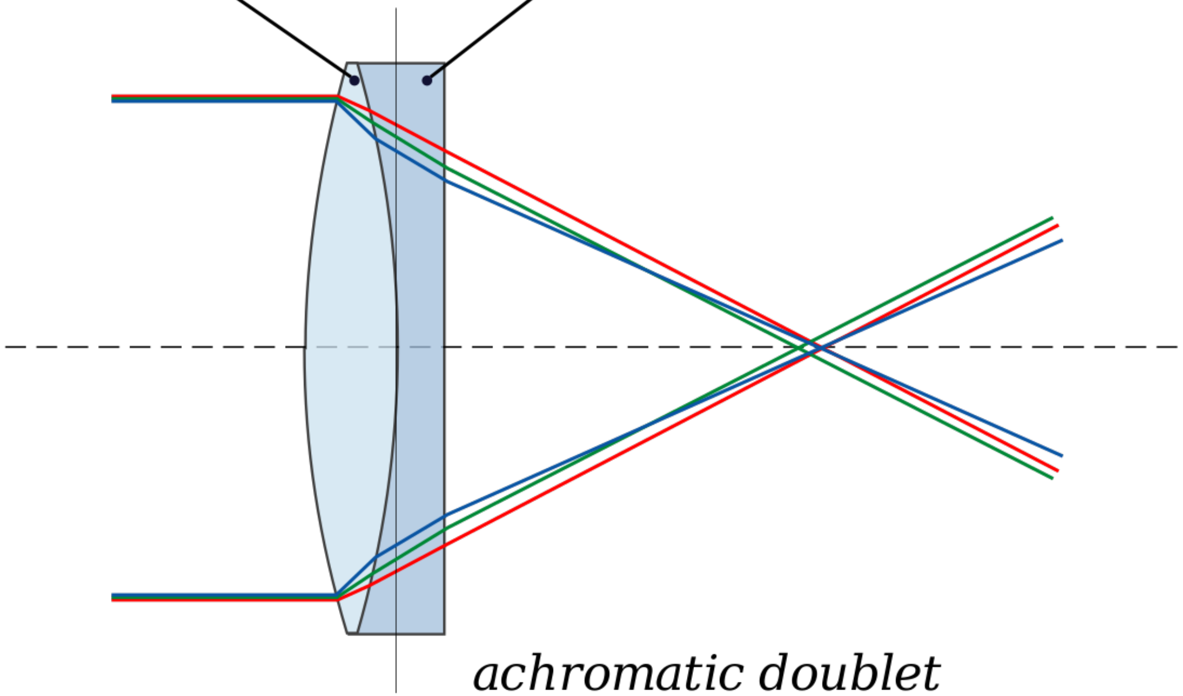
$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

Optical aberrations

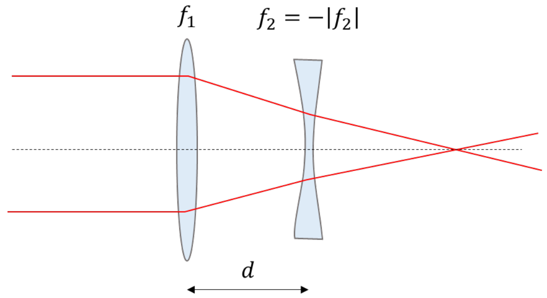
Among the various optical aberrations found in lens based optics there is spherical aberration, chromatic aberration, coma, tilt, astigmatism etc.



chromatic aberration



achromatic doublet



For deriving the condition for achromatization, let us take the two lens system assuming thin lenses separated by a distance d:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

and

$$\frac{1}{f_1} = (n_1 - 1)\underbrace{\left[\frac{1}{R_1} - \frac{1}{R_2}\right]}_{u_1} \qquad \frac{1}{f_2} = (n_2 - 1)\underbrace{\left[\frac{1}{R_3} - \frac{1}{R_4}\right]}_{u_2}$$

For blue (B) and red (R) light, we have the refractive indexes n_{1R}, n_{2R} and n_{1B}, n_{2B}, respectively. For achromatic lens systems, we impose that $f_R = f_B$ or in terms of refractive power $1/f_R = 1/f_B$. Using above equations we get:

$$(n_{1R} - 1)u_1 + (n_{2R} - 1)u_2 - d(n_{1R} - 1)u_1(n_{2R} - 1)u_2 = (n_{1B} - 1)u_1 + (n_{2B} - 1)u_2 - d(n_{1B} - 1)u_1(n_{2B} - 1)u_2$$

We simplify the system by gluing the two lenses together (d=0) and obtain

$$\frac{u_1}{u_2} = \frac{n_{2B} - n_{2R}}{n_{1R} - n_{1B}} = -\frac{n_{2B} - n_{2R}}{n_{1B} - n_{1R}} \qquad (1)$$

Generally the focal length is determined in the yellow (Y) spectral domain and we have:

$$\frac{1}{f_{1Y}} = (n_{1Y} - 1)u_1 \quad \text{and} \quad \frac{1}{f_{2Y}} = (n_{2Y} - 1)u_2 \quad \text{and hence} \quad \frac{u_1}{u_2} = \frac{f_{2Y}(n_{2Y} - 1)}{f_{1Y}(n_{1Y} - 1)}$$

With (1) we have:

$$\frac{f_{2Y}(n_{2Y} - 1)}{f_{1Y}(n_{1Y} - 1)} = -\frac{n_{2B} - n_{2R}}{n_{1B} - n_{1R}} \quad \text{or} \quad \frac{f_{2Y}}{f_{1Y}} = -\frac{(n_{1Y} - 1)/(n_{1B} - n_{1R})}{(n_{2Y} - 1)/(n_{2B} - n_{2R})}$$

The terms in the nominator and denominator are called constringence or **Abbe Number v**. The latter is used by all lens making engineers to design lens systems. For the achromaticity condition we therefore have using:

$$v_1 = \frac{n_{1Y} - 1}{n_{1B} - n_{1R}} \qquad v_2 = \frac{n_{2Y} - 1}{n_{2B} - n_{2R}} \qquad \frac{f_{2Y}}{f_{1Y}} = -\frac{v_1}{v_2} \quad \text{or} \quad f_{1Y}v_1 + f_{2Y}v_2 = 0$$

In order to provide precise wavelengths for blue, yellow and red (and hence precise values for the Abbe Number v, several conventions are used, e.g.:

