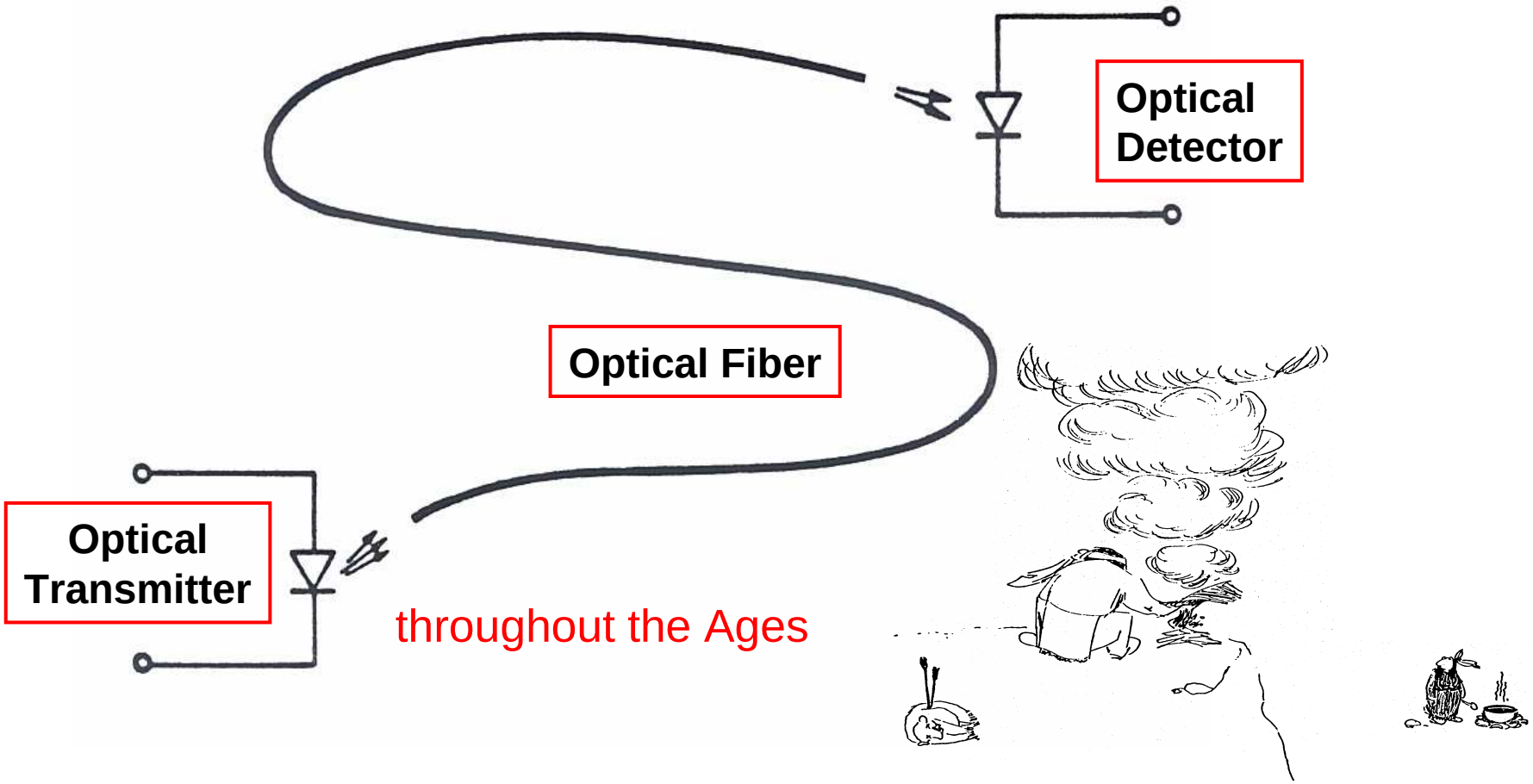
Optical-Polymer and Polymer-Clad-Silica-Fiber Data Buses for Vehicles and Airplanes

Principles, Limits and New Trends

Otto Strobel, Daniel Seibl, Jan Lubkoll, Uwe Strauß

Optical Transmission



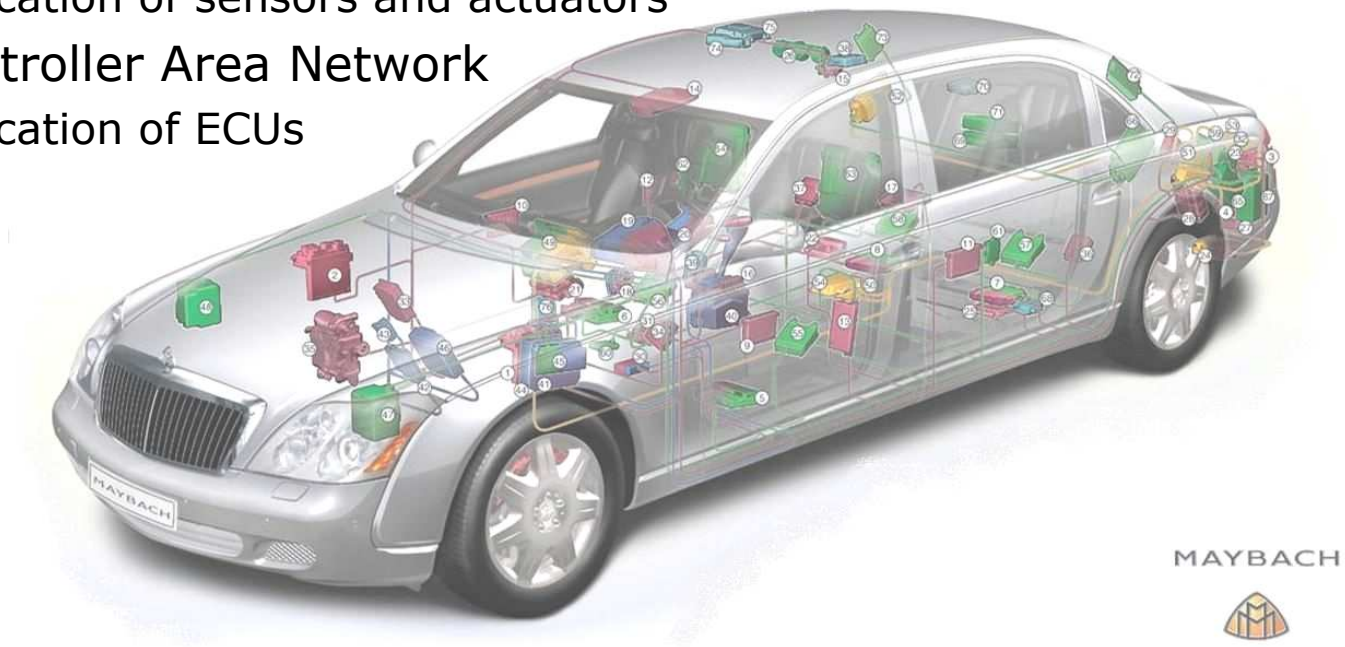
Contents

- Introduction to Automotive Systems
  - MOST: Media Oriented Systems Transport
- Principle Considerations
  - Components for fiber-optic systems
    - o System-relevant characteristics of fibers, transmitters and detectors and their limitations
- Future technologies for Automotive Systems
  - Alternative components to overcome conventional limitations
  - High speed optical data buses for automotive applications
  - Limits and future applications of high-speed automotive data buses in vehicles and airplanes

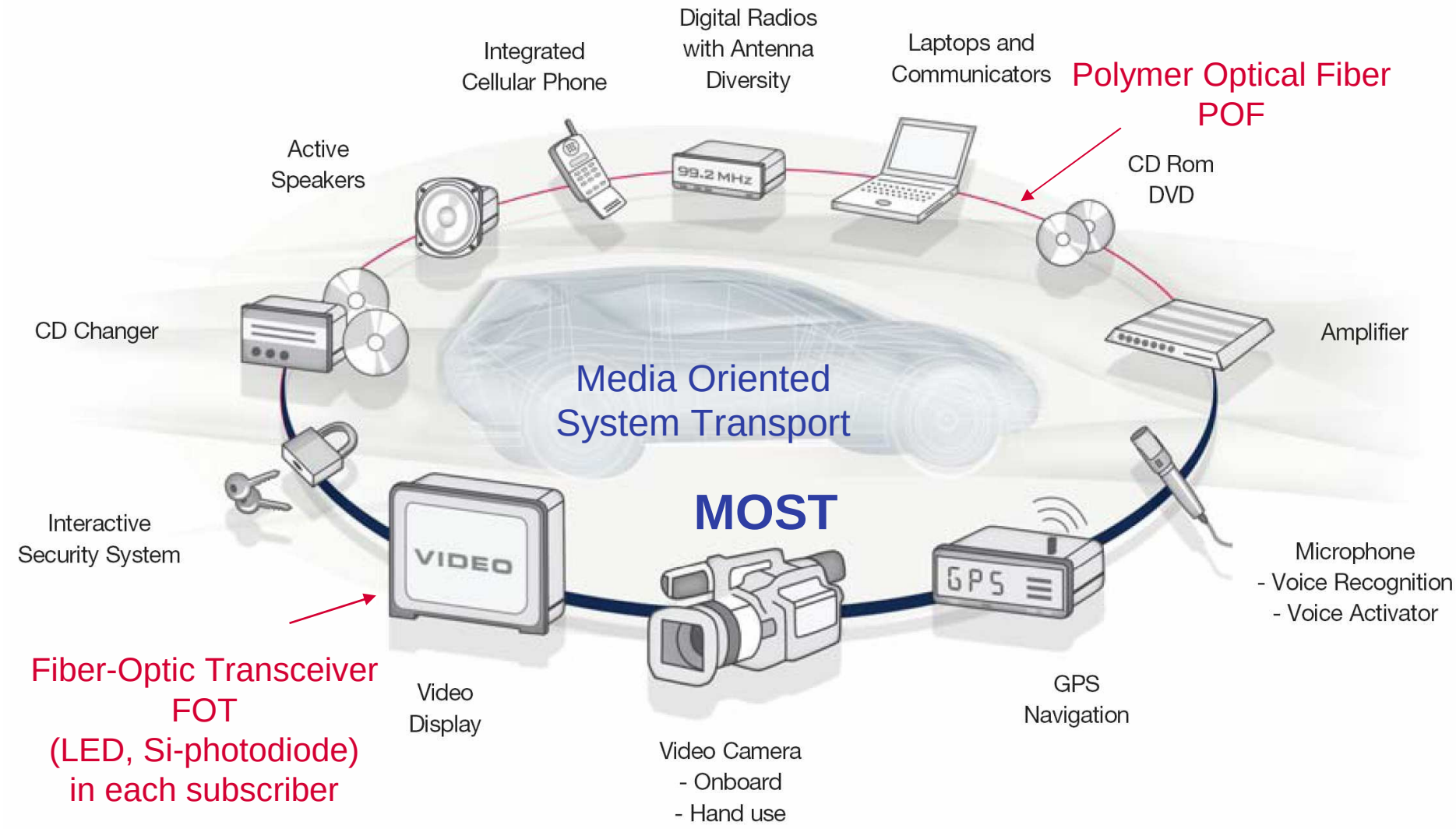
Different Data Bus Technologies in Vehicles

MOST – Media Oriented Systems Transport

- MOST: Media Oriented Systems Transport
  Network for Multimedia Data
- LIN: Local Interconnect Network
  Communication of sensors and actuators
- CAN: Controller Area Network
  Communication of ECUs

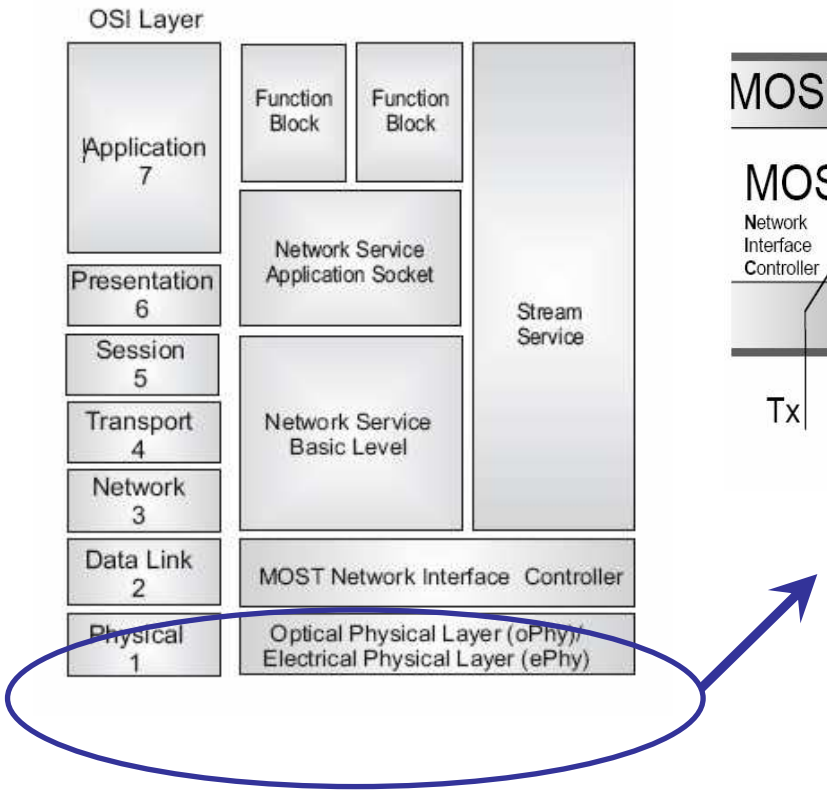


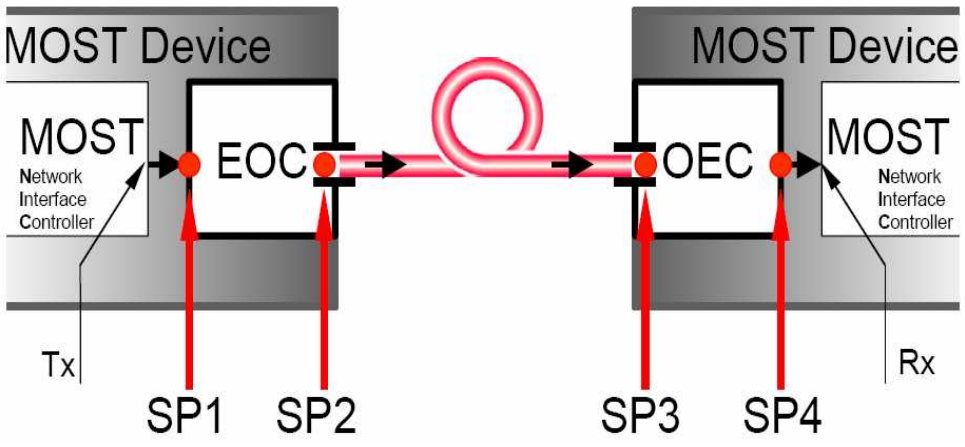
Optical Data Bus Technologies for Automotive Applications



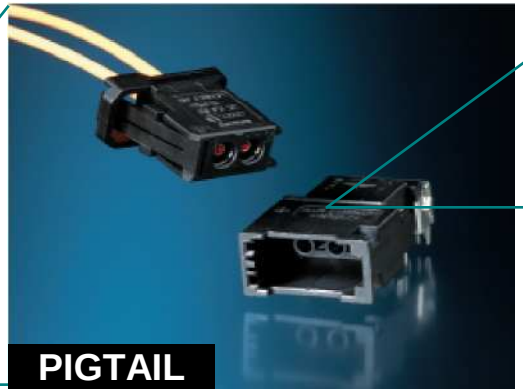
Media Oriented Systems Transport

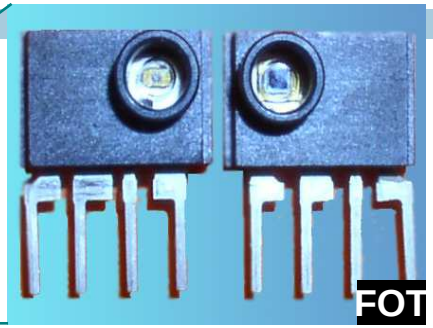
- Standards based upon the ISO-OSI layer model





MOST Physical Layer Components





Device

Pigtail is integrated in ECU

Function:
MOST Device e.g.:
CD-Player, Amplifier

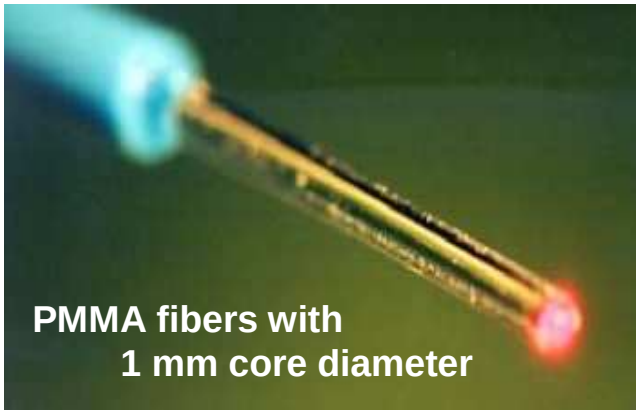
Connector

FOT is integrated

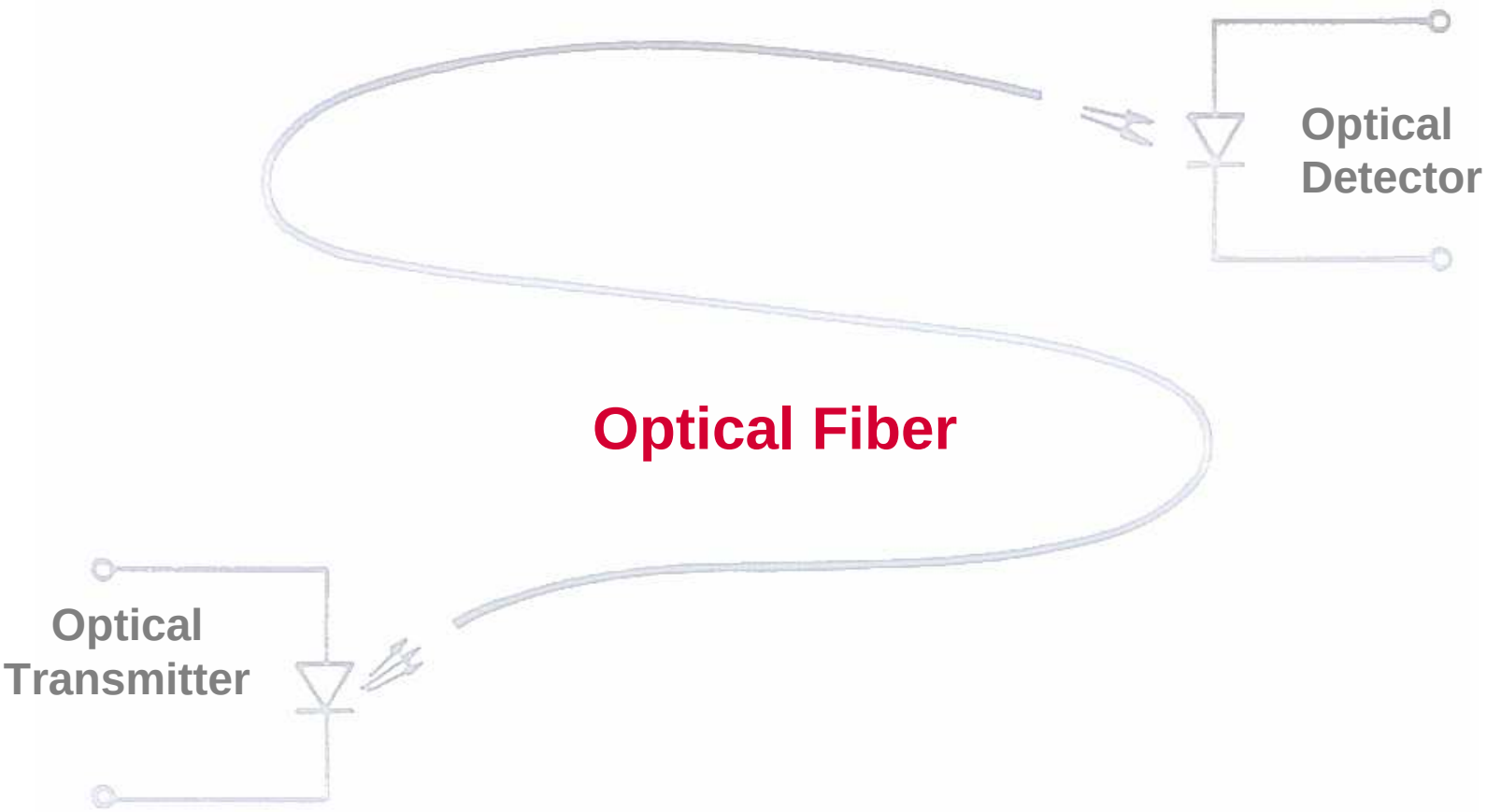
Function:
Represents the interface to the fiber

Component

Consists of two devices:
Fiber optical
Transmitter & Receiver



Principle Considerations



Advantages of Fiber-Optic Systems

- **Low attenuation**
- **High bandwidth**
- **Low weight and small size**
- **Non-sensitivity against electromagnetic interference**
- **Electrical isolation**
- **Low crosstalk**

