Qualified Partner Programme QPP

Fiber Optic Transmission Theory

Felice Guarna

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Introduction

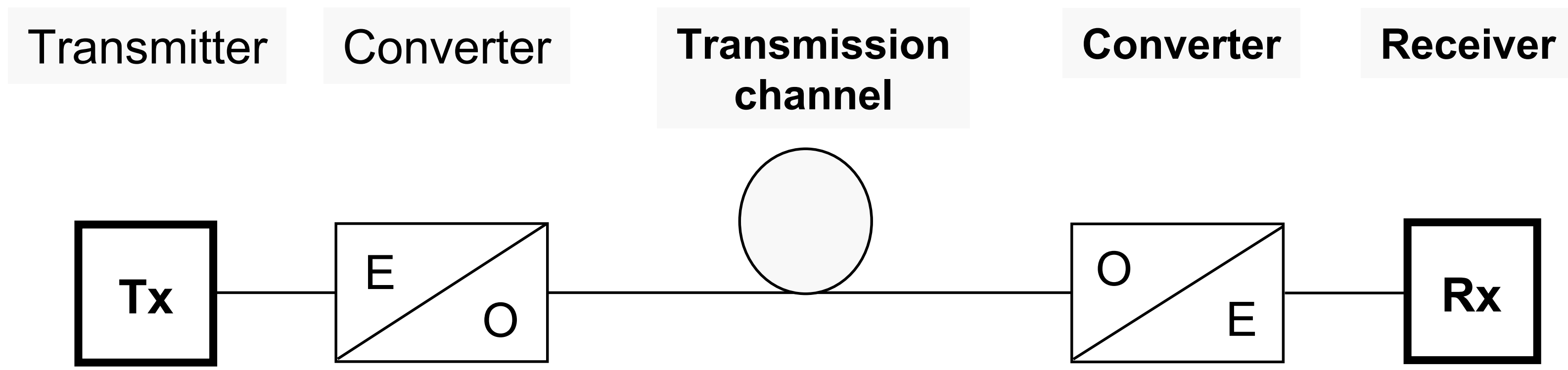
Optical communication is as old as humanity itself, since from time immemorial optical messages have been exchanged, e.g. in the form of:

- hand signals
- smoke signals
- by optical telegraph

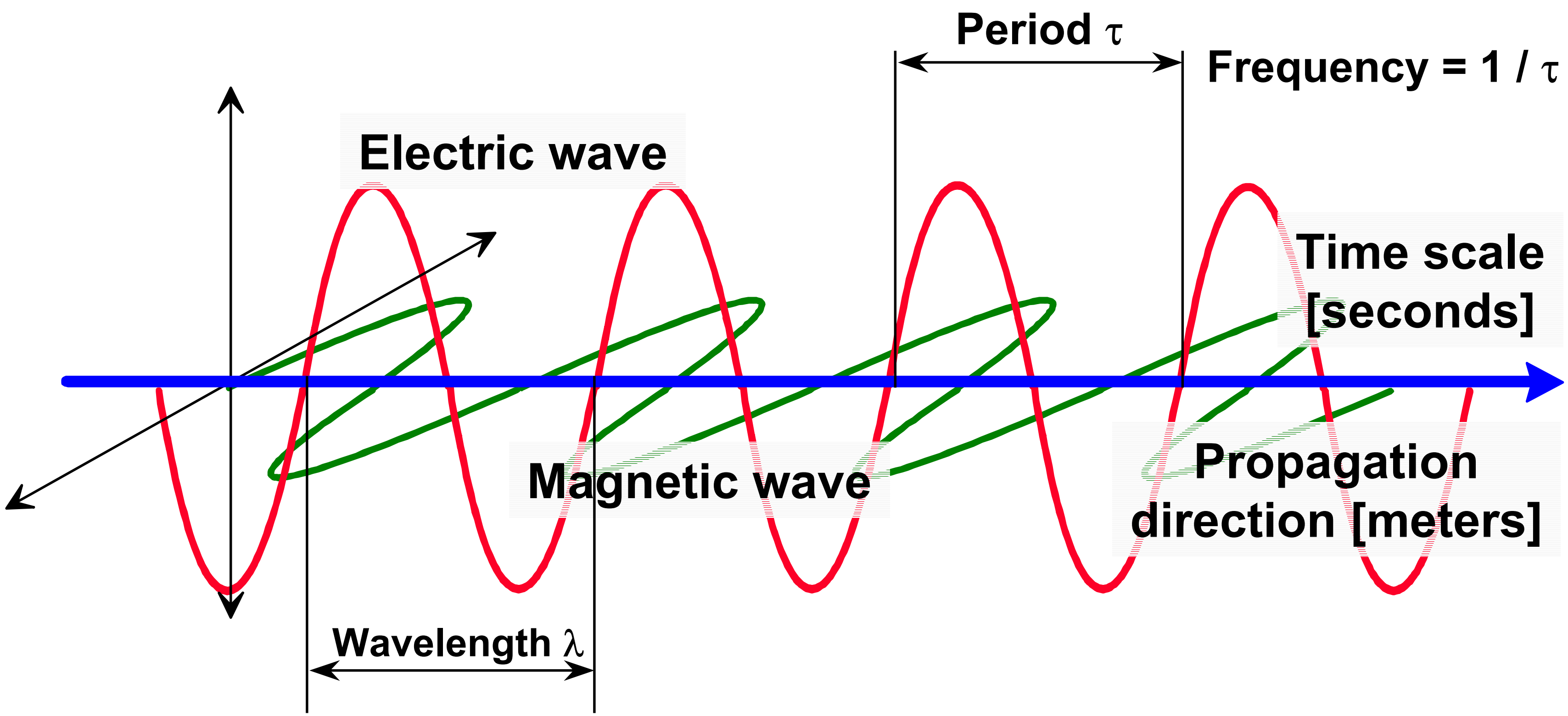
To the optical information technology as we know it today - and as it is described in this presentation - two developments were crucial:

- The transmission of light over an optically transparent matter (1870 first attempts by Mister Tyndall, 1970 first FO by Fa. Corning)
- Availability of the LASER, in 1960