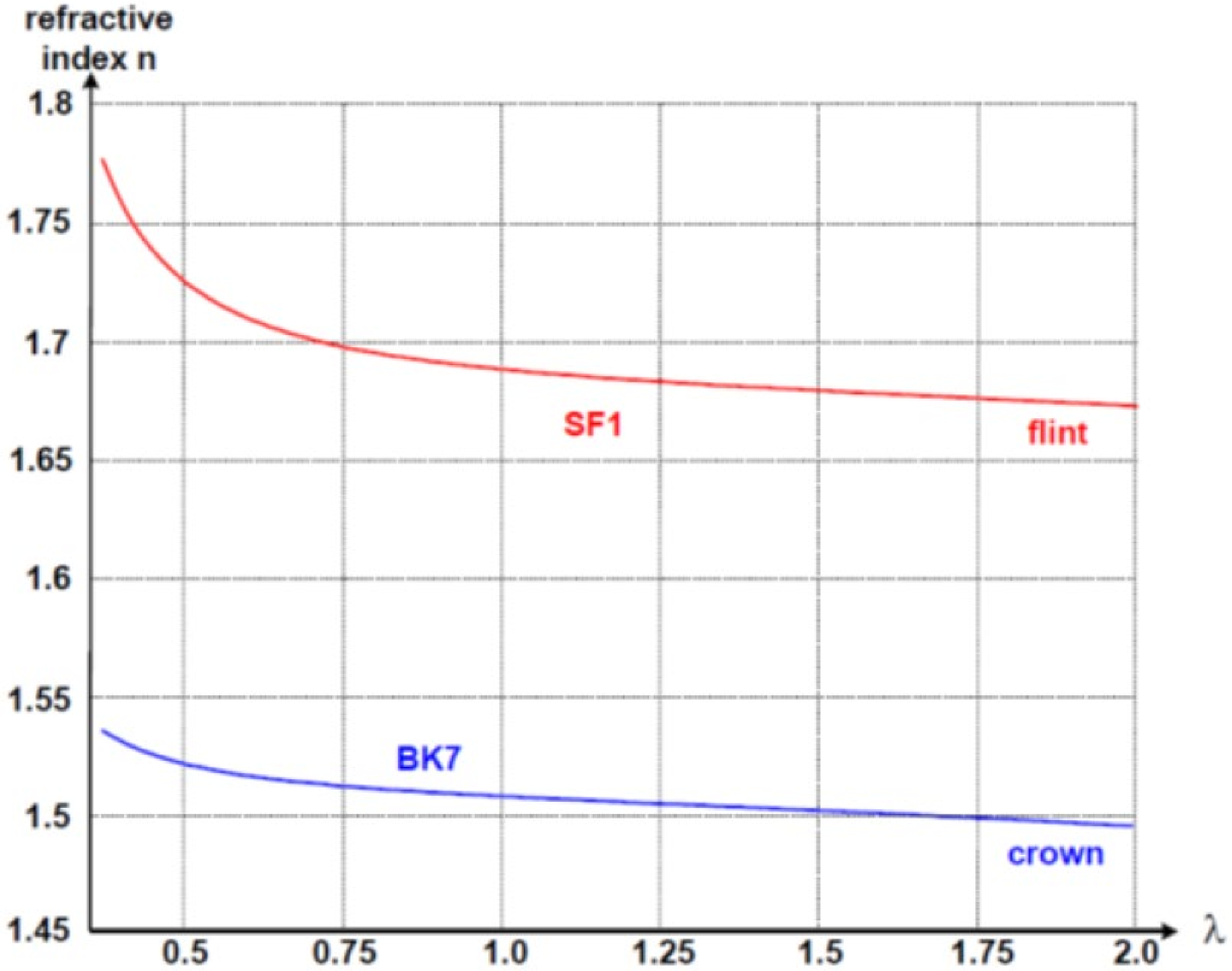
Blue (B): 486.1327 nm H-line (F)
Yellow (Y): 587.5618 nm He line (d)
Red (R): 656.2816 nm H – line (C)

and therefore

$$v_d = \frac{n_d - 1}{n_F - n_C}$$

Using this convention, the achromaticity condition becomes: $f_1 v_{d1} + f_2 v_{d2} = 0$

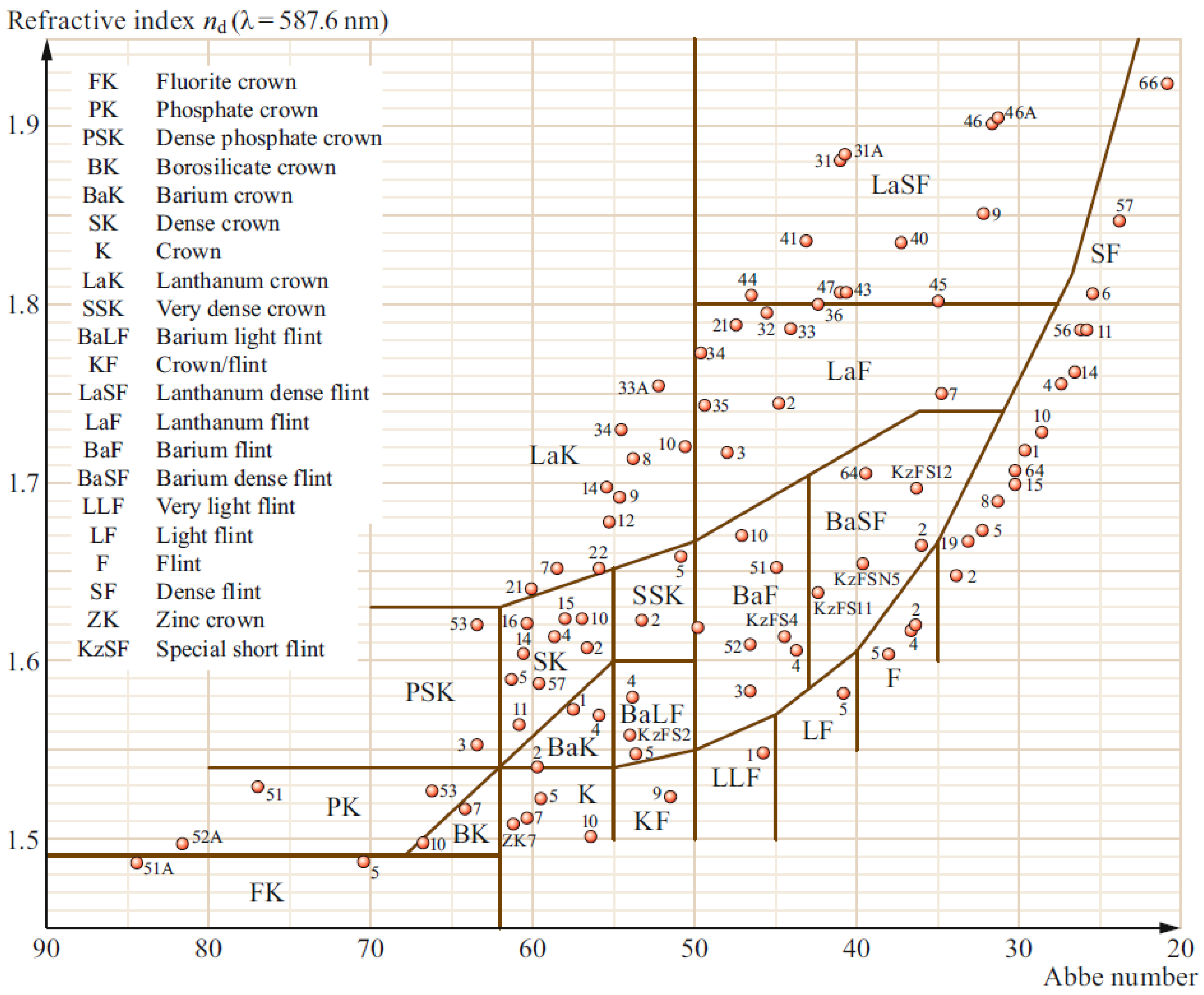
Dispersion of typical optical glasses



Flint glass, e.g. **SF1**
SiO_2: about 62 %
Na_2O: about 6 %
K_2O: about 8 %
PbO: about 24 %

Crown glass, e.g. Borosilicate glass from Schott **BK7, typically**
SiO_2: 70–80 wt%
B_2O_3 :7–13 wt%
Na_2O or K_2O : 4–8 wt%
Al_2O_3: 2–8 wt%

Abbe number of optical glasses



Abbe number:

$$\nu_d = \frac{n_d - 1}{n_F - n_C}$$

Refractive indexes at specific wavelengths (d, F, C). There are different choices.