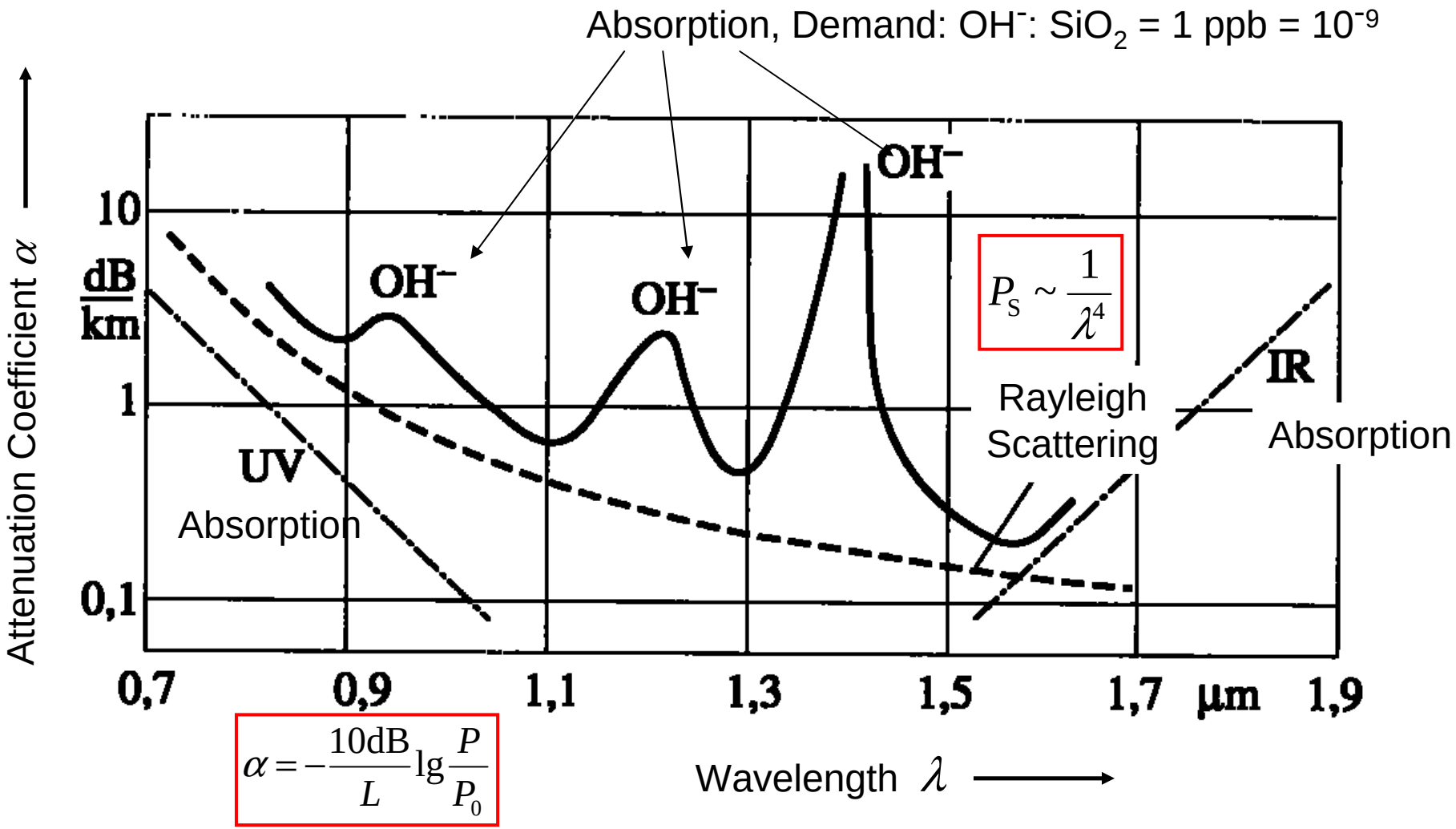
Transmission capacity = Bandwidth-length product:

$$B \cdot L = Max!$$

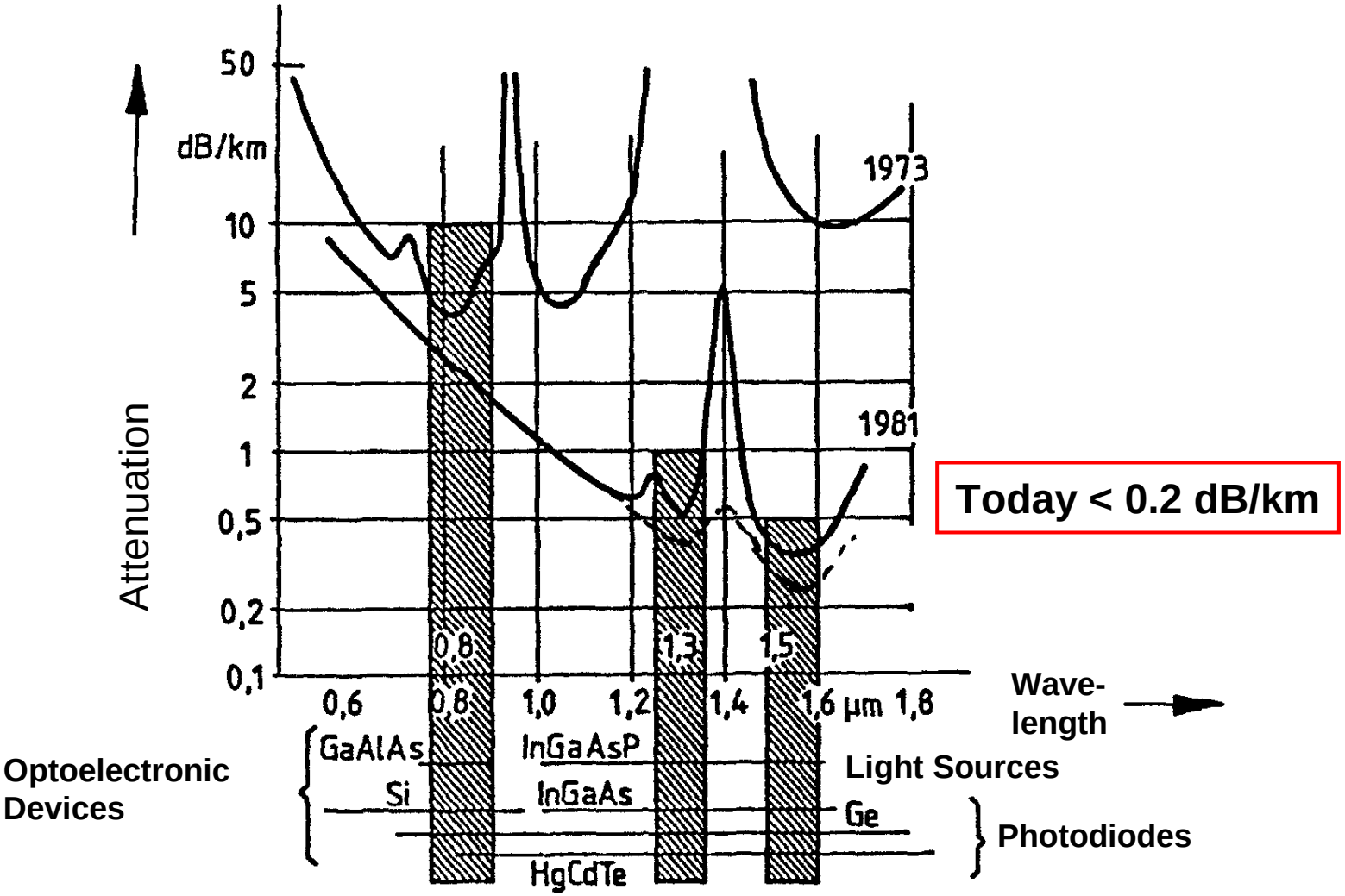
Demands on Optical Fibers

- **Proper Waveguiding**
- **Low loss of optical power**
- **Low dispersion of optical signals**
- **Large temperature range operation**
- **Non-sensitivity against distortions**

Attenuation Coefficient Versus Wavelength of Glass Fibers

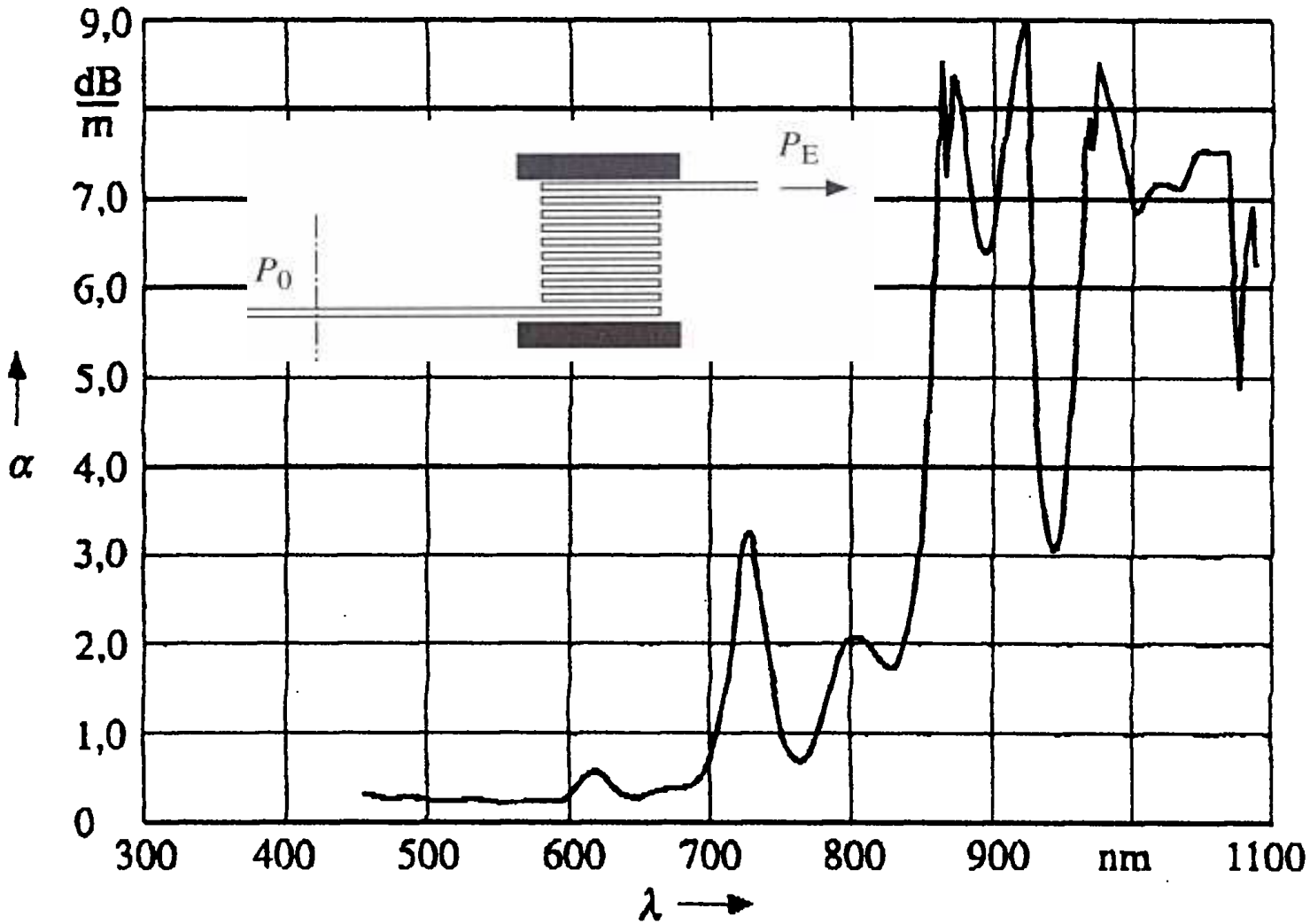


Spectral Attenuation of Glassfibers and Optoelectronic Devices

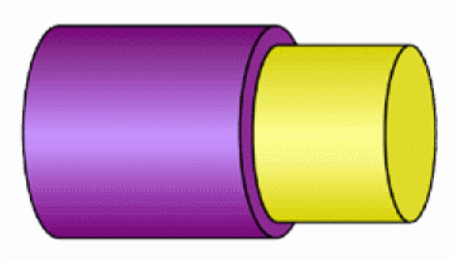


Today < 0.2 dB/km

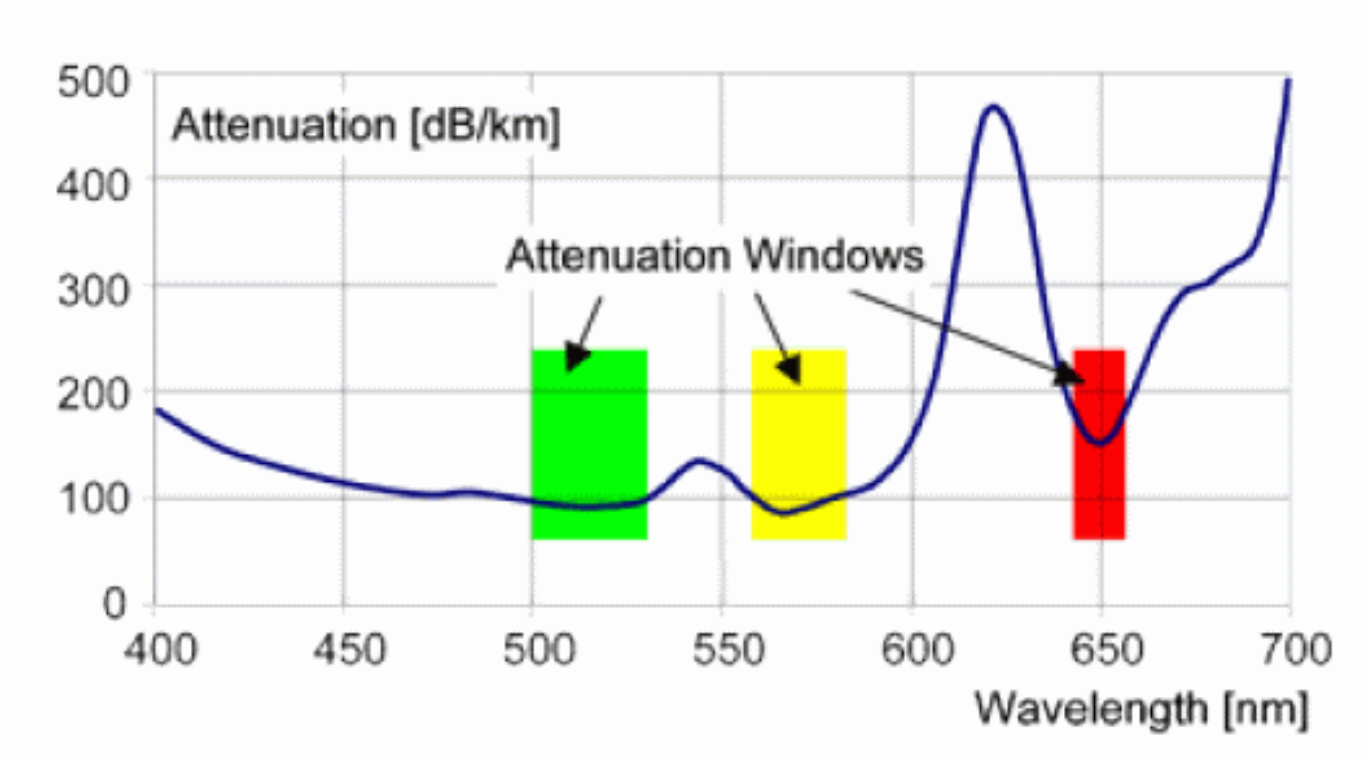
Attenuation Coefficient of a PMMA Fiber



Polymer Optical Fiber (PMMA)

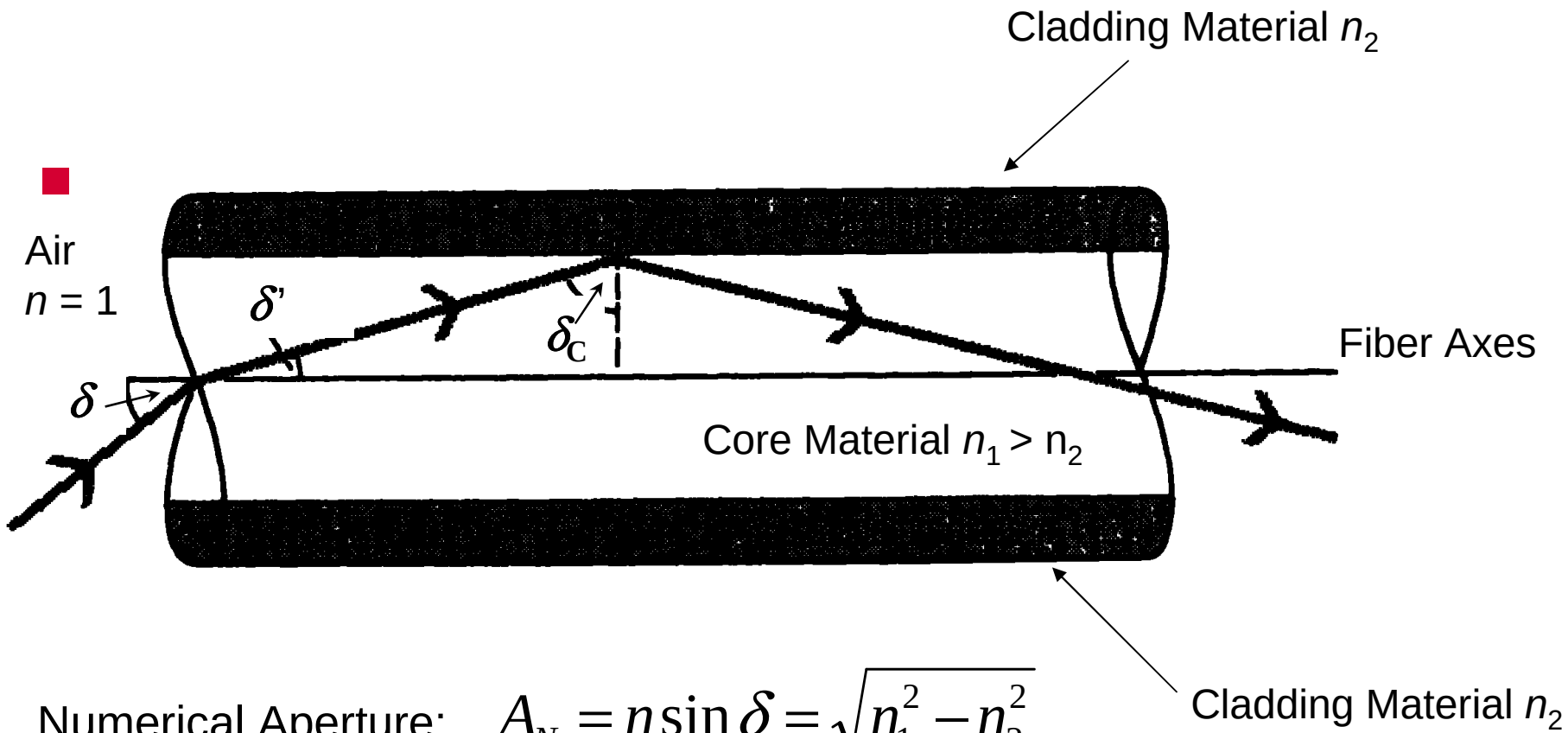


PMMA core
∅ typical 1 mm
n = 1,492



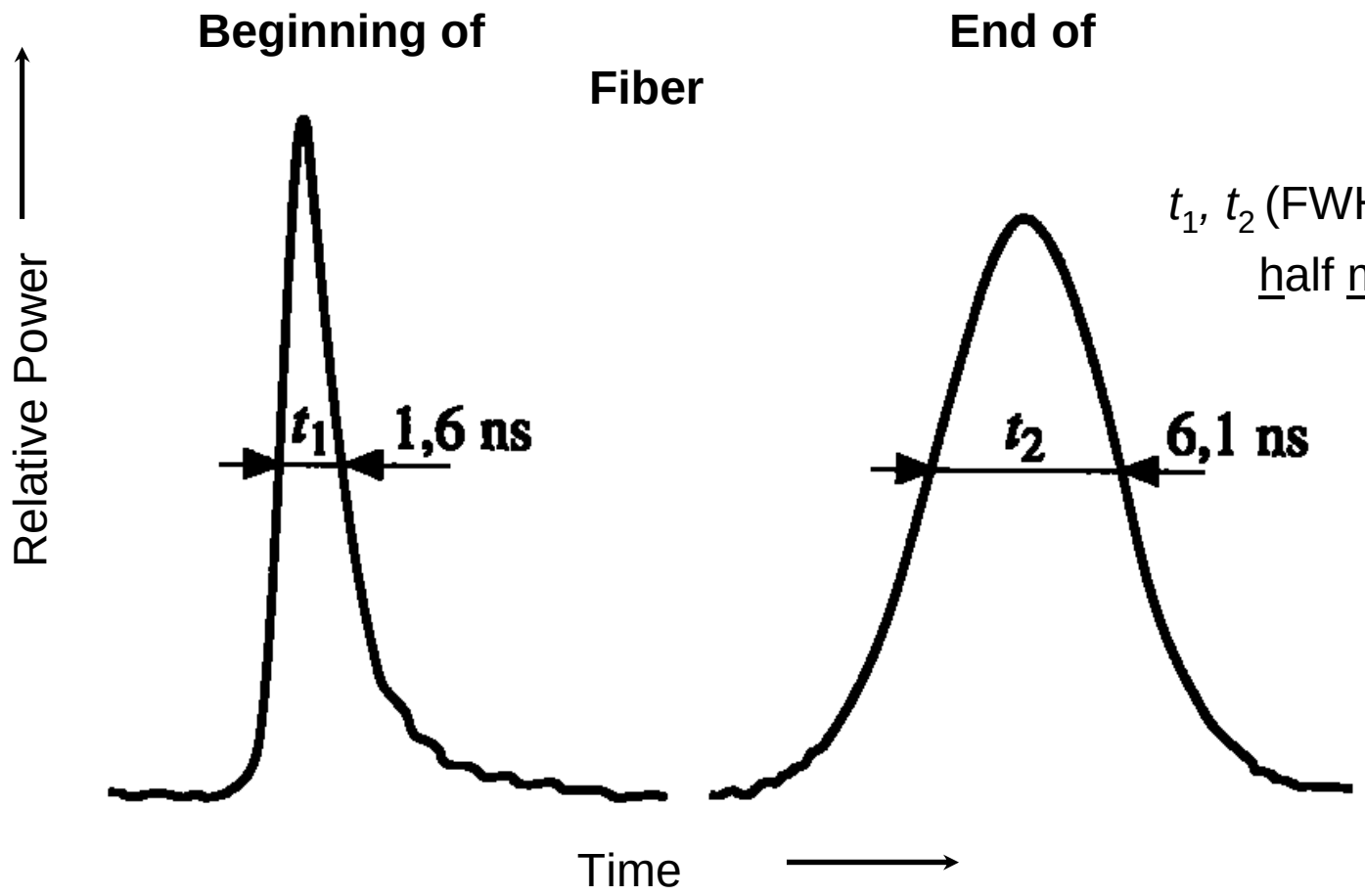
- Low price
- Robustness
- Simple connector fitting
- Attenuation between 0.2 and 0.4 dB/m for red LEDs
  - Depends on the changing wavelength of the LED between -40°C and +85°C operating temperature

Light Guidance in an Optical Waveguide



Numerical Aperture: $A_N = n \sin\delta = \sqrt{n_1^2 - n_2^2}$

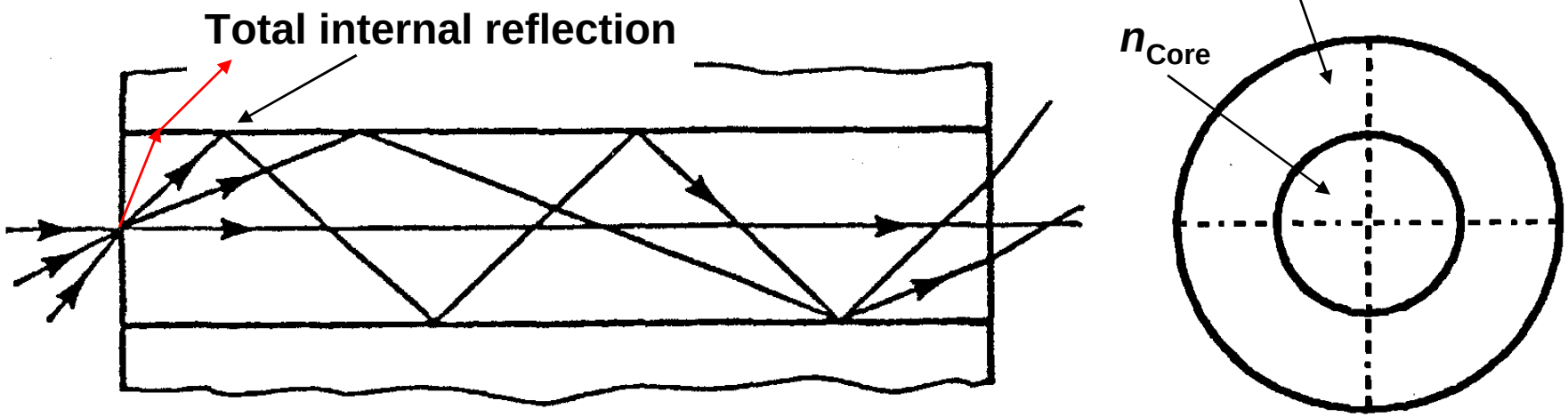
Transmitter and Receiver Pulse



t_1, t_2 (FWHM, full width at half maximum).