The principle of an optical communication system

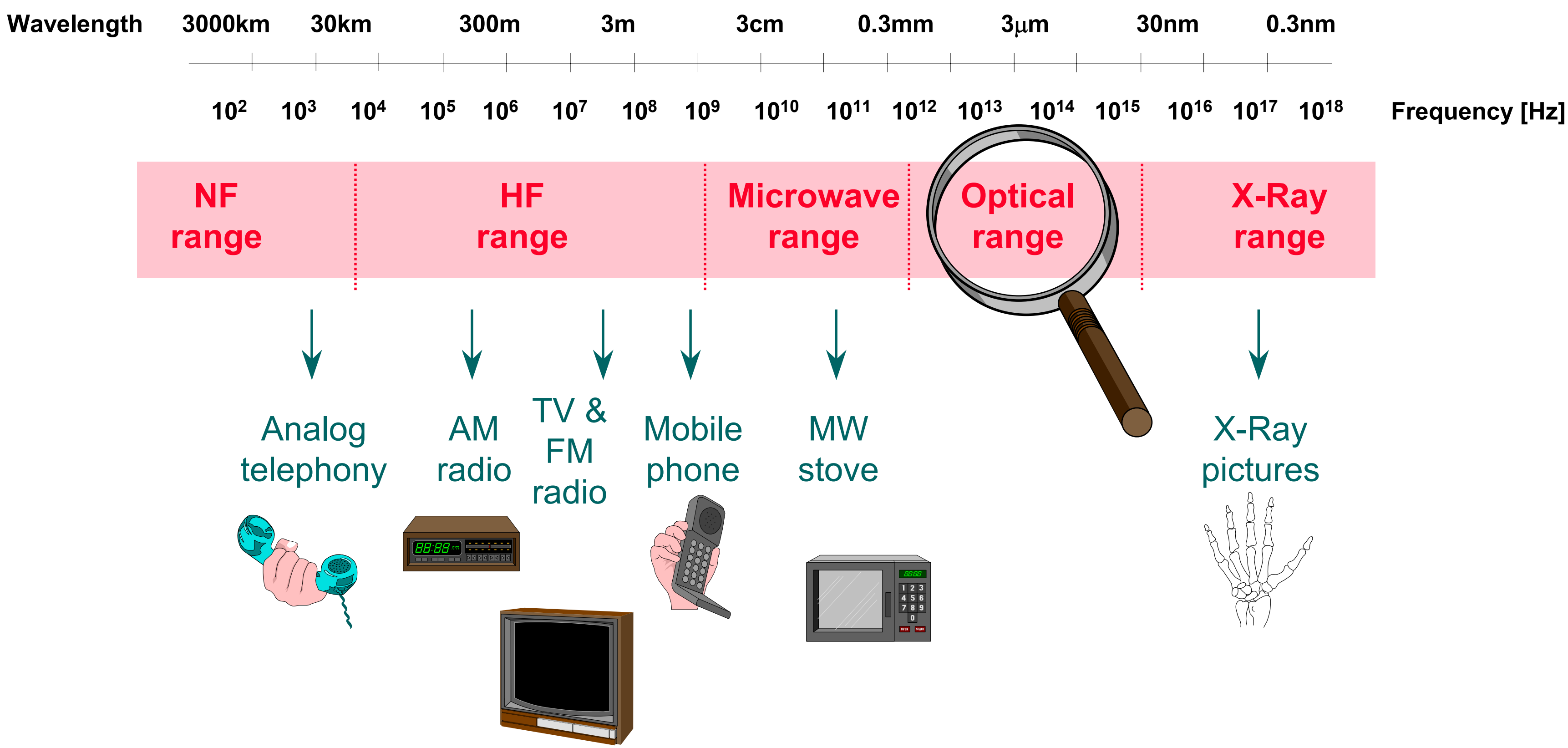


The electromagnetic wave

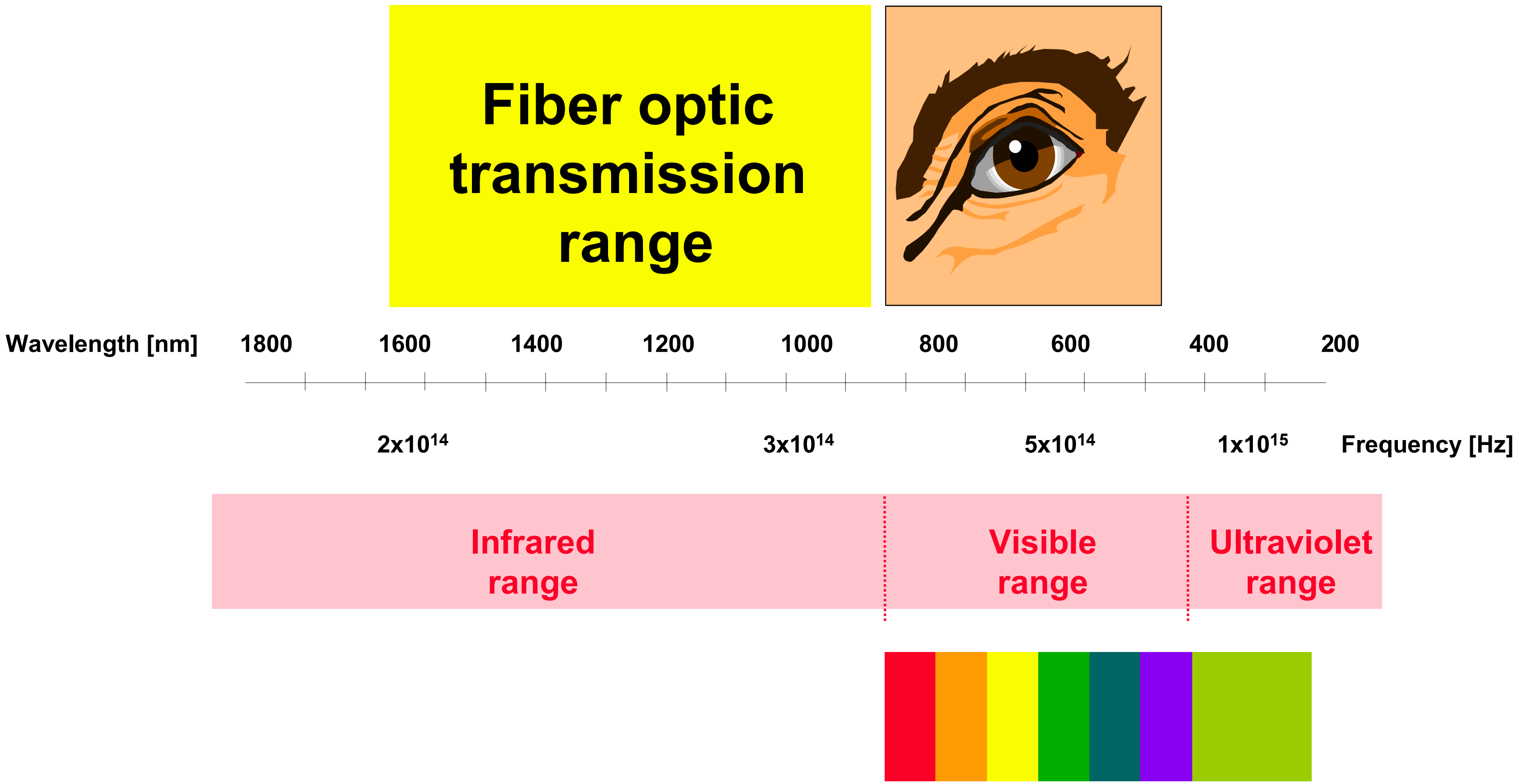


Light is an electromagnetic wave and can be described with the equations of Maxwell.

Wavelength range of electromagnetic transmission



Wavelength range of optical transmission



Velocity of electromagnetic wave

(Velocity of light in vacuum)

Velocity of light (electromagnetic radiation) is:

- ☑ C_0 = Wavelength x frequency
- ☑ C_0 = 299793 km / s

Remarks: An x-ray-beam (λ = 0.3 nm), a radar-beam (λ = 10 cm ~ 3 GHz) or an infrared-beam (λ = 840 nm) have the same velocity in vacuum

Refractive index

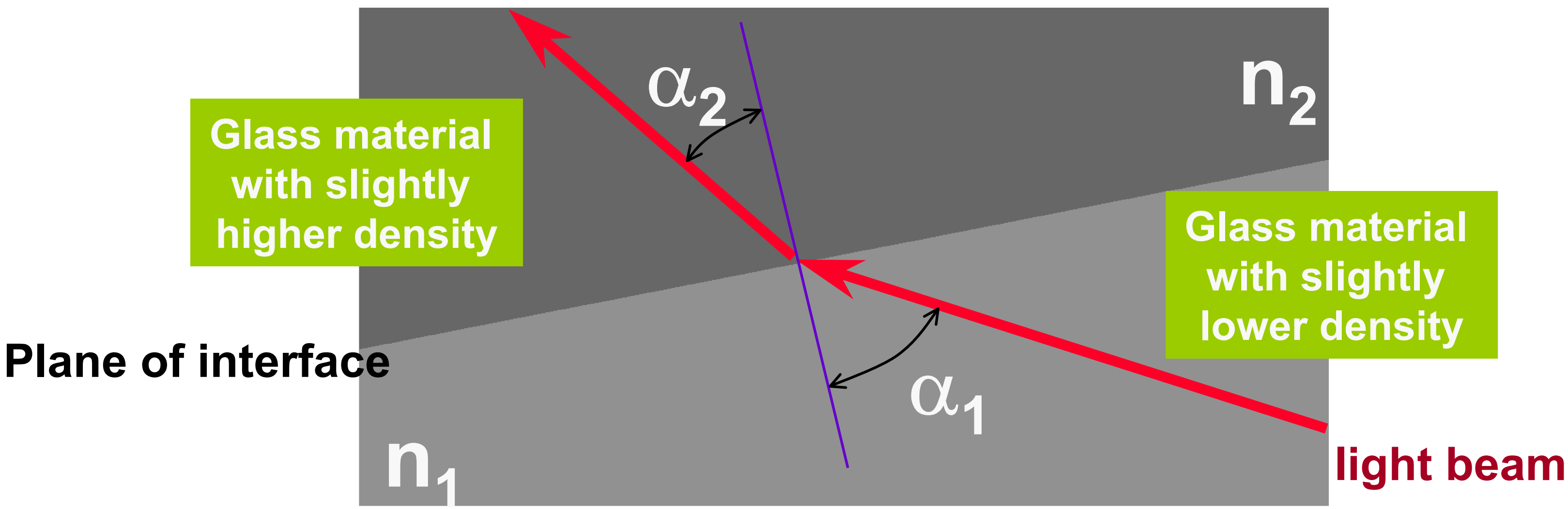
(Change of velocity of light in matter)

Velocity of light (electromagnetic radiation) is:

- always smaller than in vacuum, it is
  C_{n} (Velocity of Light in Matter)
- $n = C_0 / C_n$
- n is defined as refractive index (n = 1 in Vacuum)
  n is dependent on density of matter and wavelength

Remarks: $n_{Air} = 1{,}0003$, $n_{core} = 1{,}5000$ or $n_{Sugar\ Water} = 1{,}8300$

