TECHNICAL UNIVERSITY
OF CLUJ-NAPOCA
ROMANIA

Faculty of Electronics, Telecom and Info Technology

Lecture 2

Optoelectronic Systems for Telecom (SOT)

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Drd Loredana Buzura
Basis of Electronics Department

Outlines

- Photonics: motivation
  - Photonics for 5G
  - Industry 4.0
  - Quantum computing
- Introduction to optical communications (OC)
  - Basic concepts (ray and wave optics)
  - Dispersion types
  - Historical perspective

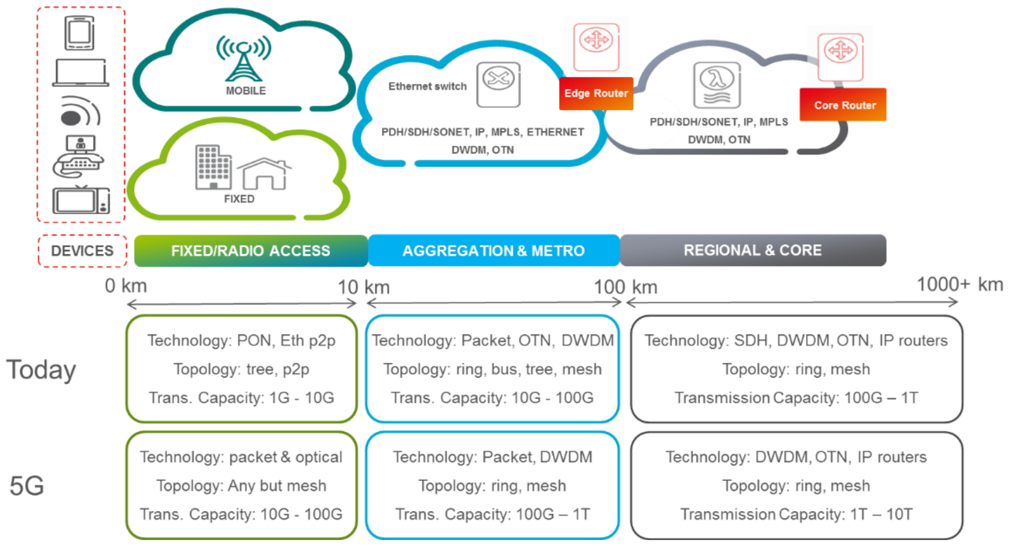
- Structure of optical fibers
- Ray picture of fiber optic transmission
  - Snell's Law, Total internal reflection
- Wave picture of fiber optic transmission
  - Modes, multimode and single mode fibers
- Attenuation in optical fibers
- Dispersion in optical fibers

Recommendation Maxwell Equations – electromagnetic waves, prof Tiusan Coriolan, Physics Department TUCN: https://web.microsoftstream.com/video/54cf301b-f11e-47d2-8faa-849f567939c9?list=user&userId=e1bb802a-7e81-48da-ab4c-c83119a08622

I. Motivation and perspective

- **Photonics for 5G**
- References:

Robero Sabella, *Ericsson,* IEEE 5G Tech Focus: Volume 2, Number 2, May 2018, https://futurenetworks.ieee.org/tech-focus/may-2018/photonics-for-5g-networks



	FIXED/RADIO ACCESS	AGGREGATION & METRO	REGIONAL & CORE
Today	Technology: PON, Eth p2p Topology: tree, p2p Trans. Capacity: 1G - 10G	Technology: Packet, OTN, DWDM Topology: ring, bus, tree, mesh Trans. Capacity: 10G - 100G	Technology: SDH, DWDM, OTN, IP routers Topology: ring, mesh Transmission Capacity: 100G – 1T
5G	Technology: packet & optical Topology: Any but mesh Trans. Capacity: 10G - 100G	Technology: Packet, DWDM Topology: ring, mesh Trans. Capacity: 100G – 1T	Technology: DWDM, OTN, IP routers Topology: ring, mesh Transmission Capacity: 1T – 10T

Photonic technology will play a key role in 5G networks in different contexts. In 5G transport it will allow the transmission and routing of **huge amounts of data traffic at an acceptable cost** and the transformation of the radio access network. In **data center, photonic interconnect and switching will allow the realization of a new architecture able to strongly reduce the energy consumption while providing a high level of flexibility in resource utilization**. In future hardware platforms, photonic **chip-to-chip interconnect** will allow a significant increase **of bandwidth density** leading to dramatically scaled up global capacity of those platforms. Integrated photonics will be a key technology to **realize components and modules at the right costs, while greatly reducing energy consumption and footprin**t.

Future photonics: 5G

- Jeff Hetch- Future Photonics: 5G—Optics will be indispensable for 5G networks, https://www.laserfocusworld.com/fiber-optics/article/14074687/optics-will-be-indispensable-for-5g-networks
- https://www.laserfocusworld.com/home/contact/16572176/jeff-hecht
- Annual Laser Market Review & Forecast 2020: Laser markets navigate turbulent times, https://www.laserfocusworld.com/lasers-sources/article/14073907/laser-markets-navigate-turbulent-times

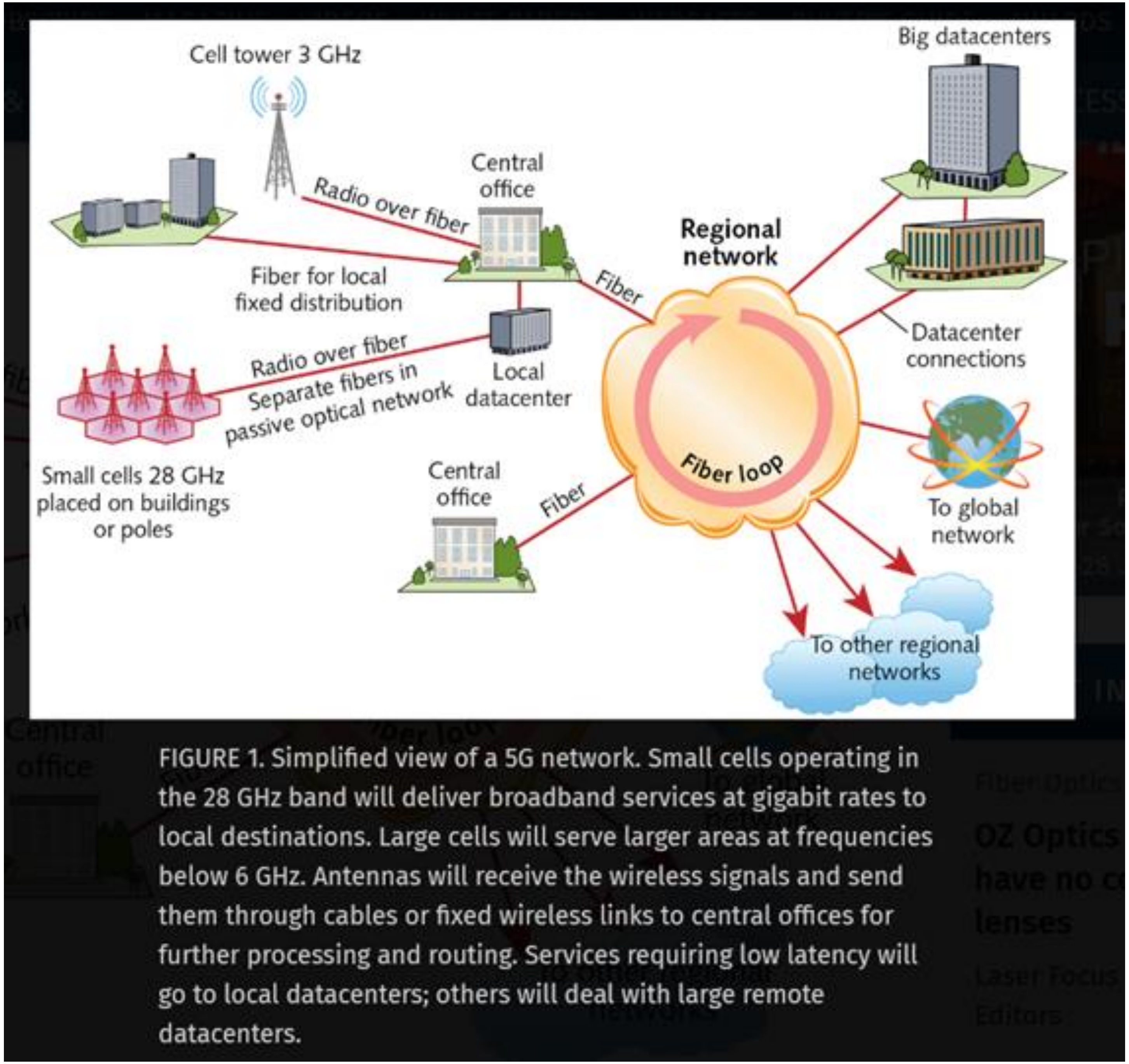


FIGURE 1. Simplified view of a 5G network. Small cells operating in the 28 GHz band will deliver broadband services at gigabit rates to local destinations. Large cells will serve larger areas at frequencies below 6 GHz. Antennas will receive the wireless signals and send them through cables or fixed wireless links to central offices for further processing and routing. Services requiring low latency will go to local datacenters; others will deal with large remote datacenters.

Self-driving vehicles: Many challenges remain for autonomous navigation

- https://www.laserfocusworld.com/test-measurement/article/14169619/selfdriving-vehicles-many-challenges-remain-for-autonomous-navigation

- https://www.laserfocusworld.com/blogs/article/14040682/safety-questions-raised-about-1550-nm-lidar

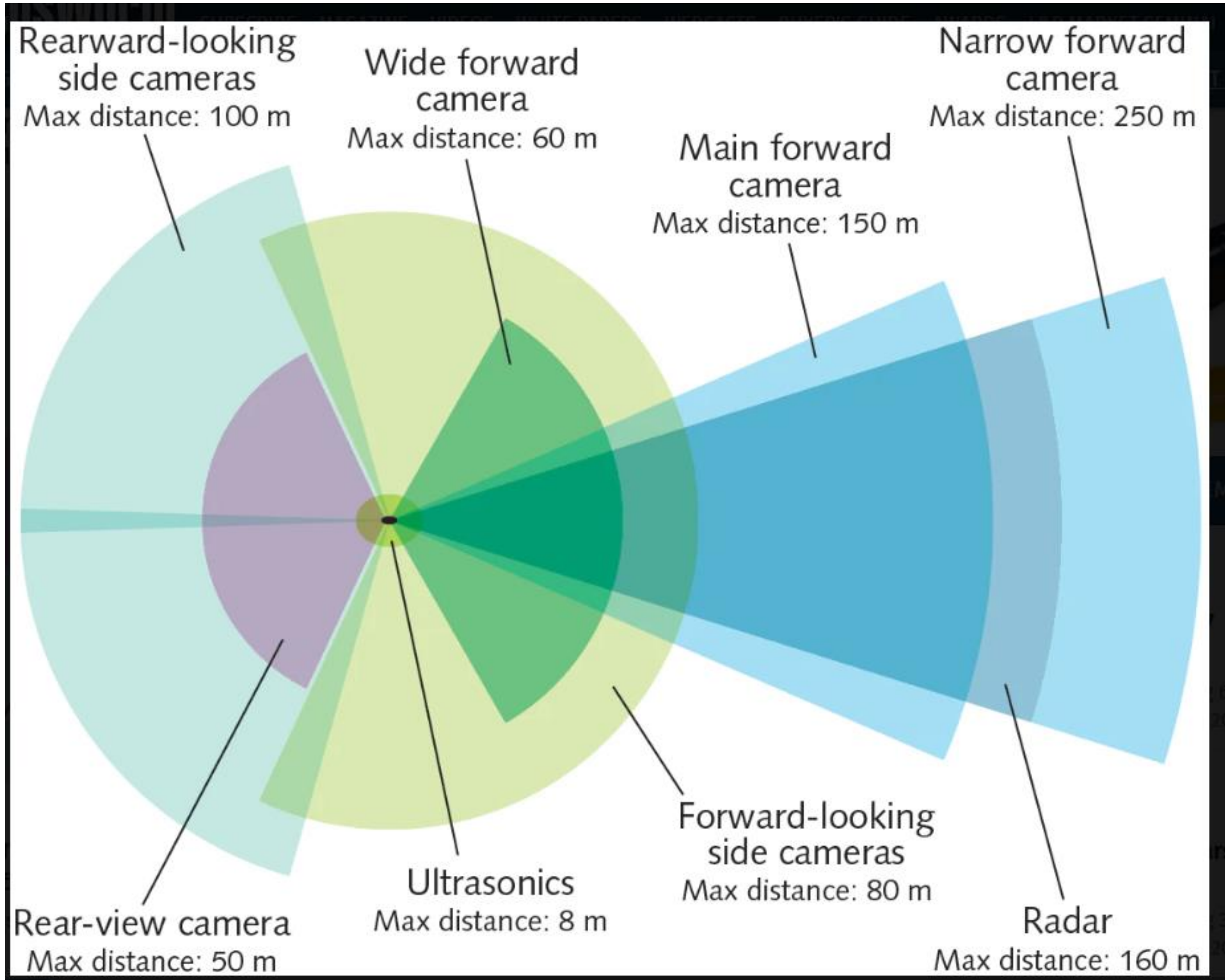


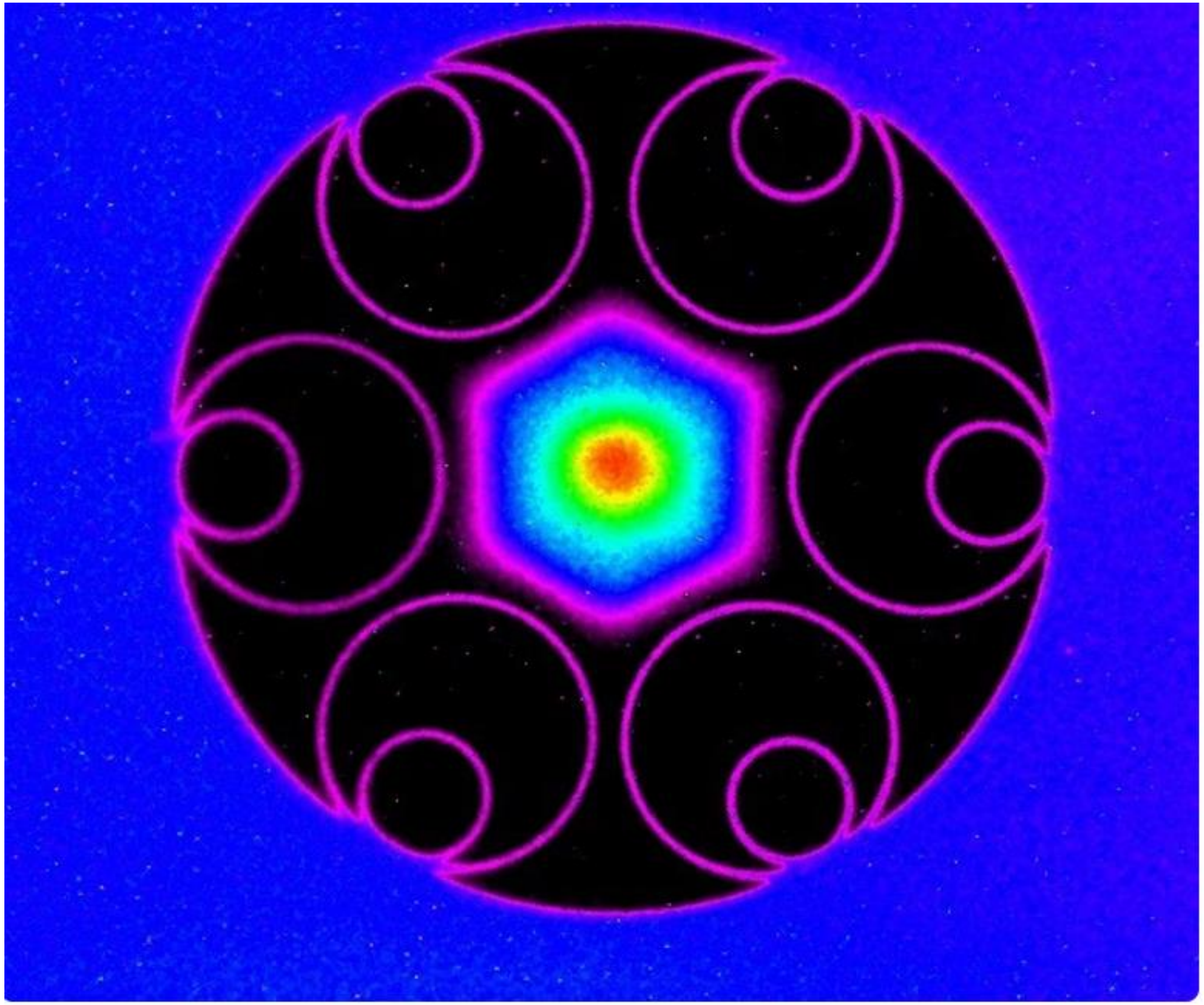
FIGURE 1. Ranges of sensors used in Tesla Autopilot.

Optical Fiber for Telecommunications: Hollow-core fiber loss below 1 dB/km could lead to applications

https://www.laserfocusworld.com/fiber-optics/article/14069142/hollowcore-fiber-loss-below-1-dbkm-could-lead-to-applications

Trans oceanic USA-France:

https://www.theregister.com/2018/07/18/google_dunant_cable/

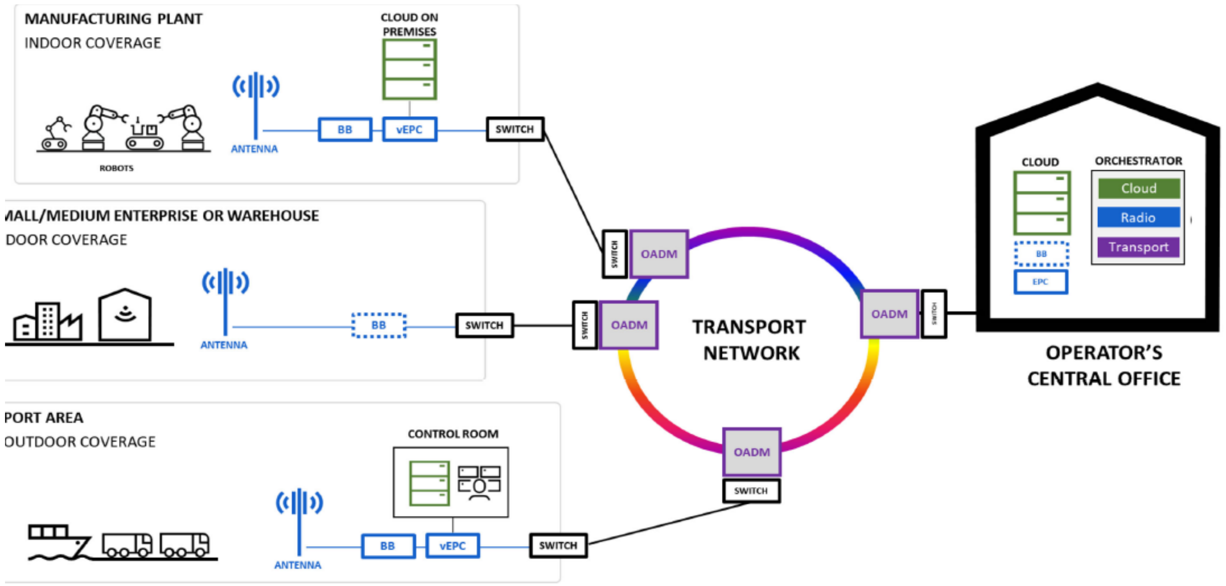


Microscopic cross-section of the record-setting low-loss hollow-core fiber. Thin hollow glass cylinders shown in pink run the length of the fiber, effectively creating bars that prevent the hexagonal light modes trapped in the center of

Optical transport for Industry 4.0 [Invited]

Roberto Sabella,†,* Paola Iovanna, Giulio Bottari, AND Fabio Cavaliere
Ericsson Research, Pisa, Italy

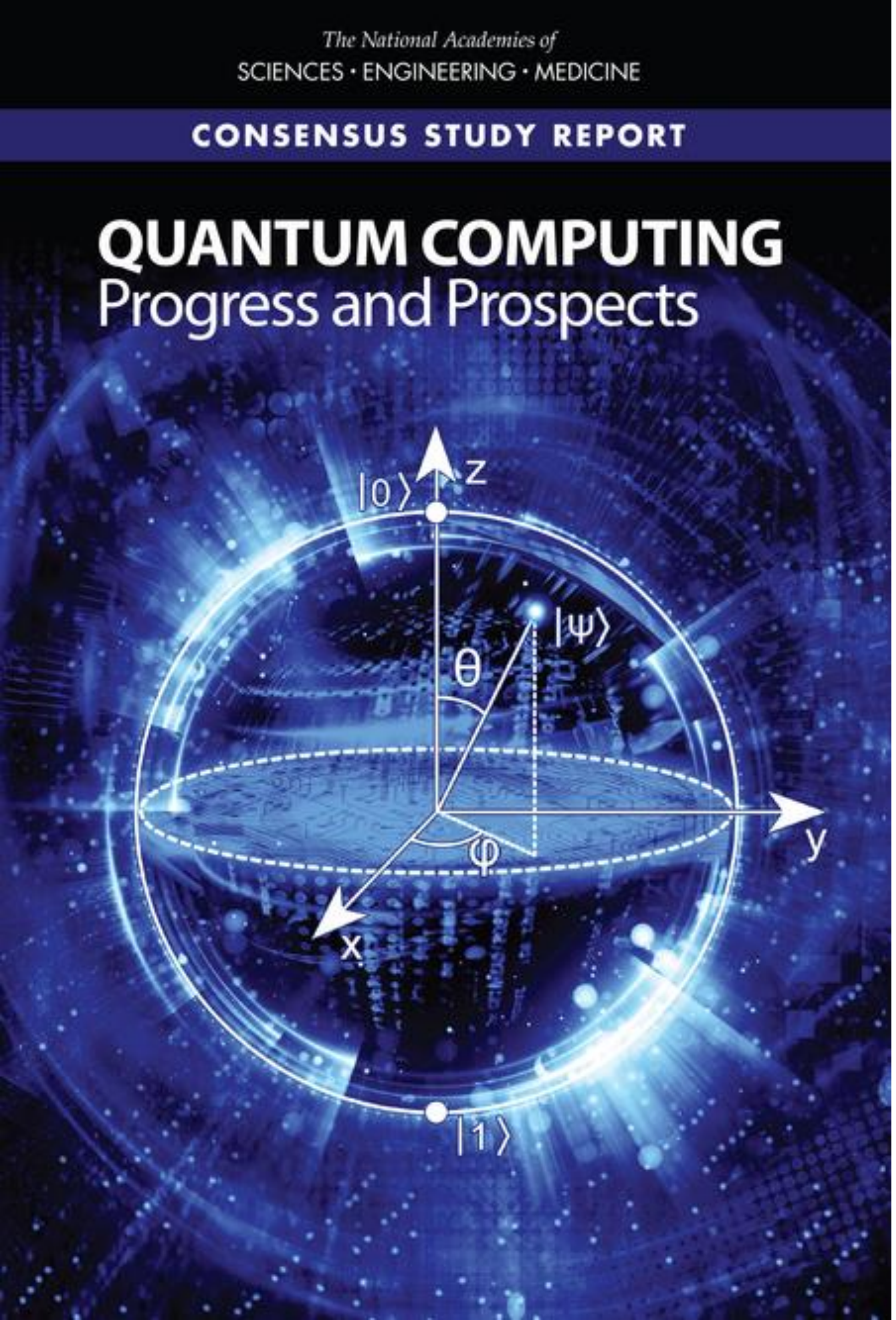
https://tendercapital.com/en/industry-4-0-the-future-of-the-connected-factory/
https://www.ericsson.com/en/blog/2018/10/cyber-physical-systems-for-industry-4.0
https://www.ericsson.com/en/blog/2018/2/step-inside-the-future-factory



3. Example of a transport network scenario [28] to serve different vertical needs.

Towards optical quantum computing-MIT Press, http://news.mit.edu/2017/toward-optical-quantum-computing-0616

- in the latest issue of *Physical Review Letters*, MIT researchers describe a new technique for enabling photon-photon interactions at room temperature, using a silicon crystal with distinctive patterns etched into it. In physics jargon, the crystal introduces “nonlinearities” into the transmission of an optical signal.

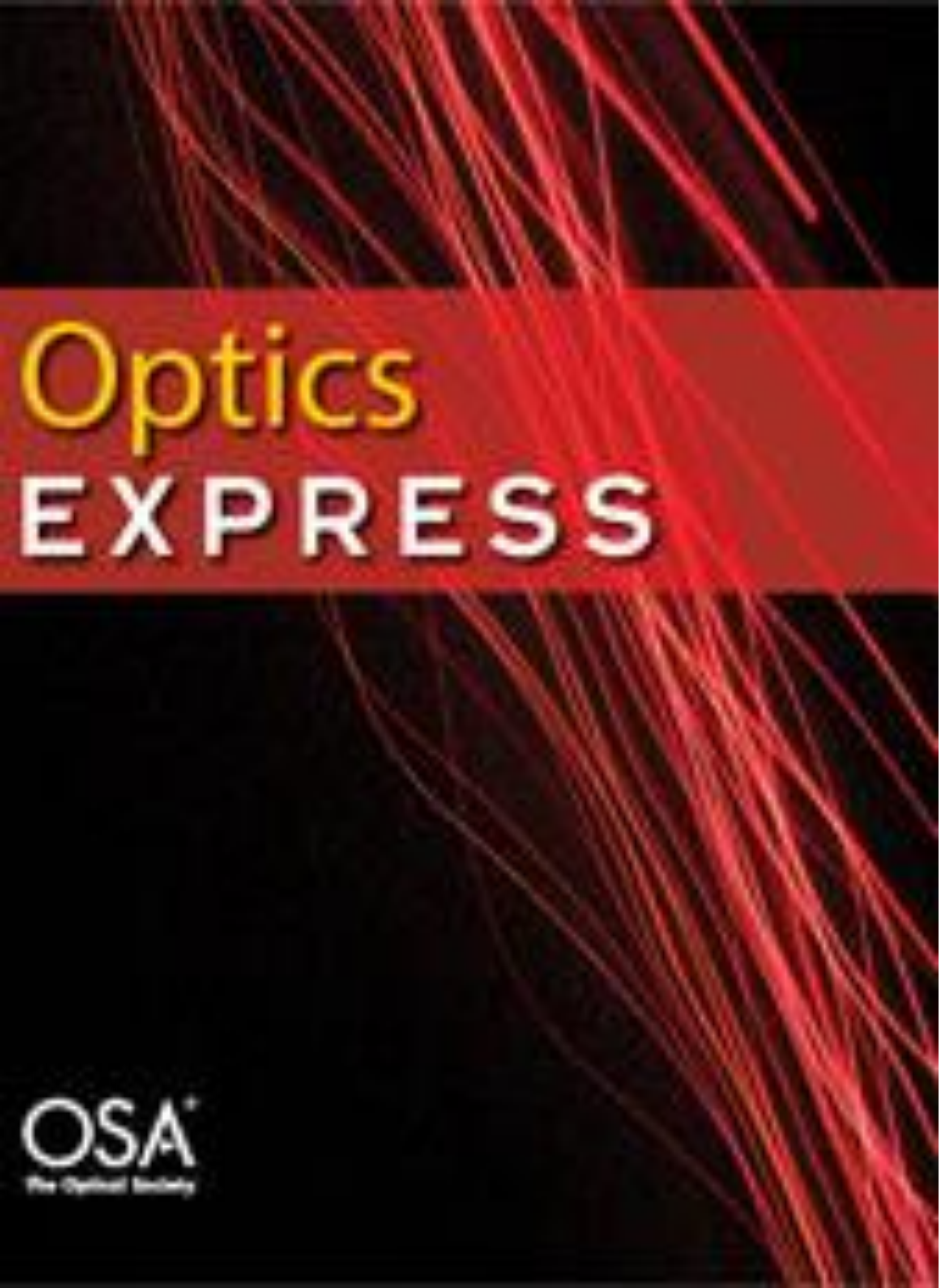

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

QUANTUM COMPUTING
Progress and Prospects

Recommended bibliography (2019)- https://www.nap.edu/read/25196/chapter/7

- A strategy for connecting multiple qubit subsystems into a much larger system is to use quantum communication channels. One viable approach involves preparing one of the ions in a subsystem in a particular excited state and inducing it to emit a photon in such a way that **the quantum state of the photon (for example, its polarization or frequency)** is entangled with the ion qubit [25,26]. Two identical setups are used in the two subsystems to generate one photon from each ion, and the two photons can be interfered on a 50/50 beamsplitter and detected on the output ports of the beamsplitter. When both output ports simultaneously record detection of a photon [27], it signals that the two ions that generated the photons have been prepared in a maximally entangled state [28,29].



Fiber-optic transmission and networking: the previous 20 and the next 20 years [Invited]

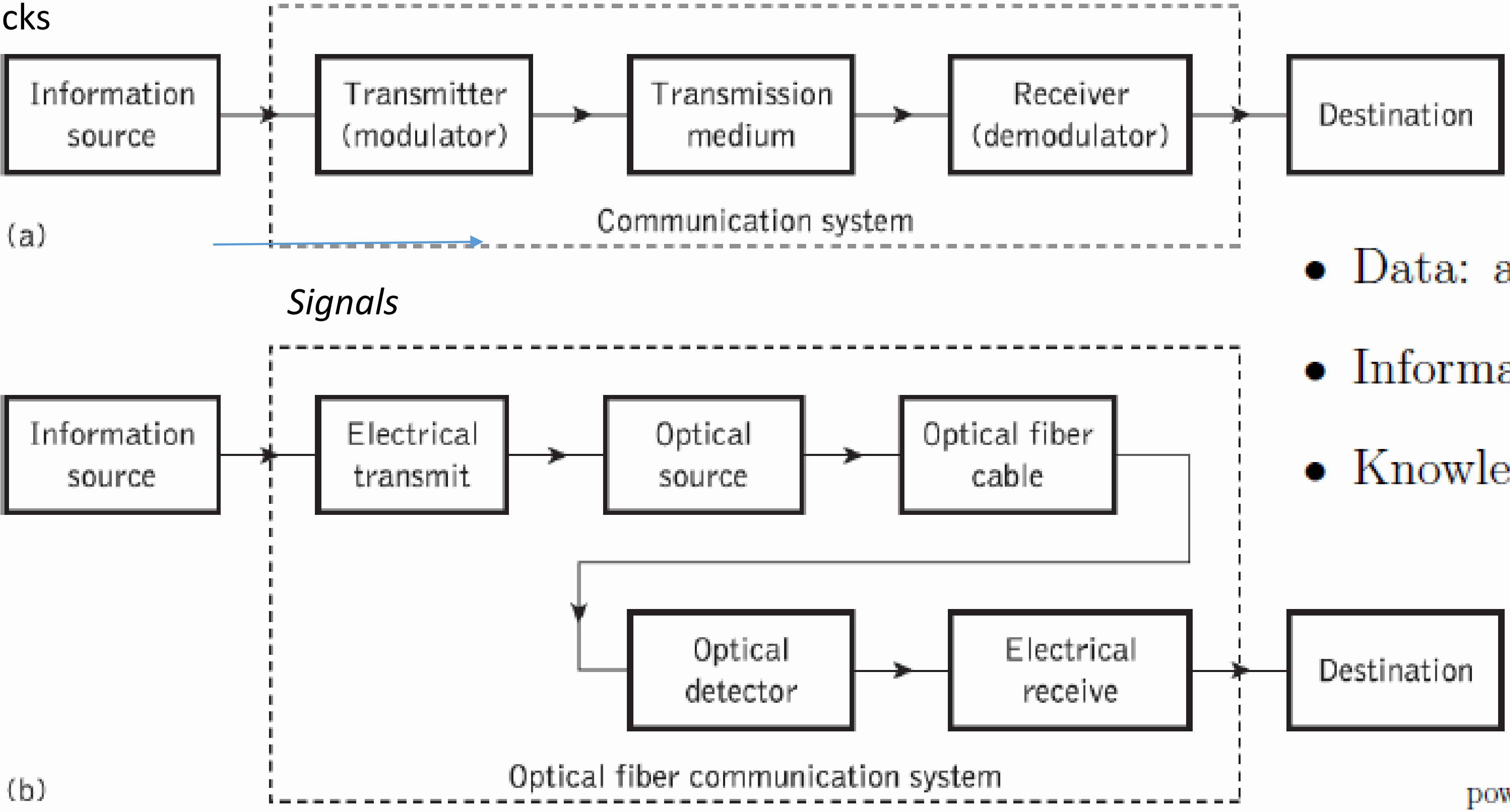
Peter J. Winzer, David T. Neilson, and Andrew R. Chraplyvy , 2018, Optics Express (open access)

https://www.osapublishing.org/oe/abstract.cfm?uri=oe-26-18-24190

Abstract: Focusing on the optical transport and switching layer, we cover aspects of large-scale spatial multiplexing, massive opto-electronic arrays and holistic optics-electronics-DSP integration, as well as optical node architectures for switching and multiplexing of spatial and spectral superchannels.

II. Introduction to optical communications (OC)

spoken words, a still or moving image, the measurement of a physical characteristic, or values of bank accounts or stocks



- Data: any recorded event
- Information: acquired data
- Knowledge: useful data

$$\mathrm{SNR} = 10\log_{10}(P_S/P_N)$$

$$\text{power (in dBm)} = 10\log_{10}\left(\frac{\text{power}}{1\ \text{mW}}\right),$$

Information, message, data, signals

Information has to do with the content or interpretation of something such as spoken words, a still or moving image, the measurement of a physical characteristic, or values of bank accounts or stocks.

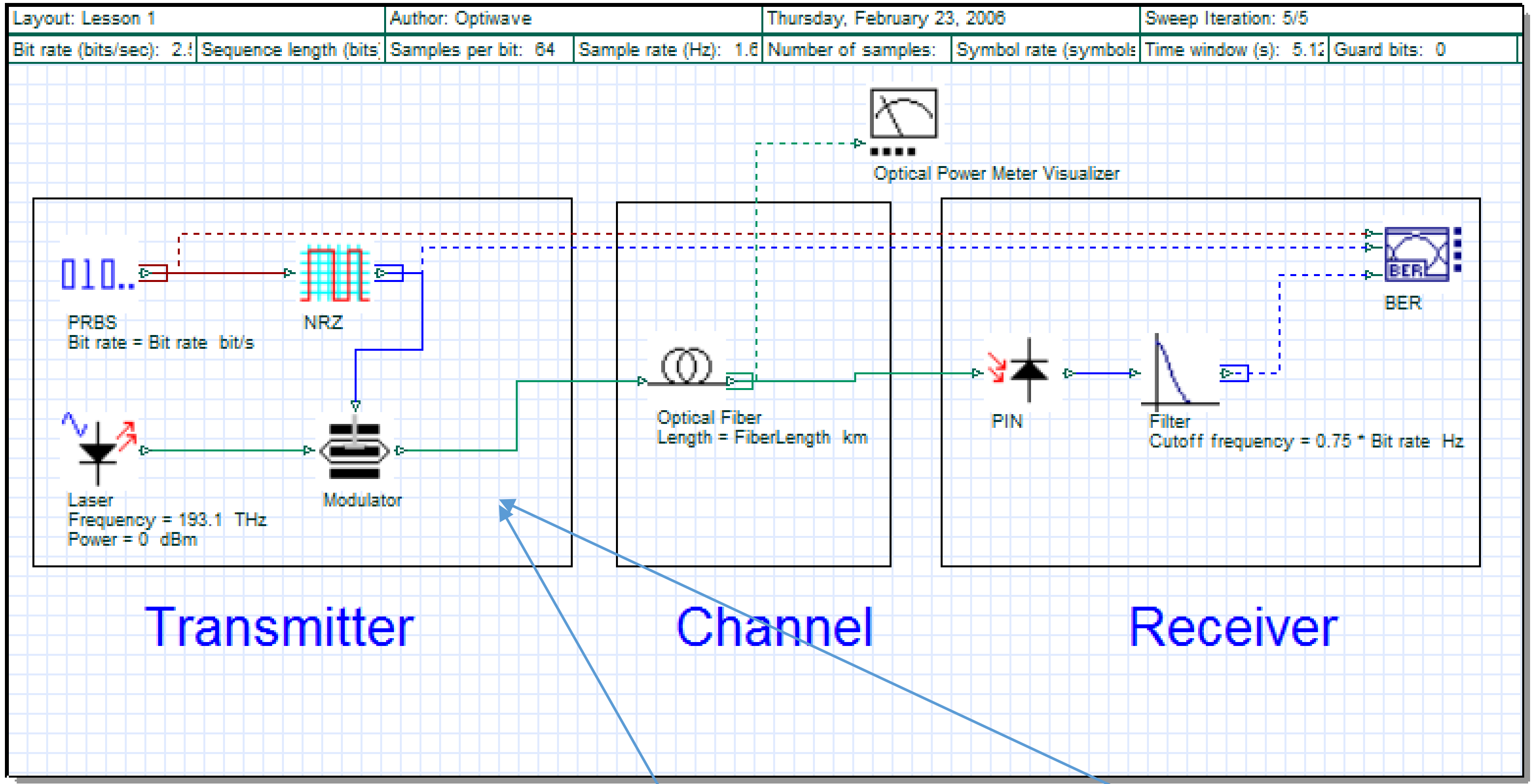
■ A *message* may be considered as the physical manifestation of the information produced by the source. That is, it can range from a single number or symbol to a long string of sentences.

■ The word *data* refers to facts, concepts, or instructions presented as some type of encoded entities that are used to convey the information. These can include arrays of integers, lines of text, video frames, digital images, and so on. Although the words *data* and *message* each have a specific definition, these terms often are used interchangeably in the literature since they represent physical embodiments of information.

■ ***Signals* are electromagnetic waves (in encoded electrical or optical formats) used to transport the data over a physical medium**.

First Lab – Optiwave OptiPerformer

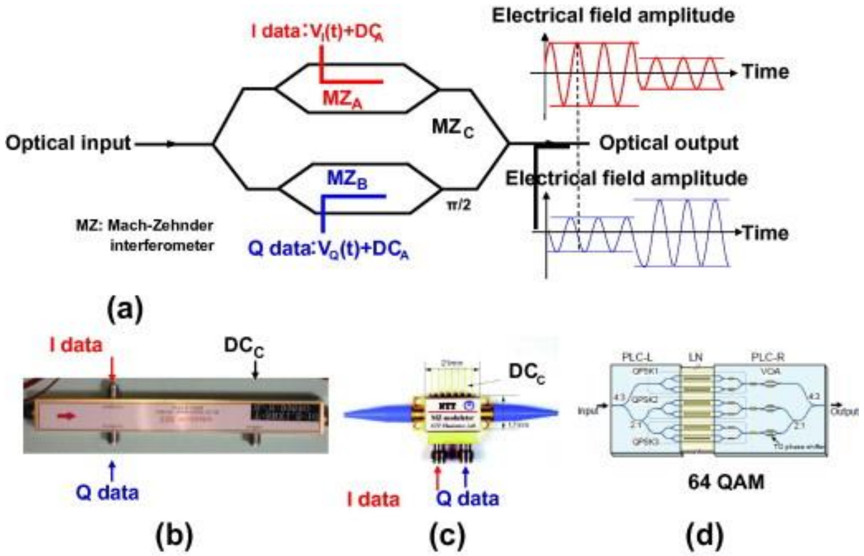
Attenuation may have influence on the BER – first attempt



Layout: Lesson 1	Author: Optiwave	Thursday, February 23, 2006	Sweep Iteration: 5/5

Bit rate (bits/sec): 2.!	Sequence length (bits	Samples per bit: 64	Sample rate (Hz): 1.6	Number of samples:	Symbol rate (symbols	Time window (s): 5.12	Guard bits: 0

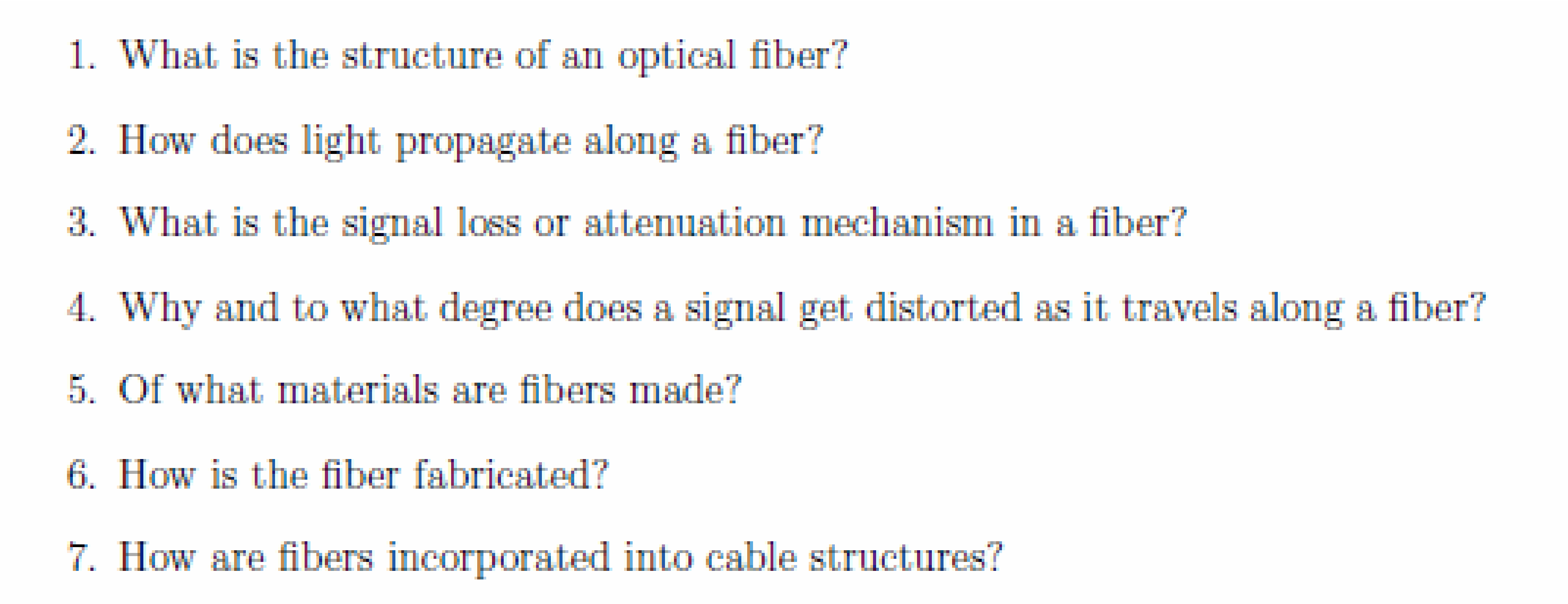
Modulation can be performed by Mach-Zehnder Modulator



Interferometers are investigative tools used in many fields of science and engineering. They are called interferometers because they work by merging two or more sources of light to create an interference pattern, which can be measured and analyzed; hence 'Interfere-o-meter', or interferometer.