Mode Dispersion of Optical Fibers

Different transit times of optical pulses for different modes

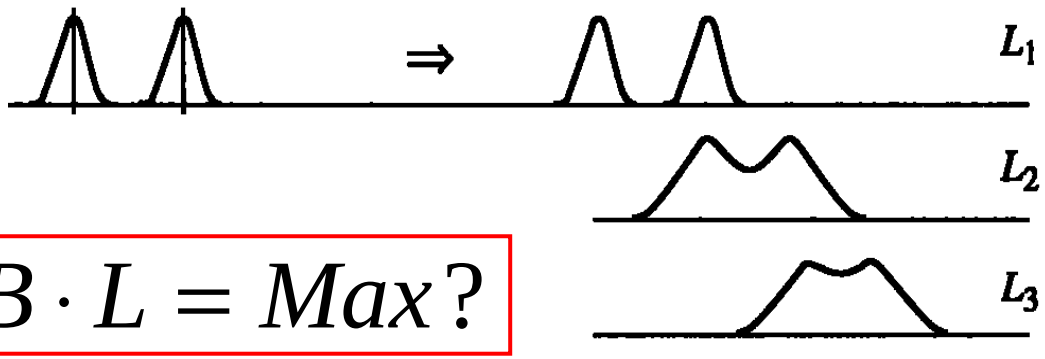


Pulsebroadening

Pulse Development in an Optical Fiber

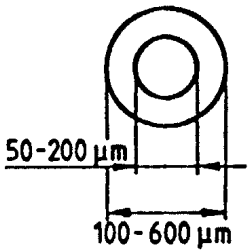
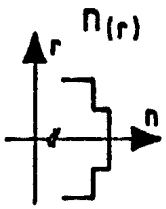
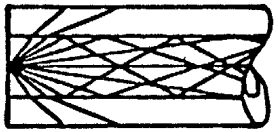
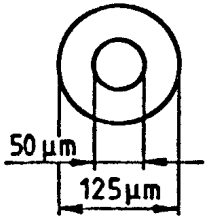
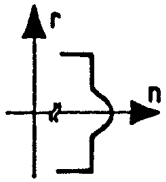
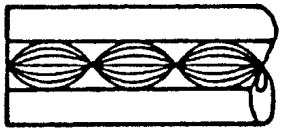
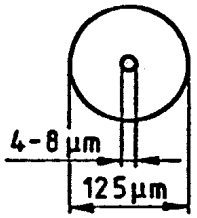
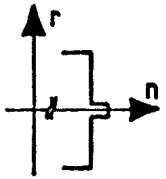
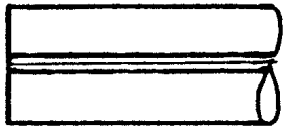
Input pulses

Output pulses after length L_i



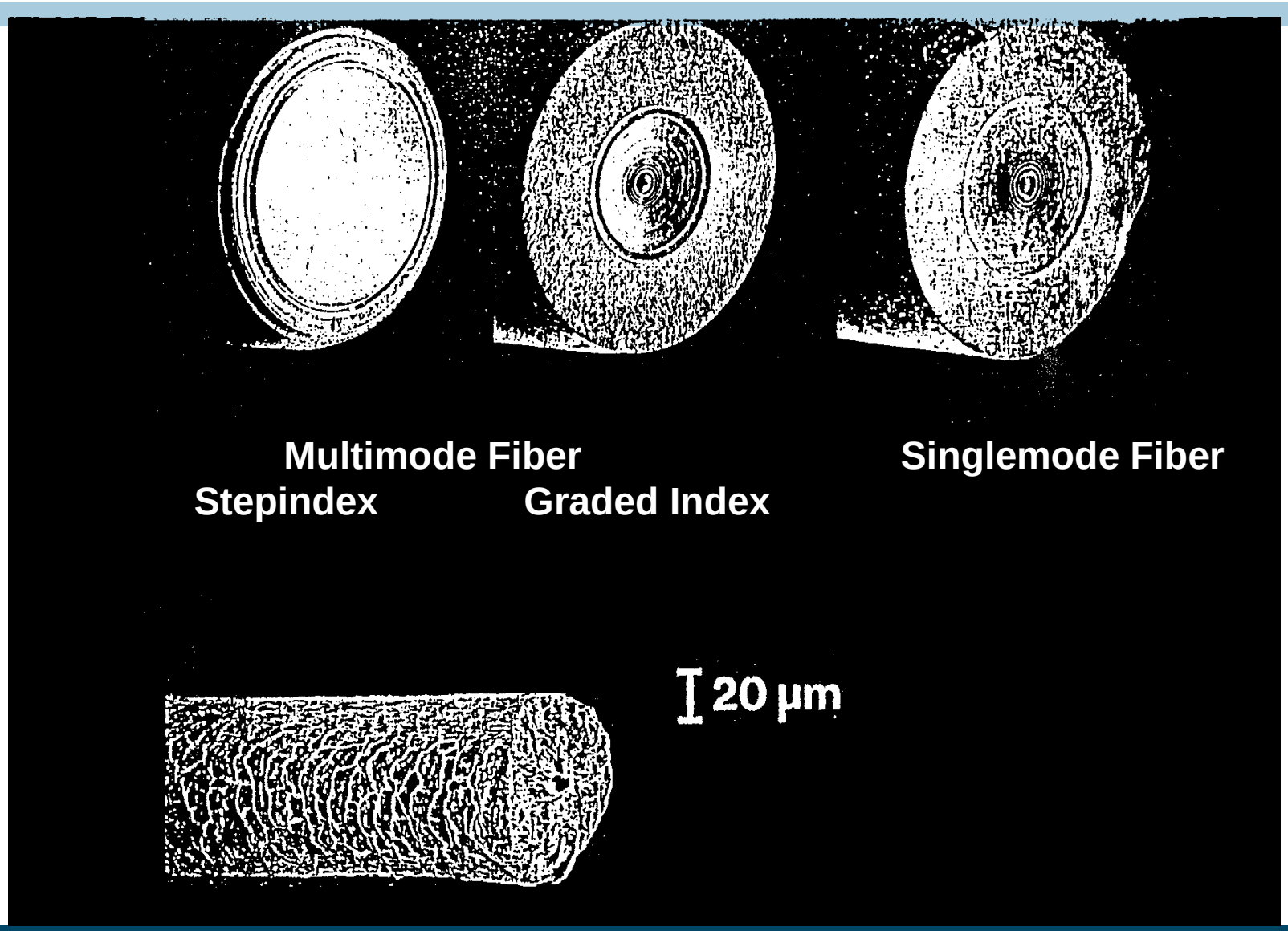
$$B \cdot L = Max?$$

Fiber Types

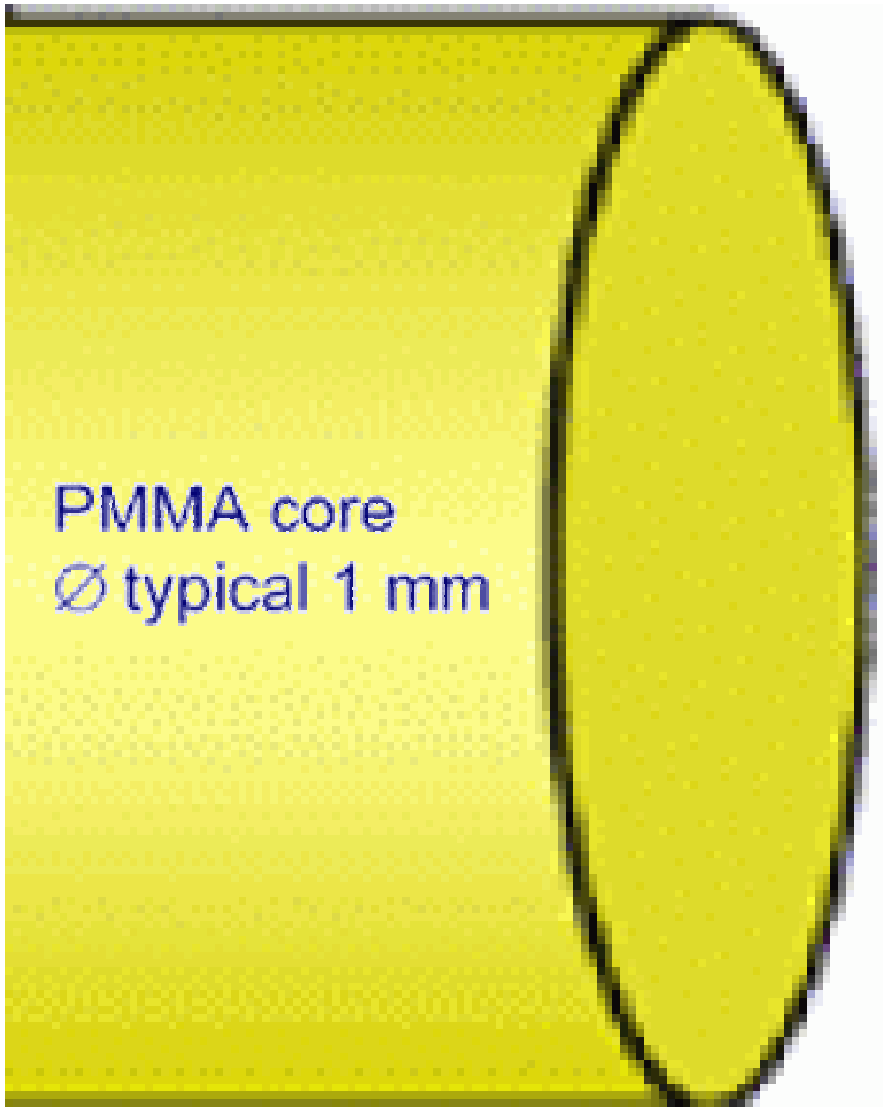
Cross Section	Refraction Index	Propagation of Light	
		 $g \neq \text{const}$	**Multimode Stepindex Fiber**
		 $g \approx \text{const}$	**Multimode Graded Index Fiber**
			**Monomode Fiber**

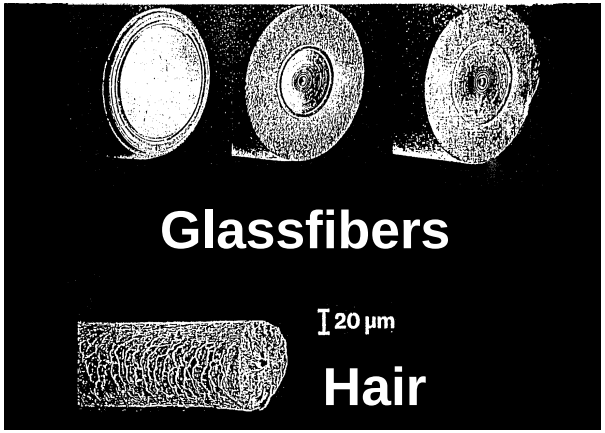
Optical Path Length: $g = n \cdot L$

Typical Communication Glassfibers and Woman Hair



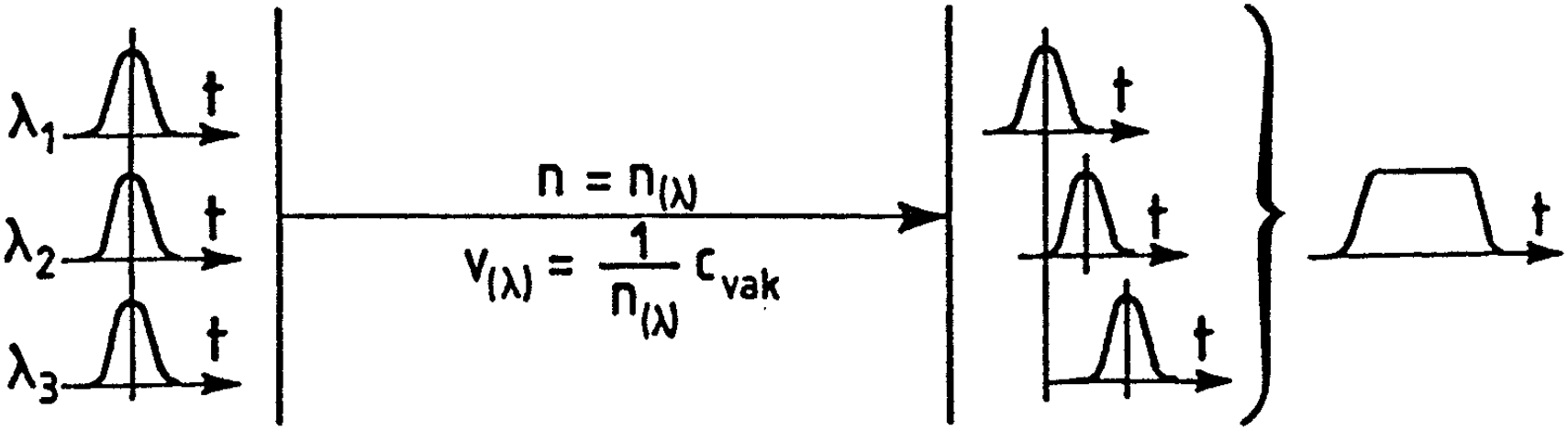
Polymer- and Glassfibers





Material Dispersion

Different Transit Times of Optical Pulses for different Wavelengths



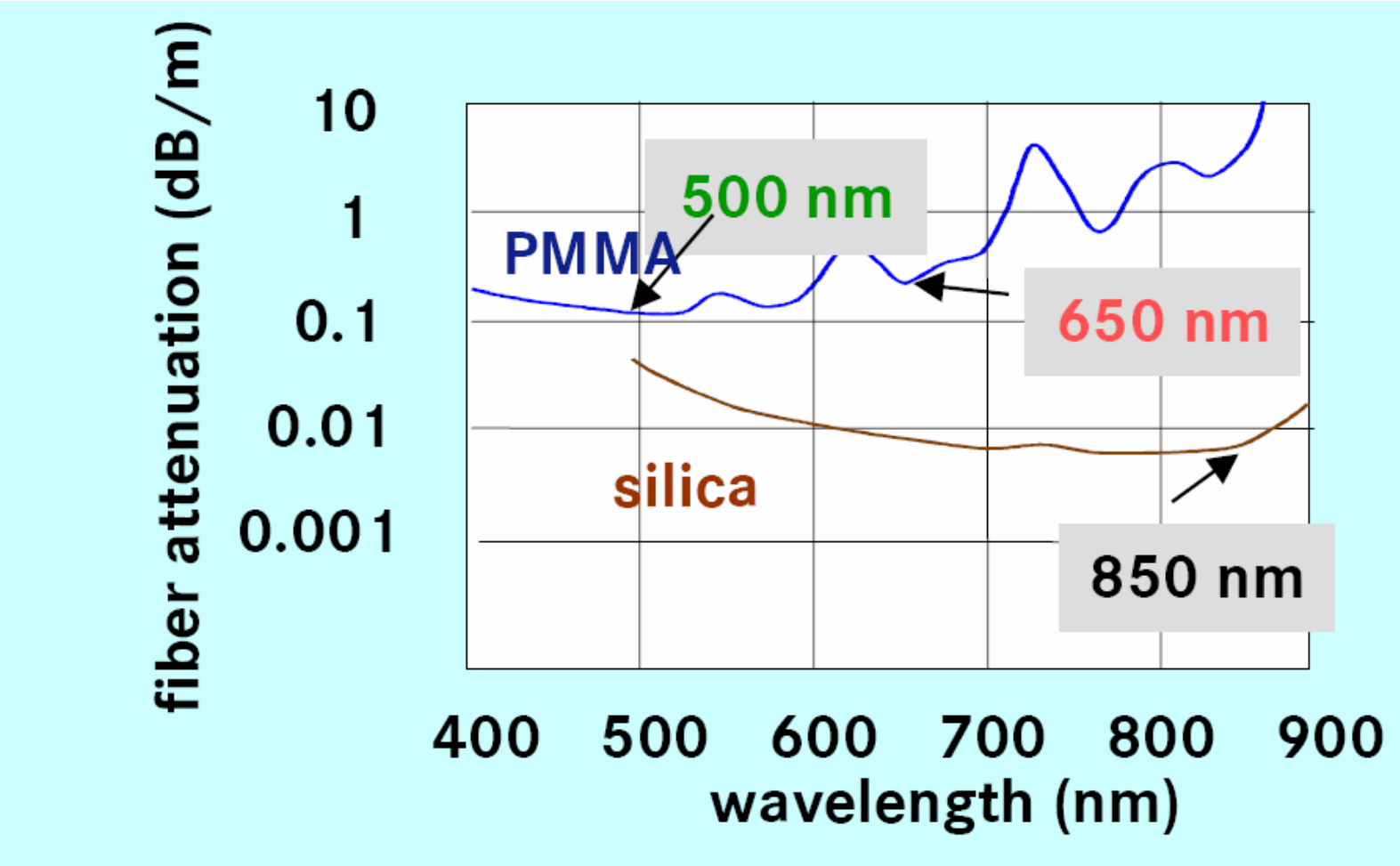
$$B \cdot L = Max\,?$$

Pulsebroadening

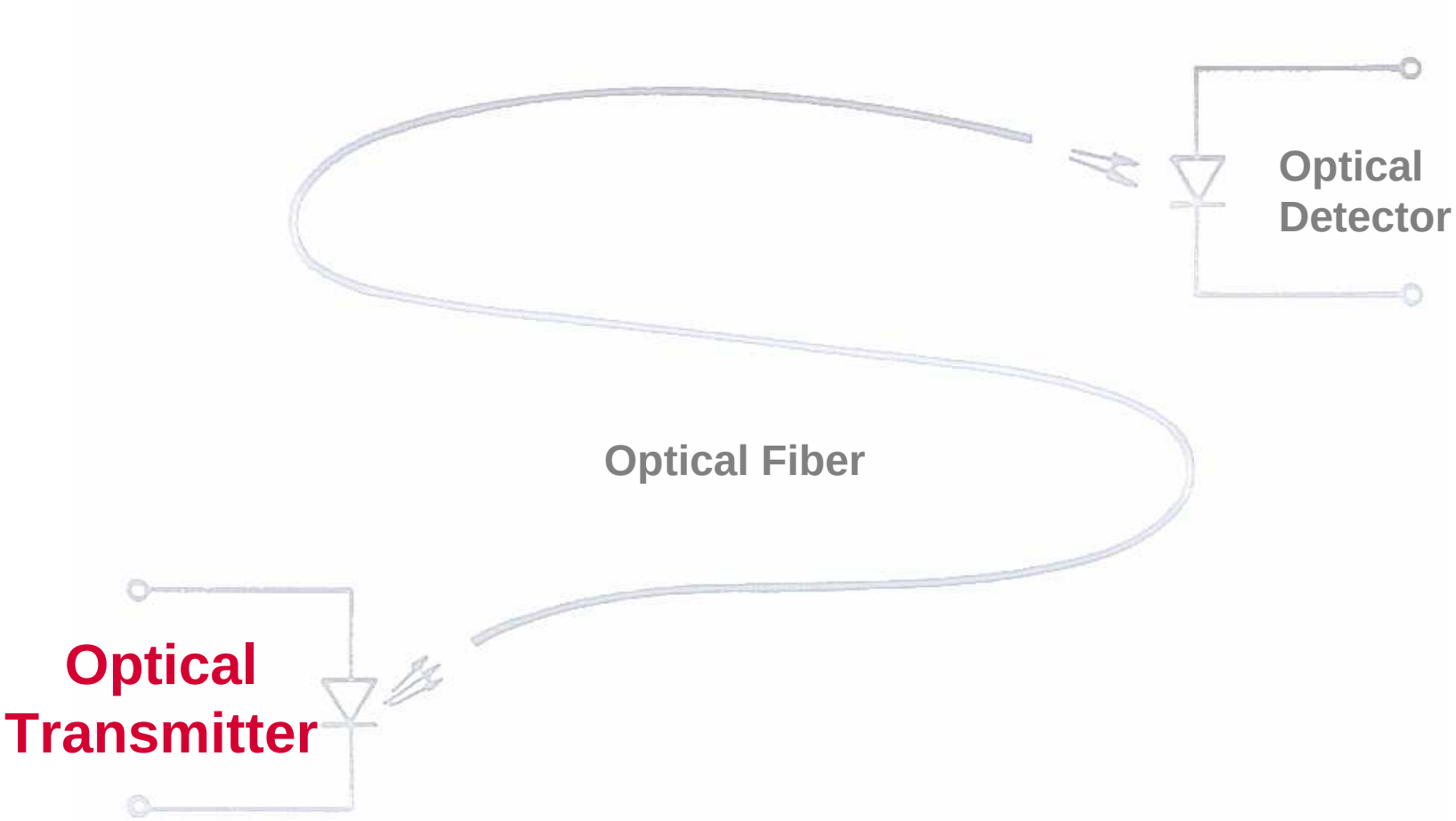
Fiber Types

Type	Profile	Size	Attenuation	Bandwidth-Length Product
Plastic Fiber	Step Index	950/1000 µm	0,2 dB/m	< 100 MHz·m
PCS Fiber	Step Index	100 - 600 µm	6 dB/km	< 10 MHz·km
Multimode Glass	Step Index	> 100 µm	3 - 5 dB/km	20 MHz·km
Multimode Glass	Graded Index	50/125 µm	2 dB/km (0.85 µm) 0,4 dB/km (1,3 µm) 0,2 dB/km (1,55 µm)	500 MHz·km
Monomode Glass		5 - 10 µm		> 100 Gbit·km/s