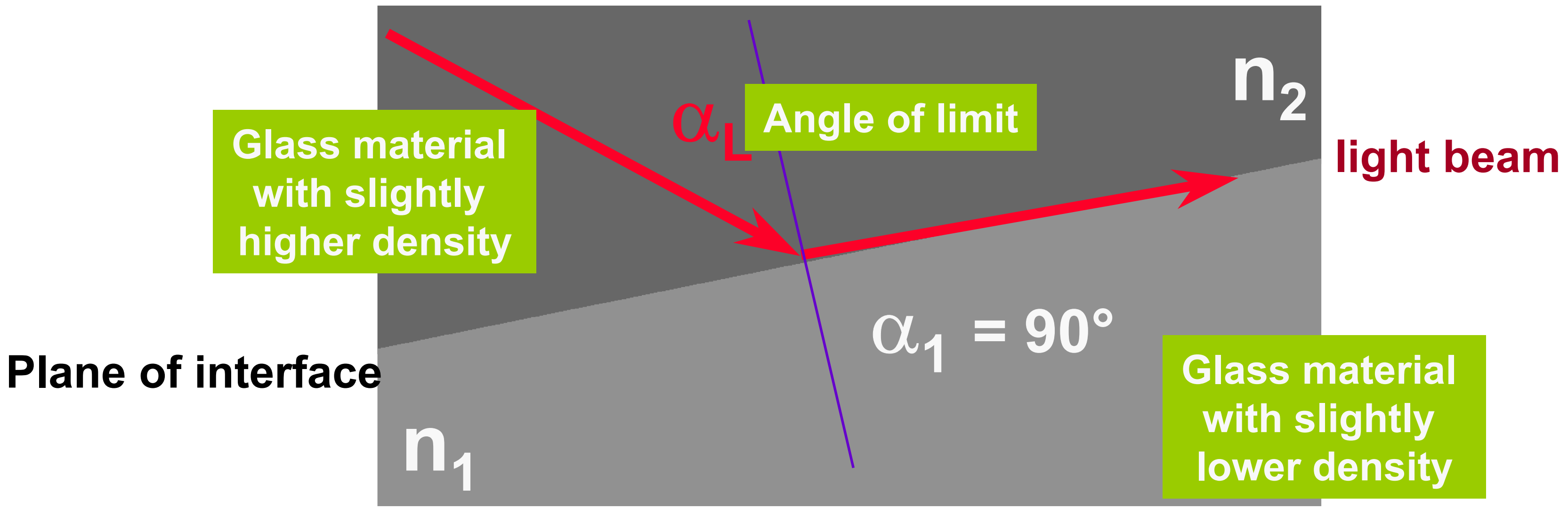
Refraction



Remarks: $n_1 < n_2$ **and** $\alpha_1 > \alpha_2$

$$\sin \alpha_2 / \sin \alpha_1 = n_1 / n_2$$

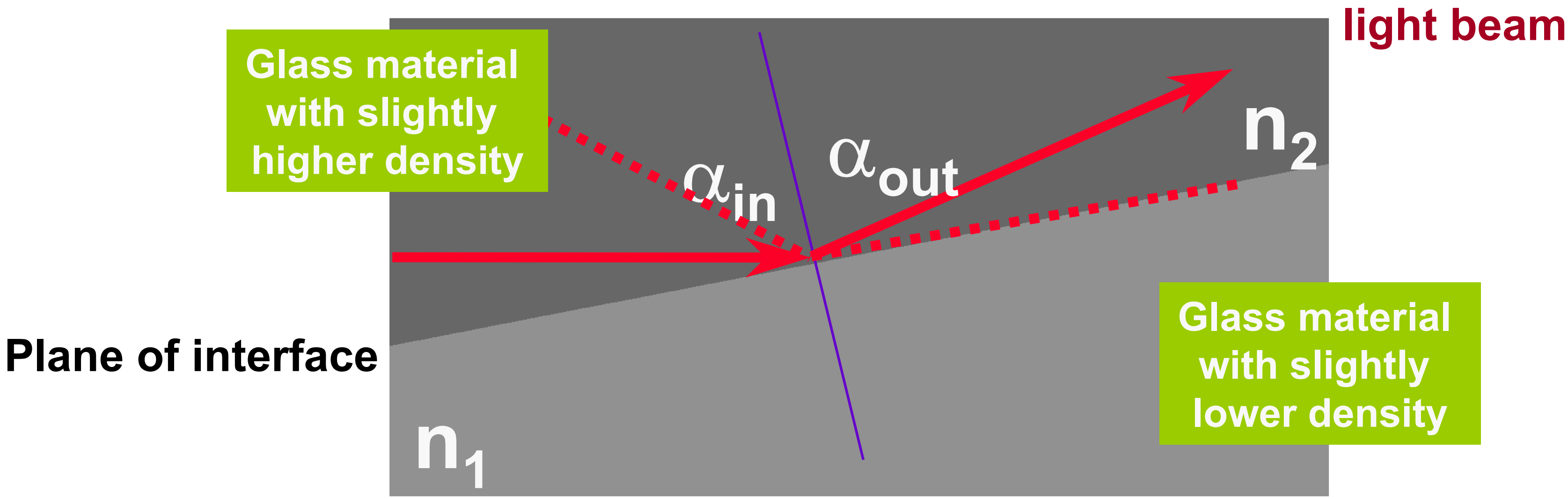
Total refraction, angle of limit



$\sin \alpha_1 = 1 \rightarrow \sin \alpha_L = n_1 / n_2$

Remarks: $n_1 < n_2$ and $\alpha_2 = \alpha_L$

Reflection



Remarks: $n_1 < n_2$ **and** $\alpha_{in} = \alpha_{out}$

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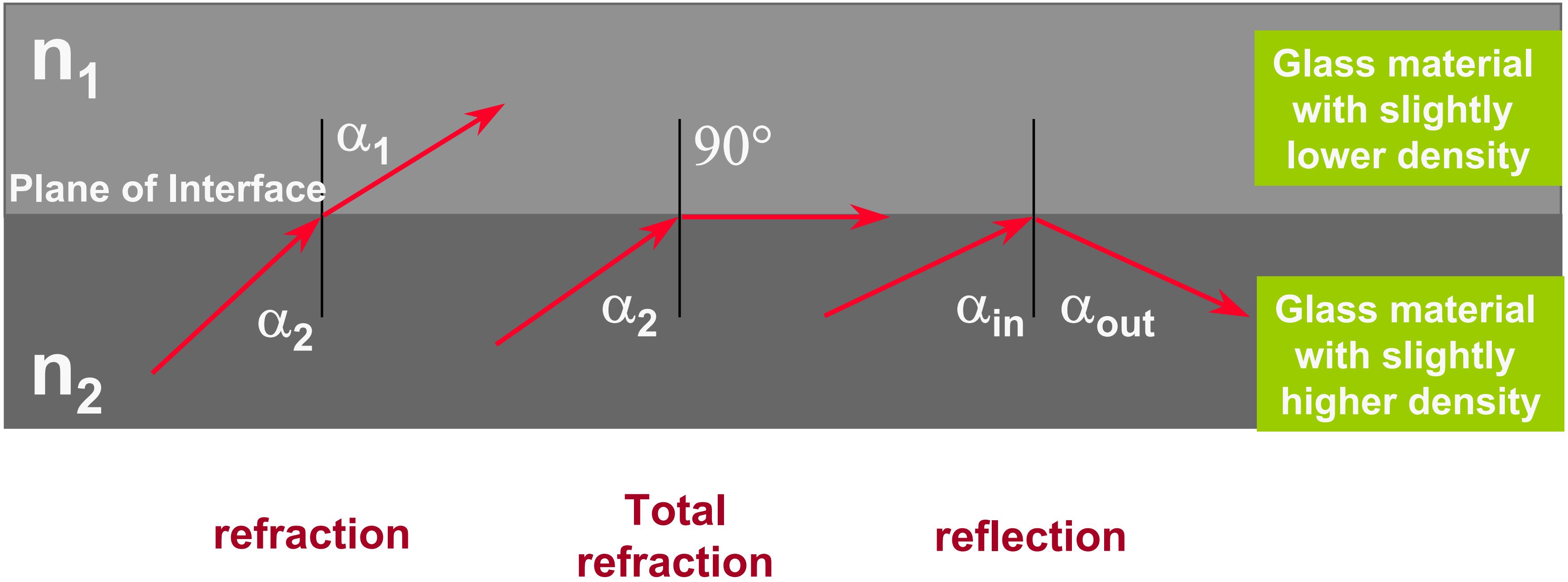
Summary



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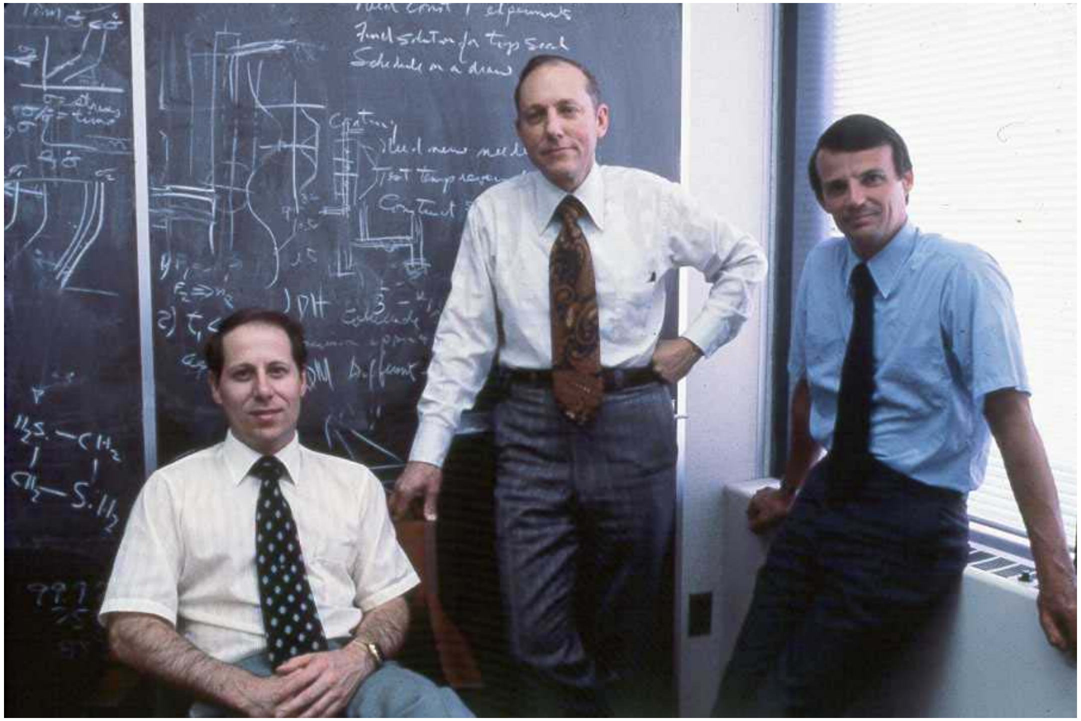
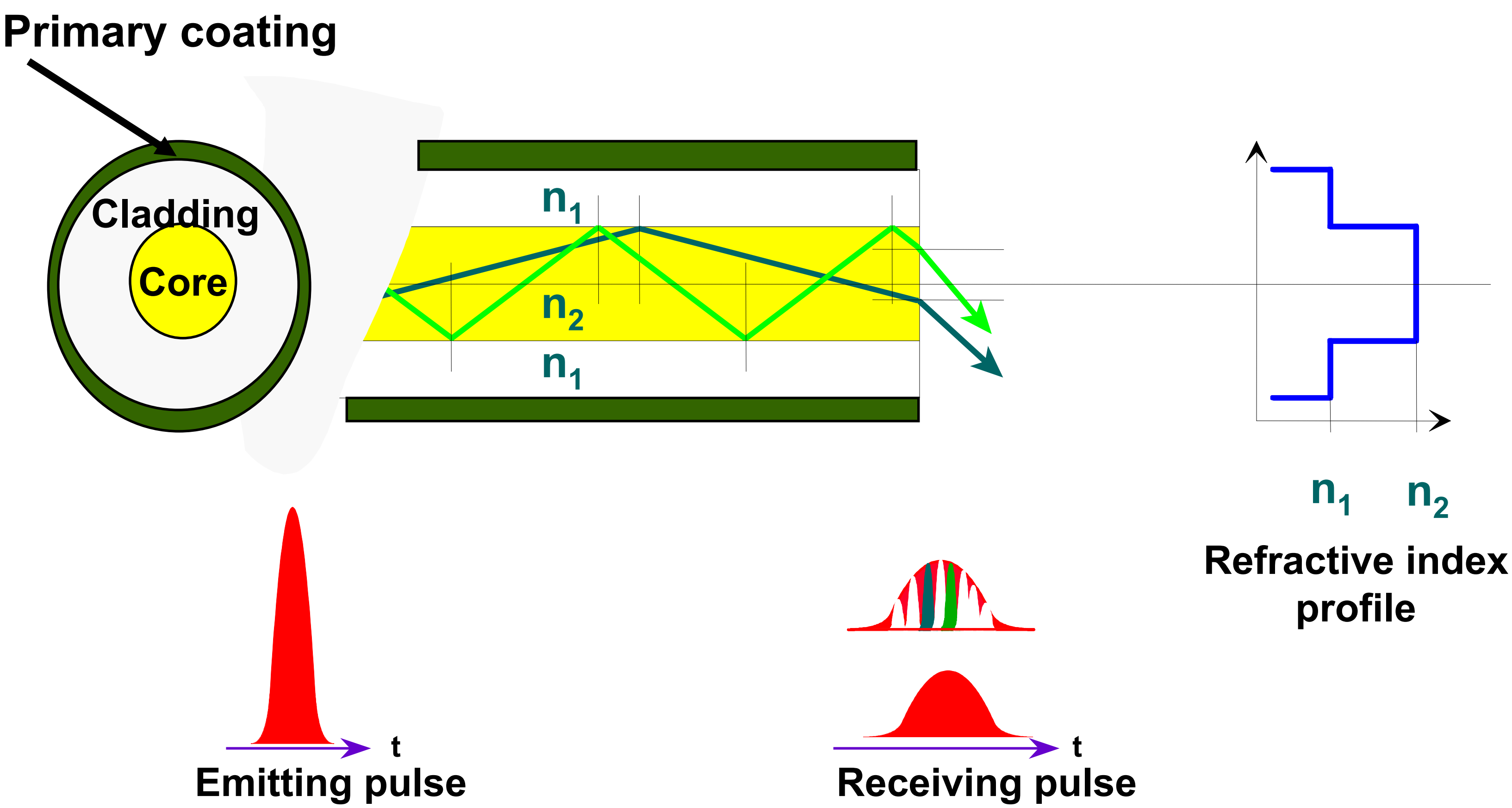
Where all began