Mach–Zehnder **interferometer** is a device used to determine the relative phase shift variations between two collimated beams derived by splitting light from a single source

Fibers and nature of light – basic concepts



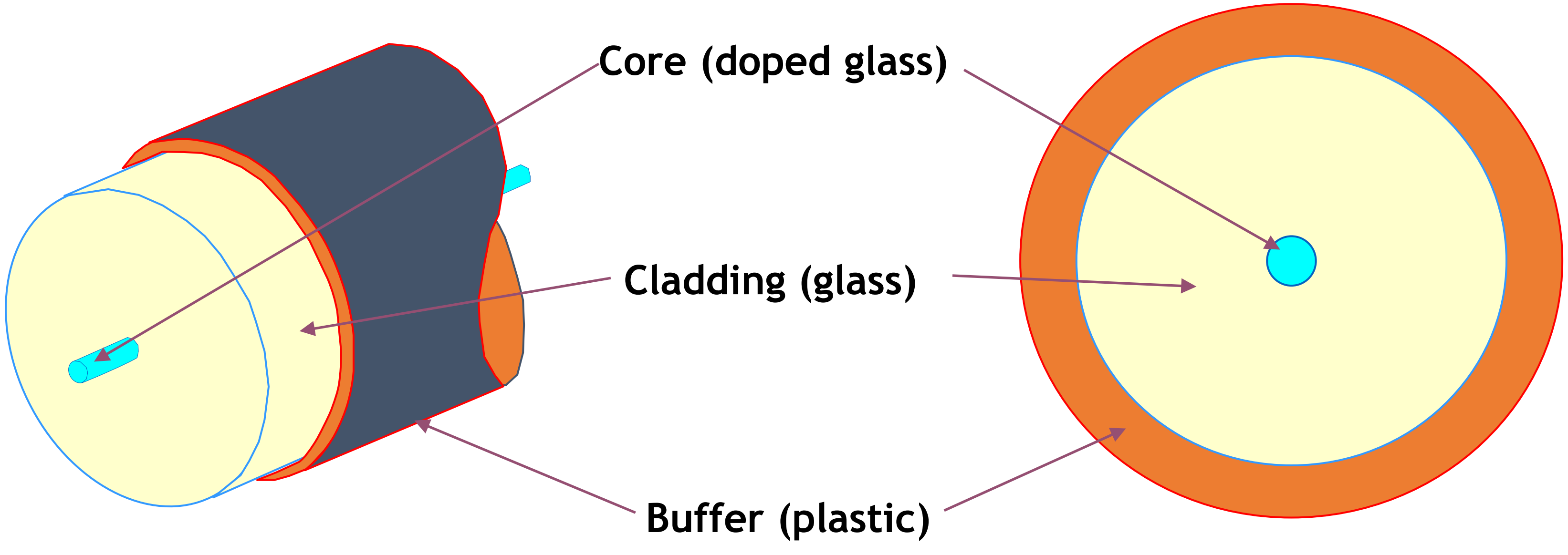
1. What is the structure of an optical fiber?
2. How does light propagate along a fiber?
3. What is the signal loss or attenuation mechanism in a fiber?
4. Why and to what degree does a signal get distorted as it travels along a fiber?
5. Of what materials are fibers made?
6. How is the fiber fabricated?
7. How are fibers incorporated into cable structures?

The Structure of an Optical Fiber

An optical fiber is made up of:

- Doped core: refractive index $n_1 \cong 1.5$
- Cladding: refractive index $n_1 > n_2$
- Buffer (or primary coating): protects fiber from damage

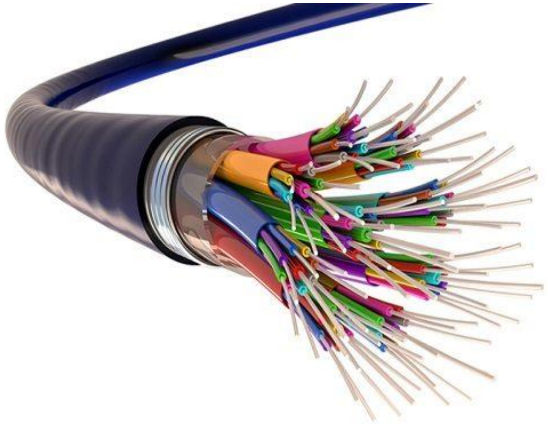
remember from Optoelectronics!!!



perspective view

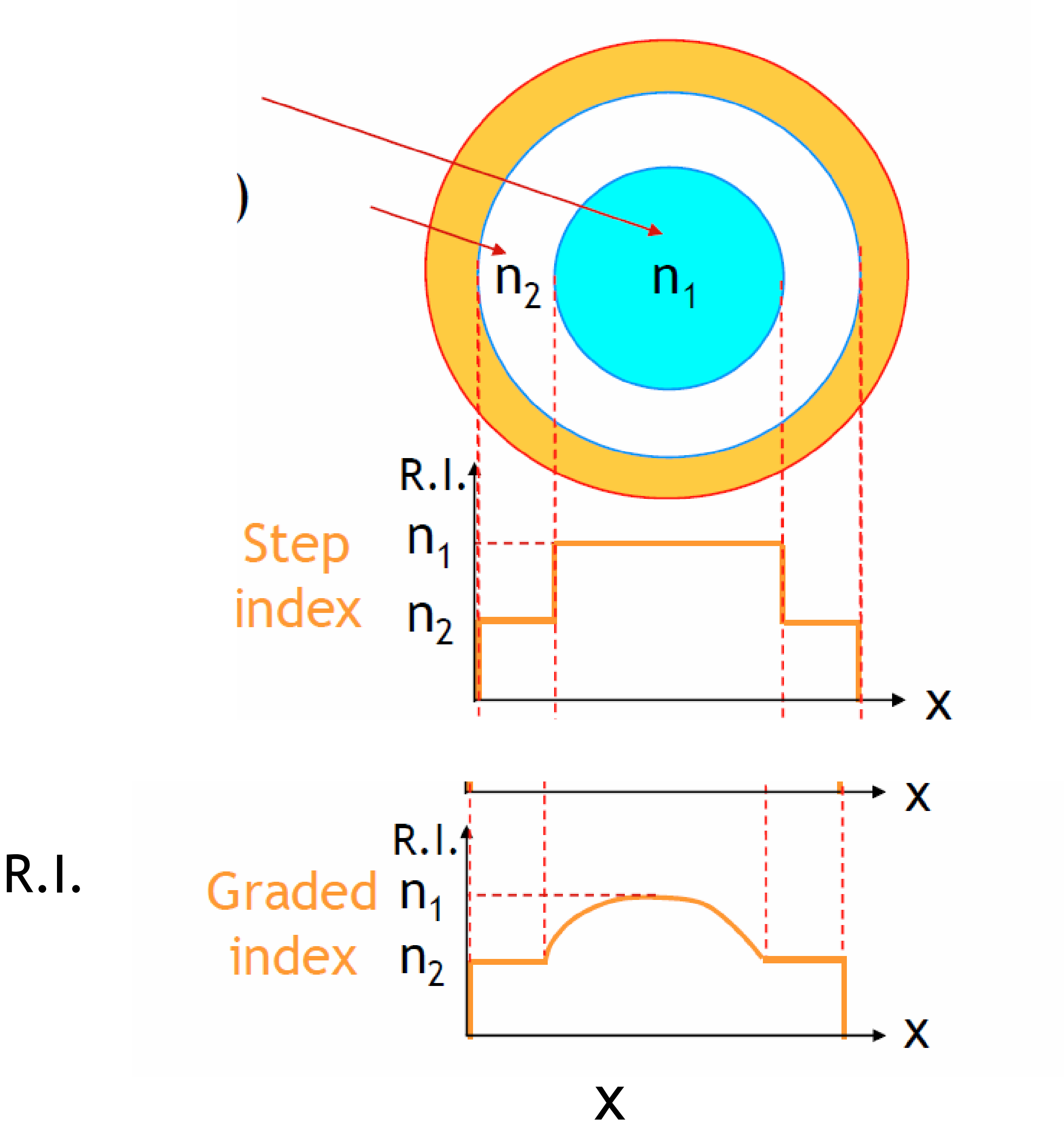
transverse section

Fiber <> Cable!!!!!!



Fiber Refractive Index Profile Concept

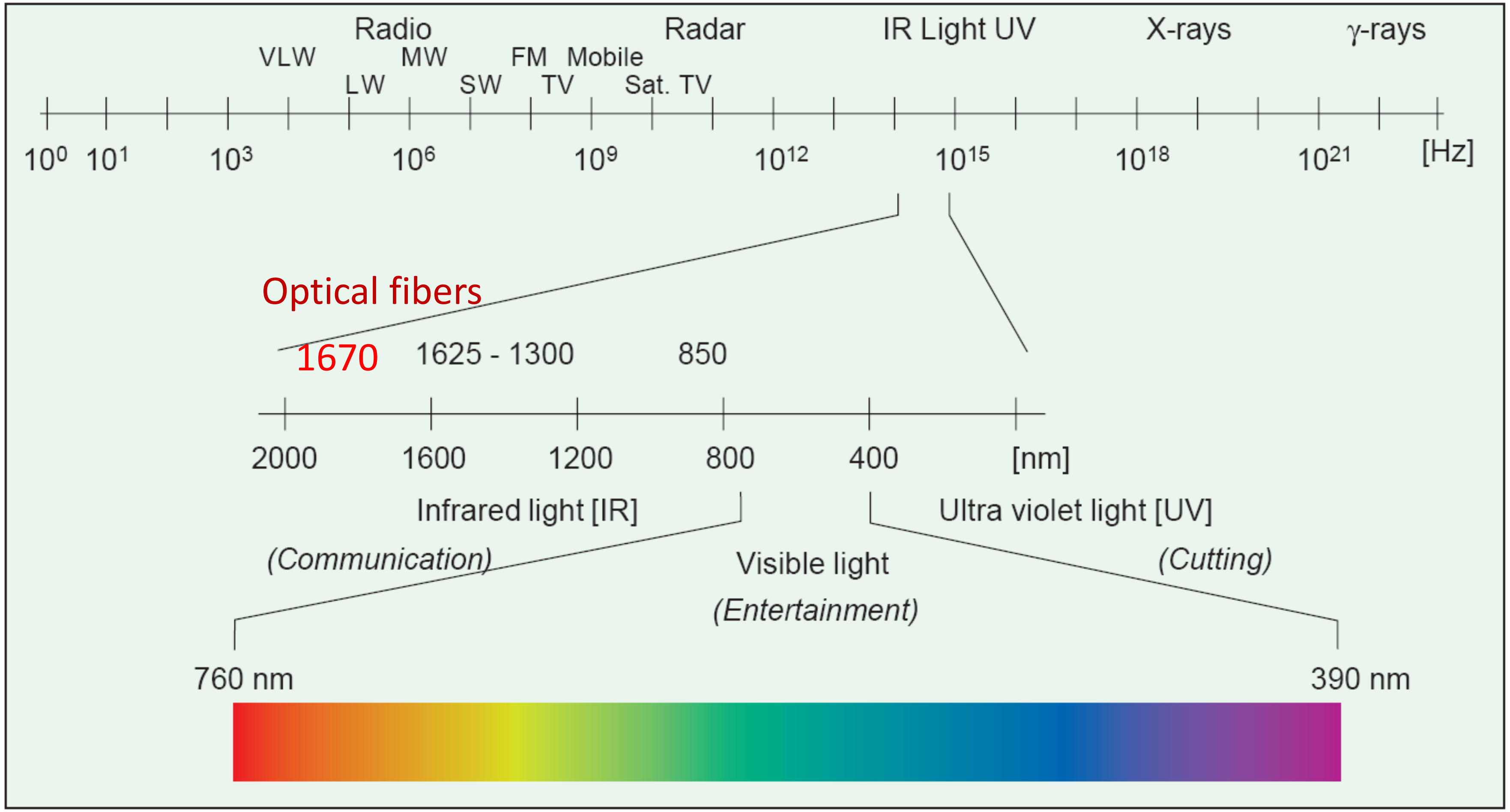
- Core Refractive Index (n_1)
- Cladding Refractive Index (n_2)
- Step Index Profile
- Graded Index Profile
- $n_1 - n_2 << 1$
- Question: Why different profiles?



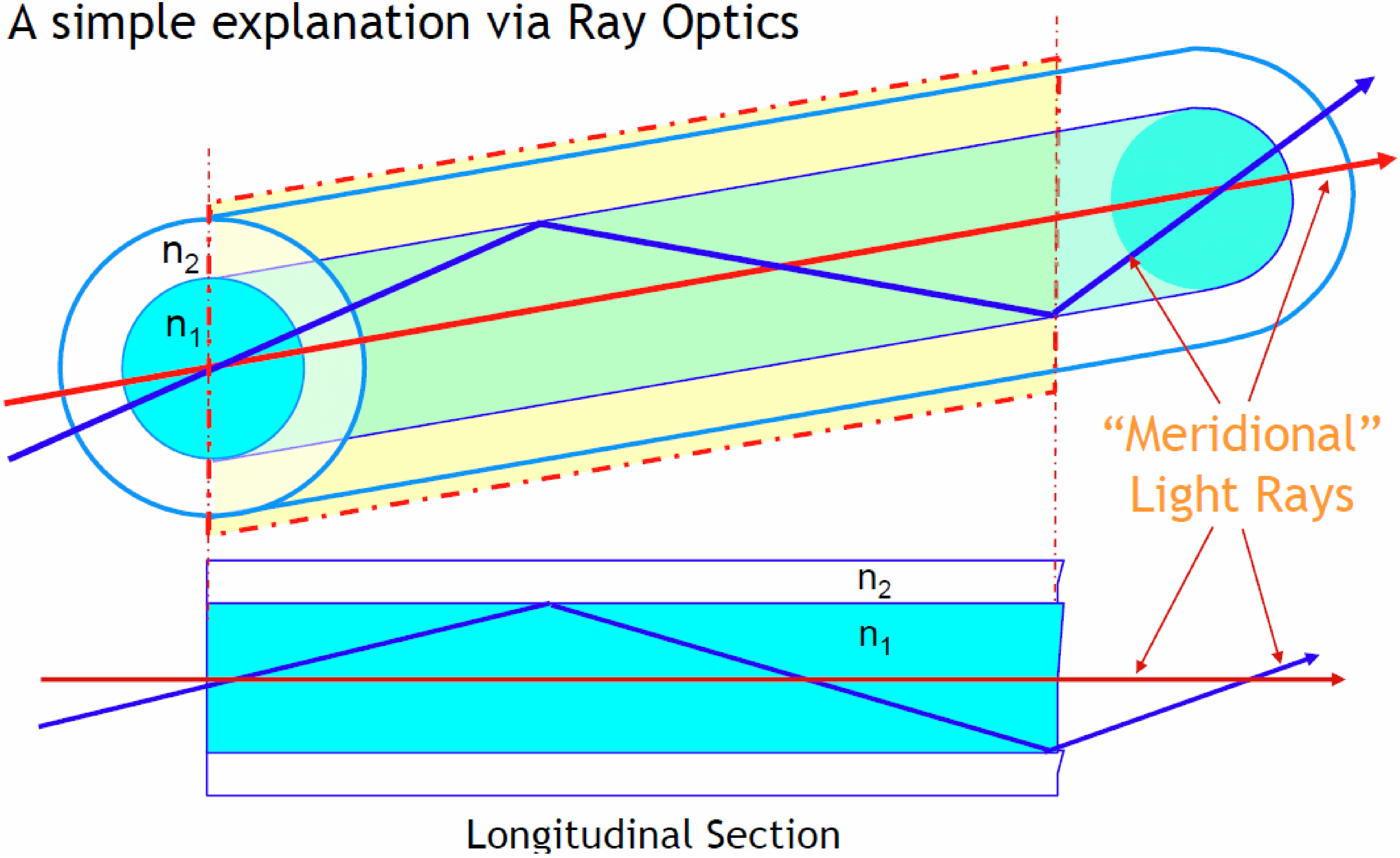
Reminder……………………………

Optoelectronic EM Spectrum

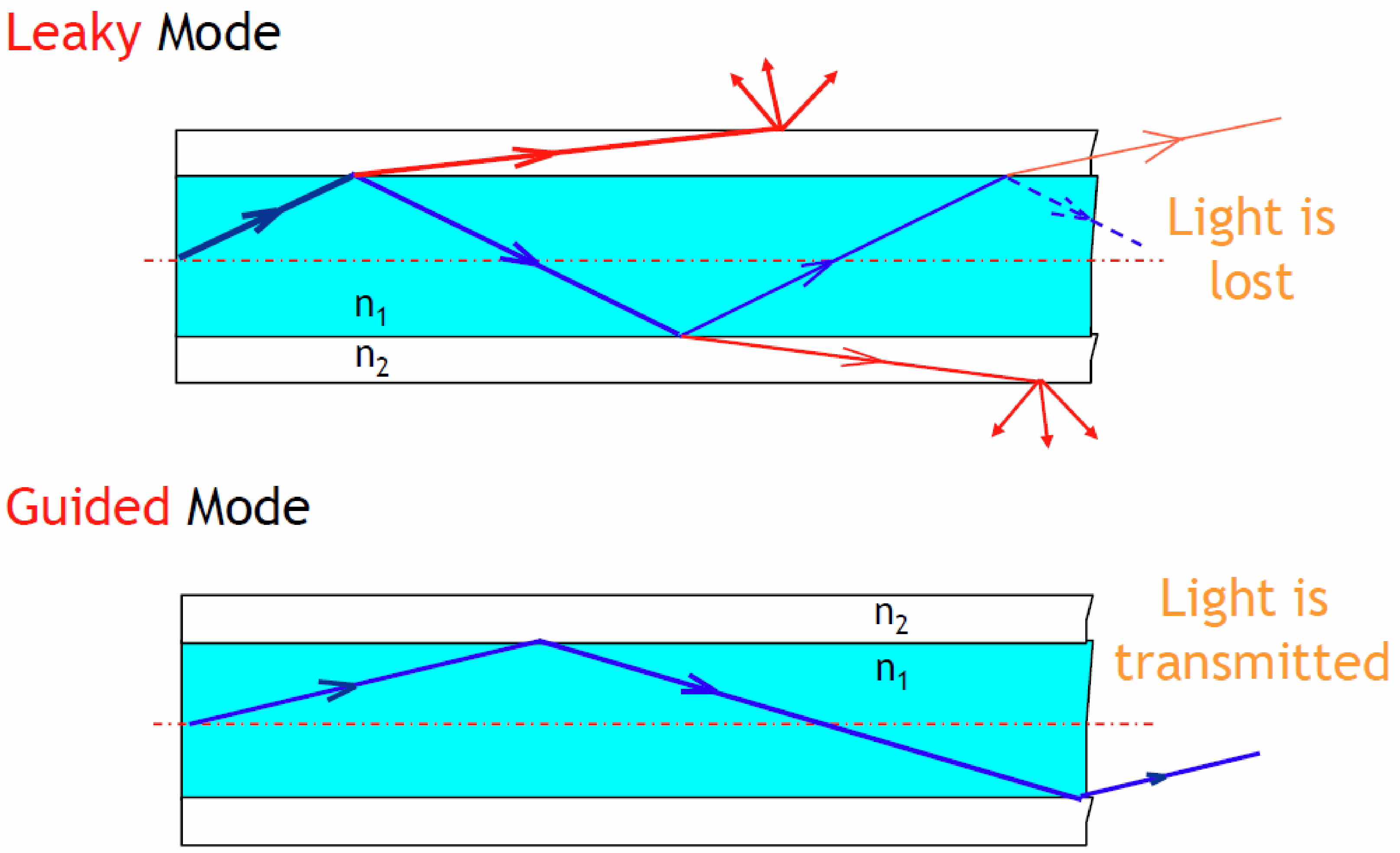
The electromagnetic spectrum



A simple explanation via Ray Optics



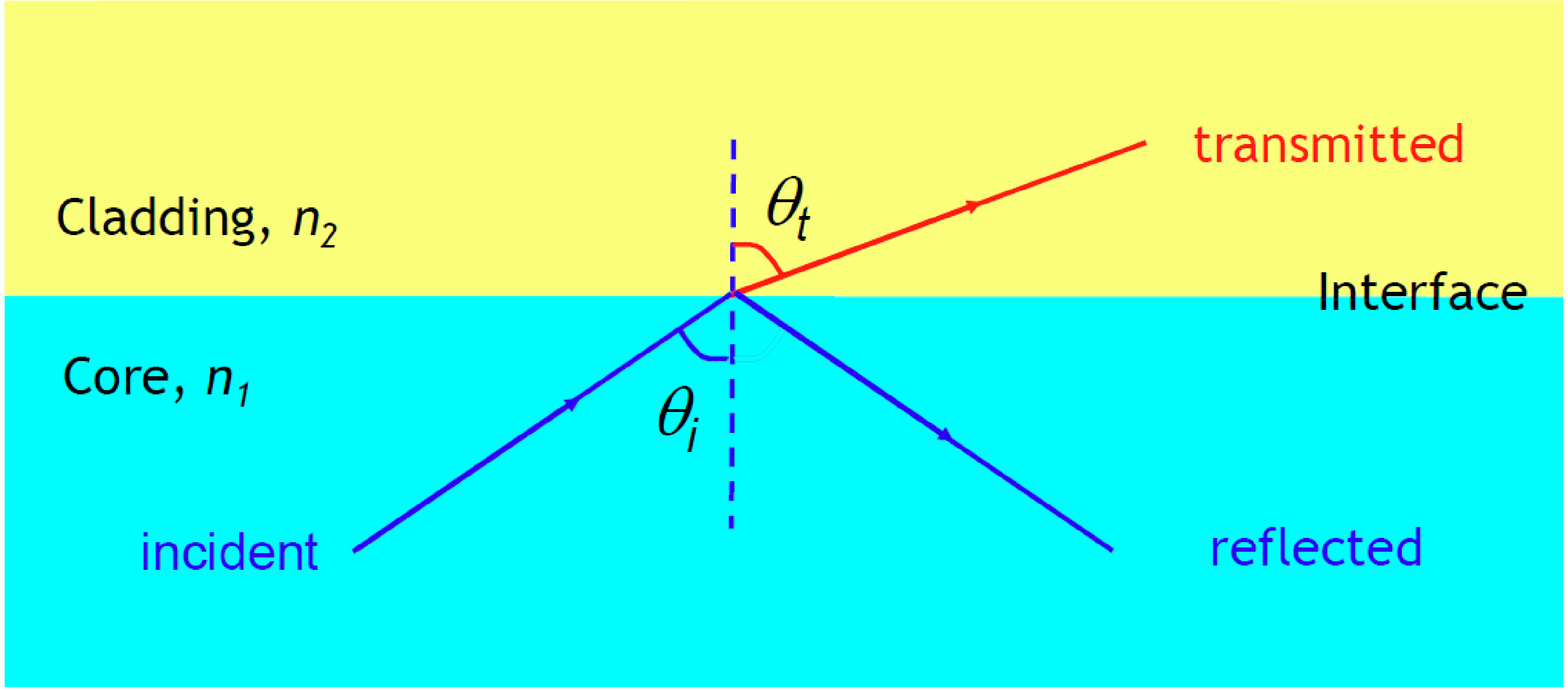
Ray optics


Leaky Mode
n$_1$
n$_2$
Light is lost
Guided Mode
n$_2$
n$_1$
Light is transmitted

Snell Law

Angle of Incidence θ_i = Angle of Reflection θ_r

Snell's Law: $n_1 \sin\theta_i = n_2 \sin\theta_t$

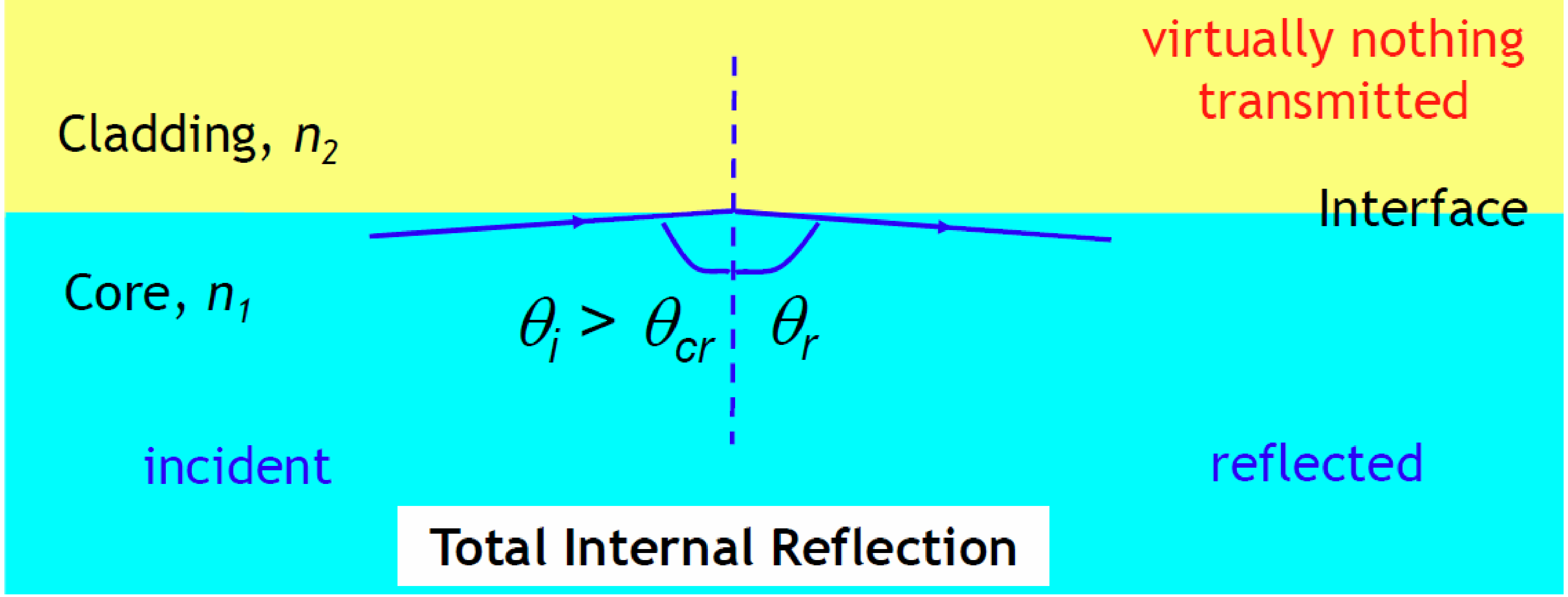


TIR (total internal reflection)

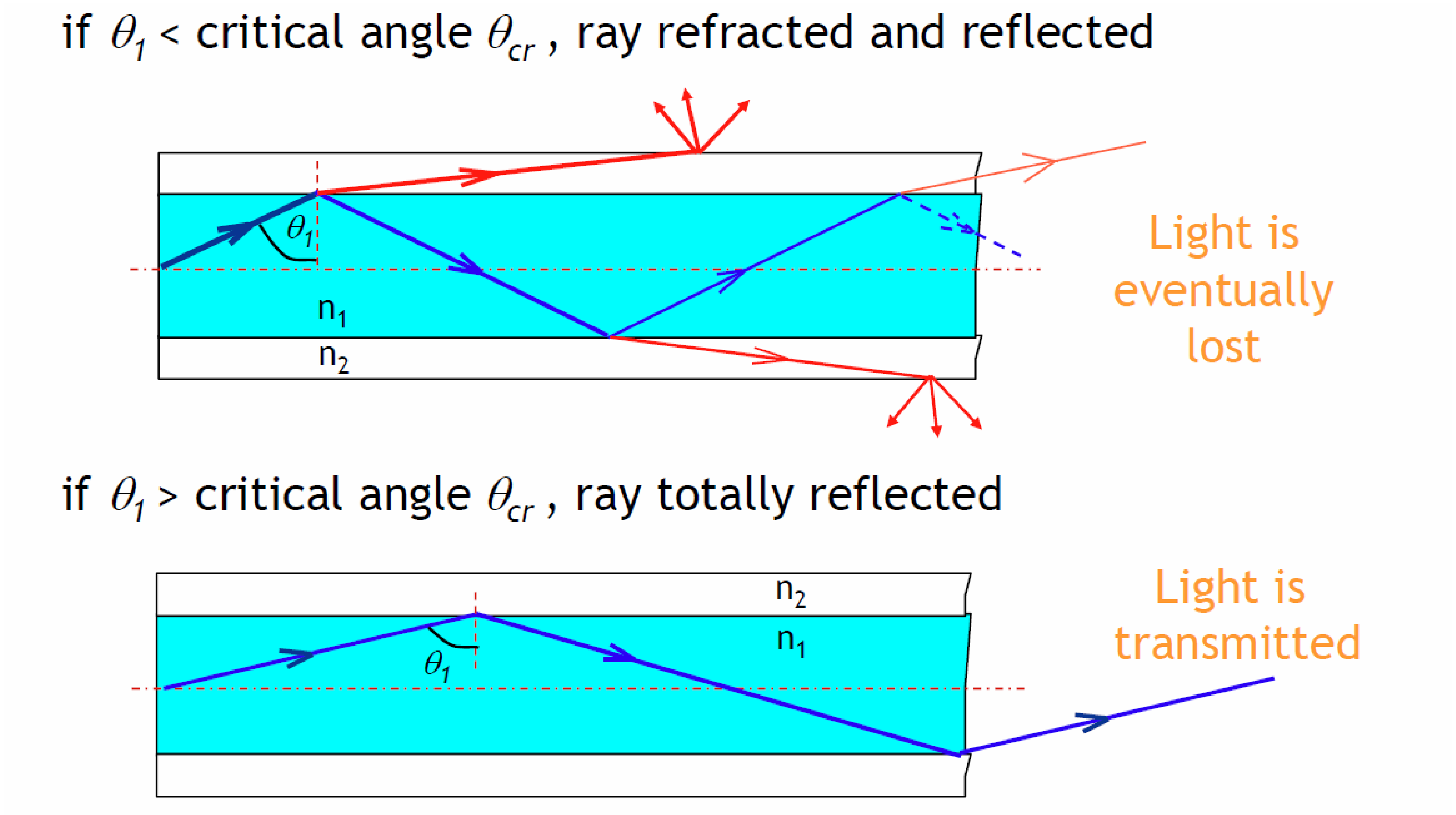
As θ_i *increases…* θ_t increases… until $\theta_t = 90°$

Value of θ_i (where $\theta_t = 90°$) = "Critical Angle" = θ_{cr}

For $\theta_i > \theta_{cr}$, the ray is totally reflected



Contribution to the signal loss



if θ_1 < critical angle θ_{cr}, ray refracted and reflected

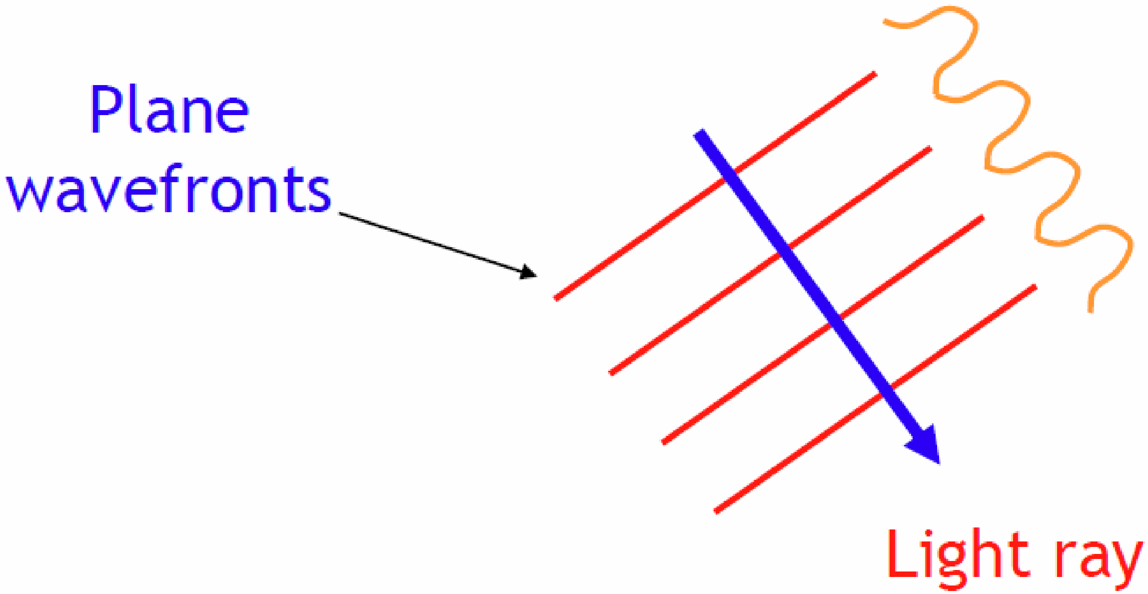
Light is eventually lost

if θ_1 > critical angle θ_{cr}, ray totally reflected

Light is transmitted

Wave optics

- Light is an electromagnetic field
- Propagates as a wave $E(z, t) = E\cos(\omega t - \beta z)$
- Ray = vector of the direction of wave propagation

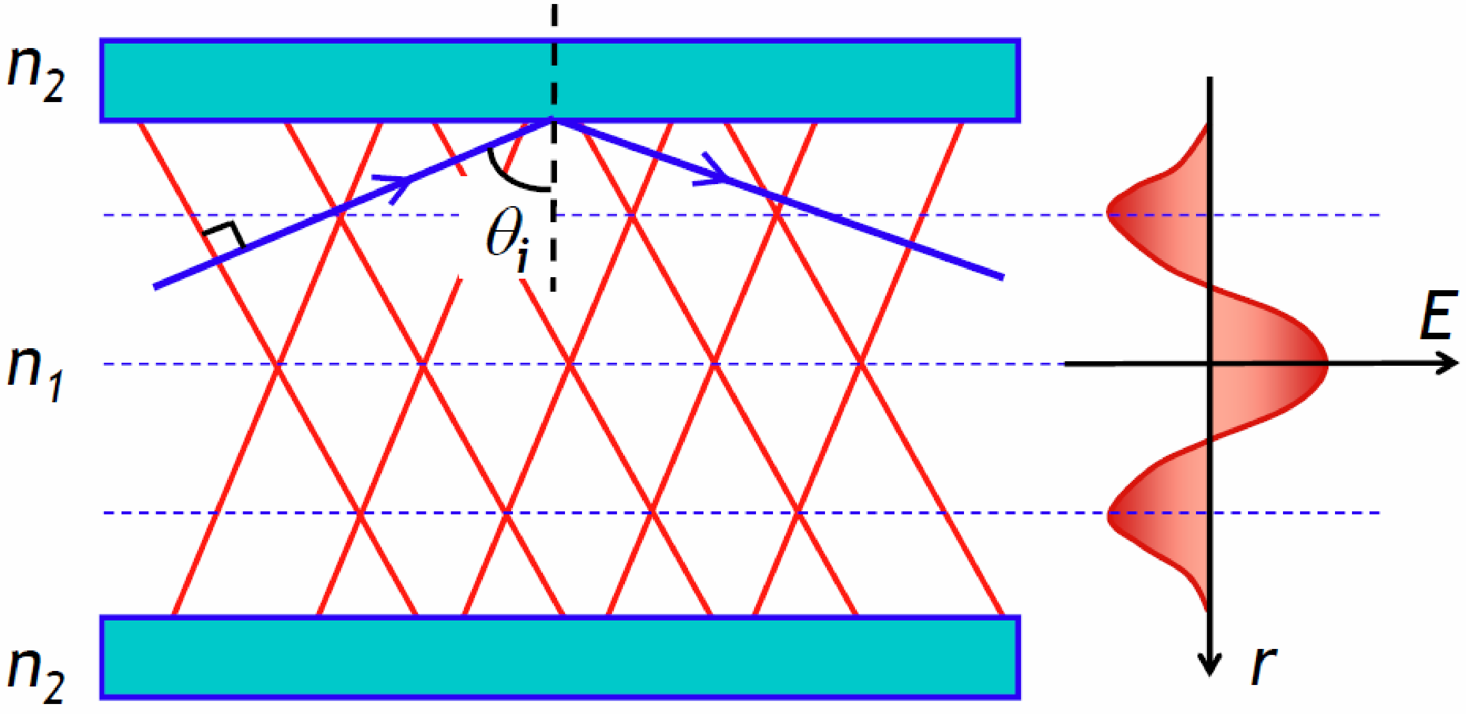


Rays, Wave fronts and Modes

Waves reflecting inside fiber interfere

Only rays yielding a standing wave allowed

Each allowed ray is a "mode" of the fiber



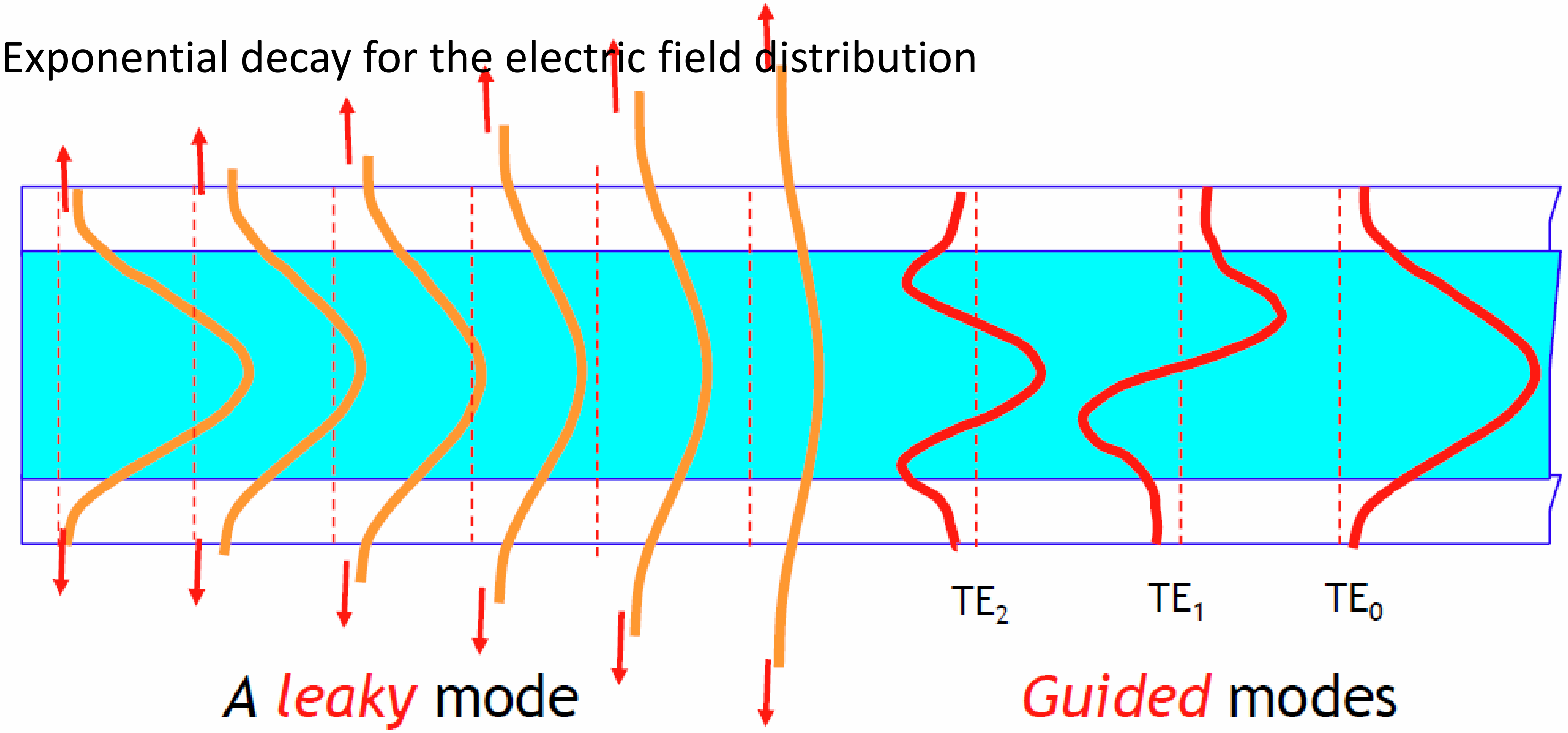
Wave presentation of the modes (wave optics)

Solve Maxwell's equations

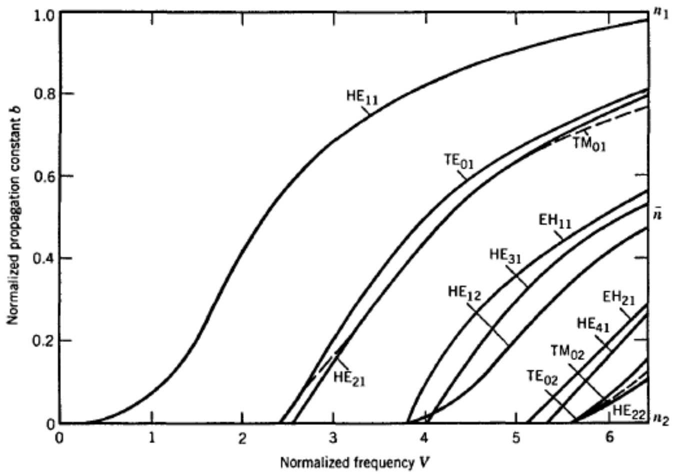
A finite number of *guided* modes

An infinite number of *radiation (leaky)* modes

Exponential decay for the electric field distribution

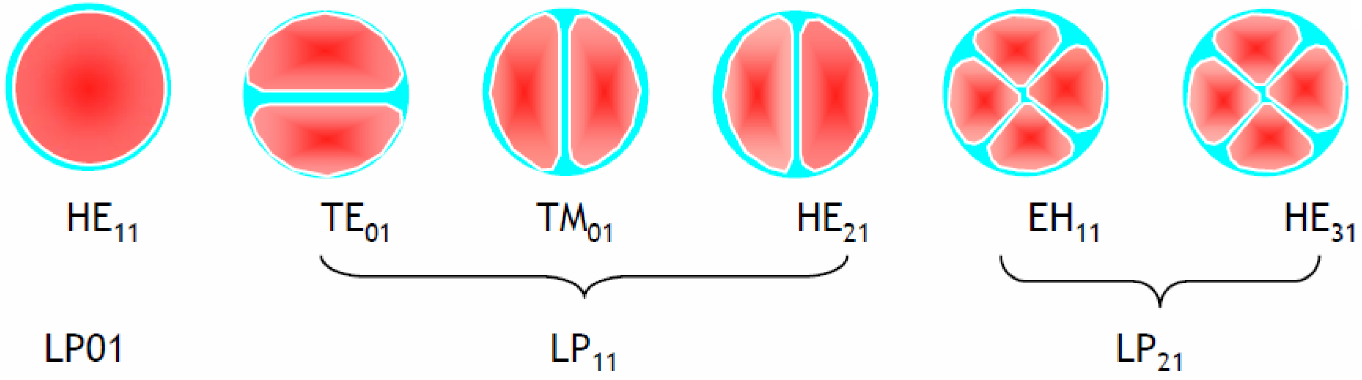


Guided modes in optical fibers



In any waveguide, many modes can form at once

Below are some guided modes of an optical fiber



Cross-sectional view of fiber core the intensity distribution

Different modes can propagate simultaneously

$$V = \frac{2\pi a}{\lambda}\sqrt{{n_1}^2 - {n_2}^2} \quad = \frac{2\pi a}{\lambda}\mathrm{NA},$$

A multimode fiber. Also single mode fiber.