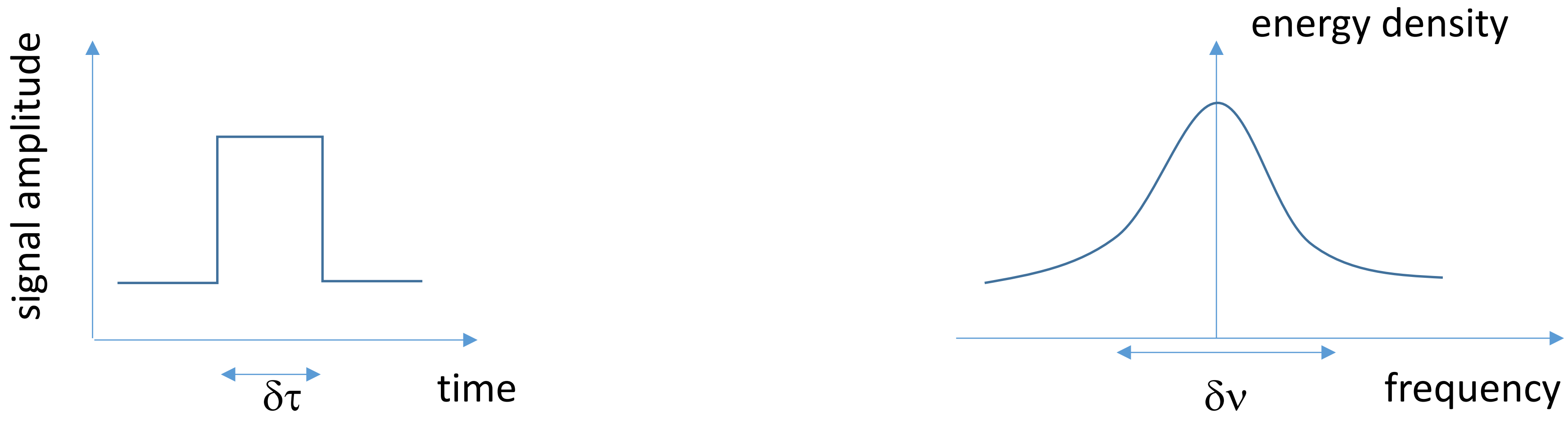
n_F: 486.1327 nm H-line
n_d: 587.5618 nm He line
n_C: 656.2816 nm H-line

R.E. Fisher describes this task as follows: “The designer is faced with a myriad of potential glass types to use and in reality, the task is both a science as well as an art“ [121]. The problem is the refractive index and the Abbe number are by no menas the only selection criteria. Further properties such as optical homogeneity, chemical resistance, workability, commercial availability and/or others must be taken into account. Fisher's “Glass View“ program offers help. The computer presents the glass map (Abbe diagram) with information about the selected criteria, e.g. classes of delivery time, selection of types with properties (e.g. climate resistance) within a prescribed class, or with thermal expansion values within a specified region, or with a price within a defined region, or combinations thereof.

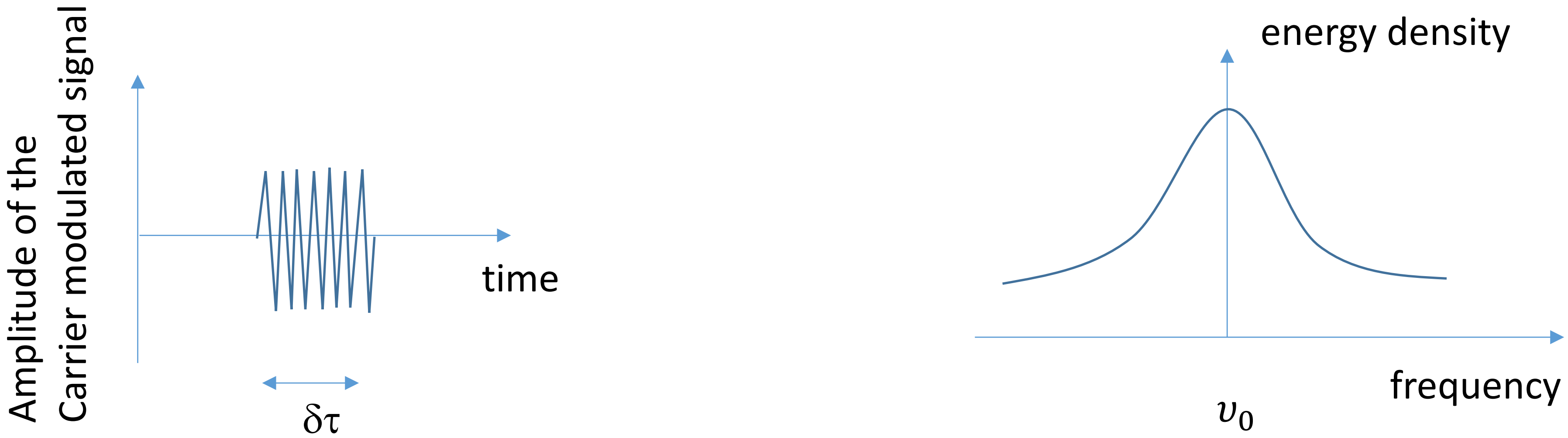
R.E. Fisher, M.J. Thomas, R.M. Hudyma: "Optical glass selection using computerized data base" SPIE Vol. 1535, 78 -88 (1991)

2.5 Optical fibers

Optical data transmission



The pulse signal in the time domain is transformed into a broad frequency spectrum in the frequency domain with a bandwidth δν. This signal is transported by a carrier electromagnetic wave at frequency υ_0.