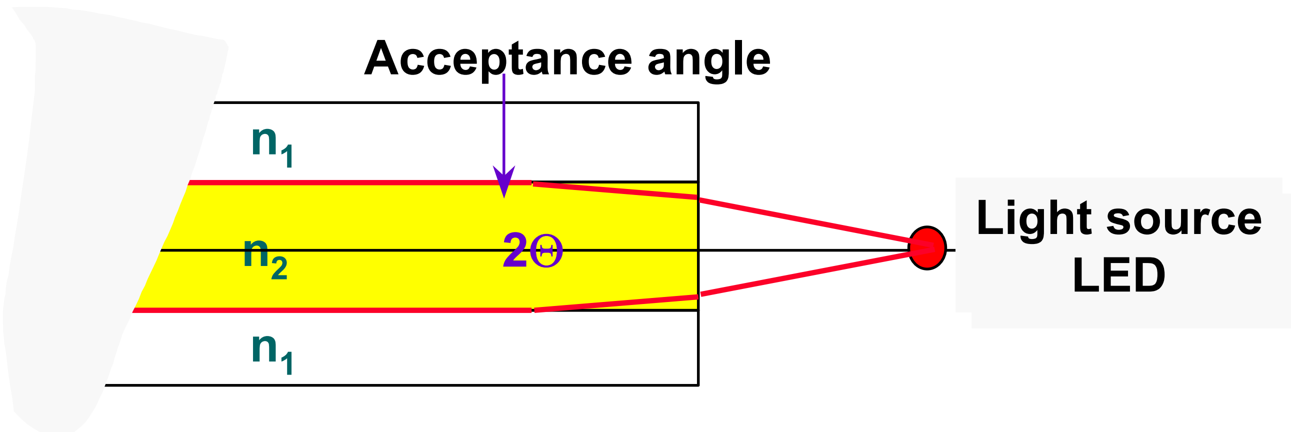


Three **Corning** scientists, Drs. Donald Keck (seated, left), Robert Maurer and Peter Schultz, are credited with developing the world's first commercially viable optical fiber in 1970.

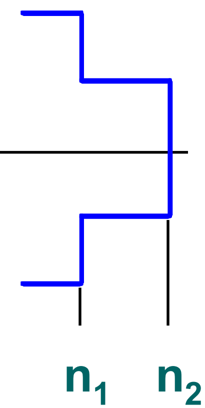
Structure of fiber



Numerical aperture



Numerical Aperture NA = sin Θ = $(n_2^2 - n_1^2)^{0.5}$



Remarks: NA = 0.3 typical value for step index Fiber → Θ ~ 17.5 °

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Numerical Aperture NA and transmission performance

- Large values of NA mean large values of Θ , meaning more light power will be coupled into the fiber
- Large values of NA mean more modes in the fiber
- More modes mean lower bandwidth
- Large values of NA mean lower bending induced attenuation of the fiber

Remarks: Two Fibers with NA = 0.2 & 0.4 ⟶ Fiber with NA = 0.2 has 8-times more bending induced attenuation than NA = 0.4 Fiber

Light on fiber optics only propagates on discrete ways

These discrete ways are called modes (in mathematical terms they are the solutions to the Maxwell equations).

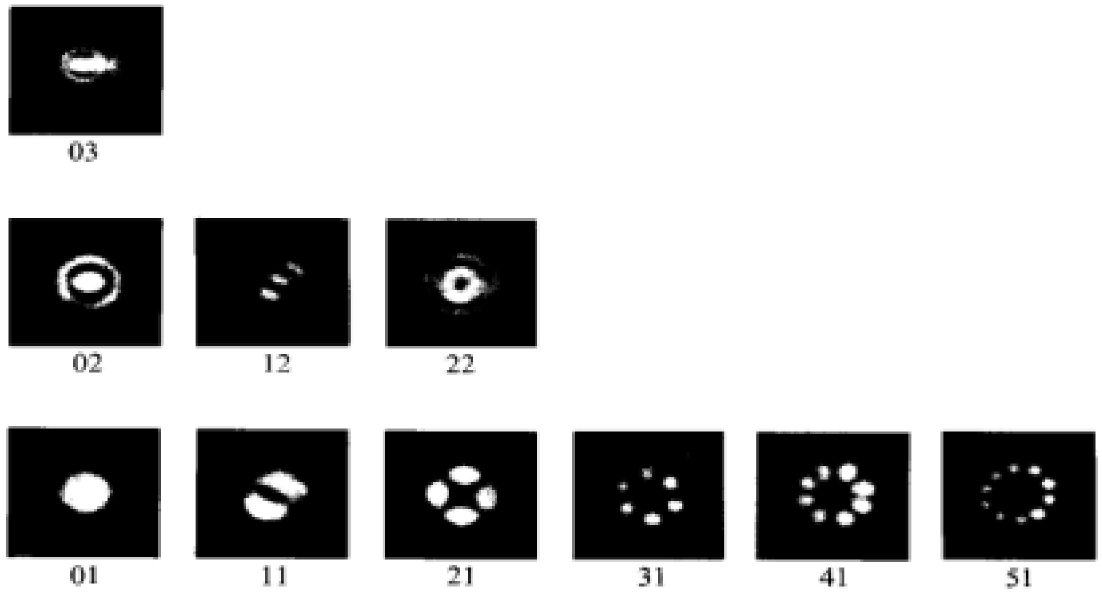
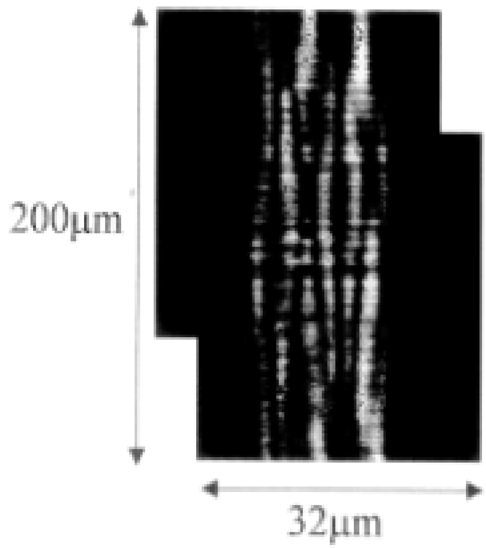


Bild 2.9 Die ersten zehn Moden $LP_{\nu\mu}$ eines Lichtwellenleiters
(Stolen, R. H.; Leibolt, W. N.: Optical fiber modes using stimulated four-photon mixing. Appl. Opt. 15 [1976] 239–243)

Modes seen in an other way (scanned from the side)



(I)

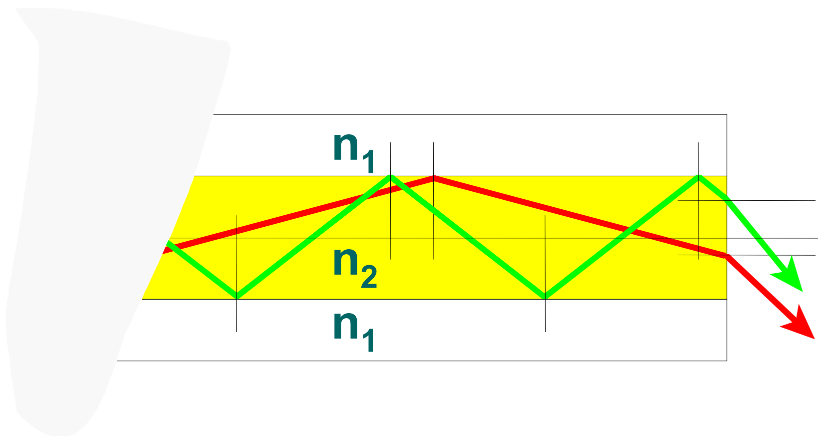
Results from a research in a Spanish university

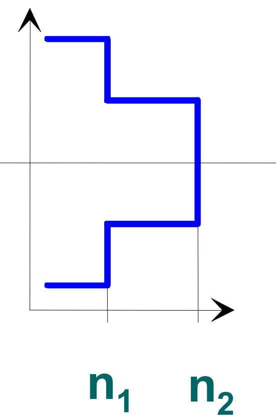
Fiber optic theory / fiber

Basically, we distinguish between two types of fiber:

- **Single-mode fiber**
  - Step index
- **Multimode fiber**
  - Step index
  - Graded index

Multimode fibers (Step index profile)





Refractive index profile
(Step index)

Number of modes $M = 0.5 \times (\pi \times d \times NA/\lambda)^2$

Remarks: ~ 680 Modes at NA = 0.2, d = 50 µm & λ = 850 nm
~ 292 Modes at NA = 0.2, d = 50 µm & λ = 1300 nm

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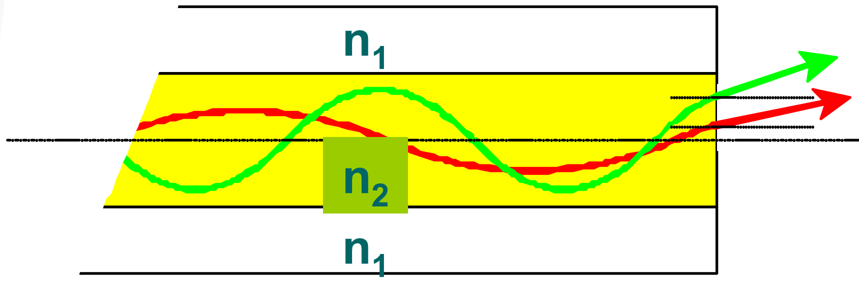
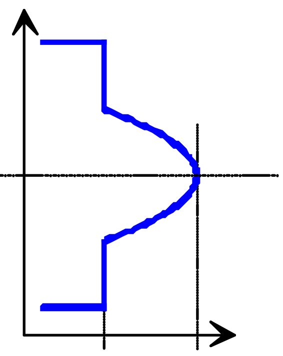
Multimode fibers (Graded index profile)





