TECHNICAL UNIVERSITY
OF CLUJ-NAPOCA
ROMANIA

Faculty of Electronics, Telecom and Info Technology

Lecture 3

Optoelectronic Systems for Telecom (SOT)

Associate prof Ramona Galatus
Drd Loredana Buzura
Basis of Electronics Department

Outlines

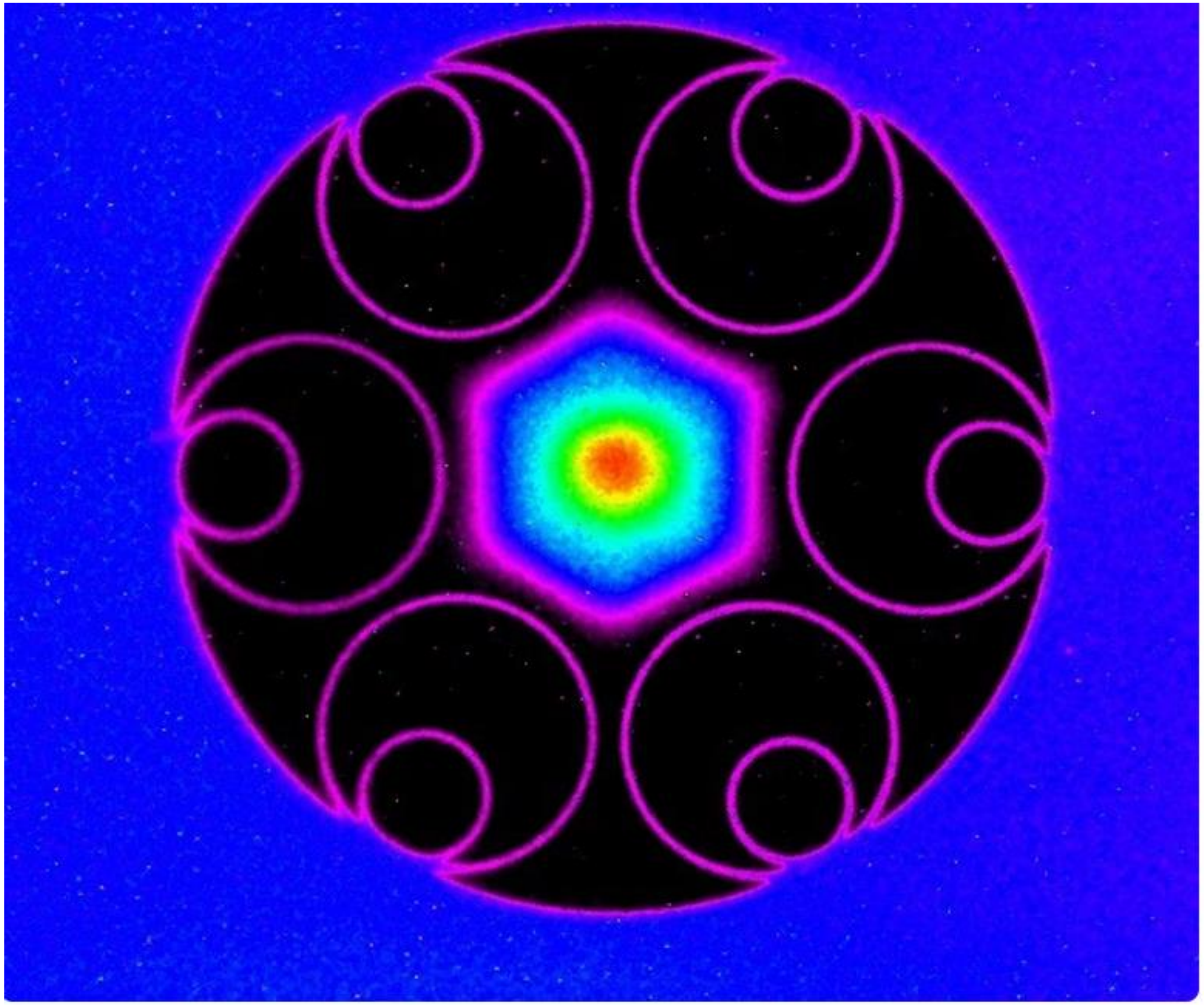
- Optical fibers types and their characteristics
- Special optical fibers
- Linear and nonlinear effects

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

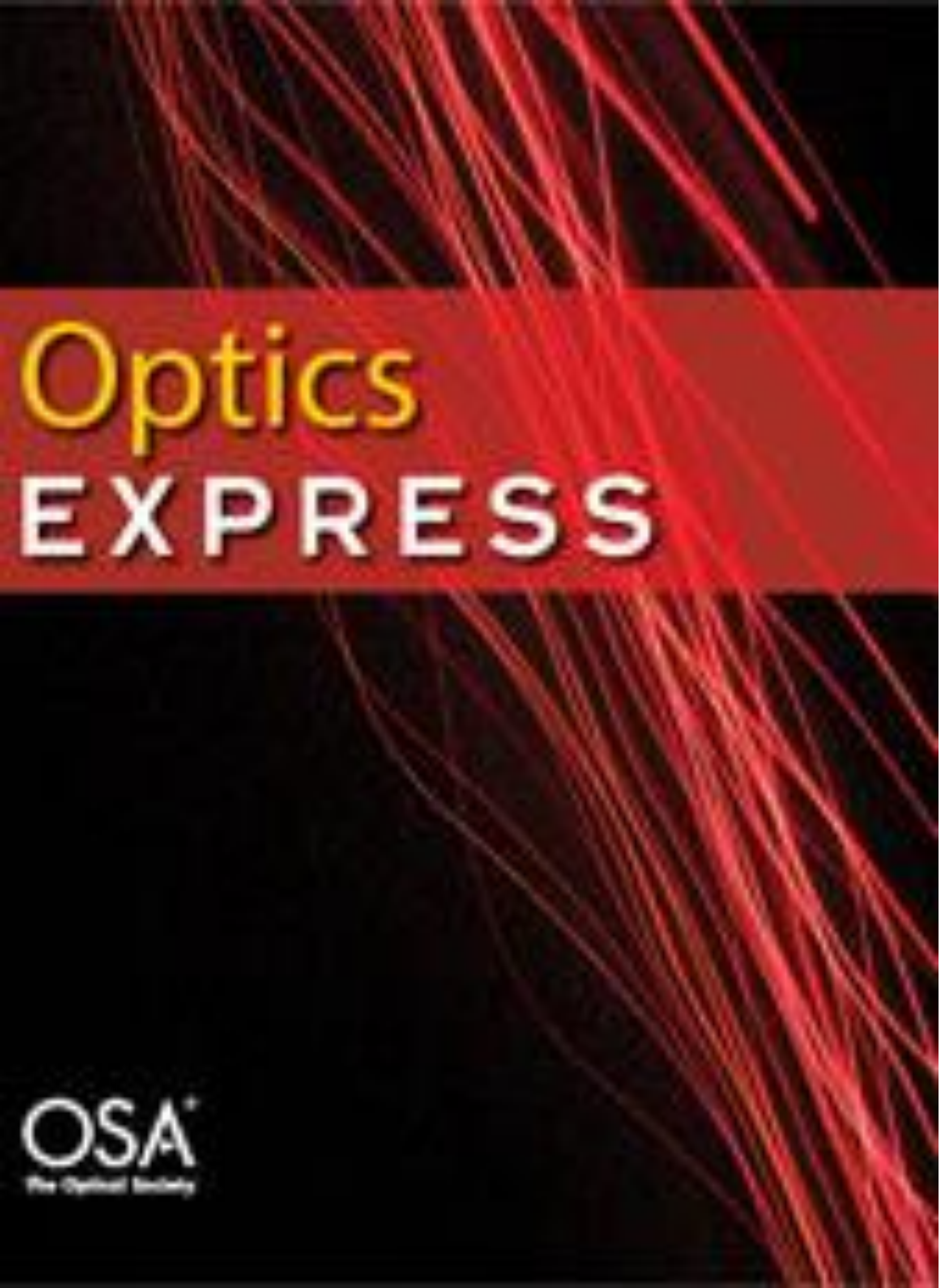
https://www.laserfocusworld.com/fiber-optics/article/14069142/hollowcore-fiber-loss-below-1-dbkm-could-lead-to-applications

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 un the length of the fiber, effectively creating bars that prevent the hexagonal light modes trapped in the center of



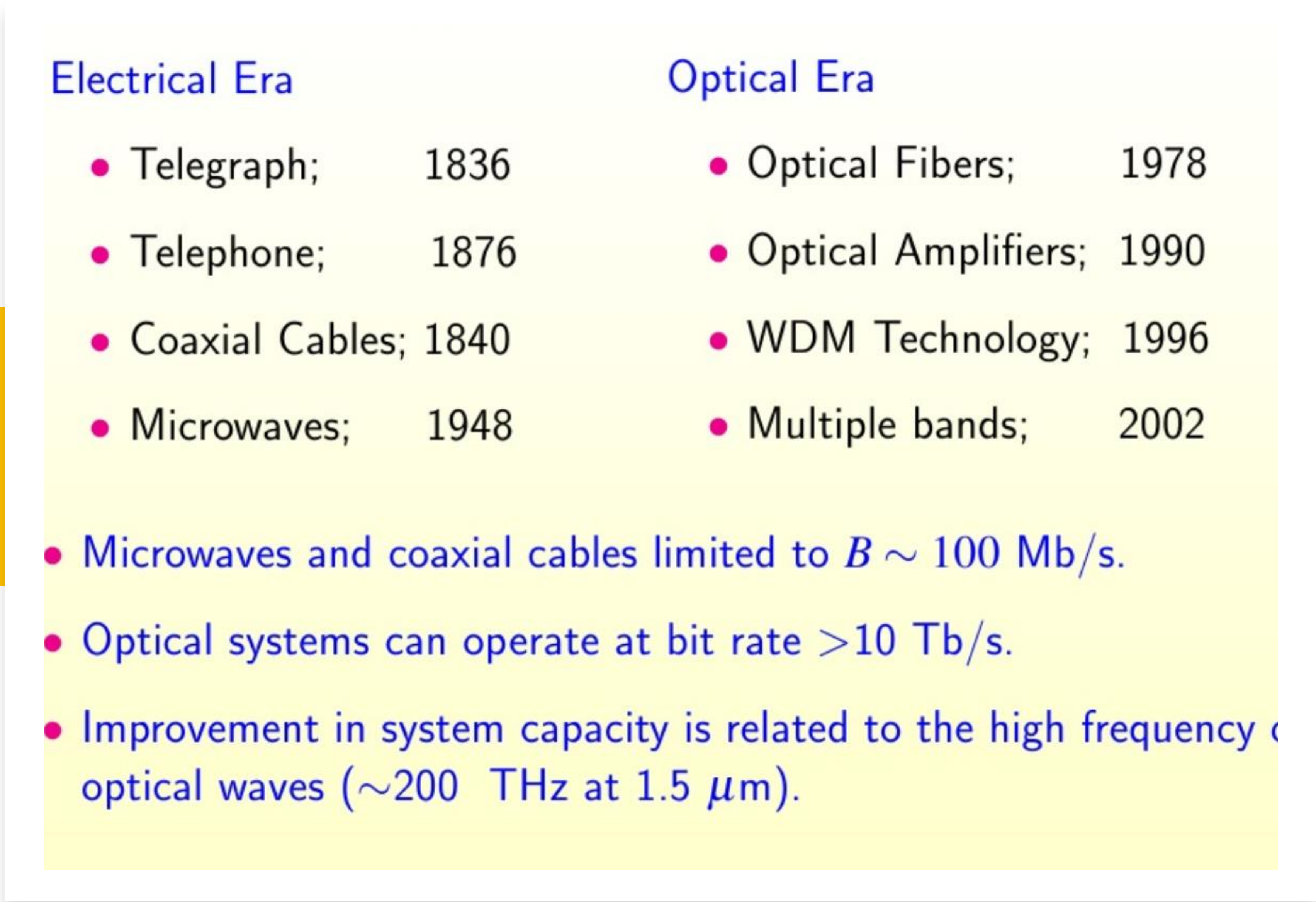
Fiber-optic transmission and networking: the previous 20 and the next 20 years [Invited]

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.

Historical perspective



Electrical Era

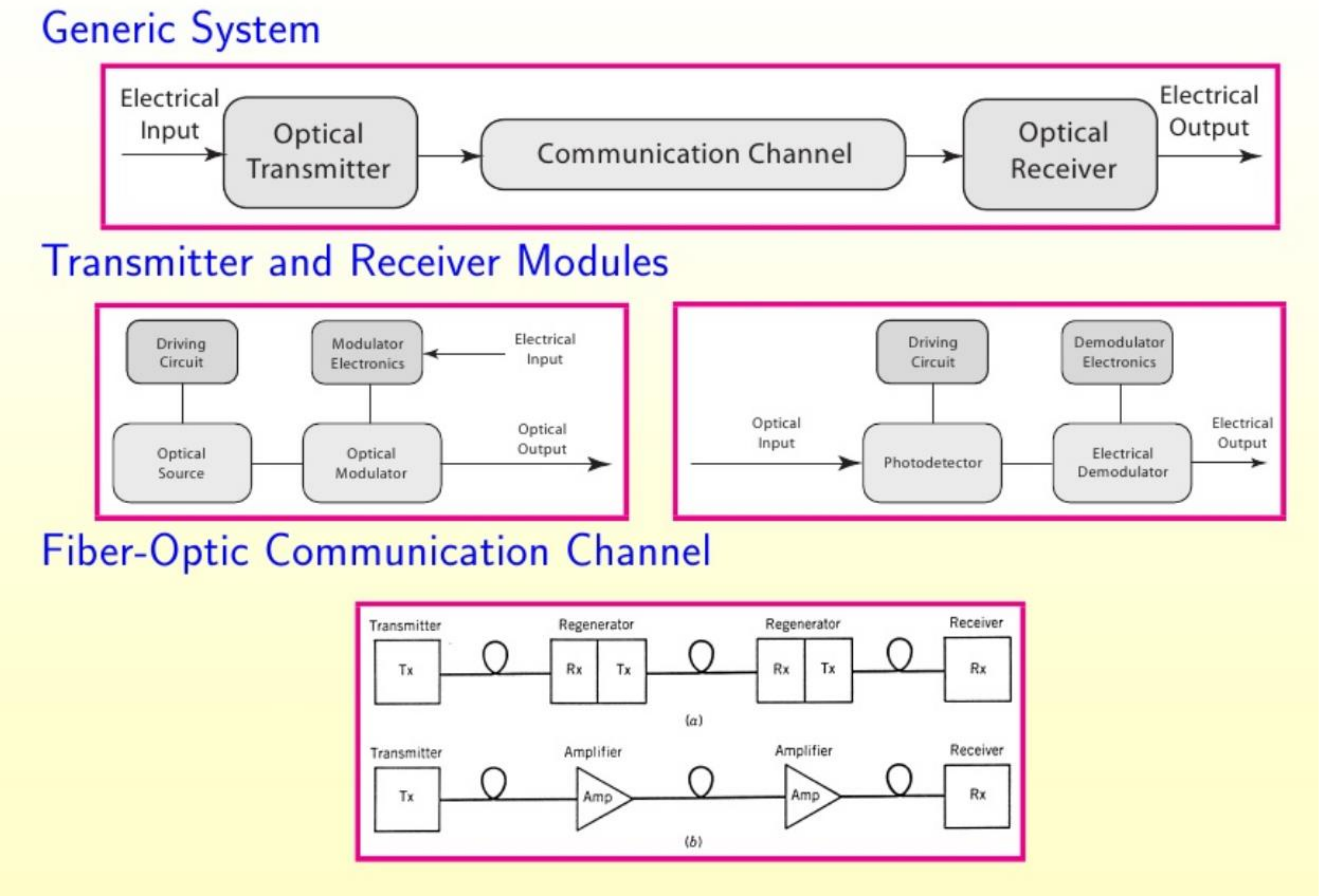
Telegraph;	1836
Telephone;	1876
Coaxial Cables;	1840
Microwaves;	1948

Optical Era

Optical Fibers;	1978
Optical Amplifiers;	1990
WDM Technology;	1996
Multiple bands;	2002

- Microwaves and coaxial cables limited to $B \sim 100$ Mb/s.
- Optical systems can operate at bit rate $>$10 Tb/s.
- Improvement in system capacity is related to the high frequency optical waves ($\sim$200 THz at 1.5 μm).

Govind Agrawal- Fiber Optic Comm



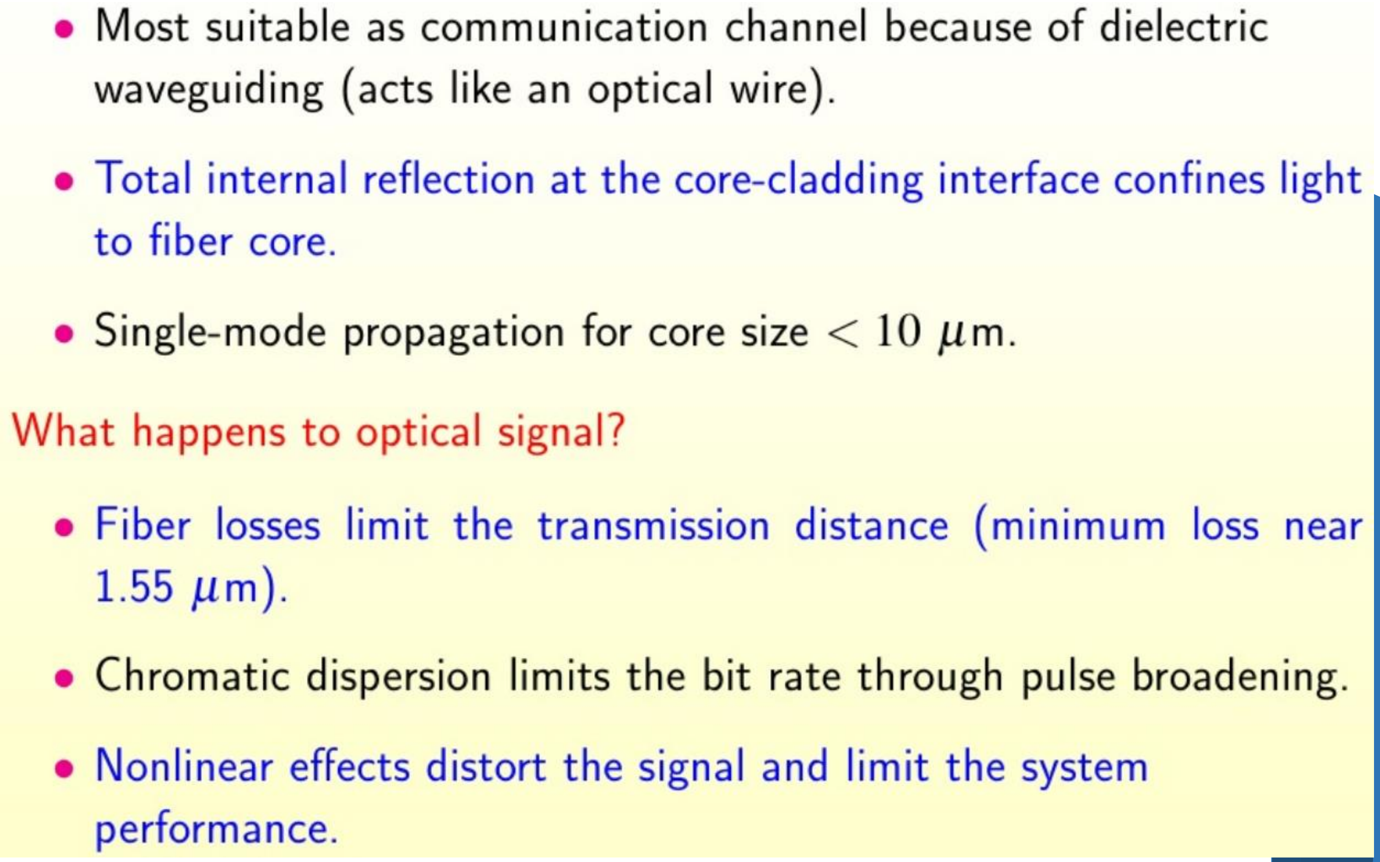
Generic System

Transmitter and Receiver Modules

Fiber-Optic Communication Channel

Govind Agrawal

I. Optical fiber types and characteristics



- Most suitable as communication channel because of dielectric waveguiding (acts like an optical wire).
- Total internal reflection at the core-cladding interface confines light to fiber core.
- Single-mode propagation for core size $< 10\ \mu$m.

What happens to optical signal?

- Fiber losses limit the transmission distance (minimum loss near 1.55 μm).
- Chromatic dispersion limits the bit rate through pulse broadening.
- Nonlinear effects distort the signal and limit the system performance.

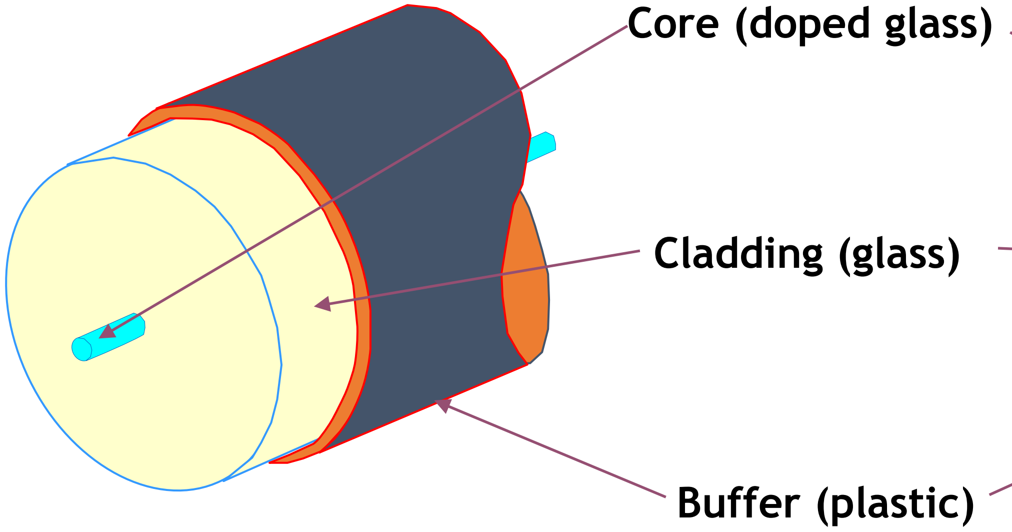
The Structure of an Optical Fiber

An optical fiber is made up of:

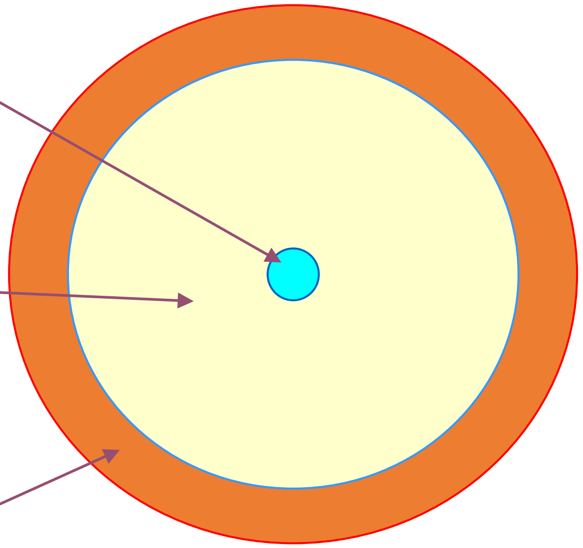
remember from Optoelectronics!!! And C2

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

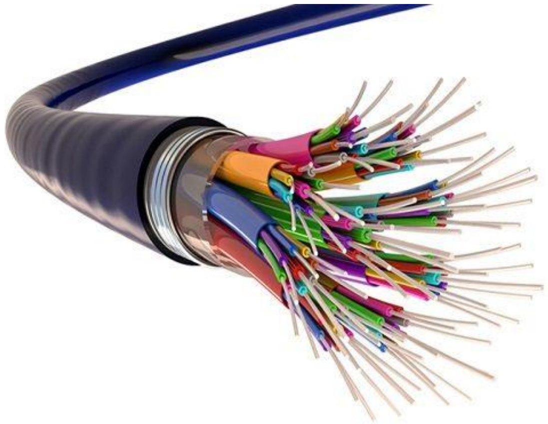
Fiber <> Cable!!!!!!