Advantages of optical waveguides

Higher carrier frequency υ_0 → Higher bandwidth

Higher carrier frequency υ_0 → Higher transmission rate

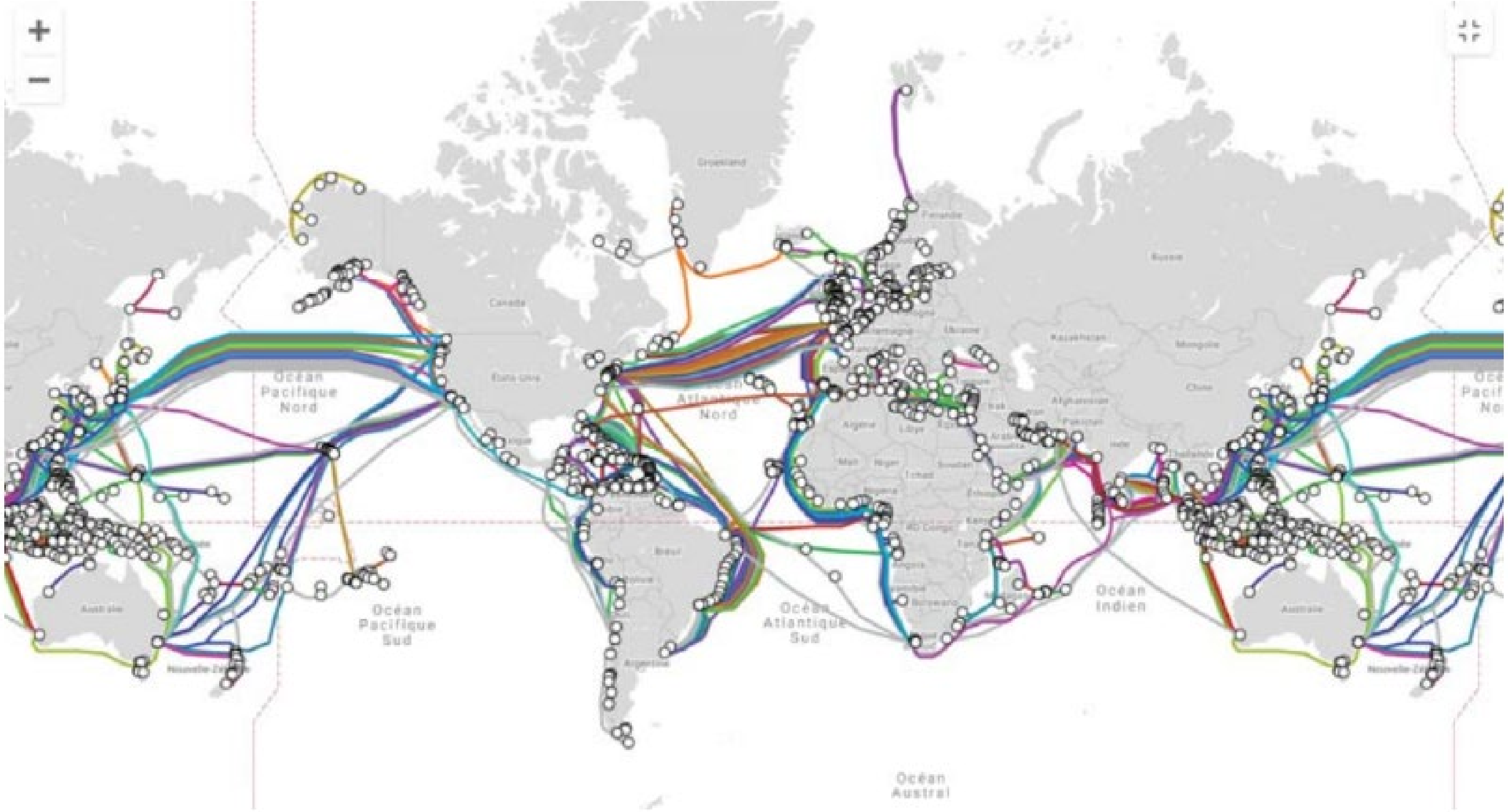
- Propagation at very high frequencies possible : $\lambda = 1550\ nm \quad v = 2 \cdot 10^{14}$ Hz
- Huge amount of information can be carried
- e.g. cabled wire-pairs: 50 simultaneous phone calls versus fiber transmission: > 50 million calls !
- High confinement: inhibition of environmental perturbations
- Immunity to electromagnetic interference
- Using appropriate fiber material can minimize losses
- e.g.in cabled wire-pairs: 10 dB/km versus in silica fibers, loss < 0.2 dB/km (amplifiers have to be used every ~ 100 km)
- Propagation time can be controlled
- Possibility to design integrated optical circuits (IOP)

  photonic integrated circuits (PIC) with diodes, lasers, sensors

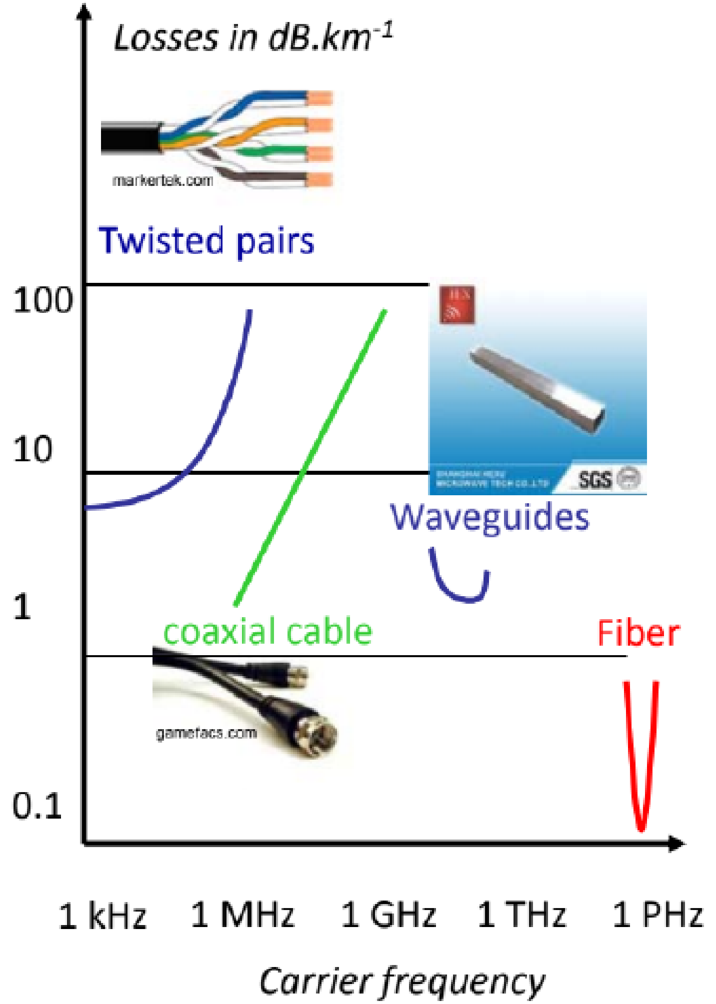
$$I_p = 10 \cdot log_{10}\left(\frac{I_0}{I}\right) \text{ dB}$$

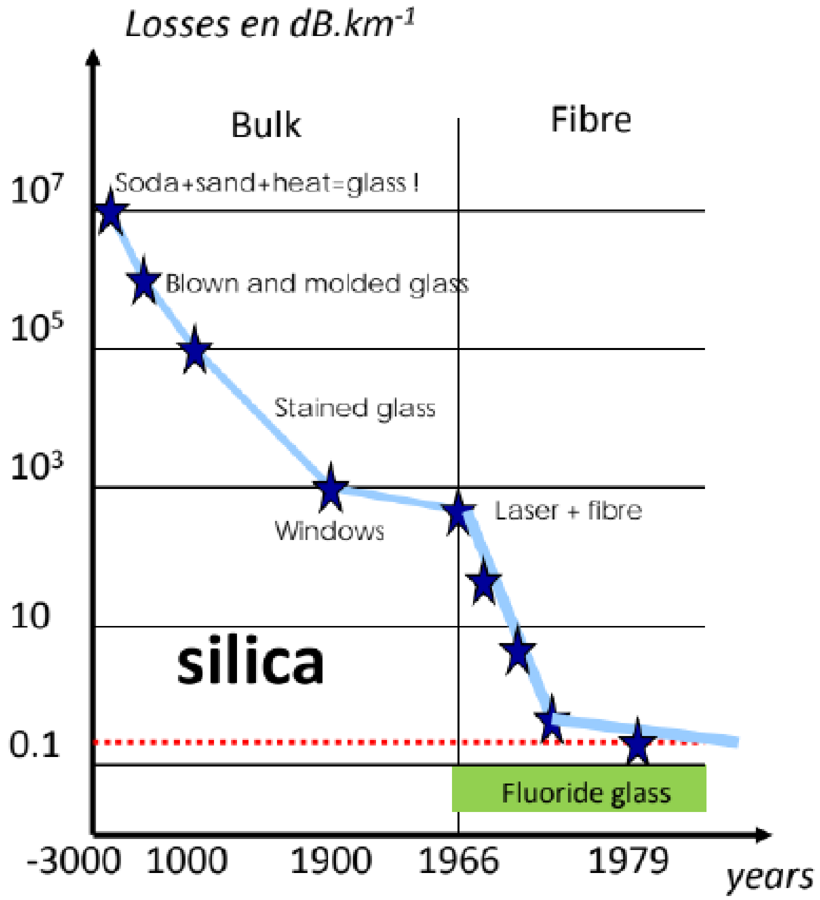
Long distance optical fiber network

80% of the long distance communications in the world go through the optical fibred network
The undersea fiber network is 1.3 billions of km long.