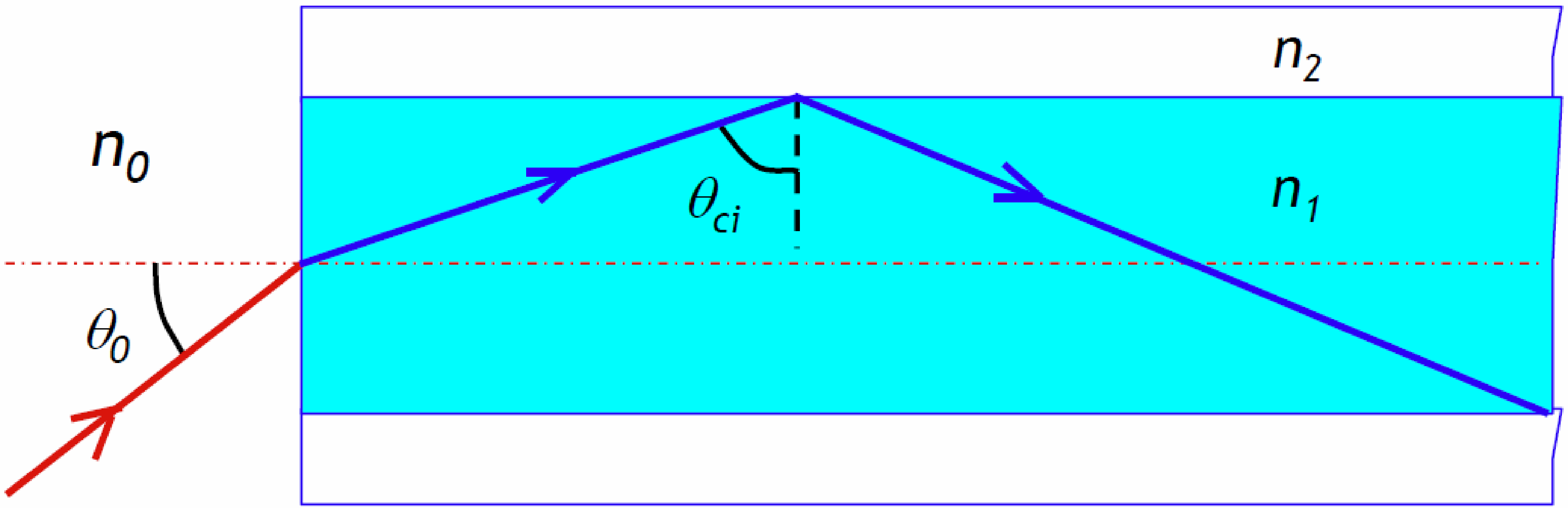
$$\frac{V^2}{2}\left(\frac{g}{g+2}\right)$$

$V < 2.4048$
Bessels

g is the profile parameter, and *V* is the normalized frequency

Numerical Aperture

NA measures light gathering ability of a fiber

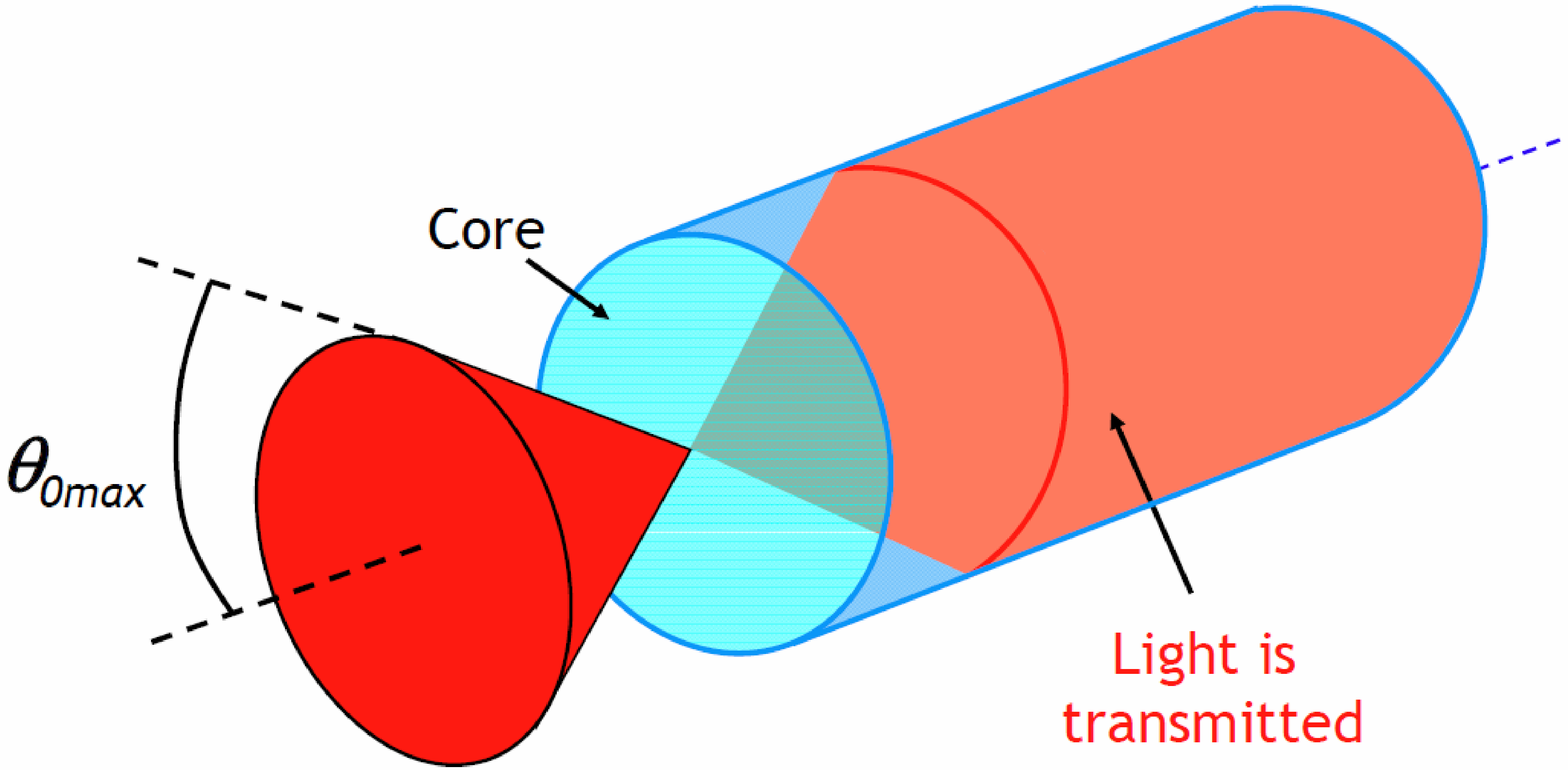


$$NA = n_0 \sin\theta_{0max} = n_1 \cos\theta_{ci} = (n_1^2 - n_2^2)^{0.5}$$

Acceptance Angle

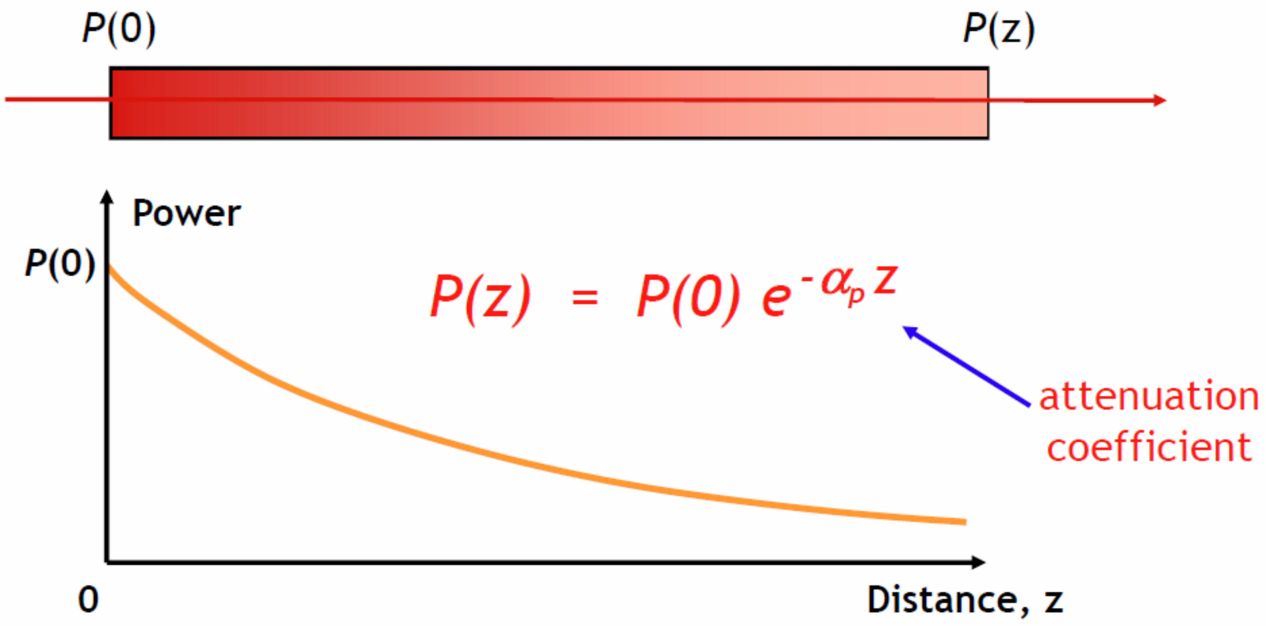
How much light can be captured by the fiber core?

Within the angle θ_{0max}, such that light is transmitted



Fiber attentuation

As light travels along a fiber, its power decreases exponentially with distance

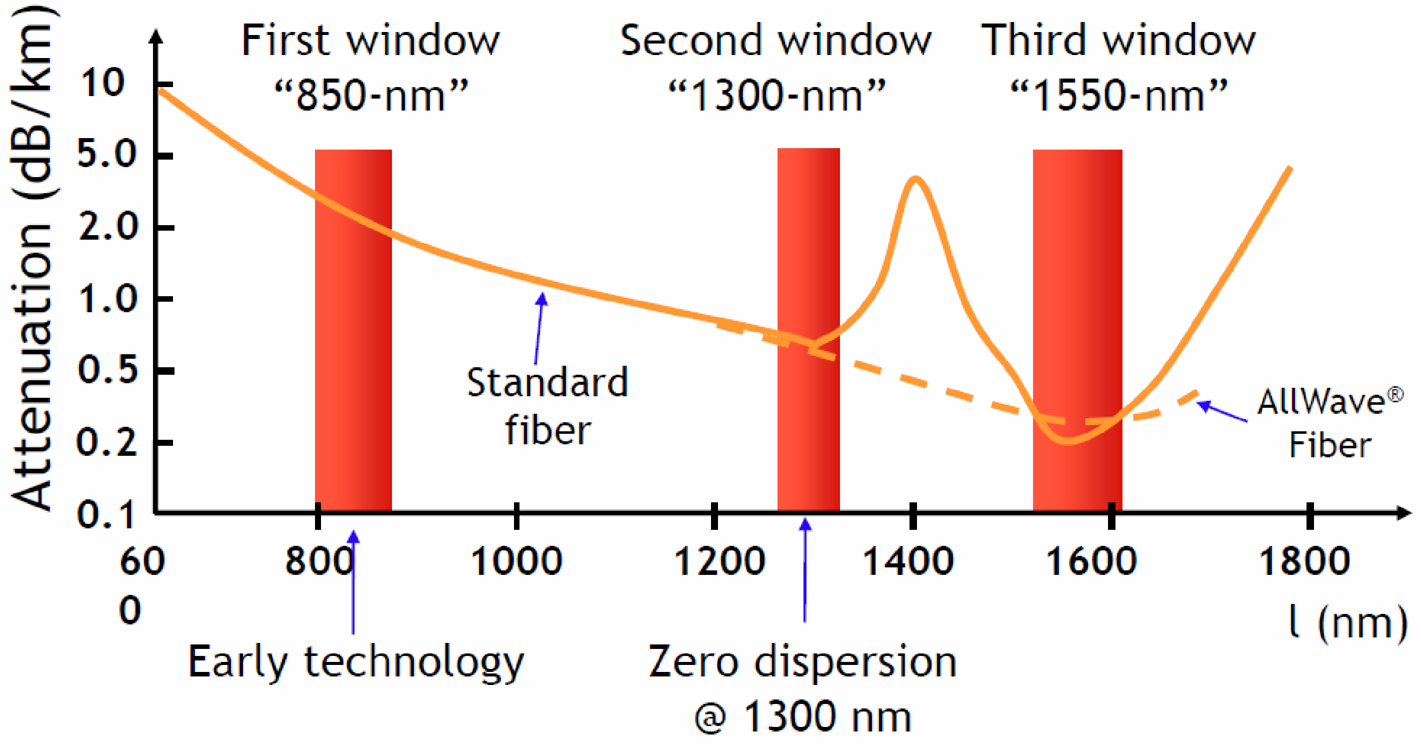


$$P(z) = P(0)\, e^{-\alpha_p z}$$

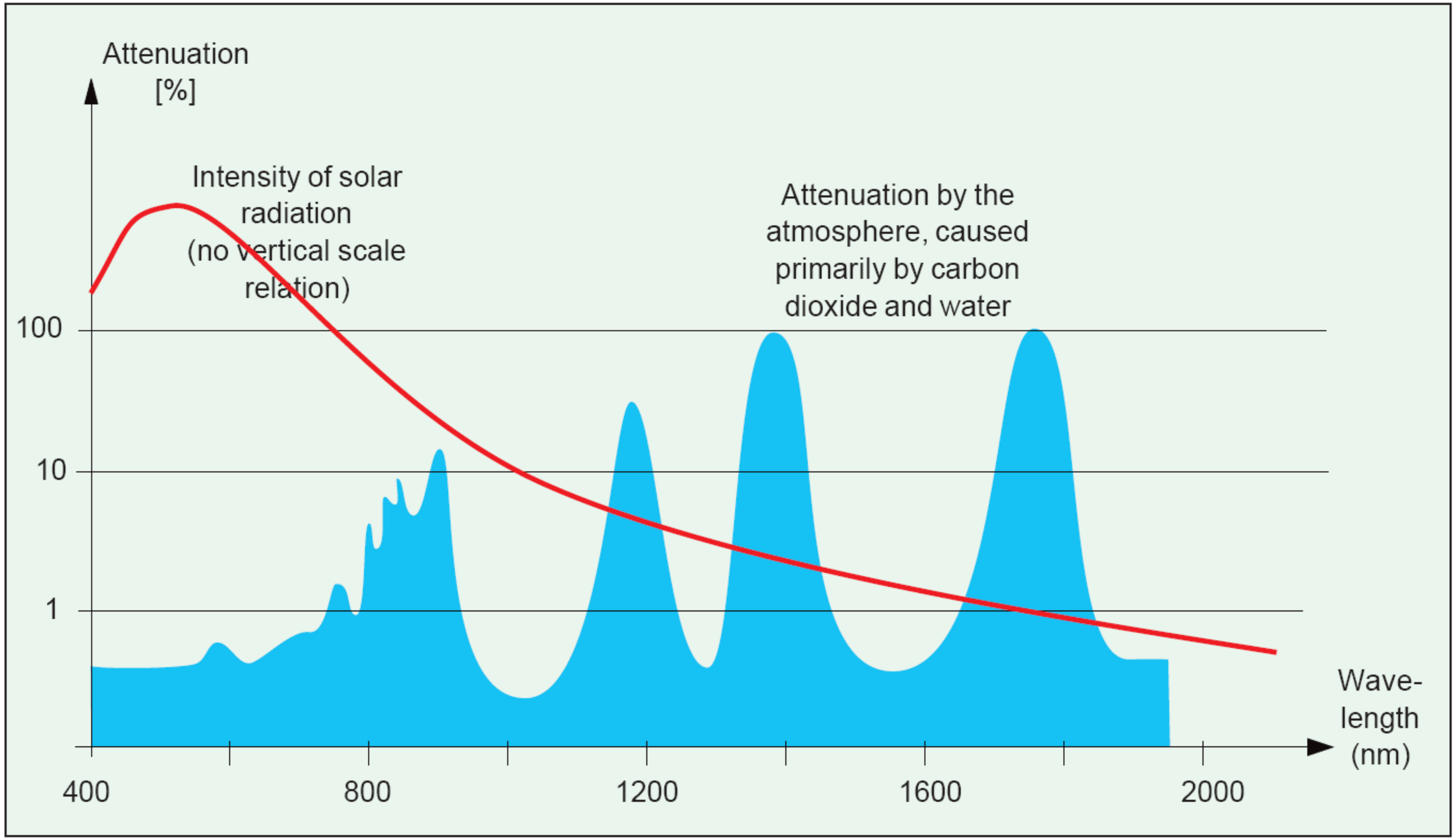
attenuation coefficient

Communication Windows and fiber attenuation

Fiber attenuation is a function of the wavelength



Attenuation in athosphere



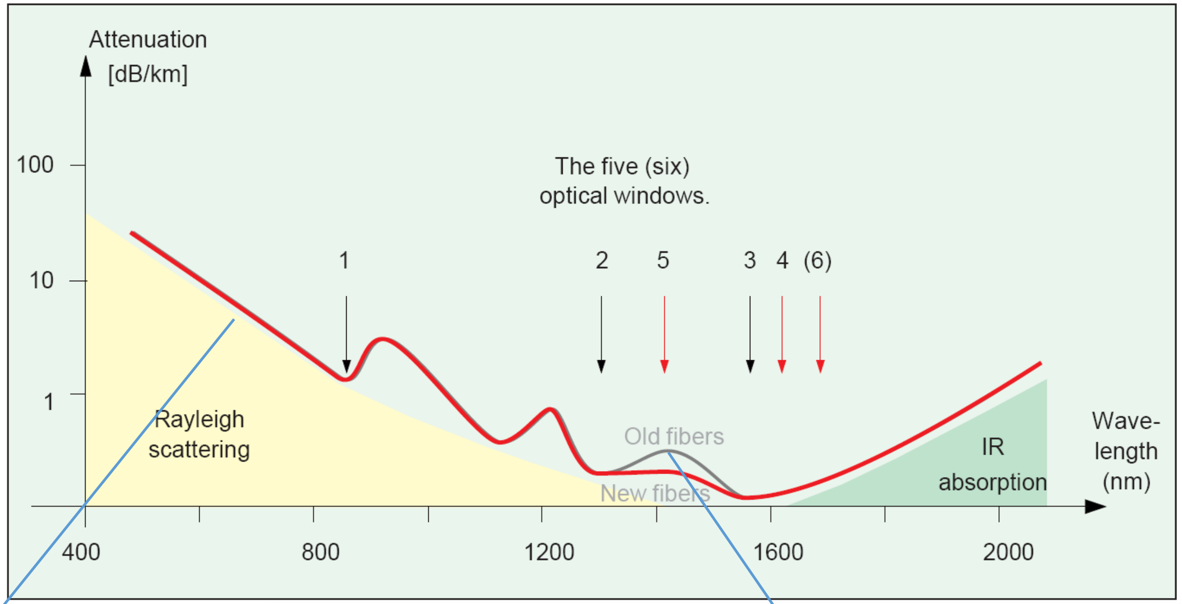
The attenuation of solar radiation by the atmosphere for wavelenghs visible to the naked human eye.

Optical Communication Bands and Attenuation

- Original band (O-band): 1260 to 1360 nm
- Extended band (E-band): 1360 to 1460 nm
- Short band (S-band): 1460 to 1530 nm
- Conventional band (C-band): 1530 to 1565 nm
- Long band (L-band): 1565 to 1625 nm
- Ultralong band (U-band): 1625 to 1675 nm

$$\alpha = -\frac{10}{z[\mathrm{km}]}\log\left(\frac{P(z)}{P(0)}\right)$$

The attenuation curve for optical fiber (glass). Note the five optical wavelength windows.



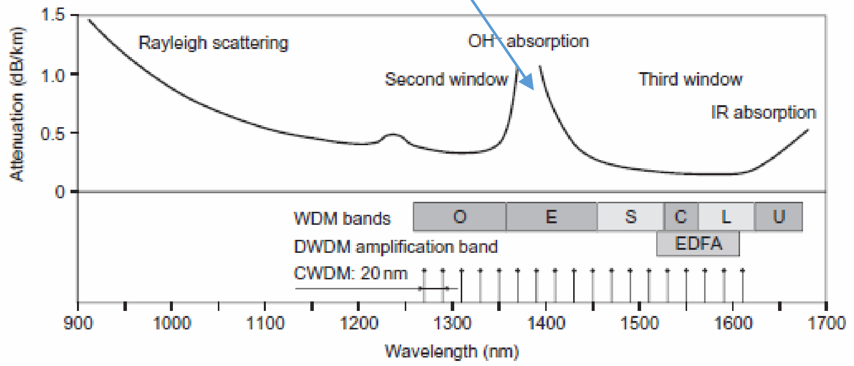
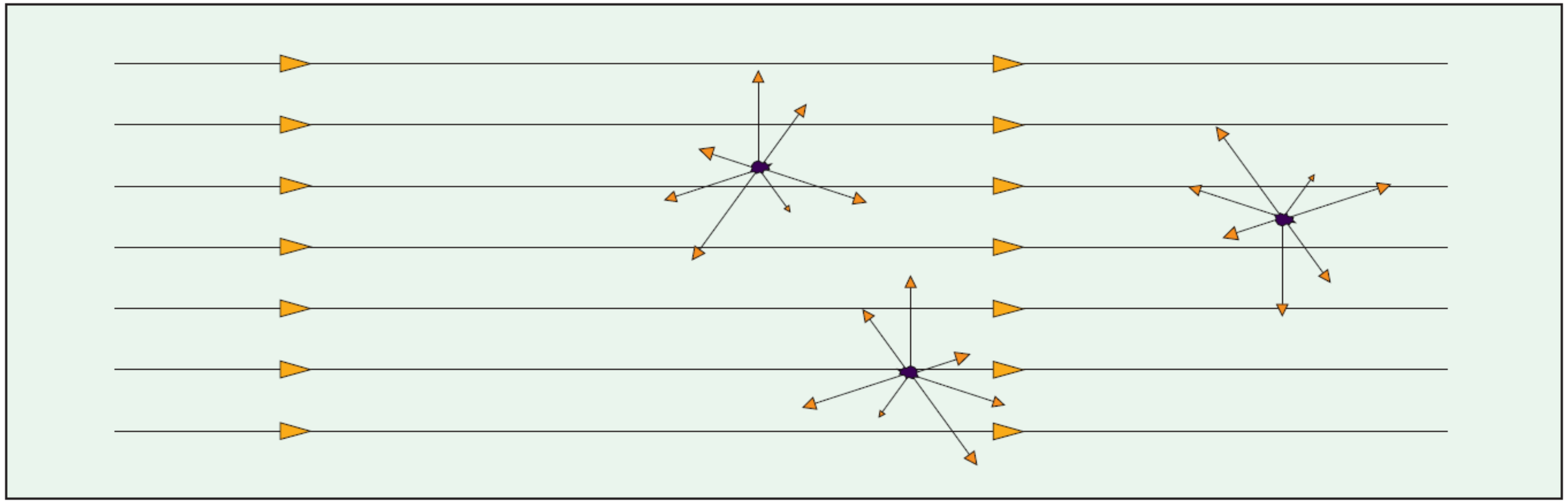


FIGURE 5.1

DWDM and CWDM channel allocation and WDM bands.

Attenuation is the slope/inclination of the graphic

Rayleigh scattering and Tyndall’s light

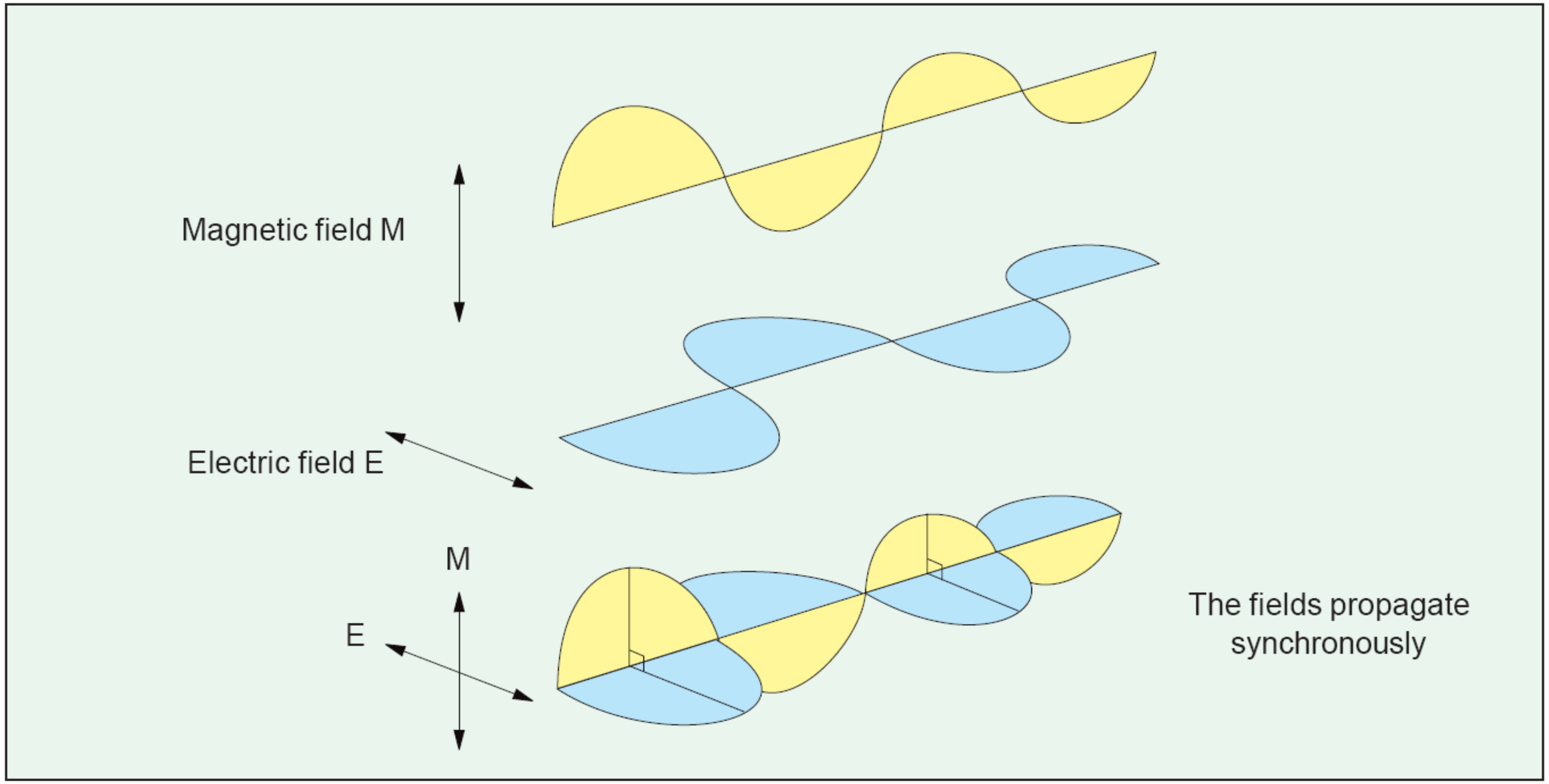


Rayleigh scattering of light due to impurities in the light transmitting.

https://www.fiberoptics4sale.com/blogs/archive-posts/95048006-optical-fiber-loss-and-attenuation

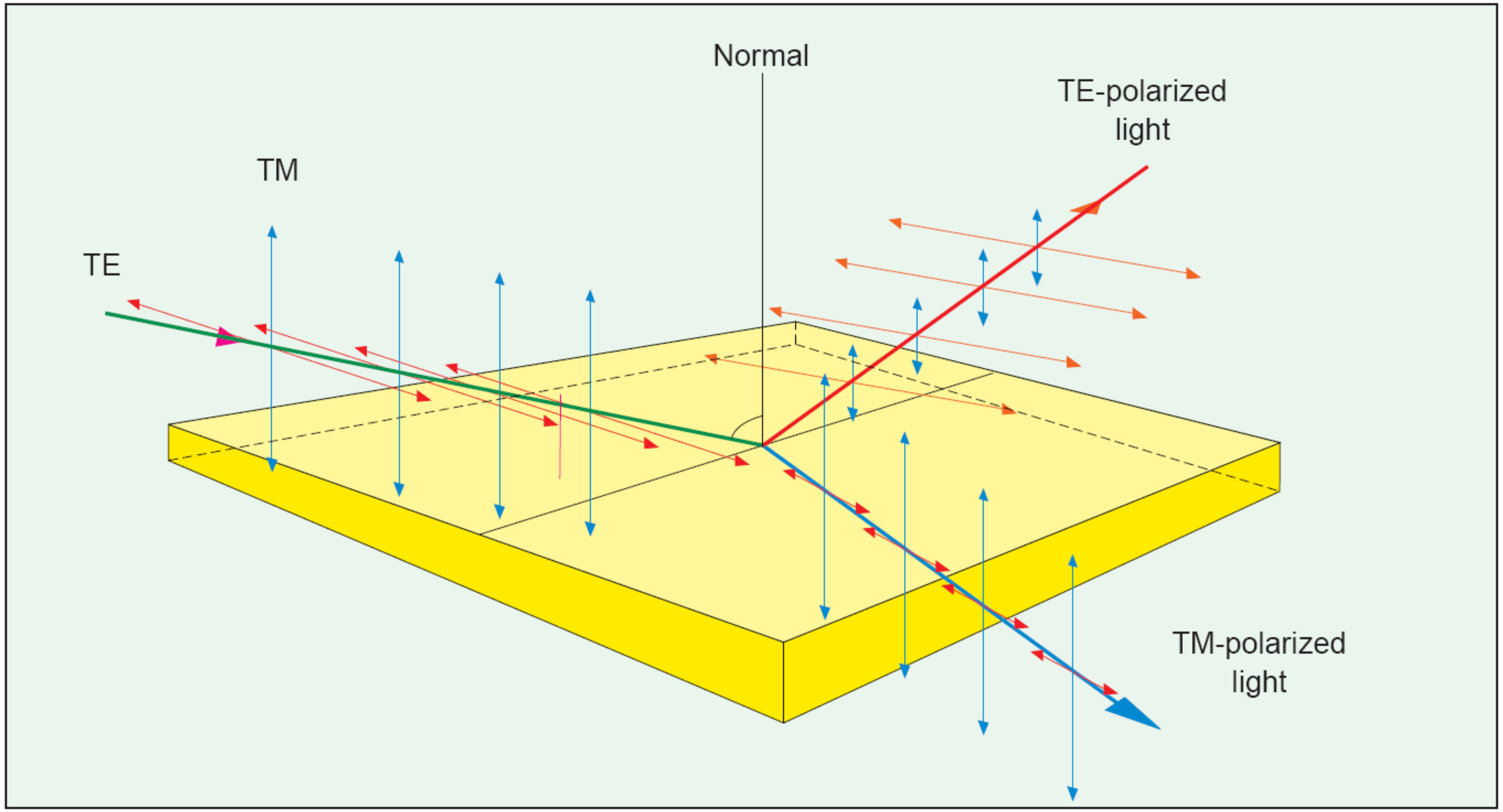
Reflection of light at 90° angle of incidence Fresnel’s laws of reflection

Polarized light



Light consists of two fields: an electrical and a magnetic field. The two fields are synchronous with field vectors that maintain a 90° phase difference to one another.

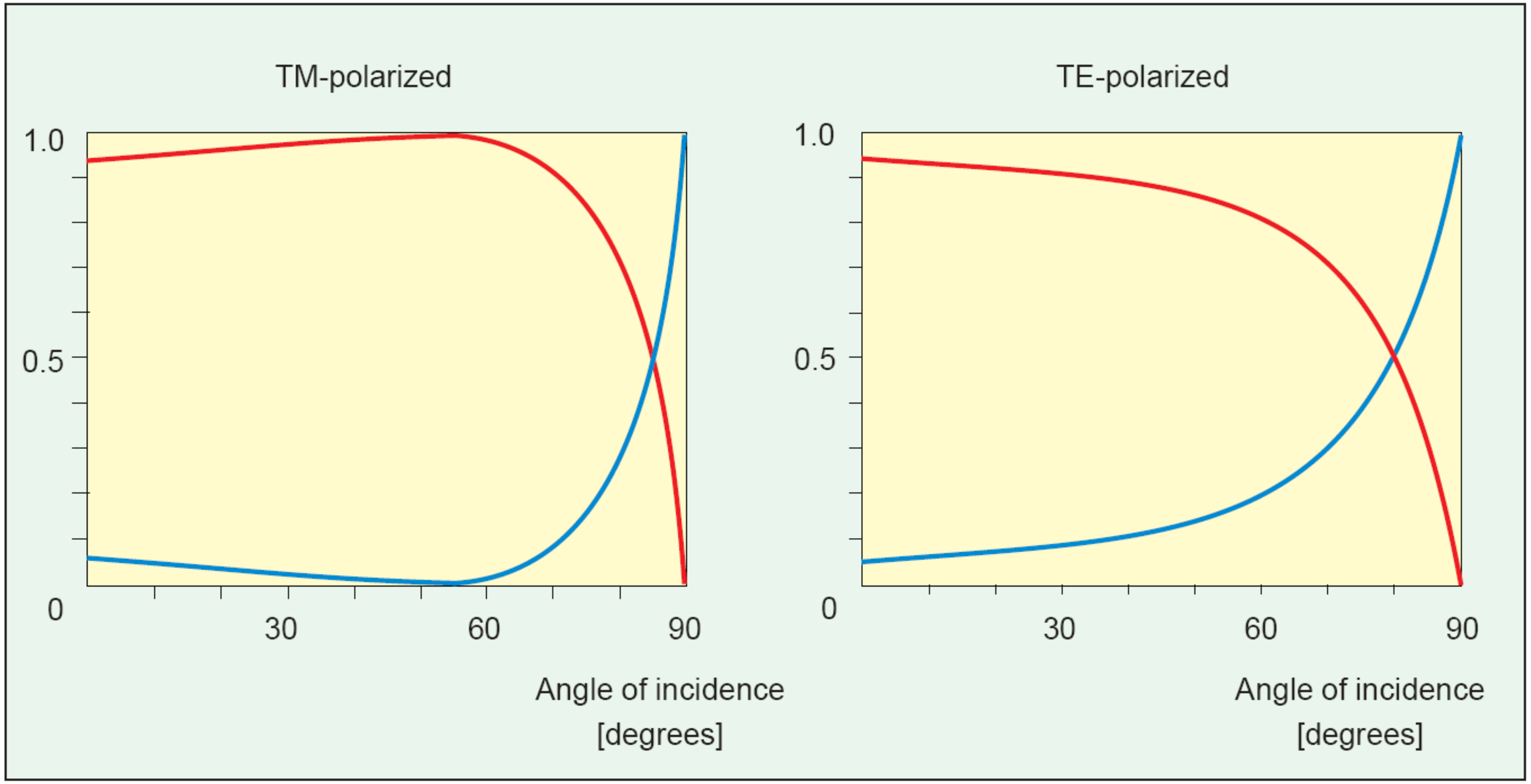
Brewster angle - polarisation



Light hitting a surface will be polarized, and the electric and magnetic fields are polarized differently.

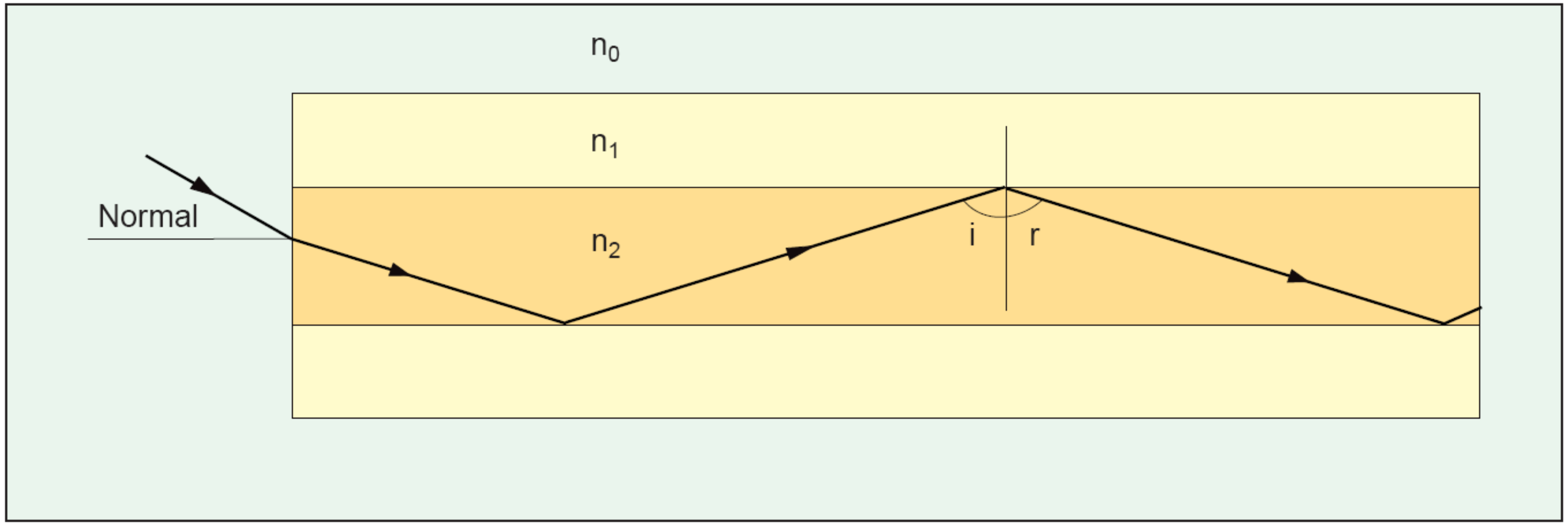
Fresnel: $$R_0 = \frac{(n_2 - n_1)^2}{(n_2 + n_1)^2}$$

$$R = \frac{1}{2}(R_S + R_P) \qquad R_S = \left[\frac{\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)}\right]^2 \qquad R_P = \left[\frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)}\right]^2$$



Graphs showing the differences in reflectance of the different polarizations.

Total reflection in a fiber



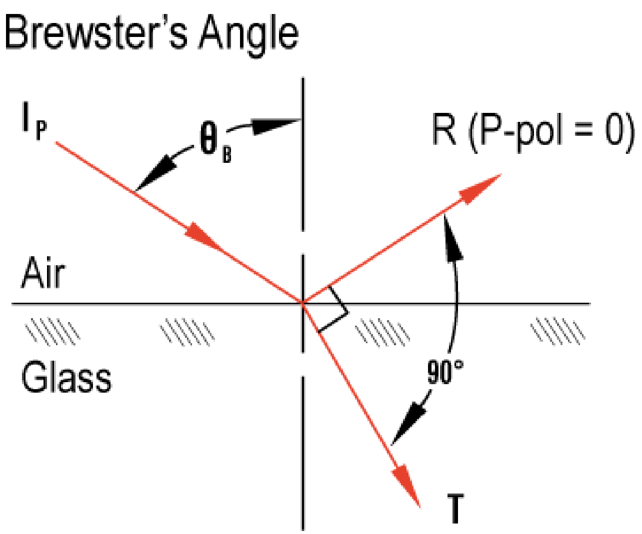
The refraction of light entering the fiber, and total reflection within the fiber.

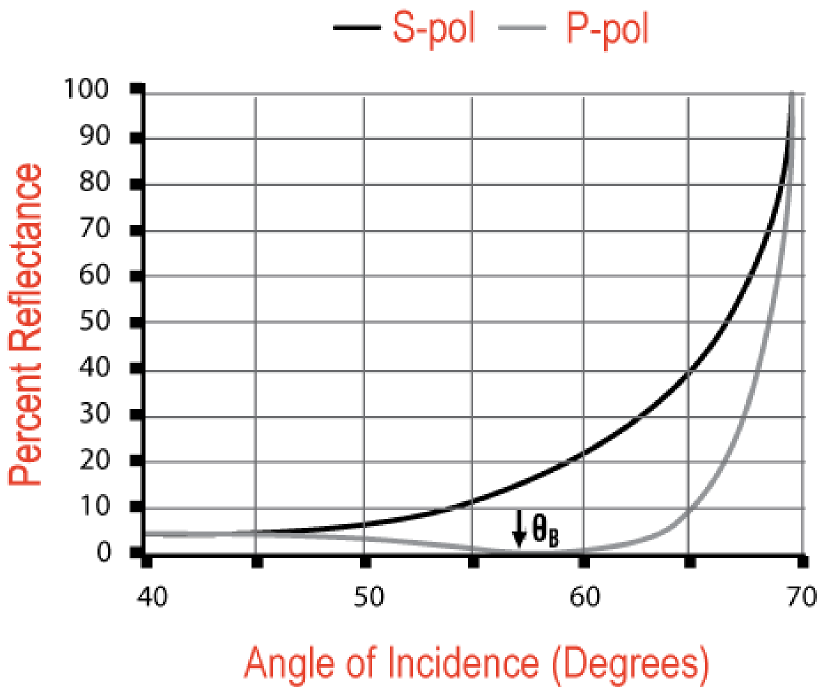
https://www.fiberoptics4sale.com/blogs/archive-posts/95048006-optical-fiber-loss-and-attenuation

Brewster Angle

$$\theta_B = \arctan\left(\frac{n_2}{n_1}\right)$$

$$R = \frac{1}{2}(R_s + R_p) \qquad R_s = \left[\frac{\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)}\right]^2 \qquad R_p = \left[\frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)}\right]^2$$



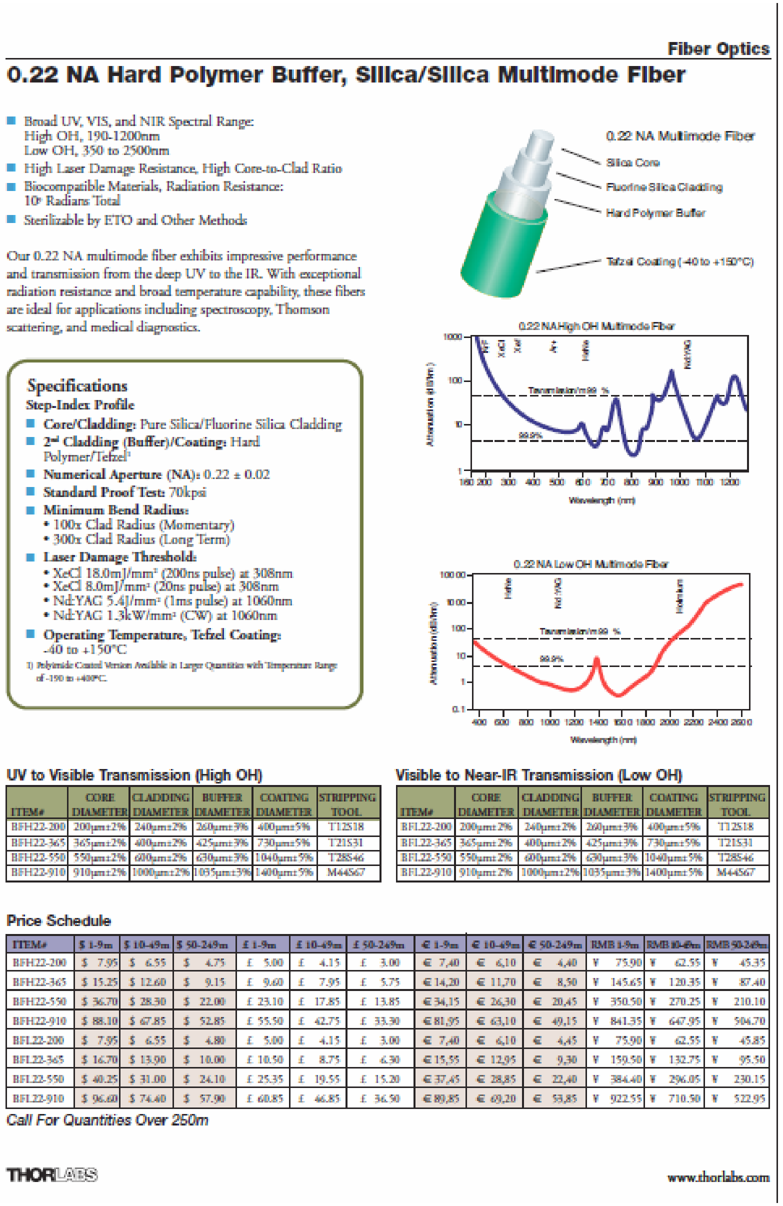


http://rmico.com/reflection-and-refraction-of-light-tutorial

https://www.its.bldrdoc.gov/fs-1037/dir-005/_0708.htm

Optical Attenuation-catalog

https://www.thorlabs.com/catreq.cfm



Fiber Optics

0.22 NA Hard Polymer Buffer, Silica/Silica Multimode Fiber

- Broad UV, VIS, and NIR Spectral Range:
  High OH, 190-1200nm
  Low OH, 350 to 2500nm
- High Laser Damage Resistance, High Core-to-Clad Ratio
- Biocompatible Materials, Radiation Resistance:
  10^6 Radians Total
- Sterilizable by ETO and Other Methods

Our 0.22 NA multimode fiber exhibits impressive performance and transmission from the deep UV to the IR. With exceptional radiation resistance and broad temperature capability, these fibers are ideal for applications including spectroscopy, Thomson scattering, and medical diagnostics.