perspective view

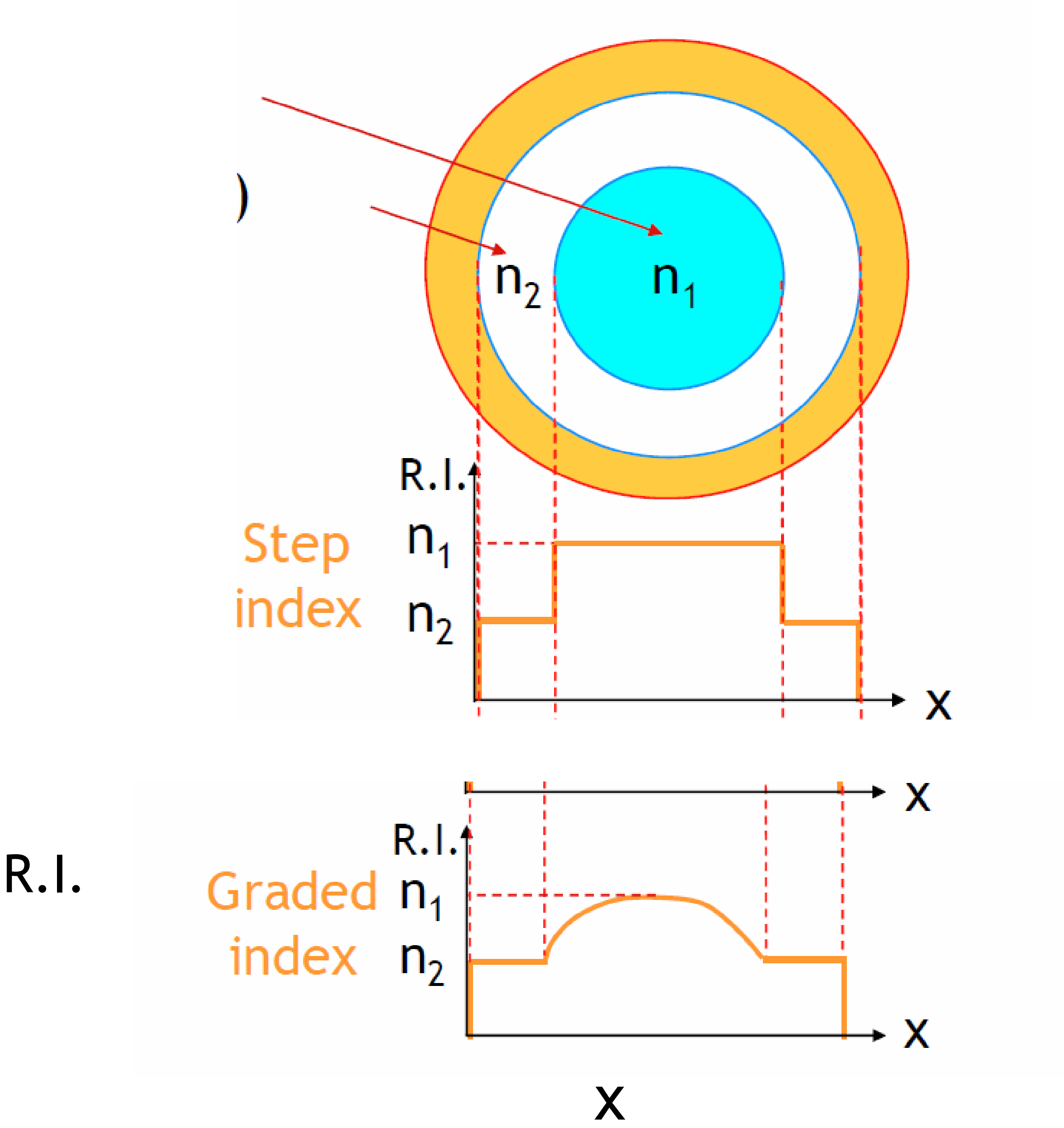


transverse section

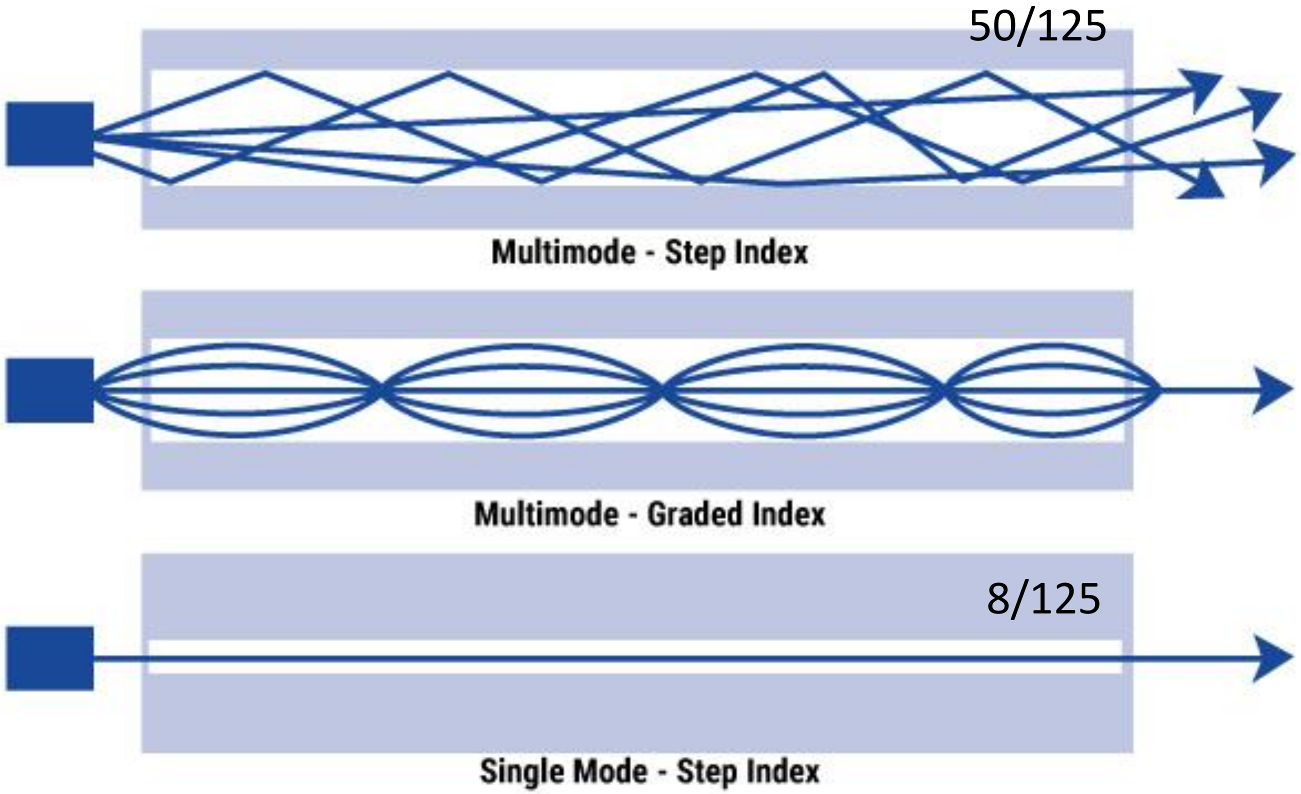


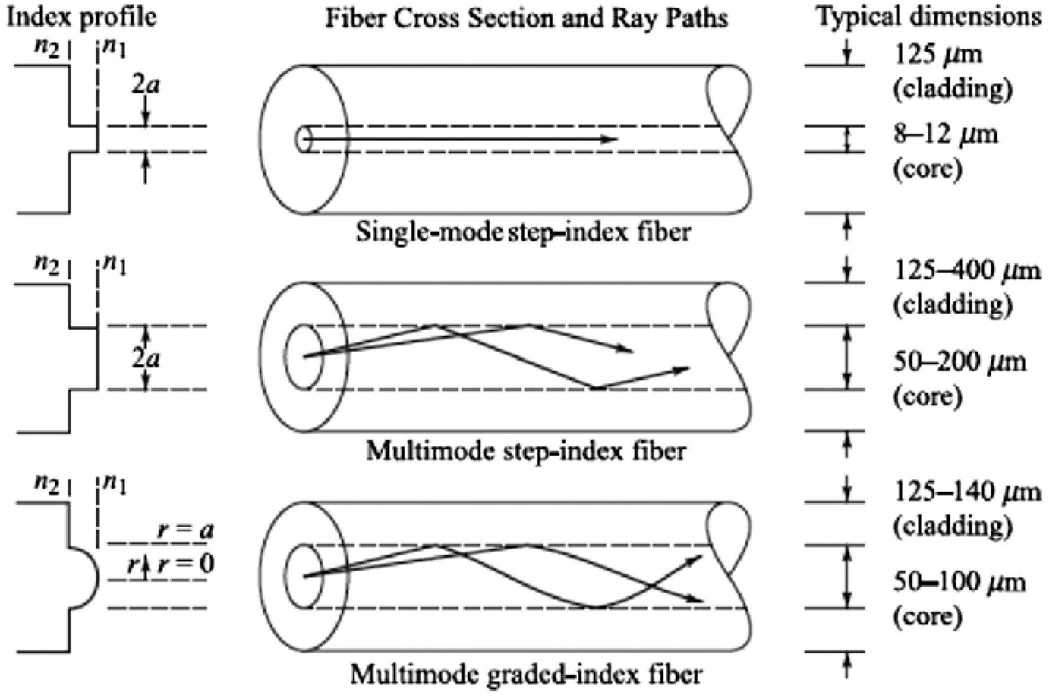
Fiber Refractive Index Profile Concept

- 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?



Longitudinal section- common fibers



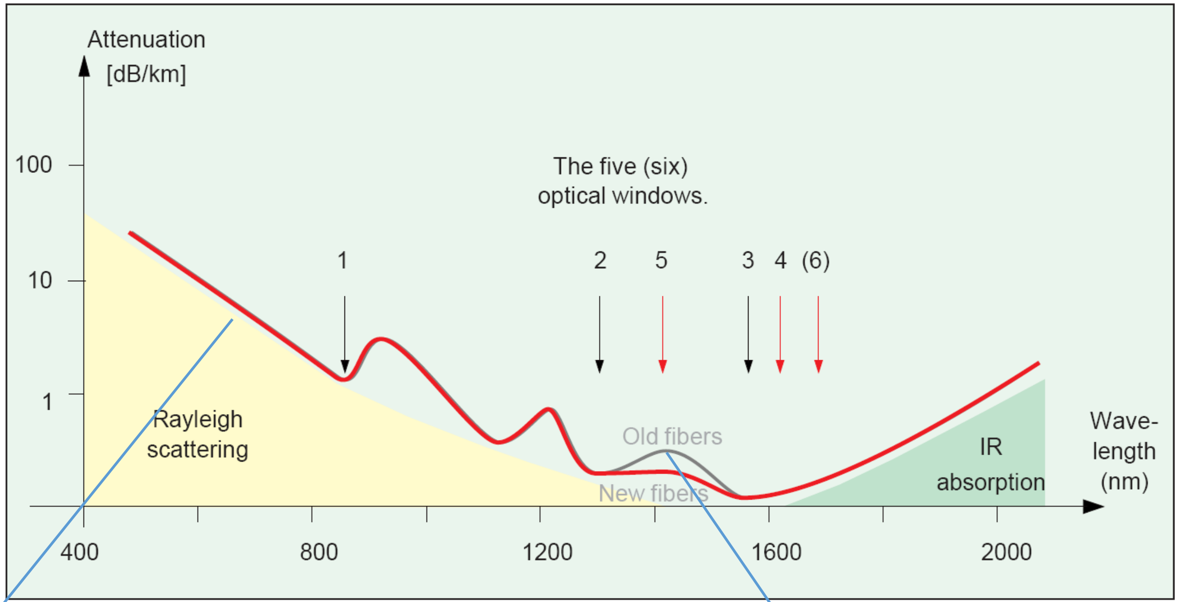


Optical Communication Bands and Attenuation

- 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.



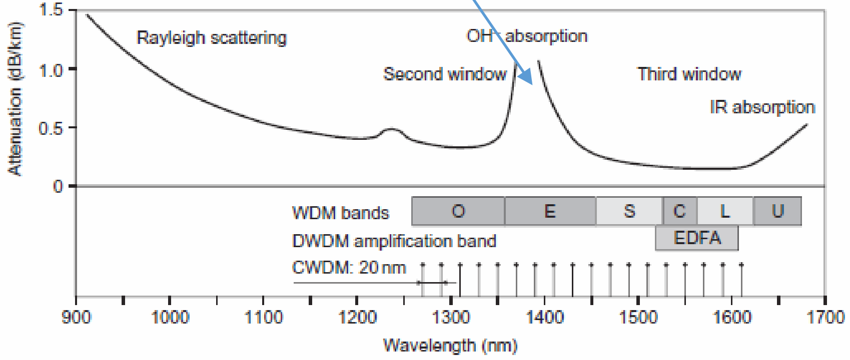


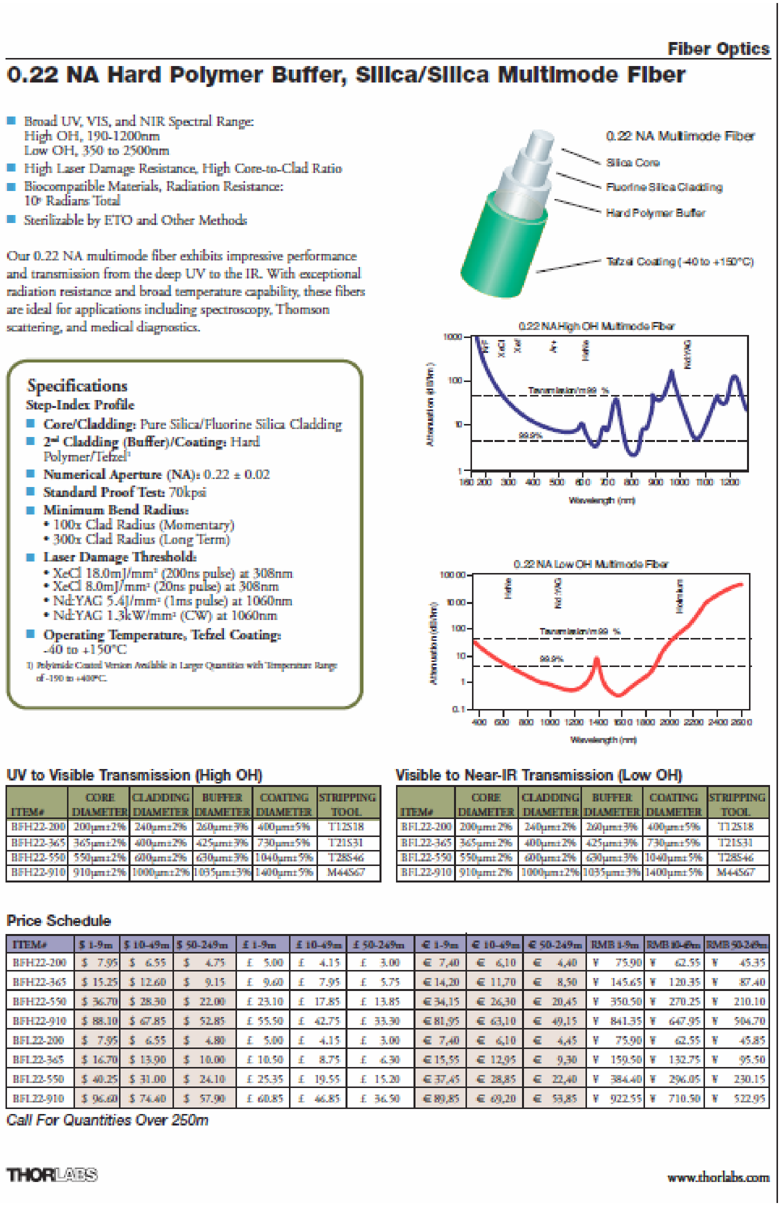
FIGURE 5.1

DWDM and CWDM channel allocation and WDM bands.

Attenuation is the slope/inclination of the graphic

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^{8} 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	£ 36.90	€ 89,85	€ 69,20	€ 53,85	¥ 922.55	¥ 710.50	¥ 522.95

Call For Quantities Over 250m

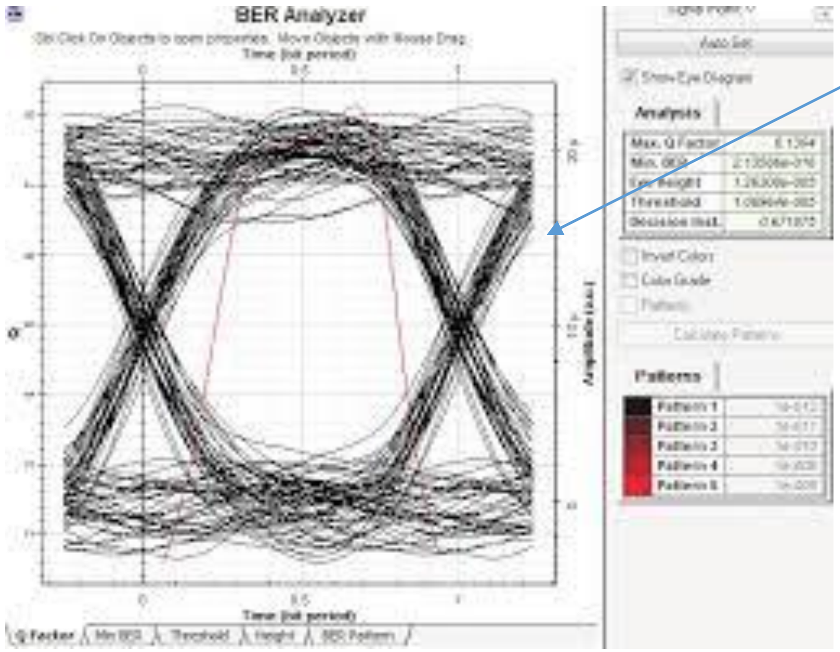
THORLABS

www.thorlabs.com

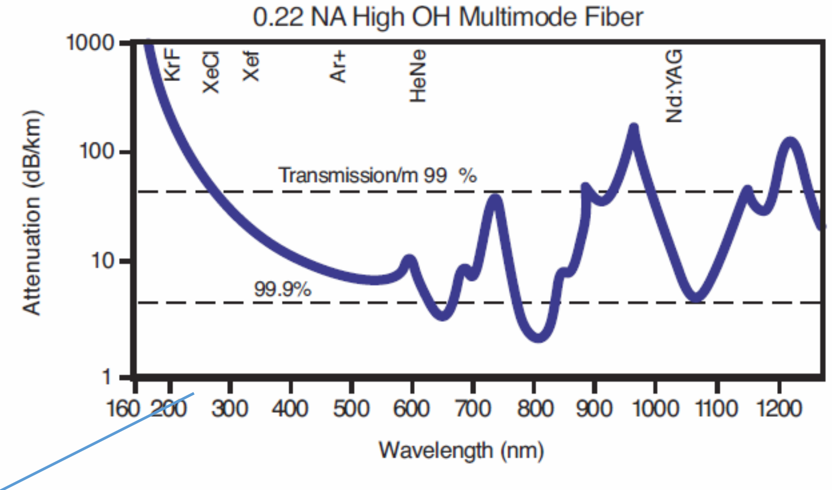
Thorlabs – vol 19 – page 1095/1105

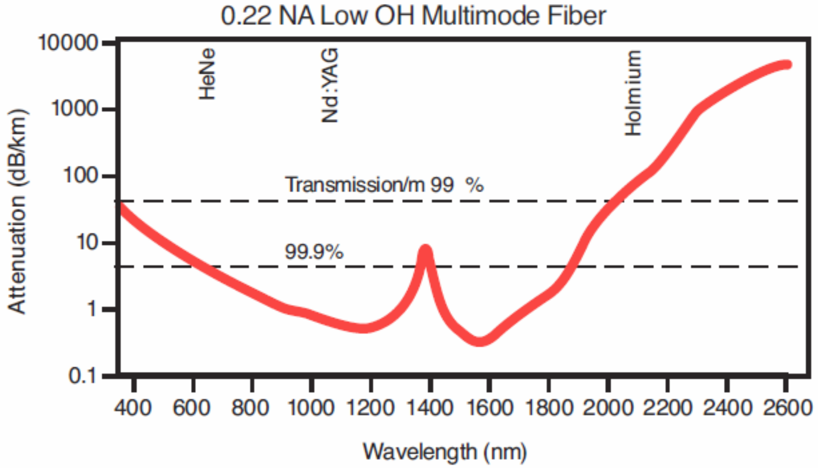
ITU-T Recommendation

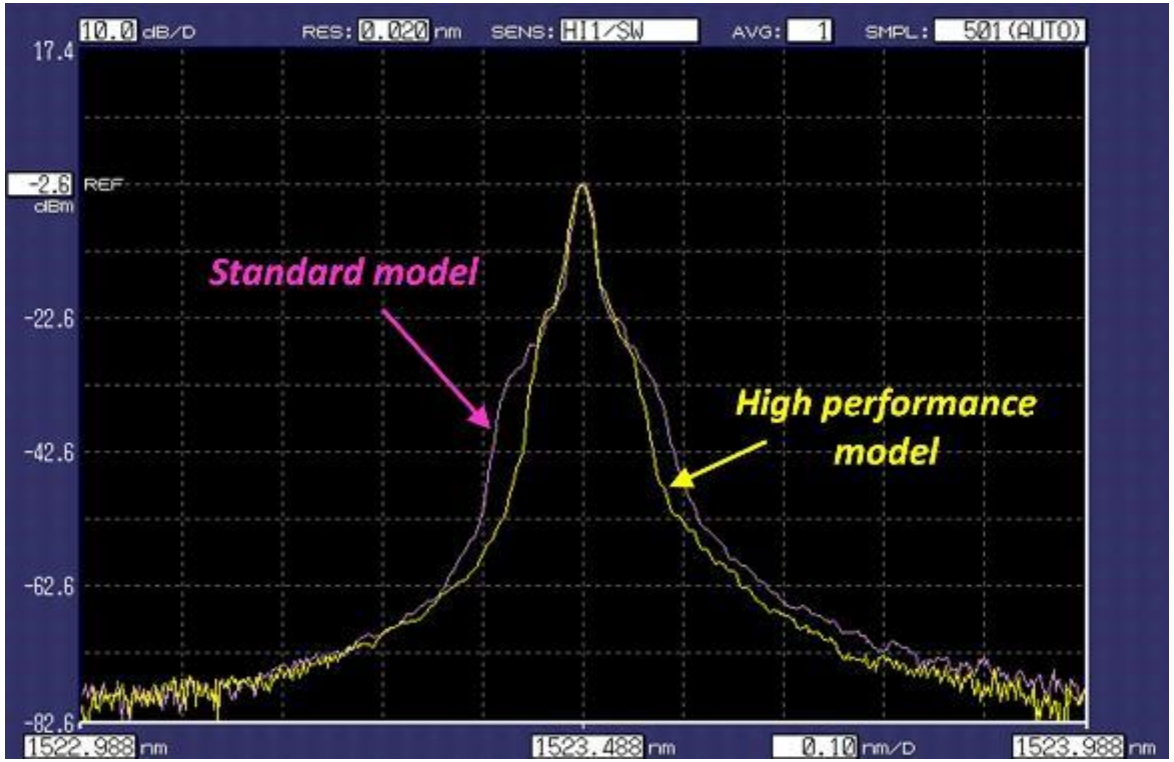
- ITU-T Recommendation G.652 (2005), *Characteristics of a single-mode optical fibre and cable.*
- ITU-T Recommendation G.653 (2003), *Characteristics of a dispersion-shifted single-mode optical fibre and cable.*
- ITU-T Recommendation G.654 (2004), *Characteristics of a cut-off shifted single-mode optical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

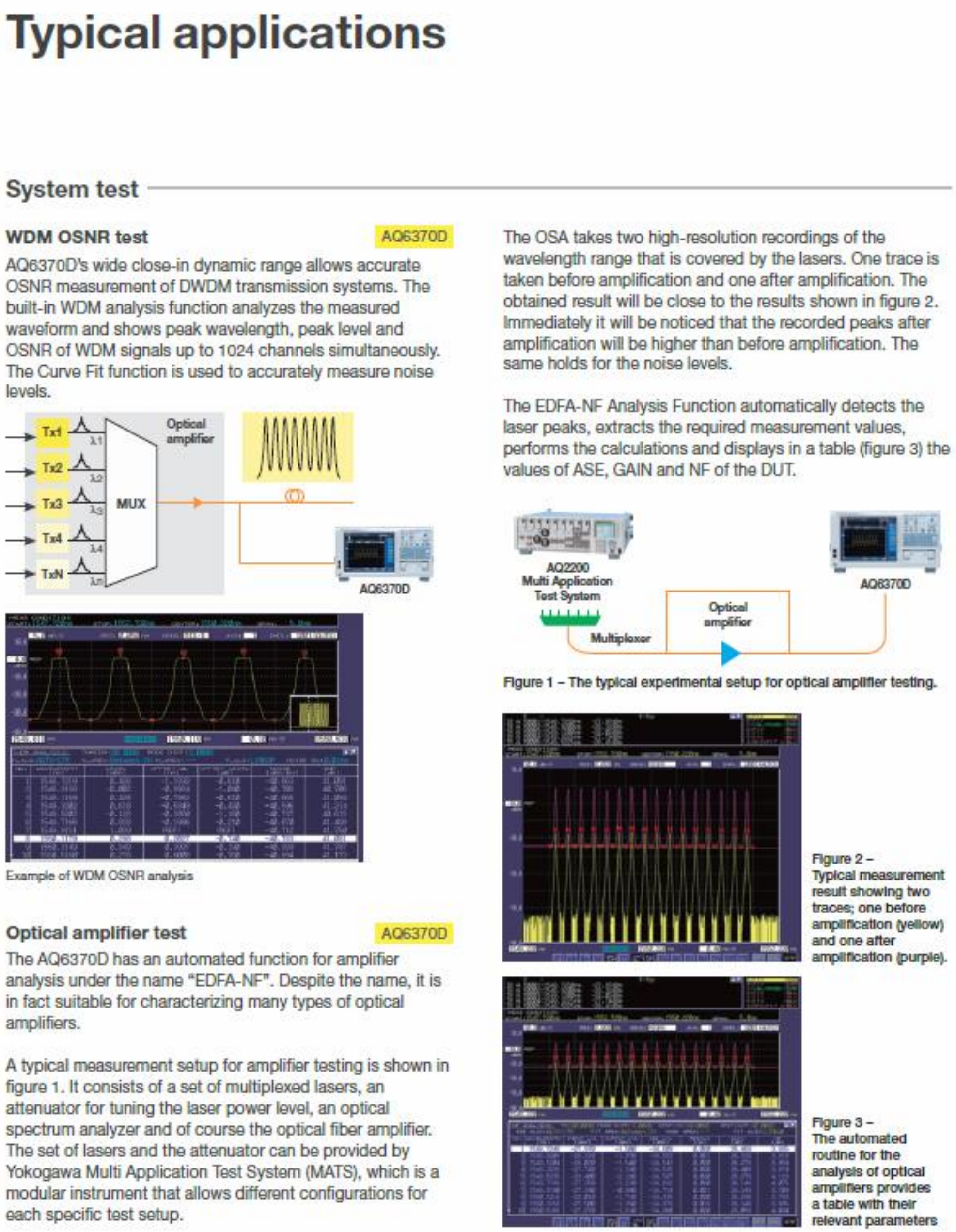


Example (Thorlabs Catalog)









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.