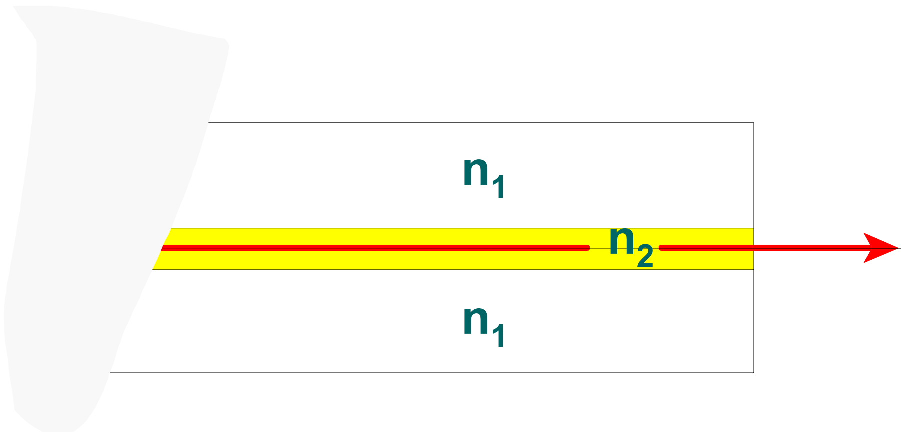
Number of modes M = 0.25x(πxdxNA/λ)²

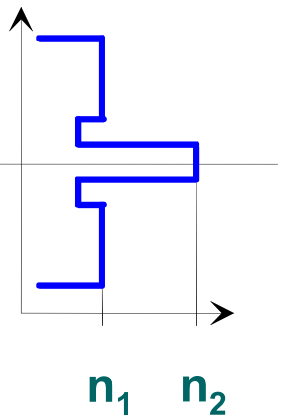
$$M = 0.25 \times (\pi \times d \times NA/\lambda)^2$$

Refractive index profile
(Graded Index)

Remarks: ~150 Modes at NA = 0.2, d = 50 µm & λ = 1300 nm

Single-mode fiber





Refractive index profile
(Step Index)

Example: n_1 =1.4570 and n_2 = 1.4625

Remarks: One mode (2 polarisations)

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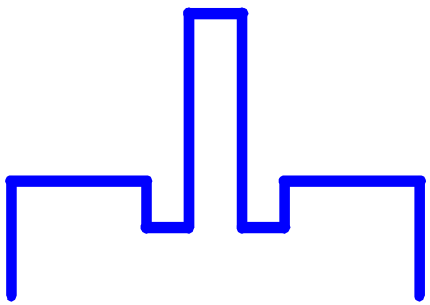
Types of refractive index profile

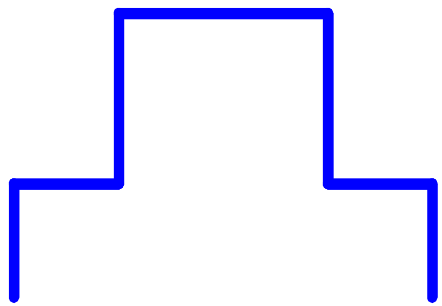
Step index



For singlemode transmission

Core size
~ 9/125 µm

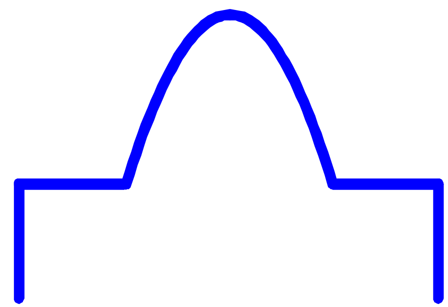
Step index



For multimode transmission

Core size
50/125 or 62.5/125 µm

Graded index



For multimode transmission

Core size
50/125 or 62.5/125 µm

Overview of the main of characteristics

	Term	Effect	Limitation
1	attenuation [dB/km]	Power loss along the of link	Transmission distance
2	Dispersion	Pulse broadening and signal weakening	Signal bandwidth & transmission distance
3	Numerical Aperture (NA) [-]	Coupling loss LED/Laser ➔ fiber fiber ➔ fiber fiber ➔ e.g. APD*	Coupling capacitance

* Avalanche photodiode

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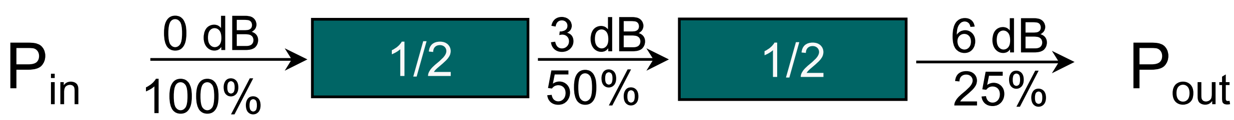
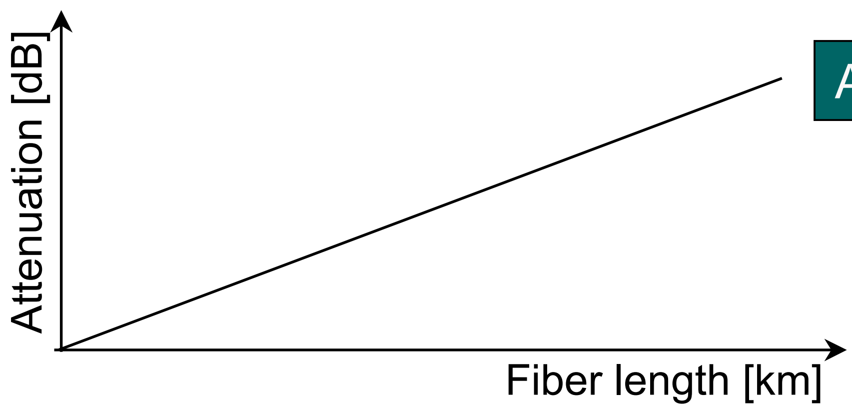
Attenuation

In fiber optics losses occur in dependence of fiber length and wave length. They are called attenuation.

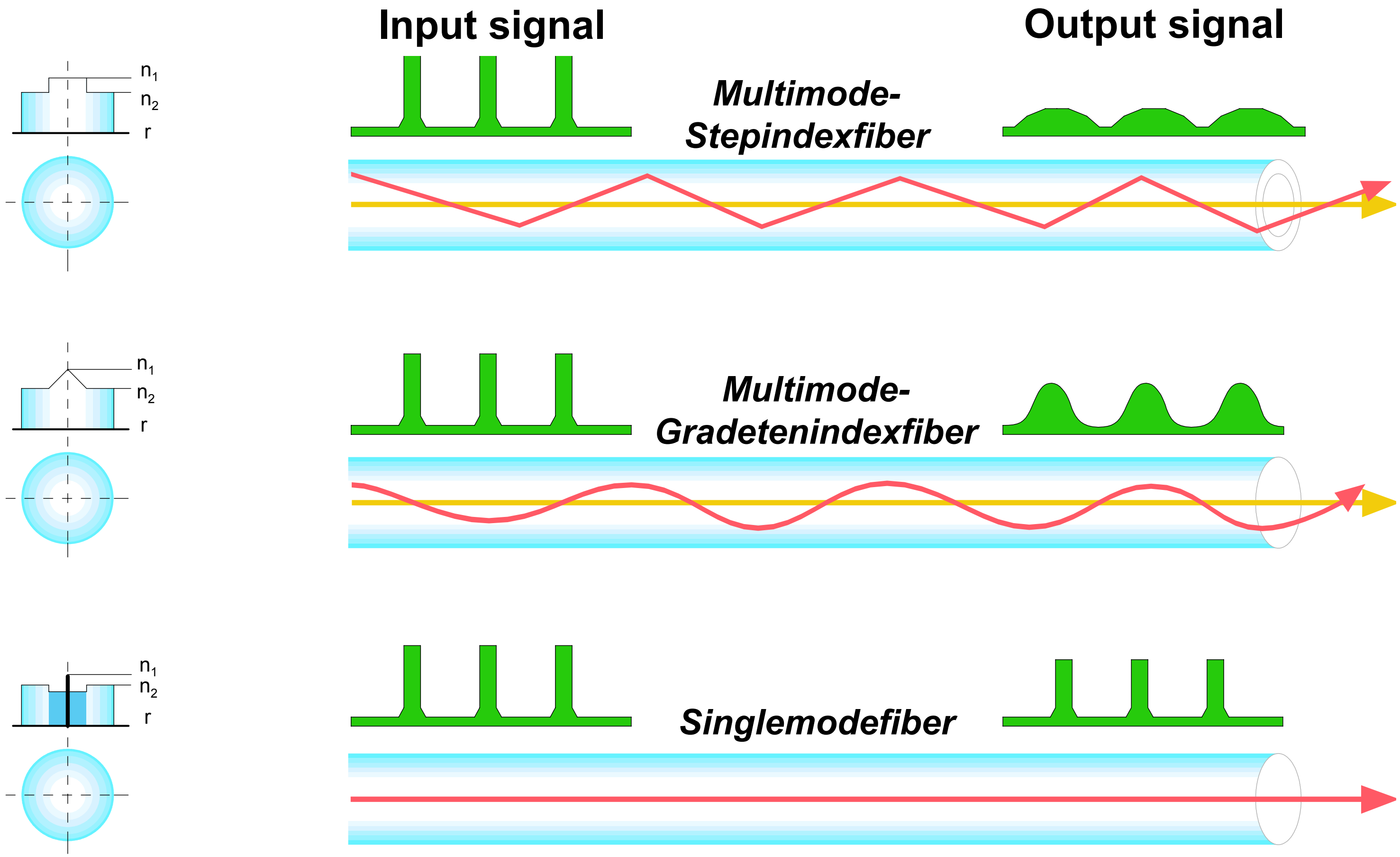
The attenuation is length dependent:



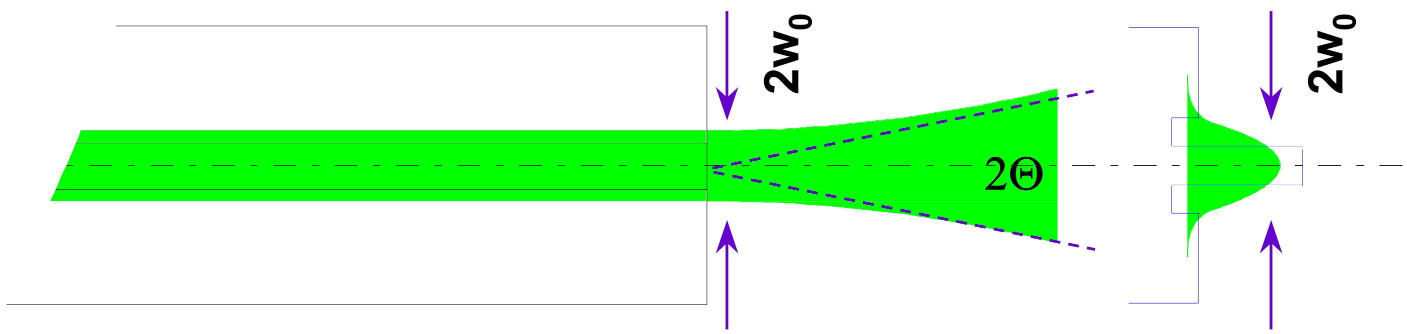


$$A = 10 \times \log (P_{in} / P_{out})$$

Attenuation



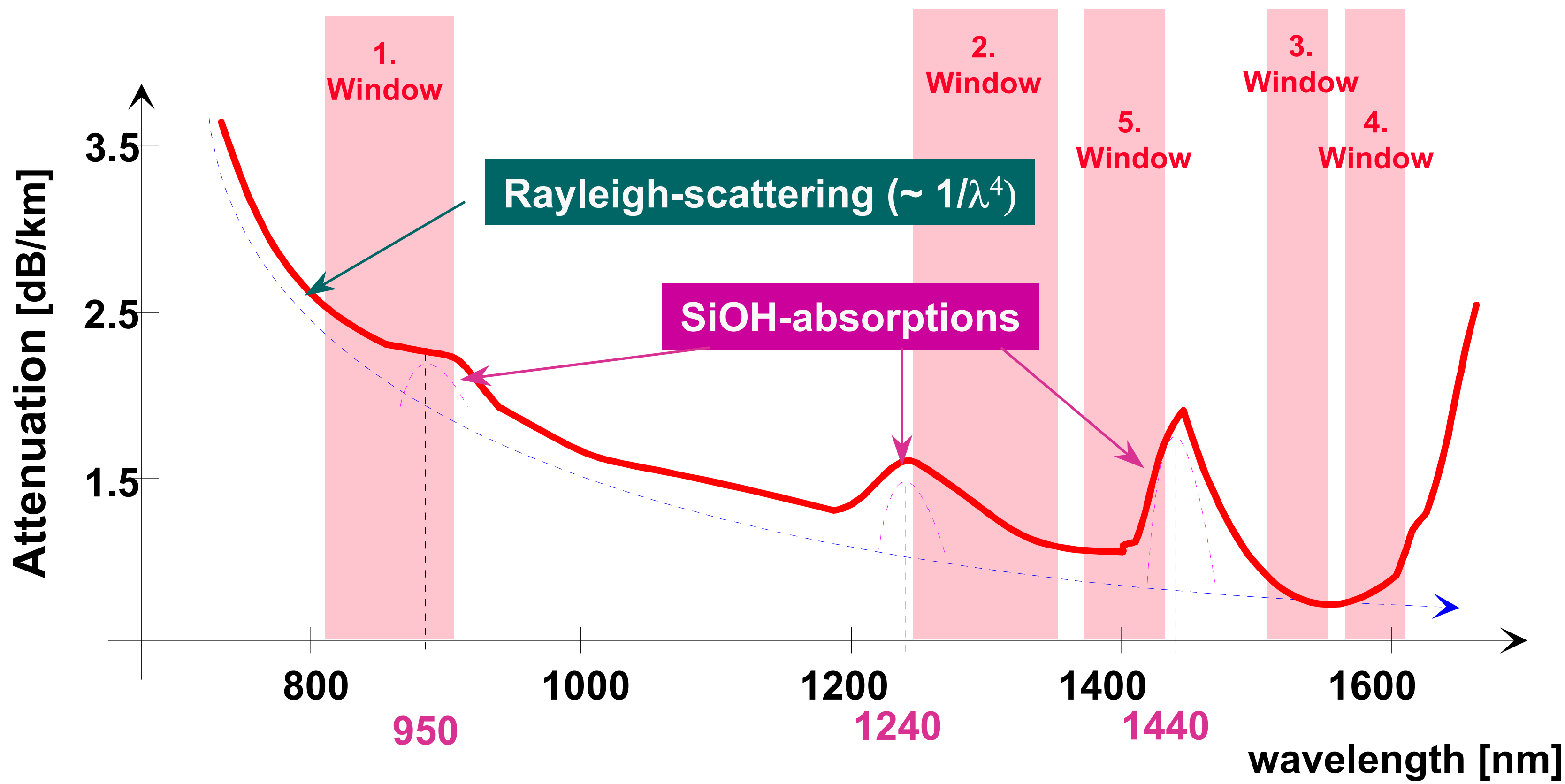
Singlemode propagation



Example: NA = 0.17 and Θ = 9.8°
Definition in SM: cut-off wavelength

Numerical Aperture:
NA = $\sin \Theta = (n_2^2 - n_1^2)^{0.5} = \lambda / \pi w_0$

The attenuation spectrum of a multimode fiber



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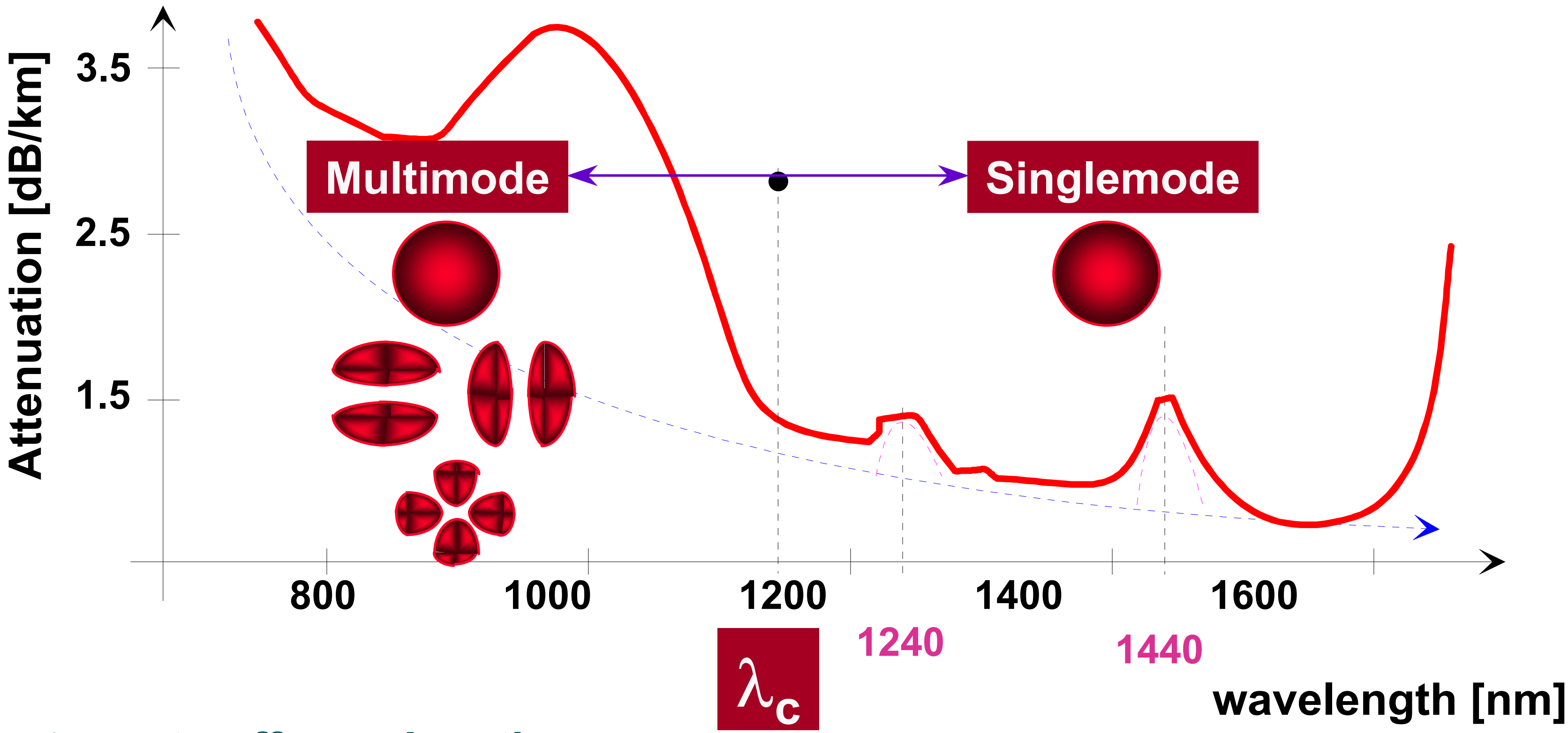
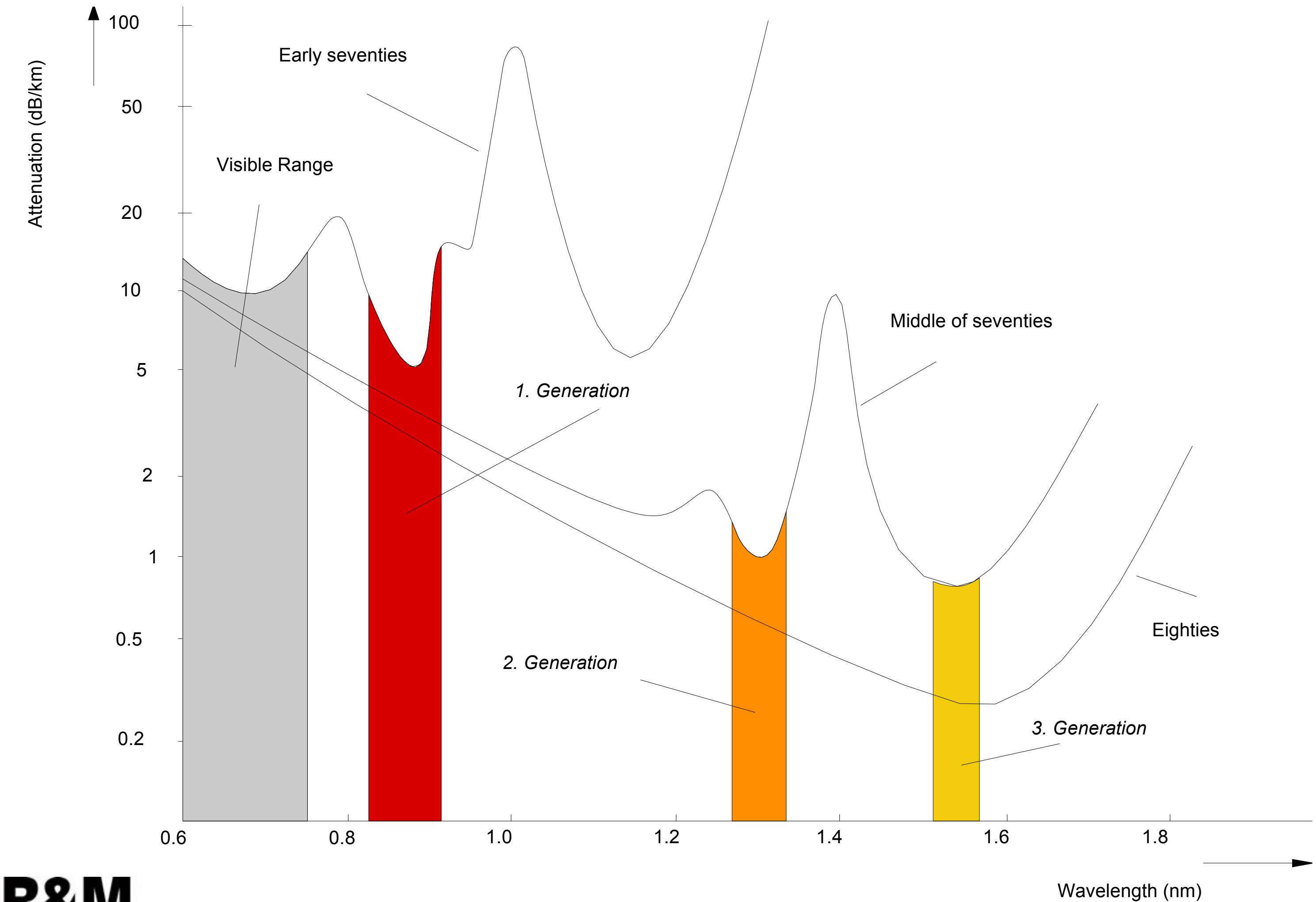
Attenuation spectrum of a single-mode fiber