Specifications

Step-Index Profile

- **Core/Cladding:** Pure Silica/Fluorine Silica Cladding
- **2nd Cladding (Buffer)/Coating:** Hard Polymer/Tefzel[1]
- **Numerical Aperture (NA):** 0.22 ± 0.02
- **Standard Proof Test:** 70kpsi
- **Minimum Bend Radius:**
  - 100x Clad Radius (Momentary)
  - 300x Clad Radius (Long Term)
- **Laser Damage Threshold:**
  - XeCl 18.0mJ/mm² (200ns pulse) at 308nm
  - XeCl 8.0mJ/mm² (20ns pulse) at 308nm
  - Nd:YAG 5.4J/mm² (1ms pulse) at 1060nm
  - Nd:YAG 1.3kW/mm² (CW) at 1060nm
- **Operating Temperature, Tefzel Coating:** -40 to +150°C

[1] Polyimide Coated Version Available in Larger Quantities with Temperature Range of -190 to +400°C.

UV to Visible Transmission (High OH)

ITEM#	CORE DIAMETER	CLADDING DIAMETER	BUFFER DIAMETER	COATING DIAMETER	STRIPPING TOOL
BFH22-200	200μm±2%	240μm±2%	260μm±3%	400μm±5%	T12S18
BFH22-365	365μm±2%	400μm±2%	425μm±3%	730μm±5%	T21S31
BFH22-550	550μm±2%	600μm±2%	630μm±3%	1040μm±5%	T28S46
BFH22-910	910μm±2%	1000μm±2%	1035μm±3%	1400μm±5%	M44S67

Visible to Near-IR Transmission (Low OH)

ITEM#	CORE DIAMETER	CLADDING DIAMETER	BUFFER DIAMETER	COATING DIAMETER	STRIPPING TOOL
BFL22-200	200μm±2%	240μm±2%	260μm±3%	400μm±5%	T12S18
BFL22-365	365μm±2%	400μm±2%	425μm±3%	730μm±5%	T21S31
BFL22-550	550μm±2%	600μm±2%	630μm±3%	1040μm±5%	T28S46
BFL22-910	910μm±2%	1000μm±2%	1035μm±3%	1400μm±5%	M44S67

Price Schedule

ITEM#	$ 1-9m	$ 10-49m	$ 50-249m	£ 1-9m	£ 10-49m	£ 50-249m	€ 1-9m	€ 10-49m	€ 50-249m	RMB 1-9m	RMB 10-49m	RMB 50-249m
BFH22-200	$ 7.95	$ 6.55	$ 4.75	£ 5.00	£ 4.15	£ 3.00	€ 7,40	€ 6,10	€ 4,40	¥ 75.90	¥ 62.55	¥ 45.35
BFH22-365	$ 15.25	$ 12.60	$ 9.15	£ 9.60	£ 7.95	£ 5.75	€ 14,20	€ 11,70	€ 8,50	¥ 145.65	¥ 120.35	¥ 87.40
BFH22-550	$ 36.70	$ 28.30	$ 22.00	£ 23.10	£ 17.85	£ 13.85	€ 34,15	€ 26,30	€ 20,45	¥ 350.50	¥ 270.25	¥ 210.10
BFH22-910	$ 88.10	$ 67.85	$ 52.85	£ 55.50	£ 42.75	£ 33.30	€ 81,95	€ 63,10	€ 49,15	¥ 841.35	¥ 647.95	¥ 504.70
BFL22-200	$ 7.95	$ 6.55	$ 4.80	£ 5.00	£ 4.15	£ 3.00	€ 7,40	€ 6,10	€ 4,45	¥ 75.90	¥ 62.55	¥ 45.85
BFL22-365	$ 16.70	$ 13.90	$ 10.00	£ 10.50	£ 8.75	£ 6.30	€ 15,55	€ 12,95	€ 9,30	¥ 159.50	¥ 132.75	¥ 95.50
BFL22-550	$ 40.25	$ 31.00	$ 24.10	£ 25.35	£ 19.55	£ 15.20	€ 37,45	€ 28,85	€ 22,40	¥ 384.40	¥ 296.05	¥ 230.15
BFL22-910	$ 96.60	$ 74.40	$ 57.90	£ 60.85	£ 46.85	£ 36.50	€ 89,85	€ 69,20	€ 53,85	¥ 922.55	¥ 710.50	¥ 522.95

Call For Quantities Over 250m

THORLABS

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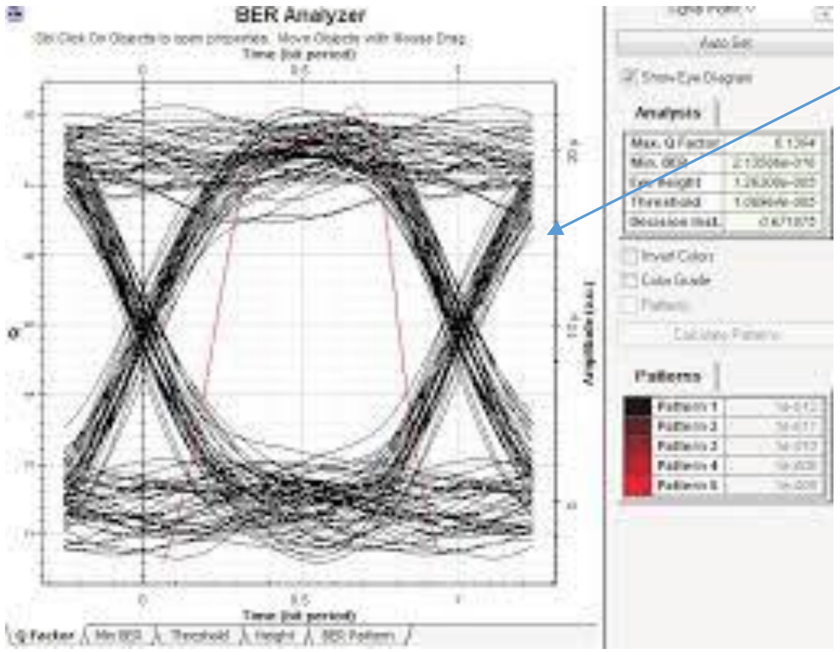
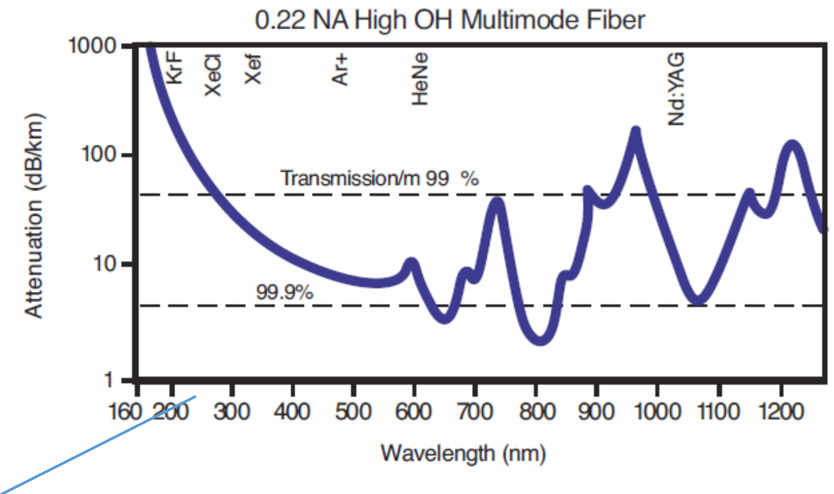
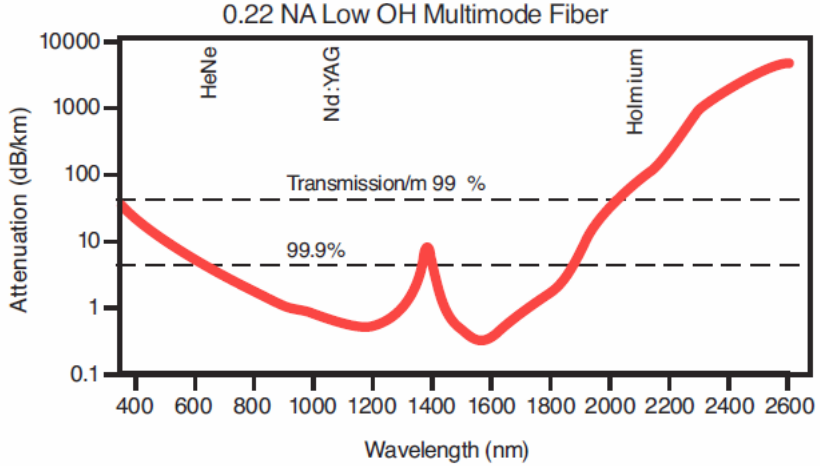
ITU-T Recommendation

- ITU-T Recommendation G.652 (2005), *Characteristics of a single-mode optical fibre and cable.*
- ITU-T Recommendation G.653 (2003), *Characteristics of a dispersion-shifted single-mode optical fibre and cable.*
- ITU-T Recommendation G.654 (2004), *Characteristics of a cut-off shifted single-mode optical fibre and cable.*
- ITU-T Recommendation G.655 (2006), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable.*

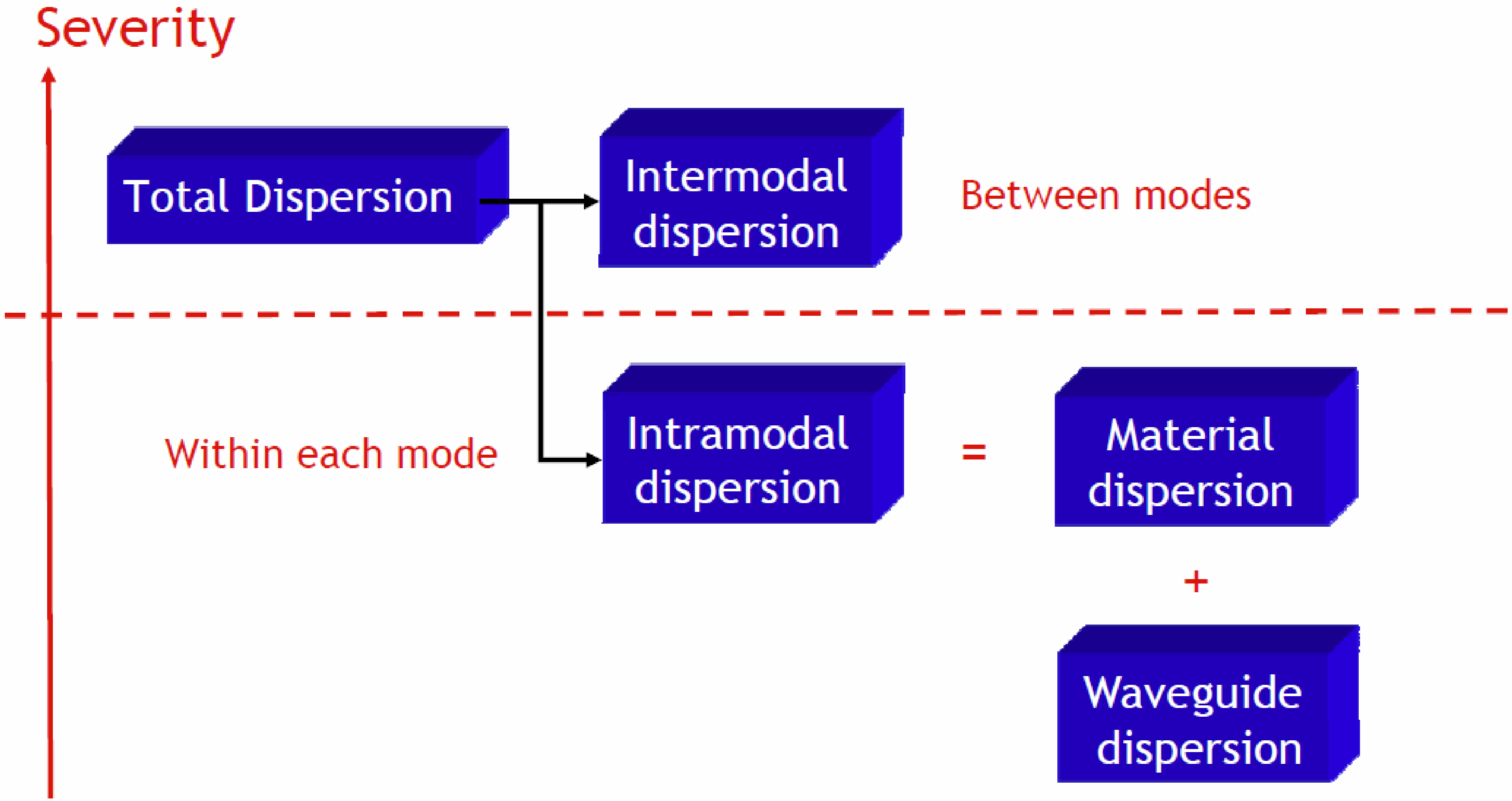


Example (Thorlabs Catalog)





Fiber dispersion is made up of several components



Severity

Total Dispersion

Intermodal dispersion

Between modes

Within each mode

Intramodal dispersion

=

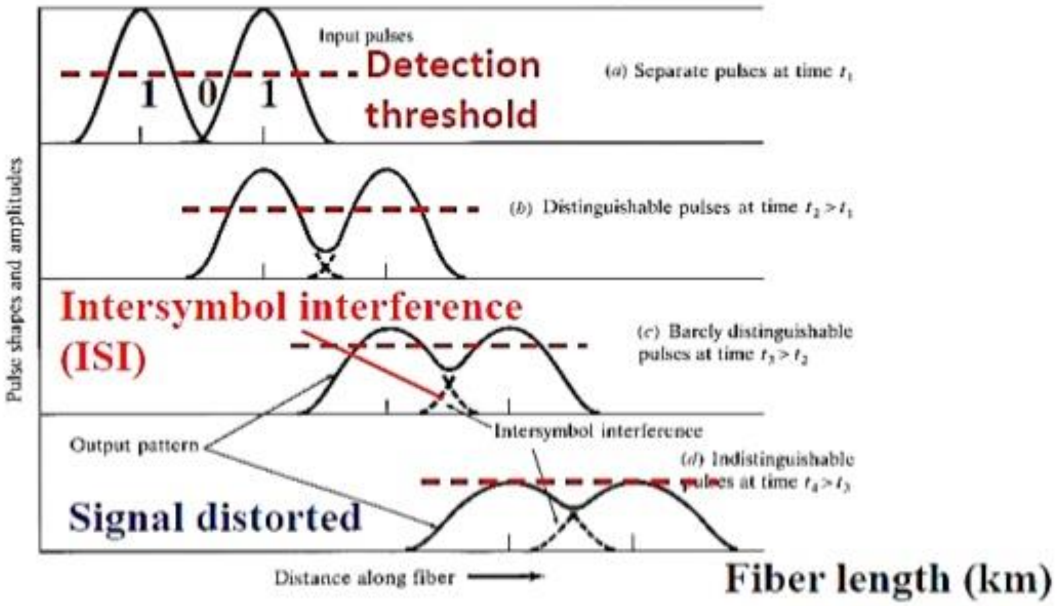
Material dispersion

+

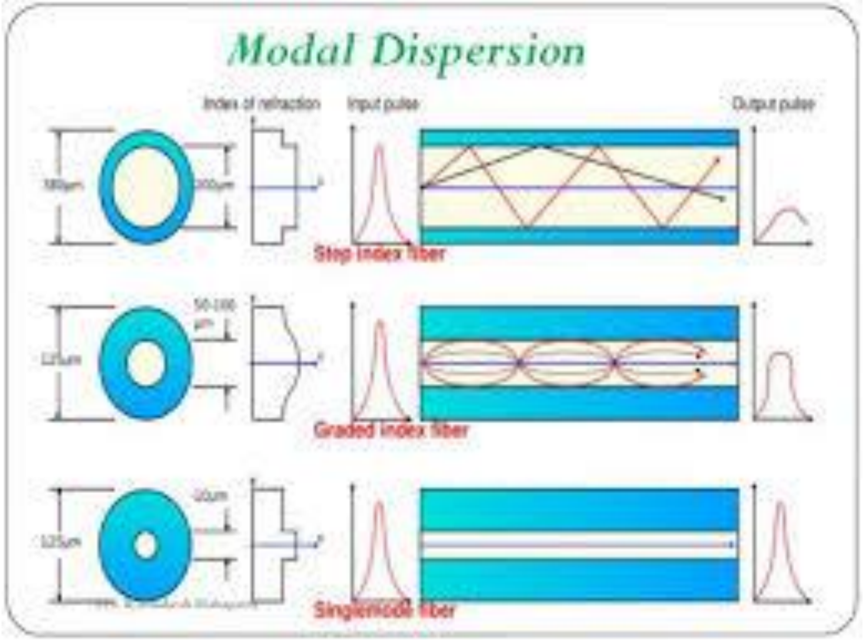
Waveguide dispersion

Dispersion

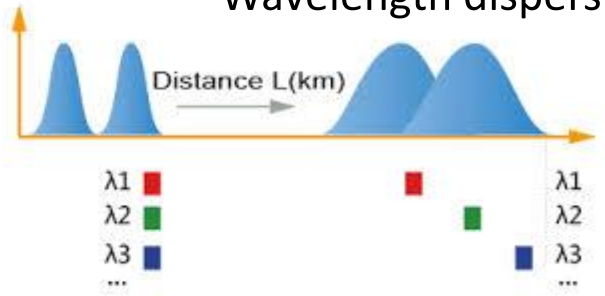
Pulse broadening limits fiber bandwidth (data rate)

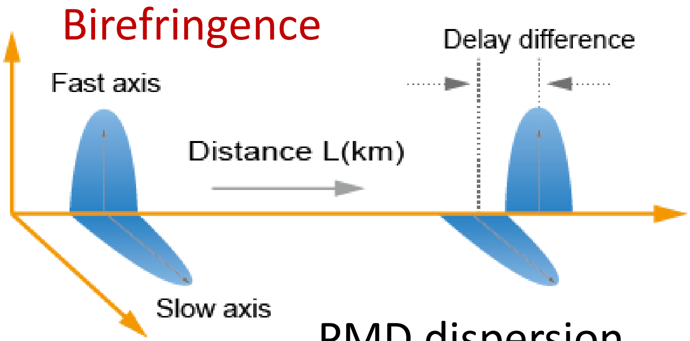


An *increasing number of errors* may be encountered on the digital optical channel as the ISI becomes more pronounced.



Wavelength dispersion/Chromatic

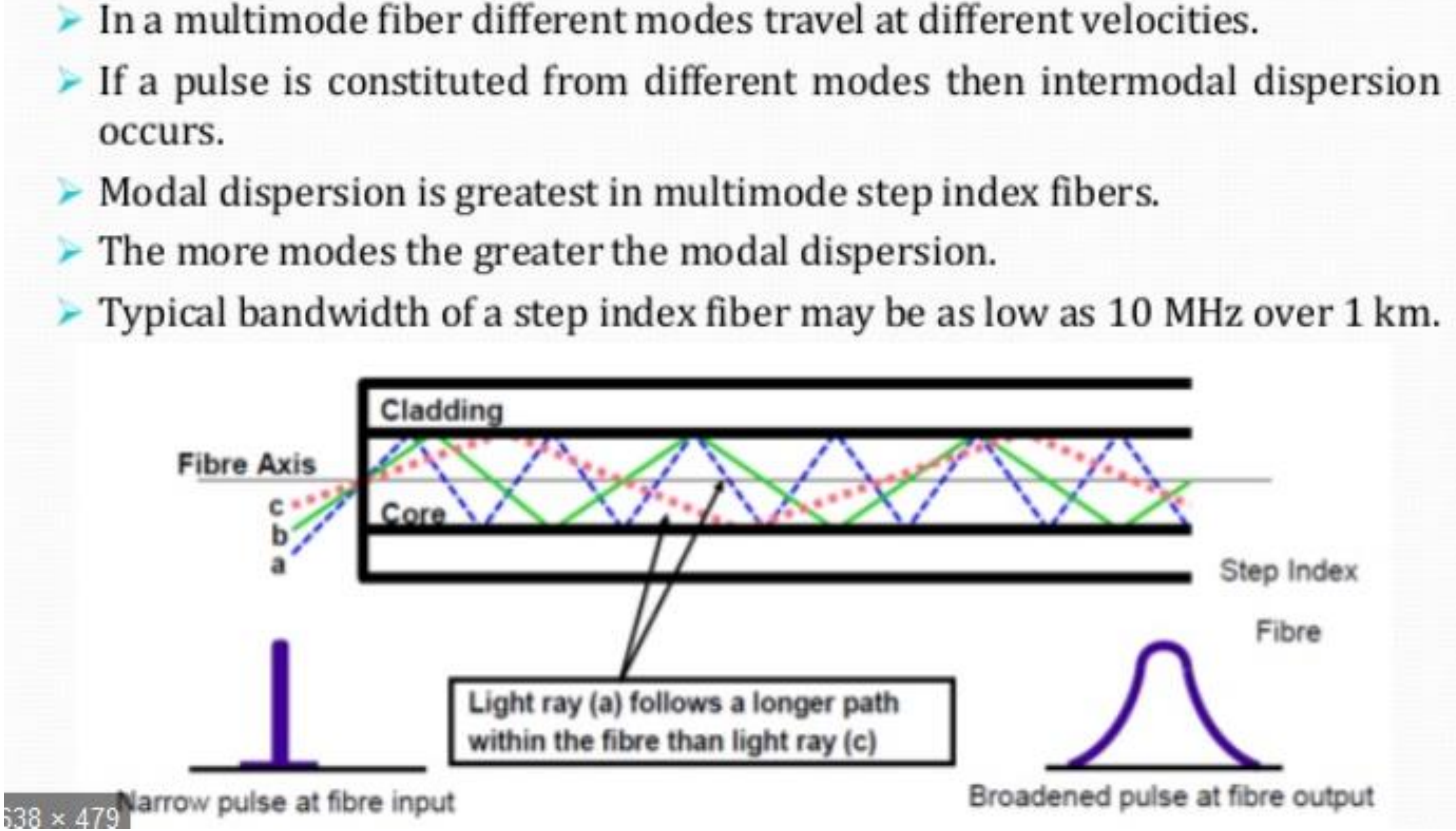




PMD dispersion

http://support.huawei.com/onlinetoolsweb/resources/en/15_dispersion.html

Intermodal Dispersion



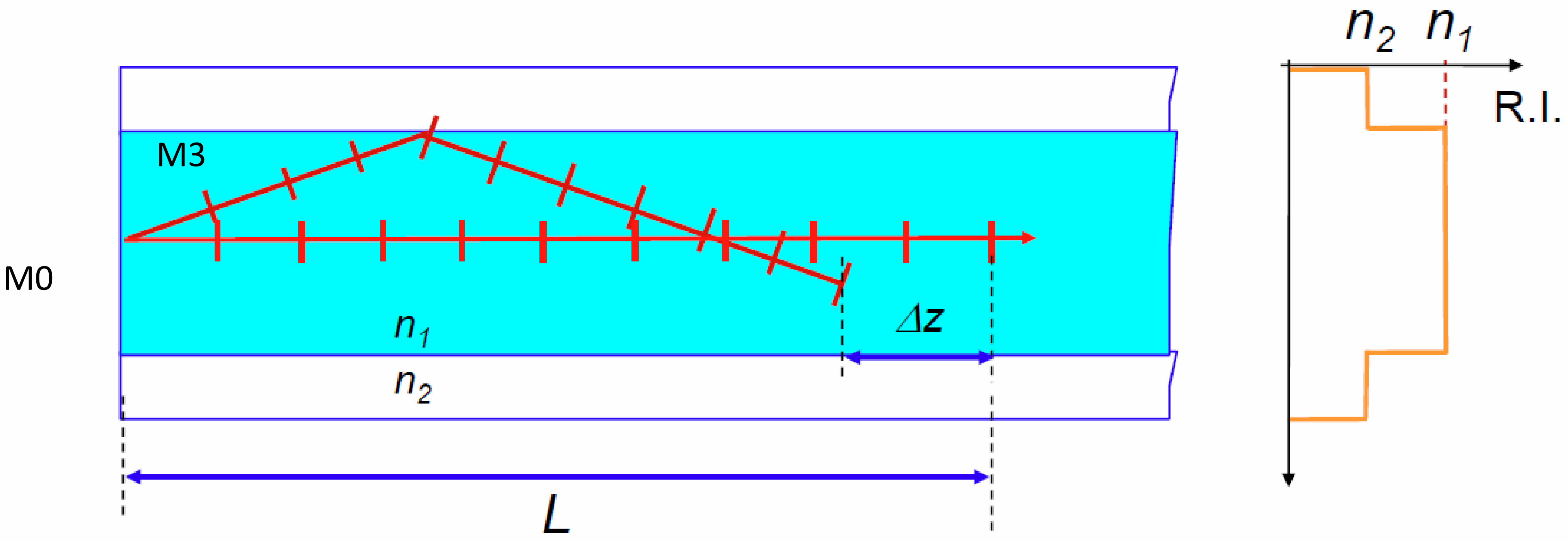
- In a multimode fiber different modes travel at different velocities.
- If a pulse is constituted from different modes then intermodal dispersion occurs.
- Modal dispersion is greatest in multimode step index fibers.
- The more modes the greater the modal dispersion.
- Typical bandwidth of a step index fiber may be as low as 10 MHz over 1 km.

Light ray (a) follows a longer path within the fibre than light ray (c)

Narrow pulse at fibre input

Broadened pulse at fibre output

Each mode experiences different group velocity

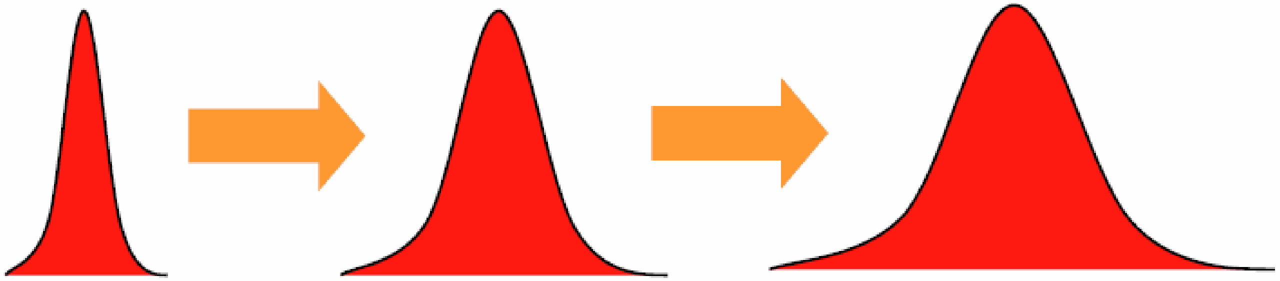


Minimum transit time $t_{min} = (L/c) \cdot n_1$

Maximum transit time $t_{max} = (L/c) \cdot (n_1^2/n_2)$

The delay difference or pulse spread in time:

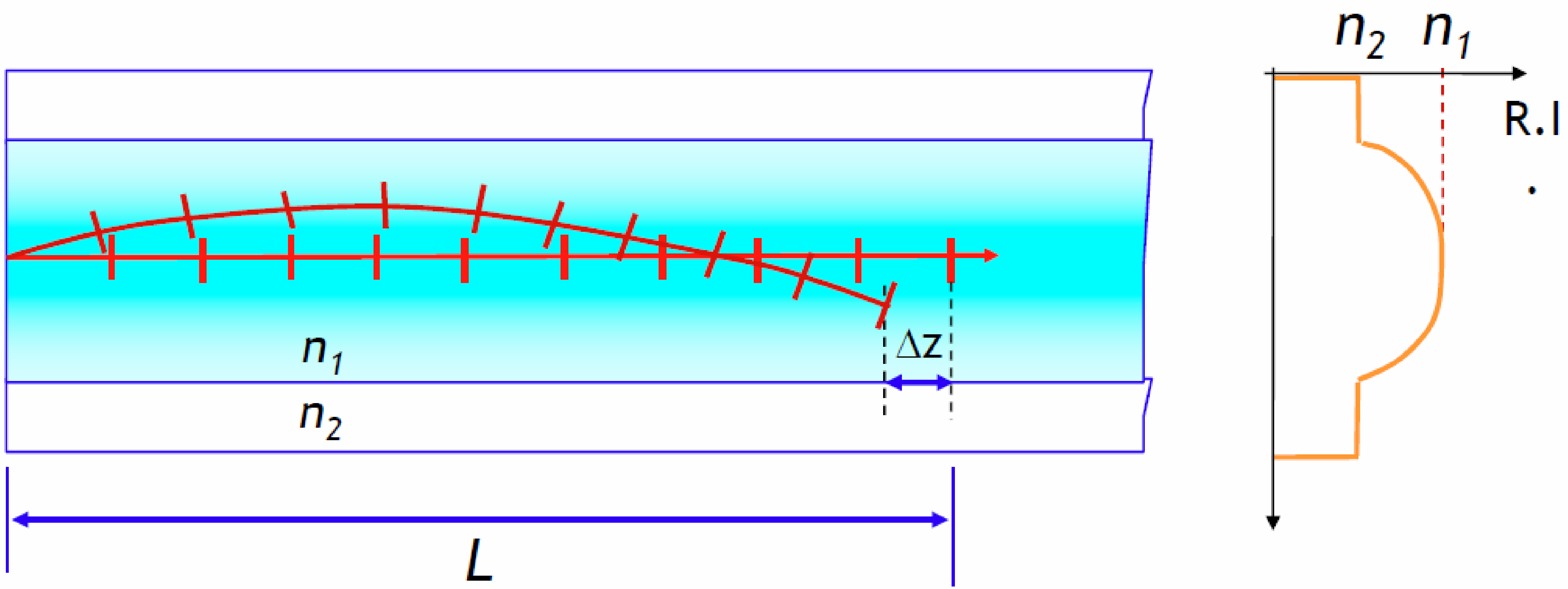
$$\delta t_{mod} = t_{max} - t_{min} = (L/c)n_1(n_1/n_2 - 1) \cong (L/c)(NA^2/2n_1)$$



The rms pulse broadening per unit length due to intermodal dispersion (for a step index fiber):

$$\sigma_{mod} \cong \frac{(NA)^2}{4\sqrt{2}n_1 c} \quad \text{ns/km}$$

Can be reduced by using a graded index profile

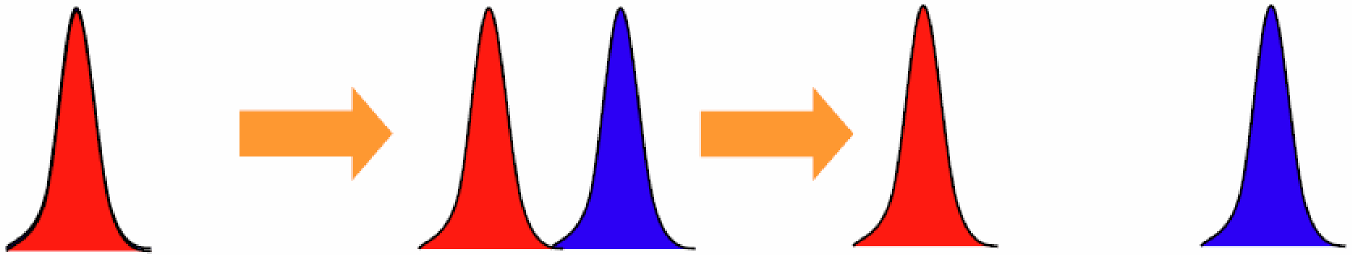


Minimized using a nearly parabolic index profile

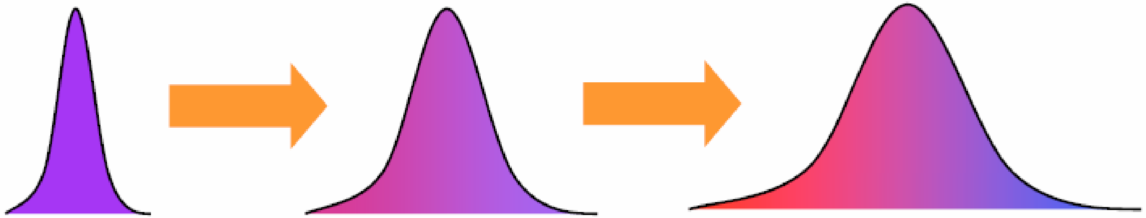
Intramodal dispersion (GVD)

Group Velocity Dispersion (GVD)

Discrete spectral components of a pulse travel at different speeds (e.g. in a multi-frequency laser)

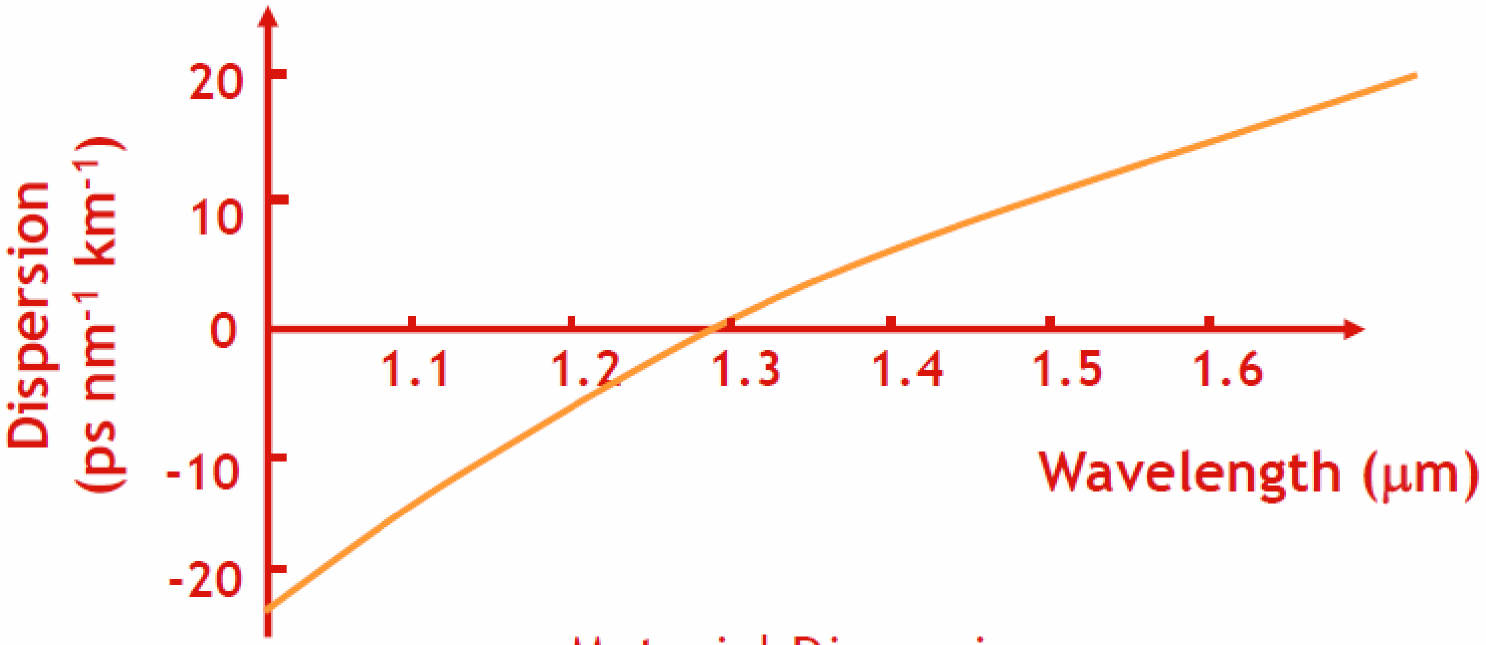


Pulse spreads out (its width increases) in time
(e.g. in a modulated single frequency laser)



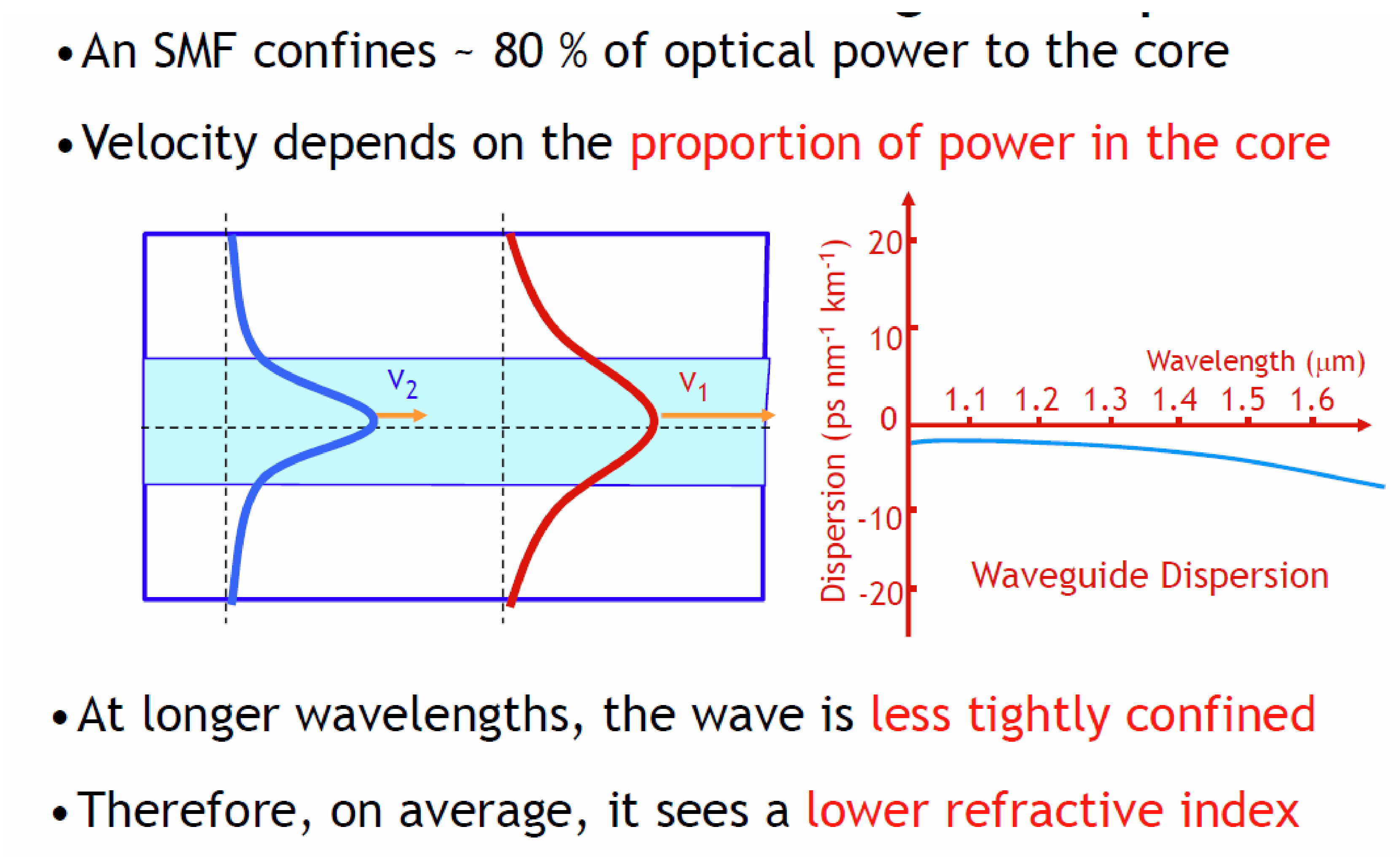
Intramodal dispersion – material dispersion

Refractive index varies with wavelength.



Material Dispersion

Intramodal dispersion – waveguide dispersion

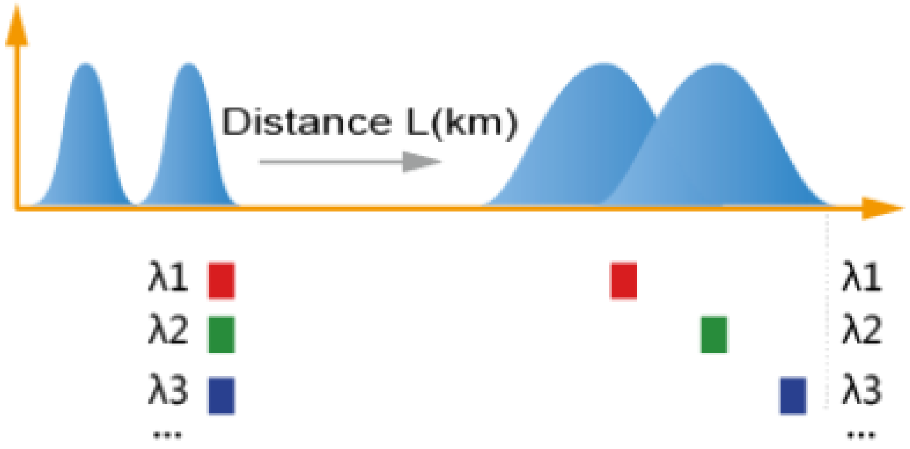


- An SMF confines ~ 80 % of optical power to the core
- Velocity depends on the proportion of power in the core

- At longer wavelengths, the wave is less tightly confined
- Therefore, on average, it sees a lower refractive index

Chromatic Dispersion (CD)

A form of dispersion where optical pulses are spread because different wavelengths are transmitted at different speeds in optical fibers and the periods for different wavelengths to traverse the same distance are different.



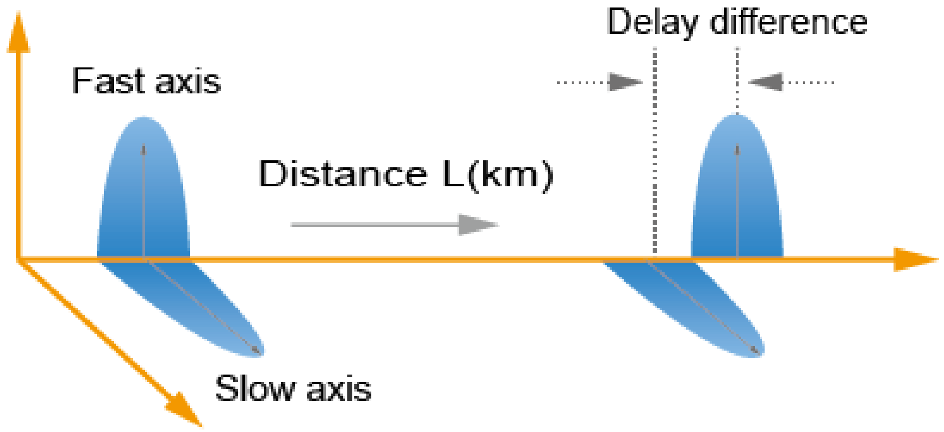
Total dispersion

- Includes Intramodal σ_c and Intermodal σ_n dispersion
- The total fiber dispersion per unit length:

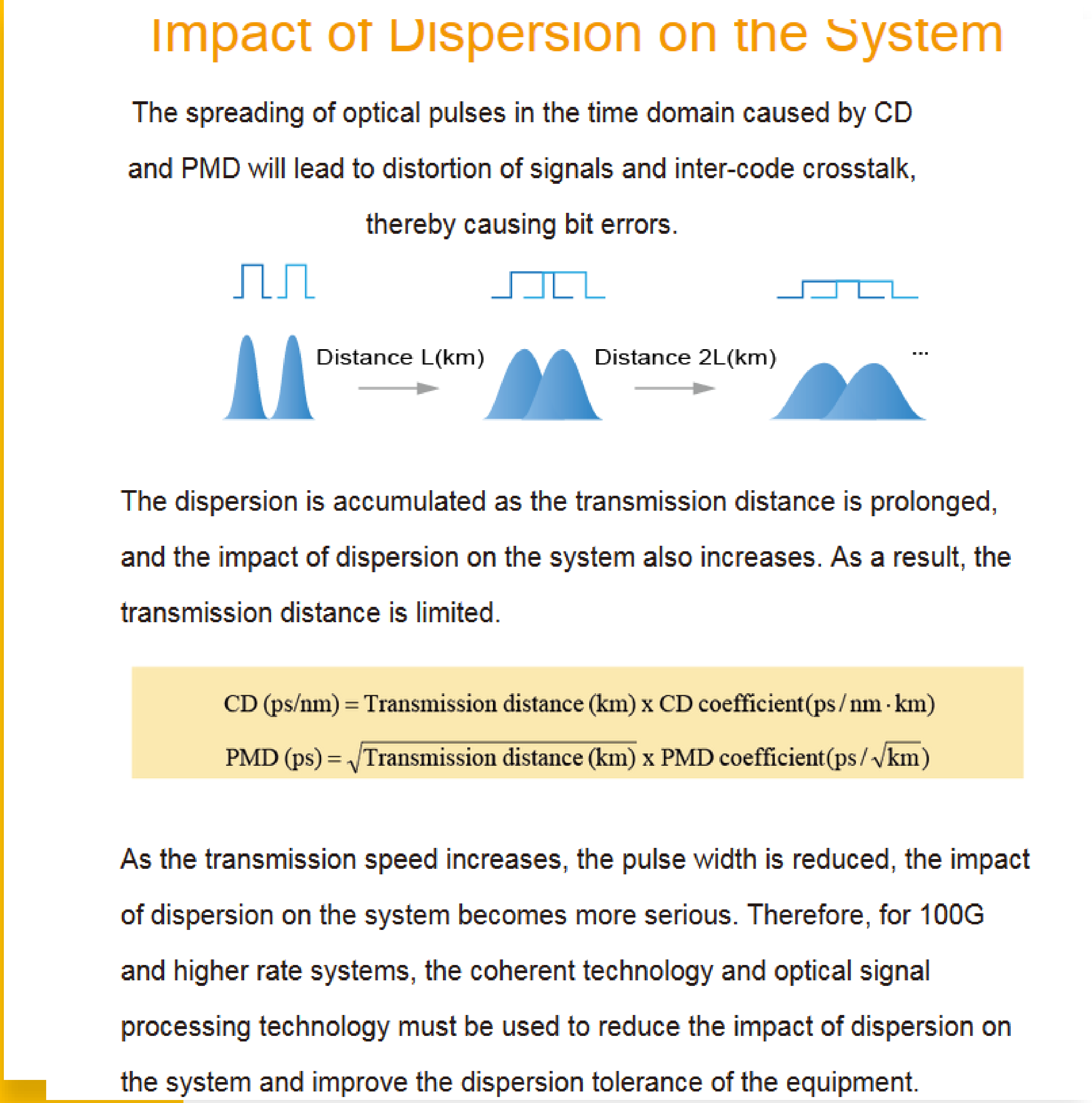
$$\sigma_T = (\sigma_c^2 + \sigma_n^2)^{1/2} \quad \text{ns/km}$$

- Pulse width will increase by s_T after 1 km

Polarization Mode Dispersion (PMD)



A form of dispersion where optical pulsesare spread because optical signals in different phase status are transmitted at different speeds due to the random birefringence of optical fibers.