Spectral Attenuation of different Fibers



Principle Considerations



Demands on Optical Transmitters

High Optical Output Power

Small Electric Input Power

Wavelength in proper Range

Small Spectral Size

Low Beam Divergence

High Speed Modulation

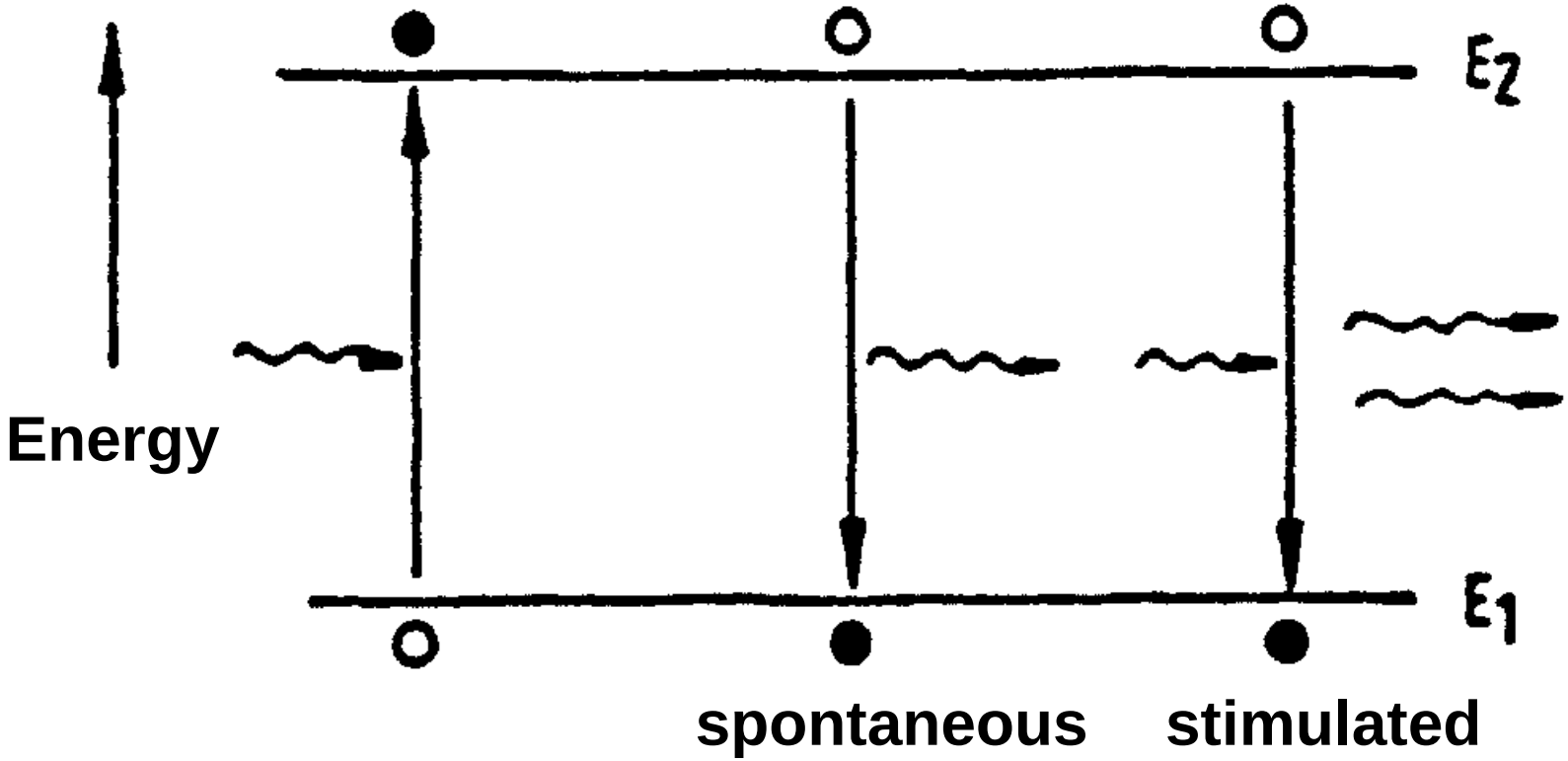
Injection Modulation Capability

Small Size

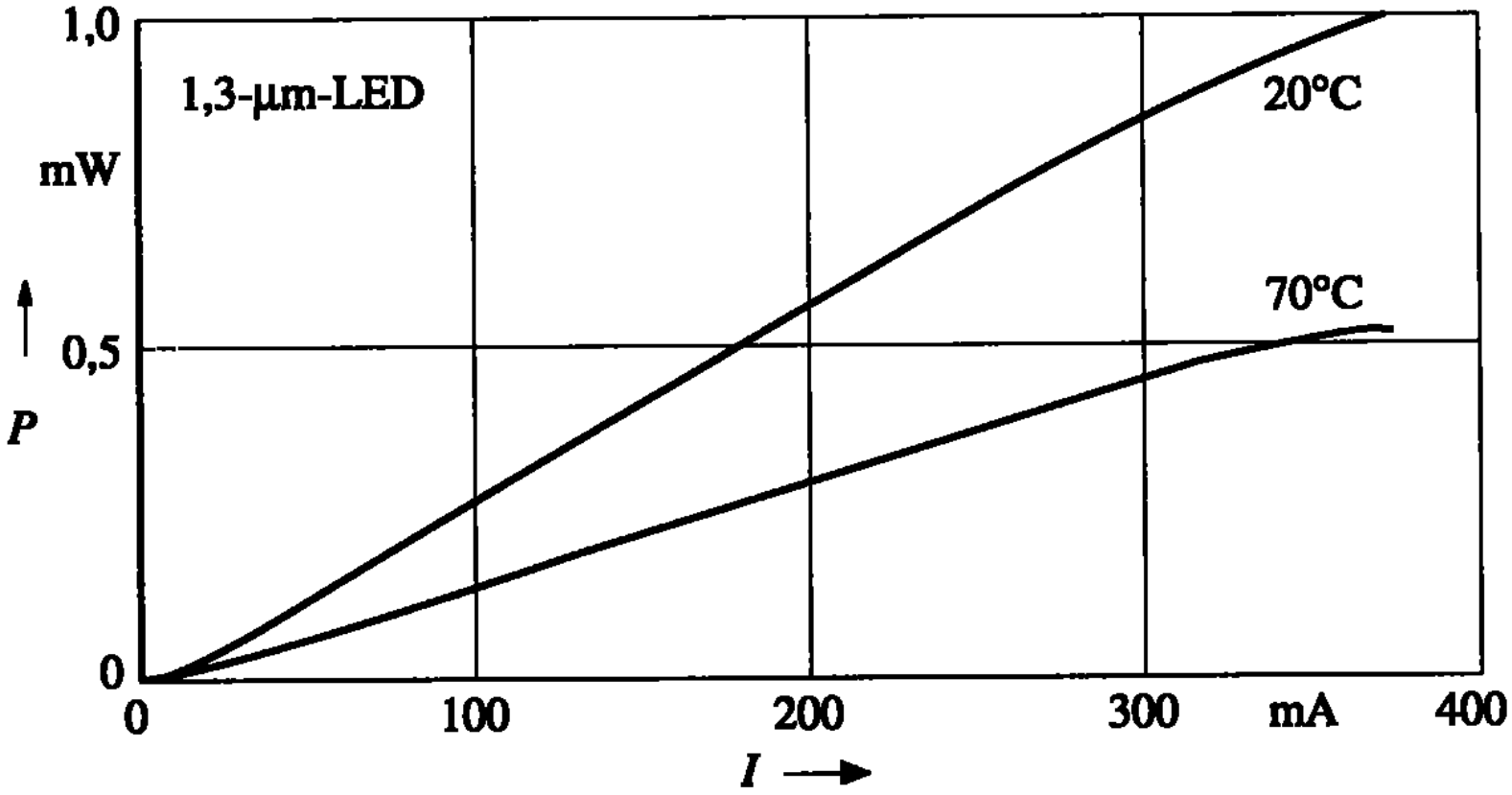
Reliability

Absorption and Emission

$$E_2 - E_1 = \Delta E = h \cdot f = \frac{h \cdot c}{\lambda}$$

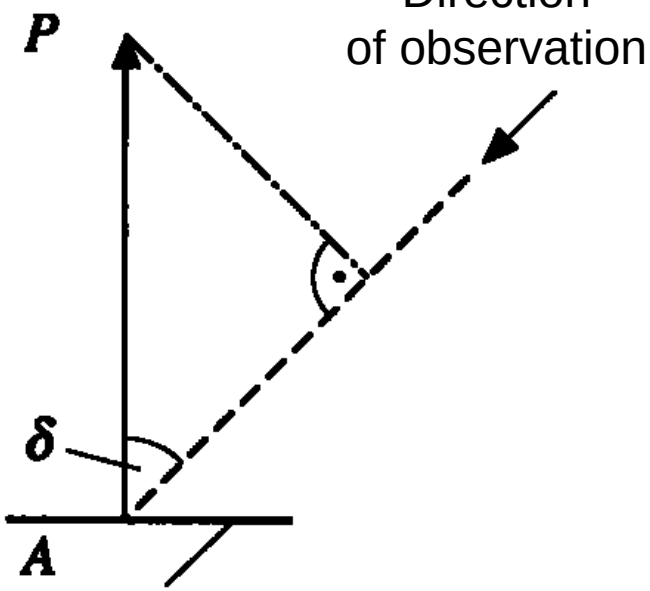


Optical Power versus Injection Current of an LED

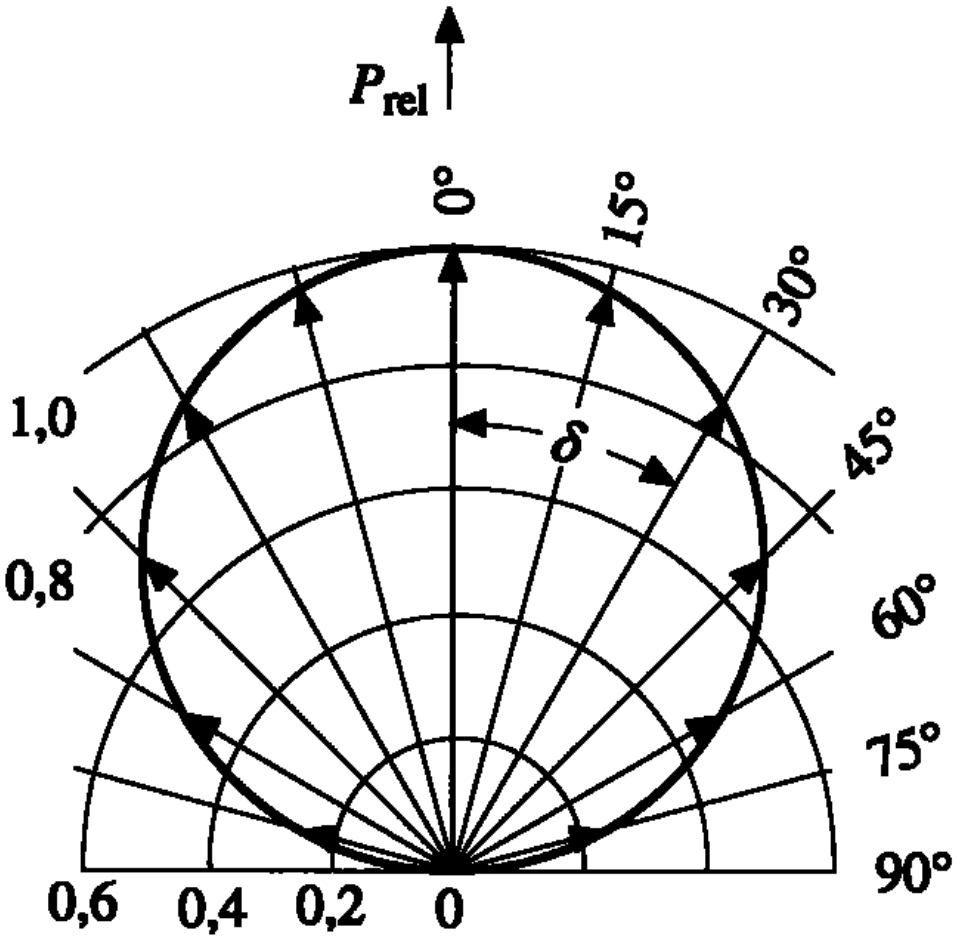


Farfield Characteristic of an LED

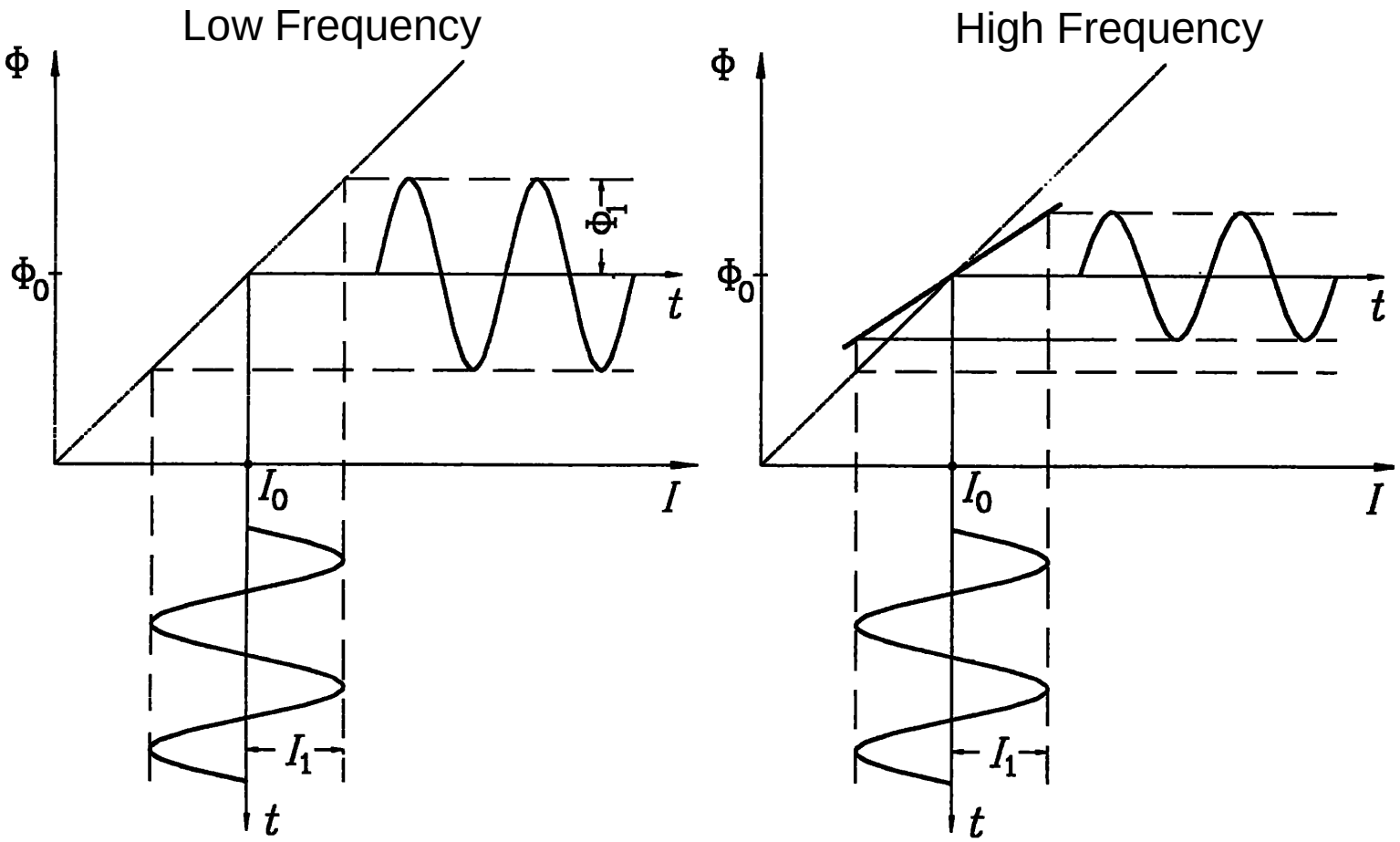
$$P \sim \cos\delta$$



Irradiant Surface

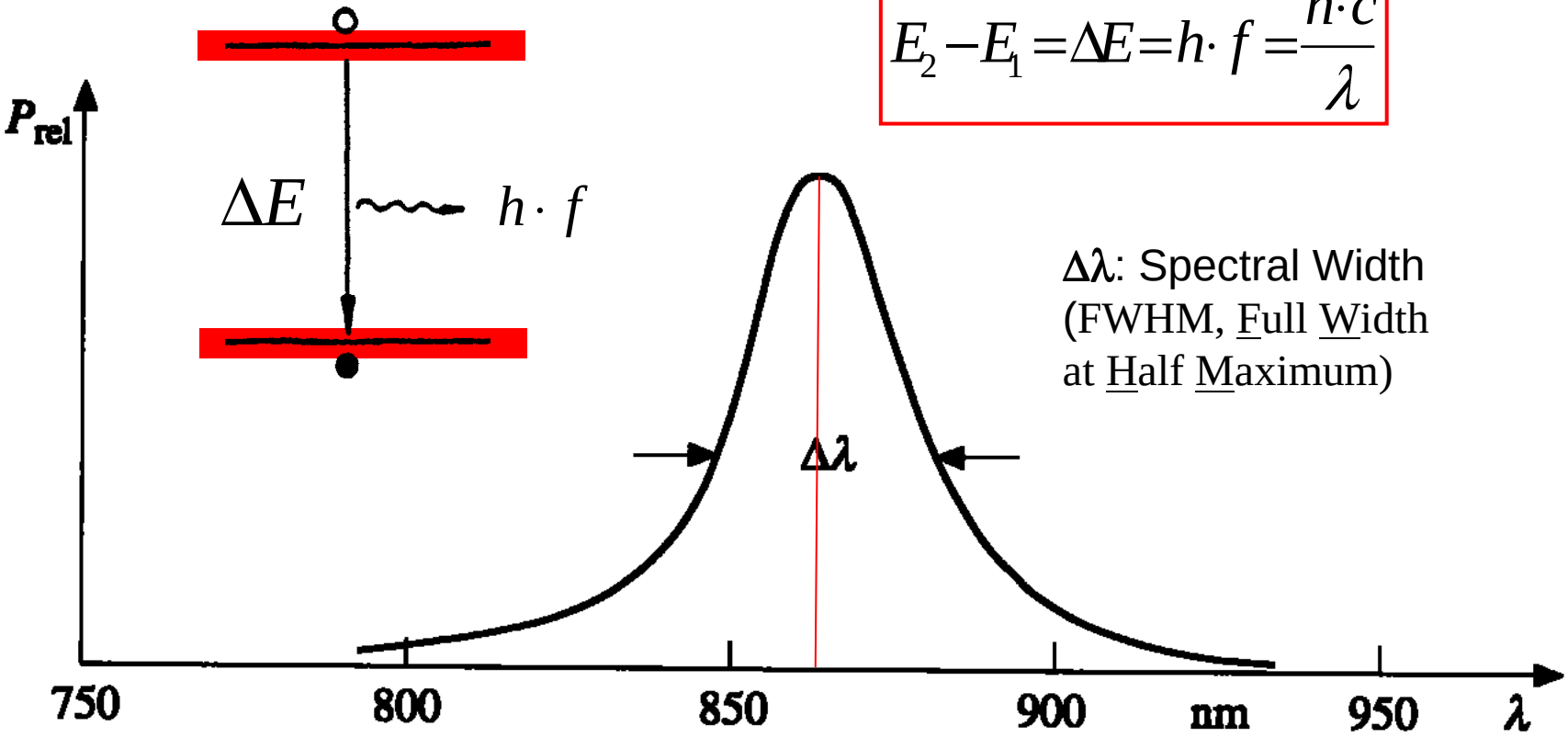


Modulation Performance at Low and High Frequencies



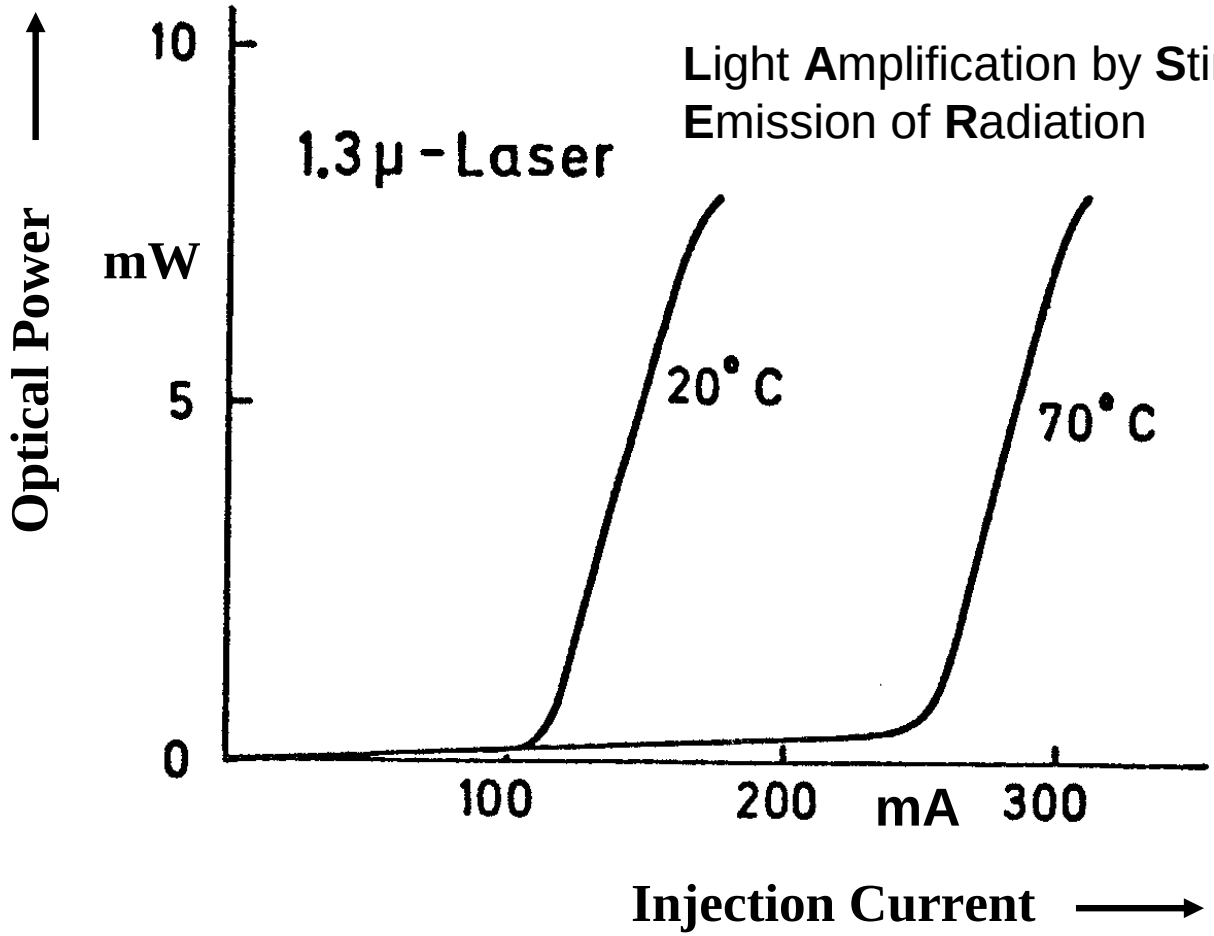
Spectral Width of an LED

$$E_2 - E_1 = \Delta E = h \cdot f = \frac{h \cdot c}{\lambda}$$



$\Delta\lambda$: Spectral Width (FWHM, Full Width at Half Maximum)

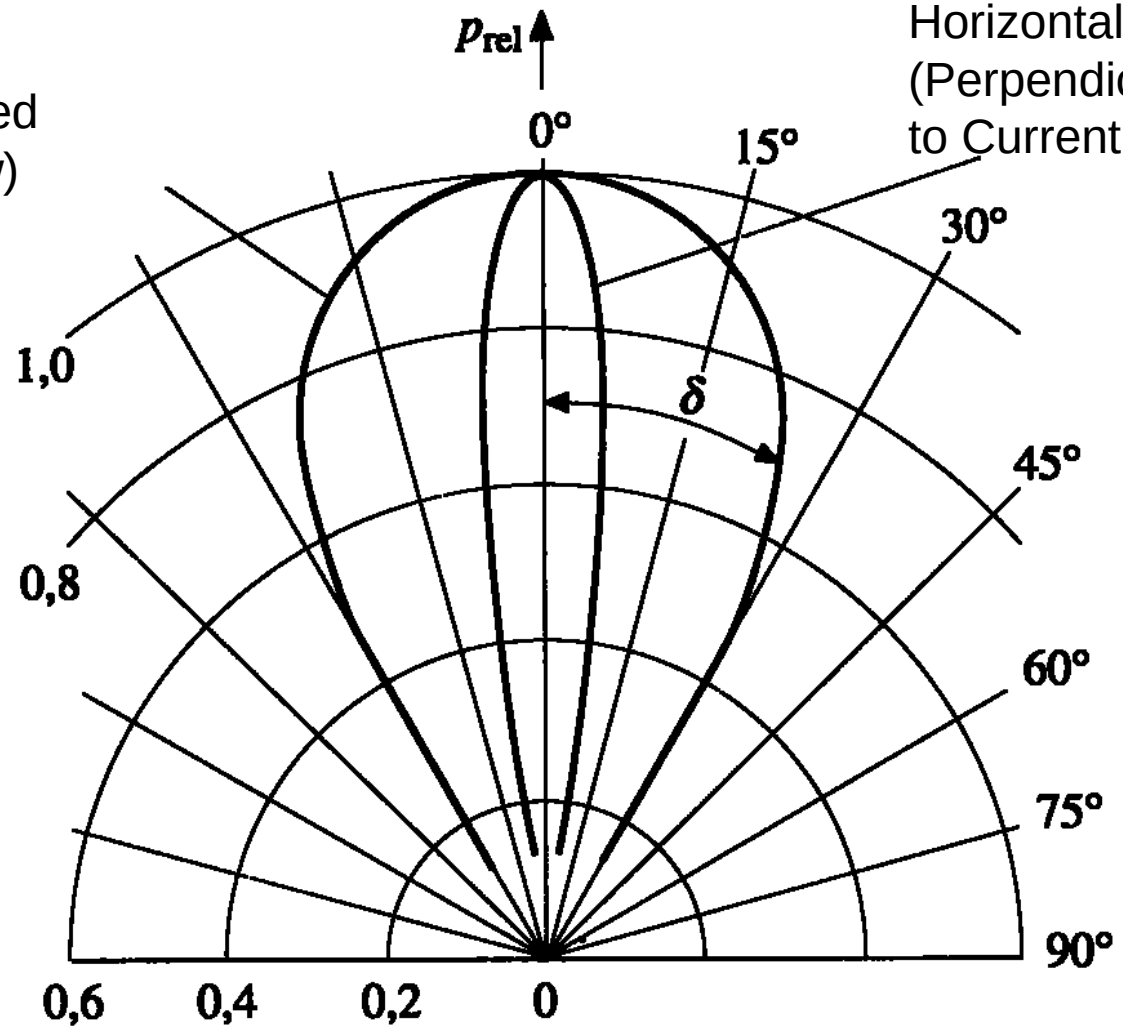
Optical Power versus Injection Current of a Semiconductor Laser



Farfield Characteristics of a Laser Diode

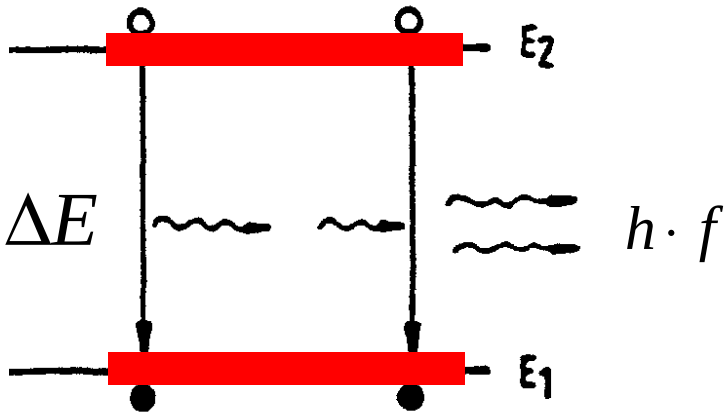
Vertical
(Parallel oriented
to Current Flow)

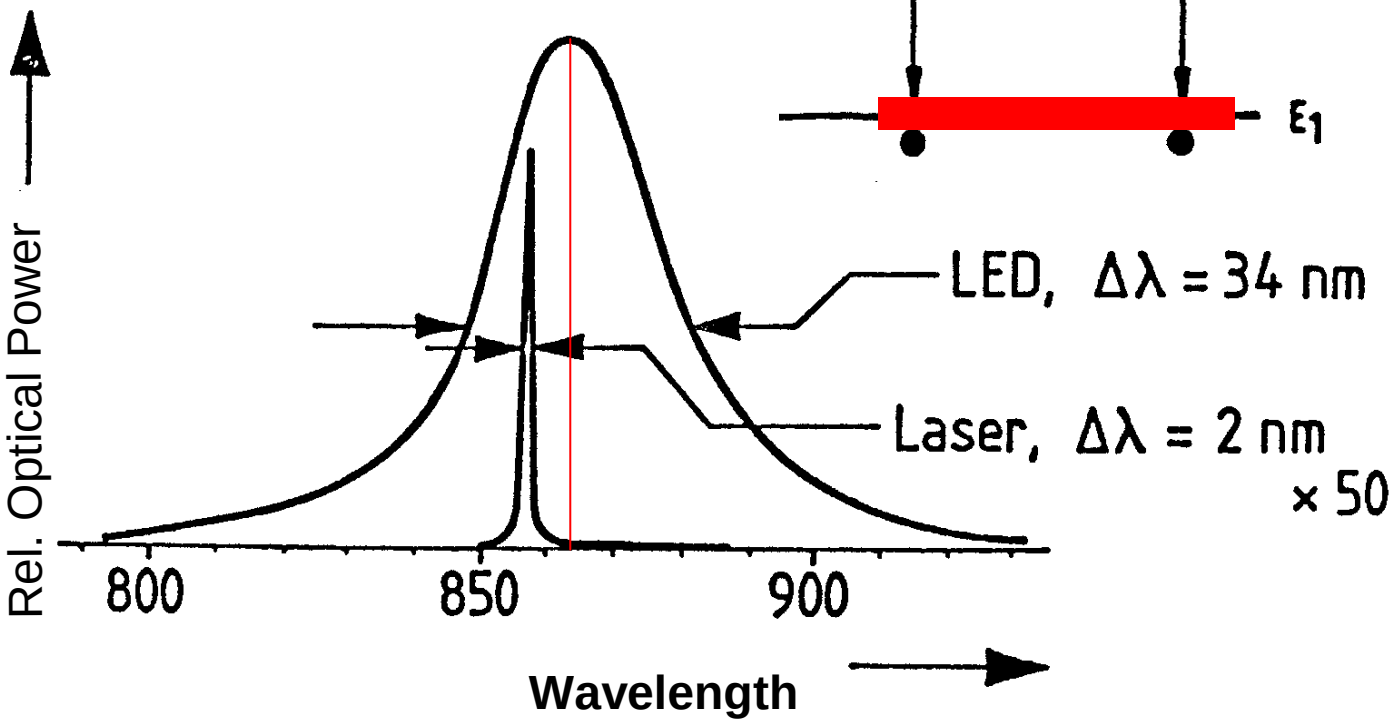
Horizontal
(Perpendicularly oriented
to Current Flow)