Losses in waveguides





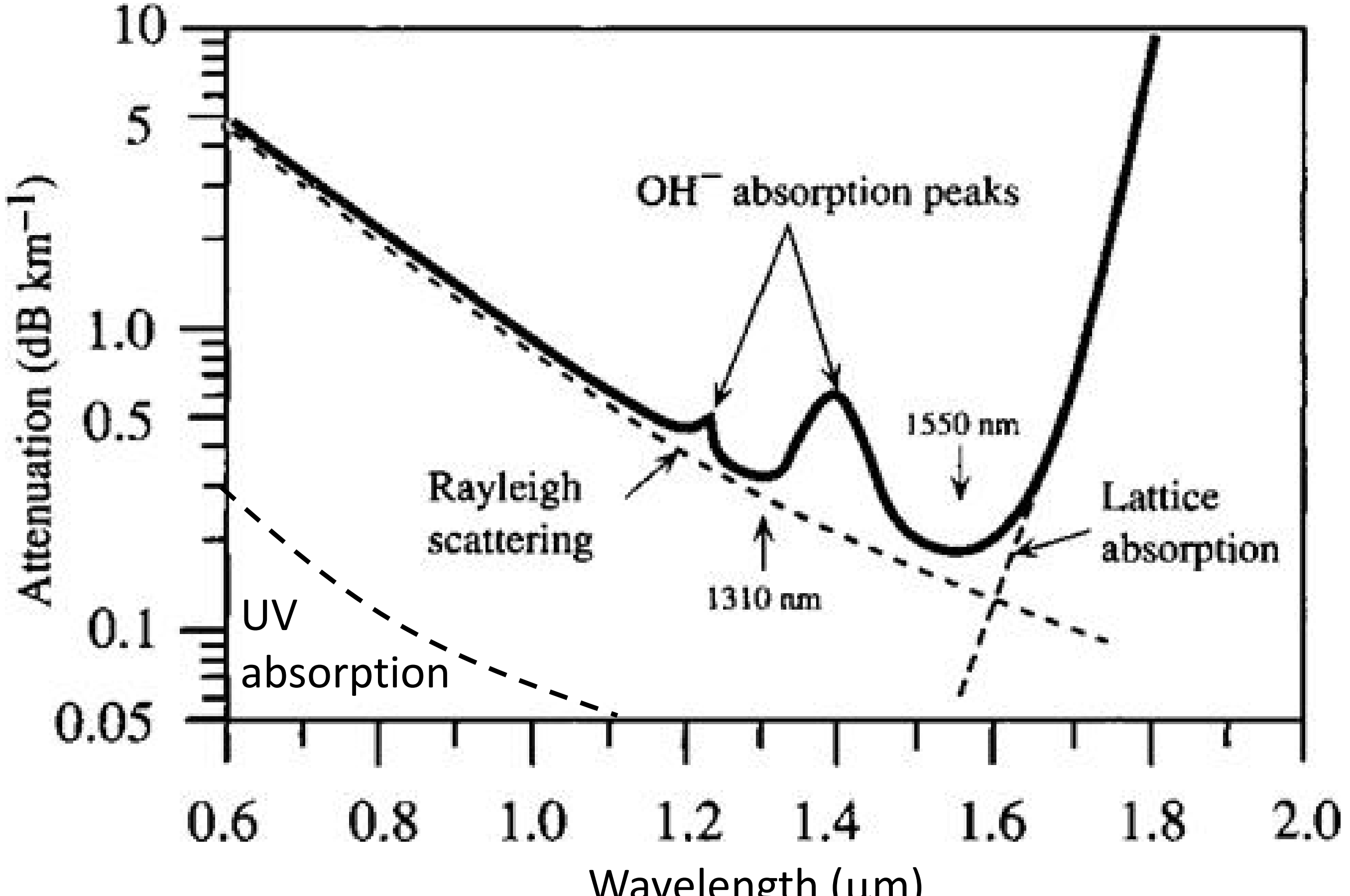
$$A_p = 10 \cdot log_{10}\left(\frac{I_0}{I}\right) \text{ dB}$$