Impact of Dispersion on the System

The spreading of optical pulses in the time domain caused by CD and PMD will lead to distortion of signals and inter-code crosstalk, thereby causing bit errors.

The dispersion is accumulated as the transmission distance is prolonged, and the impact of dispersion on the system also increases. As a result, the transmission distance is limited.

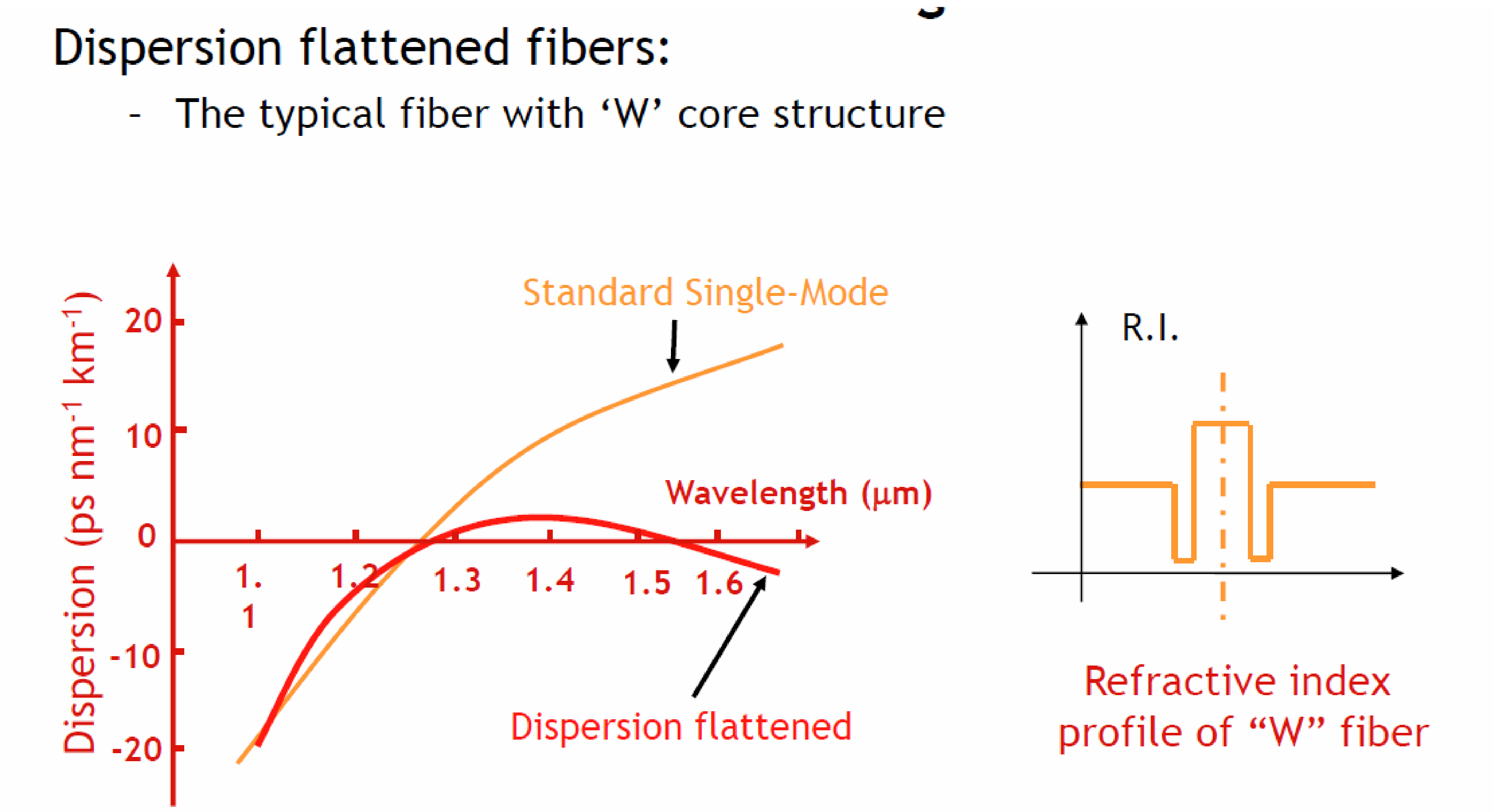
$$\text{CD (ps/nm)} = \text{Transmission distance (km)} \times \text{CD coefficient} (\text{ps} / \text{nm} \cdot \text{km})$$

$$\text{PMD (ps)} = \sqrt{\text{Transmission distance (km)}} \times \text{PMD coefficient} (\text{ps} / \sqrt{\text{km}})$$

As the transmission speed increases, the pulse width is reduced, the impact of dispersion on the system becomes more serious. Therefore, for 100G and higher rate systems, the coherent technology and optical signal processing technology must be used to reduce the impact of dispersion on the system and improve the dispersion tolerance of the equipment.

How to calculate?

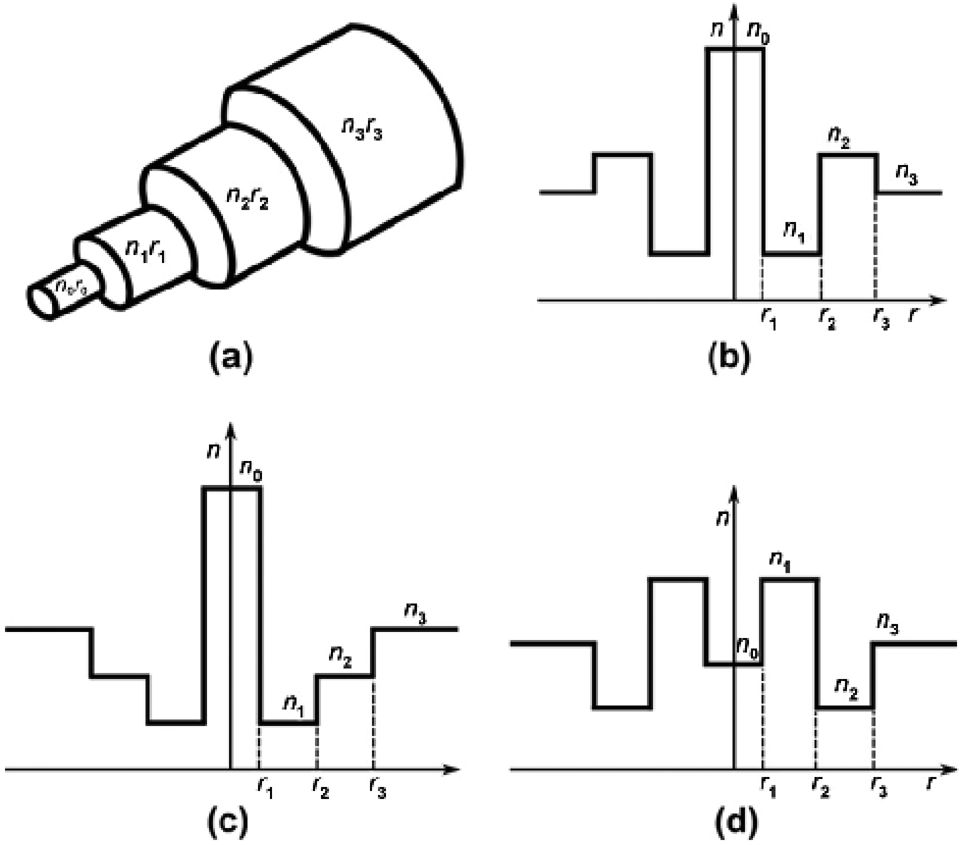
Dispersion modified **(flattened)**

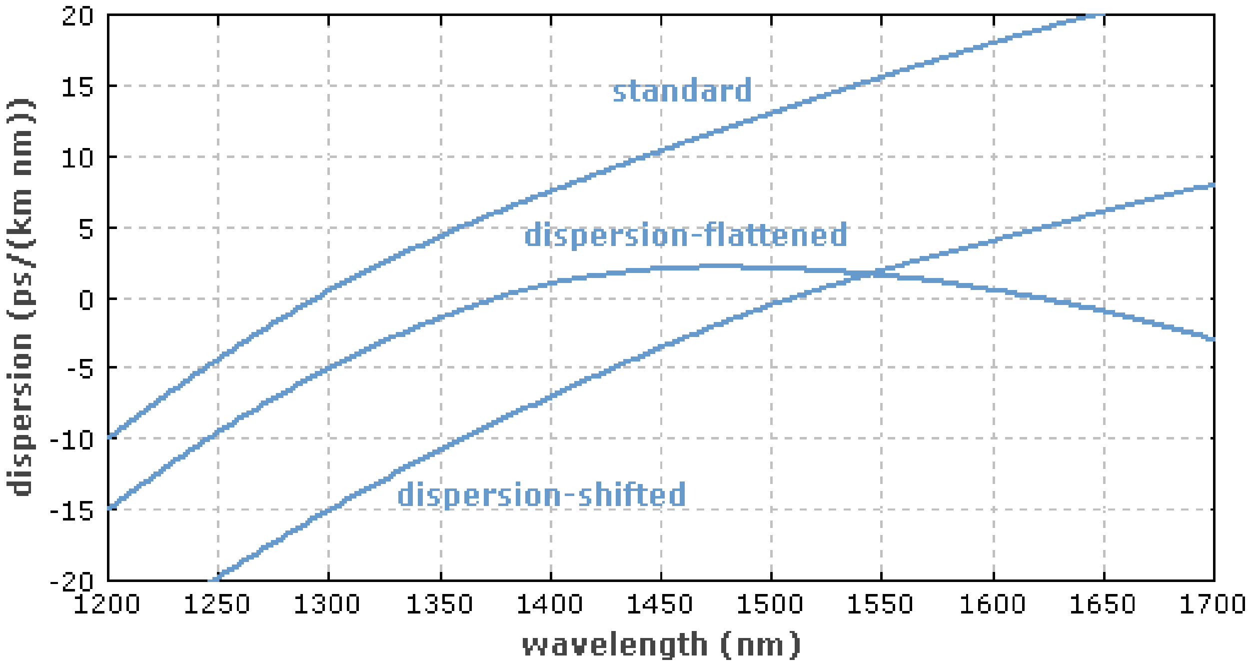


Dispersion flattened fibers:

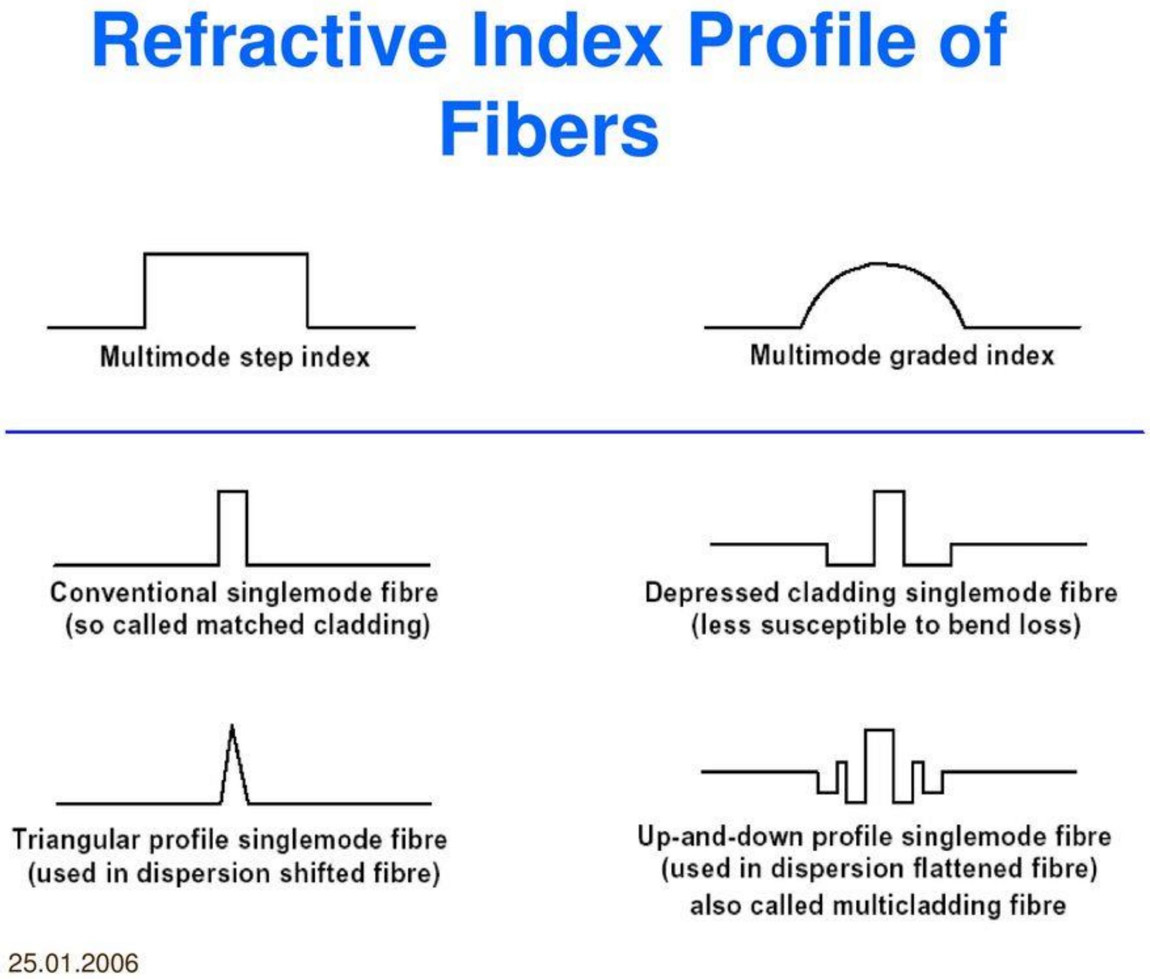
- The typical fiber with ‘W’ core structure

Dispersion shifted fibers





Review about the index profile



Refractive Index Profile of Fibers

Multimode step index

Multimode graded index

Conventional singlemode fibre
(so called matched cladding)

Depressed cladding singlemode fibre
(less susceptible to bend loss)

Triangular profile singlemode fibre
(used in dispersion shifted fibre)

Up-and-down profile singlemode fibre
(used in dispersion flattened fibre)
also called multicladding fibre

25.01.2006

$$n(\rho) = \begin{cases} n_1[1-\Delta(\rho/a)^{g}; & \rho < a, \\ n_1(1-\Delta) = n_2 \ ; & \rho \geq a, \end{cases}$$

g= parameter for index profile
g=1, triangle
g=infinite, step index
g=2, parabolic

Transversal section

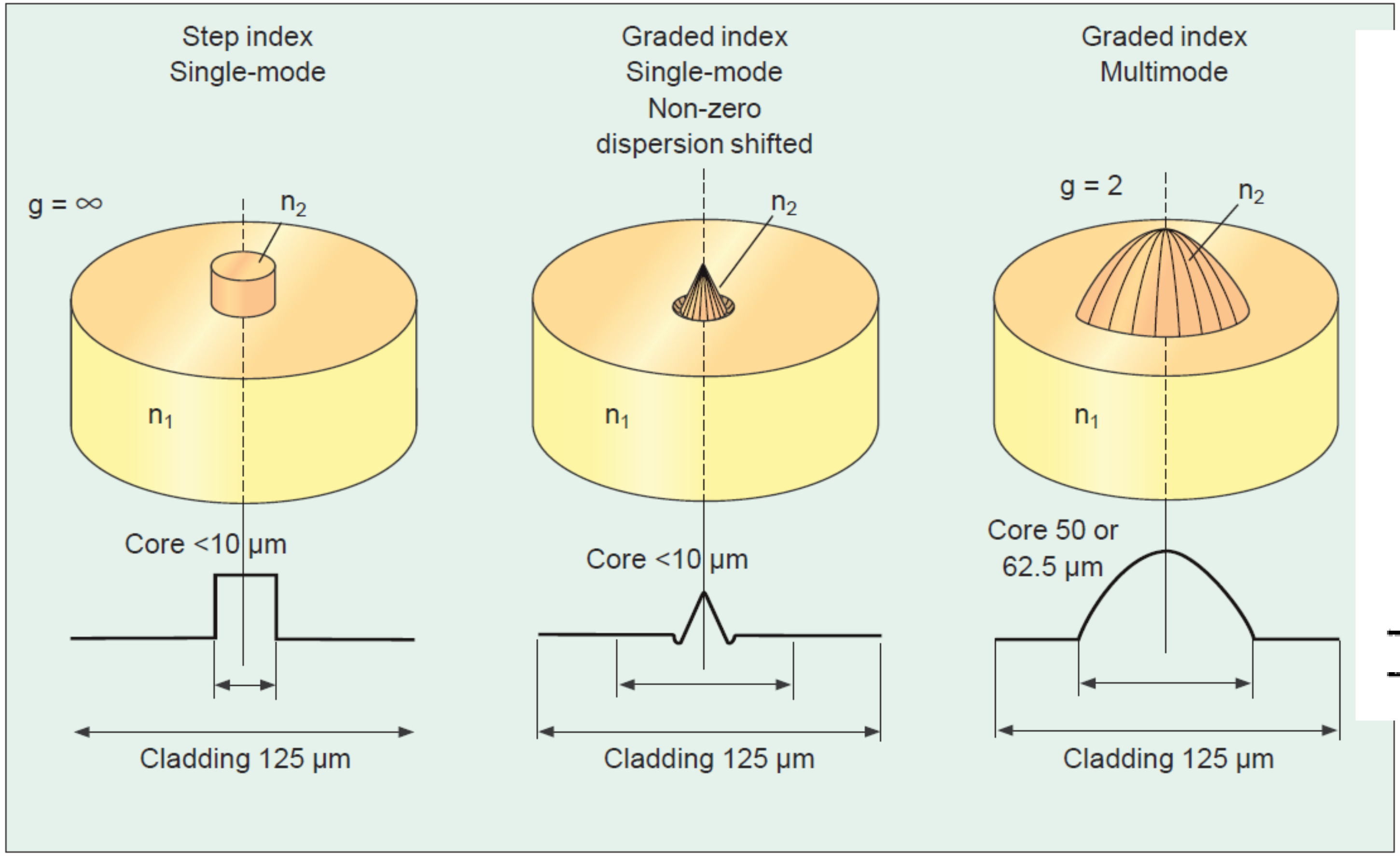
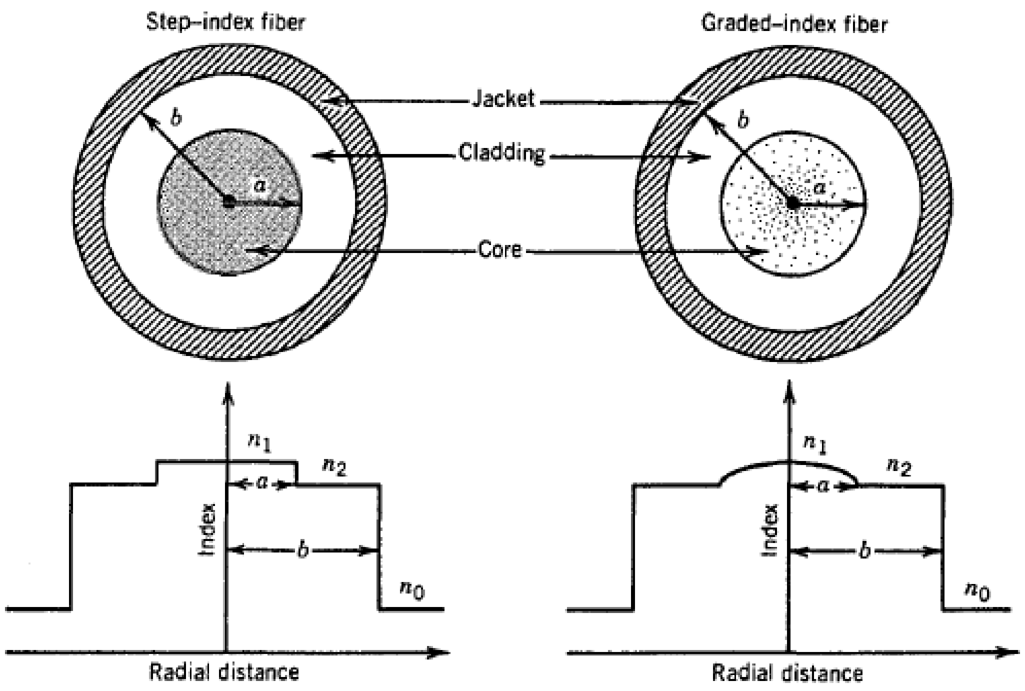
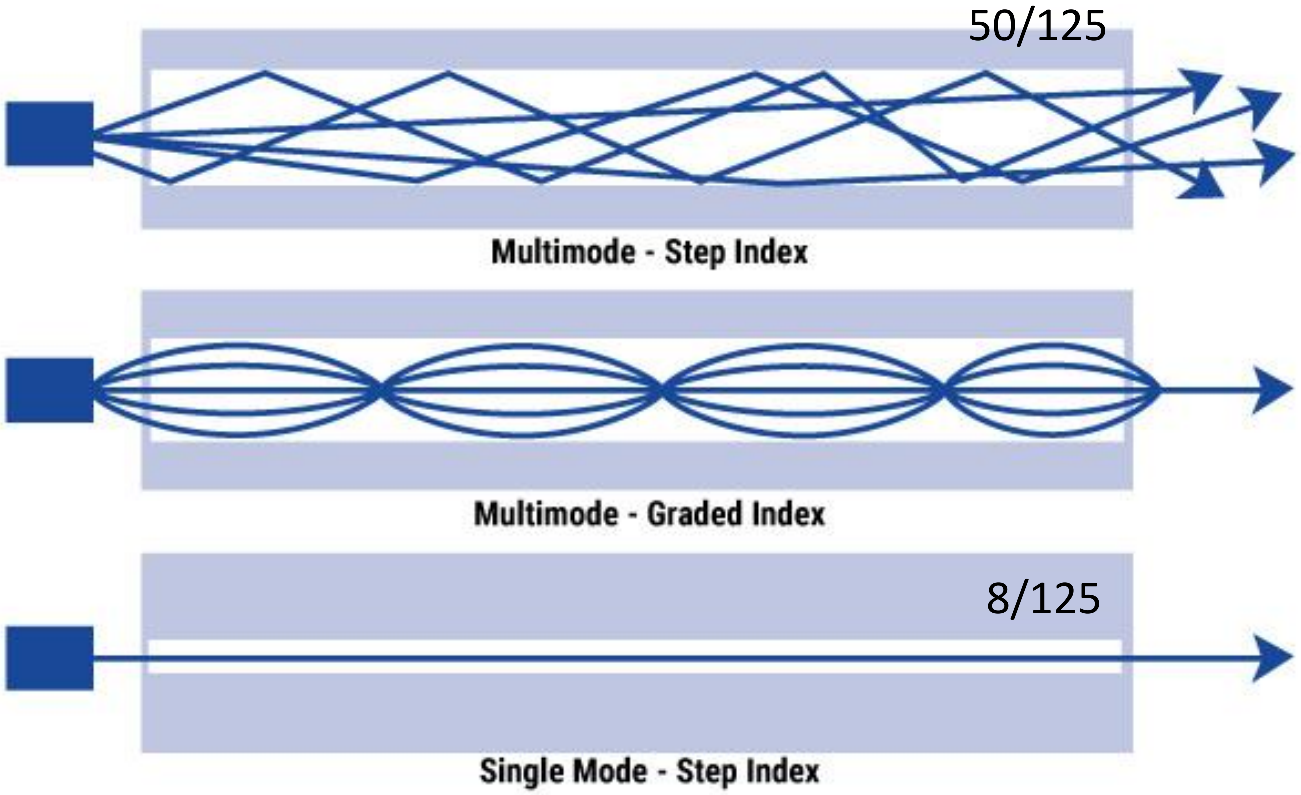
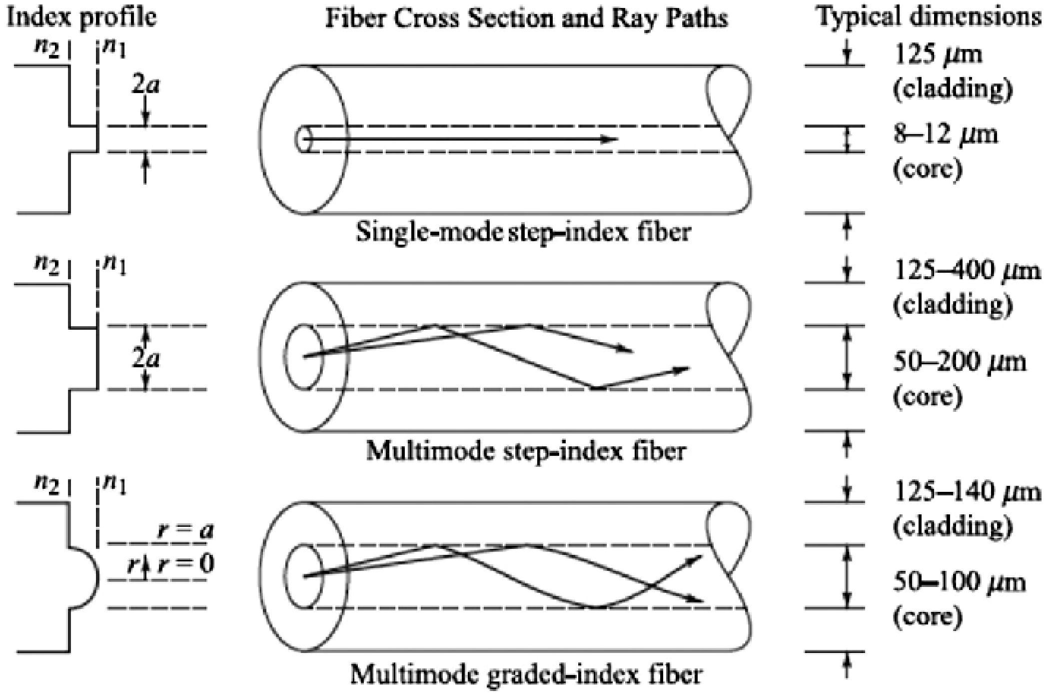


Fig. 4-1 Graphic representation of three different types of how the refractive index change in the core of an optical fiber

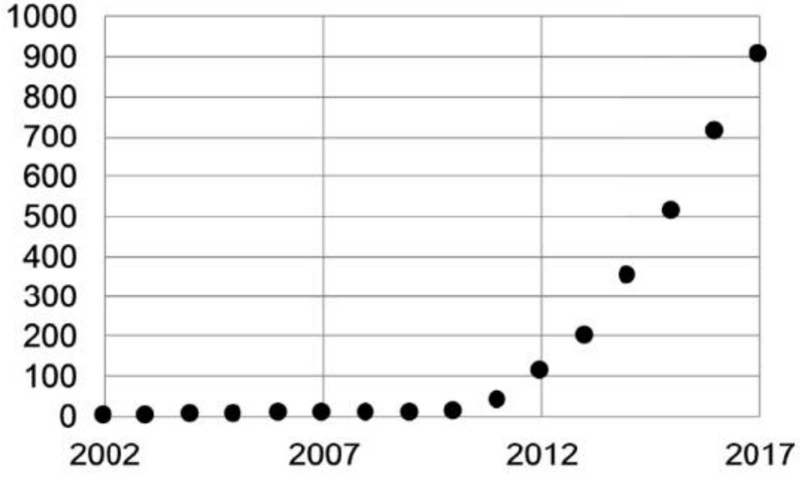


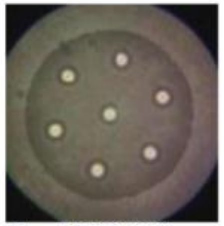
Longitudinal section



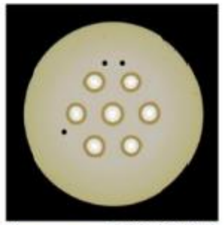


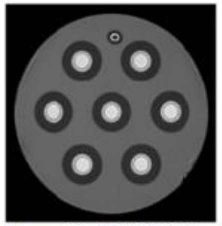
Special optical fibers (PCF)

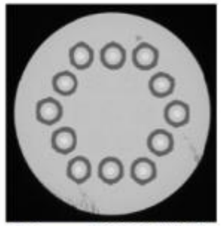


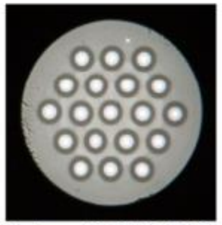

[Zhu, ECOC 2011]

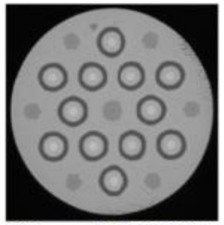

[Hayashi, ECOC 2011]


[Imamura, ECOC 2011]

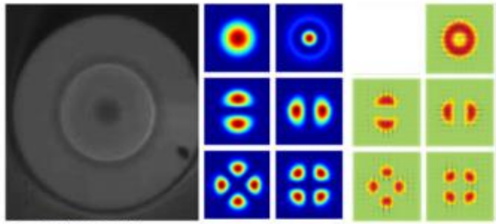

[Hayashi, OFC 2011]


[Takara, ECOC 2012]

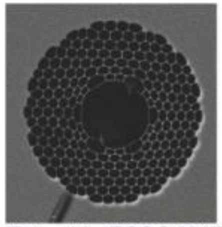

[Sakaguchi, OFC 2012]

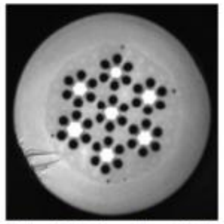

[Kobayashi, ECOC 2013]

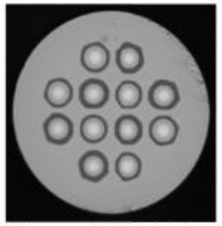

[Ryf, ECOC 2011]


[Ryf, FiO 2012]


[Doerr, ECOC 2011]


[Petrovich, ECOC 2012]


[Xia, IPS SumTop 2012]


[Mizuno, OFC 2014]

Dispersion

- **Dispersion, dispersion slope**
- **Dispersion compensation and management**
- **Kerr nonlinearities**
  - **Self-phase modulation (SPM)**
  - **Cross-phase modulation (XPM)**
  - **Four-wave mixing (FWM)**
- **Nonlinear transmission**

Representation of the propagation pulse

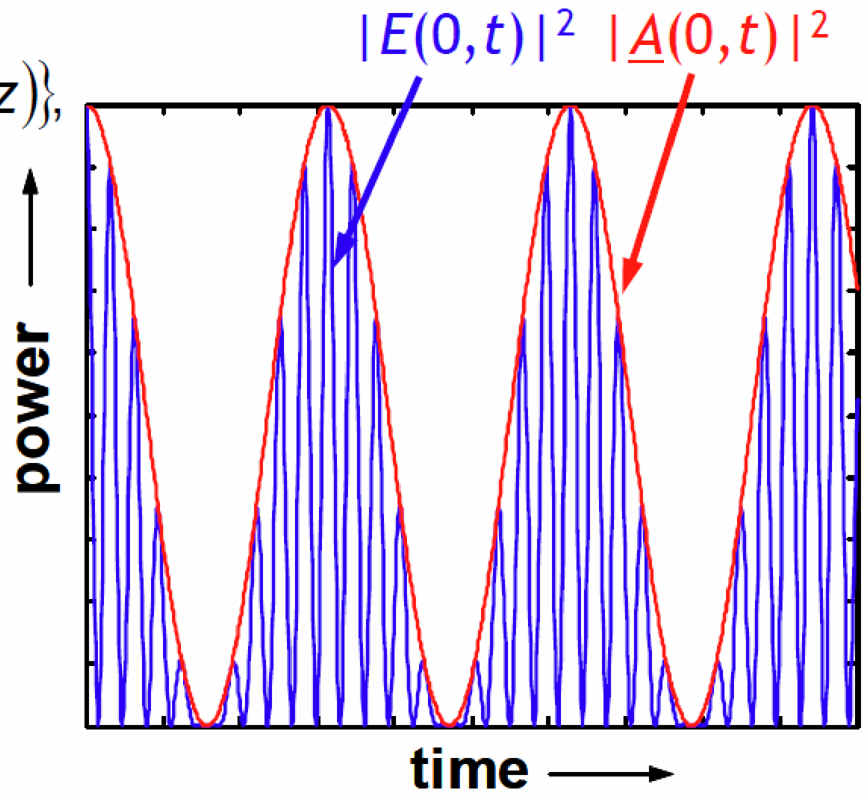
Electrical field:

$$E(z,t)=\mathrm{Re}\left\{\underline{A}(z,t)\exp\left(j\omega t-j\beta z\right)\right\},$$

with propagation constant

$$\beta=\frac{2\pi\cdot n}{\lambda},$$

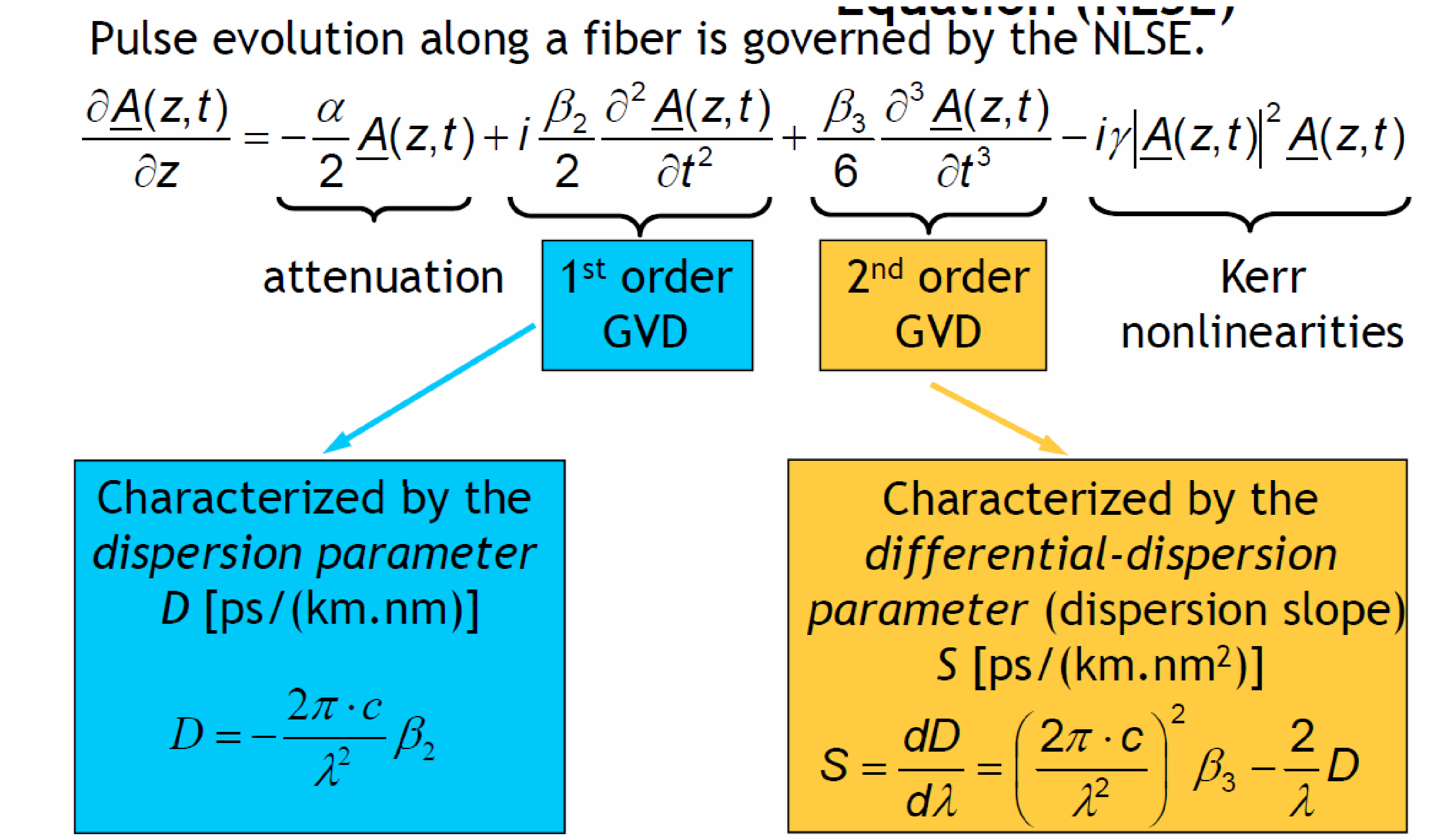
where n is the effective refractive index.



⇨ $\underline{A}(z,t)$: slowly varying complex field envelope

$|\underline{A}(z,t)|^2$: pulse shape in time domain

Schrodinger Equation



Pulse evolution along a fiber is governed by the NLSE:

$$\frac{\partial \underline{A}(z,t)}{\partial z} = \underbrace{-\frac{\alpha}{2}\underline{A}(z,t)}_{\text{attenuation}} + \underbrace{i\frac{\beta_2}{2}\frac{\partial^2 \underline{A}(z,t)}{\partial t^2}}_{\text{1st order GVD}} + \underbrace{\frac{\beta_3}{6}\frac{\partial^3 \underline{A}(z,t)}{\partial t^3}}_{\text{2nd order GVD}} \underbrace{- i\gamma\left|\underline{A}(z,t)\right|^2 \underline{A}(z,t)}_{\text{Kerr nonlinearities}}$$

Characterized by the *dispersion parameter* *D* [ps/(km.nm)]

$$D = -\frac{2\pi \cdot c}{\lambda^2}\beta_2$$

Characterized by the *differential-dispersion parameter* (dispersion slope) *S* [ps/(km.nm²)]

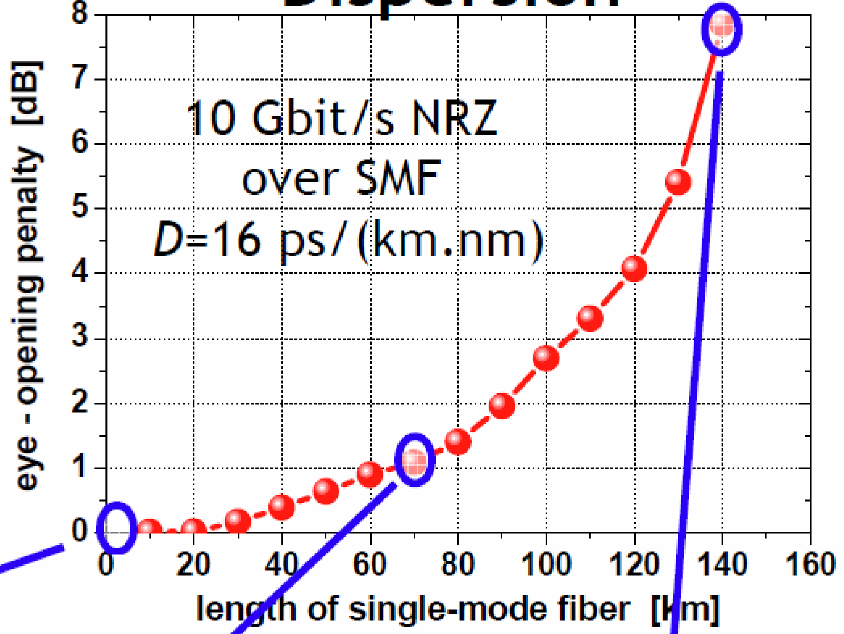
$$S = \frac{dD}{d\lambda} = \left(\frac{2\pi \cdot c}{\lambda^2}\right)^2 \beta_3 - \frac{2}{\lambda}D$$

Dispersion

Pulse broadening in the time-domain due to dispersion leads to an increased eye-closure.