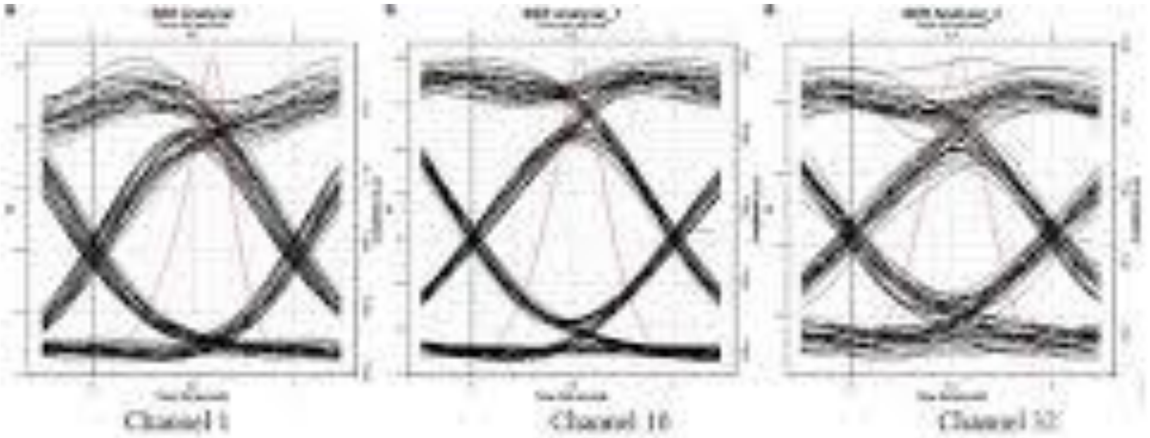
Figure 1 – The typical experimental setup for optical amplifier testing.

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

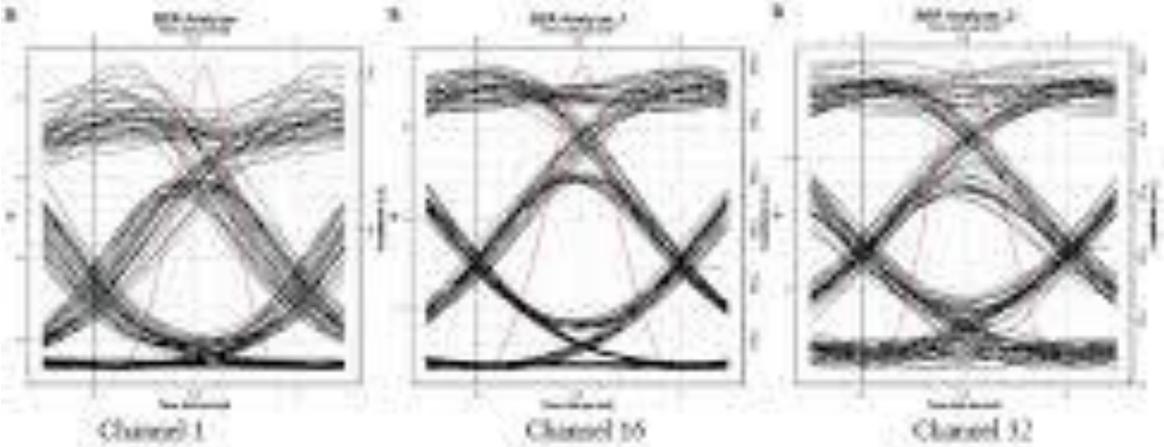
Figure 3 – The automated routine for the analysis of optical amplifiers provides a table with their relevant parameters

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

BER Analyzer



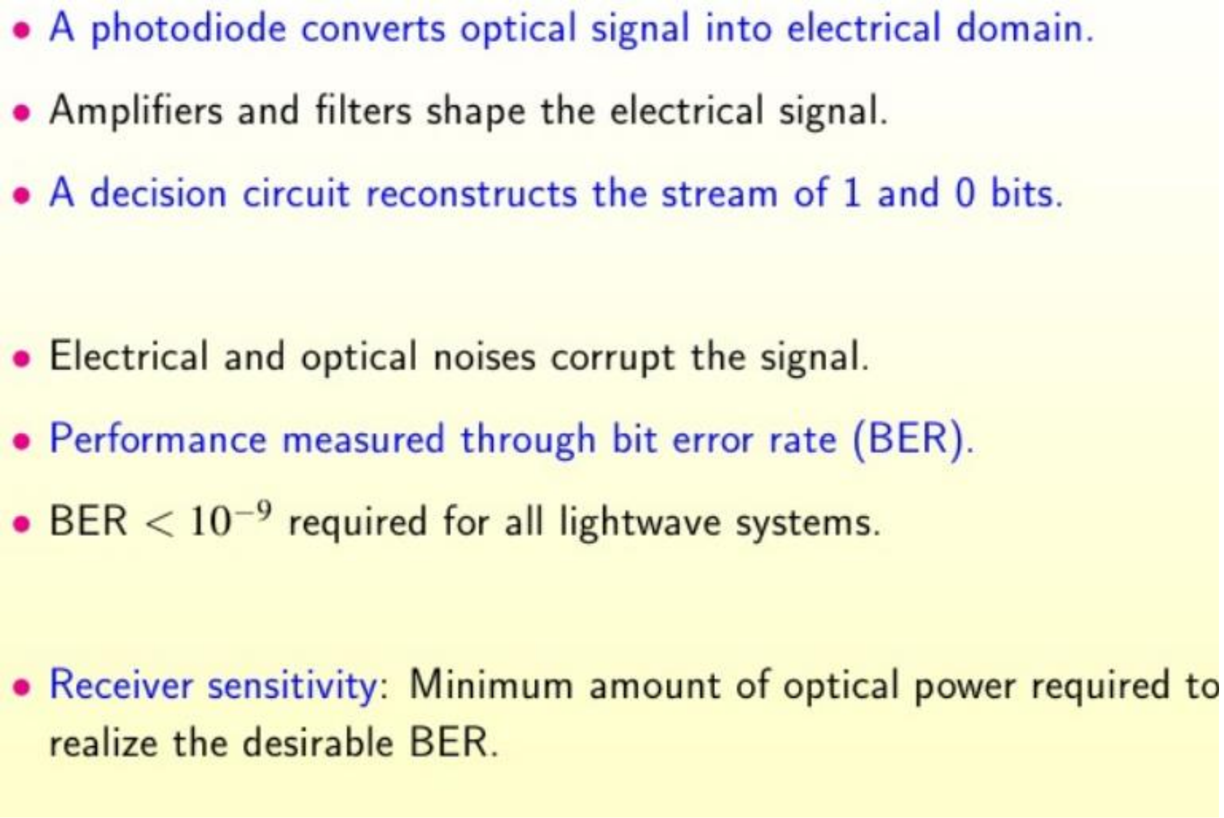
(a) RZ



(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/

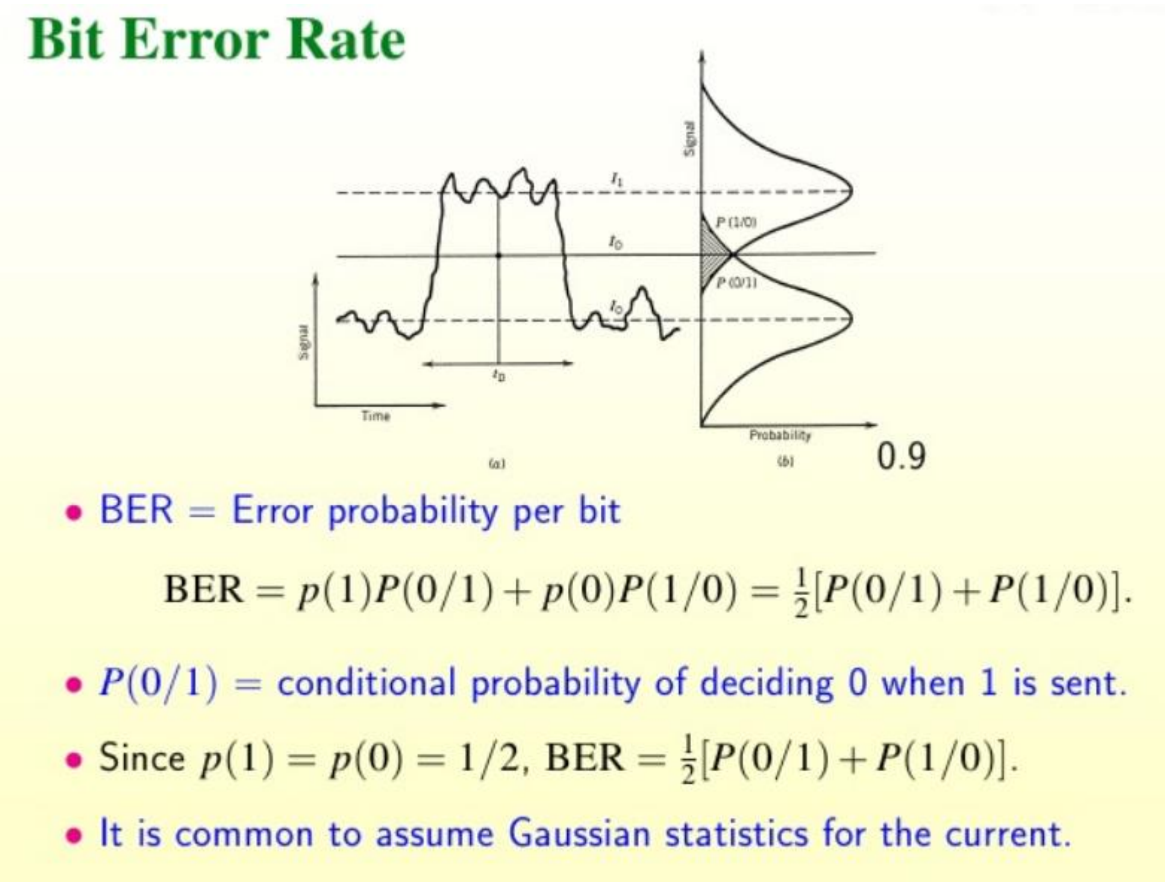
Photodiode and BER



- A photodiode converts optical signal into electrical domain.
- Amplifiers and filters shape the electrical signal.
- A decision circuit reconstructs the stream of 1 and 0 bits.

- Electrical and optical noises corrupt the signal.
- Performance measured through bit error rate (BER).
- BER $< 10^{-9}$ required for all lightwave systems.

- Receiver sensitivity: Minimum amount of optical power required to realize the desirable BER.



Bit Error Rate

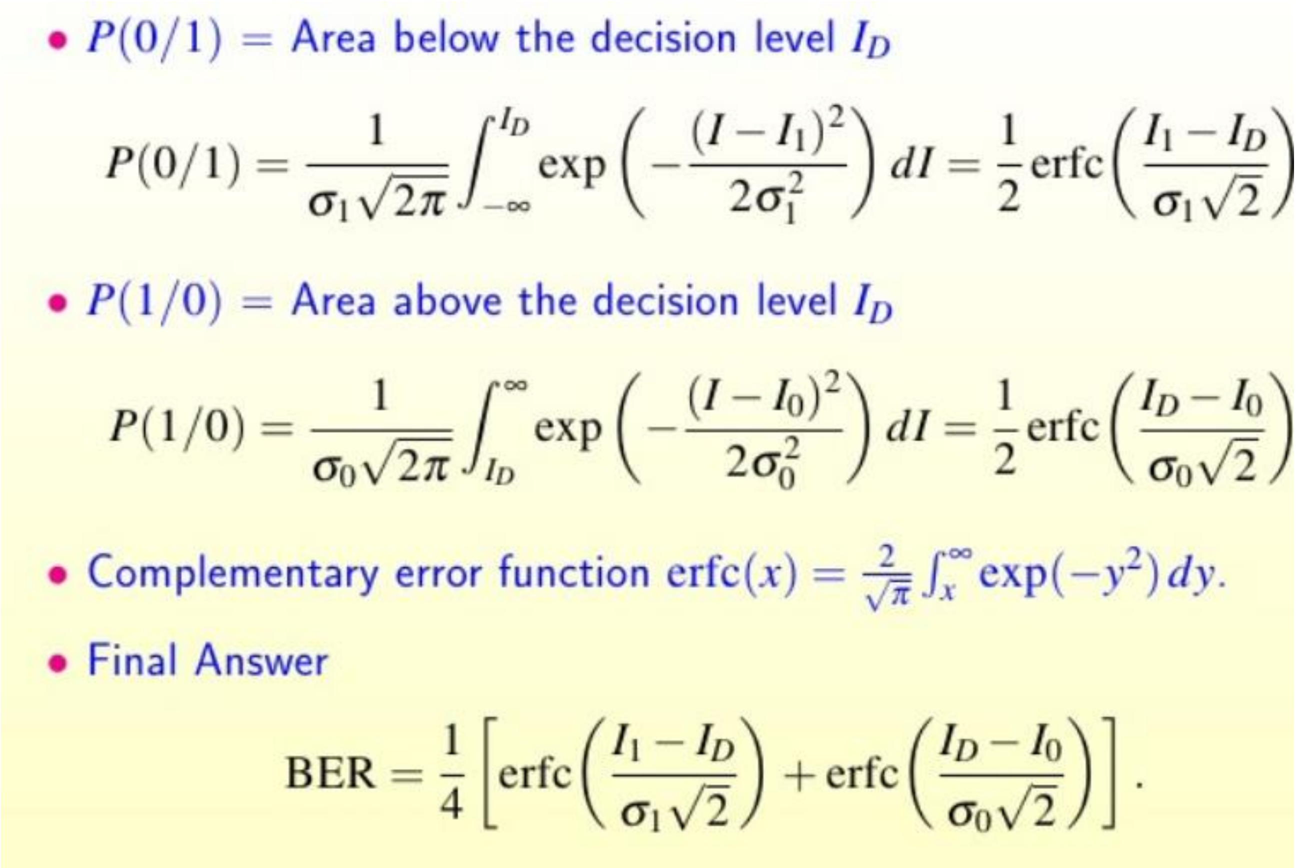
0.9

- BER = Error probability per bit

$$\mathrm{BER} = p(1)P(0/1) + p(0)P(1/0) = \tfrac{1}{2}[P(0/1) + P(1/0)].$$

- $P(0/1)$ = conditional probability of deciding 0 when 1 is sent.
- Since $p(1) = p(0) = 1/2$, $\mathrm{BER} = \frac{1}{2}[P(0/1) + P(1/0)]$.
- It is common to assume Gaussian statistics for the current.

BER



- $P(0/1)$ = Area below the decision level I_D

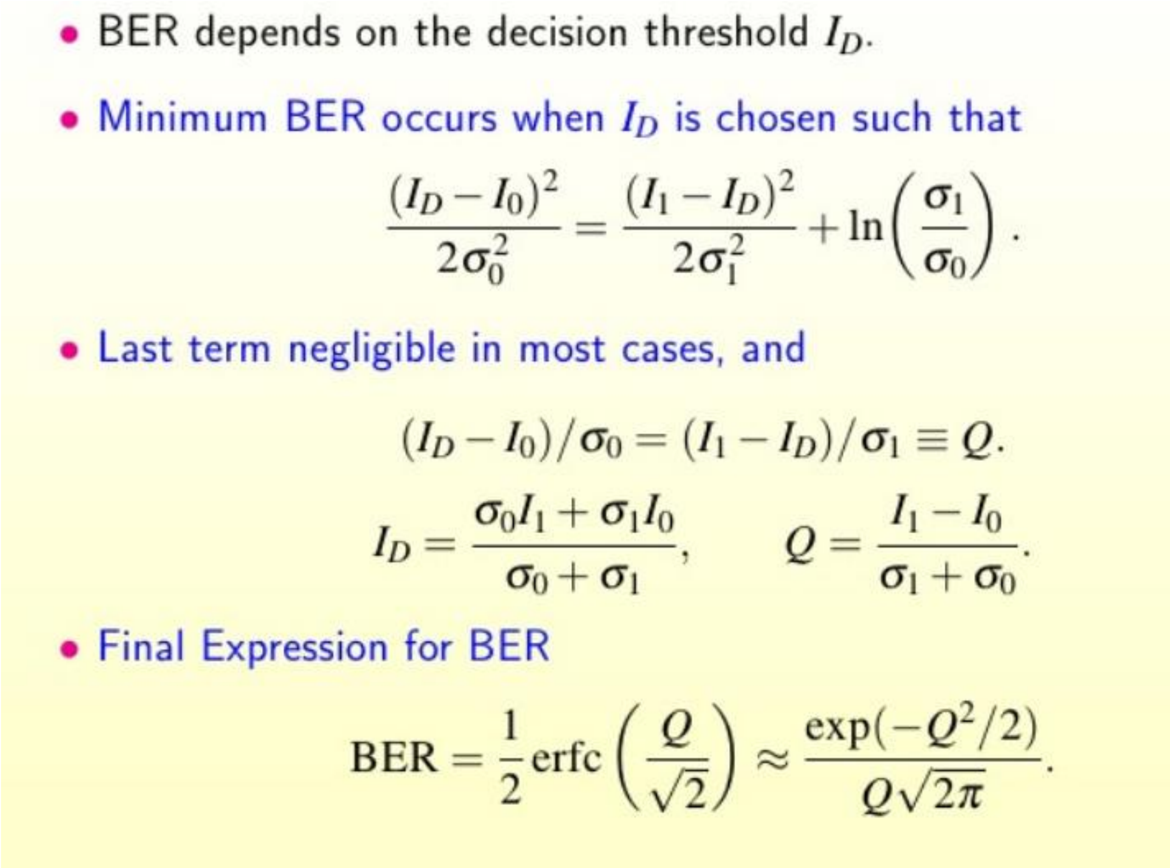
$$P(0/1) = \frac{1}{\sigma_1\sqrt{2\pi}}\int_{-\infty}^{I_D} \exp\left(-\frac{(I-I_1)^2}{2\sigma_1^2}\right) dI = \frac{1}{2}\operatorname{erfc}\left(\frac{I_1-I_D}{\sigma_1\sqrt{2}}\right)$$

- $P(1/0)$ = Area above the decision level I_D

$$P(1/0) = \frac{1}{\sigma_0\sqrt{2\pi}}\int_{I_D}^{\infty} \exp\left(-\frac{(I-I_0)^2}{2\sigma_0^2}\right) dI = \frac{1}{2}\operatorname{erfc}\left(\frac{I_D-I_0}{\sigma_0\sqrt{2}}\right)$$

- Complementary error function $\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty}\exp(-y^2)\,dy$.
- Final Answer

$$\mathrm{BER} = \frac{1}{4}\left[\operatorname{erfc}\left(\frac{I_1-I_D}{\sigma_1\sqrt{2}}\right) + \operatorname{erfc}\left(\frac{I_D-I_0}{\sigma_0\sqrt{2}}\right)\right].$$



- BER depends on the decision threshold I_D.
- Minimum BER occurs when I_D is chosen such that

$$\frac{(I_D-I_0)^2}{2\sigma_0^2} = \frac{(I_1-I_D)^2}{2\sigma_1^2} + \ln\left(\frac{\sigma_1}{\sigma_0}\right).$$

- Last term negligible in most cases, and

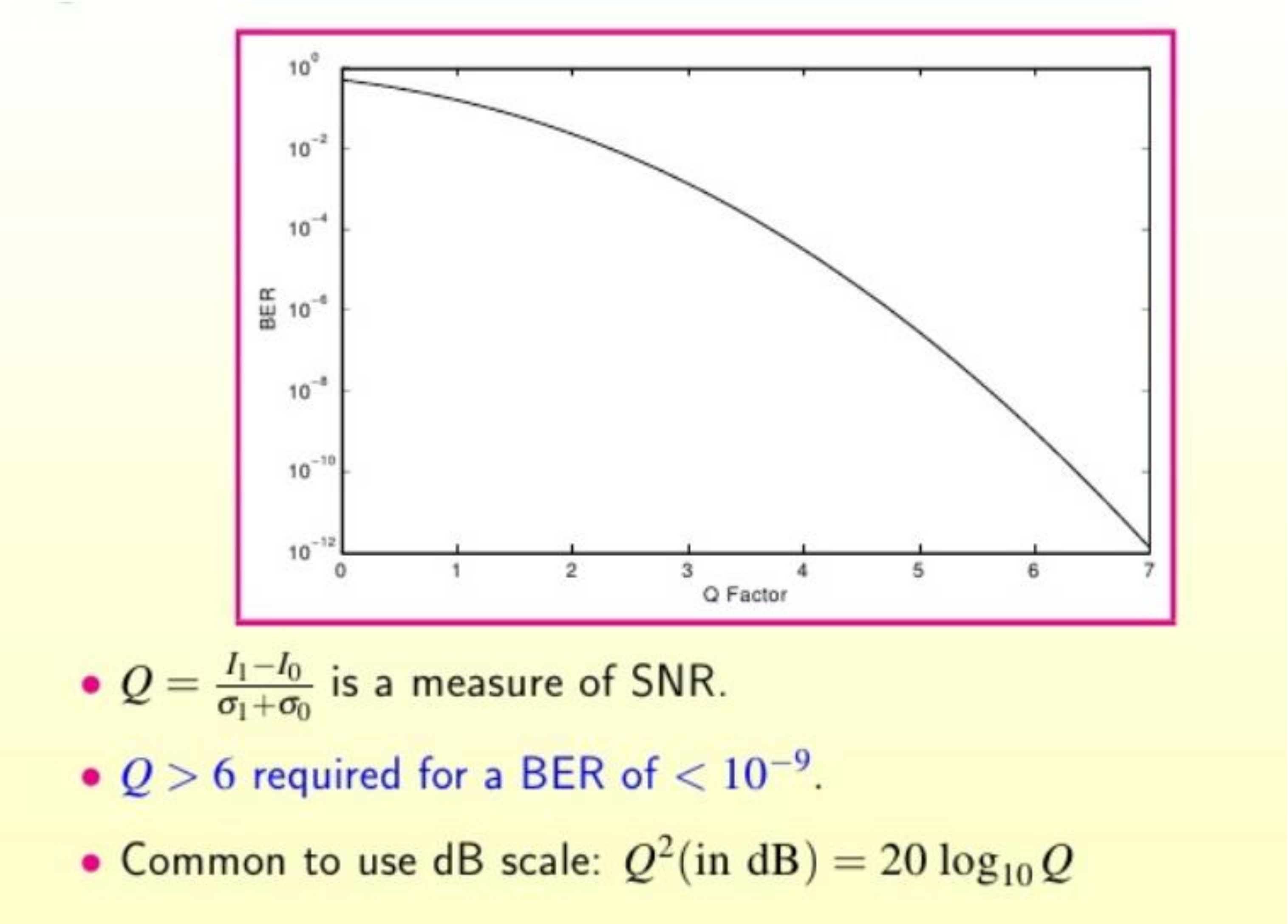
$$(I_D-I_0)/\sigma_0 = (I_1-I_D)/\sigma_1 \equiv Q.$$

$$I_D = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0+\sigma_1}, \qquad Q = \frac{I_1-I_0}{\sigma_1+\sigma_0}.$$

- Final Expression for BER

$$\mathrm{BER} = \frac{1}{2}\operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp(-Q^2/2)}{Q\sqrt{2\pi}}.$$

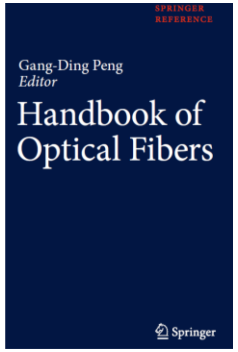
Q factor

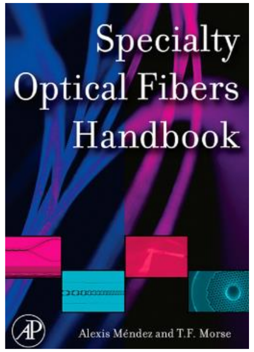


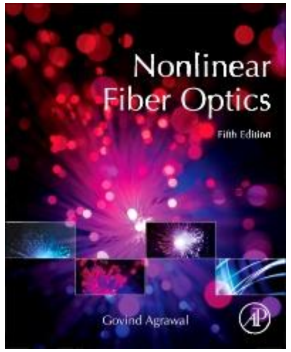
- $Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$ is a measure of SNR.
- $Q > 6$ required for a BER of $< 10^{-9}$.
- Common to use dB scale: $Q^2(\text{in dB}) = 20 \log_{10} Q$

II. Special optical fibers

More than 5 generations


SPRINGER REFERENCE
Gang-Ding Peng
Editor
Handbook of Optical Fibers
Springer


Specialty Optical Fibers Handbook
Alexis Méndez and T.F. Morse


Nonlinear Fiber Optics
Fifth Edition
Govind Agrawal

- WHY:
  - Optical fiber fabrication technology (Handbook of OF)
  - Optical fiber materials (Specialty OF Handbook)
  - Optical fiber transmission phenomena (Nonlinear fiber optics)


- 0.8-μm systems (1980); Graded-index fibers
- 1.3-μm systems (1985); Single-mode fibers
- 1.55-μm systems (1990); Single-mode lasers
- WDM systems (1996); Optical amplifiers
- L and S bands (2002); Raman amplification

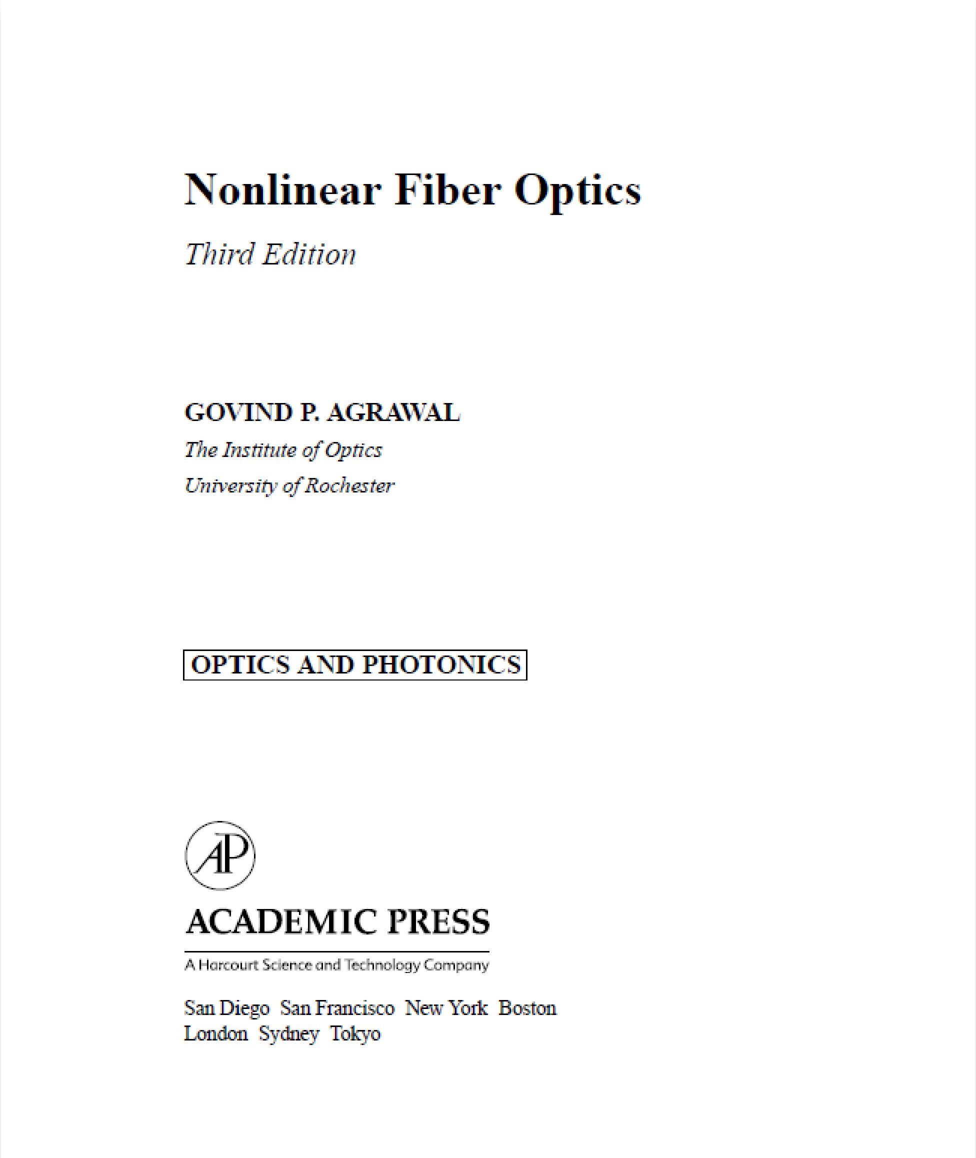
ETC

Why?