10 dB/km : T=10%

0.1 dB/km : T=98%

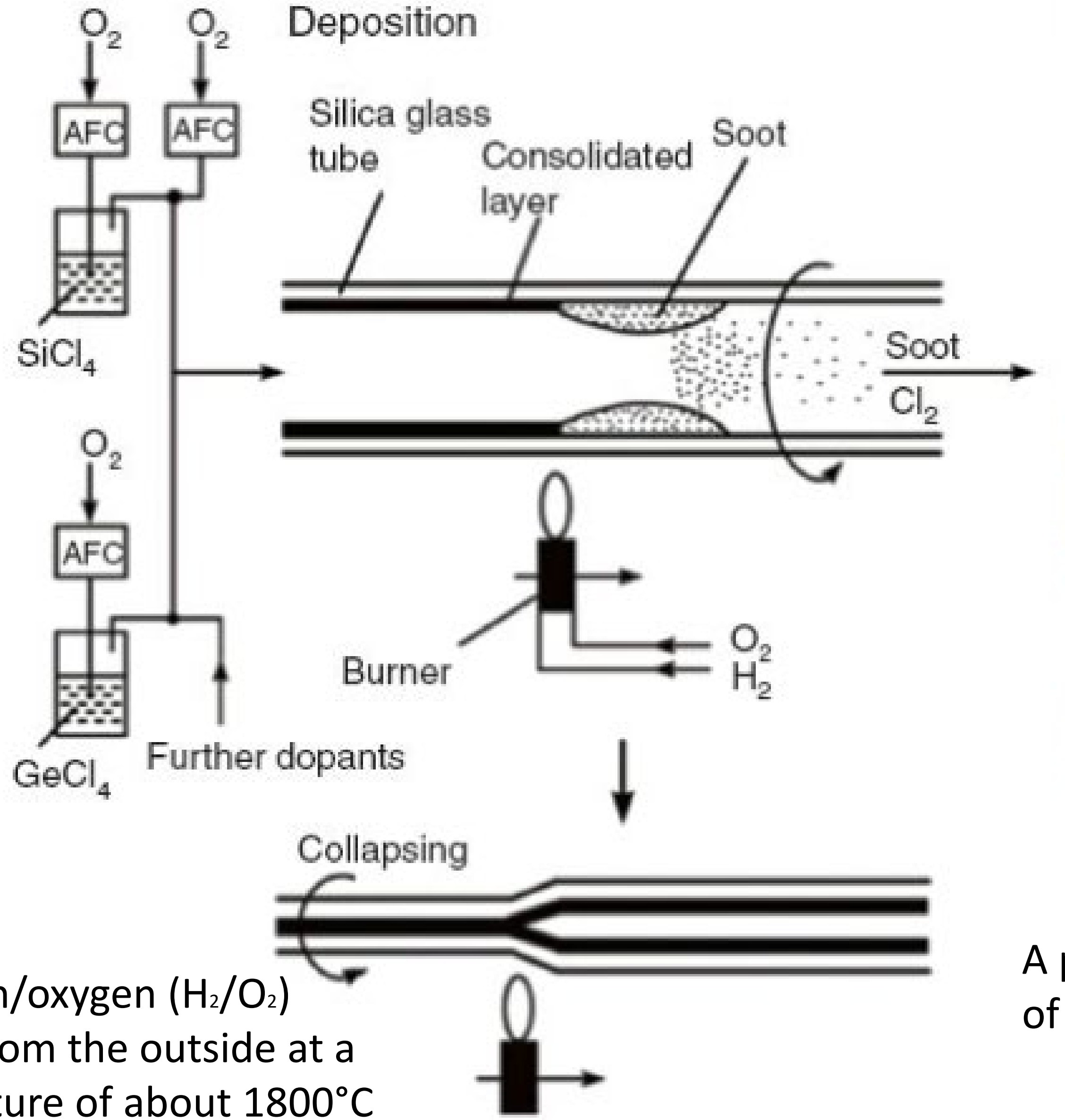
Losses in silica optical fibres

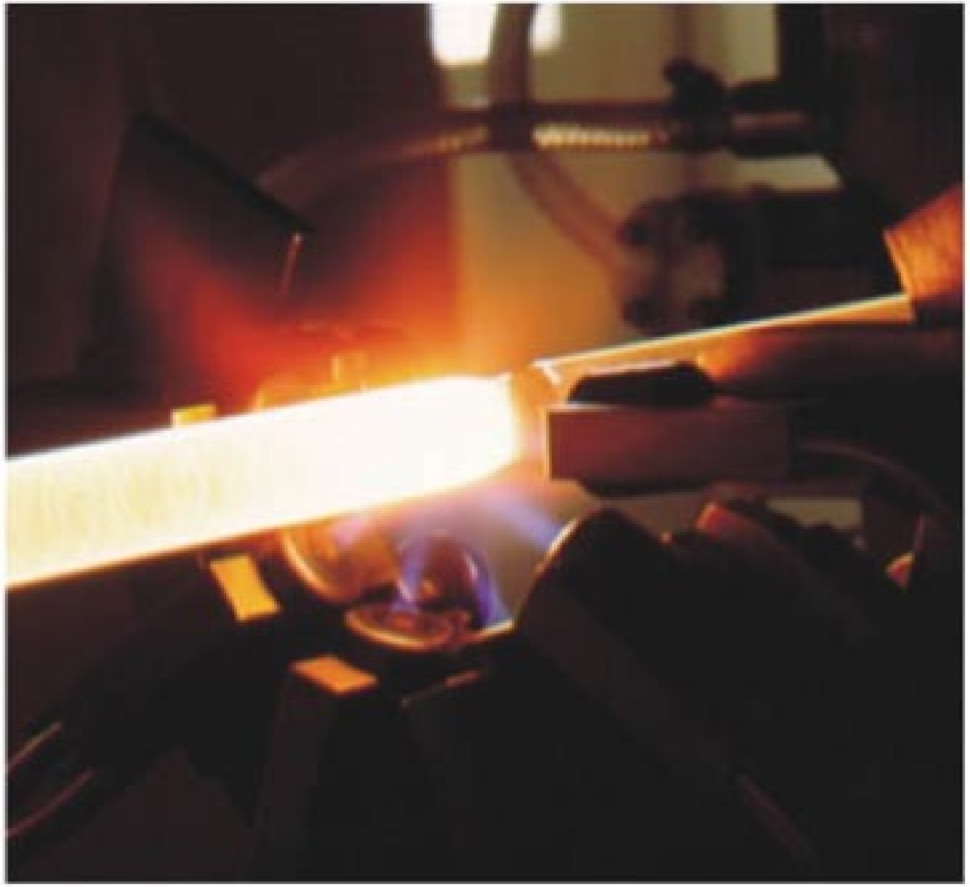
In vapor phase deposited GeO_2-SiO_2 glasses, transition metal ion impurities can be reduced to < l ppb. P_2O_5-doped silica claddings were globally established.
OH absorption can be reduced by carefully preparing dry glass fibers. Complete elimination of OH^- is difficult.



Note: An attenuation of 0.2 dB km^{-1} means a power loss of 5% after 1 km, 37% in 10 km or 99% in 100 km. Therefore amplifiers are needed (every 10-100 km) to carry the signal over large distances.

Fabrication of fiber preforms via modified chemical vapor deposition (MCVD)





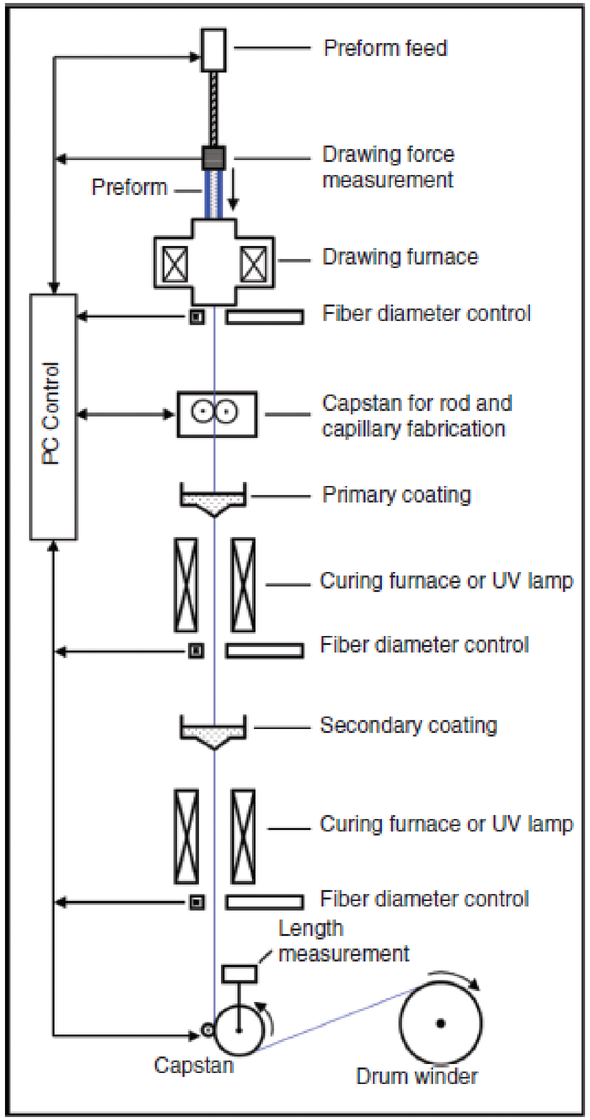
Silica glass tube with the burner

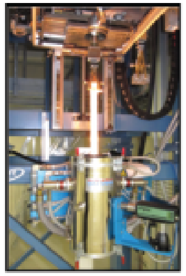
Hydrogen/oxygen (H_2/O_2) burner from the outside at a temperature of about 1800°C