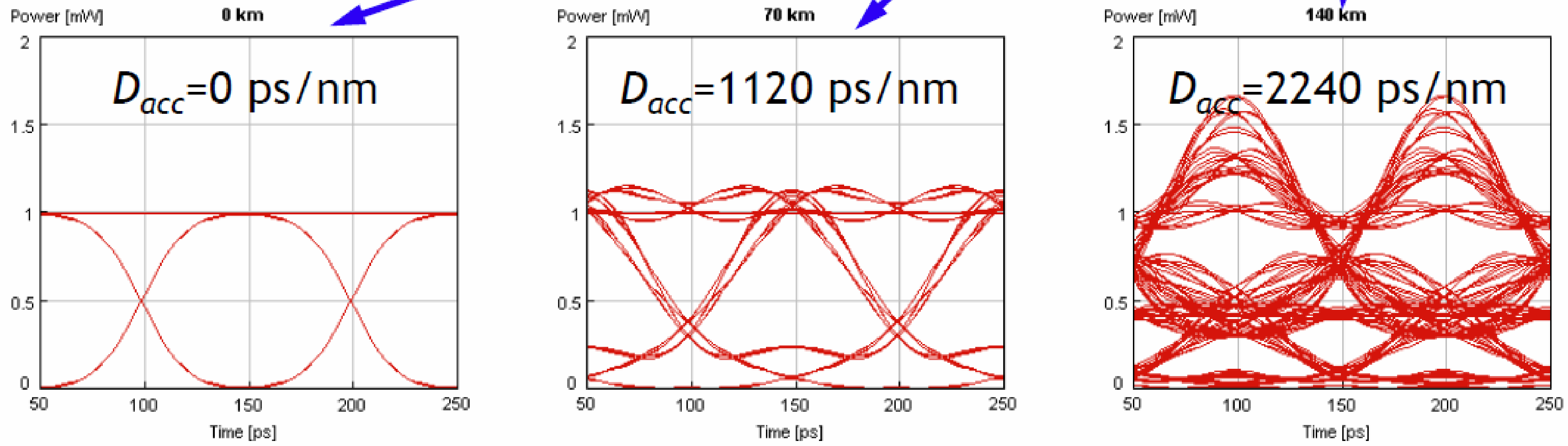
Characterized by accumulated dispersion D_{acc} [ps/nm].

$$D_{acc} = D \cdot L$$



10 Gbit/s NRZ over SMF

D=16 ps/(km.nm)



D_{acc}=0 ps/nm

D_{acc}=1120 ps/nm

D_{acc}=2240 ps/nm

Consider a Gaussian shaped pulse with $\underline{A}(0,t) = \underline{A}_0 \exp\left(-\frac{1}{2}\frac{t^2}{T_0^2}\right)$

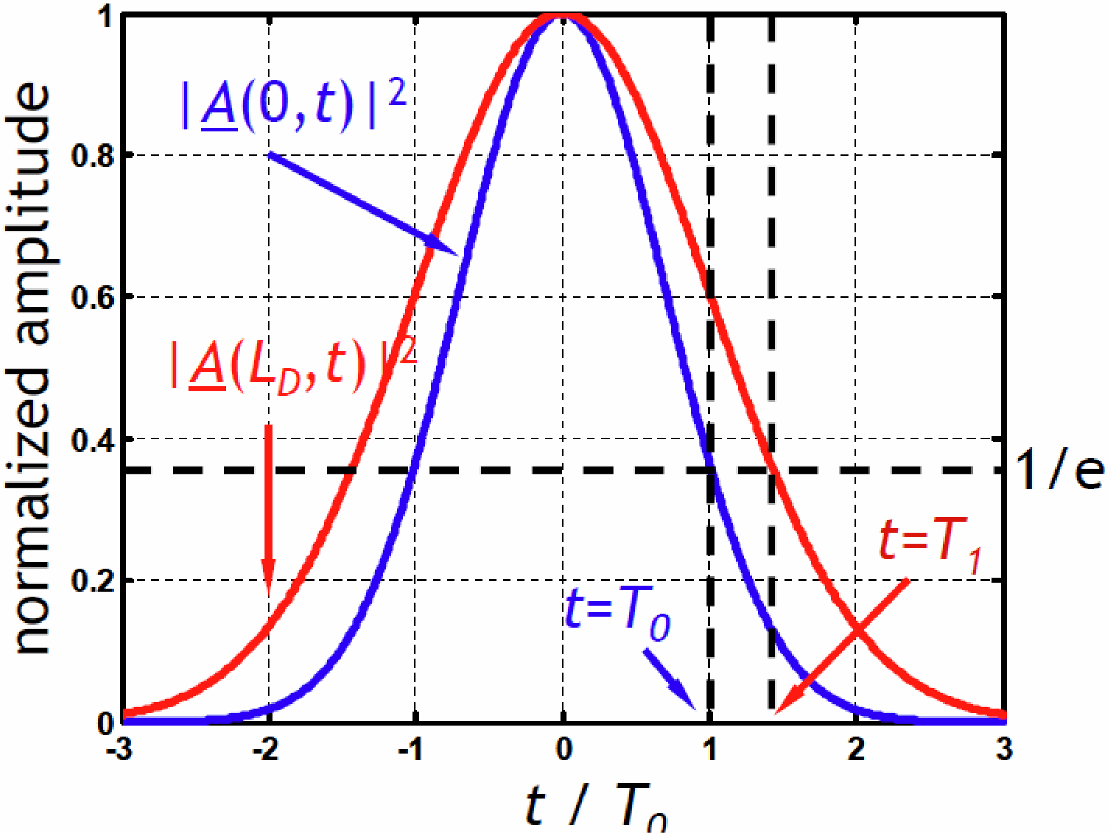
Dispersion length is defined as:

$$\boxed{L_D = \frac{T_0^2}{\left|\beta_2\right|}}$$

Pulse-shape at $z=L_D$?

Broadening factor at $z=L_D$:

$$\frac{T_1}{T_0} = \sqrt{2}$$



Dispersion is a linear effect. → It can be compensated.

Commonly used: *dispersion-compensating fiber* (DCF)

SMF

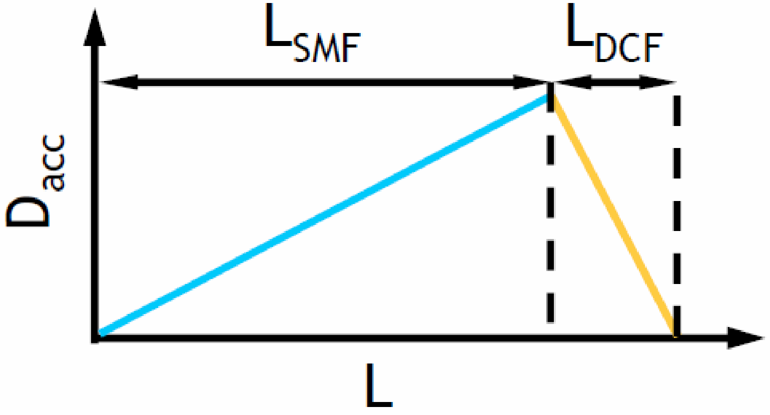
DCF

Positive dispersion parameter:

$$D_{SMF} \approx 17 \frac{ps}{km \cdot nm}$$

Negative dispersion parameter:

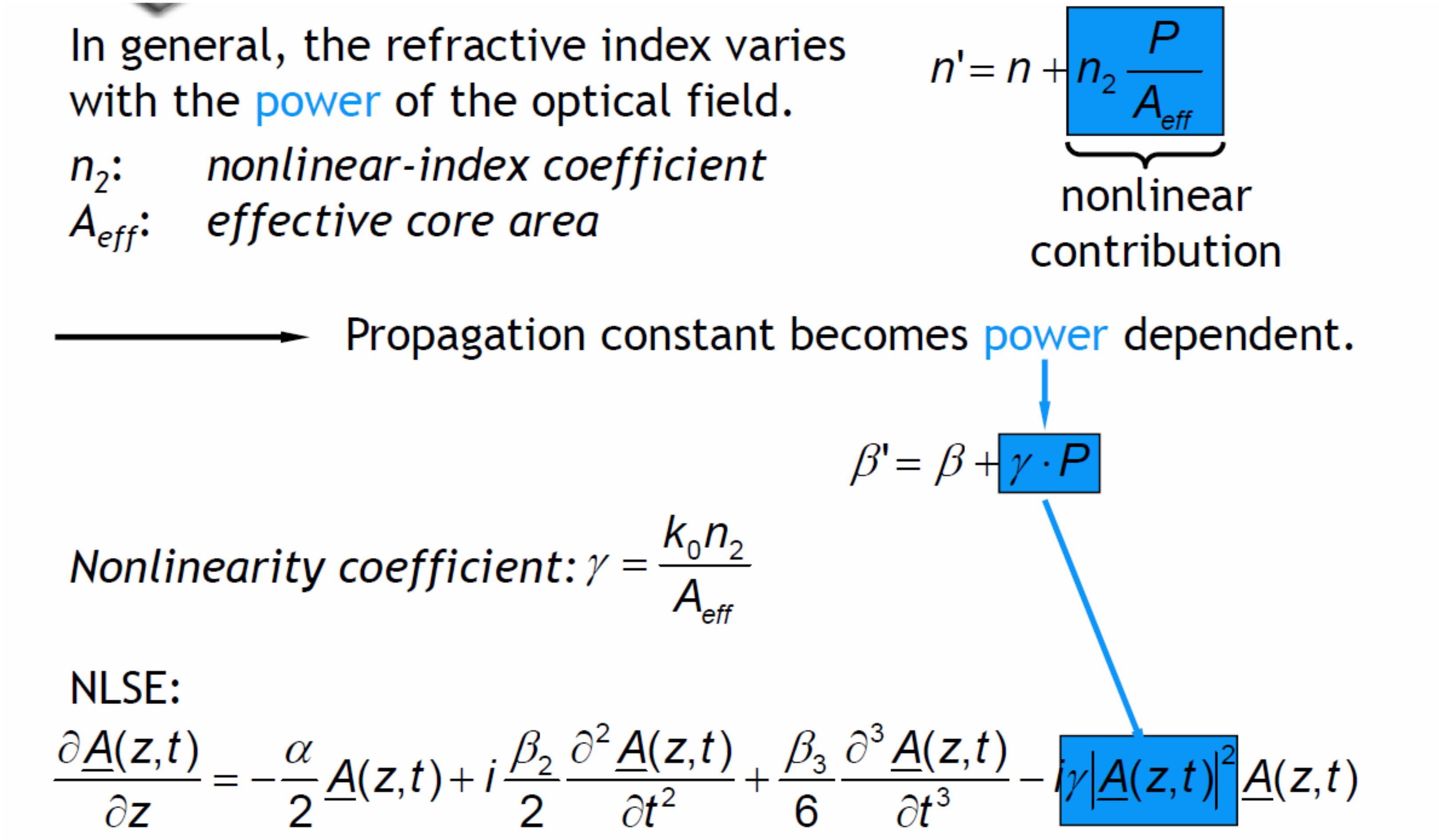
$$D_{DCF} \approx -100 \frac{ps}{km \cdot nm}$$



Requirement for complete compensation of 1st order GVD at a single wavelength:

$$\boxed{L_{SMF} D_{SMF} = -L_{DCF} D_{DCF}}$$

Kerr nonlinearities – NEXT TIME (nonlinear effects)



In general, the refractive index varies with the power of the optical field.

n_2: *nonlinear-index coefficient*
A_{eff}: *effective core area*

$$n' = n + \underbrace{\boxed{n_2 \frac{P}{A_{eff}}}}_{\text{nonlinear contribution}}$$

⟶ Propagation constant becomes power dependent.

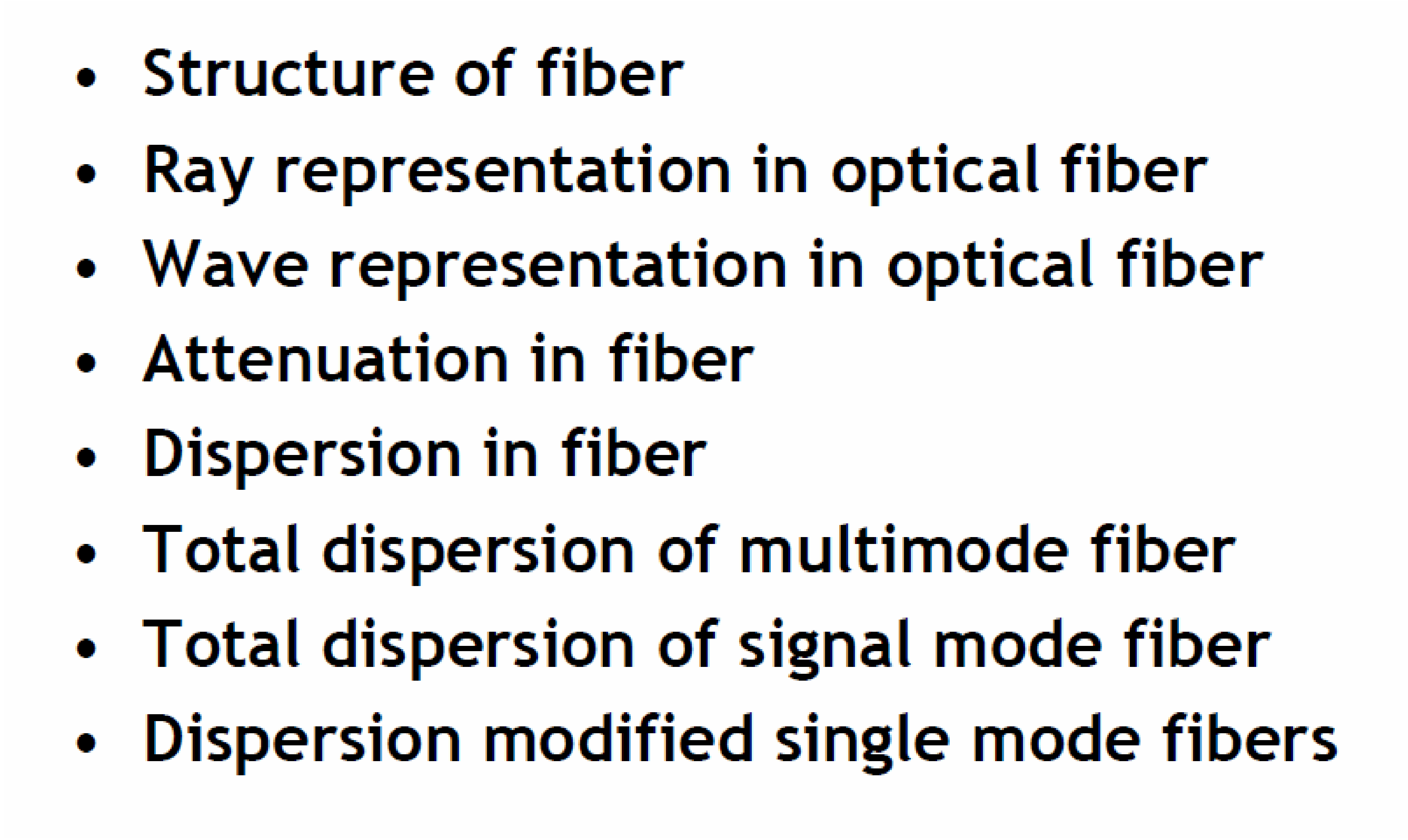
$$\beta' = \beta + \boxed{\gamma \cdot P}$$

Nonlinearity coefficient: $\gamma = \dfrac{k_0 n_2}{A_{eff}}$

NLSE:

$$\frac{\partial \underline{A}(z,t)}{\partial z} = -\frac{\alpha}{2}\underline{A}(z,t) + i\frac{\beta_2}{2}\frac{\partial^2 \underline{A}(z,t)}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 \underline{A}(z,t)}{\partial t^3} - \boxed{i\gamma\left|\underline{A}(z,t)\right|^2}\underline{A}(z,t)$$

II. Summary for Introduction for Optical Comm



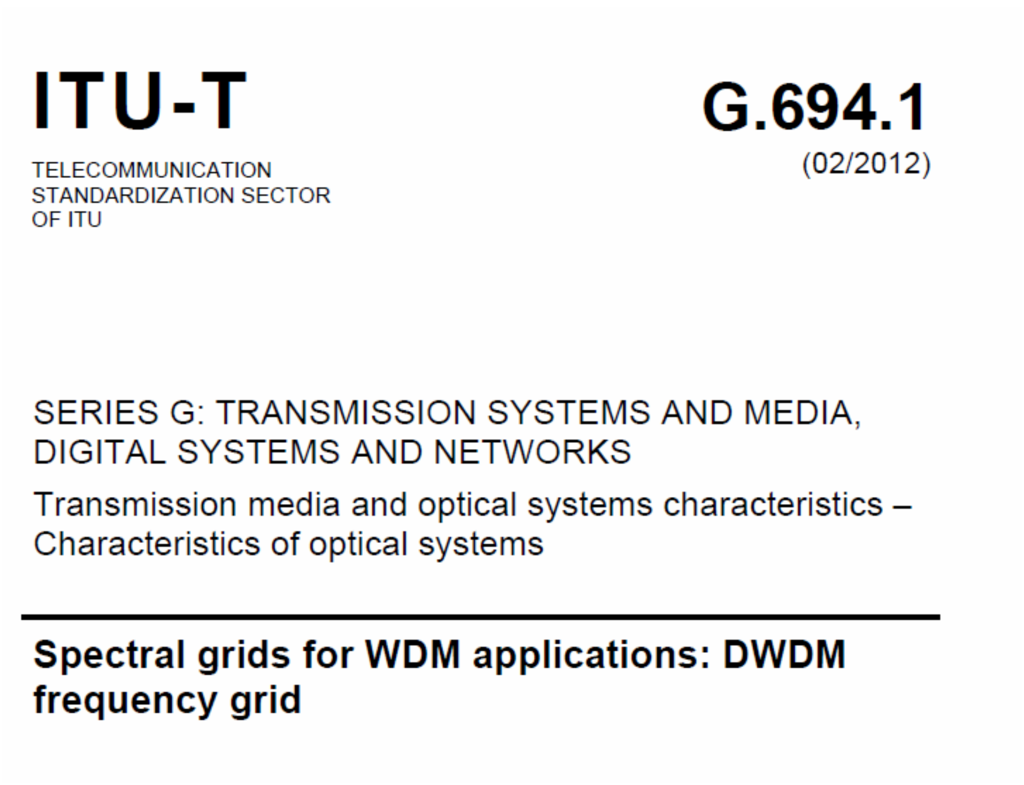
- Structure of fiber
- Ray representation in optical fiber
- Wave representation in optical fiber
- Attenuation in fiber
- Dispersion in fiber
- Total dispersion of multimode fiber
- Total dispersion of signal mode fiber
- Dispersion modified single mode fibers

Summary

- **Nonlinear Schrödinger Equation**
- **Dispersion and dispersion-compensation schemes**
- **Kerr nonlinearities**
  - **Self-phase modulation (SPM)**
  - **Cross-phase modulation (XPM)**
  - **Four-wave mixing (FWM)**
- **Dispersion-management**

OBSERVATION: During the lectures will recall these concepts

III Standardization (ITU-T) and maintenance



ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

G.694.1

(02/2012)

SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Transmission media and optical systems characteristics – Characteristics of optical systems

Spectral grids for WDM applications: DWDM frequency grid

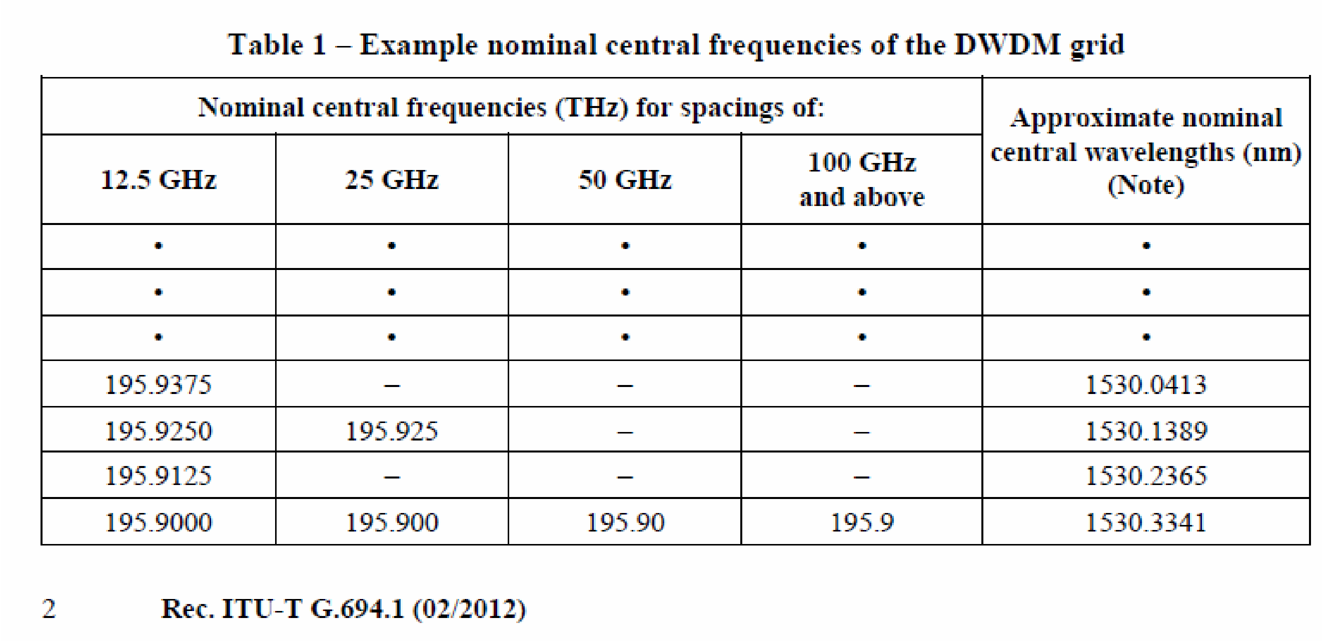


Table 1 – Example nominal central frequencies of the DWDM grid

Nominal central frequencies (THz) for spacings of:				Approximate nominal central wavelengths (nm) (Note)
12.5 GHz	25 GHz	50 GHz	100 GHz and above	
•	•	•	•	•
•	•	•	•	•
•	•	•	•	•
195.9375	–	–	–	1530.0413
195.9250	195.925	–	–	1530.1389
195.9125	–	–	–	1530.2365
195.9000	195.900	195.90	195.9	1530.3341

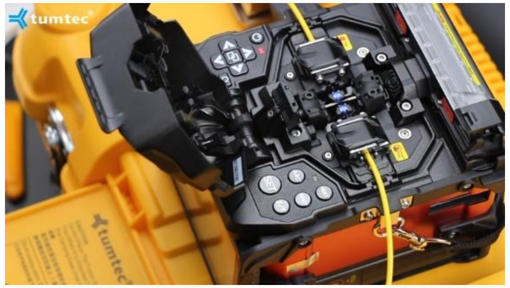
2 Rec. ITU-T G.694.1 (02/2012)

https://www.rp-photonics.com/wavelength_division_multiplexing.html

The 20th century - Metrology

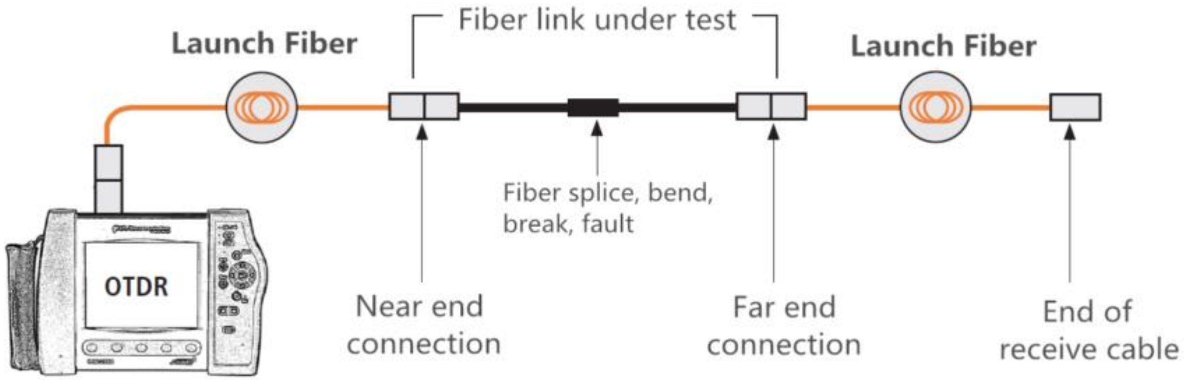
Fusion splicers or welding machines

Concepts are useful for the practical lab activities



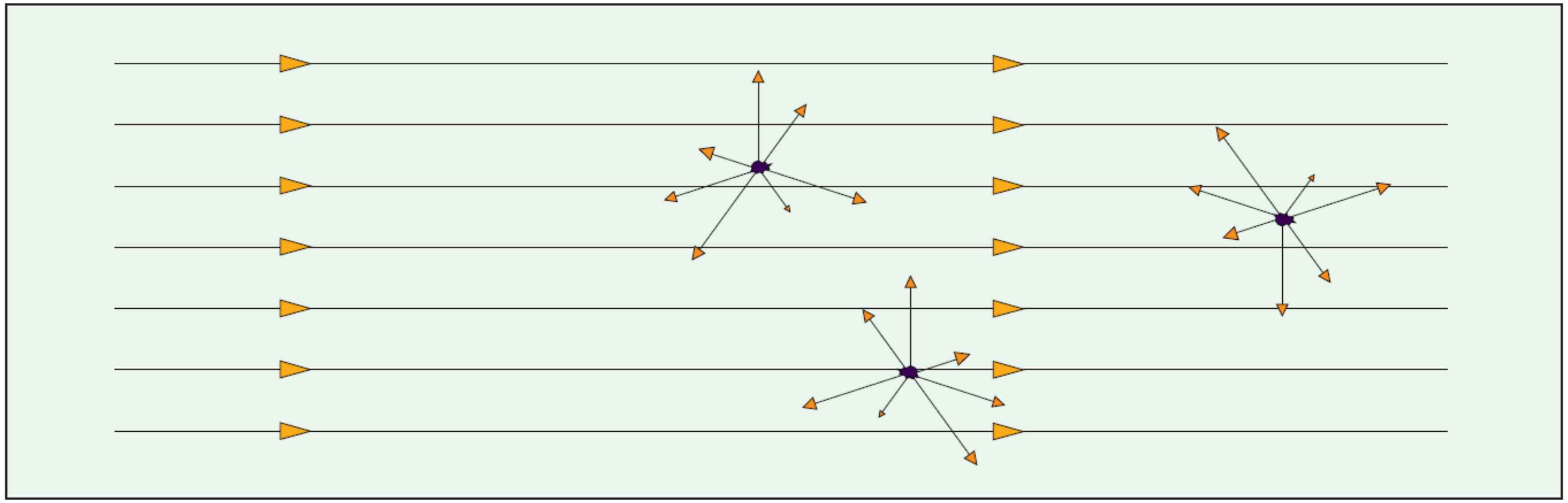
A modern handheld fusion splicer. Normally, a fiber splice loss of less than 0.05 dB (average) can be expected.

OTDR (Optical Time Domain Reflectometer) – link characterization



https://www.exfo.com/en/products/field-network-testing/otdr-iolm/iolm/
https://community.fs.com/blog/understanding-otdr-dead-zone-specifications.html

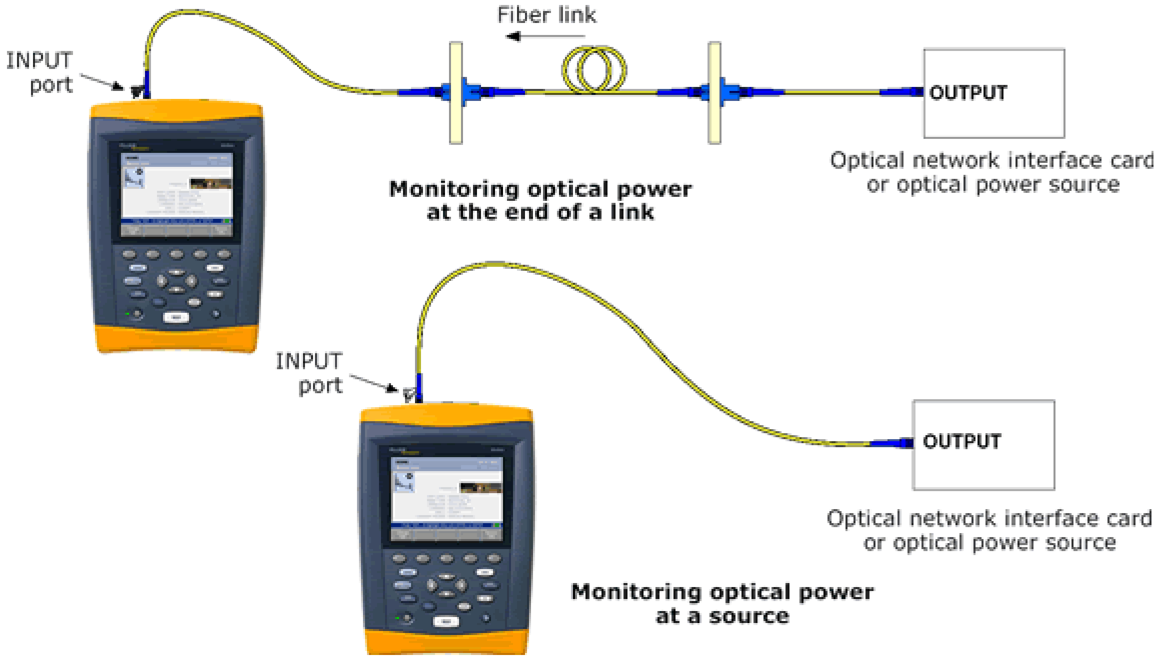
Rayleigh scattering and Tyndall's light

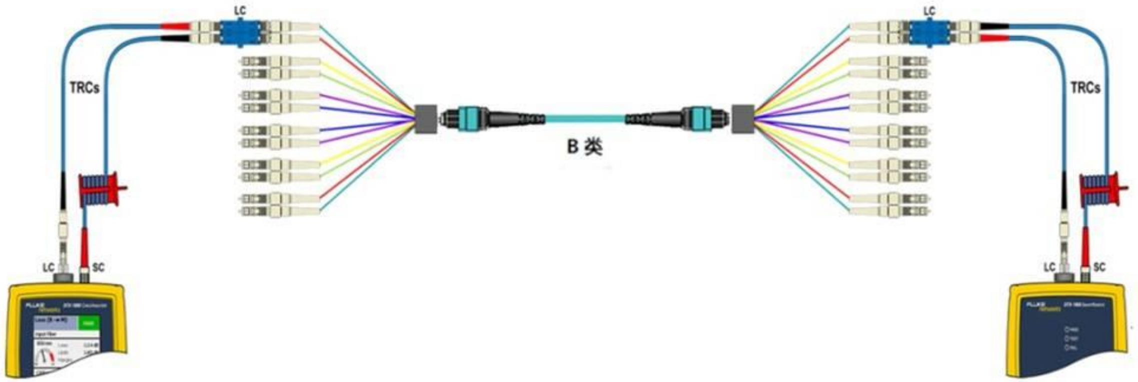


Rayleigh scattering of light due to impurities in the light transmitting.

https://www.fiberoptics4sale.com/blogs/archive-posts/95048006-optical-fiber-loss-and-attenuation

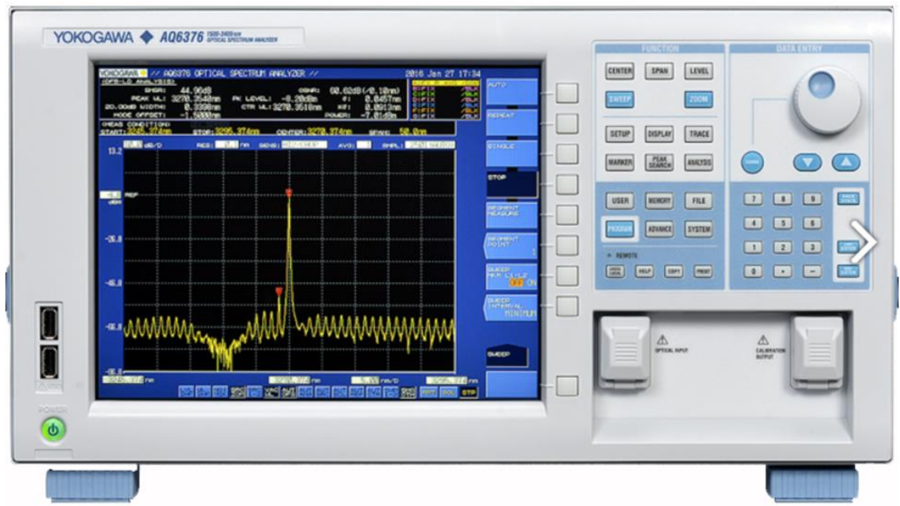
Optical power-meters

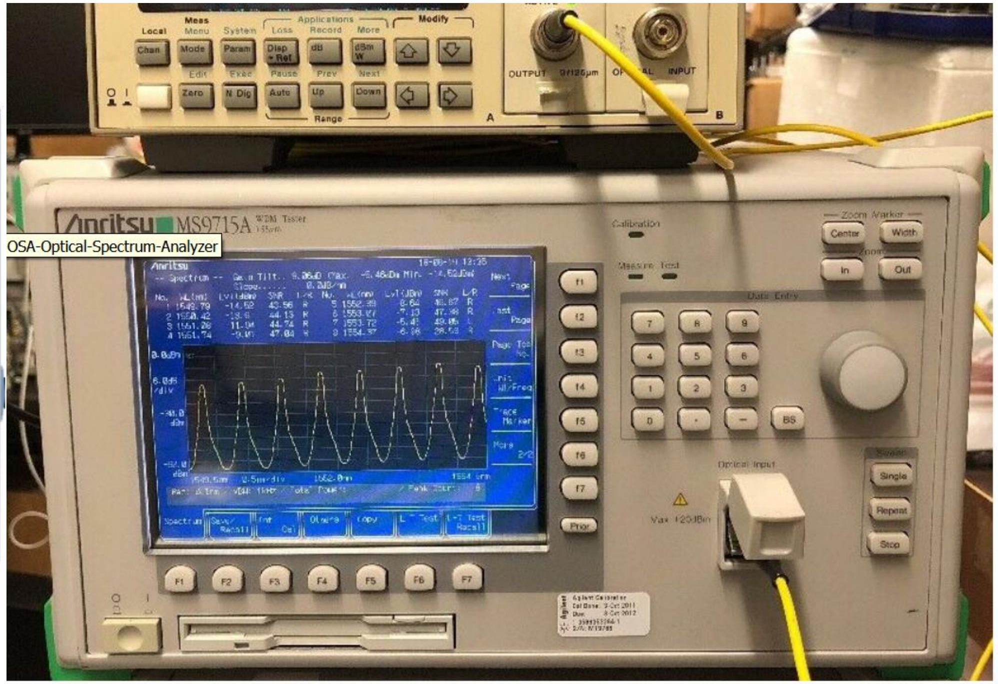


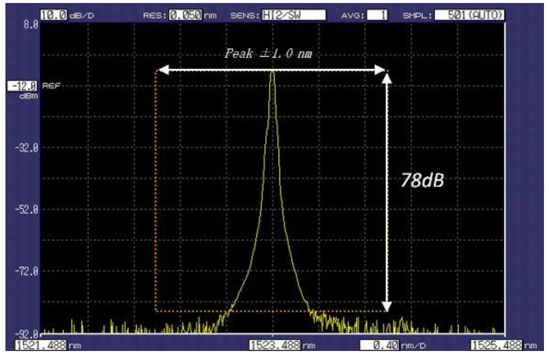


Optical Spectrum Analyzer (or OSA)

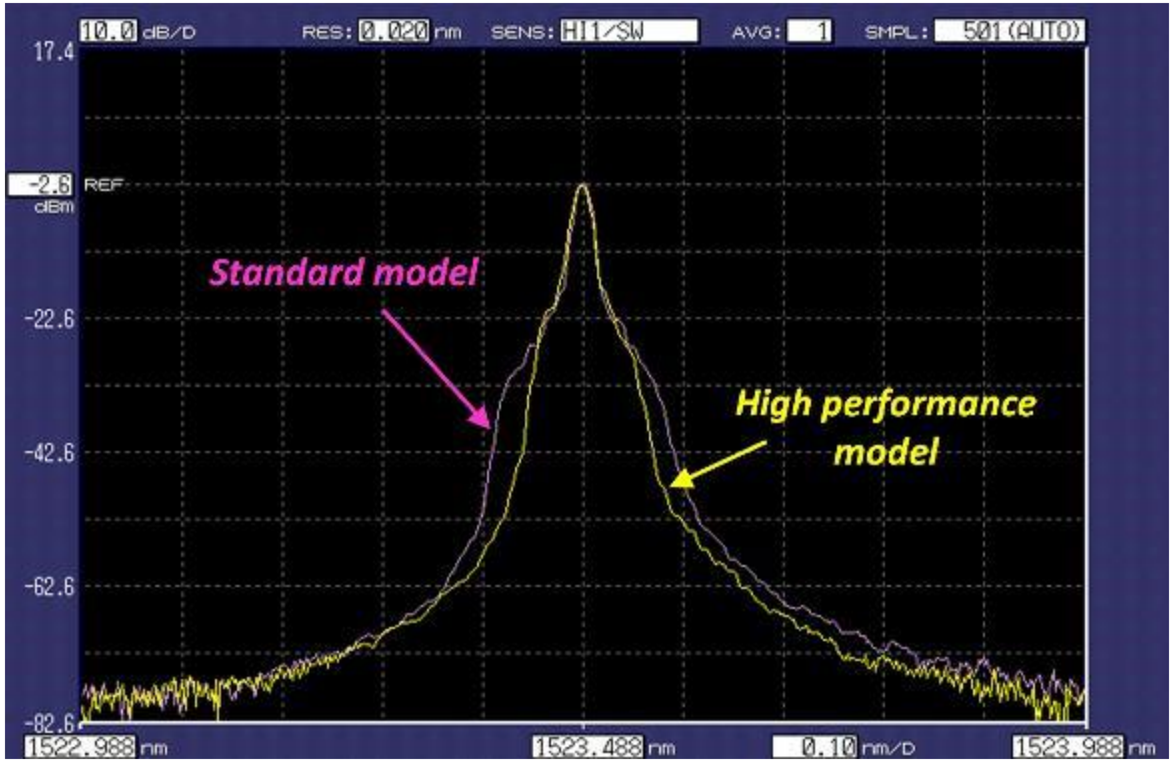
distribution of power of an optical source over a specified wavelength span.
An OSA trace displays power in the vertical scale and the wavelength in the horizontal scale.

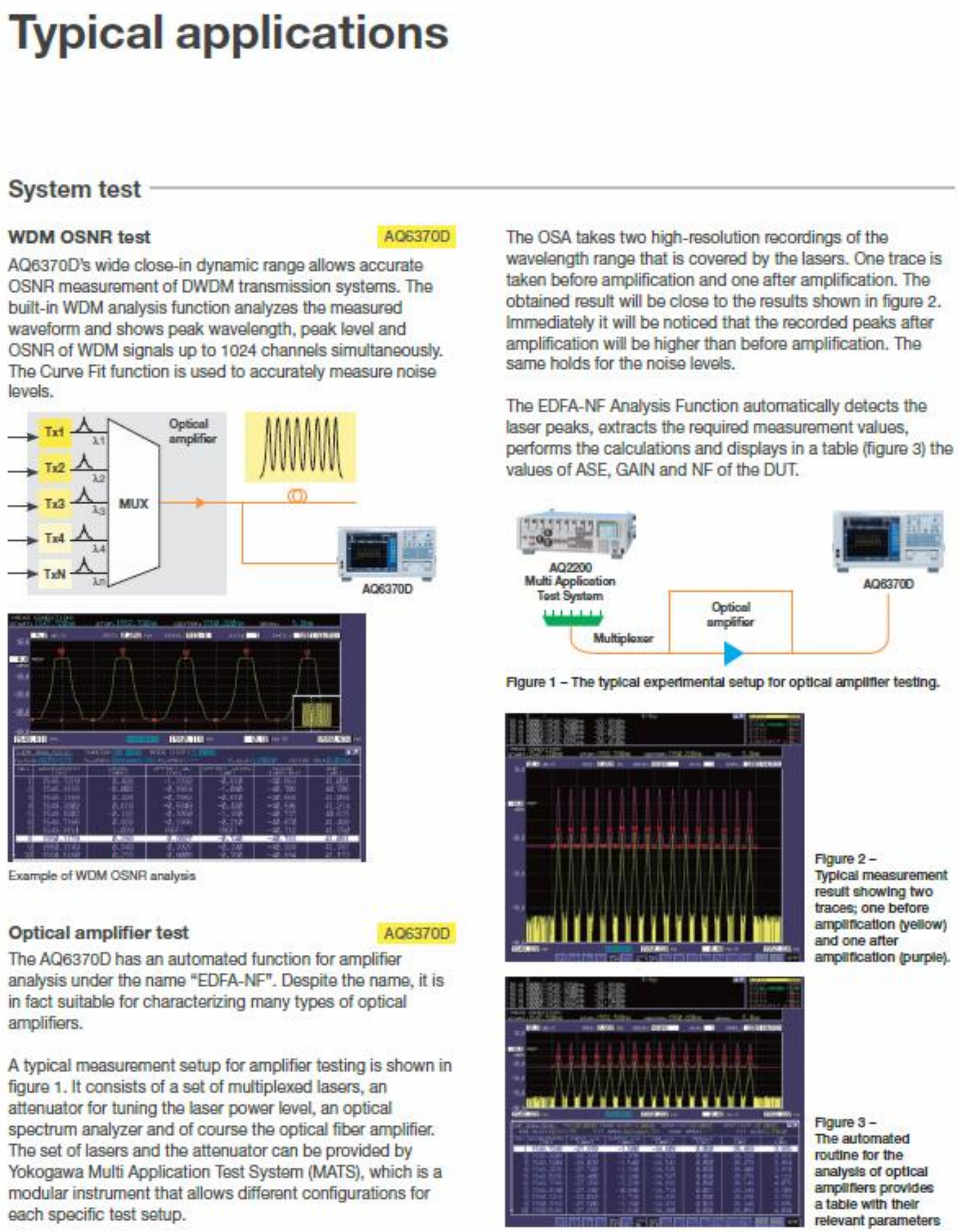






https://tmi.yokogawa.com/eu/solutions/products/optical-measuring-instruments/optical-spectrum-analyzer/
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5276&gclid=Cj0KCQjwoebsBRCHARIsAC3JP0K5FROPRD7tE736K710VYrHhPgopDHWJqGiF0Rnrzm9F7qWl8fY5Q4aAmo3EALw_wcB
https://tmi.yokogawa.com/tw/solutions/products/optical-measuring-instruments/optical-spectrum-analyzer/aq6370d-optical-spectrum-analyzer/





Typical applications

System test

WDM OSNR test

AQ6370D

AQ6370D's wide close-in dynamic range allows accurate OSNR measurement of DWDM transmission systems. The built-in WDM analysis function analyzes the measured waveform and shows peak wavelength, peak level and OSNR of WDM signals up to 1024 channels simultaneously. The Curve Fit function is used to accurately measure noise levels.

Example of WDM OSNR analysis

Optical amplifier test

AQ6370D

The AQ6370D has an automated function for amplifier analysis under the name "EDFA-NF". Despite the name, it is in fact suitable for characterizing many types of optical amplifiers.

A typical measurement setup for amplifier testing is shown in figure 1. It consists of a set of multiplexed lasers, an attenuator for tuning the laser power level, an optical spectrum analyzer and of course the optical fiber amplifier. The set of lasers and the attenuator can be provided by Yokogawa Multi Application Test System (MATS), which is a modular instrument that allows different configurations for each specific test setup.

The OSA takes two high-resolution recordings of the wavelength range that is covered by the lasers. One trace is taken before amplification and one after amplification. The obtained result will be close to the results shown in figure 2. Immediately it will be noticed that the recorded peaks after amplification will be higher than before amplification. The same holds for the noise levels.

The EDFA-NF Analysis Function automatically detects the laser peaks, extracts the required measurement values, performs the calculations and displays in a table (figure 3) the values of ASE, GAIN and NF of the DUT.

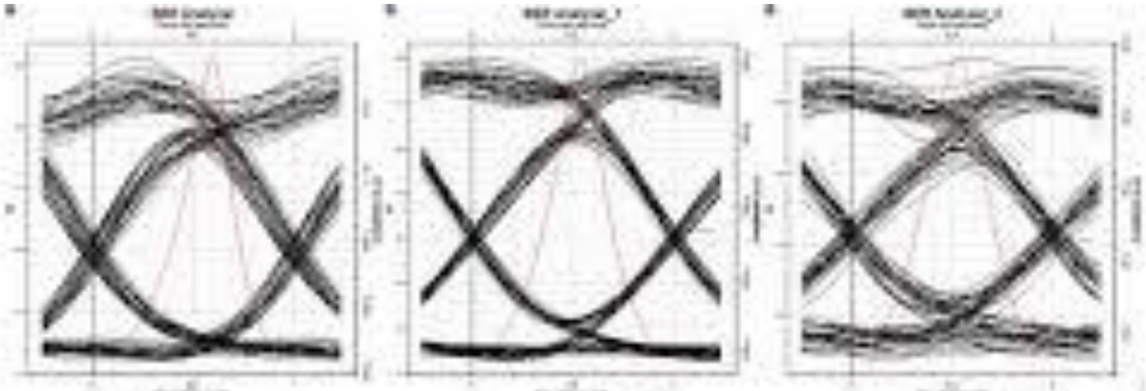
Figure 1 – The typical experimental setup for optical amplifier testing.

Figure 2 – Typical measurement result showing two traces; one before amplification (yellow) and one after amplification (purple).