- **System performance can be maximized**, and total system cost savings can be realized by choosing an optical fiber design optimized for a particular system application.
- The cabled optical fiber that forms the backbone of the physical layer is one part of an optical transmission line that also **comprises amplifiers and dispersion compensation modules** (DCMs).
- The designs of the amplifier, DCM, and cabled transmission fiber are not mutually independent, and an **integrated view of the transmission line design** is necessary to optimize performance and drive cost out of the total system.
- Is about phenomena
- Is about new manufacturing technology and new materials

Is about phenomena

- Nonlinearities
- The response of any dielectric to light becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception.
- Highly focused coherent laser light, propagating with low loss through optical fiber over long distances (kilometers), is an ideal breeding ground for nonlinear interaction with the glass material
- Although nonlinear effects were found inearly optical transmission work with analog signal delivery (CATV, etc.), muchattention lately has been given to resolution of nonlinear problems in long-haul optical communications and high-power operation in specialty fibers. In particular, new fiber types have been developed to overcome nonlinear impairments



Nonlinear Fiber Optics

Third Edition

GOVIND P. AGRAWAL
The Institute of Optics
University of Rochester

OPTICS AND PHOTONICS

ACADEMIC PRESS
A Harcourt Science and Technology Company
San Diego San Francisco New York Boston
London Sydney Tokyo

DSF fibers

- As fiber design introduced dispersion-shifted fibers (DSFs) in the early 1990s, to overcome chromatic dispersion impairments, it was soon found that multiple lightwaves, with different wavelengths, were able to efficiently interact through a four-wave mixing (FWM) process since the coupling waves were well matched in phase and group velocity. This led to the development of NZDFs that struck a balance between the high chromatic dispersion of standard single-mode fiber and the very low dispersion, at operating wavelengths, of DSFs.
- With the advent of high-power erbium-doped fiber amplifiers (EDFAs) and high-power laser diodes, many nonlinear issues arose because of the long distance between signal regeneration points and the multiple optical wavelengths that could simultaneously be used.
- In particular, stimulated Brillouin scattering became apparent (at 5–10 dBm levels with laser line widths <5 MHz). This required new features in transmitters to broaden the effective source line width. Self- and cross-phase modulation issues were also noted. Generally, these problems increased with small effective area fibers (such as those often used in specialty applications).
- In the late 1990s, Raman amplification received renewed attention because of potential noise improvements due to its distributed nature. This amplifier was based on stimulated Raman scattering of a signal wavelength by a high-powered laser pump in a transmission fiber medium.
- Homework 3.1: further study of special optical fibers – choose 2 types and make a short report (1 page)

Is about technology

- Materials
    - Pure Silica Core Fiber
    - Zero Water Peak Fiber
    - Hydrogen Aging Losses
    - DESIGN OF NONZERO DISPERSION FIBERS
    - Specialty Single-Mode Fibers (holes, INTERNAL ELECTRODES, MULTICORE FIBERS AND COMPONENTS/grattings, DOUBLE-CLAD FIBER, dopped fibers, birefringent, Photosensitive Fibers, liquid core, sapphire fibers, etc)
    - POF-plastic optical fibers
    - PCF – photonic crystal fibers
- Manufacturing Machines
    - VAPOR-DEPOSITION TECHNIQUES
    - VERTICAL AXIAL DEPOSITION
    - PLASMA CHEMICAL VAPOR DEPOSITION
    - SOL-GEL PROCESSES
    - DIRECT NANOPARTICLE DEPOSITION
    - FIBER DRAWING

Target: Low loss glass fibers for optical transmission!!

Low BER!!!

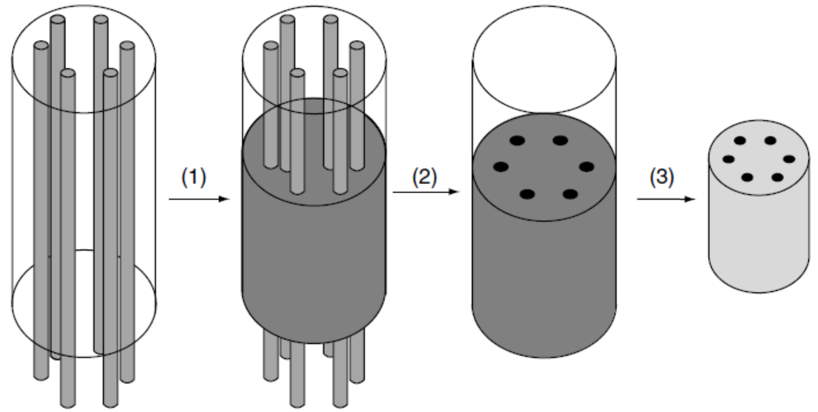
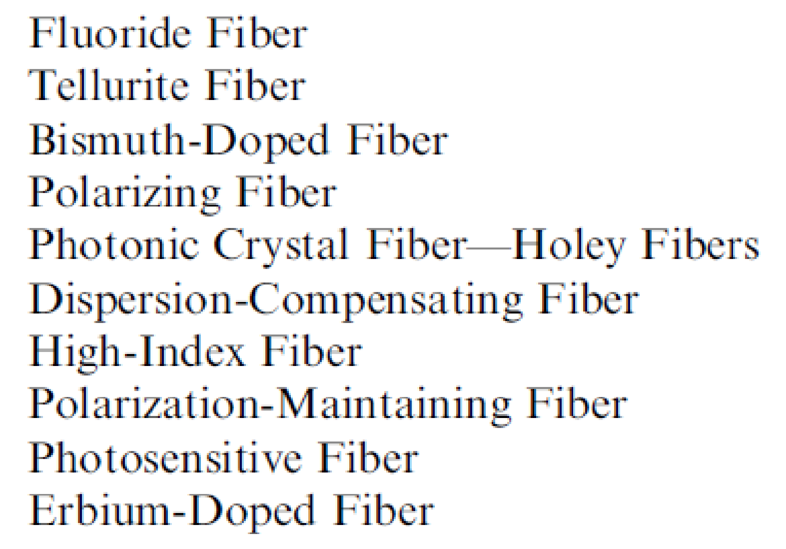


Figure 3.12 Fabrication processing of microstructured preforms using sol-gel casting. (1) Casting and gelation, (2) mandrel removal, and (3) drying, purification, and sintering of gel body.



Fluoride Fiber
Tellurite Fiber
Bismuth-Doped Fiber
Polarizing Fiber
Photonic Crystal Fiber—Holey Fibers
Dispersion-Compensating Fiber
High-Index Fiber
Polarization-Maintaining Fiber
Photosensitive Fiber
Erbium-Doped Fiber

Fiber drawing

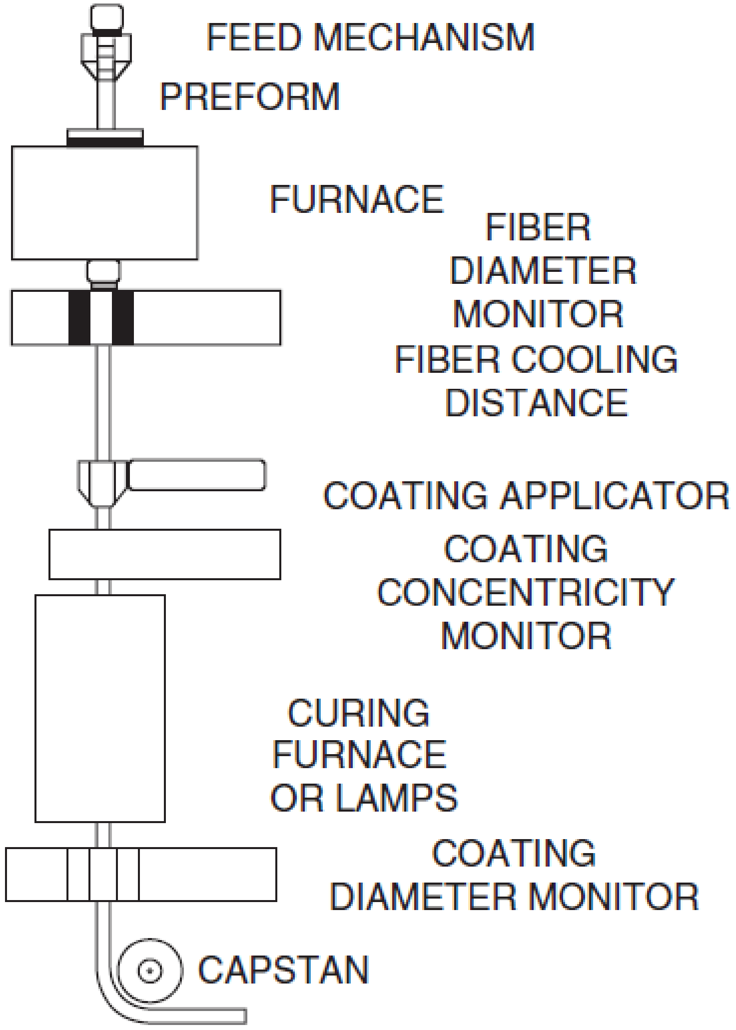
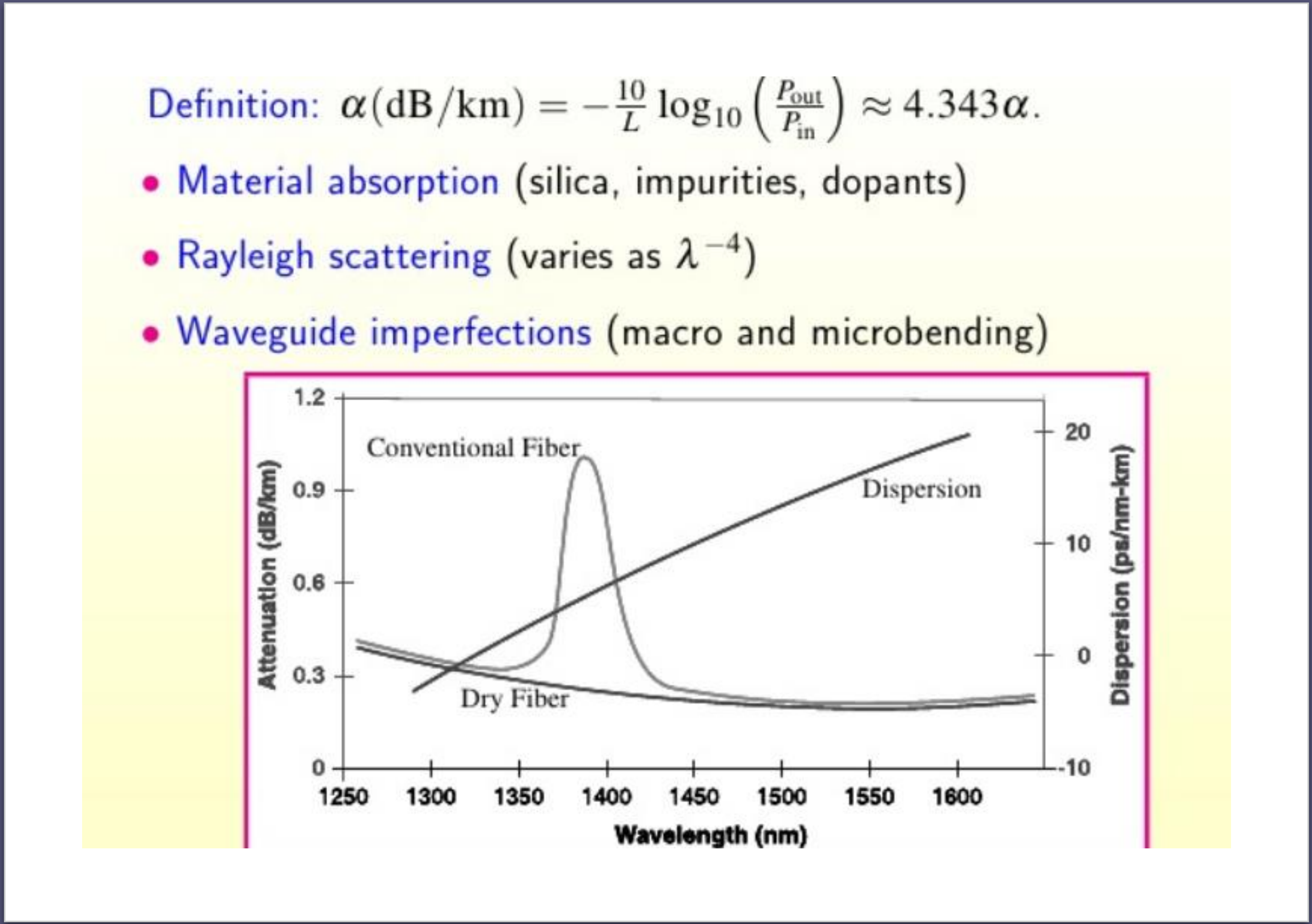


Figure 3.14 Schematic of a fiber draw tower.

III. Fiber loss: linear and nonlinear effects

- Material adsorption
- Scattering losses – linear:
  - Rayleigh
  - Mie scattering
  - Macro and microbend
  - Dispersion
- Nonlinear scattering
  - Stimulated scattering
    Brillouin
    Raman
  - Nonlinear index effects
  - Single signal – Self phase modulation
  - Multi signal – Cross Phase and FWM Intermodulation (mixing)

Linear effects



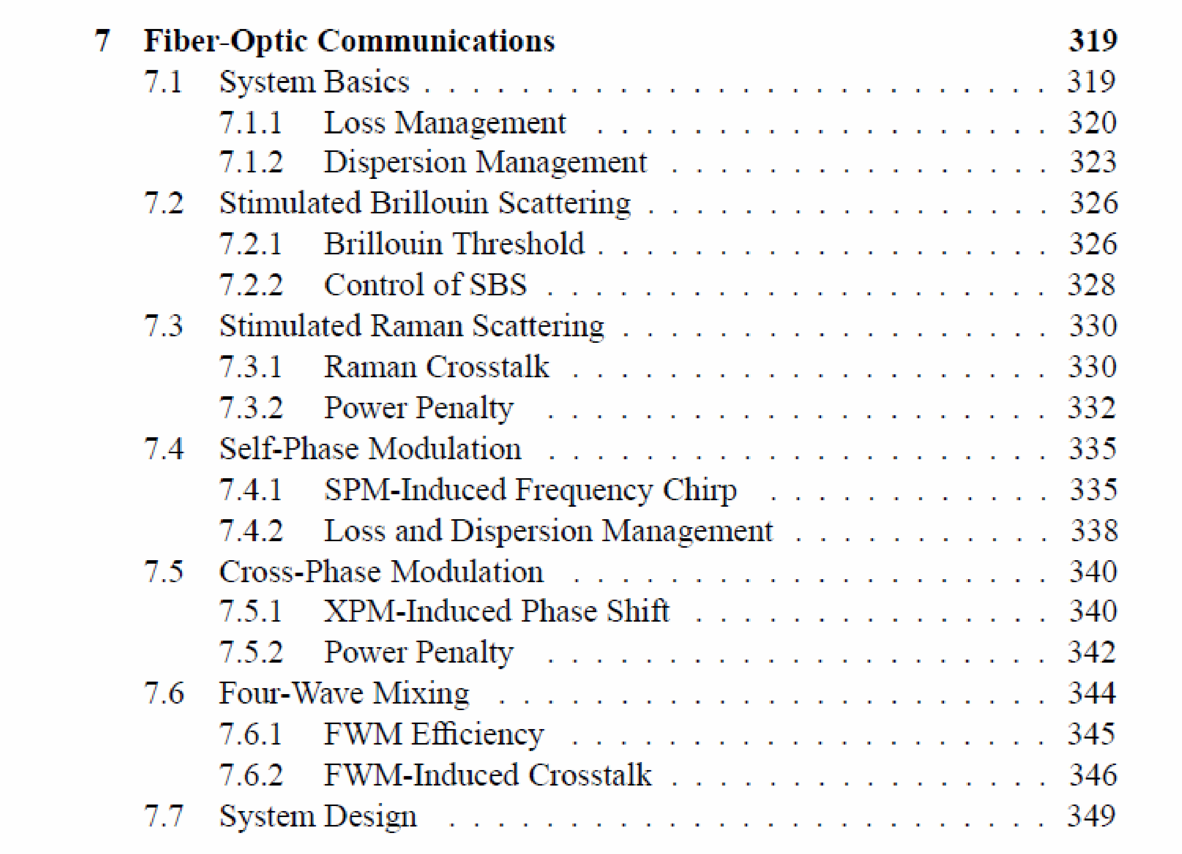
Definition: $\alpha(\mathrm{dB/km}) = -\frac{10}{L}\log_{10}\left(\frac{P_{\mathrm{out}}}{P_{\mathrm{in}}}\right) \approx 4.343\alpha.$

- Material absorption (silica, impurities, dopants)
- Rayleigh scattering (varies as λ^{-4})
- Waveguide imperfections (macro and microbending)

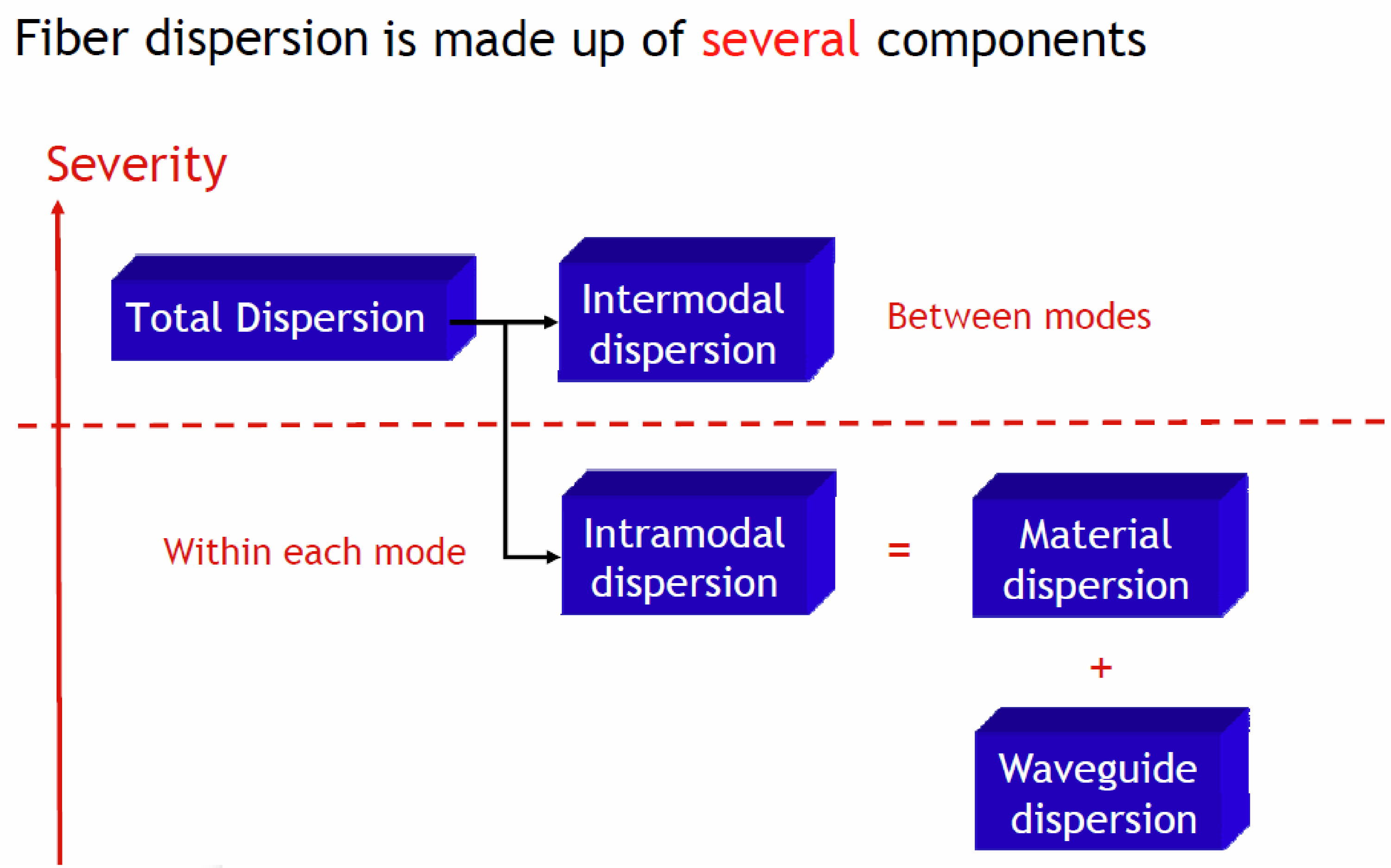
Outlines

Agrawal – Nonlinear Fiber Optics and Applications

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



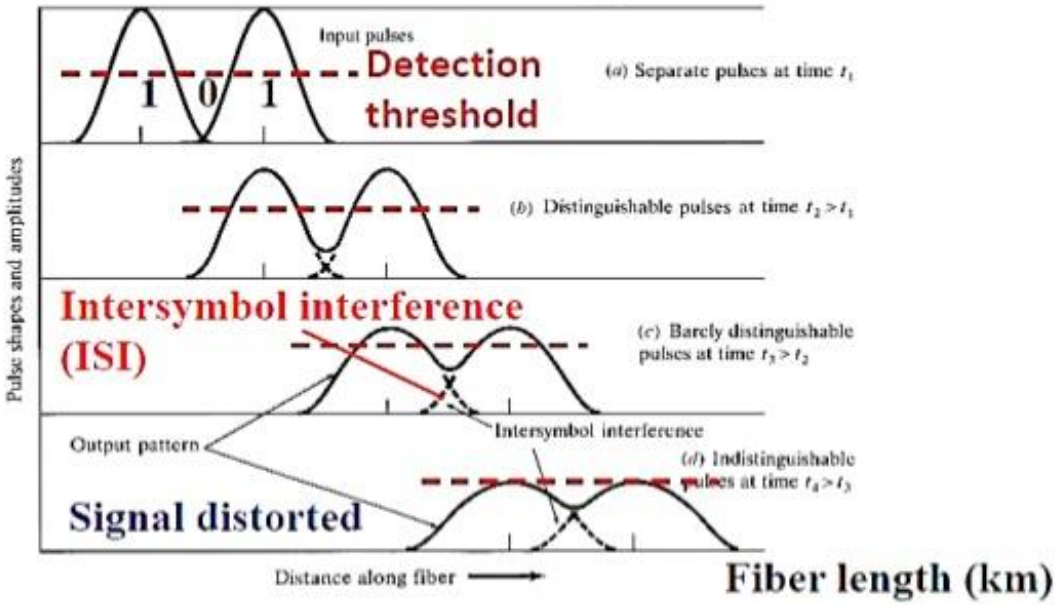
Total Dispersion



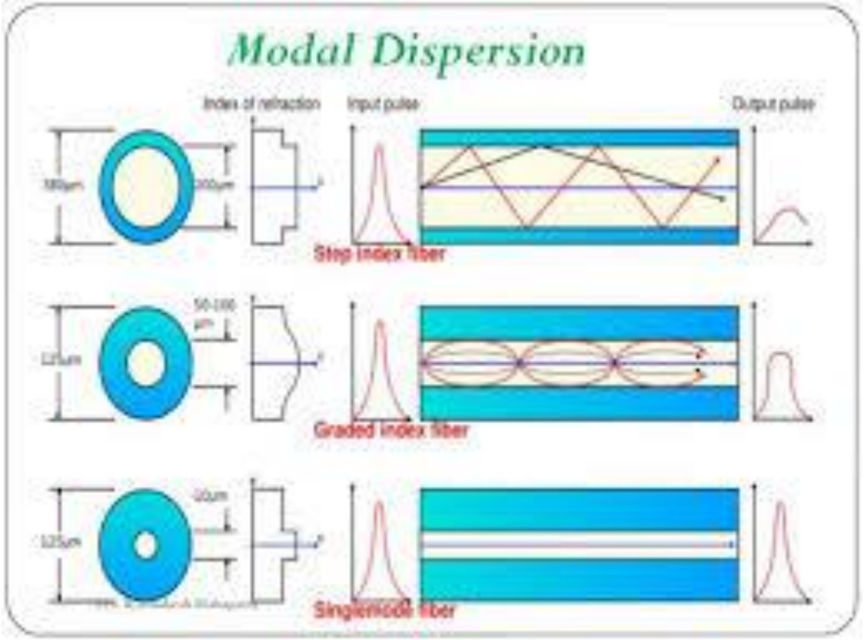
Fiber dispersion is made up of several components