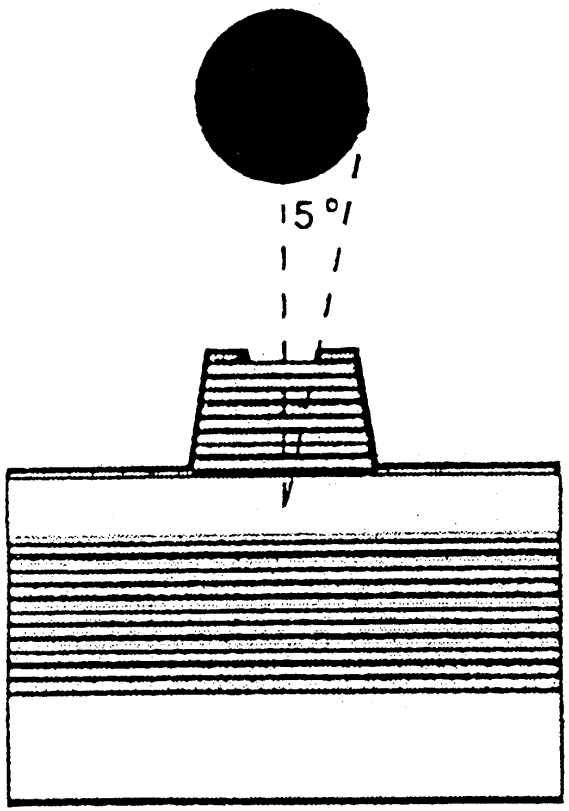
Spectral width of LED and Laser

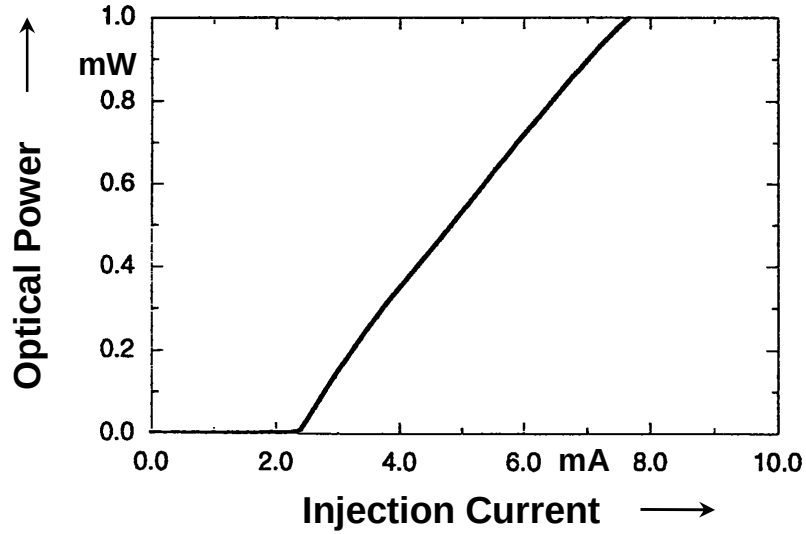
$$E_2 - E_1 = \Delta E = h \cdot f = \frac{h \cdot c}{\lambda}$$

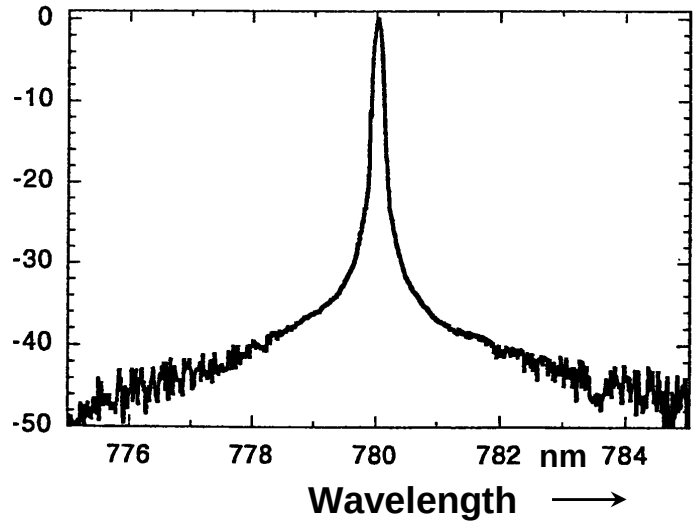




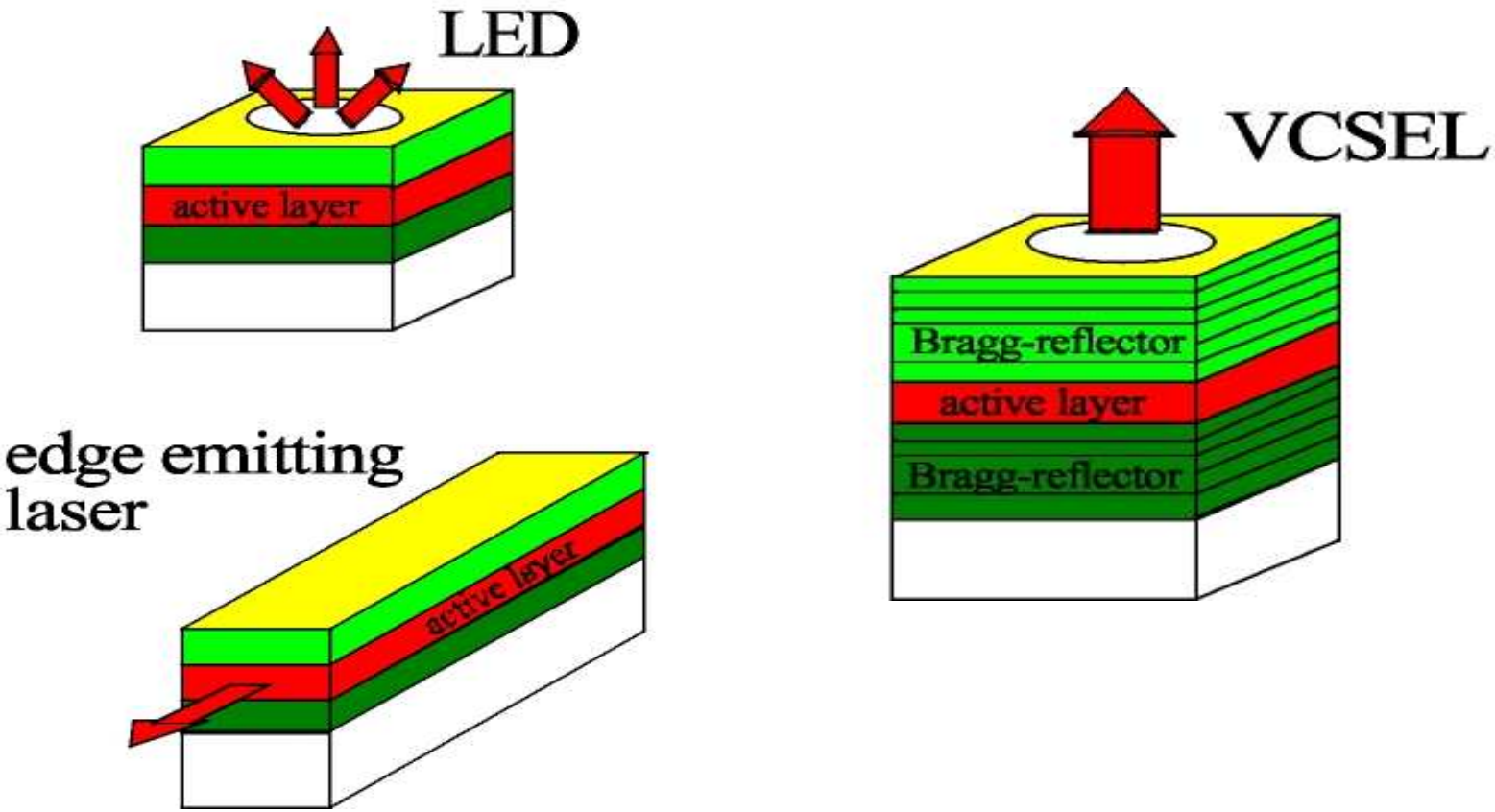
Vertical Cavity Surface Emitting Laser (VCSEL)



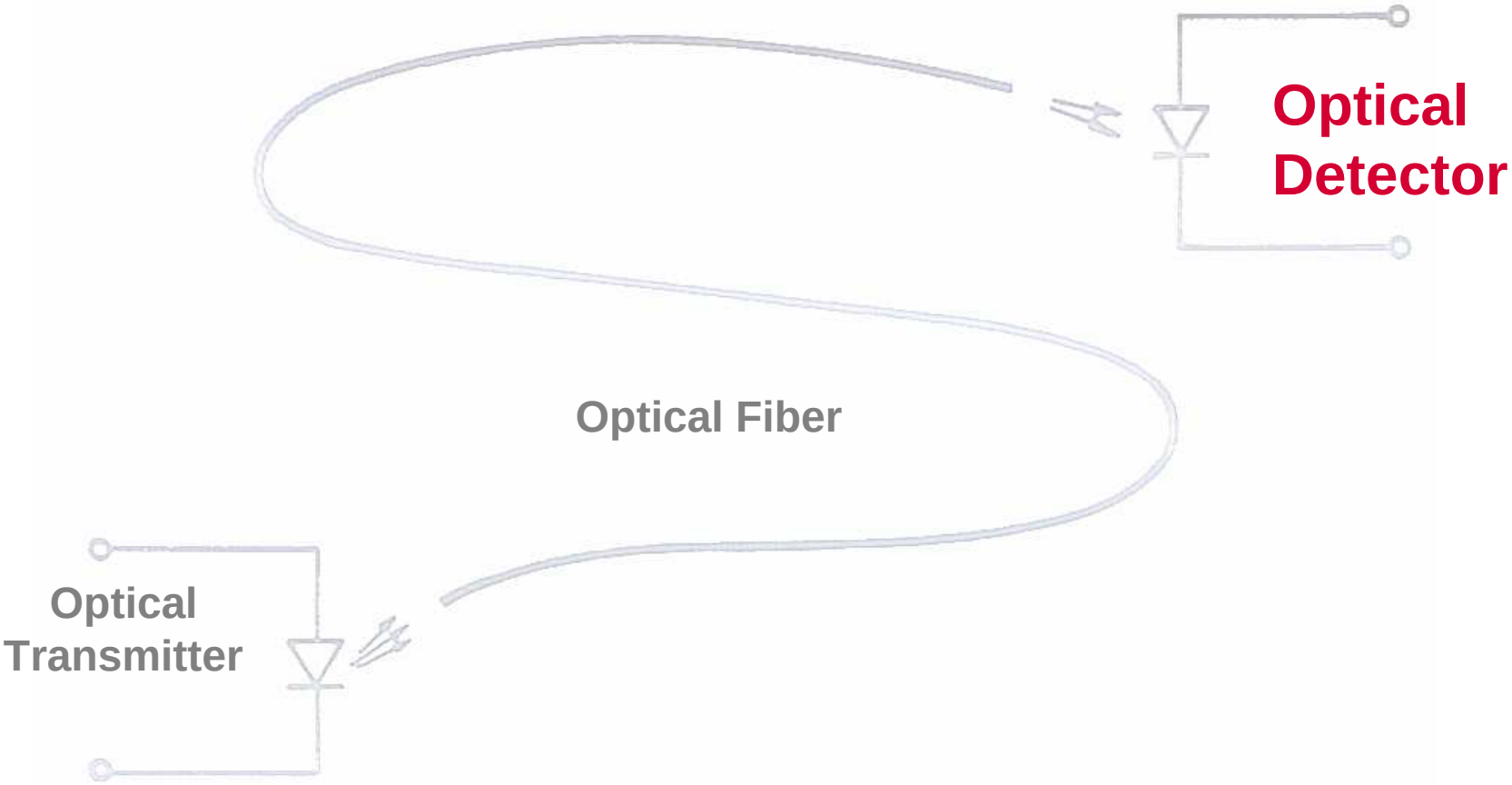




Light Sources for Fiber-Optic Systems



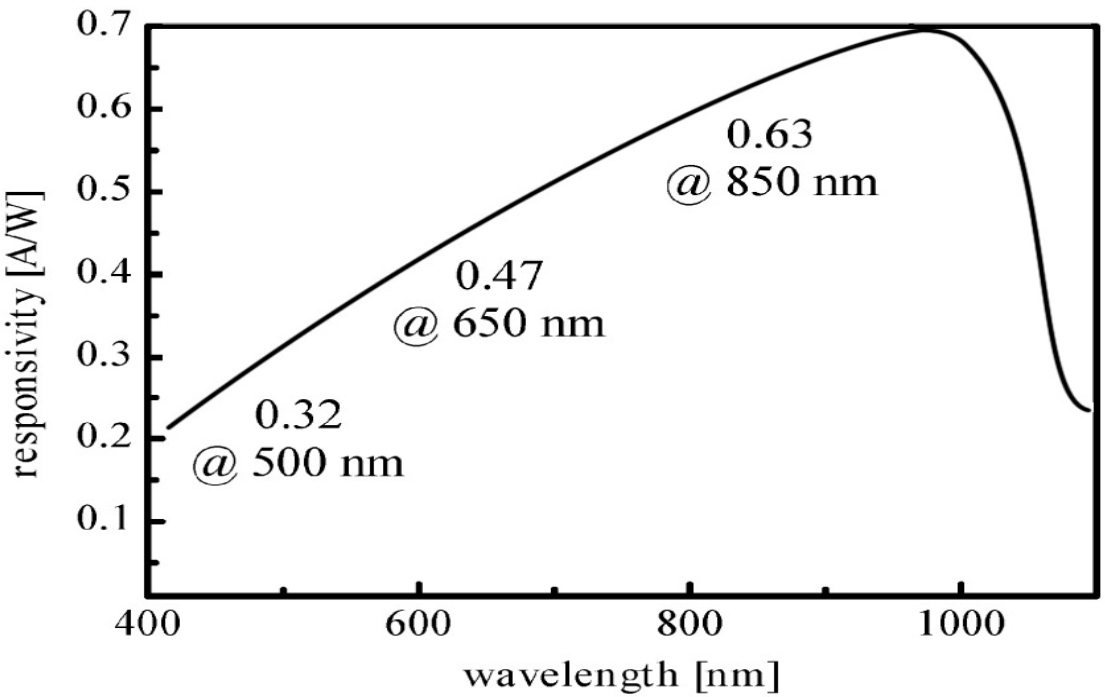
Principle Considerations



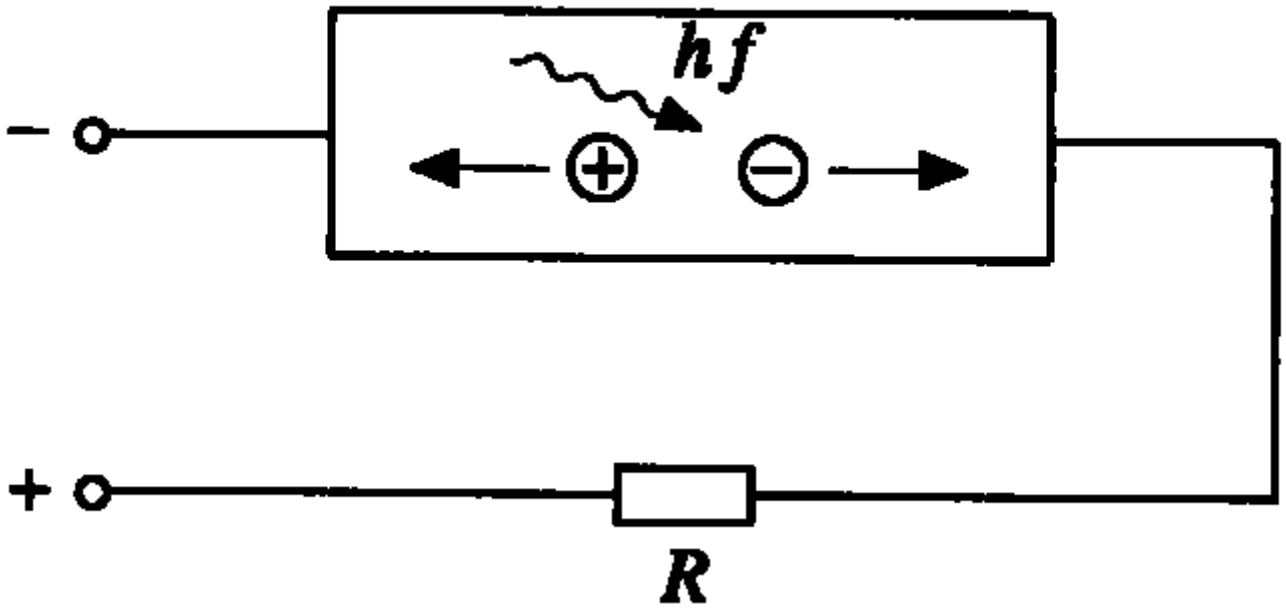
Demands on Optical Detectors

- **High sensibility**
- **Low noise**
- **Small size**
- **High bandwidth**

Spectral responsitivity of a Si pin-Photodiode



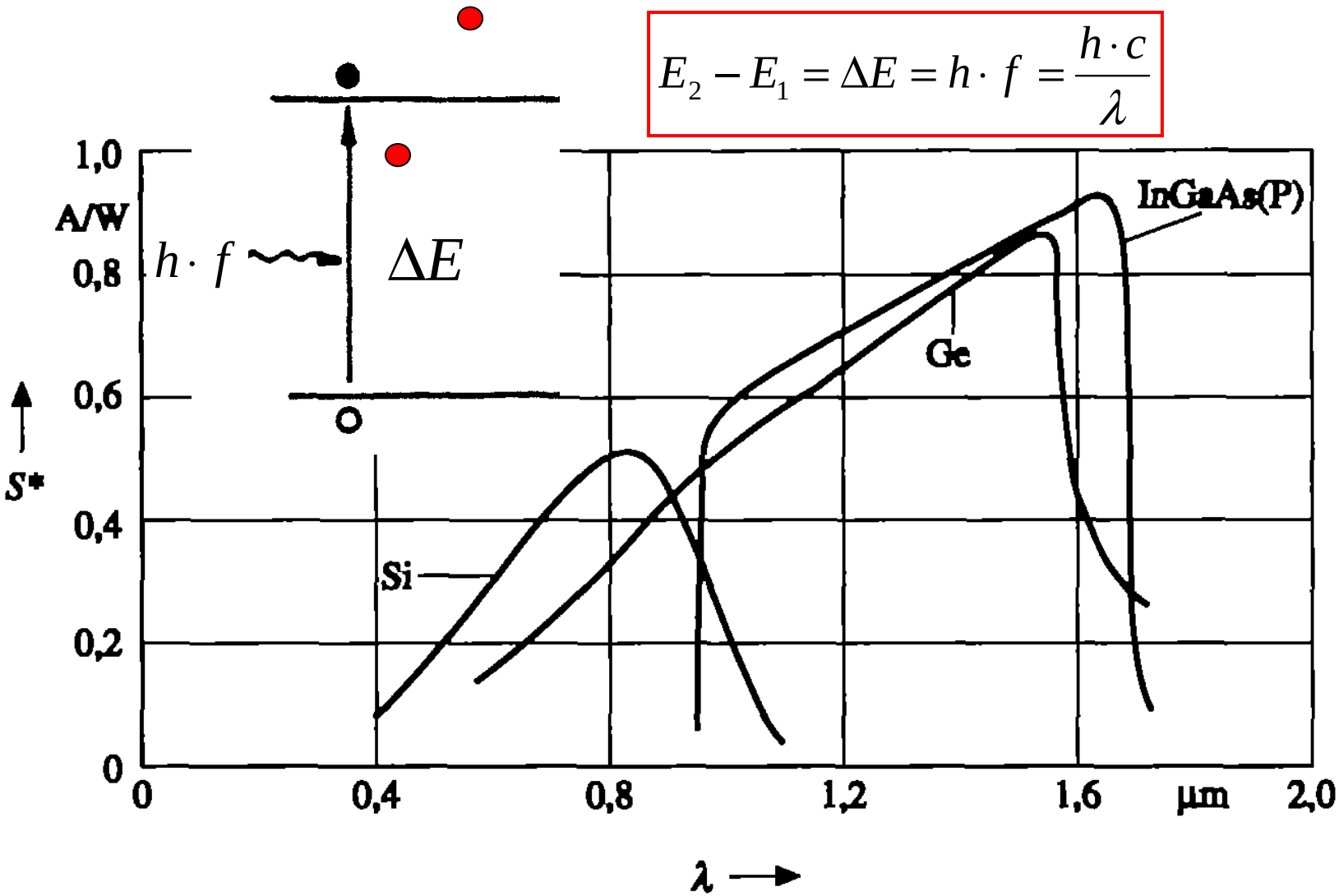
Photon Absorption and Carrier Generation