λ_c: cut - off wavelength

Changes of attenuation during the last years



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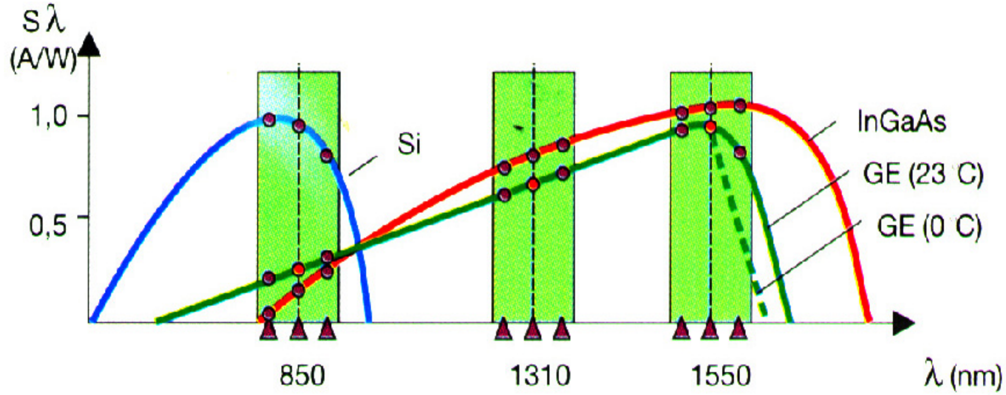
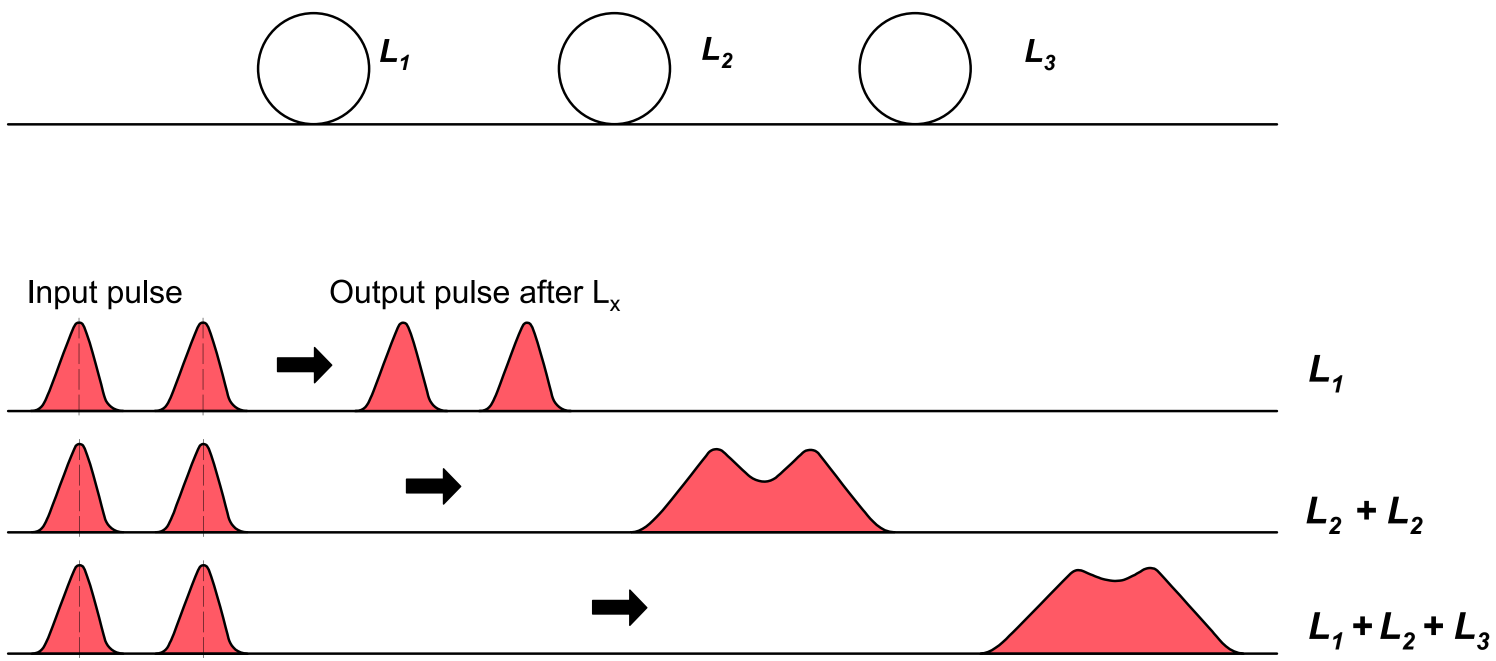
Spectral sensitivity of detectors



Als Meßwandler dienen Photodioden. Sie zeigen je nach Halbleitertyp einen spezifischen Spektralverlauf. Silizium (Si) ist nur im ersten optischen Fenster nutzbar. Dagegen können Germanium (Ge) und Indium-Gallium-Arsenid (InGaAs) auch breitbandig im zweiten und dritten Fenster eingesetzt werden, wo sie ihre max. Empfindlichkeit erreichen. Die als preiswerte Variante in allen drei Fenstern verwendete Ge-Diode weist die größte Temperaturabhängigkeit auf. Wichtig für präzise Meßergebnisse ist die Wahl der richtigen Wellenlänge und ein genügend großer Dynamik-Bereich bei Pegelsender und -empfänger.

Dispersion

By dispersion we understand the pulse broadening of a narrow input pulse which is broadened along the length of an optical fiber.