Dispersion

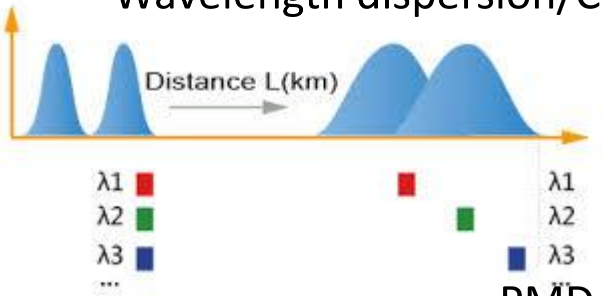
Pulse broadening limits fiber bandwidth (data rate)



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

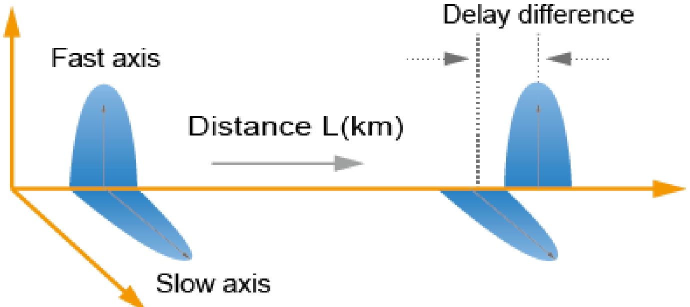


Wavelength dispersion/Chromatic



PMD dispersion

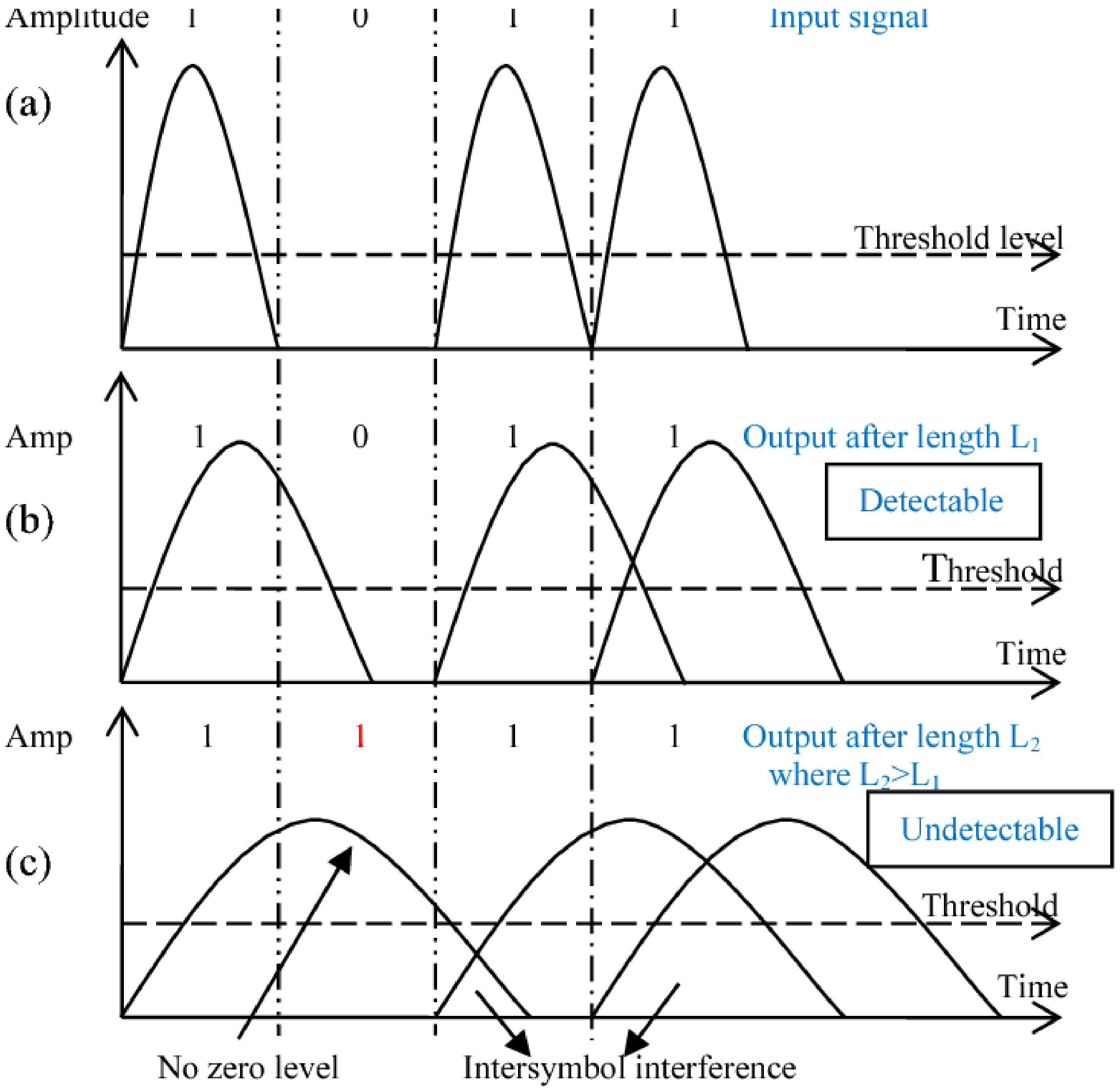
Birefringence



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

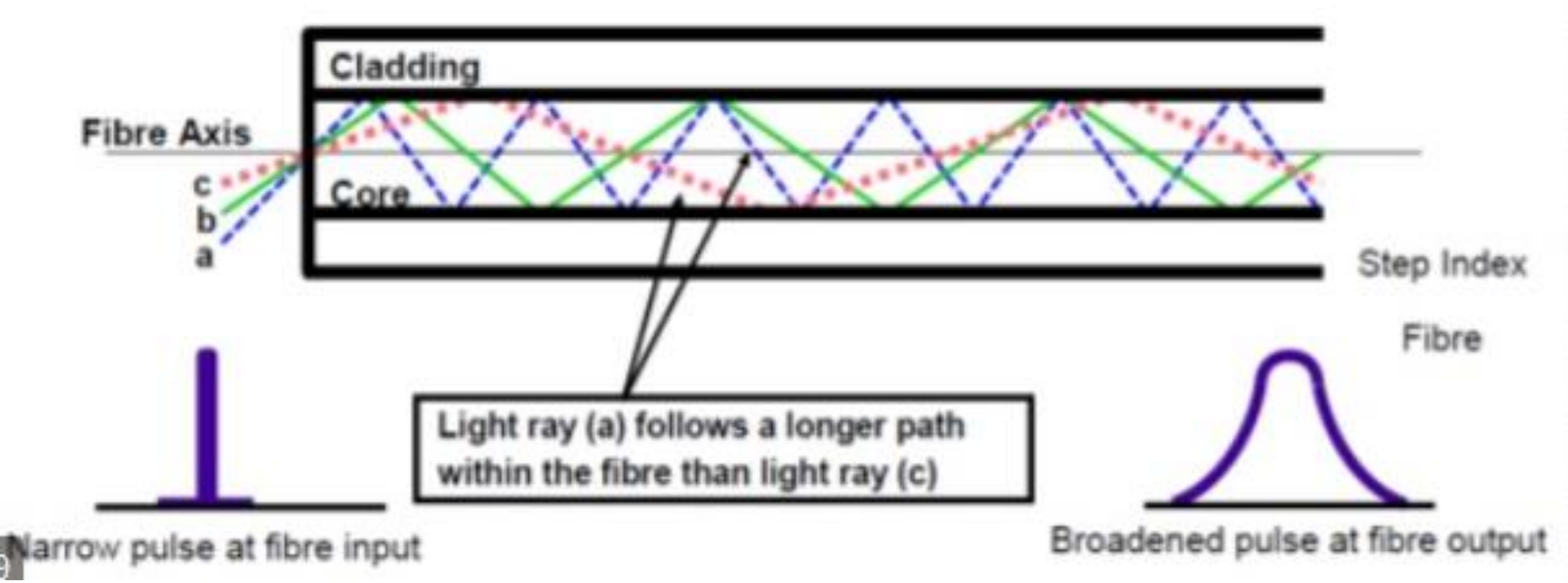
Pulse transmission effects

- Pulse broadening
- Pulse attenuation

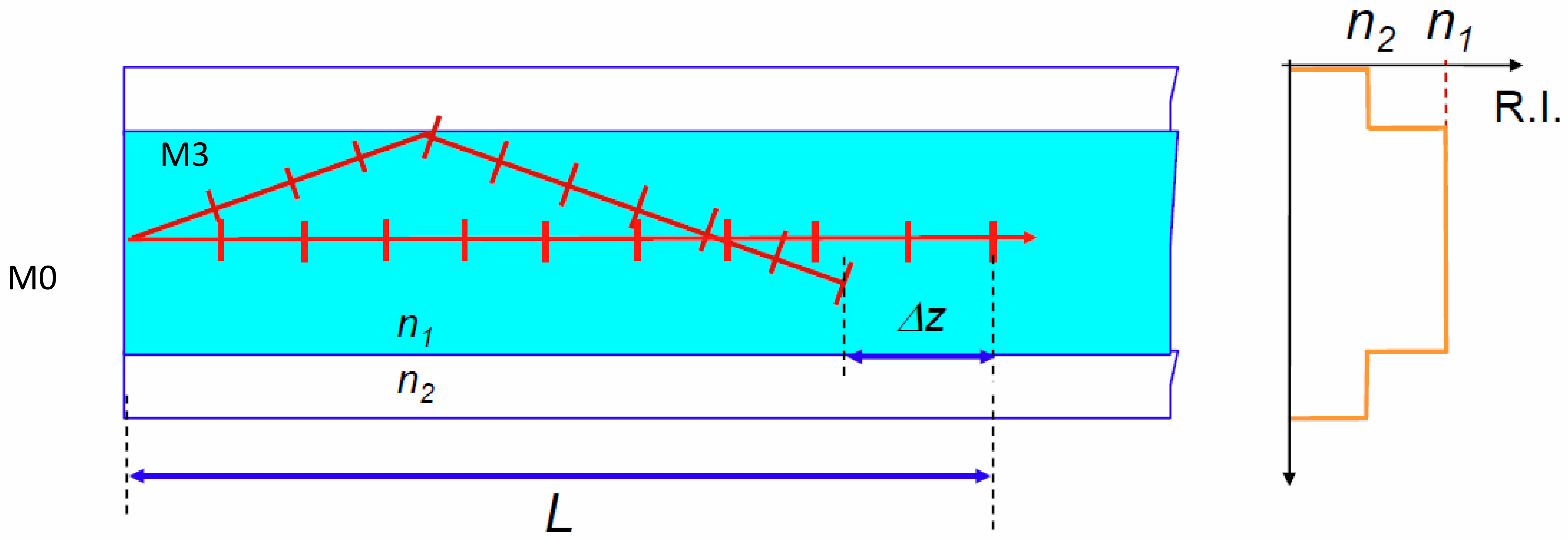


Intermodal Dispersion

- 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.



Each mode experiences different group velocity

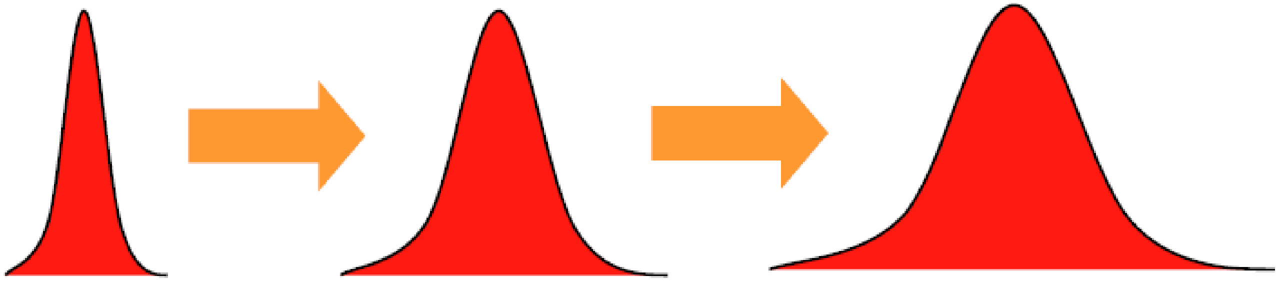


Minimum transit time $t_{min} = (L/c)\cdot n_1$

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

The delay difference or pulse spread in time:

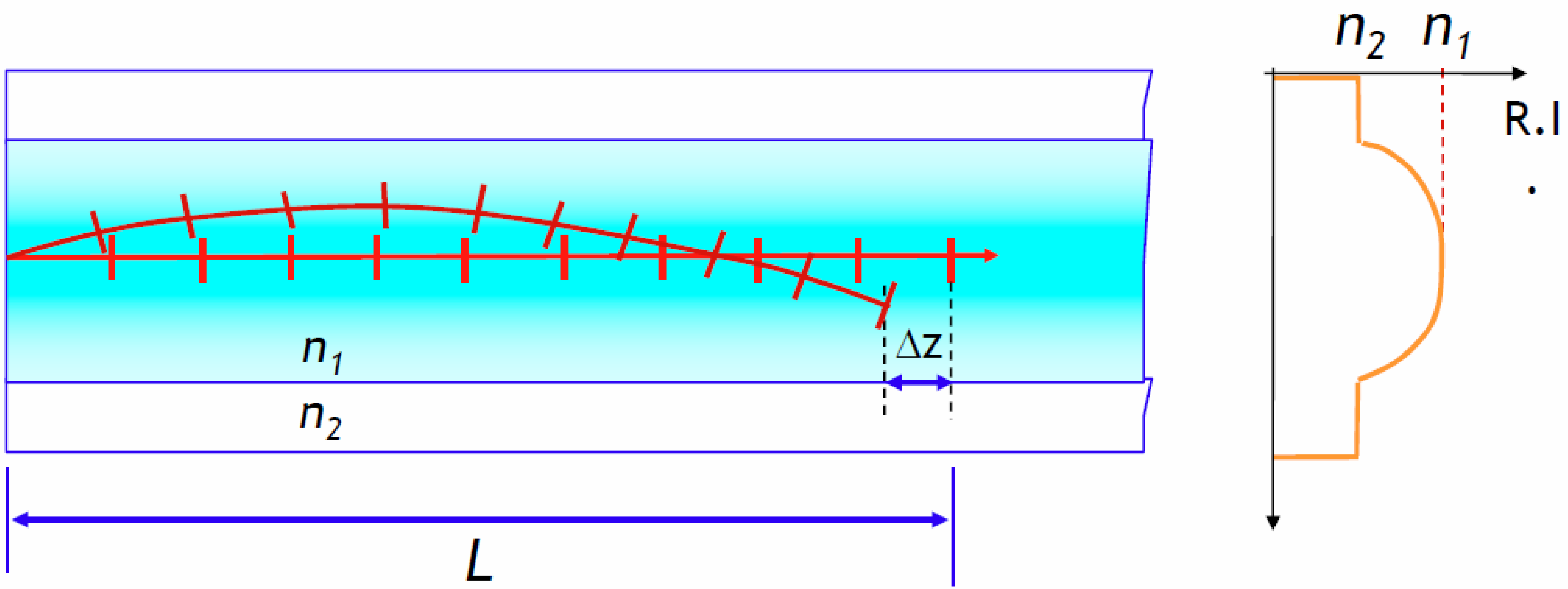
$$\delta t_{mod} = t_{max} - t_{min} = (L/c)n_1(n_1/n_2 - 1) \cong (L/c)(NA^2/2n_1)$$



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

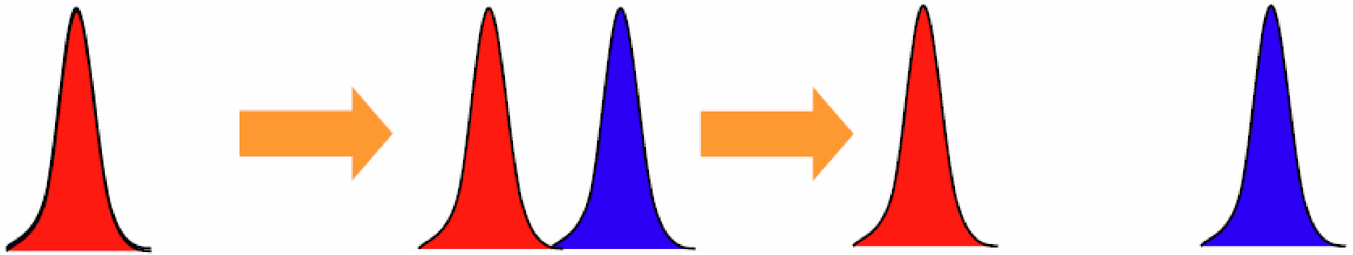


Minimized using a nearly parabolic index profile

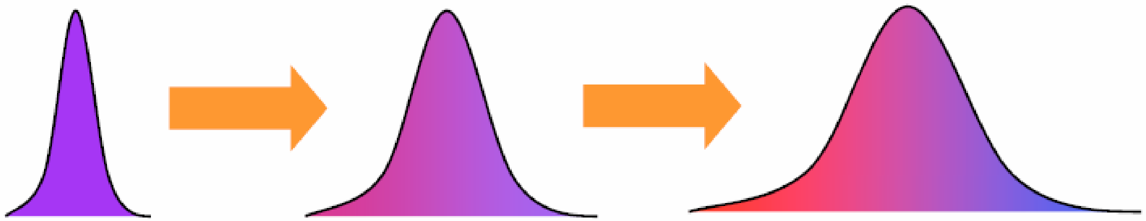
Intramodal dispersion (GVD)

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)



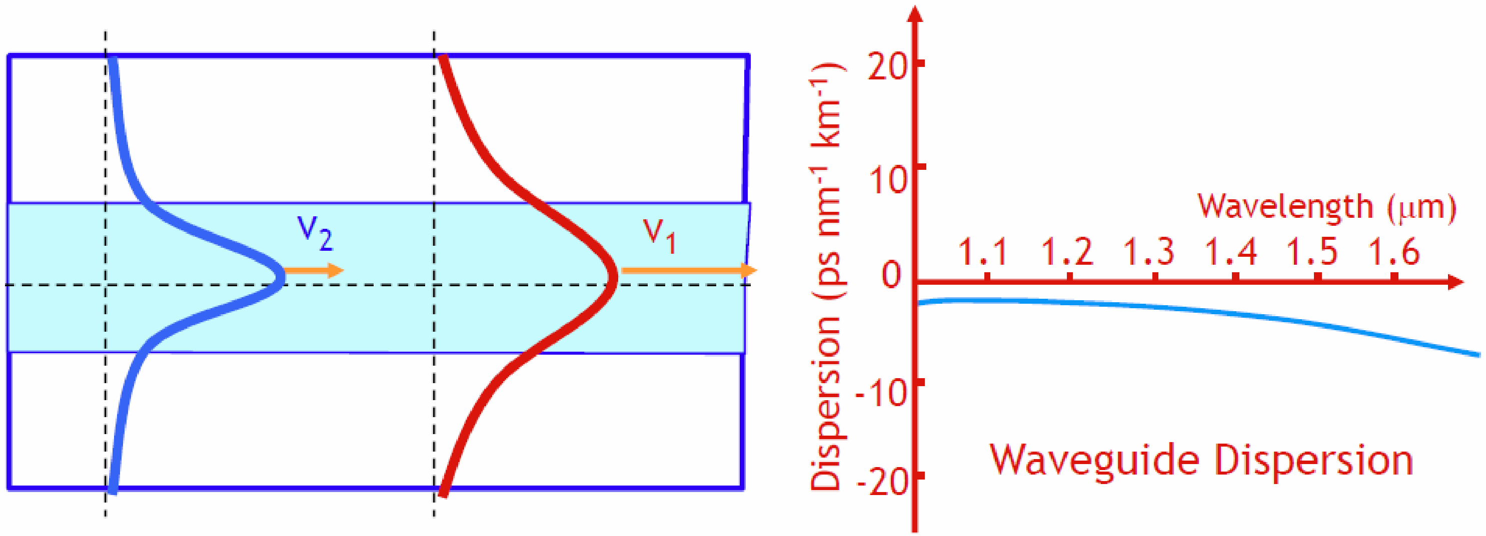
Intramodal dispersion – material dispersion

Refractive index varies with wavelength.

Material Dispersion

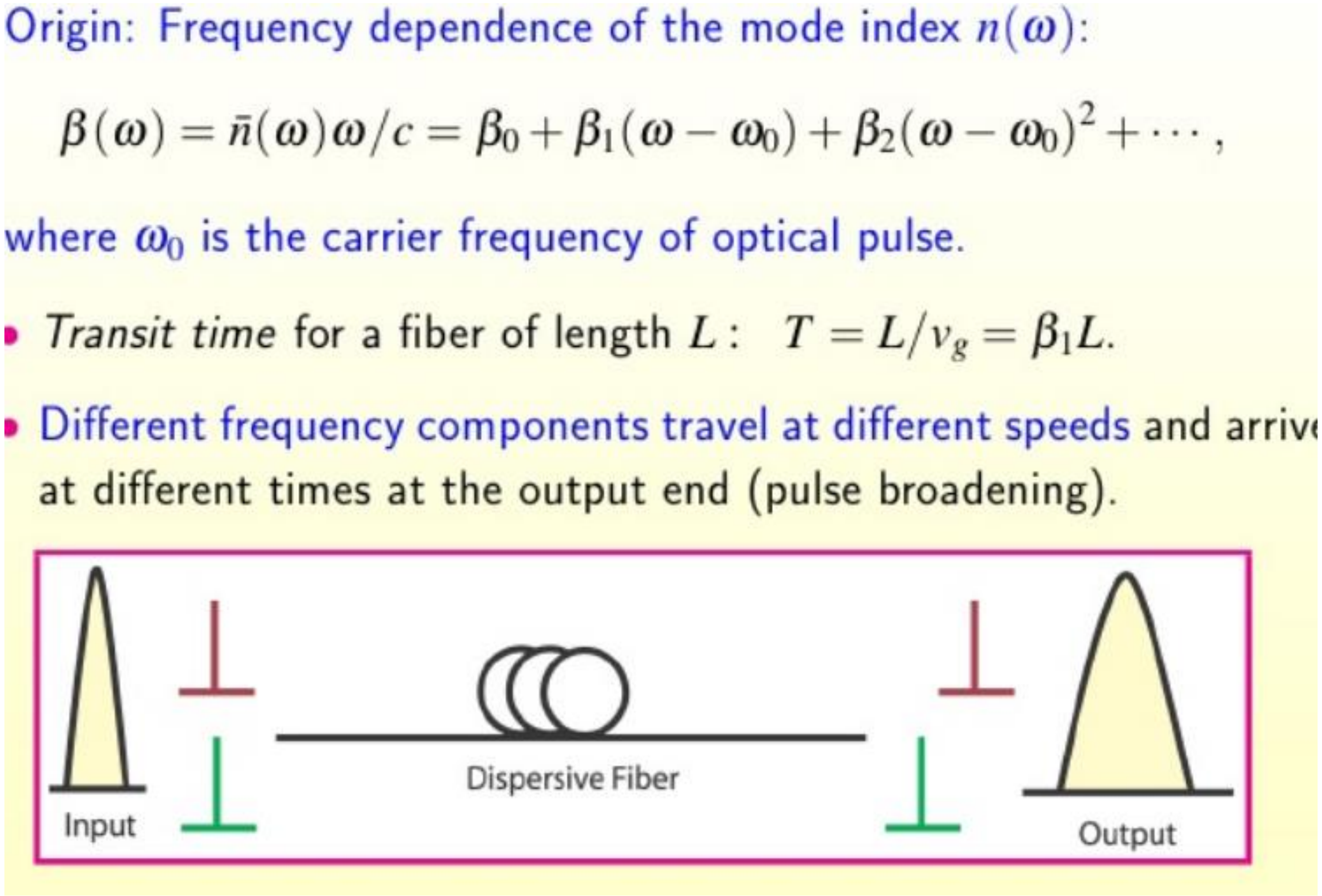
Intramodal dispersion – waveguide dispersion

- 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

Fiber dispersion -cap 2.3-



Origin: Frequency dependence of the mode index $n(\omega)$:

$$\beta(\omega) = \bar{n}(\omega)\omega/c = \beta_0 + \beta_1(\omega - \omega_0) + \beta_2(\omega - \omega_0)^2 + \cdots ,$$

where ω_0 is the carrier frequency of optical pulse.