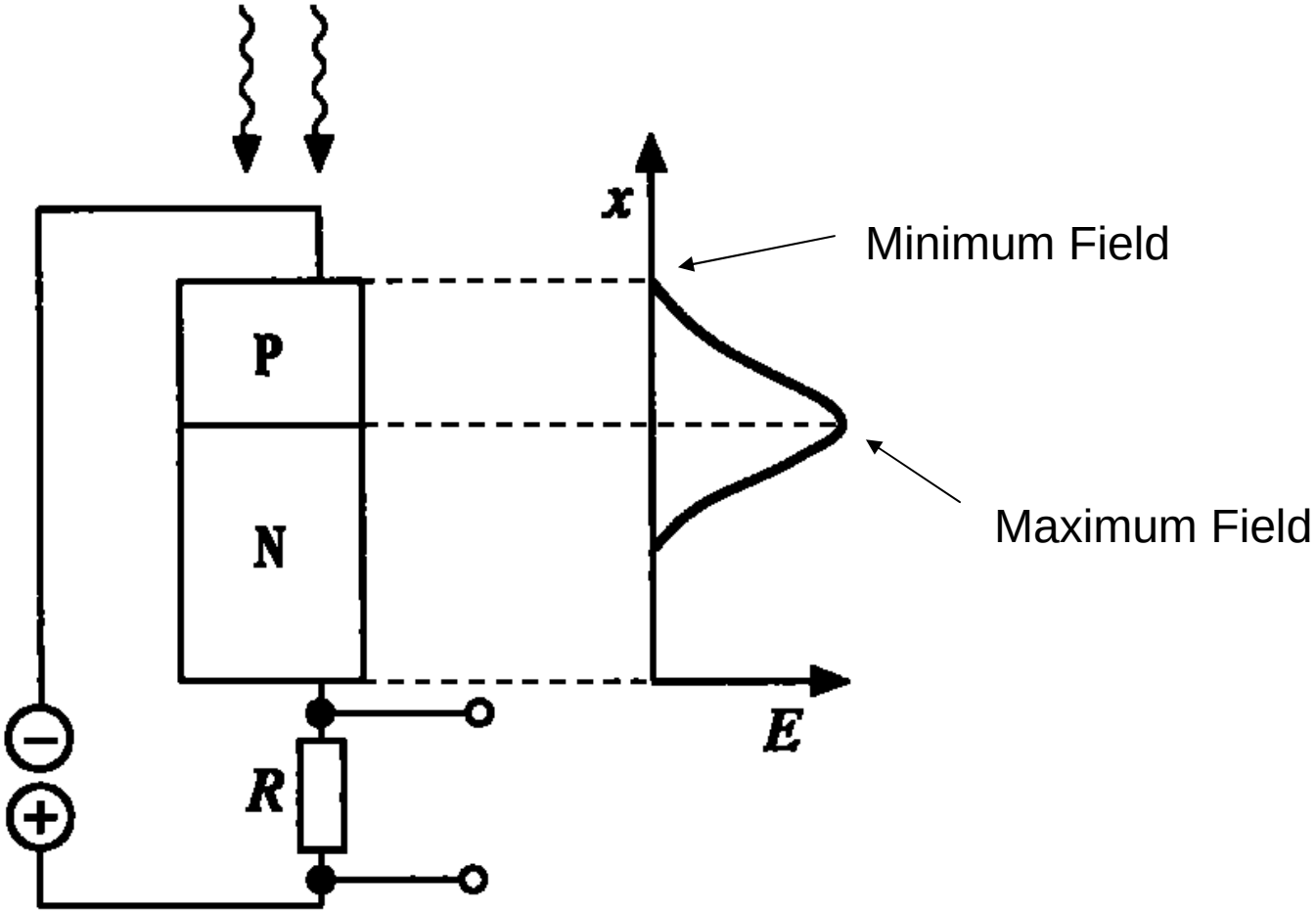
R: Load Resistor

Responsivity versus Wavelength of various Semi-Conductor Materials

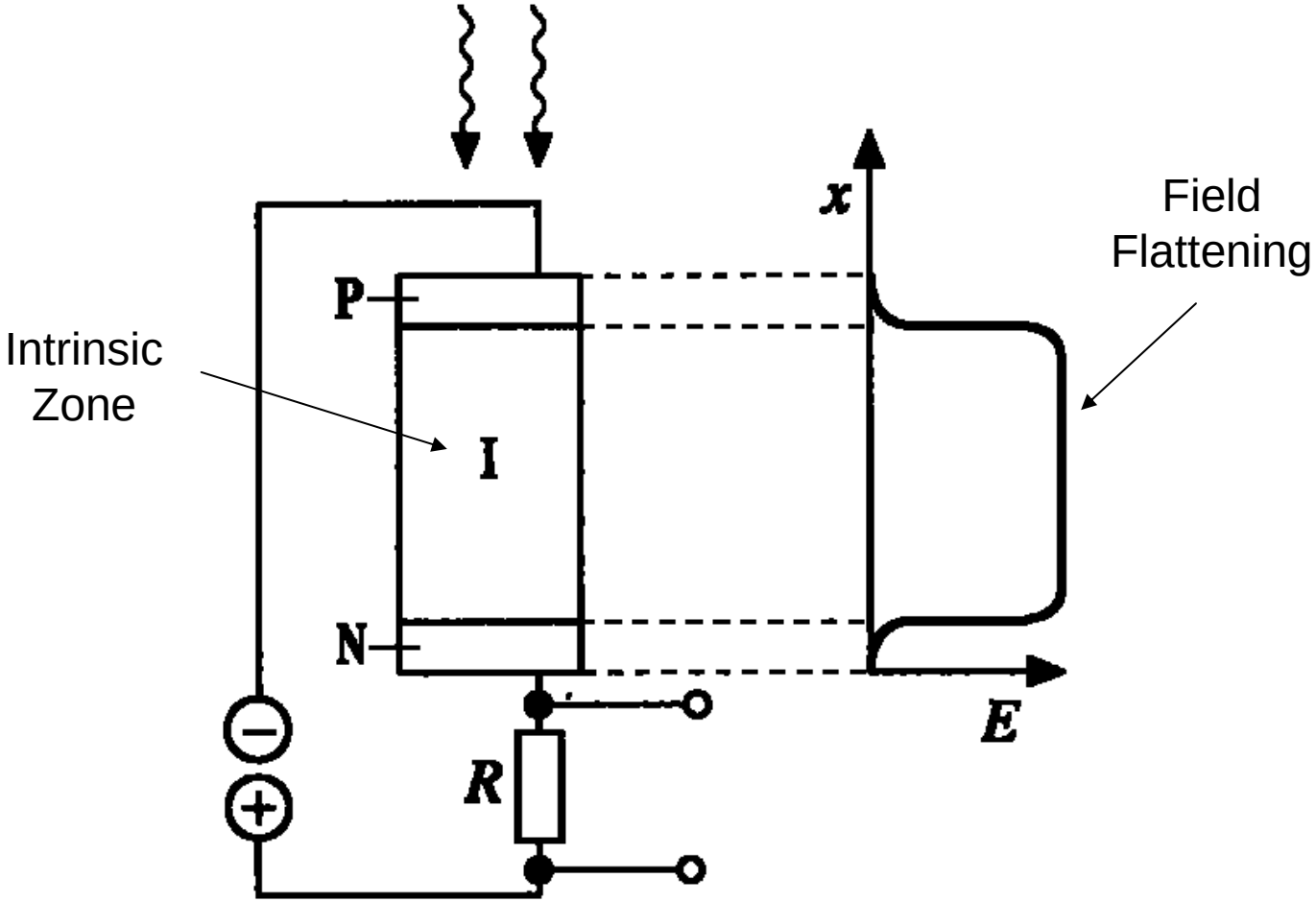
$$E_2 - E_1 = \Delta E = h \cdot f = \frac{h \cdot c}{\lambda}$$



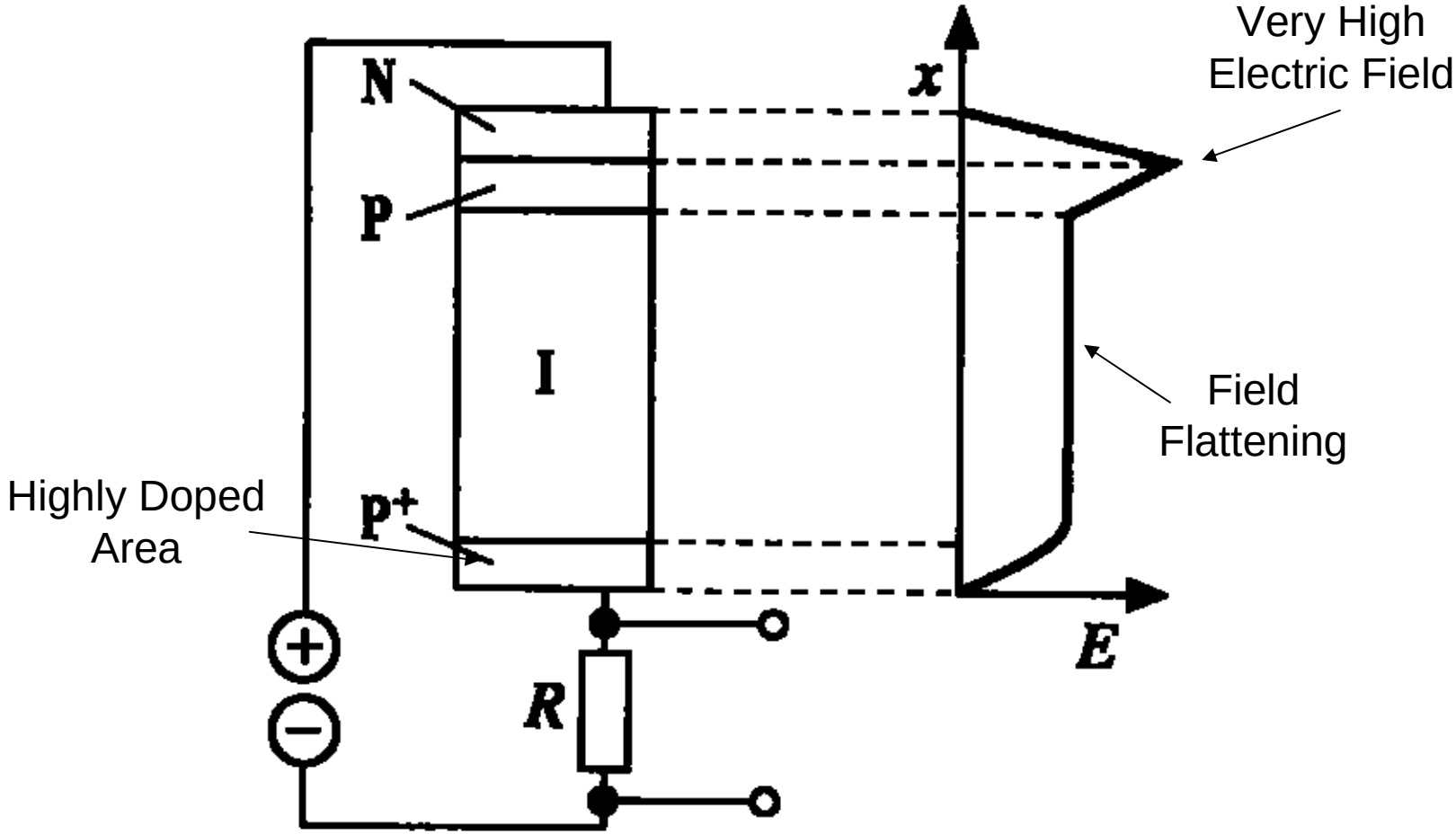
Historical pn-Photodiode and Electric Field Distribution



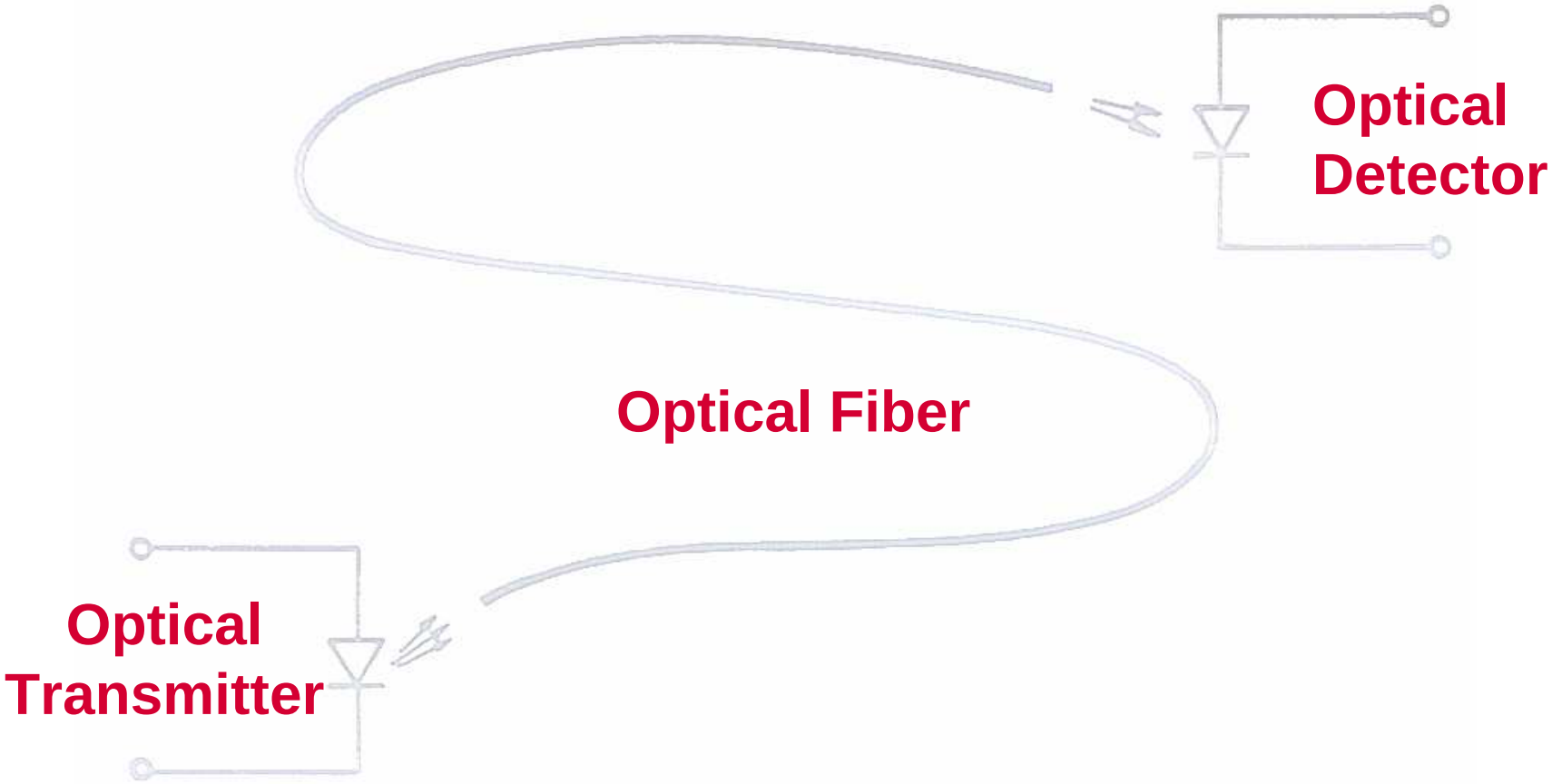
pin-Photodiode and Electric Field Distribution



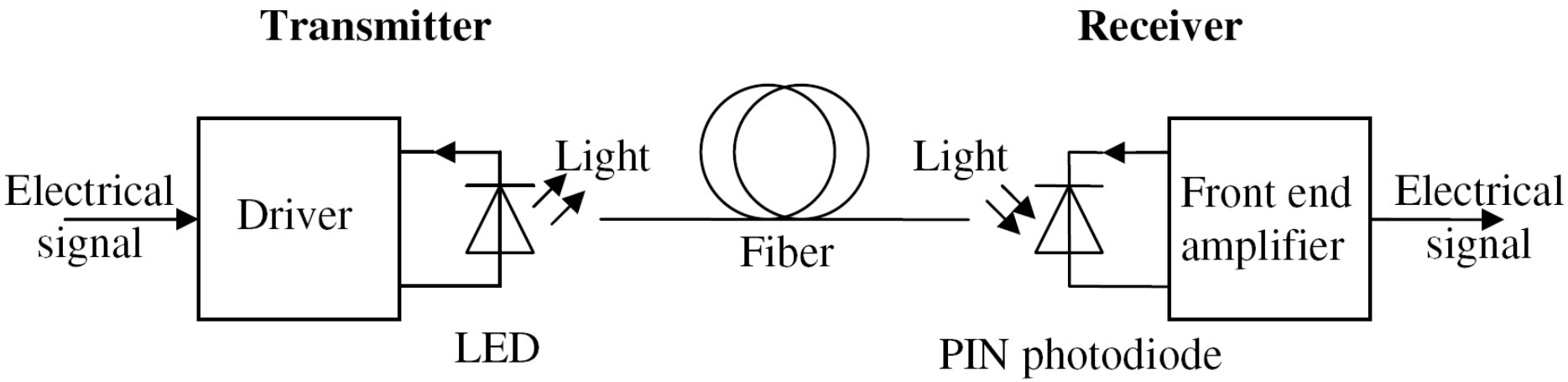
Avalanche Photodiode (APD) and Electric Field Distribution



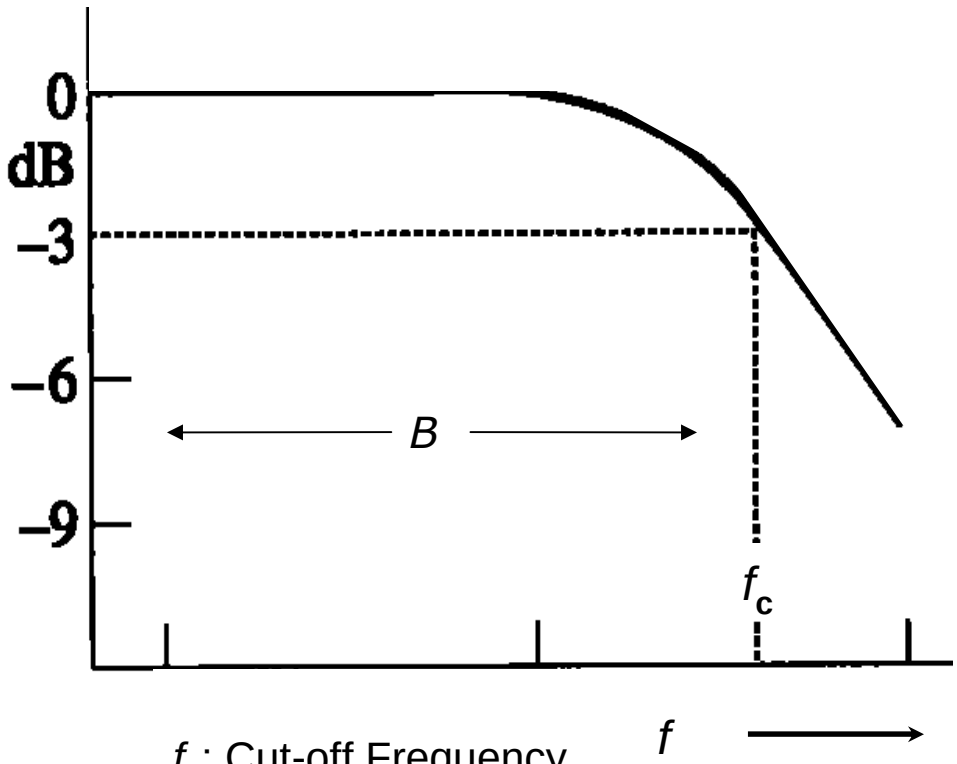
System Considerations



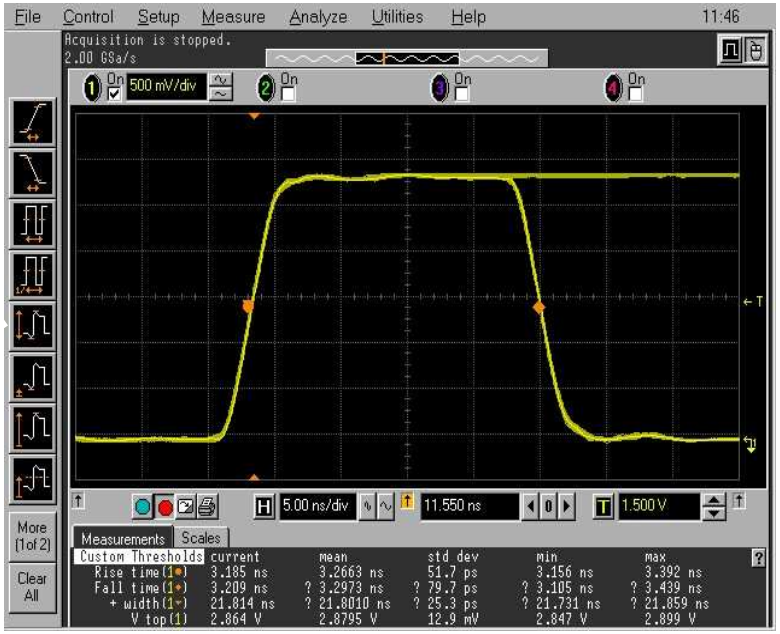
System Integration



System Modulation Transfer Function and Data Signal



f_c: Cut-off Frequency
B: Bandwidth



25 Mbit/s-Signal

Limitations of Polymer Fiber Networks

- **Best solution in terms of costs for state of the art systems**
  - 1-mm-Core-Diameter POF, Red LED, Large Area Si-Photodiode
- **Most important component limitations**
  - Maximum bandwidth of LED < 100 MHz
  - Maximum temperature of PMMA Fiber ≈ 85°C
  - Minimum attenuation (for red LED) of PMMA Fiber ≈ 0.4 dB/m
  - Bandwidth-length product $B \cdot L \approx 3000$ MHz · m (e.g.150 MHz after 20 m)
  - Maximum bandwidth of typ. 1 mm^2 area Si-Photodiode ≈ 100 MHz
- **Resulting system limitations**
  - Maximum data rate ≈ 150 MBit/s
  - Maximum temperature range: –40°C to +85°C
  - Maximum link length < 10 m

Restrictions by POF Networks

Conclusions

- POF-Systems are not suited for data ranges in Gbit/s region, temperature demands up to 125 °C, and link length > 20m necessary for future use in

- Sensor systems for safety applications
- Engine management systems
- Drive by wire systems
- Video processing for driver assistance and autonomous driving

Therefore alternative solutions have to be found!

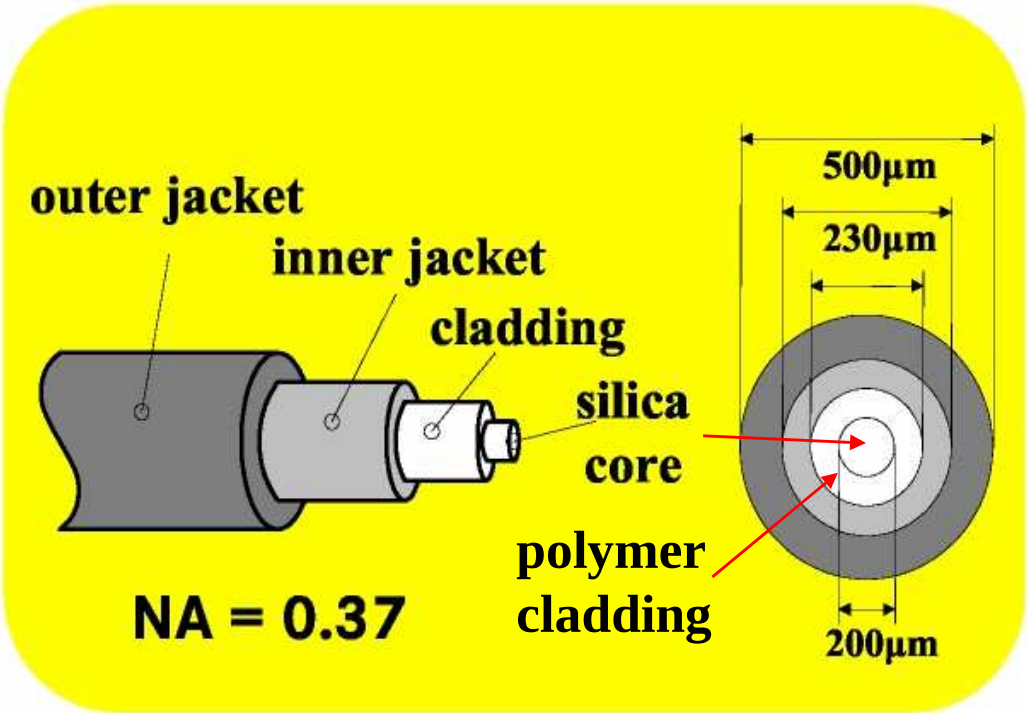
Future Technologies based on PCS Fibers and VCSELs

Polymer-Cladded Silica fibers (PCS) with 200 µm core

- Minimum attenuation at 850 nm ≈ 0.005 dB/m
  After 20 m ≈ 98%
  (16 % for PMMA fibers)

- Maximum temperature: 125°C

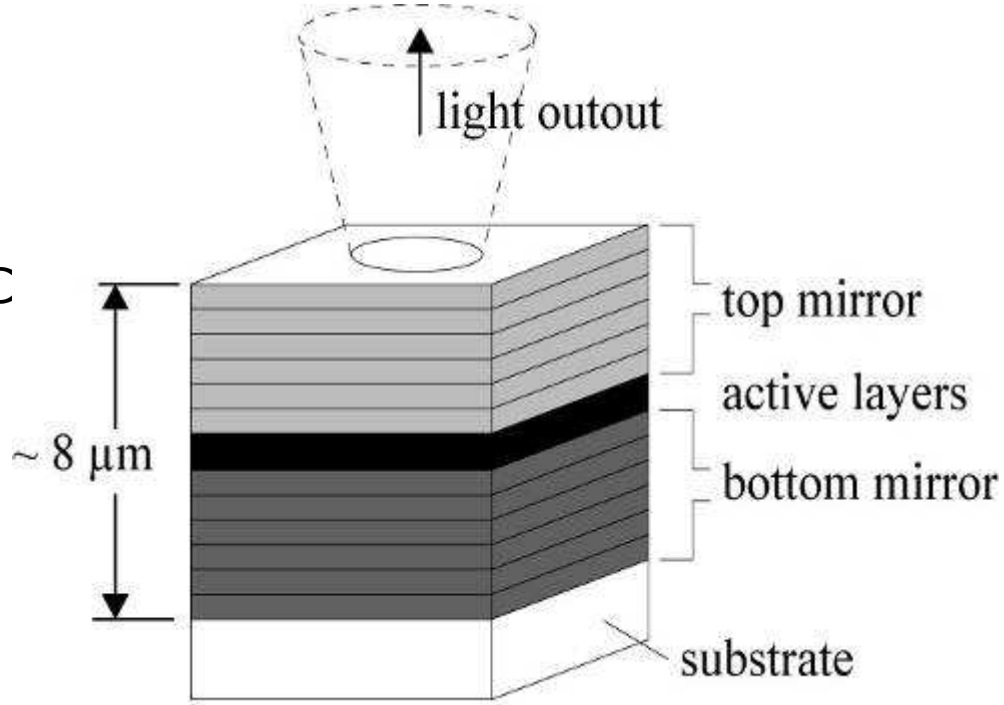
- No bandwidth restrictions,
  $B{\cdot}L$ = 20 GHz·m
  After 20 m ≈ 1 GHz
  (150 MHz for PMMA fibers)



VCSEL Transmitter

- **Vertical Cavity Surface Emitting Laser (VCSEL) at 850 nm**

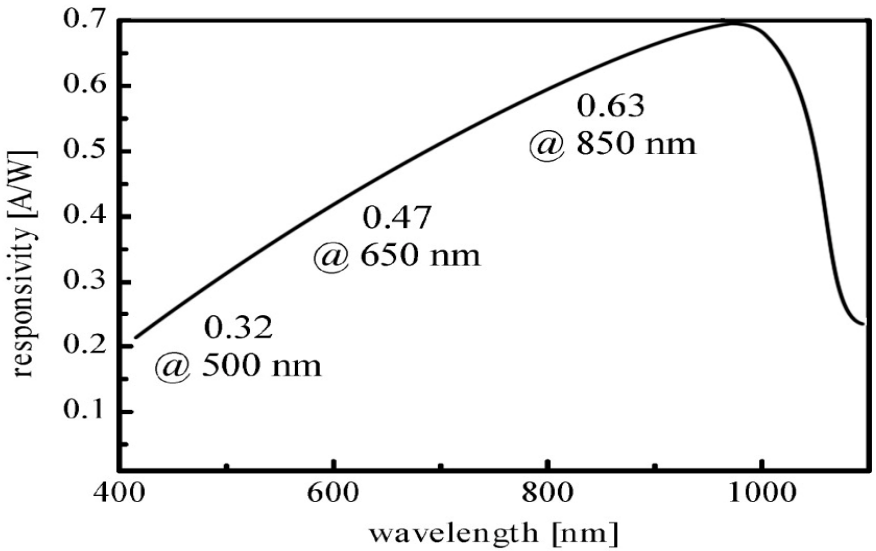
  - Maximum bandwidth > 1 GHz
  - Low injection current
  - Coupling efficiency > 90%
  - Maximum temperature: 125°C