A preform is typicall 300 mm long and has a diameter of 2 mm

K. Schuster et al., Adv. Opt. Techn. 2014; 3(4): 447–468

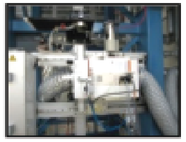
Fiber drawing



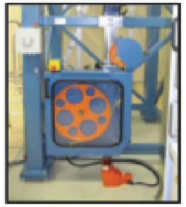


Drawing furnace with preform

Capstan for rods and capillaries



UV curing lamp



Capstan for optical fibers

Preform speed : v_P

Fiber speed : v_f

Preform diameter : d_p Preform length : l_p

Fiber diameter : d_f Fiber length : l_f

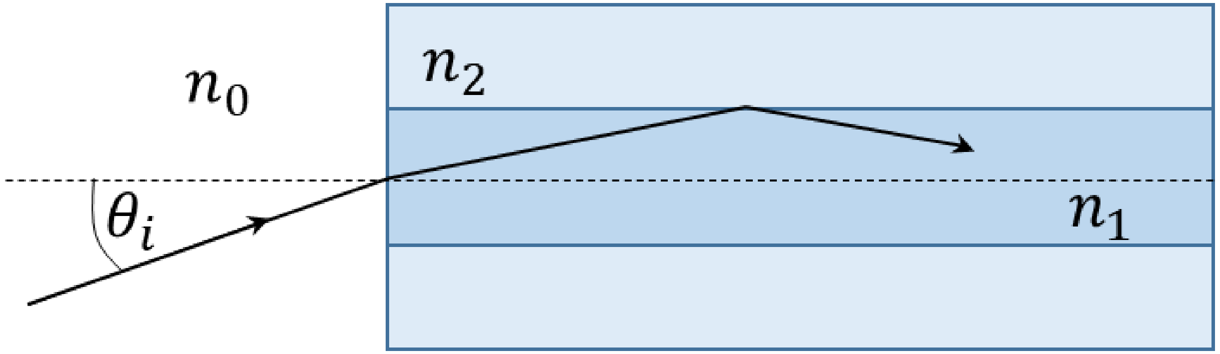
$$\frac{v_f}{v_p} = \frac{d_p^2}{d_f^2}$$ (drawing ratio)

$$\frac{l_f}{l_p} = \frac{d_p^2}{d_f^2}$$

Crucible and drum must be of highest purity Pt.

K. Schuster et al., Adv. Opt. Techn. 2014; 3(4): 447–468

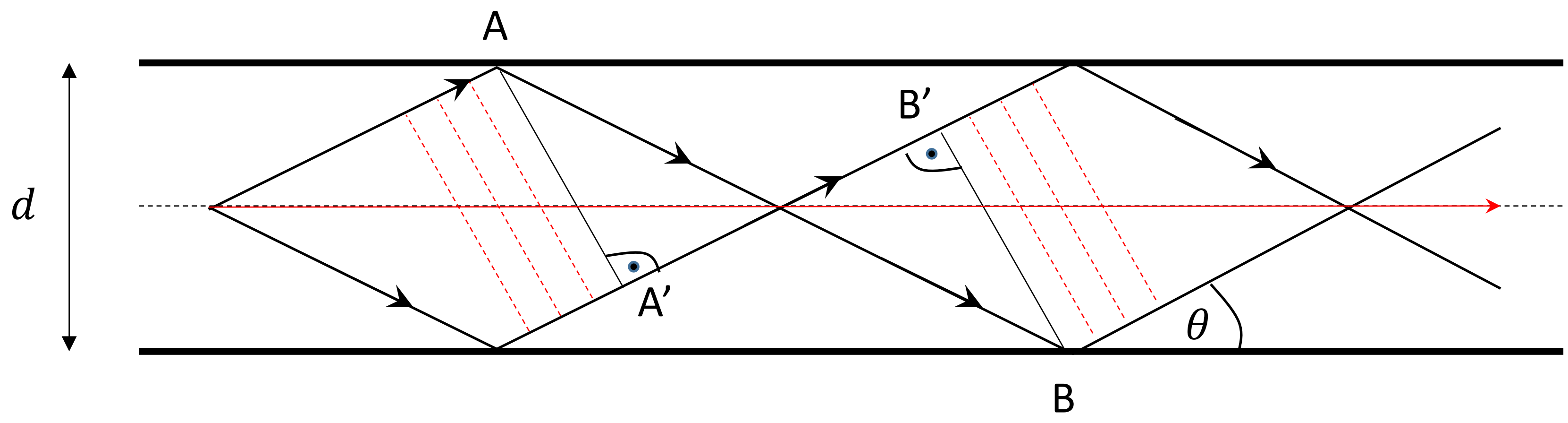
Angle of incidence and numerical aperture



Waveguiding is enabled by total reflection at the interface between a high refractive index core ($n_1 = 1.4508$) and a lower refractive index cladding ($n_2 = 1.4469$). In order to ensure total reflectance inside the fibre, the angle of incidence θ_i has to be smaller than a certain value θ_c . The numerical aperture (NA) is defined as the sine of θ_c:

$$NA = sin(\theta_c) = \sqrt{(n_1^2 - n_2^2)}$$

Guided modes: a simplified illustration using a planar metallic waveguide (air-metal interface)



In order to have constructive interference, the phase difference between AB and A'B' must be $p \cdot 2\pi$:

$AB - A'B' = 2 \cdot d\ sin\theta$ therefore $k_0 \cdot AB + 2\pi - k_0 \cdot A'B' = p \cdot 2\pi$ and using $k_0 = {}^{2\pi}/_{\lambda}$ we obtain:

$$sin\theta_m = m\frac{\lambda_0}{2d} \quad \text{with m = p-1}$$

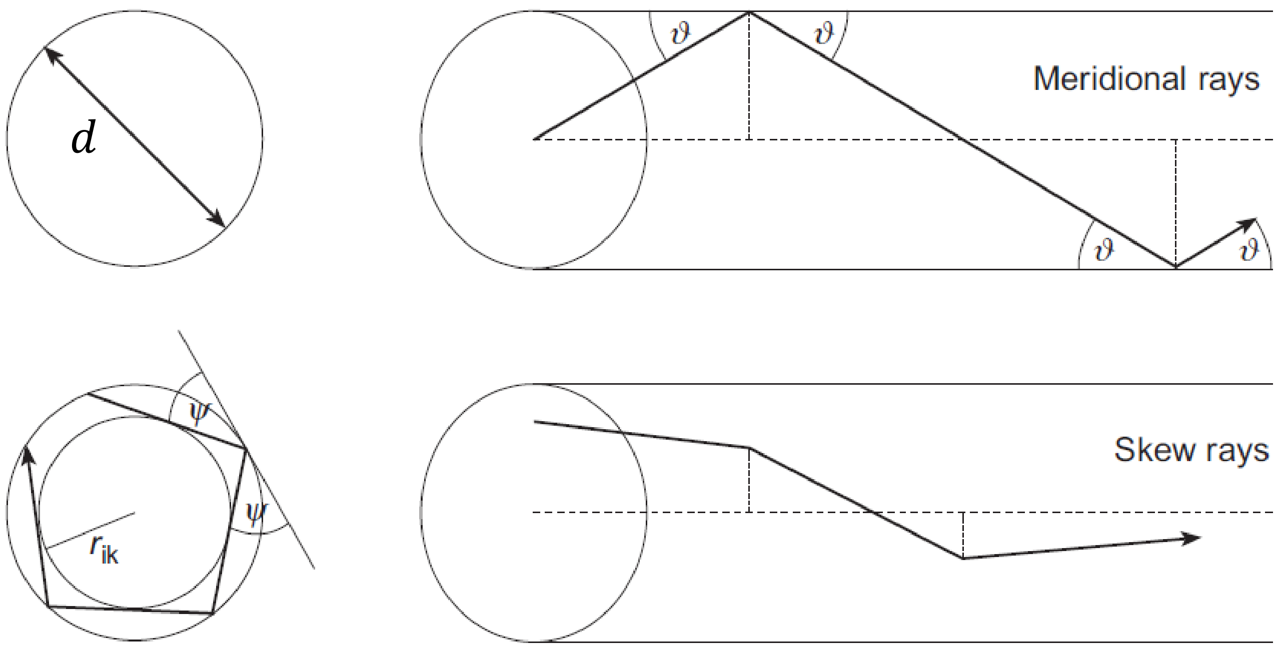
There is a critical distance d, below which only one mode with m= 0 ($\theta_m = 0$) is allowed.