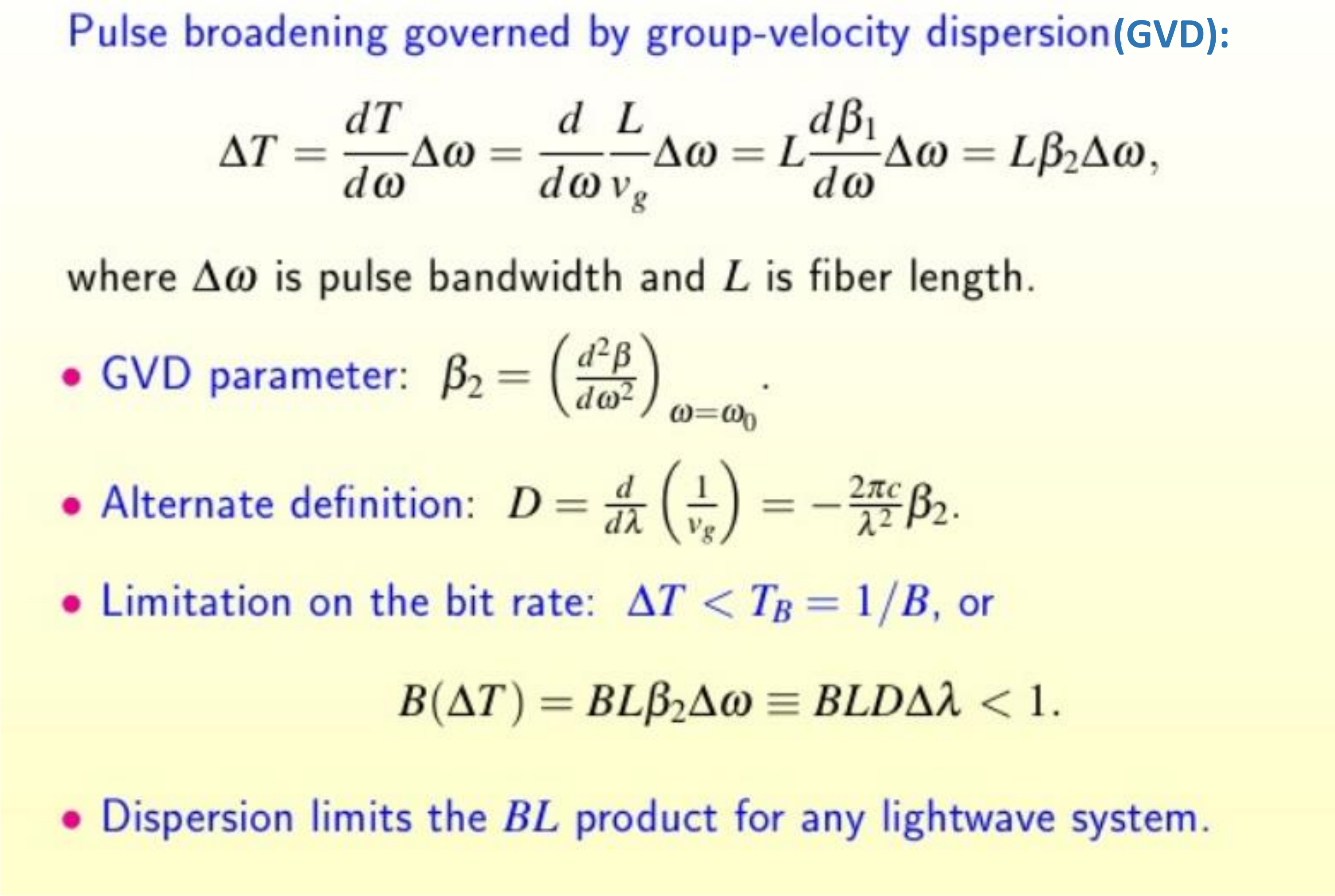
- *Transit time* for a fiber of length L: $T = L/v_g = \beta_1 L.$
- Different frequency components travel at different speeds and arriv at different times at the output end (pulse broadening).

Group velocity

$$v^{(p)} = \frac{\bar{\omega}}{\bar{k}}.$$

Wave number k

$$k = n(\omega)\frac{\omega}{c},$$



Pulse broadening governed by group-velocity dispersion**(GVD):**

$$\Delta T = \frac{dT}{d\omega}\Delta\omega = \frac{d}{d\omega}\frac{L}{v_g}\Delta\omega = L\frac{d\beta_1}{d\omega}\Delta\omega = L\beta_2\Delta\omega,$$

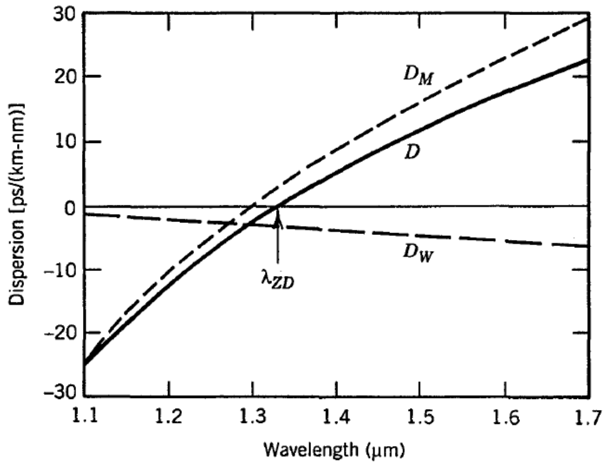
where $\Delta\omega$ is pulse bandwidth and L is fiber length.

- GVD parameter: $\beta_2 = \left(\frac{d^2\beta}{d\omega^2}\right)_{\omega=\omega_0}$.
- Alternate definition: $D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2$.
- Limitation on the bit rate: $\Delta T < T_B = 1/B$, or

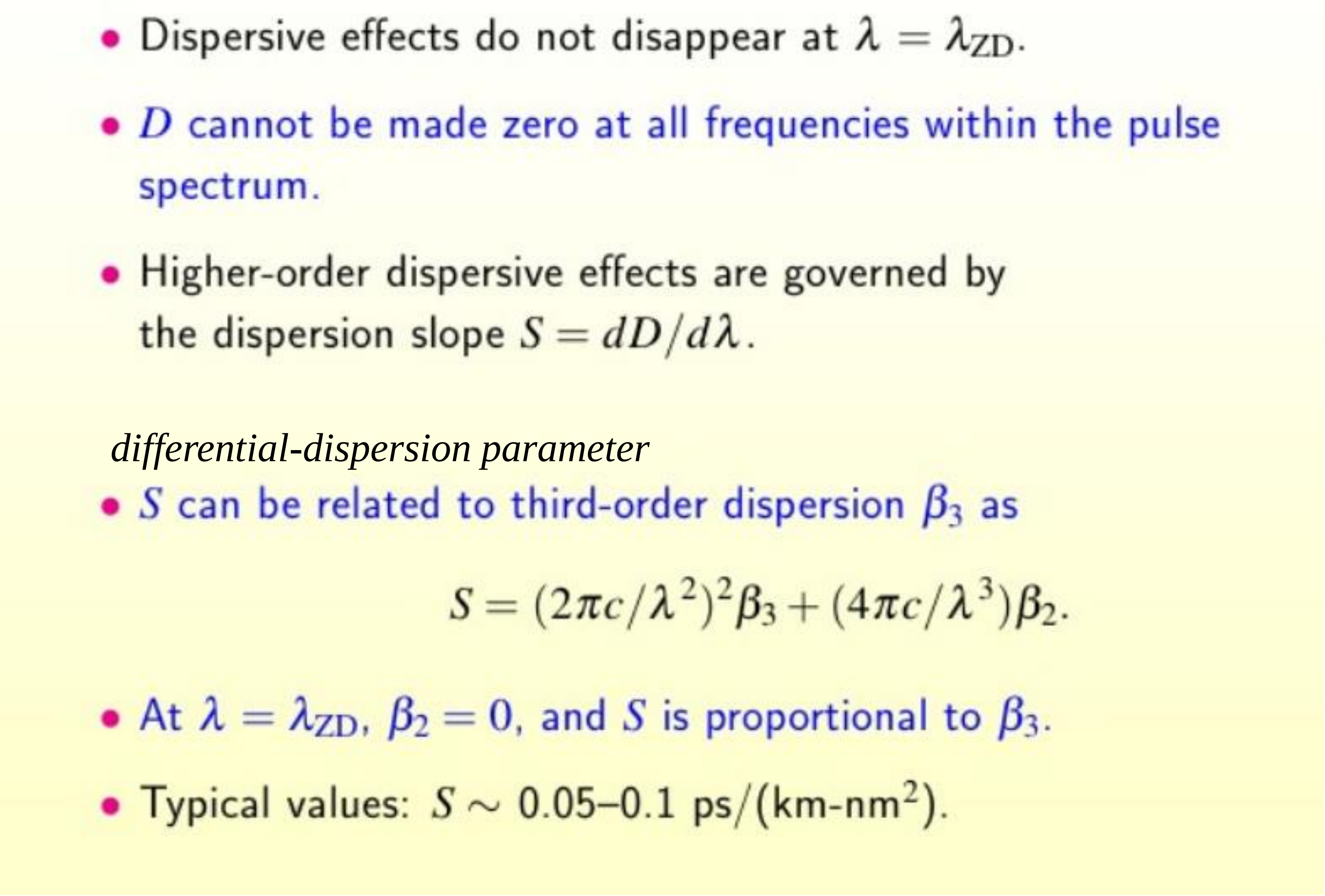
$$B(\Delta T) = BL\beta_2\Delta\omega \equiv BLD\Delta\lambda < 1.$$

- Dispersion limits the BL product for any lightwave system.

Fiber dispersion
-material – 2.3.2.
-waveguide-2.3.3.



High order Fiber dispersion
- cap 2.3.4-



- Dispersive effects do not disappear at $\lambda = \lambda_{\mathrm{ZD}}$.
- D cannot be made zero at all frequencies within the pulse spectrum.
- Higher-order dispersive effects are governed by the dispersion slope $S = dD/d\lambda$.

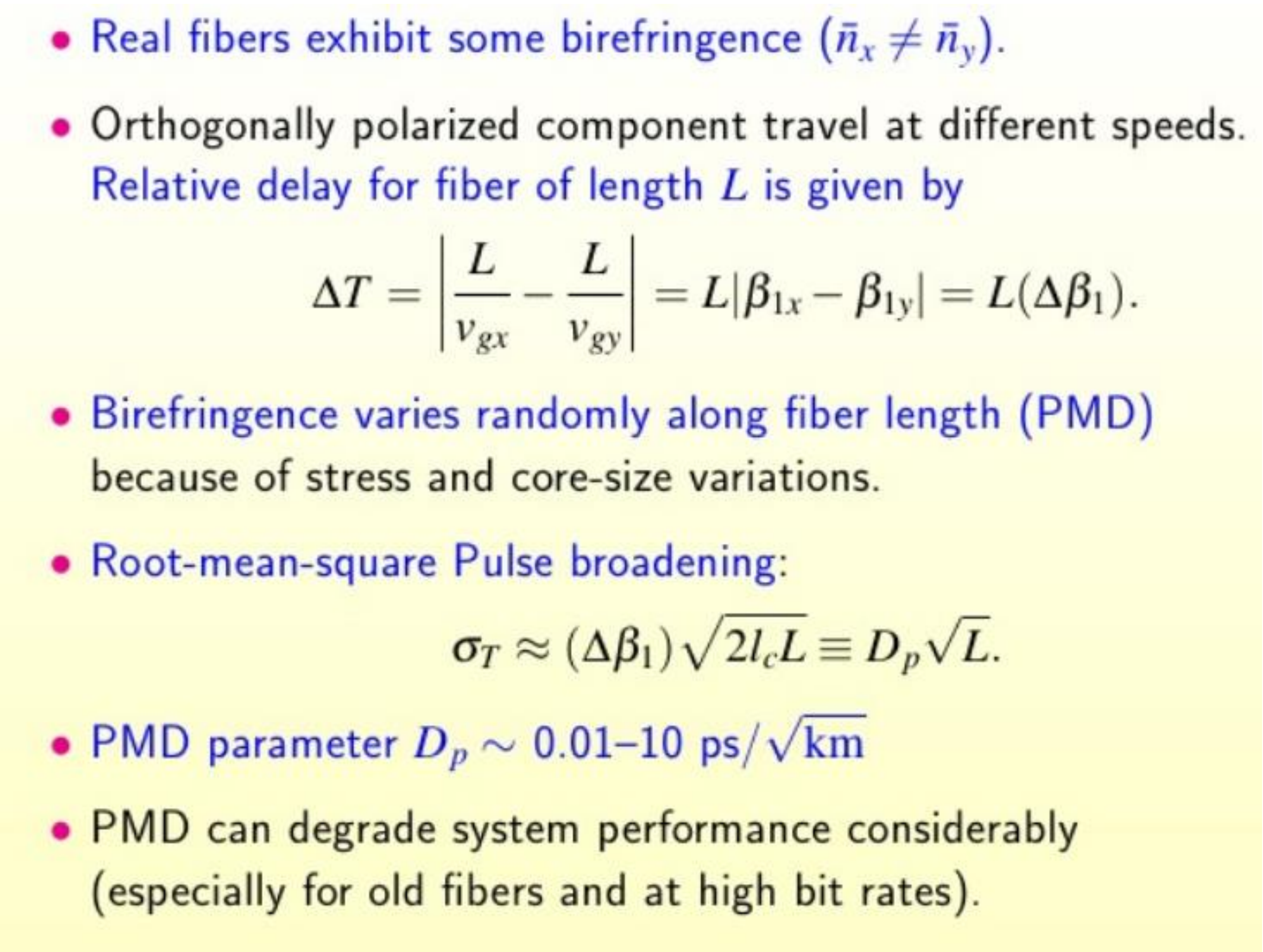
differential-dispersion parameter

- S can be related to third-order dispersion β_3 as

$$S = (2\pi c/\lambda^2)^2\beta_3 + (4\pi c/\lambda^3)\beta_2.$$

- At $\lambda = \lambda_{\mathrm{ZD}}$, $\beta_2 = 0$, and S is proportional to β_3.
- Typical values: $S \sim 0.05$–0.1 ps/(km-nm^2).

Polarization mode dispersion
- cap 2.3.5-



- Real fibers exhibit some birefringence ($\bar{n}_x \neq \bar{n}_y$).
- Orthogonally polarized component travel at different speeds. Relative delay for fiber of length L is given by

$$\Delta T = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right| = L|\beta_{1x} - \beta_{1y}| = L(\Delta\beta_1).$$

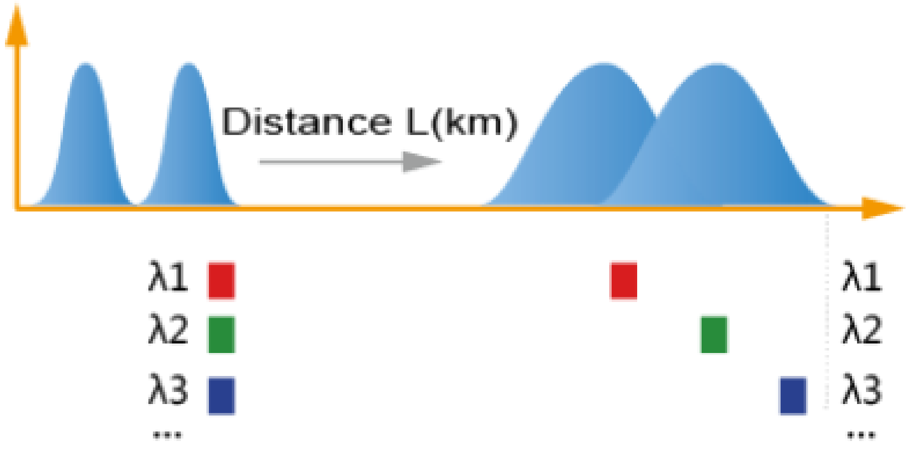
- Birefringence varies randomly along fiber length (PMD) because of stress and core-size variations.
- Root-mean-square Pulse broadening:

$$\sigma_T \approx (\Delta\beta_1)\sqrt{2l_c L} \equiv D_p\sqrt{L}.$$

- PMD parameter $D_p \sim 0.01\text{–}10 \text{ ps}/\sqrt{\text{km}}$
- PMD can degrade system performance considerably (especially for old fibers and at high bit rates).

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.



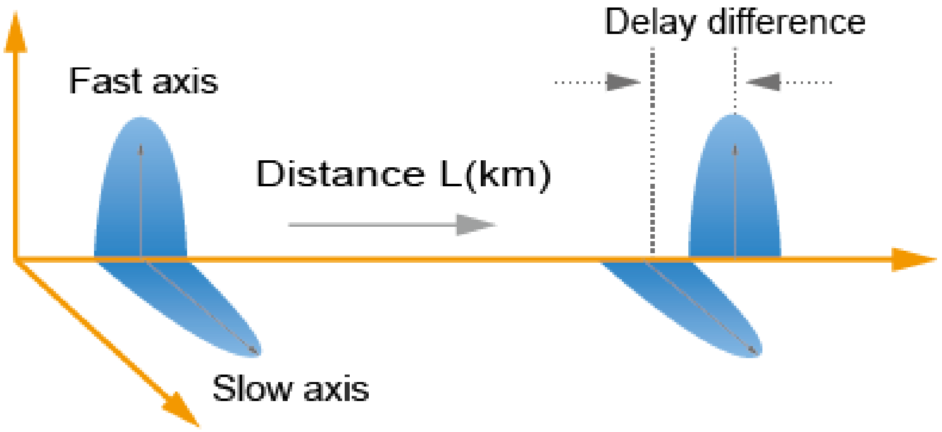
Total dispersion

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

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

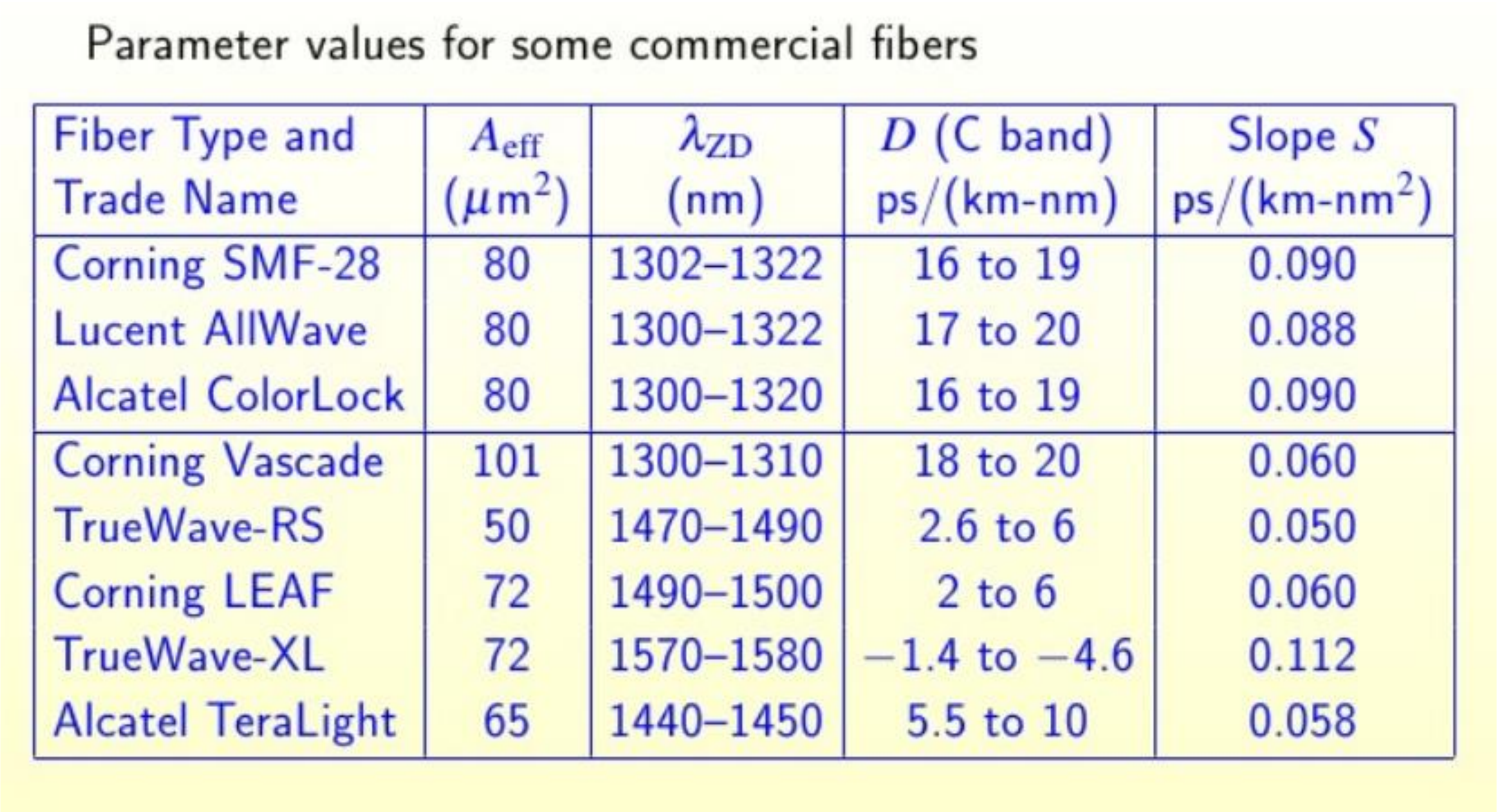
- Pulse width will increase by s_T after 1 km

Polarization Mode Dispersion (PMD)



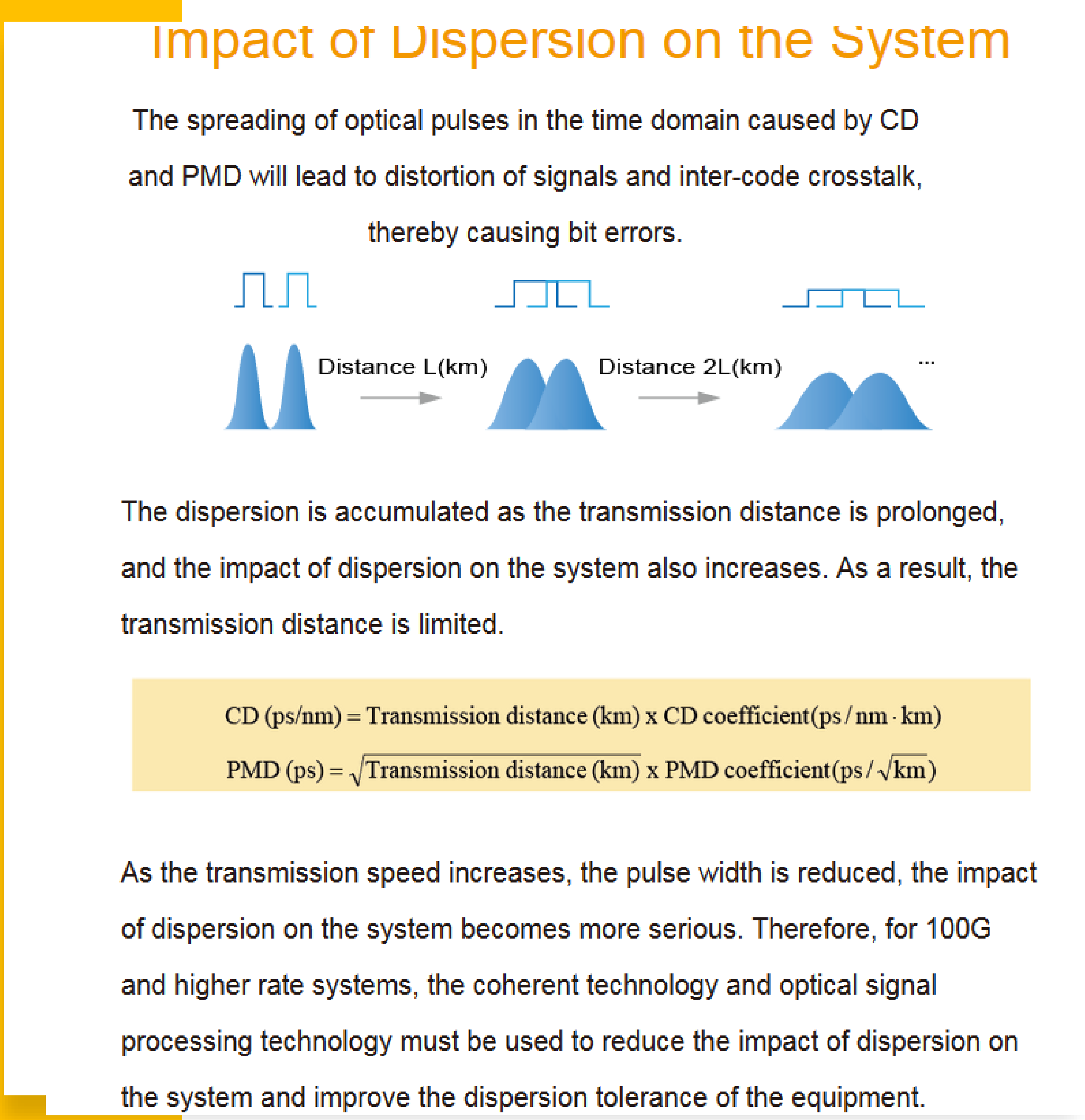
A form of dispersion where optical pulsesare spread because optical signals in different phase status are transmitted at different speeds due to the random birefringence of optical fibers.