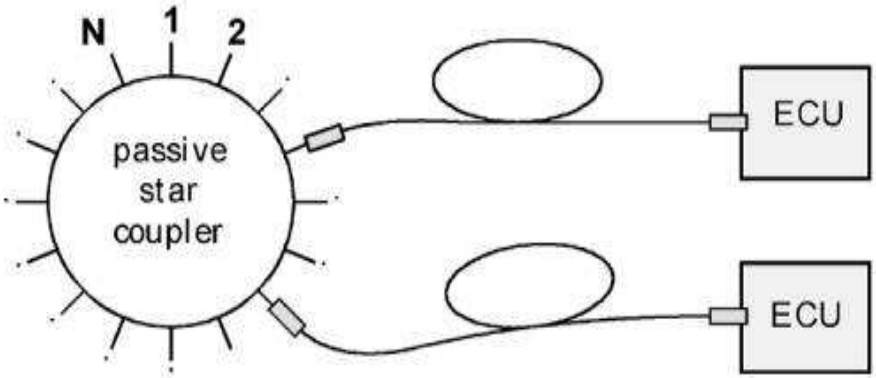
Receiver

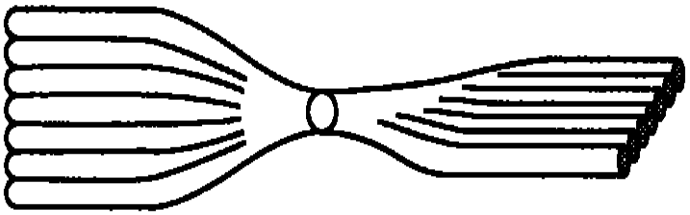
Si–pin-Photodiode

- Small area
  (due to small PCS fiber core)
  low junction capacity
  Maximum bandwidth ≈ 1.5 GHz
- Low coupling loss
- High spectral sensitivity at
  850 nm (comp. to PMMA-Syst.
  at 650 nm.: 1.3 dB gain)

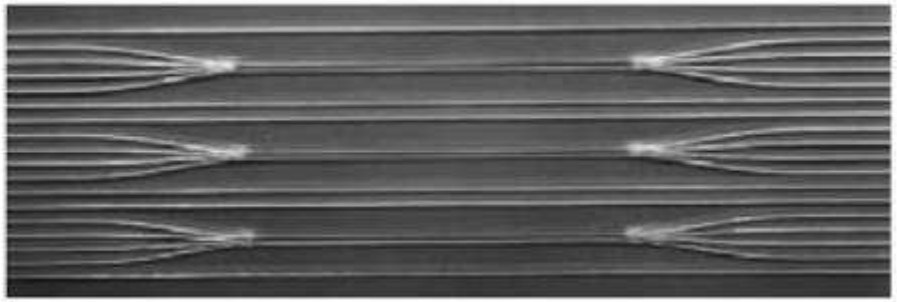


Passive Star Network for Safety-Relevant Systems





- **PCS Fiber-optic star coupler**

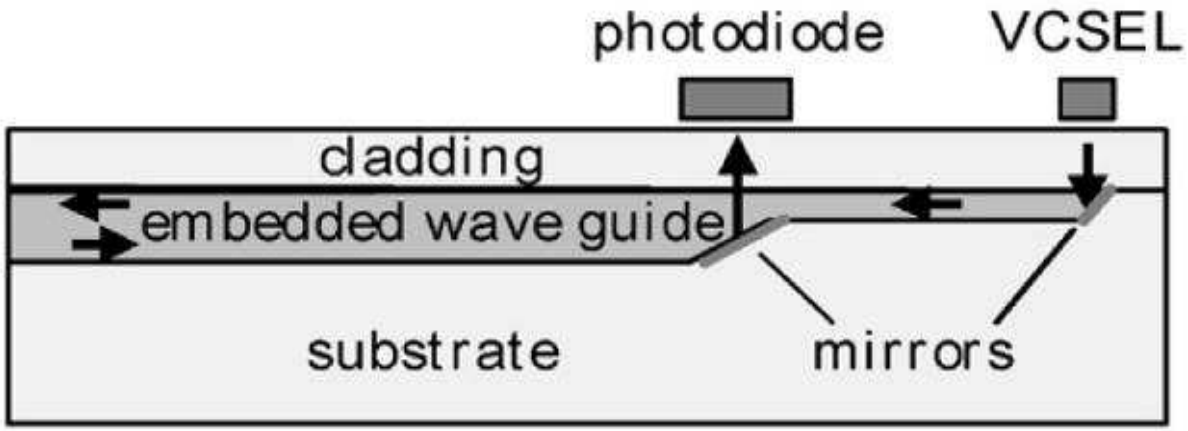


- **Planar optical waveguides for star coupler structures**

  200 µm x 200 µm waveguides

Planar Bi-Directional Transceiver

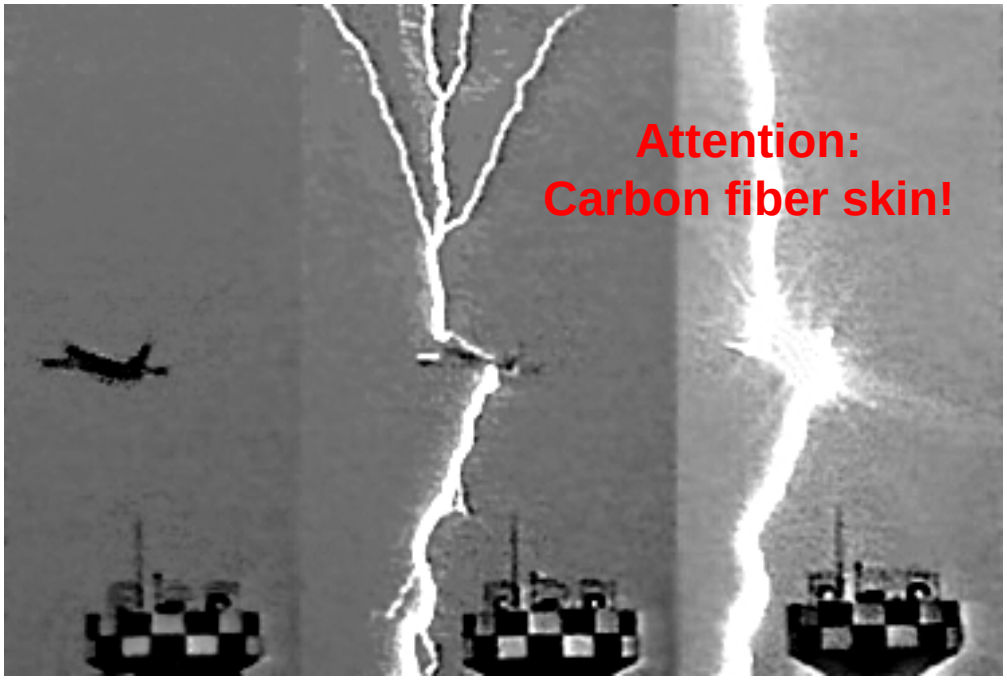
- **Integration in planar flat printed circuits**



Concepts for Aircrafts

Lightning Strike

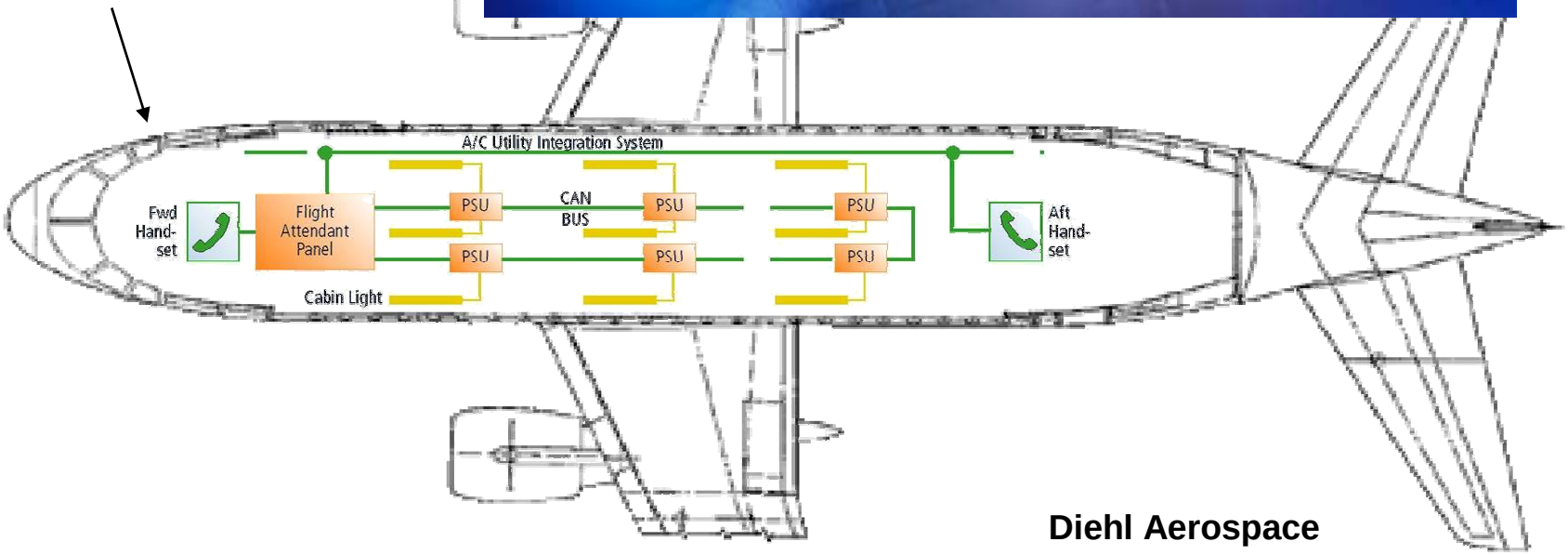
- Nowadays aircrafts have a metal fuselage
  - Faraday's cage effect
    - good passive lightning protection granted
  - heavy, high fuel consumption
- Future aircrafts are using more and more carbon fiber fuselage
  - less weight
  - less fuel consumption
  - less/no Faraday's cage effect
    - more protections needed



Airbus Cabin Management Systems

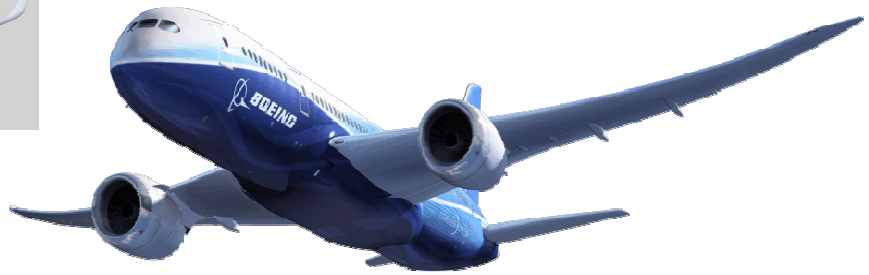
Cabin Management

Carbon fiber skin



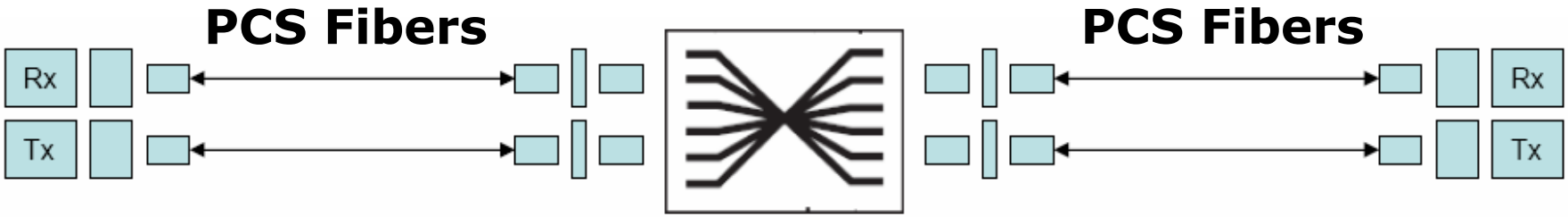
Diehl Aerospace

Optical Data Bus for Airbus A320 (A30X) or Boeing 787 (new 737)



System Features:

10 MBit/s, 100 m, 8 by 8 ports



Transceiver:

Tx: Transmitter

Rx: Receiver

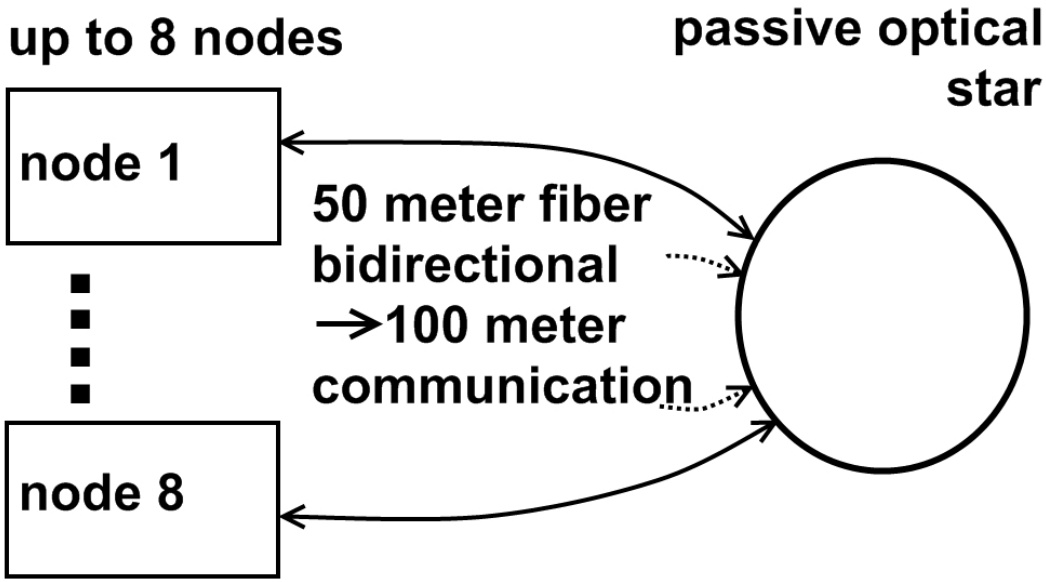
PCS Star Coupler

Diehl Aerospace

Actual Solutions

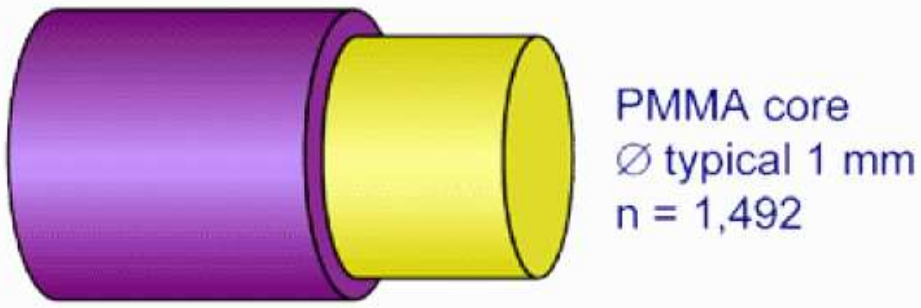
- Data rate: 10 MBit/s
- Operating temperature: -40 °C…+85 °C
- Distance between two nodes: 100 m
  (50 m ↔ optical star ↔ 50 m)

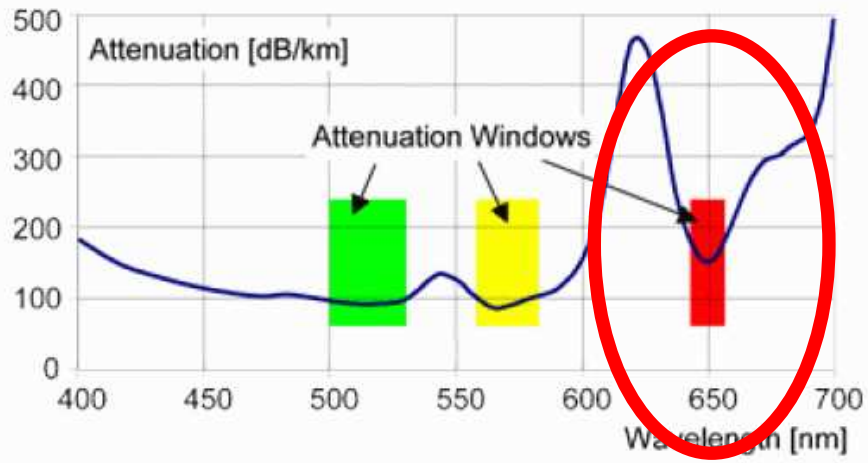
- Passive star network



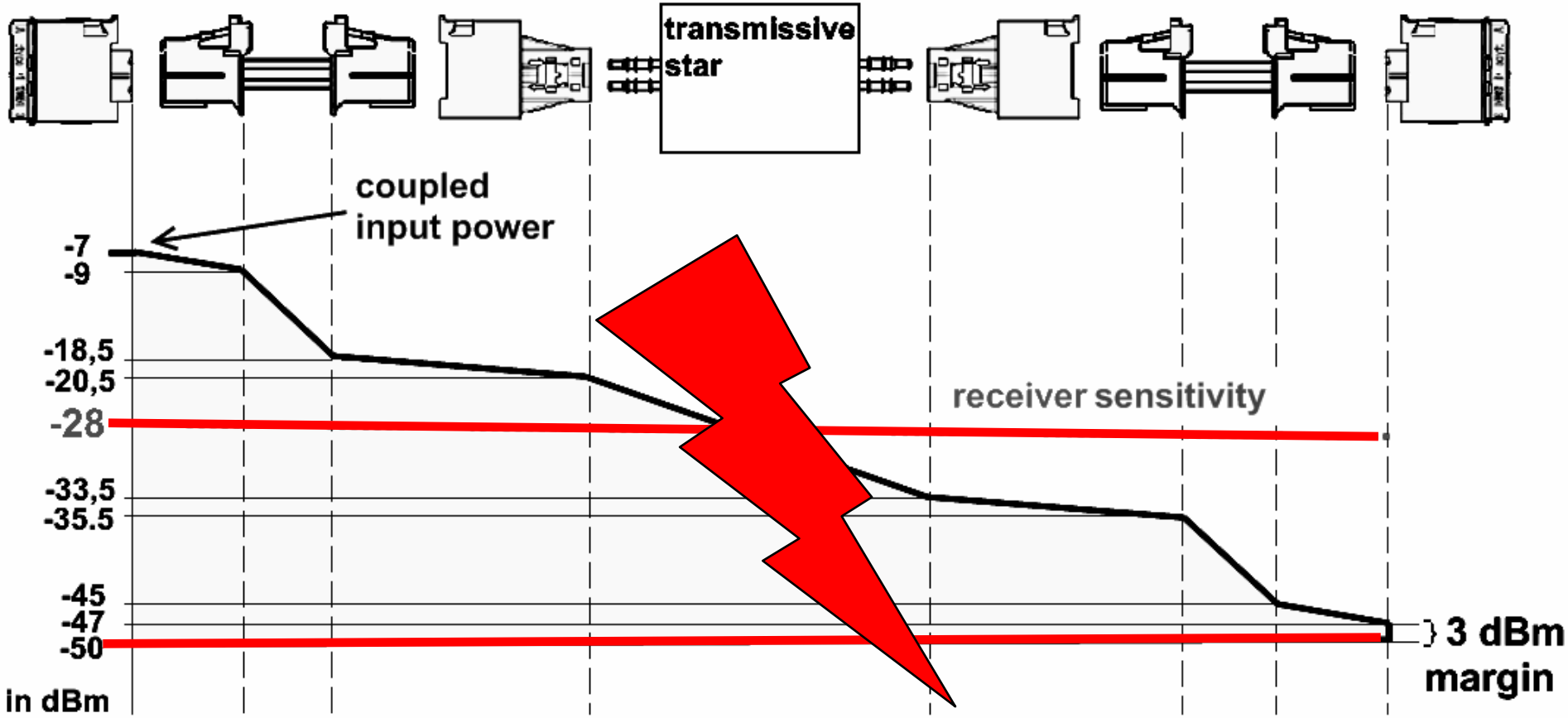
POF

- Simple connector fitting
- Low price
- Robustness
- 650 nm attenuation of ~0.19 dB/m





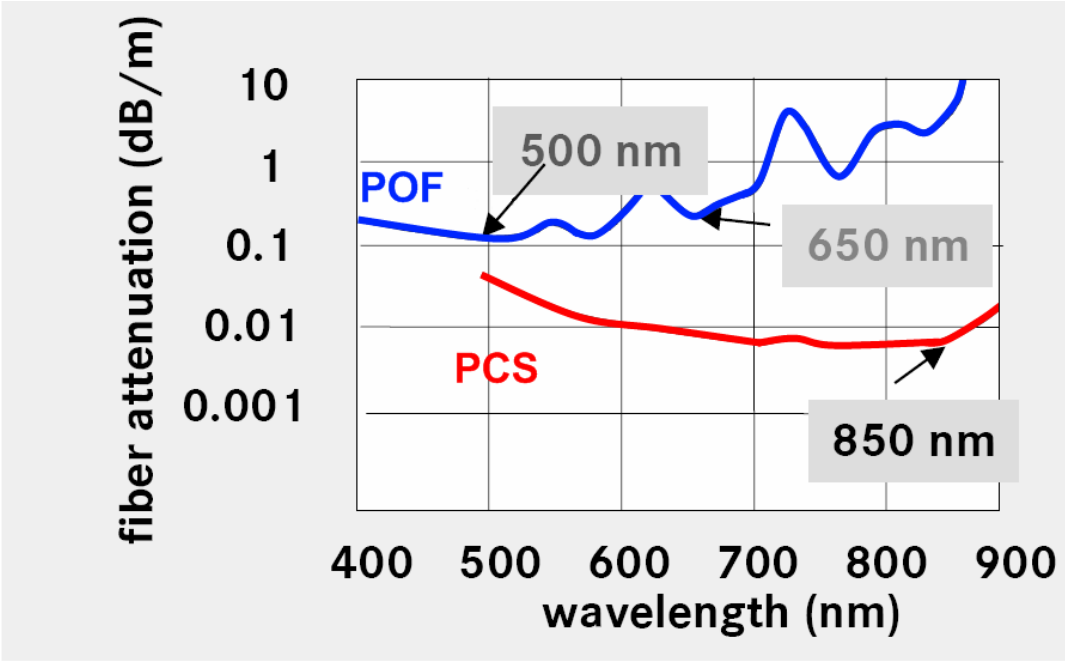
POF - Problems

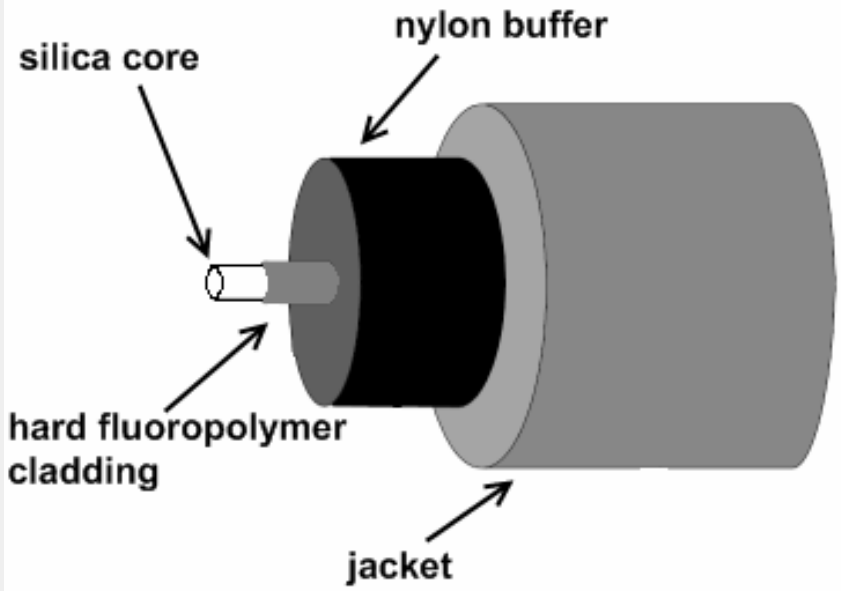


– Optical power budget POF

Polymer-Clad-Silica Fibers

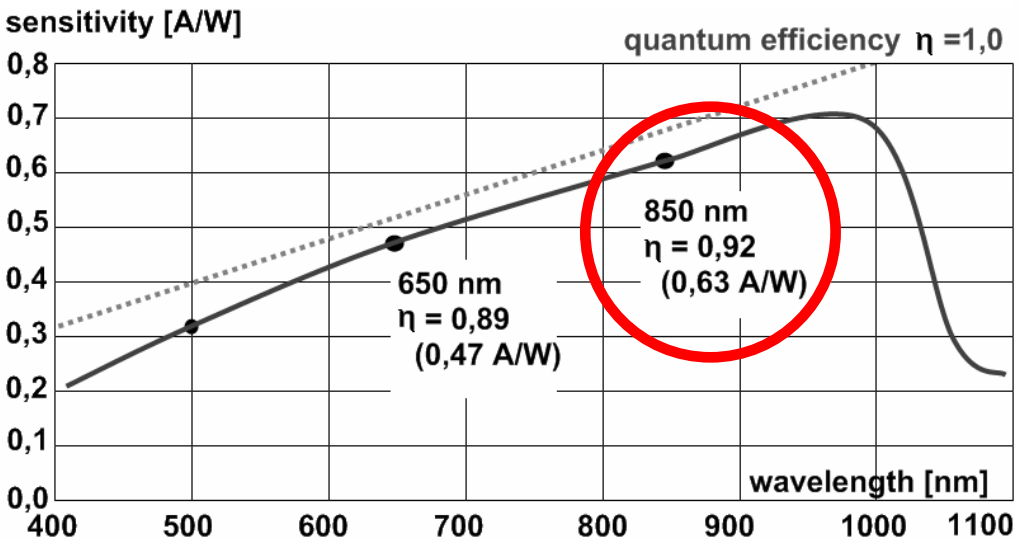
- Combines the POF advantages with the standard silica fiber advantages
  - Low attenuation (0.008 dB/m at 850 nm)
  - Good connector fitting
  - Robust 200 µm step index fiber