Figure 3 – The automated routine for the analysis of optical amplifiers provides a table with their relevant parameters

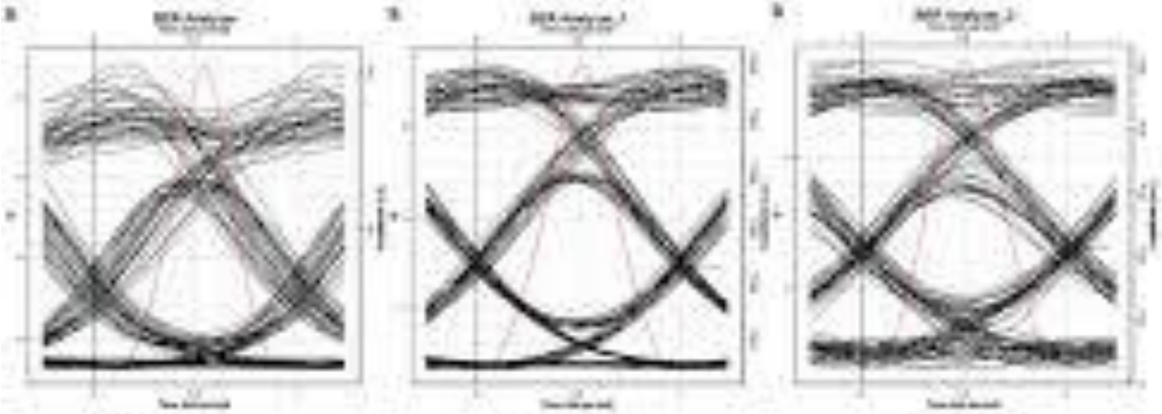
https://tmi.yokogawa.com/tw/solutions/products/optical-measuring-instruments/optical-spectrum-analyzer/aq6370d-optical-spectrum-analyzer/#Documents-Downloads____downloads_9

BER Analyzer



Channel 1 Channel 16 Channel 32

(a) RZ

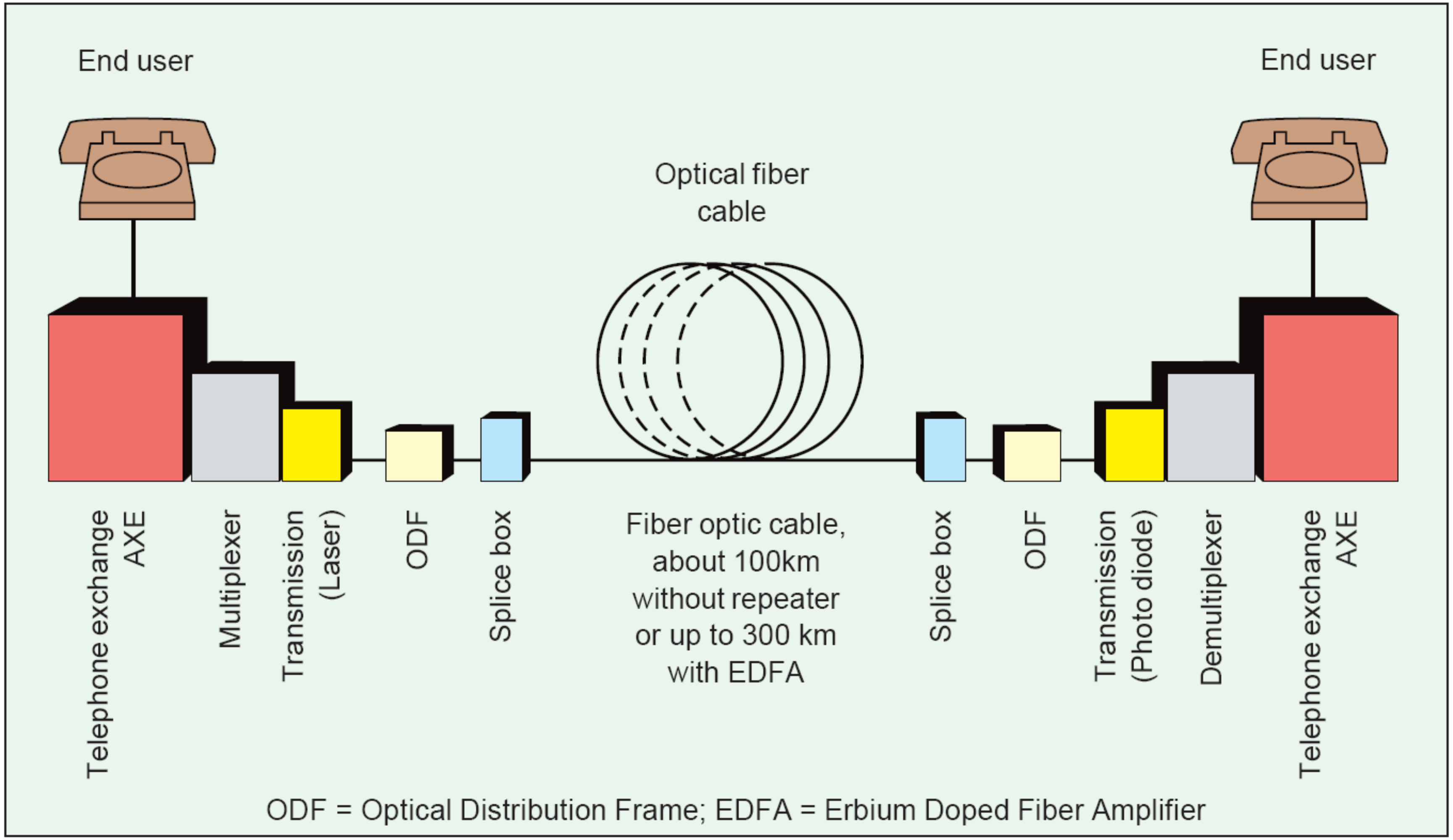


Channel 1 Channel 16 Channel 32

(b) NRZ

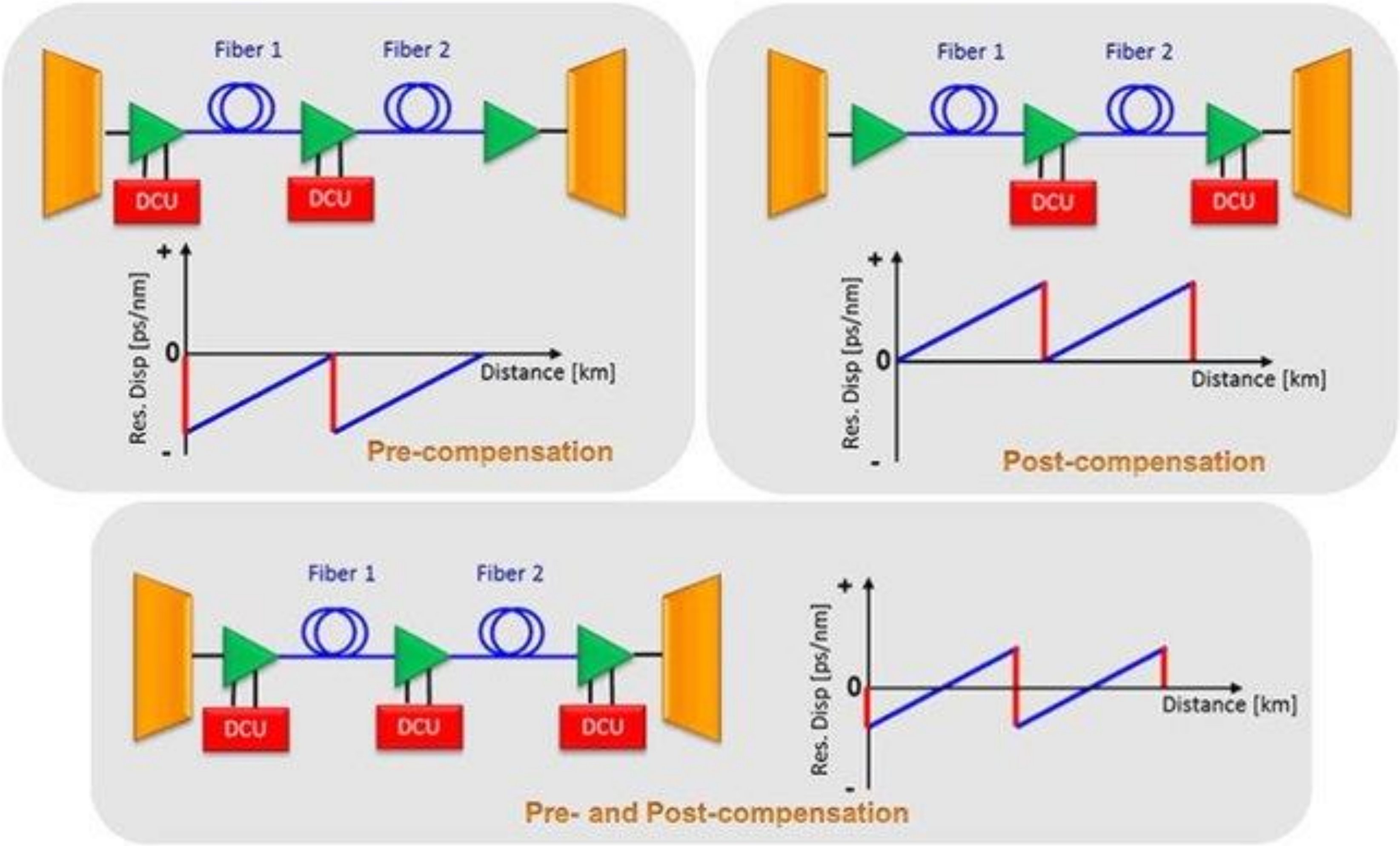
https://www.testandmeasurementtips.com/ber-analyzer-gets-multichannel-support-fec-pattern-generation-isi-and-error-count-import-to-handle-400-gbe-transceiver-tests/

Optical Link with EDFA (amplification)



The major parts of a fiberoptic communication system.

Optical link with dispersion compensation fibers



http://mapyourtech.com/entries/general/dispersion-compensation-an-introduction

DWDM point-to-point

-> abbreviations

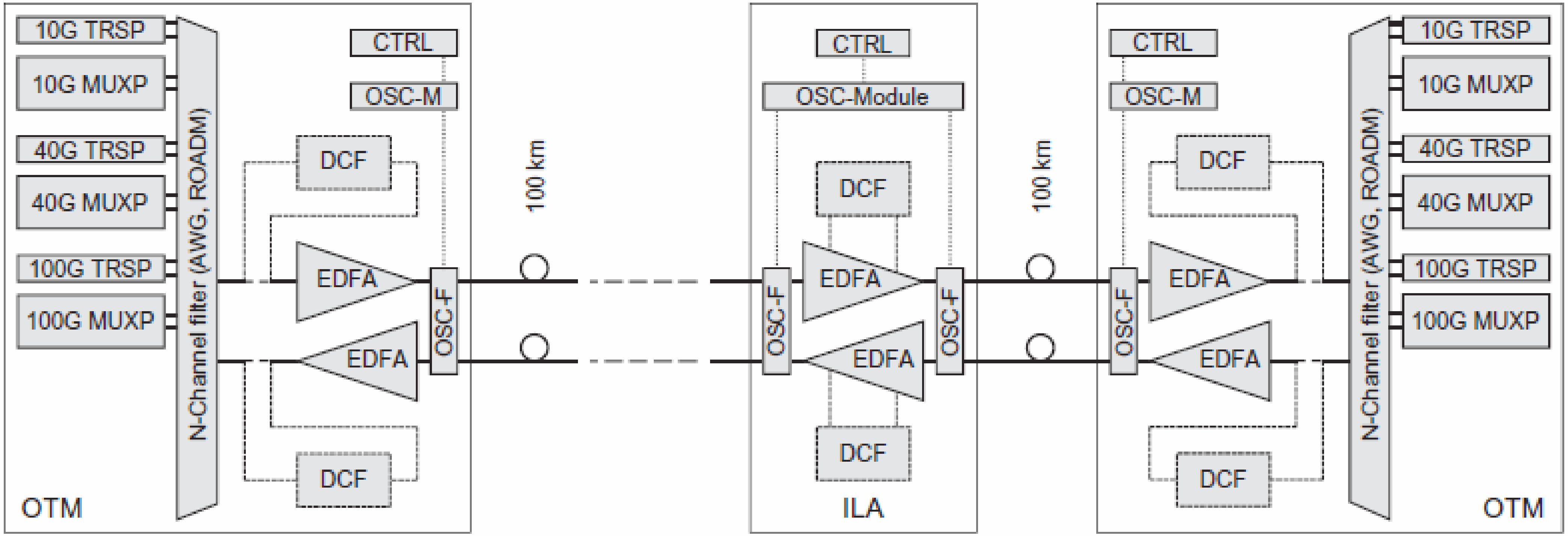


FIGURE 5.10

DWDM point-to-point system.

https://www.juniper.net/documentation/en_US/junos/topics/concept/ptx3k-iplc-ila-osc-communication-understand.html

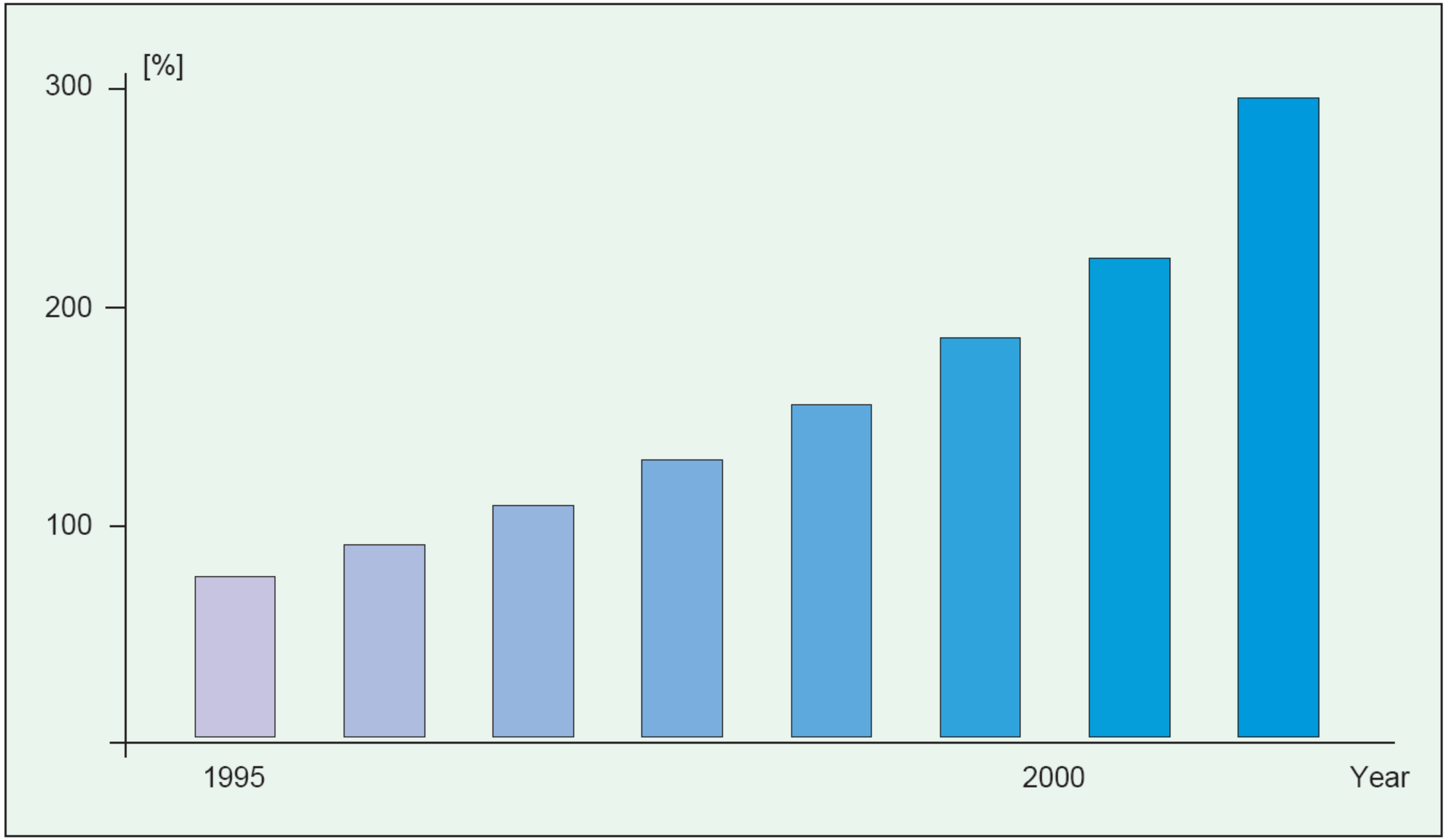


Diagram showing the expected large growth in the demand for optical fiber.

Photonics 21 – Vision Paper 2019 (Report)

Mission 2030: winning the future

- **Light detection and ranging (LiDAR)- the "eyes" for safe automated driving. LIDAR** is these days touted as one of the key enablers of self-driving cars. Yet it also opens up completely new applications in precision farming, in the conservation of biological diversity, in remote sensing and meteorology, in the gaming industry, in robotics and autonomous logistics, and in the optimization of both wind and solar power generation.
- **Optical fibres** are basic optical components that come in many different forms. One of these is the basis for the fibre-optic data transmission that already is at the heart of modern communication, and will become even more critical going forward (dry fibers for WDM thousands channels). Optical fibres are also fitted in numerous sensors and used for power transmission. In medicine, they serve as light guides and for imaging, while their use in endoscopes also facilitates minimally invasive surgery.
- **Laser diodes** are widely used in barcode readers and laser printers. They are also common in laser pointers and range finders. However, high-power laser diodes likewise deliver leading-edge performance gains to industrial applications such as cutting, drilling and welding. Medical applications, too, include various forms of laser diagnostics and laser surgery. Laser diodes are key components in the 3D scanners that open the door to virtual reality, mixed reality and holography applications. Many of the most advanced 3D printers today use laser diodes to manufacture individualized, next-generation products.
- In 2030, our mobility will be based on multimodal transport. Driving will be automated, connected and electric to maximize safety, efficiency and comfort. Photonics provides essential components, systems and production tools for all aspects of connected mobility, from driver assistance and traffic monitoring to photonics-based IT and telecommunications.
- Rich visual communications such as augmented reality and 3D display technology are transforming every aspect of the manufacturing process, from product design to production to maintenance.

Innovation pipeline in photonics for IT

- **Support a powerful and secure telecommunications infrastructure** that fully meets the requirements of the Industrial Internet. Machine-to-machine communication in a fully digital industrial value chain has much more exacting demands in terms of speed, reliability, latency and security. Pervasive connectivity makes every industrial company vulnerable to various forms of illegal access, including industrial espionage and sabotage by state actors. The European Commission, member state governments and the private sector must urgently step up efforts to secure Europe's digital infrastructure. SMEs, in particular, often do not invest sufficient resources in cybersecurity.
- Smart, connected street lights, traffic signals and illuminated traffic signs will be able to adapt to lighting conditions or the volume of traffic. Street lights will also serve as sensors and transmitters for fully automated driving technology and other wireless communications.

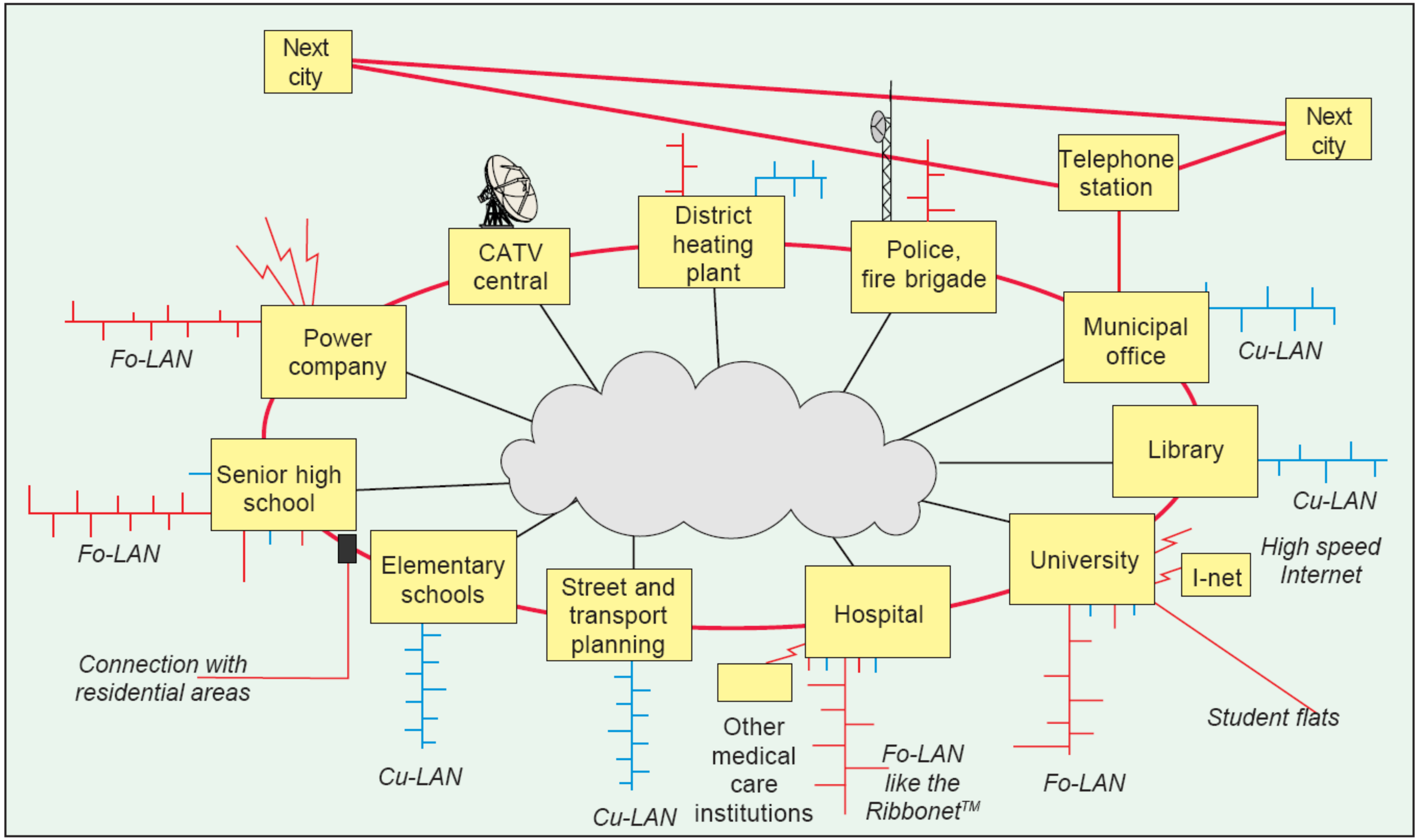
• Interior and exterior lighting can be used for data transmission, such as Wi-Fi that uses LEDs (and is thus called Li-Fi). This will provide yet another avenue for universal connectivity.

• Public security will be improved by new technologies for the video surveillance of public spaces and critical infrastructure. Photonics will enrich images with other data such as polarization, distances and spectral analysis.

- This is no longer theory. It is now possible to build optical components on a micro scale, a step comparable to the transition from conventional electronics to microelectronics in the 1960s. These photonic components are already being deployed in telecommunications – in the transceivers that translate between electronic and fibre optic hardware, for example. Using optical circuits at the microprocessor level is significantly more complex, but innovation is advancing on a broad front. Current developments in Europe and the United States focus on optical connectors between circuit boards, removing a significant bottleneck in computing speed. Within a decade, the same is envisioned for chip-to-chip. The ultimate leap would be to abandon these "optoelectronic" components in favor of fully optical microprocessors, in which all electronic signals are replaced by photons, even inside the chip. A first step in that direction will be purpose-built optical computers designed to meet specific needs, such as accelerating the solution of optimization problems like the "travelling salesman".
- Europe has several growing clusters in optical computing
- **Innovation pipeline in photonics for IT**
- The shift from electronic to photonic technology in telecommunications and other areas of IT is taking place on multiple fronts. As it progresses, it is building the basis for a steady stream of bandwidth-hungry products and services. Other emerging technologies are equally promising:
- Quantum encryption using photons will extend current algorithm-based encryption technology, taking cyber-security to the next level.
- ***" It is now possible to build optical components on a micro scale, a step comparable to the transition from conventional electronics to microelectronics in the 1960s."***

- Optical wireless communications (OWC) is seeing a lot of interest as an additional method of broadband connectivity. OWC is also being developed as a way to provide telecommunications access in rural and remote regions using high-altitude balloons or drones, usually in combination with conventional wireless technologies.
- Photonic data storage is another technology on the path to fully optical computing. An optical memory involving no electronics at all would allow very large amounts of data to be read or written at a much faster speed than current technology.
- Organic optoelectronics, too, is an area where product developers are working to transcend the physical performance limits of conventional microelectronics. The first products in the pipeline include data centre components that use polymer-based optical waveguides to build a higher density of photonic circuits, thereby enabling higher data speeds at lower cost.
- Optical computing will drive artificial intelligence and smart robotics, as deep learning requires an enormous amount of computing power in the smallest possible spaces.

Optical fiber community access network



Sketchy drawing of an optical fiber community access network.

CHAPTER 2 Transceivers, Packaging, and Photonic Integration

Handbook of Fiber Optic Data Communication. A Practical Guide to Optical Networking-Academic Press (2013)

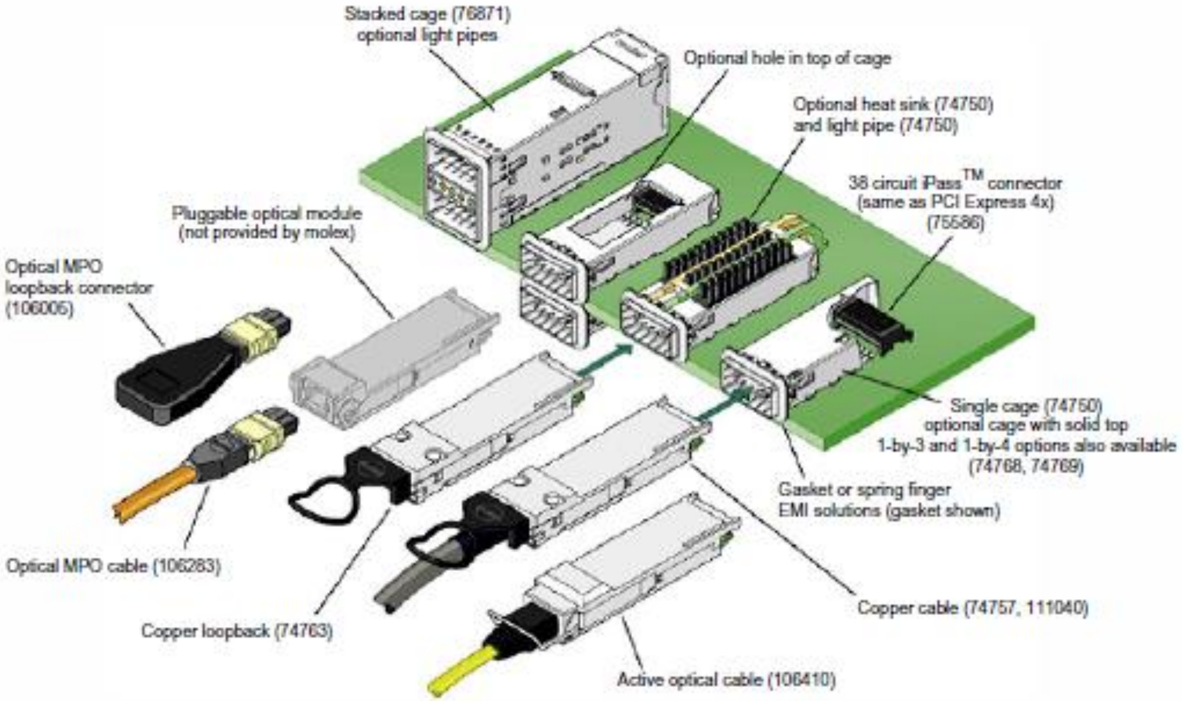


FIGURE 2.3

QSFP + pluggable interface, hosting a range of electrical and optical I/O solutions [10].

FIGURE 2.4

Basic building blocks of a pluggable transceiver [11].

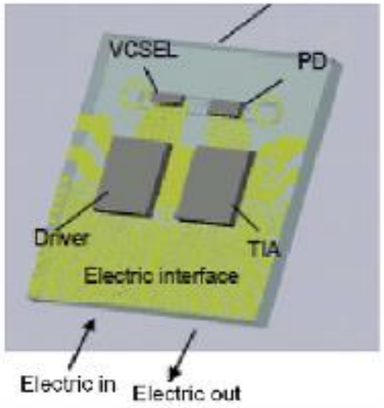


FIGURE 2.5

Pyrex optical subassembly carrying transmit and receive functions [12].

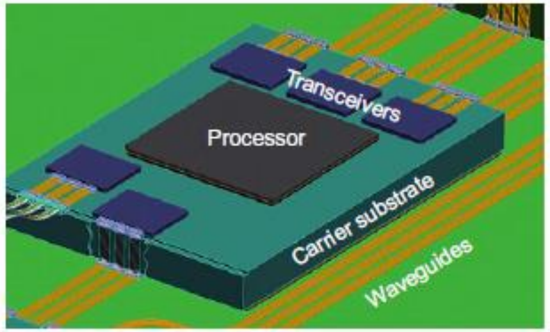
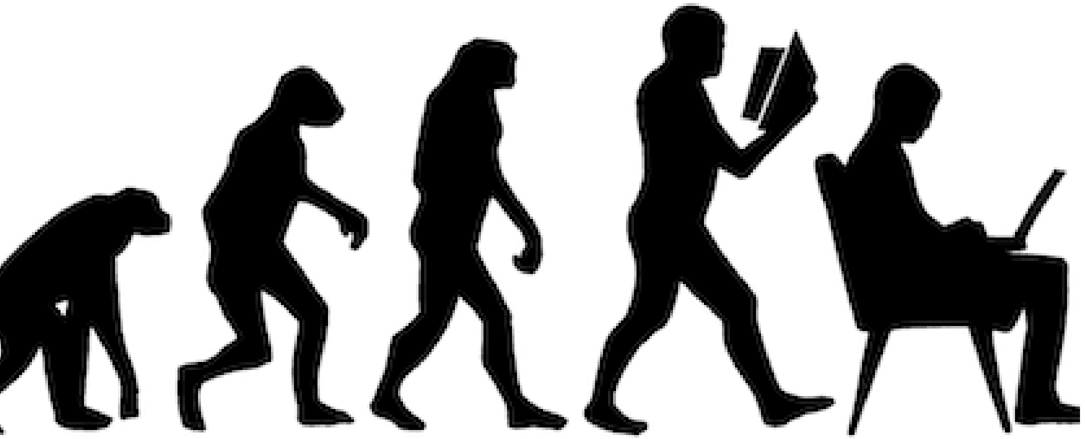


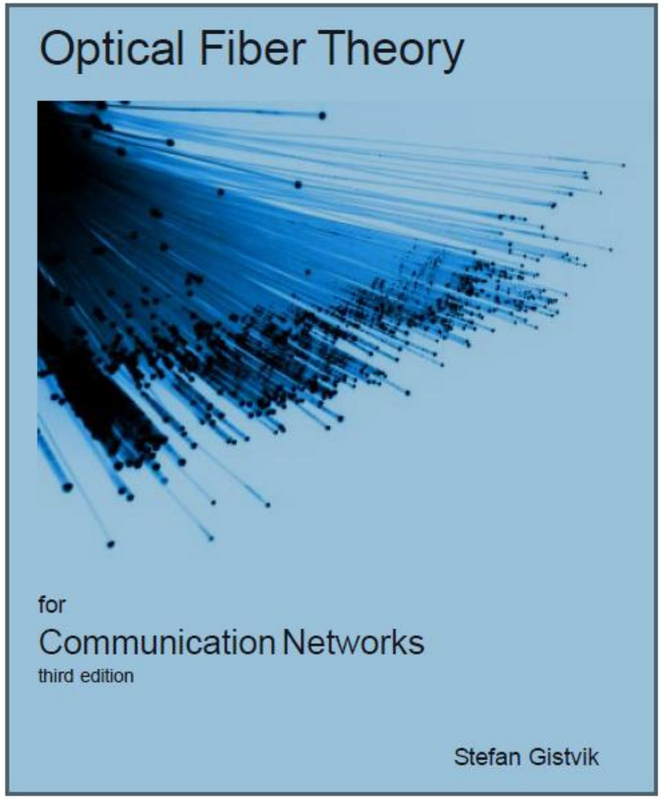
FIGURE 2.11

Chip-level assembly of a silicon photonics device together with a CMOS logic chip on a carrier substrate.

IV. In the beginning….



Ericsson book: Cap 1 – historical perspective



Optical Fiber Theory

for
Communication Networks
third edition

Stefan Gistvik

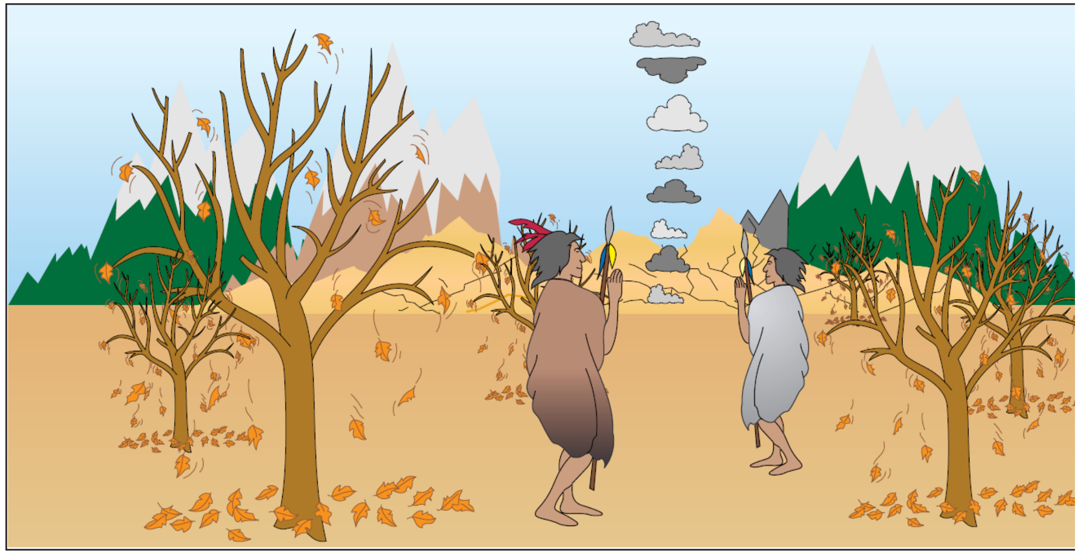
Chapter 1: A look back in time and today (Ericsson book)

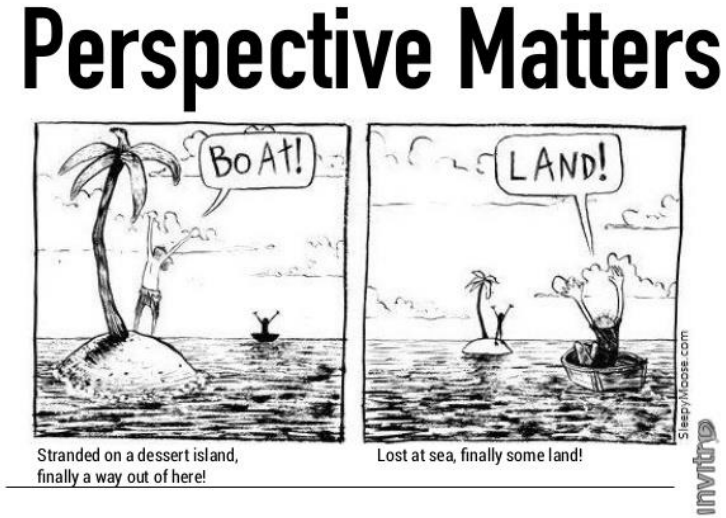
Antiquity

- Early signal towers and lighthouses, for all their usefulness, were still able to convey only very simple messages.

Generally, no light meant one state, while a light signaled a change in that state.

- The next advance needed was the ability to send more detailed information with the light.
- A simple but notable example is the signal that prompted Paul Revere's ride at the start of the American Revolution. By prearranged code, one light hung in the tower of Boston's Old North Church signaled a British attack by land, while two lights meant an invasion by sea. The two lamps that shone in the tower not only conveyed a change in state, but also provided a critical detail about that change.



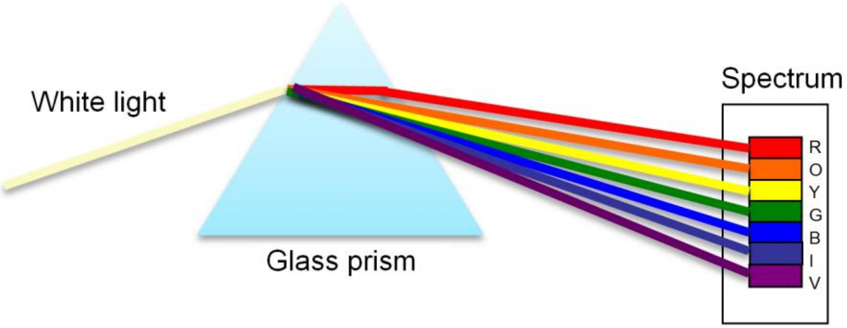


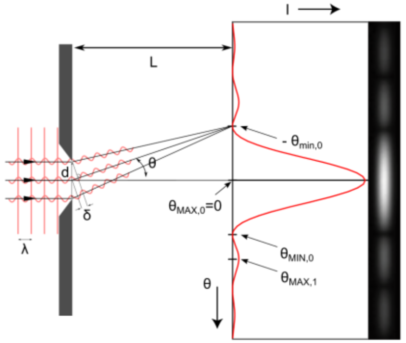
Probably the first optical communication was puffs of smoke from camp fires, which were given meaning by varying the size and space (period) between each puff.

Snell formula and TIR

- The Greek philosophers Pythagoras, Democritus, Empedocles, Plato, Aristotle, and others developed several theories of the nature of light.
- Law of Reflection, enunciated by Euclid (300 B.c.E.) in his book Catoptrics
- The apparent bending of objects partly immersed in water is mentioned in Plato's Republic.
- Refraction was studied by Cleomedes (50 A.D.) and later by Claudius Ptolemy (130 A.D.) of Alexandria, who tabulated fairly precise measurements of the angles of incidence and refraction for several media
- Several glass and crystal spheres have been found among Roman ruins, and a planar convex lens was recovered in Pompeii, Italy
- The Roman philosopher Seneca (3 B.c.E.-65 A.D.) pointed out that a glass globe filled with water could be used for magnifying purposes (zoom lens)
- Optics was studied and extended, especially by Arabian scientist, Alhazen (ca. 1000 A.D.). He elaborated on the Law of Reflection, putting the angles of incidence and reflection in the same plane normal to the interface ; he studied spherical and parabolic mirrors and gave a detailed description of the human eye
- Alhazen's work was translated into Latin, and it had a great effect on the writings of Robert Grosseteste (1 175-1253), Bishop of Lincoln, and on the Polish mathematician Vitello (or Witelo), both of whom were influential in rekindling the study of Optics. Their works were known to the Franciscan Roger Bacon (1215- 1294), who is considered by many to be the first scientist in the modem sense. He used the lenses for correcting vision and even hinted at the possibility of combining lenses to form a telescope. European paintings were depicting monks wearing eyeglasses!!!!!
- And alchemists had come up with a liquid amalgam of tin and mercury that was rubbed onto the back of glass plates to make mirrors. Leonardo da Vinci (1452-1519) described the “Camera obscura” the mirrors and Giovanni Battista Della Porta (1 535-1 6lS), who discussed multiple mirrors and combinations of positive and negative lenses in his “Magia naturalis” (1589)
- 1621 -The first of these discoveries was made by Willebrord Snell, a Dutch mathematician who in 1621 wrote the formula for the principle of *refraction* or the bending of light as it passes from one medium into another.
- Snell’s formula, which was only published 70 years after his death, stated that every transparent substance had a particular index of refraction and the amount that the light would bend was based on the relative refractive indices of the two materials through which the light was passing. Air has a refractive index of 1, for example, while water has a refractive index of 1.33.
- In 1840, Daniel Colladon(Swiss) and Jaques Babinet (French) demonstrated that bright light could be guided through jets of water through the principle of total internal reflection (TIR). It took John Tyndall, a natural philosopher and physicist from Ireland, to bring the phenomenon to greater attention. In 1854, Tyndall performed the demonstration before the British Royal Society and made it part of his published works in 1871, casting a shadow over the contribution of Colladon and Babinet. Tyndall is now widely credited with discovering TIR, although Colladon and Babinet had demonstrated it 14 years previously.