Commercial fibers example



Parameter values for some commercial fibers

Fiber Type and Trade Name	A_{eff} (μm^2)	λ_{ZD} (nm)	D (C band) ps/(km-nm)	Slope S ps/(km-nm^2)
Corning SMF-28	80	1302–1322	16 to 19	0.090
Lucent AllWave	80	1300–1322	17 to 20	0.088
Alcatel ColorLock	80	1300–1320	16 to 19	0.090
Corning Vascade	101	1300–1310	18 to 20	0.060
TrueWave-RS	50	1470–1490	2.6 to 6	0.050
Corning LEAF	72	1490–1500	2 to 6	0.060
TrueWave-XL	72	1570–1580	-1.4 to -4.6	0.112
Alcatel TeraLight	65	1440–1450	5.5 to 10	0.058



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.

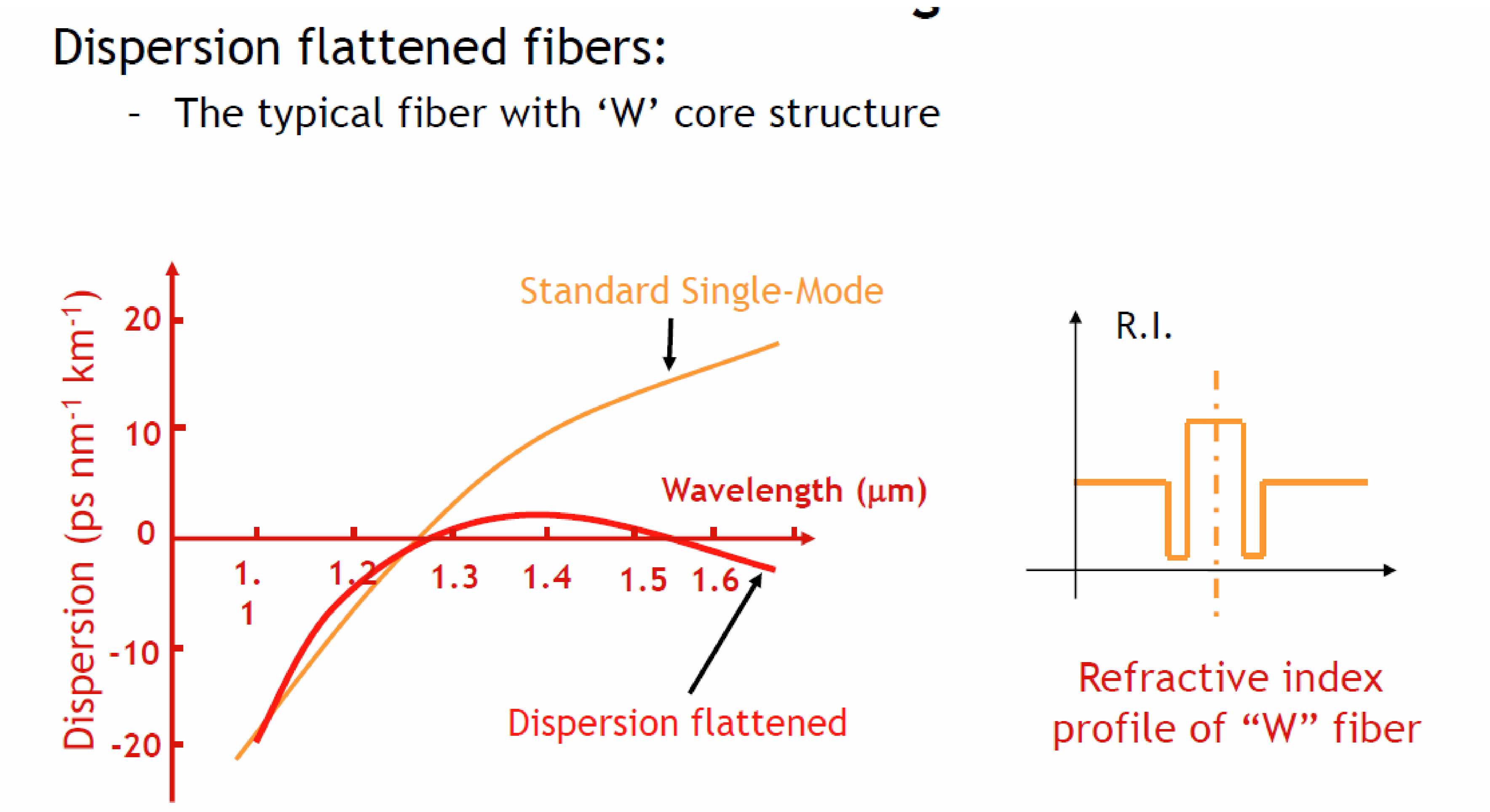
$$\text{CD (ps/nm)} = \text{Transmission distance (km) x CD coefficient} (\text{ps}/\text{nm}\cdot\text{km})$$

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

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)

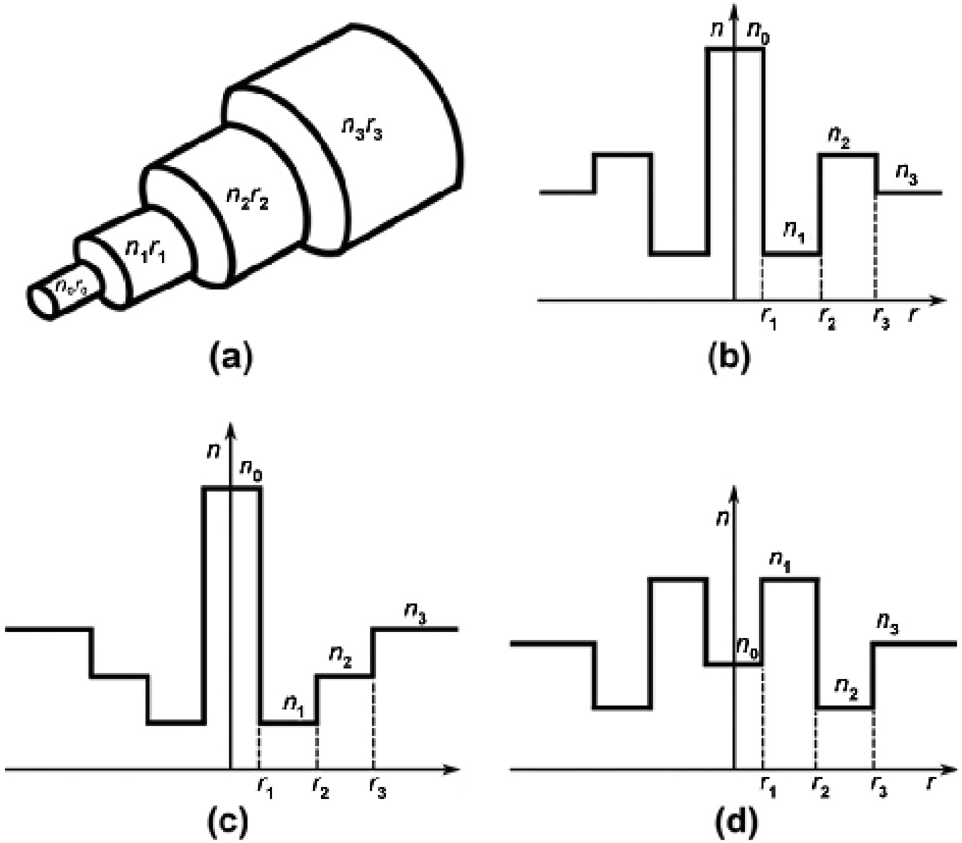


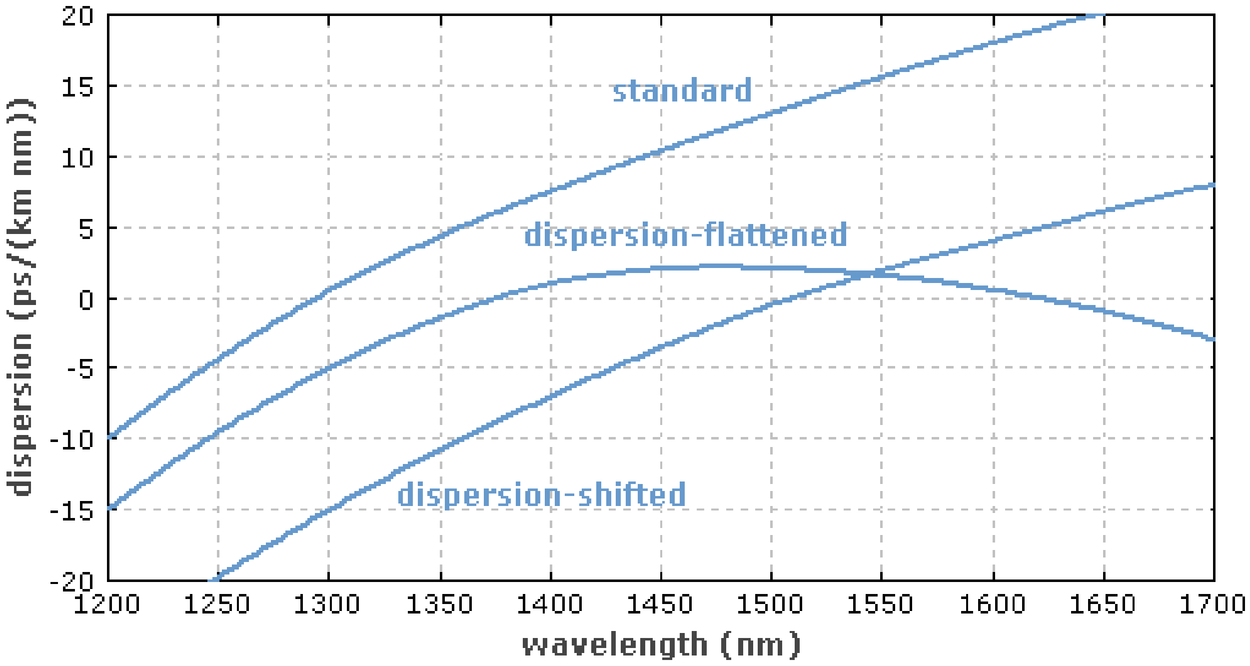
Dispersion flattened fibers:

- The typical fiber with ‘W’ core structure

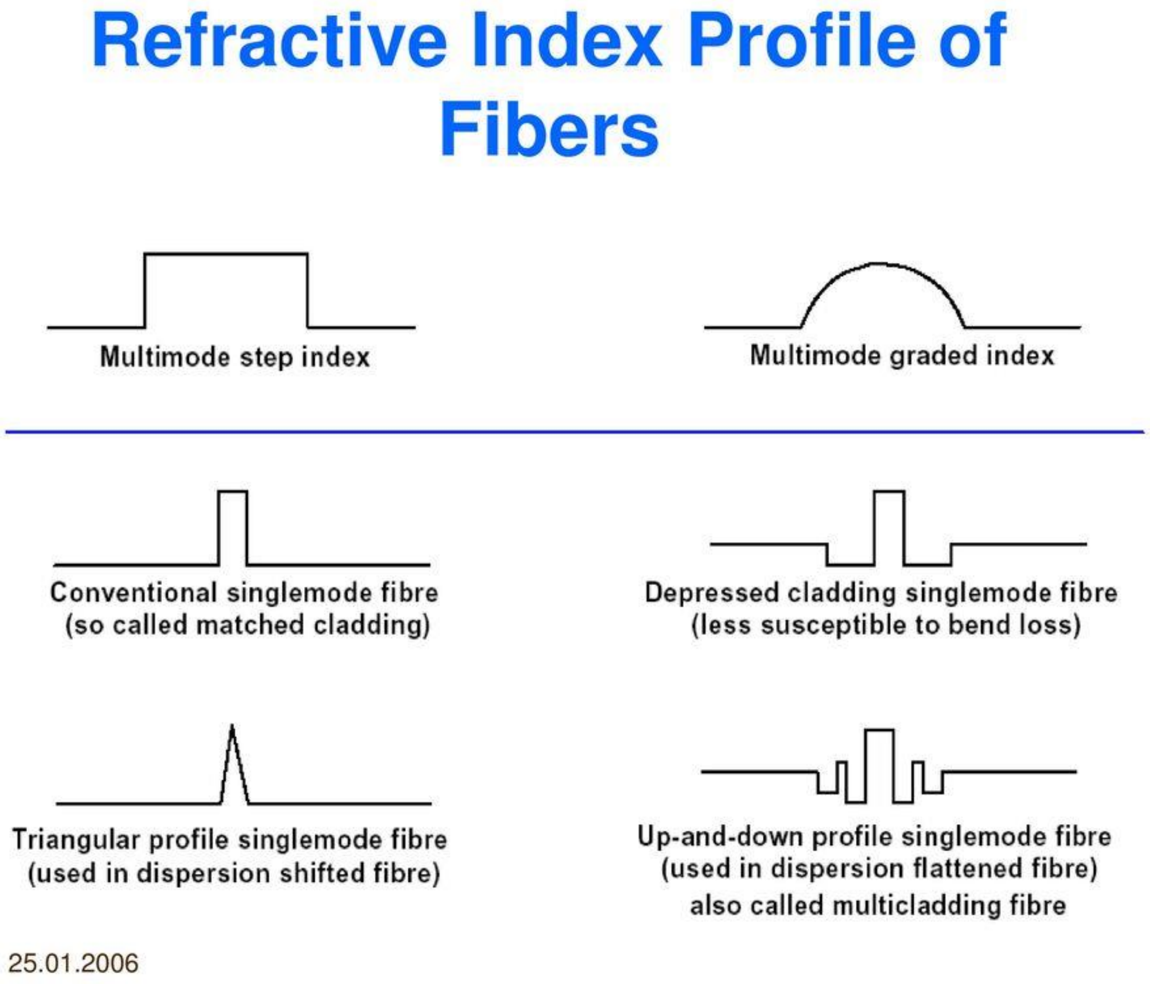
Refractive index profile of “W” fiber

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

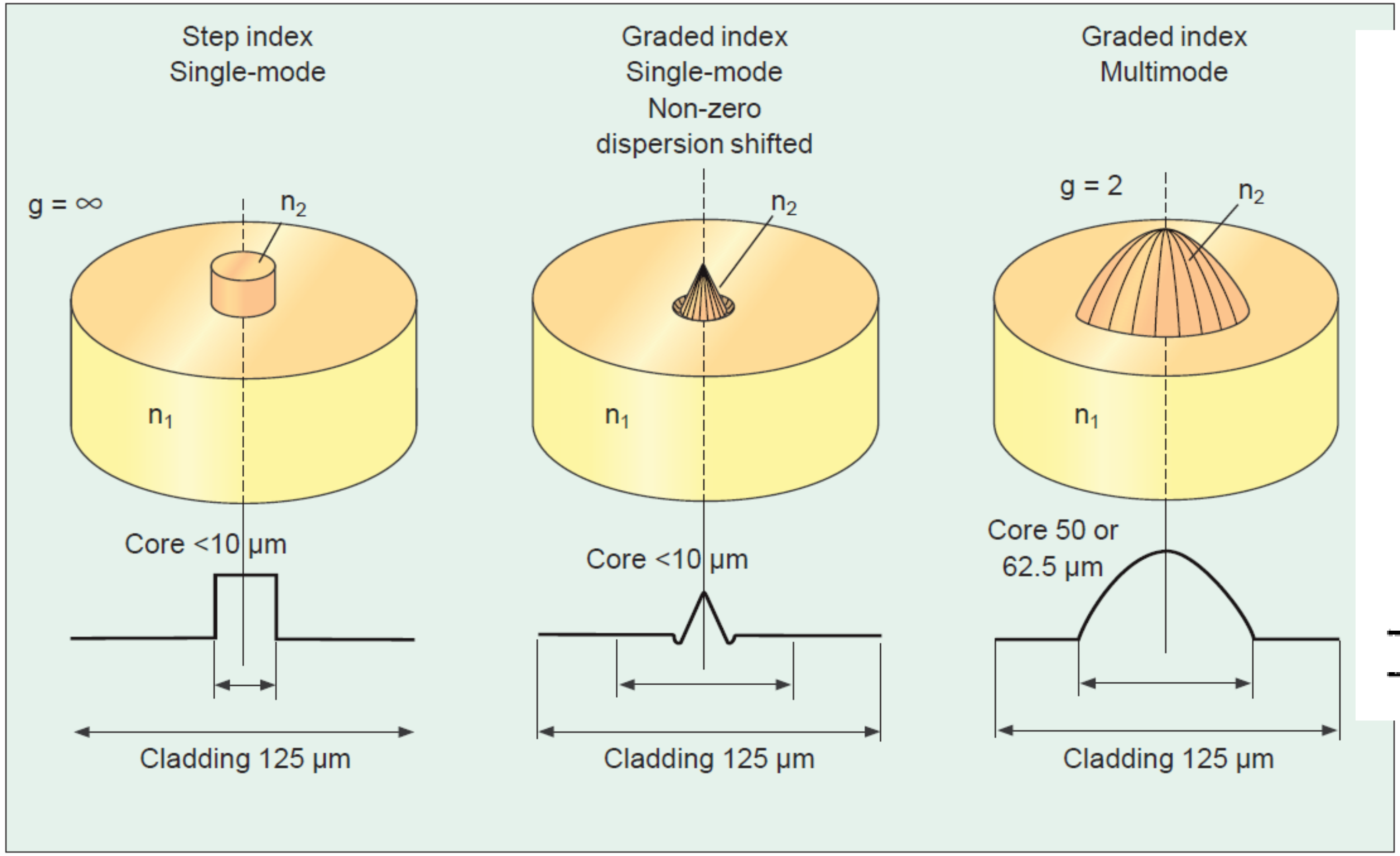
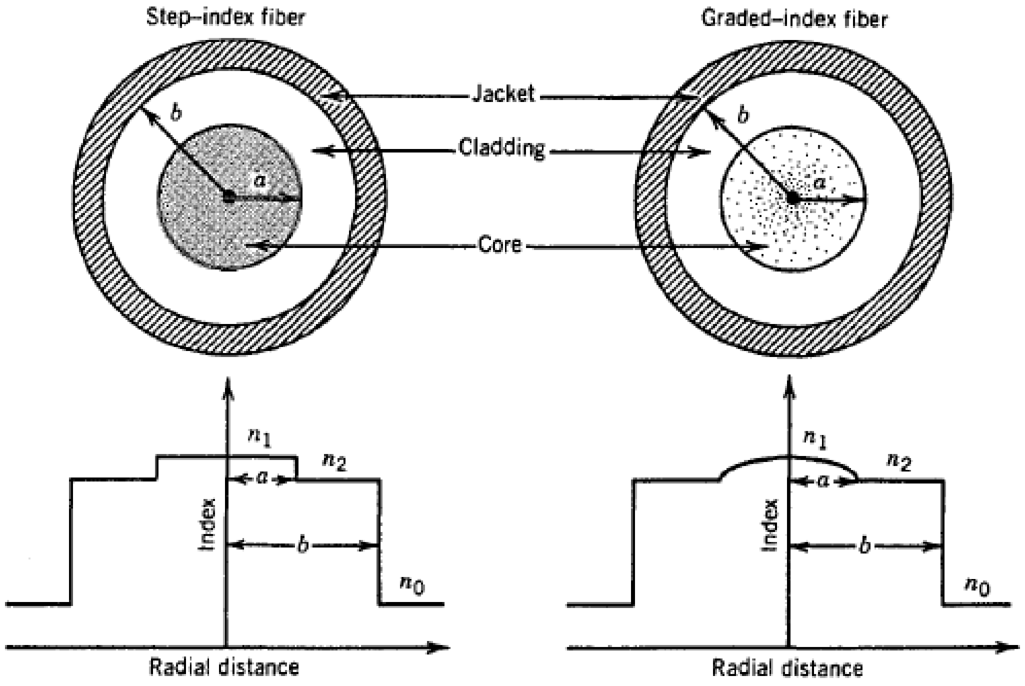
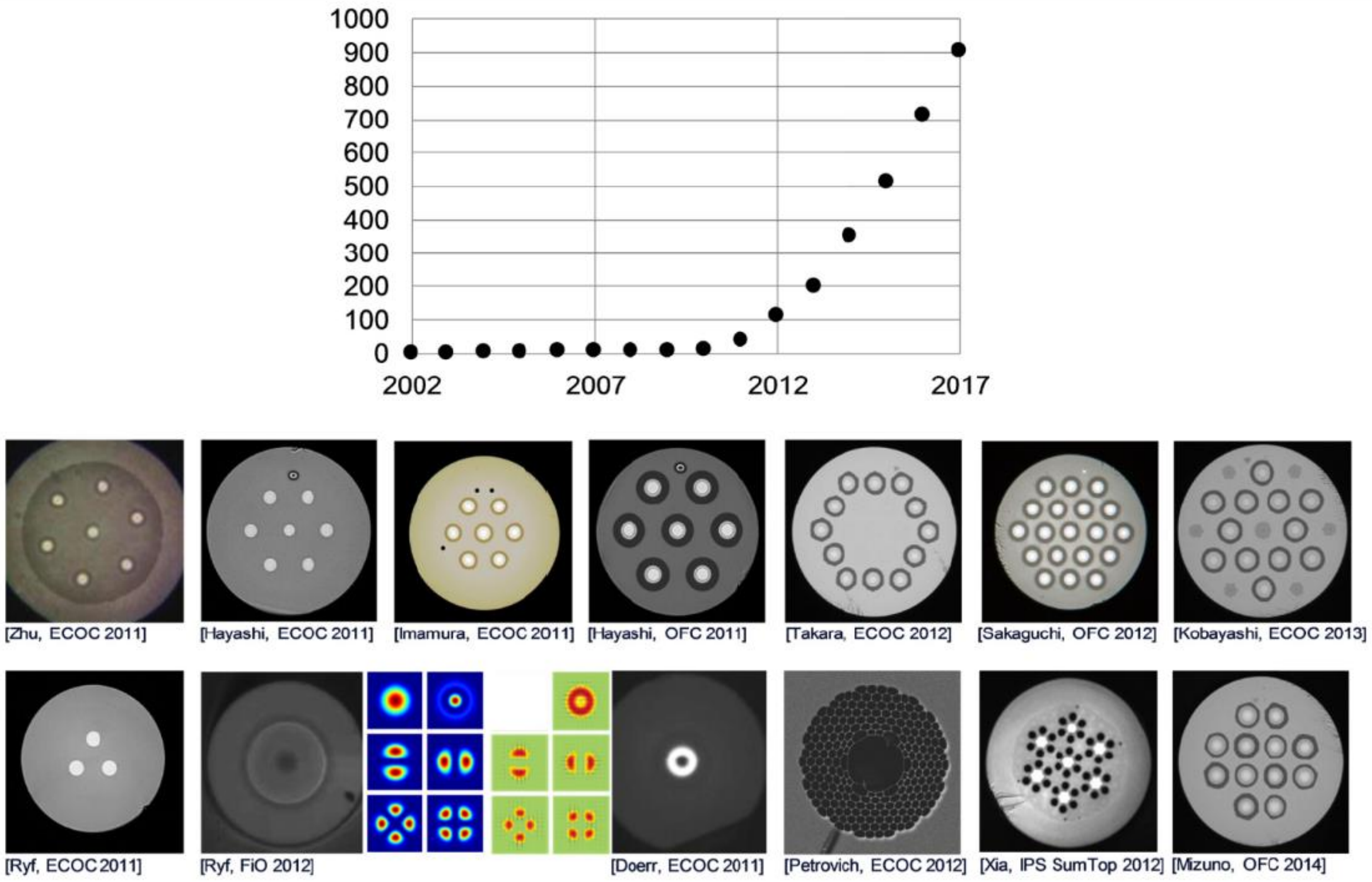


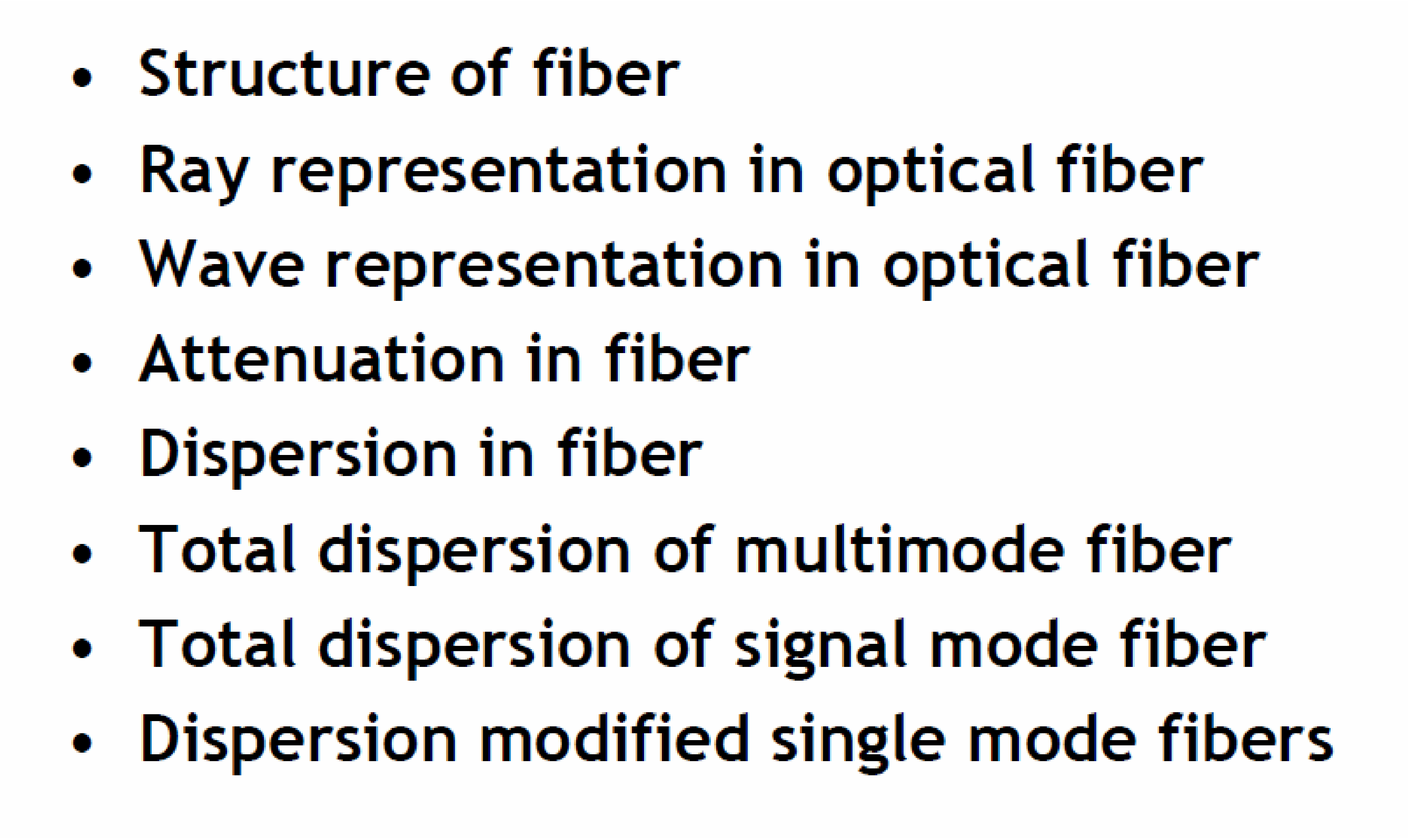
Fig. 4-1 Graphic representation of three different types of how the refractive index change in the core of an optical fiber