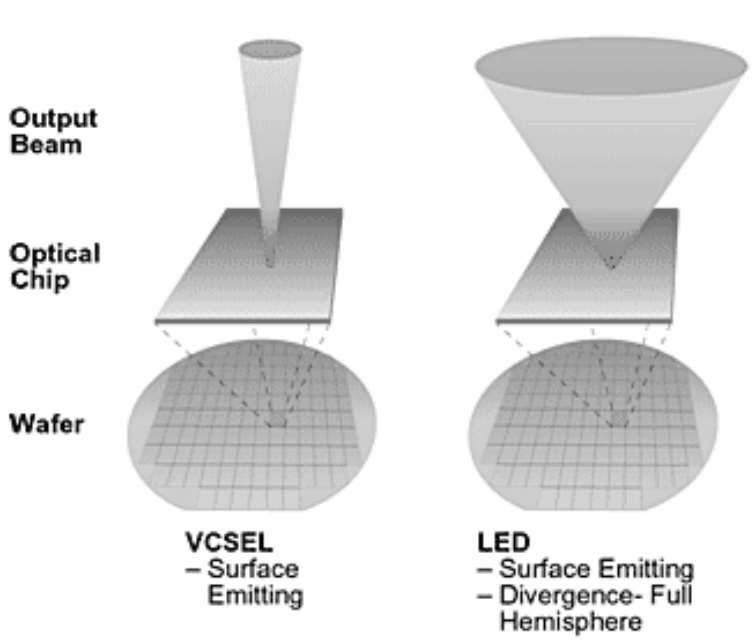




Vertical-Cavity Surface-Emitting Laser (VCSEL)

- Small output beam divergence
  - high coupling efficiency
- Low current consumption
- Small spectral width
- 850 nm VCSEL
  - higher receiver relative sensitivity





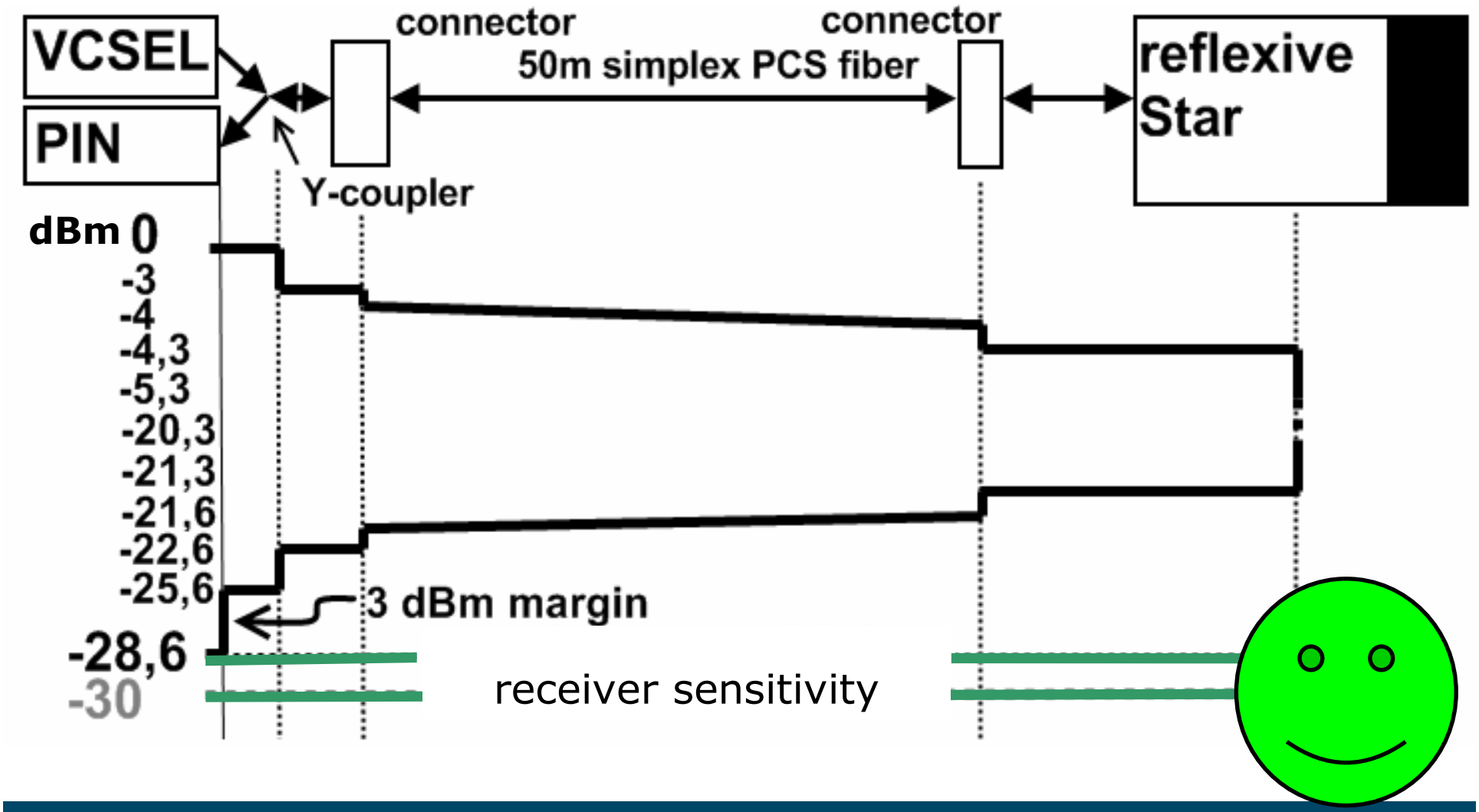
VCSEL and PCS

- Higher output power
  - above 0 dBm
- Better receiver sensitivity
  - about -30 dBm
- Low fiber attenuation
  - about 0.8 dB / 100 m instead of 19 dB / 100 m (POF)

} **30 dB link budget (incl. 3 dB margin)**

- Additional design options, like reflexive optical star
- → Less fibers needed, less weight

VCSEL and PCS

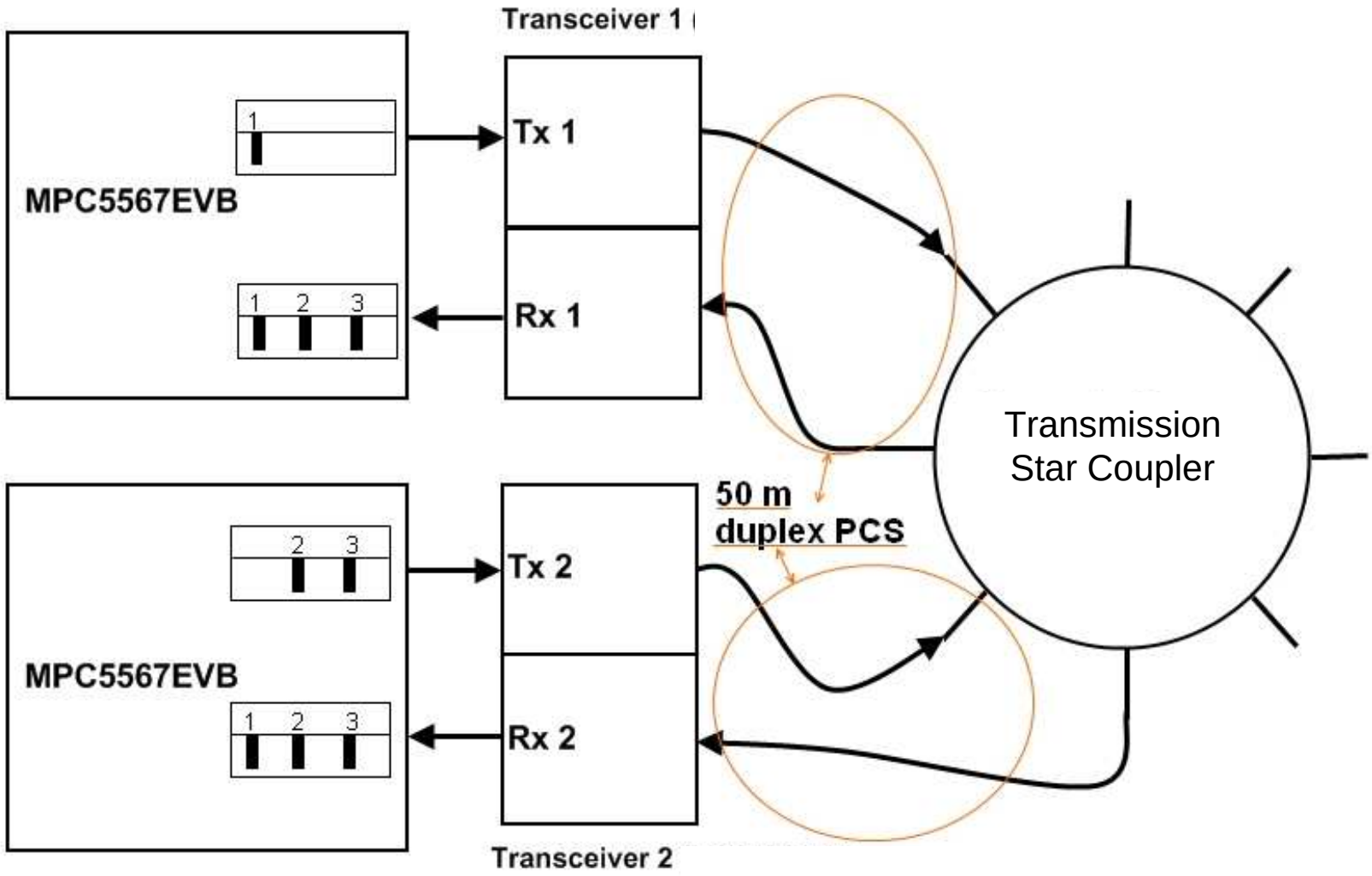


Aircraft Related Conclusions

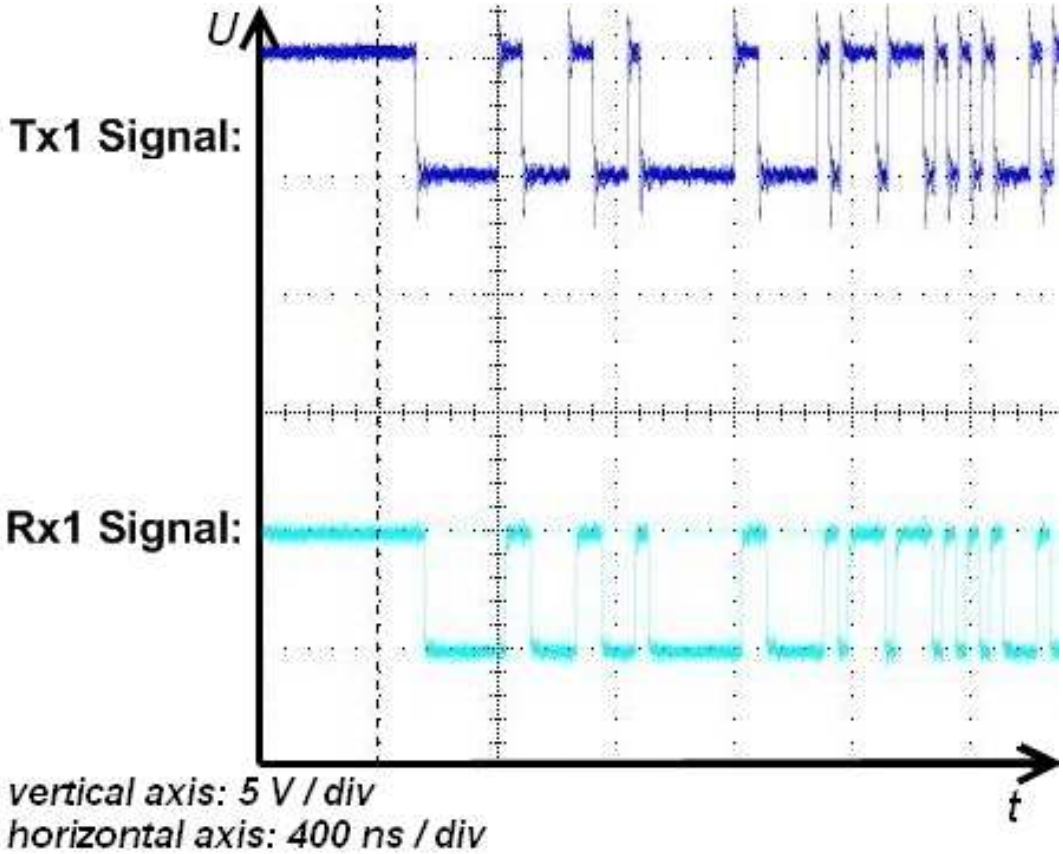
- More and more carbon-fiber fuselage components
  - stronger lightning influences
    - more problems in signal transmission

- Adequate optical solutions have to be used
  - simple point-to-point connections → POF + LED
  - complex optical networks over the whole plane → PCS + VCSEL

Prototype



Transmitted Data Signal



Application Roadmap for Automotive Data Buses

- Telematics (MOST)
- ring network
- passenger compartment
- 22.5 MBit/s

2002

- Telematics (MOST III) 150 MBit/s

(2007 MOST 150)

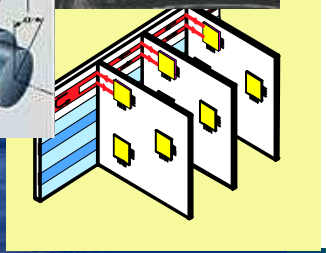
2007-2009

20XX

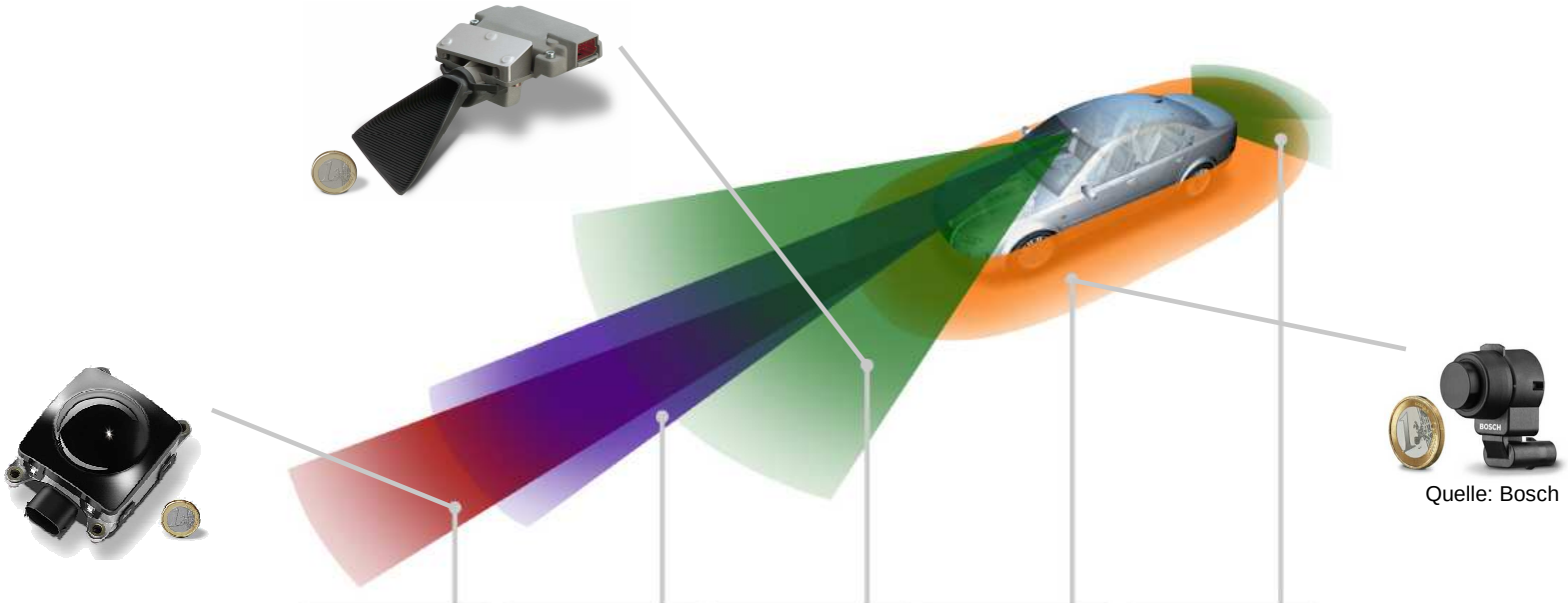
- x-by-wire
- engine management
- sensor networks for safety applications
- T > 85℃

20XX

- complex video processing systems for driver assistance
- Gbit/s



Sensors for Vehicle Environment Investigation

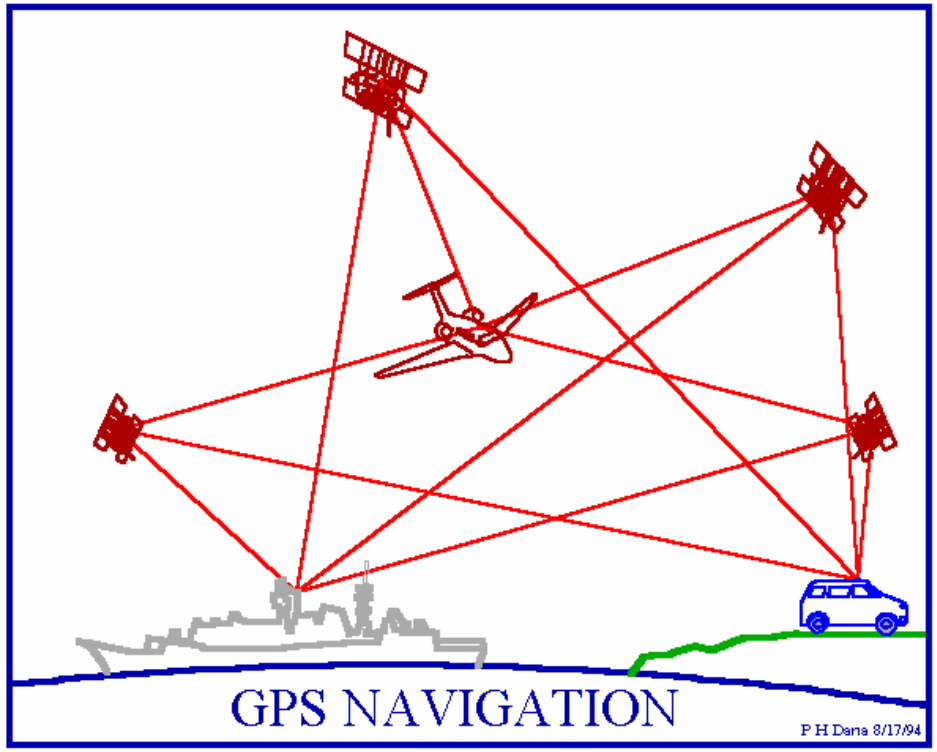


Quelle: Bosch

- Long-Range Radar Infrared Video Ultrasonic Video
- Long Distance Area Night Vision Medium Area Near Area Rear Area
- < 200 m < 150 m < 80m < 4m

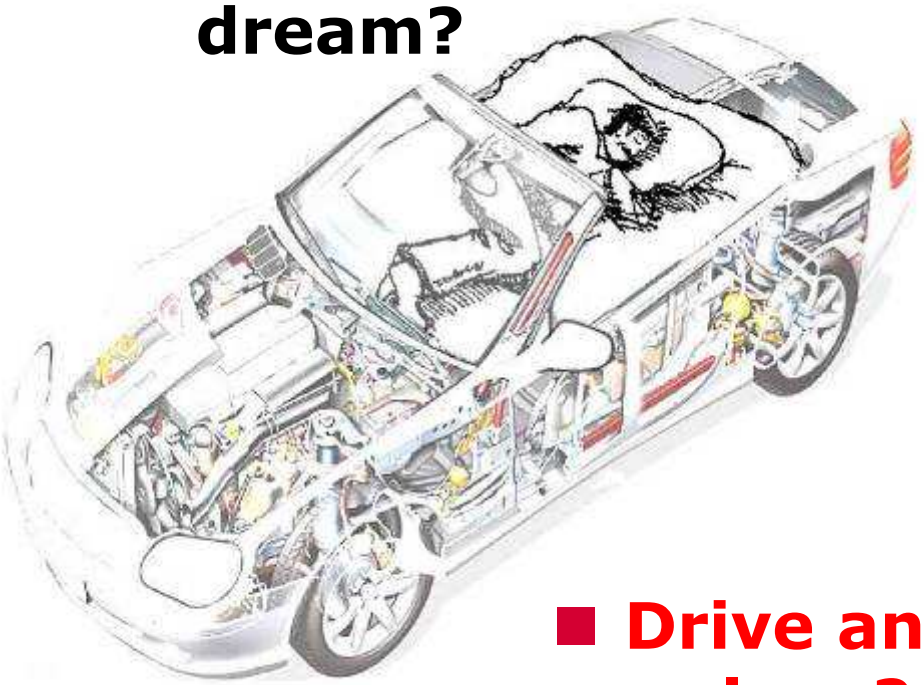
Global Positioning System

GPS Satellite in orbit



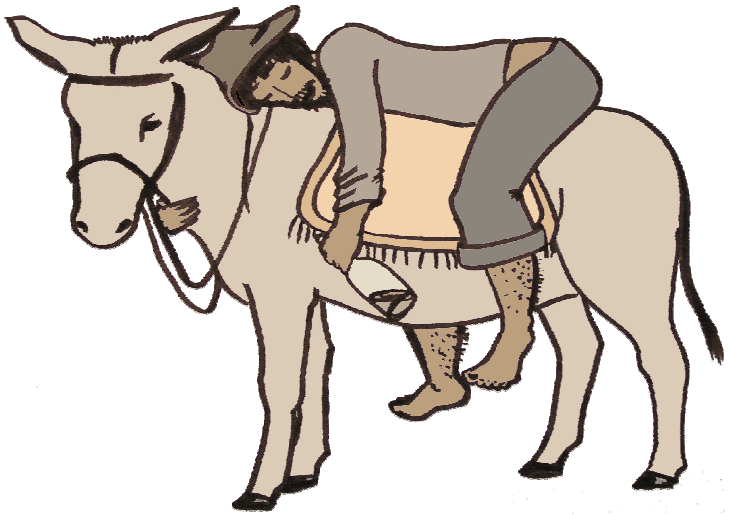
Final Technology for Autonomous Locomotion

- **Autonomous driving a dream?**



- **Drive and sleep?**

- **The donkey brings you home!**



Diploma Thesis Daniel Seibl

University of Appl. Sciences
in cooperation with

MBtech
Mercedes-Benz technology

Internship Uwe Strauß
Bachelor Thesis Jan Lubkoll

University of Appl. Sciences
in cooperation with

DIEHL
Aerospace

Thank you for your attention!

Otto Strobel

http://www2.hs-esslingen.de/~strobel/