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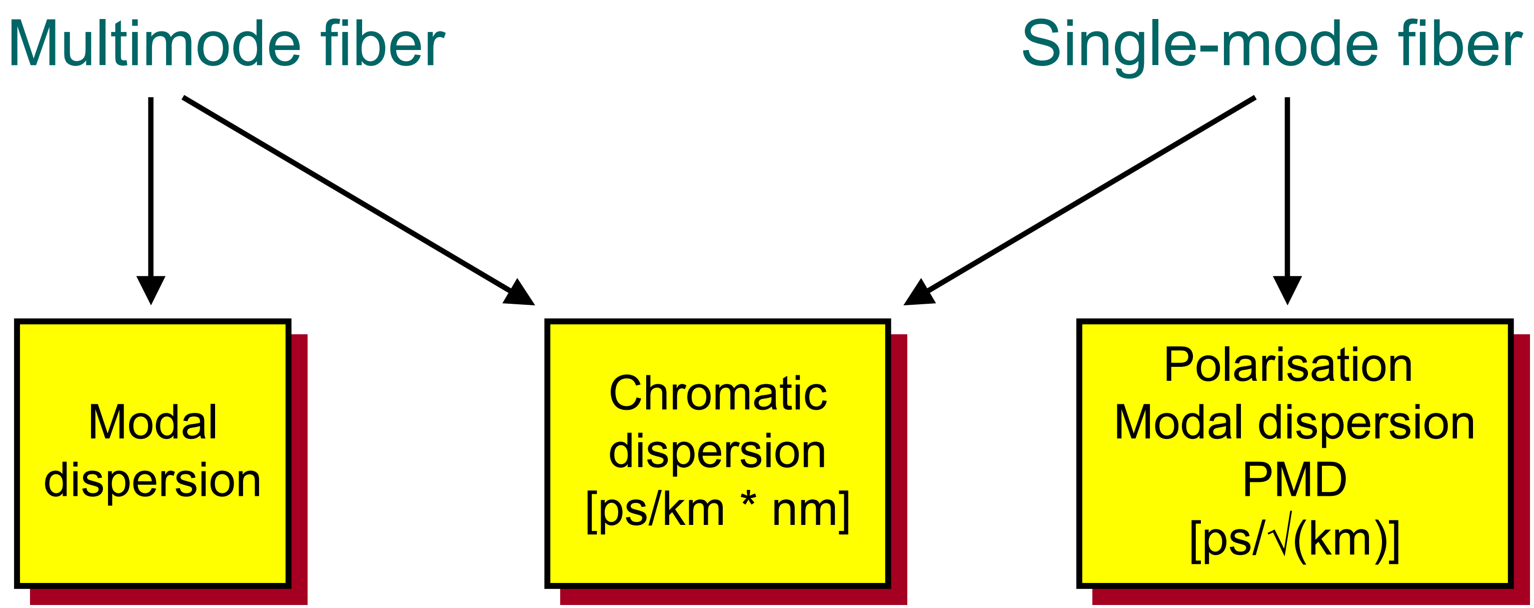
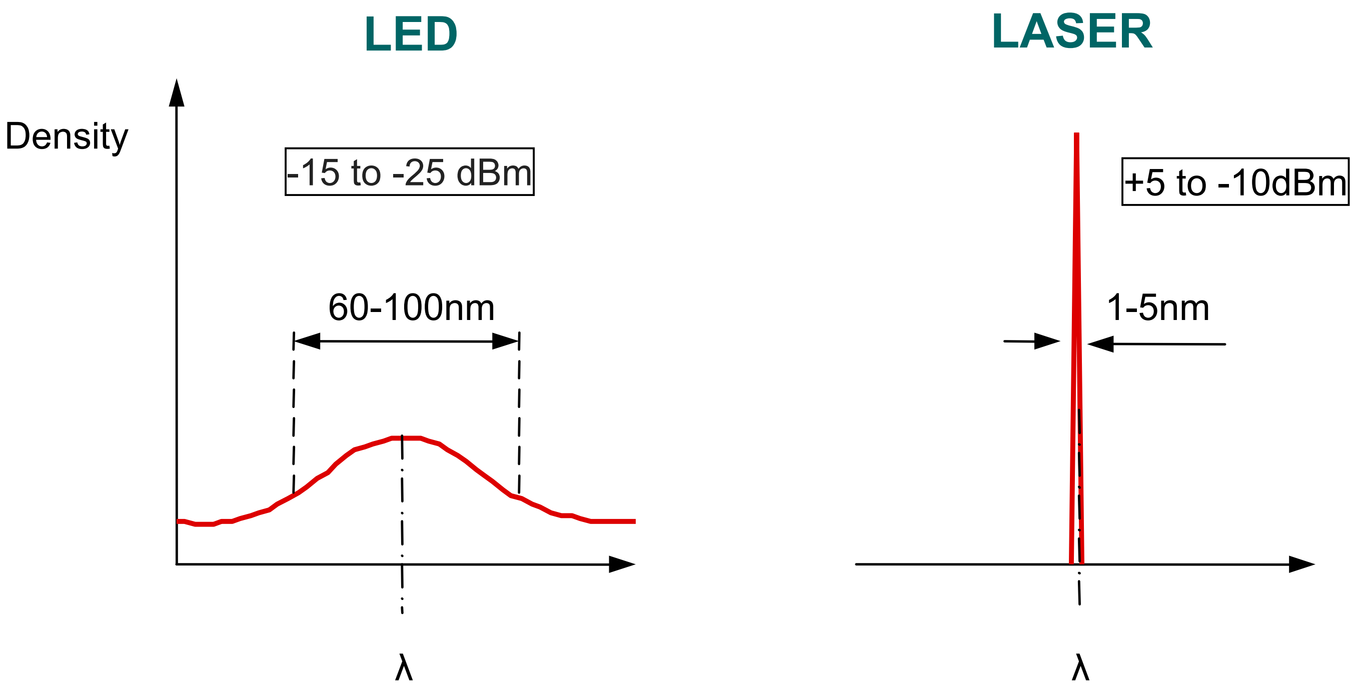
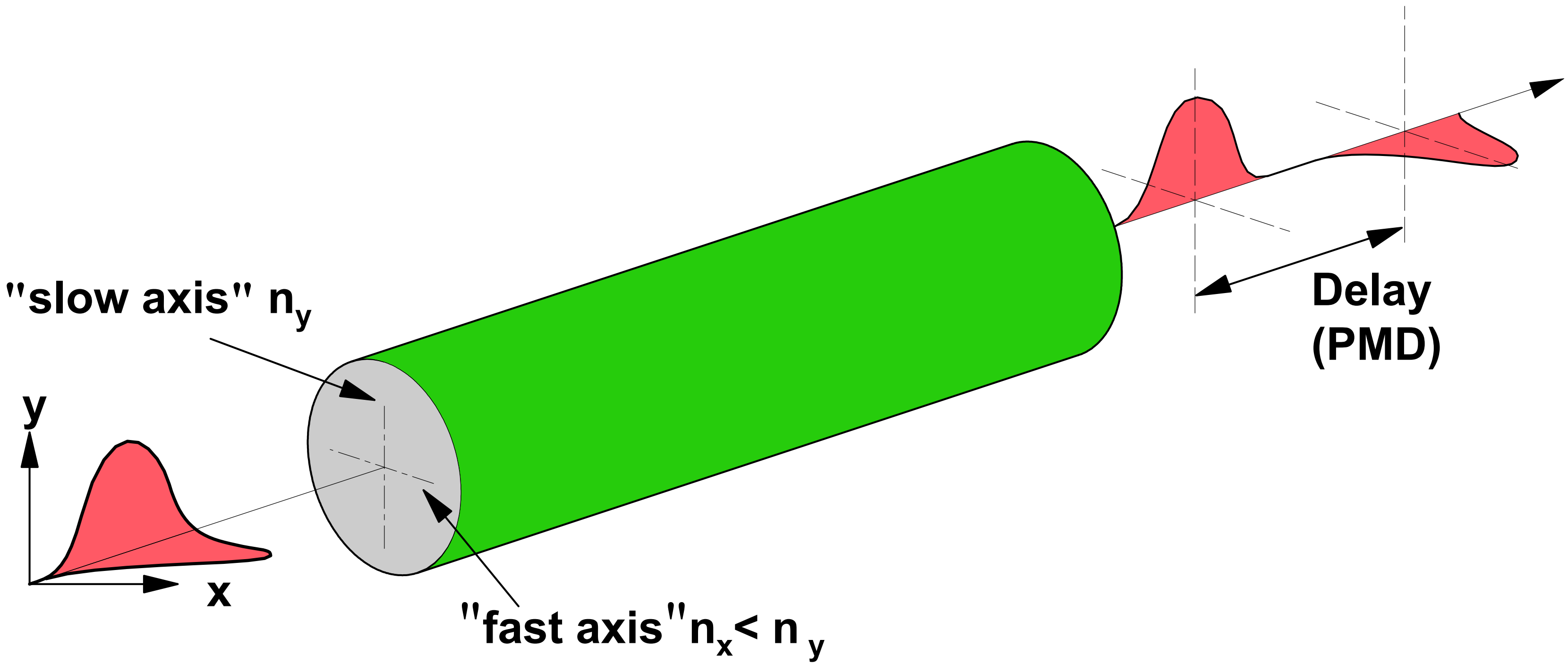
Dispersion types



Power spectrum of a LASER or LED source

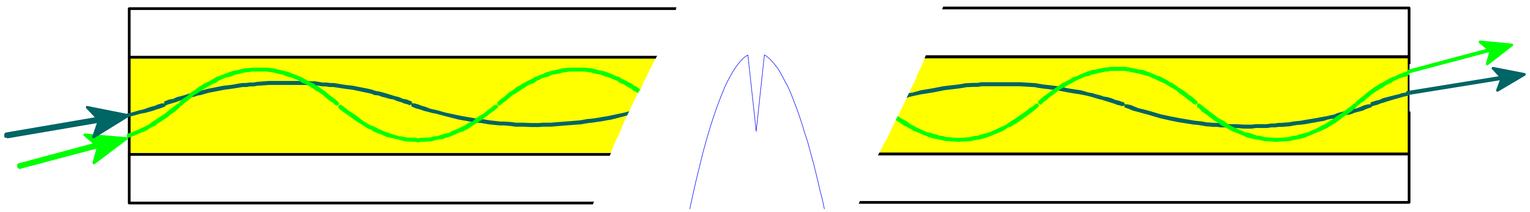


PMD of a single mode fiber

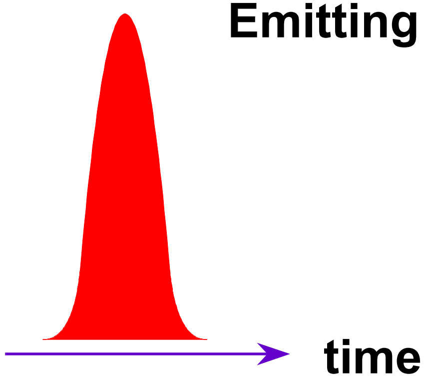


Modal dispersion of a multimode fiber

Step or graded index profile

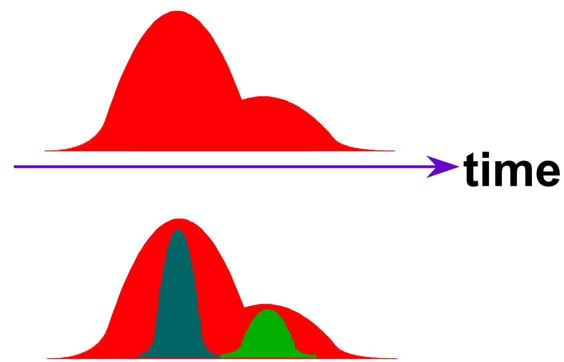


Emitting pulse



Pulse distortion due to Refractive index deformation

Receiving pulse



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What we have learned about fo characteristics

	Term	Effect	Limitation
1	Attenuation	Power loss along the fo link	Transmission Distance
2	Dispersion	Pulse broadening and signal weakening	Signal bandwidth ↳ transmission distance
3	Numerical aperture	Coupling loss LED/Laser ➔ fiber fiber ➔ fiber fiber ➔ e.g. APD*	Coupling capacitance

* Avalanche Photodiode

Launch conditions

There are 2 ways to send light on a MM fiber (called launch conditions).

- **Overfilled launch**
  - The core of the fiber is completely illuminated (=> all theoretically possible modes are stimulated).
  - Typically by means of LED.
  - Present bandwidth details usually base on a measurement by means of a overfilled launch.
- **Restricted launch (e.g. with Gigabit Ethernet)**
  - The core of the fiber is not completely illuminated (=> not all the theoretically possible modes are stimulated).
  - Typically by means of VCSE or laser.
  - Usually, bandwidths are larger with the restricted launch in comparison with the overfilled launch.

Laser safety

- Depending on the power and the distance to the place of exit, laser radiation can cause eye damages (here: retina) as well as skin damage.

- There are different danger potentials with a laser. They are described in IEC / EN 60825.
  - Classes 1, 2, 3A, 3B and class 4.
  - The higher the class the greater the danger potential

- In addition to the international standards there are also national laws, regulations and guidelines to be observed, as well as the safety regulations of the manufacturer, and the instructions of the laser safety agent.

Any questions?

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