17th century

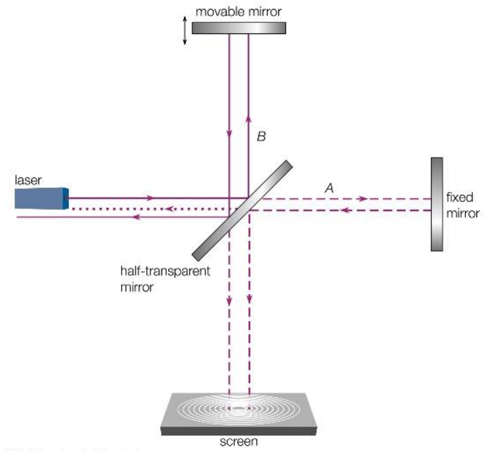




- 1608 - Hans Lippershey (1587-1 6 19), a Dutch spectacle maker, applied for a patent on the refracting telescope. Galileo Galilei read about that and he had built his own instrument.
- The compound microscope was invented at just about the same time, possibly by the Dutchman Zacharias Janssen (1588-1 632). The microscope's concave eyepiece was replaced with a convex lens by Francisco Fontana (1580-1656) of Naples, and a similar change in the telescope was introduced by Johannes Kepler (1 571-1630).
- 1611 - Kepler published his Dioptrice.
- He had discovered total internal reflection and arrived at the small angle approximation to the Law of Refraction, in which case the incident and transmission angles are proportional. He evolved a treatment of first-order Optics for thin-lens systems and in his book describes the detailed operation of both the Keplerian (positive eyepiece) and Galilean (negative eyepiece) telescopes
- 1637- Rene Descartes (1596-1650) was the first to publish the now familiar formulation of the Law of Refraction in terms of sines. Descartes deduced the law using a model in which light was viewed as a pressure transmitted by an elastic medium; as he put it in his book La Dioptrique (1637)
- Professor Francesco Maria Grimaldi (1618-1663) at the Jesuit College in Bologna->phenomenon of diffraction, that is, the deviation from rectilinear propagation that occurs when light advances
- Robert Hooke (1635-1703), curator of experiments for the Royal Society, London, later also observed diffraction effects. This was the beginning of wave theory
- Within a year of
- 1 year after Galileo's death, Isaac Newton (1642-1727) was born. The thrust of Newton's scientific effort was to build on direct observation and avoid speculative hypotheses. Thus he remained ambivalent for a long while about the actual nature of light. Was it corpuscular-a stream of particles, as some maintained? Or was light a wave in an all-pervading medium, the aether? At the age of 23, he began his now famous experiments on dispersion

Speed of light, Wave and Corpuscular Theory

- Newton- his work simultaneously embraced both the wave and emission (corpuscular) theories, he did become more committed to the latter as he grew older. His main reason for rejecting the wave theory as it stood then was the daunting problem of explaining rectilinear propagation in terms of waves that spread out in all directions.
- Christiaan Huygens (1 629-1 695), on the continent, was greatly extending the wave theory. Unlike Descartes, Hooke, and Newton, Huygens correctly concluded that light effectively slowed down on entering more dense media. He was able to derive the Laws of Reflection and Refraction and even explained the double refraction of calcite, using his wave theory. And it was while working with calcite that he discovered the phenomenon of polarization
- Dane Ole Christensen Romer (1644-1710) estimates the light speed. Huygens and Newton, among others, were quite convinced of the validity of Romer's work. Independently estimating the Earth's orbital diameter, they assigned values to c equivalent to 2.3 X 10^8 m/s and 2.4 X 10^8 m/s, respectively
- The wave theory of light was reborn at the hands of Dr. Thomas Young (1773-1829), one of the truly great minds of the century
- Augustin Jean Fresnel (1788-1827), born in Broglie, Normandy, began his brilliant revival of the wave theory in France, unaware of the efforts of Young some 13 years earlier. Fresnel synthesized the concepts of Huygens's wave description and the interference principle.
- The first terrestrial determination of the speed of light was performed by Armand Hippolyte Louis Fizeau (18 19-1 896) in 1849.
- Jean Bernard Leon Foucault (1819-1 868) was also involved in research on the speed of light.
- Michael Faraday (1791-1867) established an interrelationship between electromagnetism and light when he found that the polarization direction of a beam could be altered by a strong magnetic field applied to the medium.
- James Clerk Maxwell (1831-1879) brilliantly summarized and extended all the empirical knowledge on the subject in a single set of mathematical equations. Beginning with this remarkably succinct and beautifully symmetrical synthesis, he was able to show, purely theoretically, that the electromagnetic field could propagate as a transverse wave in the luminiferous aether.
- 1888- Heinrich Rudolf Hertz (1857-1 894) verified the existence of long electromagnetic wave
- Michelson, professor of physics at Case School of Applied Science in Cleveland, Ohio, joined with Edward Williams Morley (1 838-1 923), a well-known professor of chemistry at Western Reserve, to redo the experiment with considerably greater precision –Experiment Michelson-Morley



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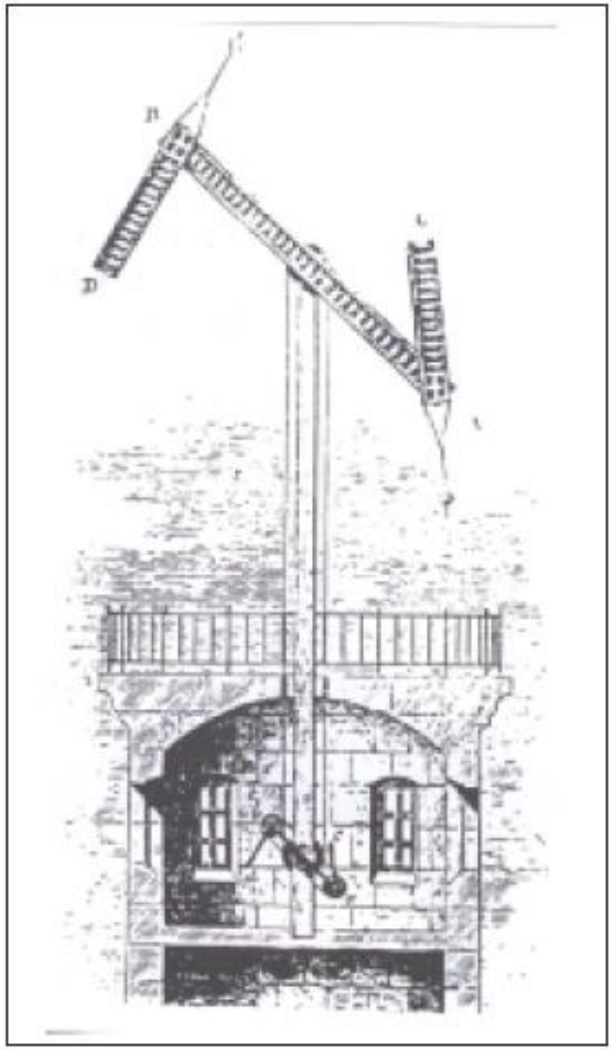
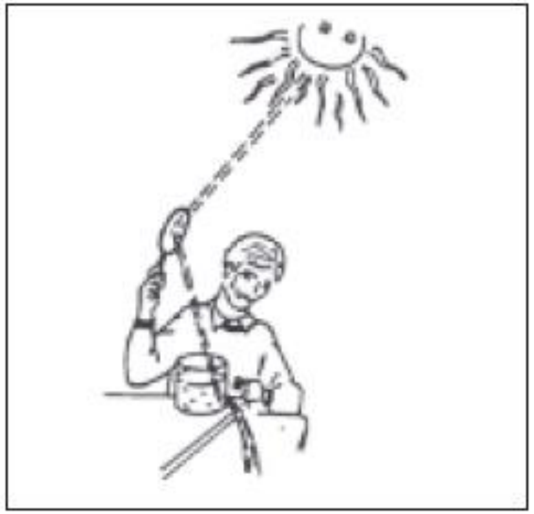
The 18th century



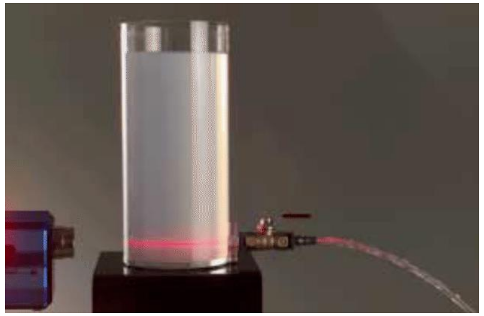
One of the many towers that carried messages across long distance in western Europe.

The 19th century



By demonstrating that light could travel along a bent water jet, the principle of optical transmission in light conductors was established.

John Tyndall to demonstrate that light can be guided by a water jet

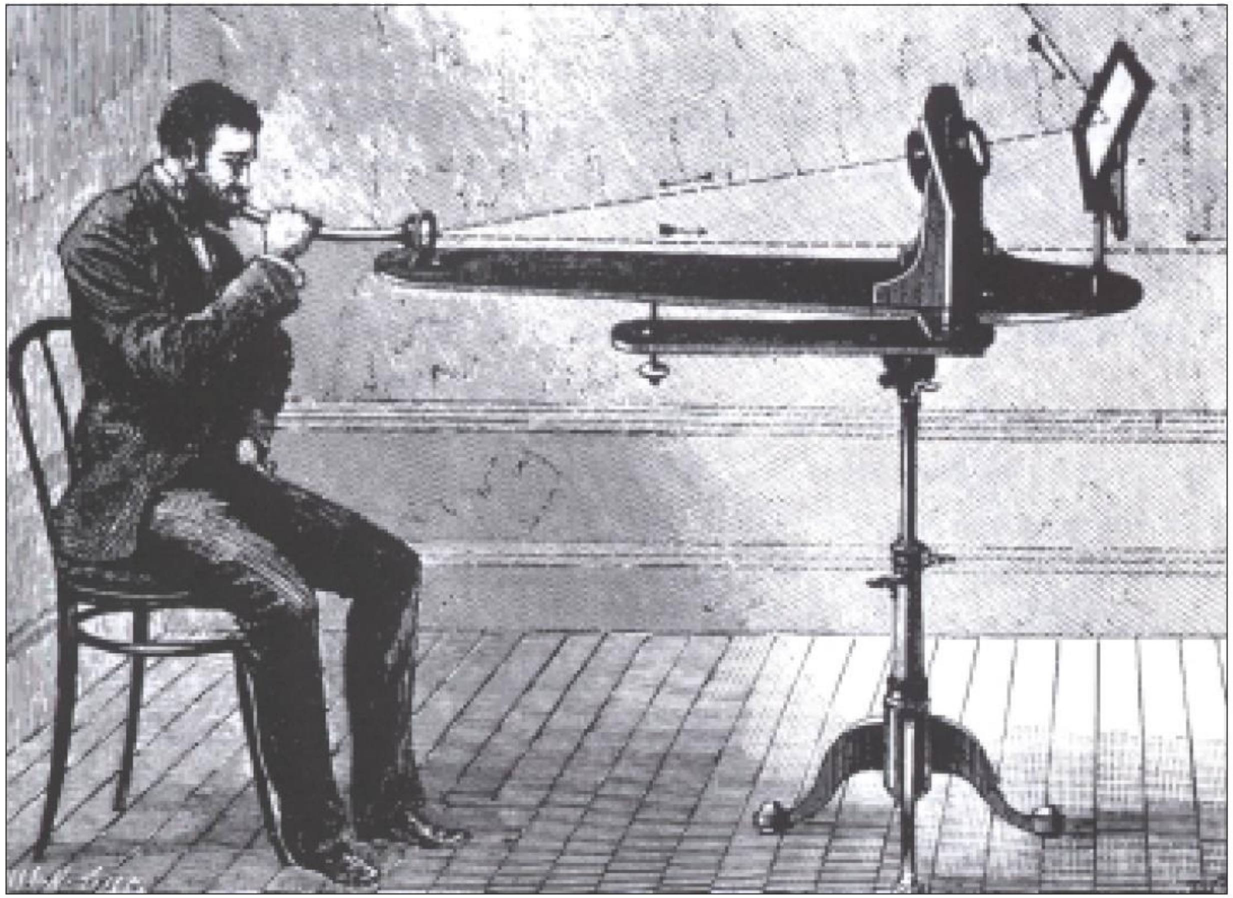


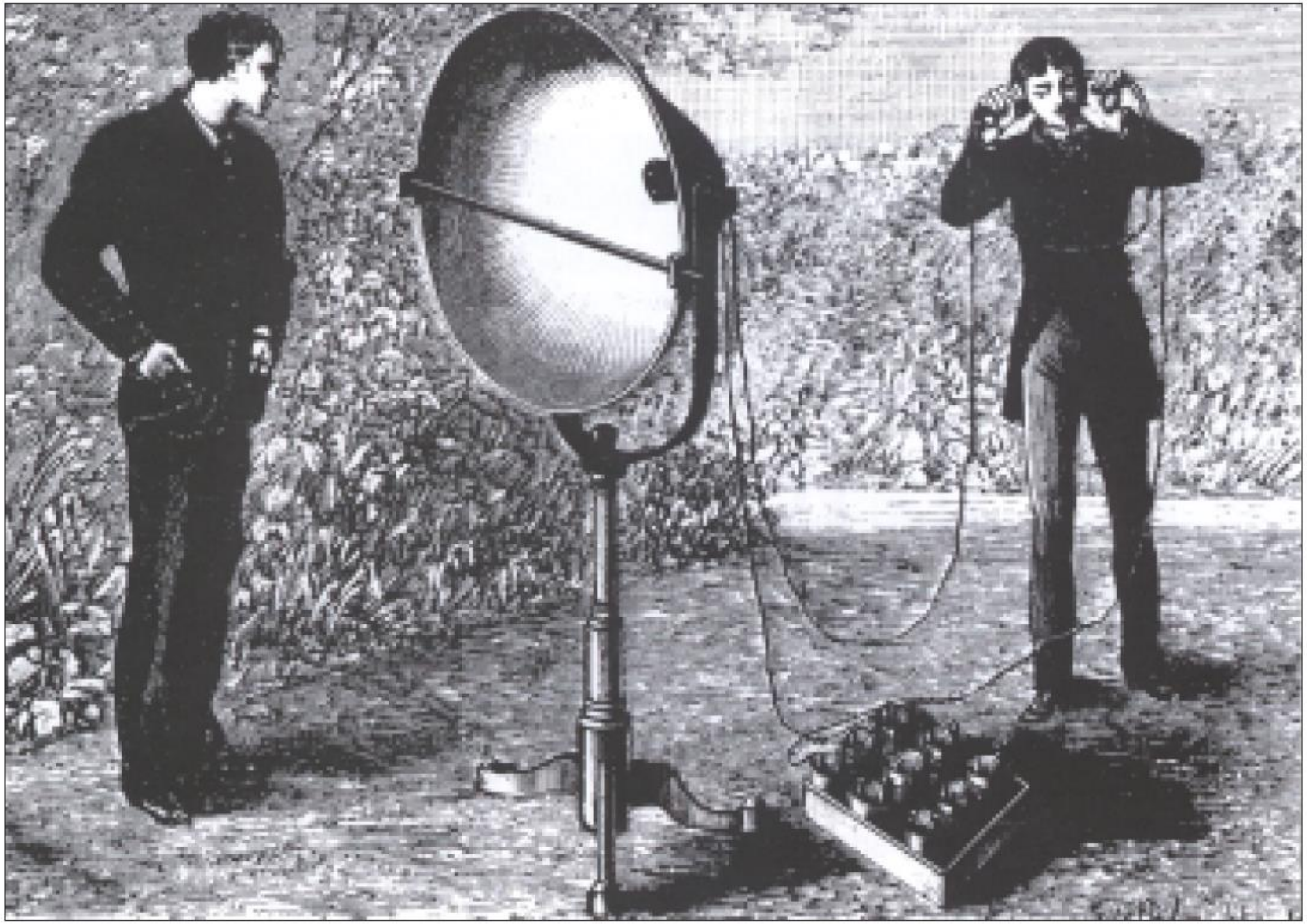
Theory of Relativity and Quantum Mechanics

- Jules Henri Poincare (1854-1912) was perhaps the first to grasp the significance of the experimental inability to observe any effects of motion relative to the aether
- In 1905 Albert Einstein (1879-1955) introduced his Special Theory of Relativity and photoelectric effect
- 1900, Max Karl Ernst Ludwig Planck (1858-1947) introduced the hesitant beginnings of what was to become yet another great revolution in scientific thought Quantum Mechanics. The quantum of radiant energy or “photon," as it came to be called, had an energy proportional to its frequency v, that is, E = hv, where h is known as Planck's constant
- Early quantum theory was profoundly re-conceived in the mid-1920s by Erwin Schrödinger, Werner Heisenberg, Max Born, De Broglie, Pauli, Dirac and others.
- Thus photons, protons, electrons, neutrons, and so forth-the whole lot, have both particle and wave manifestations. Still, the matter was by no means settled. "Every physicist thinks that he knows what a photon is," wrote Einstein. "I spent my life to find out what a photon is and I still don't know it.

Alexander Graham Bell’s “photophone”

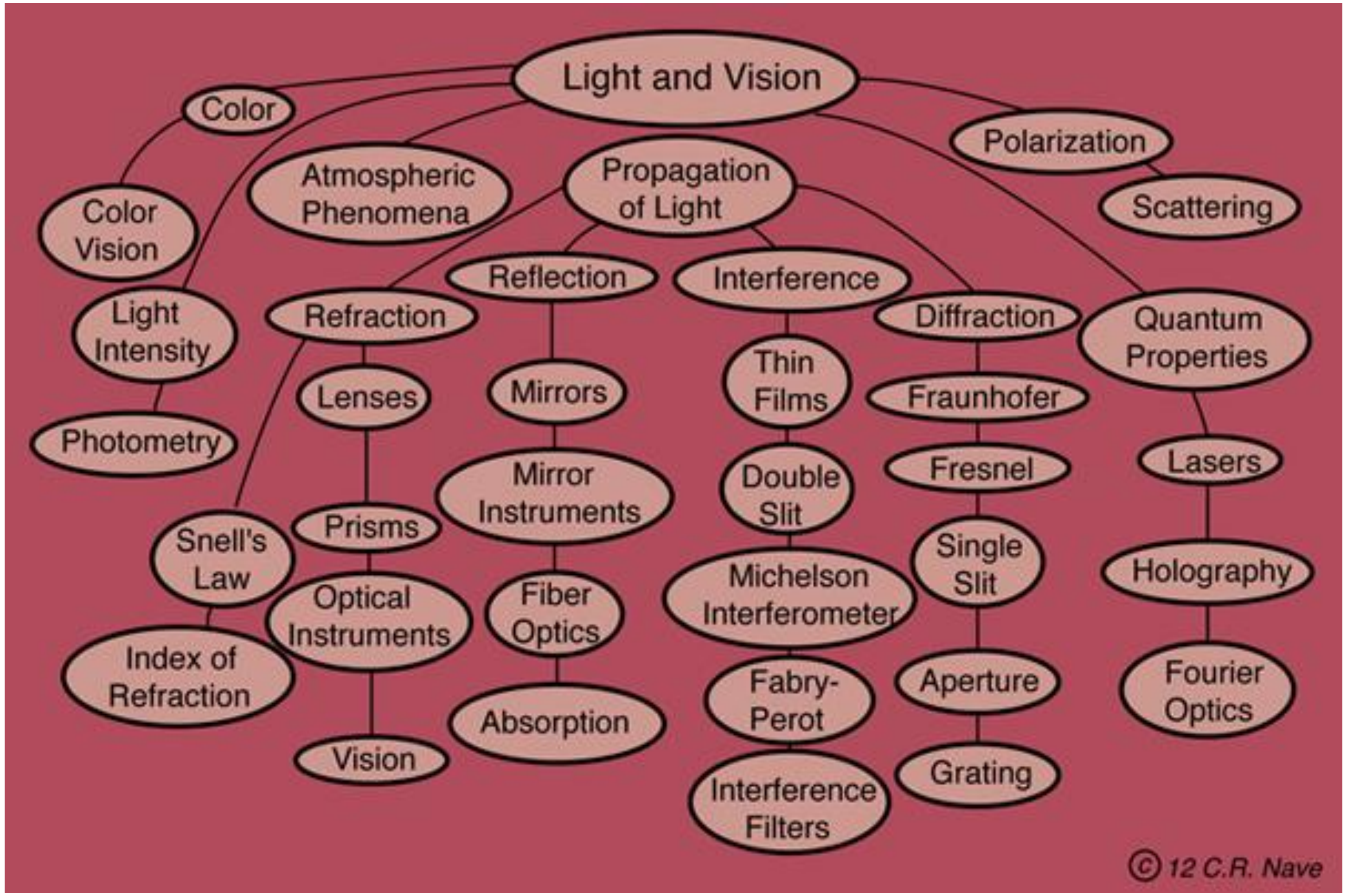
- In 1880, Alexander Graham Bell demonstrated his photophone, one of the first true attempts to carry complex signals with light.
- It was also the first device to transmit signals wirelessly. The photophone gathered sunlight onto a mirror attached to a mouthpiece that vibrated when a user spoke into it. The vibrating mirror reflected the light onto a receiver coated with selenium, which produced a modulated electrical signal that varied with the light coming from the sending device. The electrical signal went to headphones where the original voice input was reproduced.





Alexander Graham Bell and his collaborator at the photophone. Contemporary drawings.

Homework 2.1 – make a report of 2 pages about one of the following topic:



http://hyperphysics.phy-astr.gsu.edu/hbase/ligcon.html#c1

Historical perspective - review

Fiber-optic transmission and networking: the previous 20 and the next 20 years [Invited], Optics Express, 2018, Vol. 26, Issue 18, pp. 24190-24239 (2018), https://doi.org/10.1364/OE.26.024190

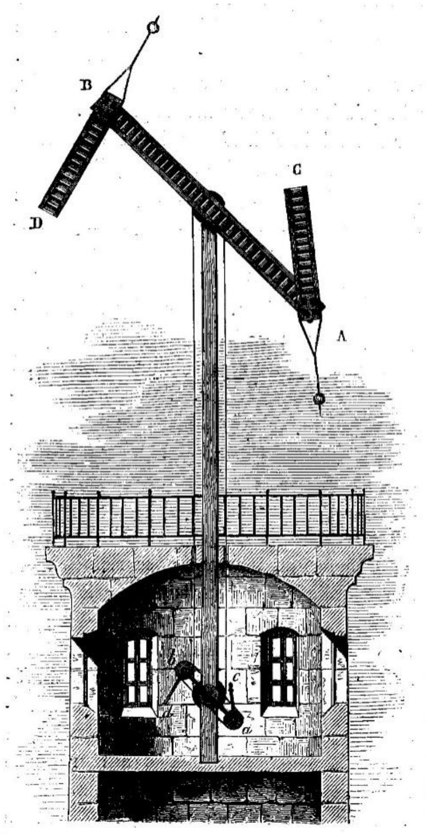


Fig. 19. — Télégraphe de Chappe.

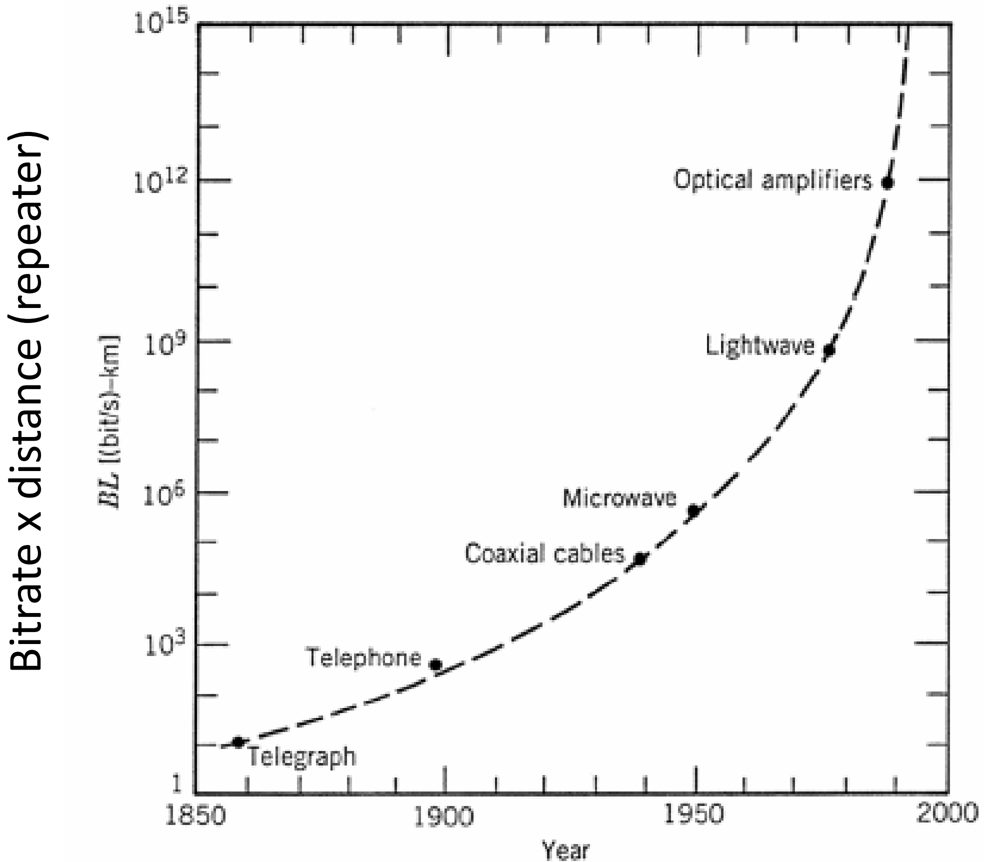
- Antiquity: mirrors, fires, smoke signals to convey information
- 1792 – Claude Shappe – opto-mechanical coded message over (~100km) with regenerators/repetors in modern-day language (optical telegraph) -> Paris-Lille (1794, 200km)

  Efficiency: 1 bit per second (low)
- 1830 – electrical comm (bit rate 10b/s)

With Morse code (~1000km) – dots and dashed

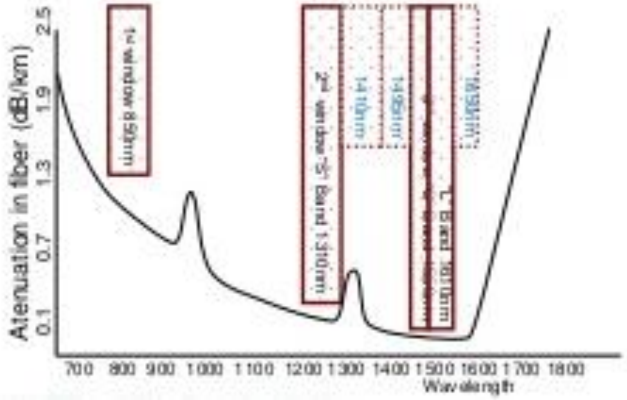
Homework 2.2 – Make a 2 pages synthesis about the the previous 20 or 2 pages about the next 20 years

- 1876 – invention of telephone – electrical signal transmission in analog form with continuously varying electrical current
- 1940 – first coaxial cable – 3MHz system with 300 voice channels or single TV channel (atten increases rapidly for 10MHz)
- 1948- Microwave comm – modulation techniques -> carrier frequency in the range of 1-10GHz (4Ghz) -> ~100Mb/s
- 1975 – coaxial at 274Mb/s (but repeater spacing ~1km)->expensive
- 1960 – LASER (coherent source) -> 1966 – OPTICAL FIBER (suitable transm medium)
- Optical fiber – 1000 dB/km (0.2dB/km)
- 1970 – fiber loses <20dB/km at 1000nm wavelength
-     - GaAs semiconductor laser were demo
- 1980 lightwave systems increased in the capacity (turning point-several generations)



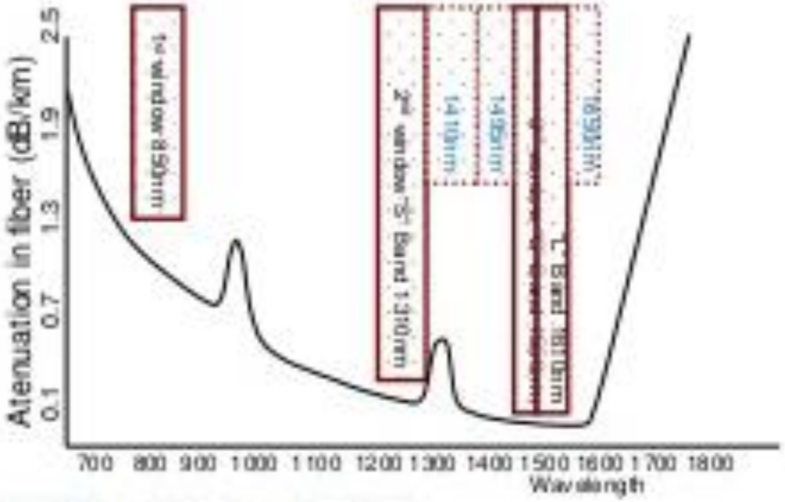
1966 (optical fibers)

Lightwave ERA



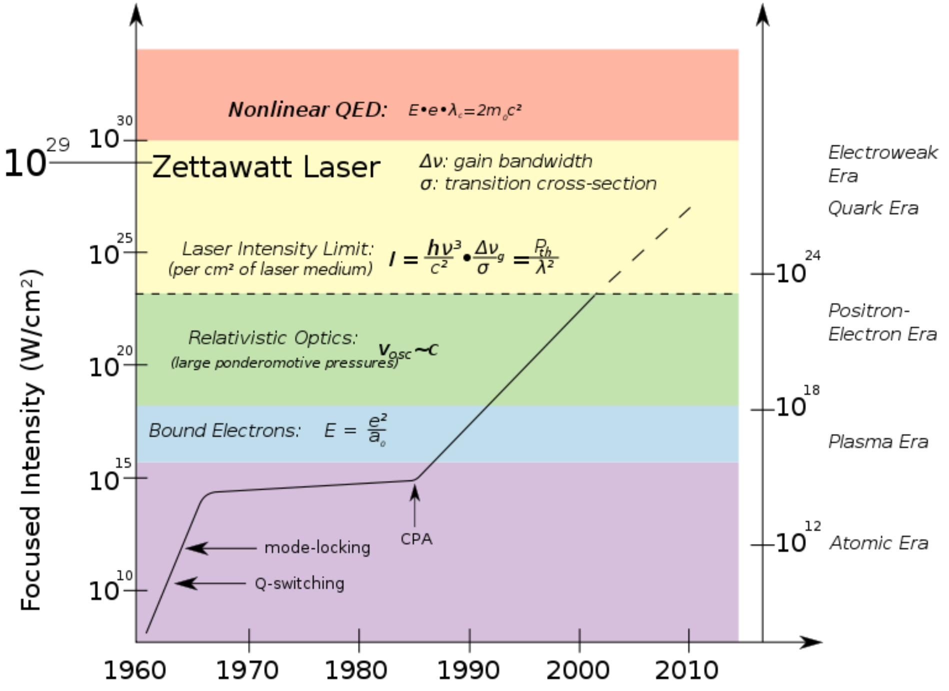
- 1975 – for 25 years several generations
- 1st – laser source at 800nm GaAs semiconductor laser (1980 commercially developed) – 45 Mb/s bit rate with 10km repeater spacing
- At 1300nm – fiber loss decrease under 1dB/km and min dispersion -> laser source (InGaAsP semiconductor laser)
- 1980 – bit rate 100Mb/s because of dispersion in multimode fiber
- 1981 – single mode fiber – 2Gb/s over 44km
- 2nd – in 1987 – bit rate 1.7 Gb/s with repeater 50km with fiber loss 0.5dB/km at 1550nm but pulse spread ->large dispersion over monomode fibers
- 3rd – dispersion shifted fibers – 1985 – 4Gb/s for 100km -> commercially 1990 (10Gb/s) with electronic repeaters at 70km
- 4th – DWDM (wavelength division and multiplexing) -> 2001 with bit rate 10Tb/s with EDFA light amplification (80km). Submarine cables.
- 5th – dry fibers – thousands of WDM channels

- WDM means ***W**avelength **D**ivision **M**ultiplexing*
  - Parallel transmission of number of wavelengths (λ) over a fiber
- Two flavors
  - **D**ense WDM (DWDM)
    - Narrow channel spacing - e.g. 0.4nm (50GHz grid) -> up to 160 λ
  - **C**oarse WDM (CWDM)
    - Wider channel spacing - 20nm (2.5THz grid) -> usually 8-16 λ



Light source -LASER

- The first laser was built in 1960 by Theodore H. Maiman at Hughes Research Laboratories CALIFORNIA, based on theoretical work by Charles Hard Townes and Arthur Leonard Schawlow (BELL LAB)
- Maiman's functional laser used a flashlamp-pumped synthetic ruby crystal to produce red laser light at 694 nanometers wavelength. The device was only capable of pulsed operation, due to its three-level pumping design scheme.
- Later that year, the Iranian physicist Ali Javan, and William R. Bennett, and Donald Herriott, constructed the first gas laser, using helium and neon that was capable of continuous operation in the infrared (U.S. Patent 3,149,290);
- later, Javan received the Albert Einstein Award in 1993.
- Basov and Javan proposed the semiconductor laser diode concept. In 1962, Robert N. Hall demonstrated the first *laser diode* device, which was made of gallium arsenide and emitted in the near-infrared band of the spectrum at 850 nm.
- Later that year, Nick Holonyak, Jr. demonstrated the first semiconductor laser with a visible emission. This first semiconductor laser could only be used in pulsed-beam operation, and when cooled to liquid nitrogen temperatures (77 K
- In 1970, Zhores Alferov, in the USSR, and Izuo Hayashi and Morton Panish of Bell Telephone Laboratories also independently developed room-temperature, continual-operation diode lasers, using the heterojunction structure.



Fiber-optic transmission and networking: the previous 20 and the next 20 years [Invited], 2019, Optics Express

History

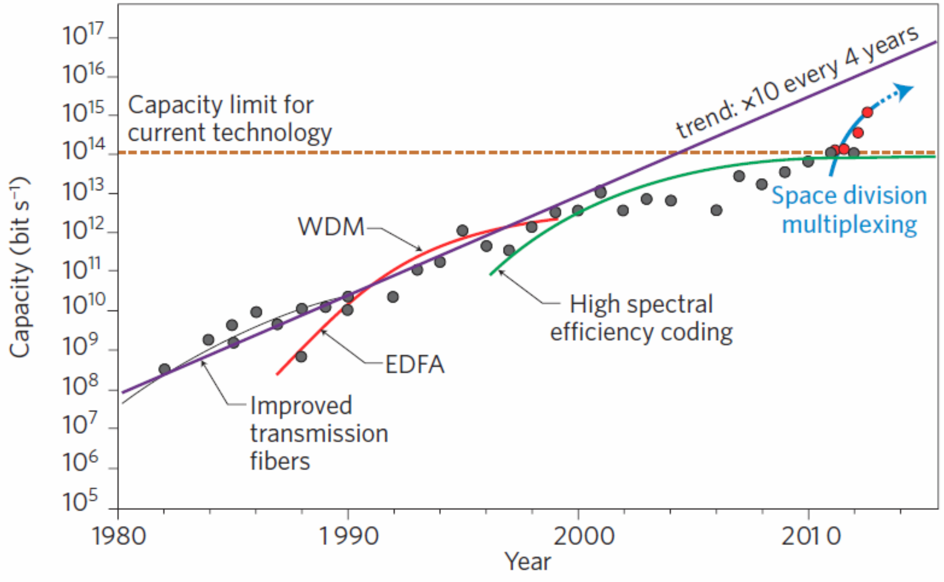
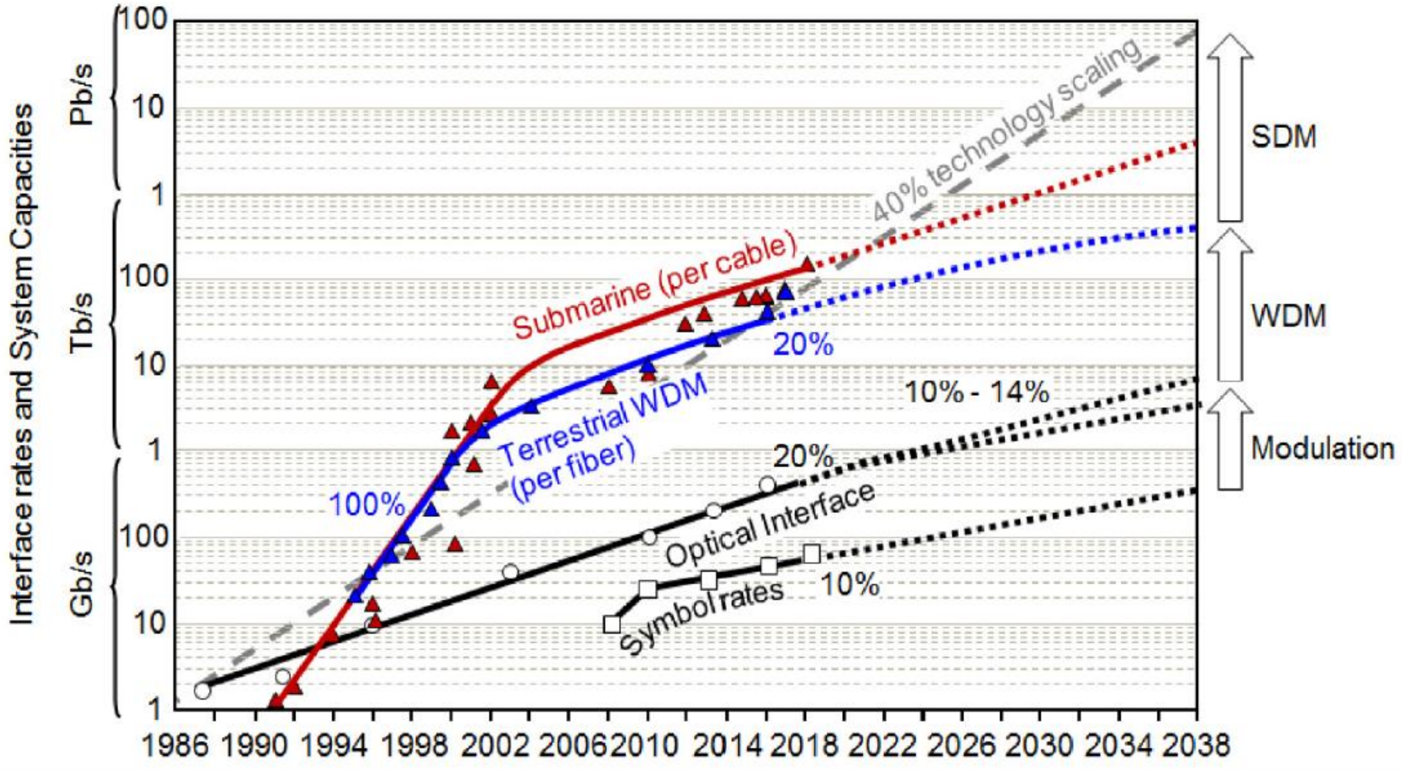


Figure 1 | The evolution of transmission capacity in optical fibres as evidenced by state-of-the-art laboratory transmission demonstrations.



optimize multiplexing in
time, wavelength, polarization and phase

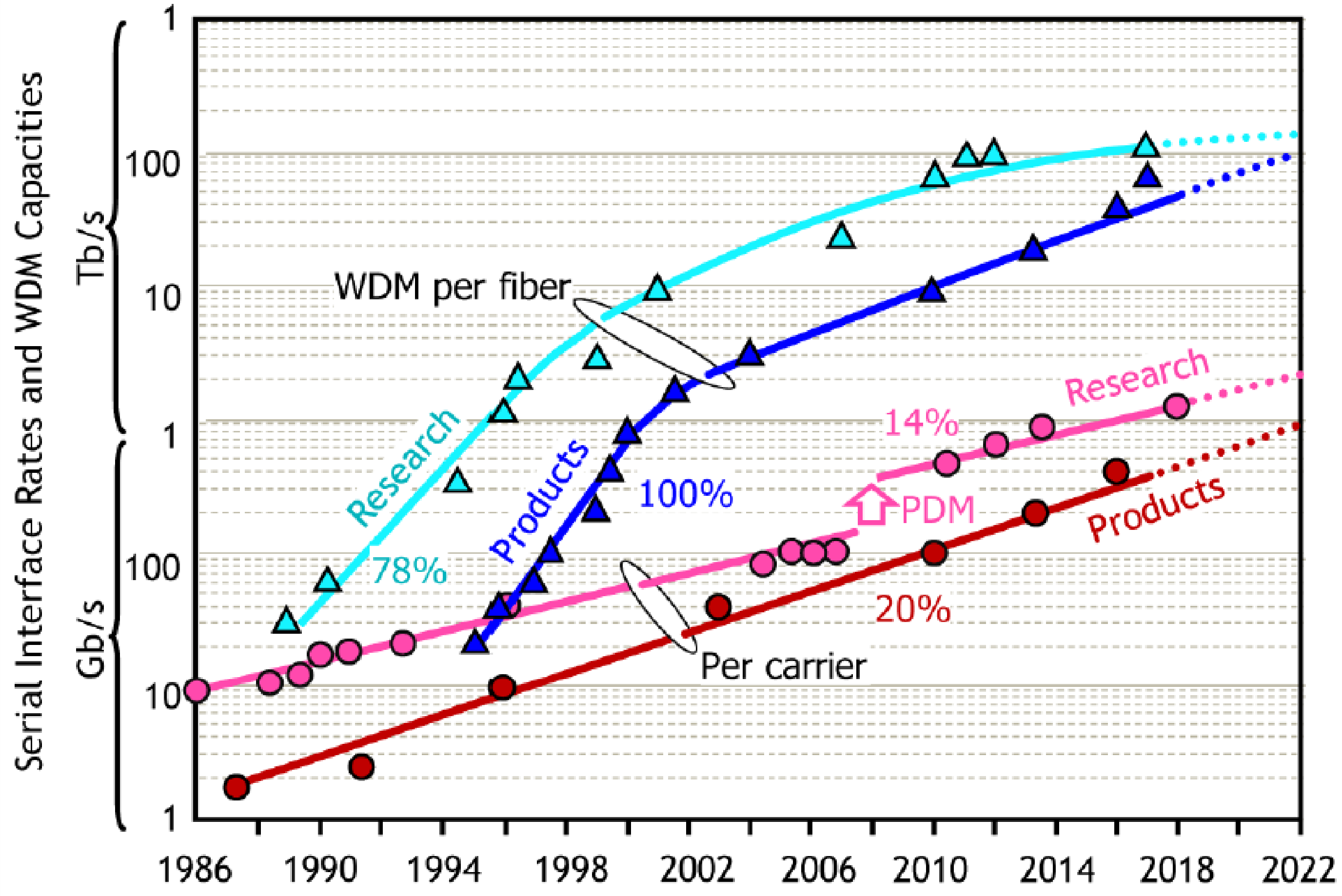
SDM-space division and multiplexing
WDM- wavelength division and multiplexing

(1) the era of regeneration (1977 ~1995),

(2) the era of amplified dispersion-managed systems (1995 ~2008),

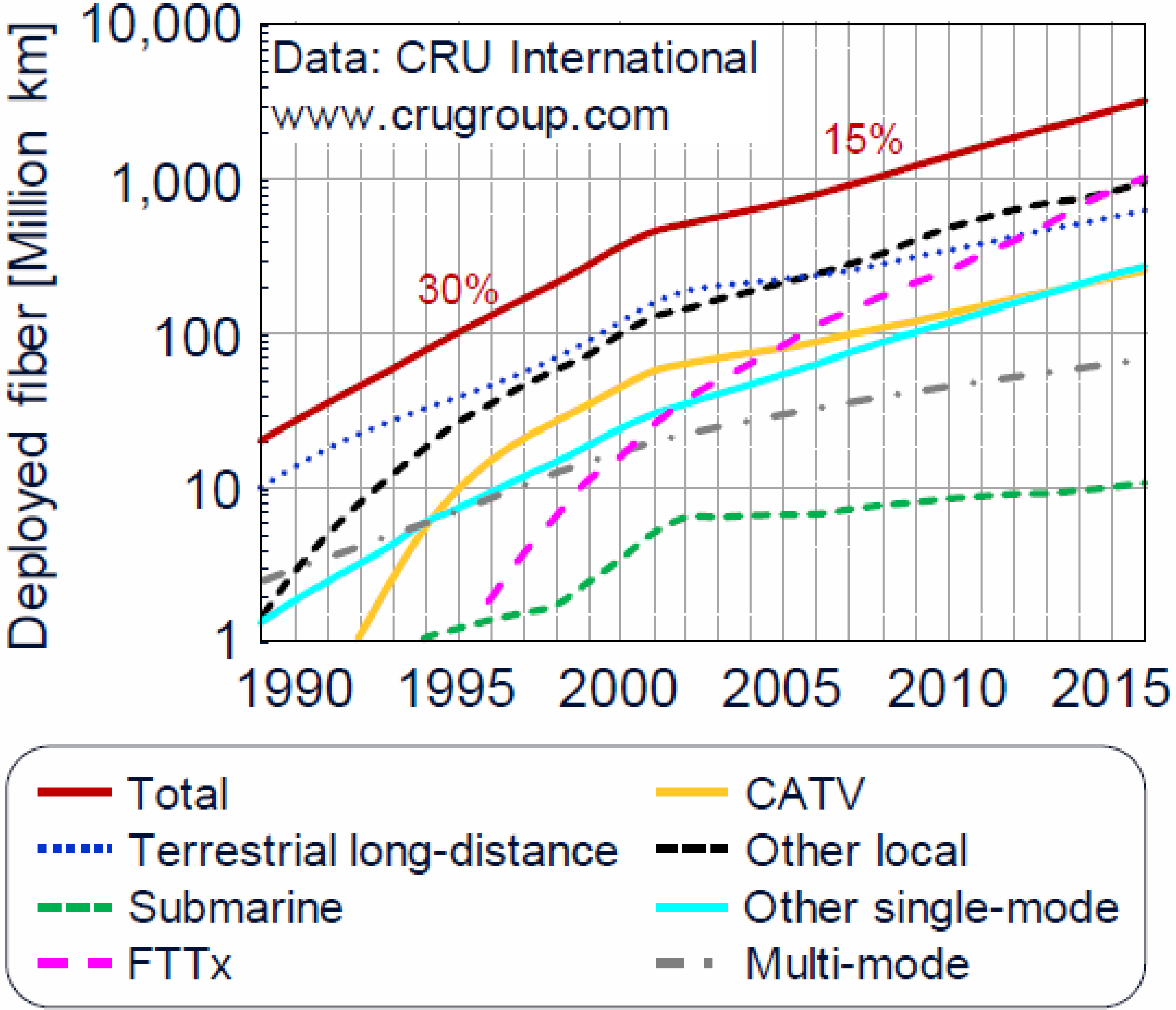
(3) the era of amplified coherent systems (2008 ~present), and

(4) the era of space division multiplexing (actively researched since ~2008)



optimize multiplexing in time, wavelength, polarization and phase
Commercial systems now utilize all four dimensions

Space-division multiplexing in optical fibres
D. J. Richardson1*, J. M. Fini2 and L. E. Nelson3
Nature Photonics 2013

Deployed fiber [Million km]
10,000
1,000
100
10
1
1990
1995
2000
2005
2010
2015
Data: CRU International
www.crugroup.com
30%
15%
Total
Terrestrial long-distance
Submarine
FTTx
CATV
Other local
Other single-mode
Multi-mode

Questions?

Deadline Homework in this lecture: 2 weeks