In real optical fibers, there are «skew» modes besides meridional rays. Also, the phase change induced by total reflection depends on the angle of reflection and is not just π as for the metal waveguide. The treatment is more complicated. After quite some iterations one can obtain the number of modes N_{modes}:

$$N_{modes} \approx \frac{g}{g+2}\frac{V^2}{2} \quad \text{with} \quad V = \pi\frac{d}{\lambda}NA$$

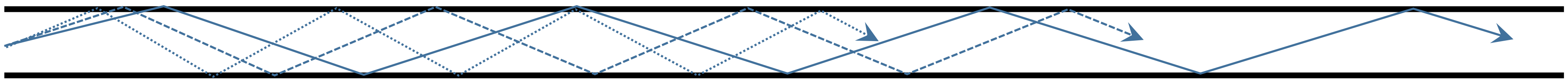
For $V_{SMF} < 2.405$ one obtains a single mode fibre.

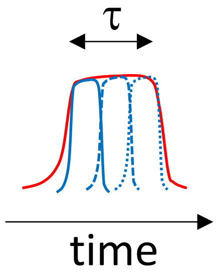
V is called the normalized wave number (or V-number). g is the refractive index profile parameter: e.g. $g = \infty$ for step index fibers and $g = 2$ for parabolic profiles.



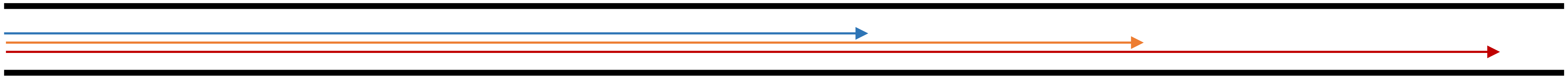
Origin of dispersion in glass fibers

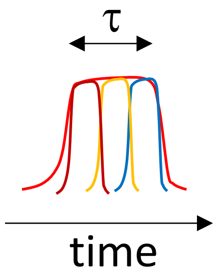
Each propagation mode has a different path length





Typically, if two signal peaks are separated by 50 ns they can no more be resolved after a 2 km transmission length.
Because of mode coupling, modes are mixed after a certain transmission length.
(remediation: use quadratic index or graded index fibers or use single mode fibers)



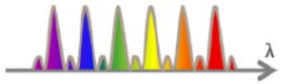


Typically, the pulse broadening for a light source with a spectral width of 1 nm is about 60 ns for a transmission length of 2 km.

There is a further dispersion factor (even though less important than in the other two) which is polarization dispersion. This type of dispersion is also active in single mode fibers and depends on the small refractive index variation between perpendicular and parallel polarized light $n_{\perp}$ and $n_{\parallel}$, respectively. Polarization dispersion is typically less than 1 ps/$\sqrt{km}$

Single mode fibers are interesting, since their overall dispersion is lower. Two ways can be used to transmit more bit/s:

Time Division Multiplexing



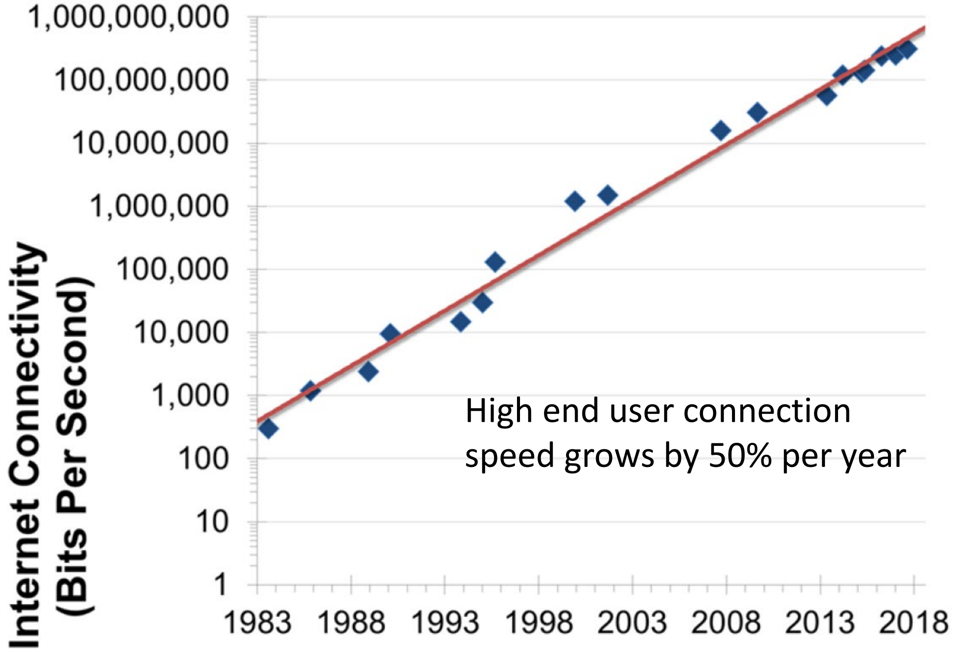
Wavelength Division Multiplexing

also

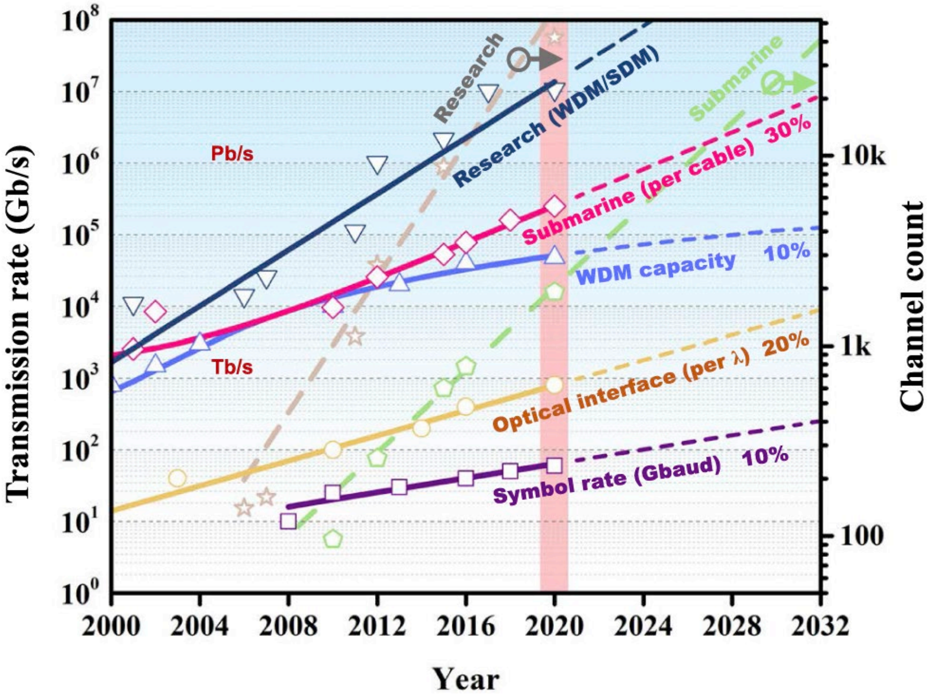
Space Division Multiplexing

Polarization Division Multiplexing

Transmission capacity of optical fibers must keep pace with internet traffic growth 20%-30%



"Nielsens Law" of internet bandusage



https://doi.org/10.1515/nanoph-2020-0309