Special optical fibers (PCF)



Summary Optical Comm Syst



- 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

Dispersion

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

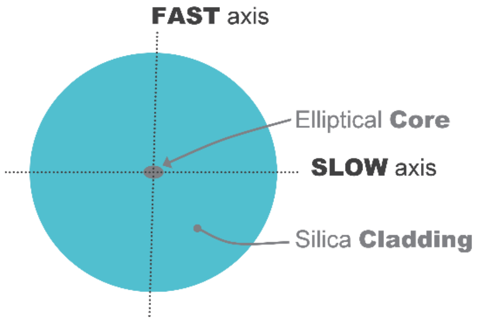
Dispersion

- **Definition:** any effect that causes different components of a transmitted signal to travel at **different velocities** in an optical fiber
- Intersymbol interference- may limit the distance a pulse can travel

Types:

- **Intermodal**: each mode travels at a different velocity
- **Chromatic**: each wavelength travels at a slightly different velocity in a fiber (dispersion compensation fibers). Ranges from 1.453 at 850 nm to 1.445 at 1550 nm. Example: Dcd = 2 ps/(km x nm) at 1550 nm
- **Polarization mode dispersion** (PMD) - arises in single-mode fibers because the two fundamental orthogonal polarization modes in a fiber travel at slightly different speeds owing to fiber birefringence - 10 Gbps and higher

Form birefringence in an elliptical core



Representation of the propagation pulse

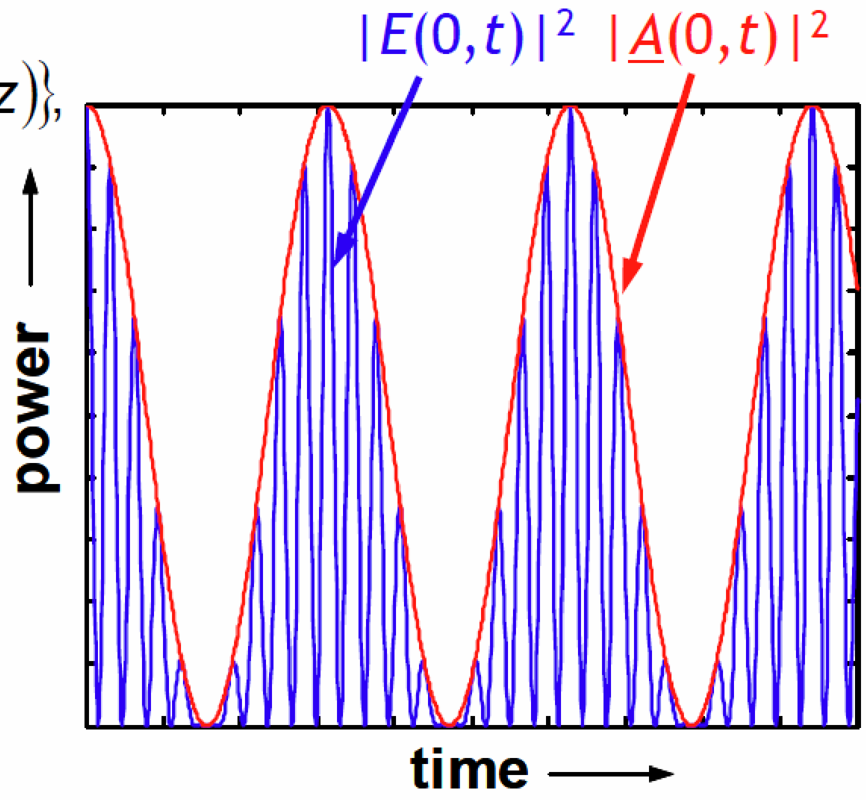
Electrical field:

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

with propagation constant

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

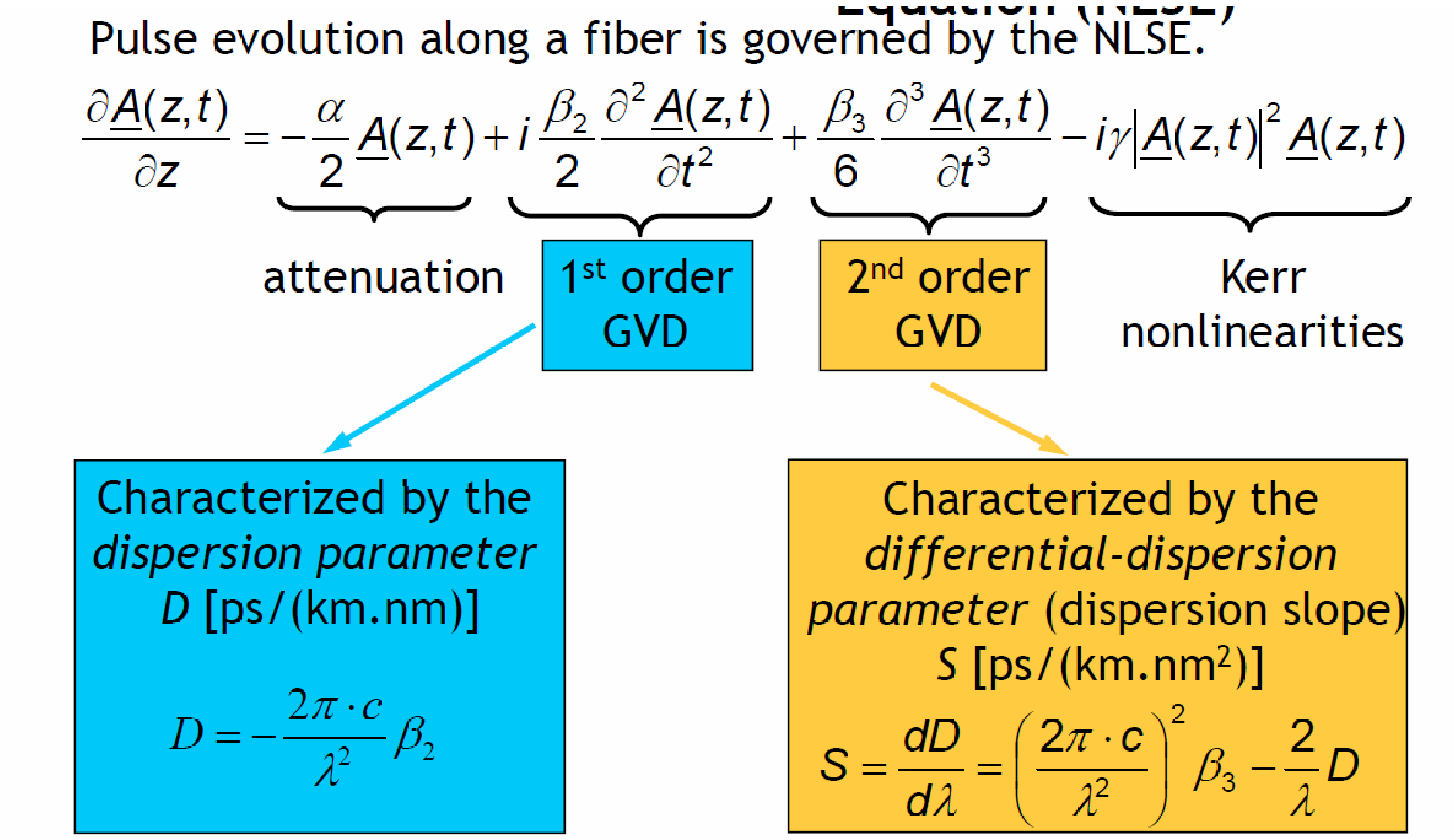
where n is the effective refractive index.



⇨ $\underline{A}(z,t)$: 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.

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

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.nm^2)]

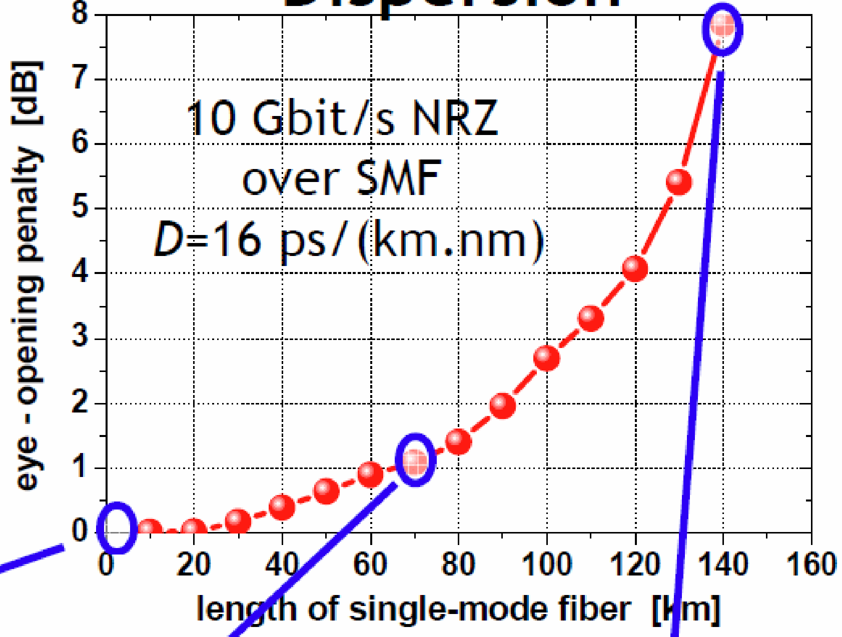
$$S = \frac{dD}{d\lambda} = \left(\frac{2\pi \cdot c}{\lambda^2}\right)^2 \beta_3 - \frac{2}{\lambda}D$$

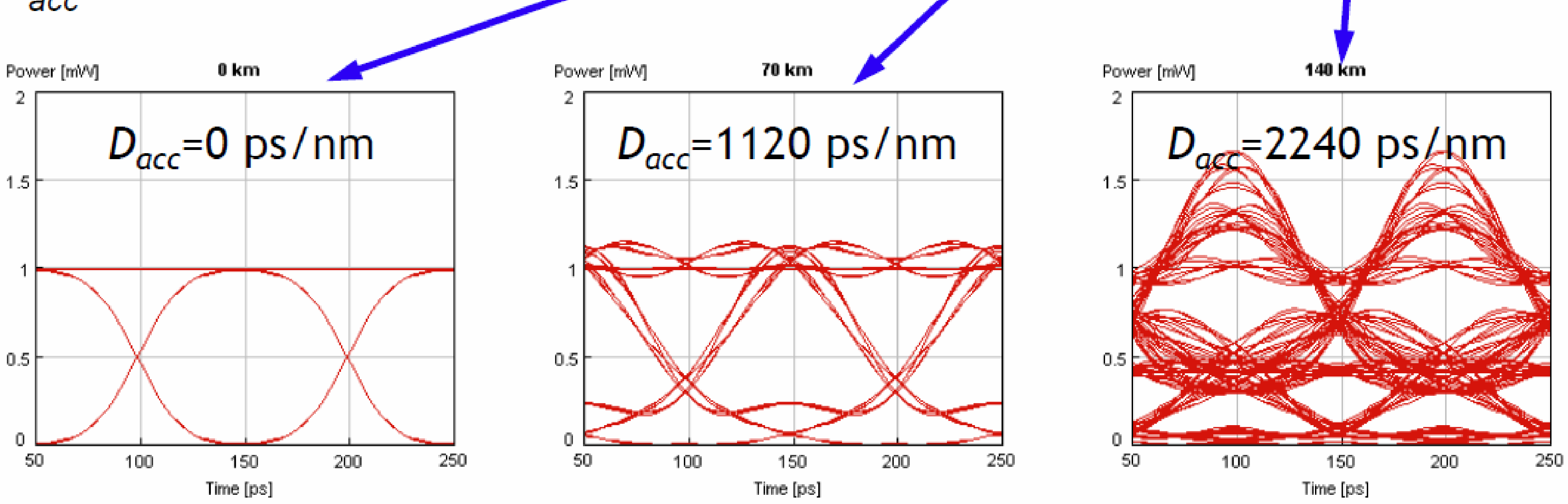
Dispersion

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

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

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





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:

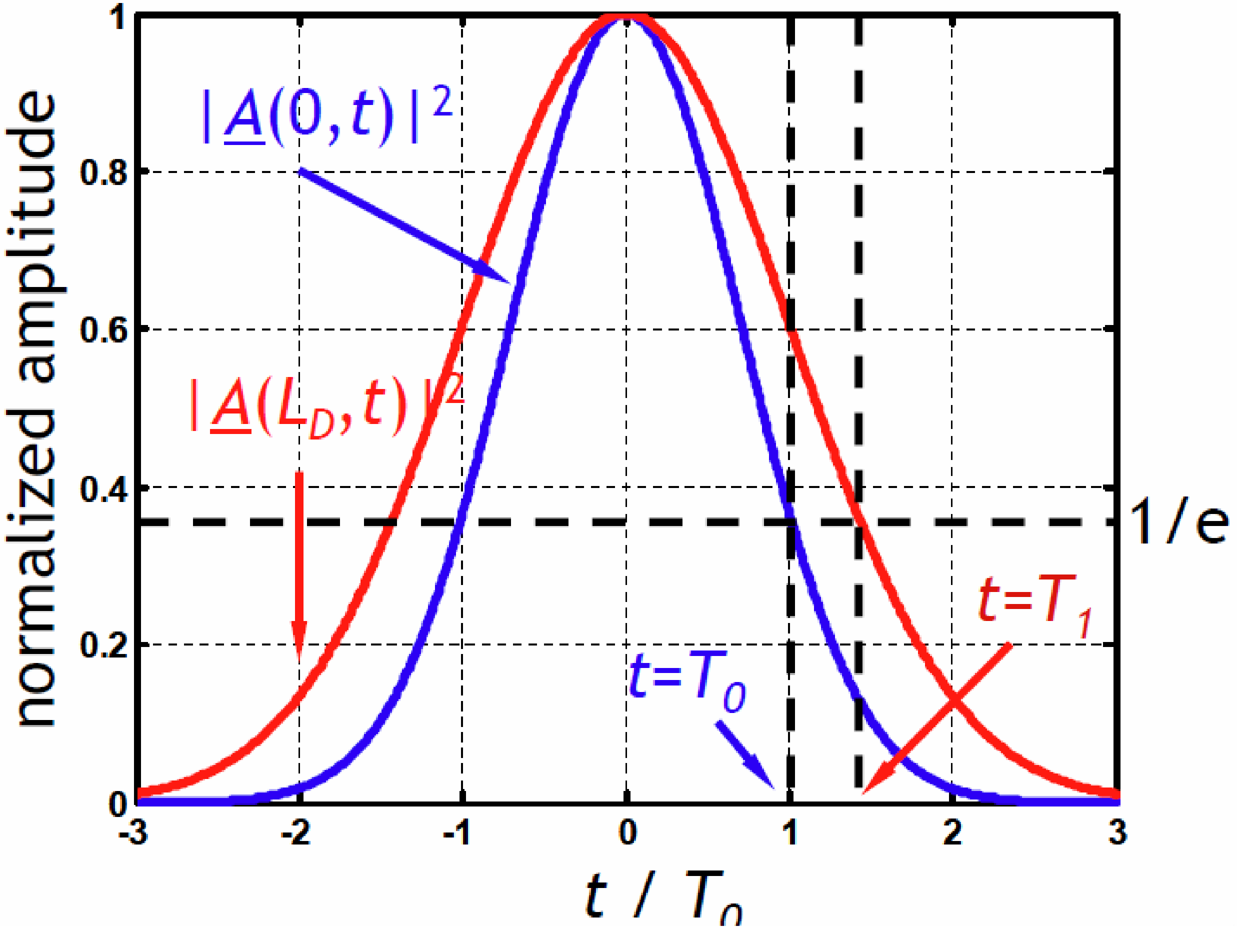
$\beta = \frac{2\pi \cdot n}{\lambda}$,

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

Pulse-shape at $z=L_D$?

Broadening factor at $z=L_D$:

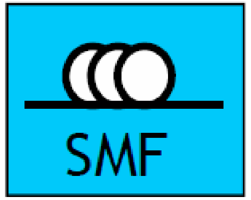
$$\frac{T_1}{T_0} = \sqrt{2}$$

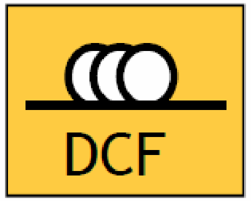


Dispersion length = Power is constant over a certain length

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

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



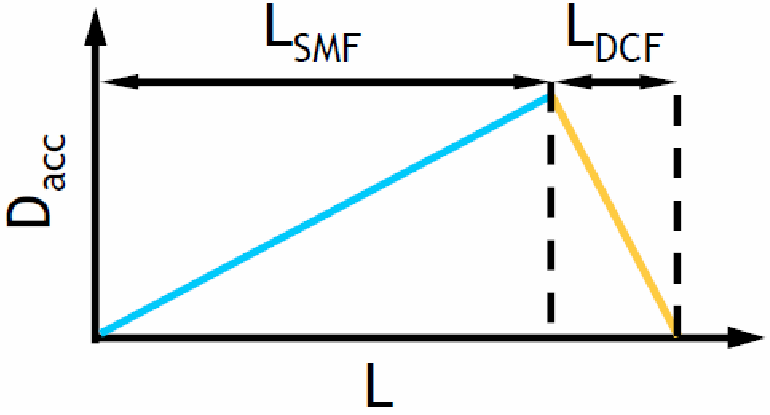


Positive dispersion parameter:

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

Negative dispersion parameter:

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



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

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

The information-carrying capacity

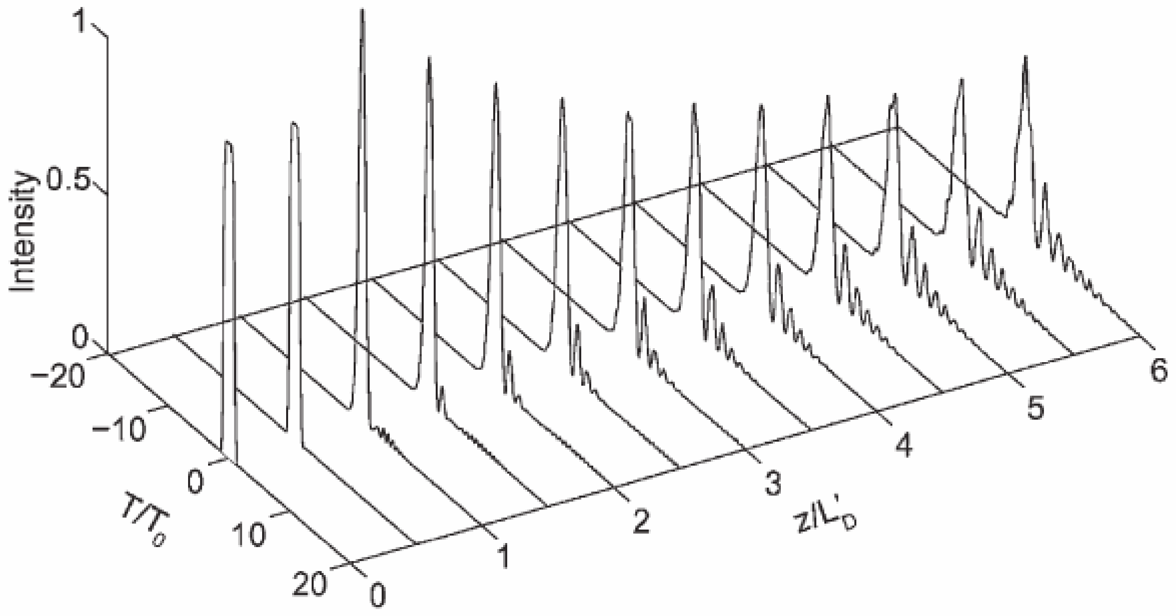
- Limitations by various internal distortion mechanisms, such as
  - signal dispersion factors - which cause optical signal pulses to broaden as they travel along a fiber
    - Inter-Multimodal
    - chromatic
    - polarization mode dispersions,
  - nonlinear effects (WDM systems)- high power densities (optical power per cross-sectional area) in a fiber
    - Their impact on signal fidelity includes
      - shifting of power between wavelength channels,
      - appearances of spurious signals at other wavelengths, and
      - decreases in signal strength

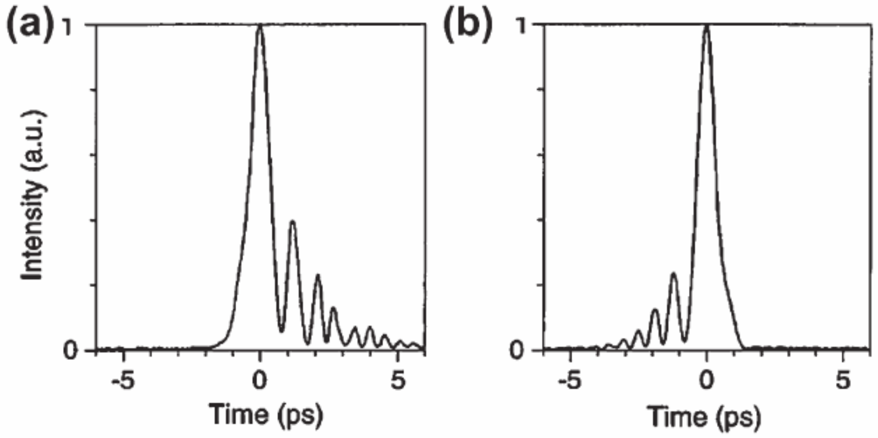
Important challenges

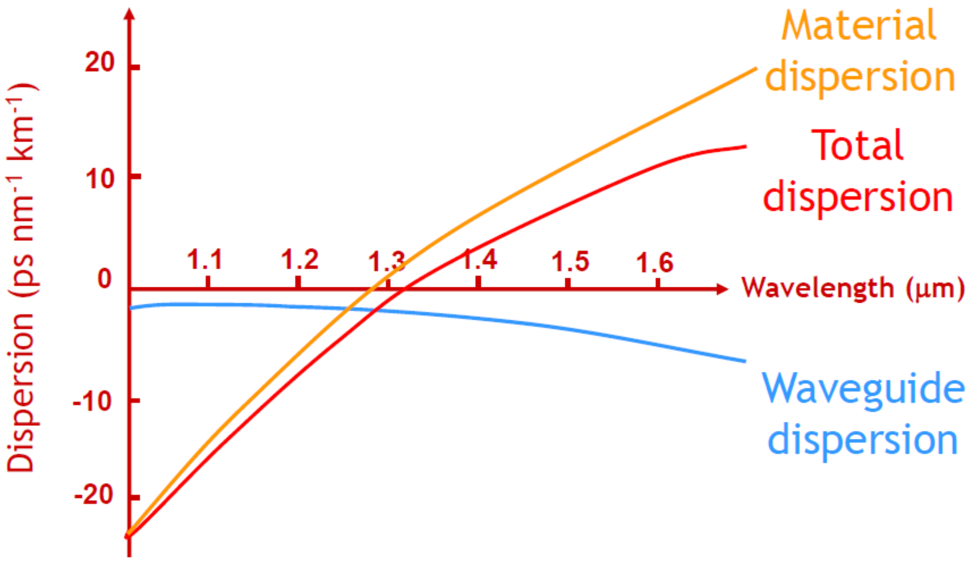
designing such multiple-channel optical networks include:

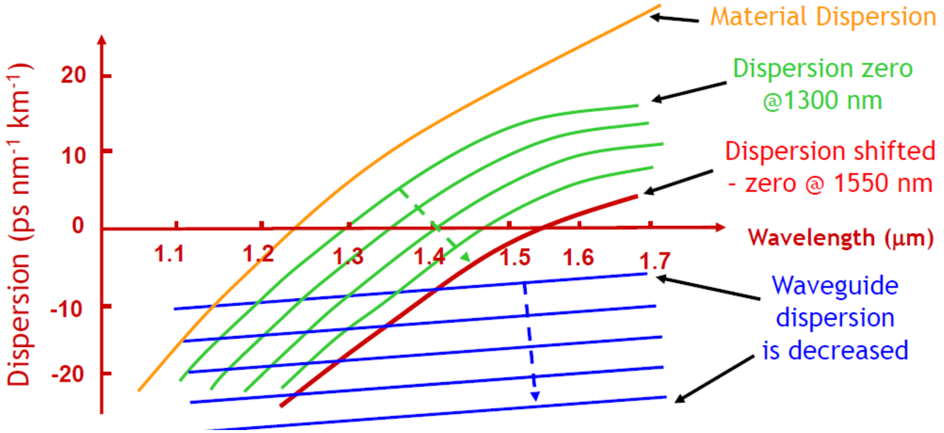
- Transmission of the different wavelength channels at the highest possible bit rate
- Transmission over the longest possible distance with the smallest number of optical amplifiers
- Network architectures that allow simple and efficient network operation, control, and management

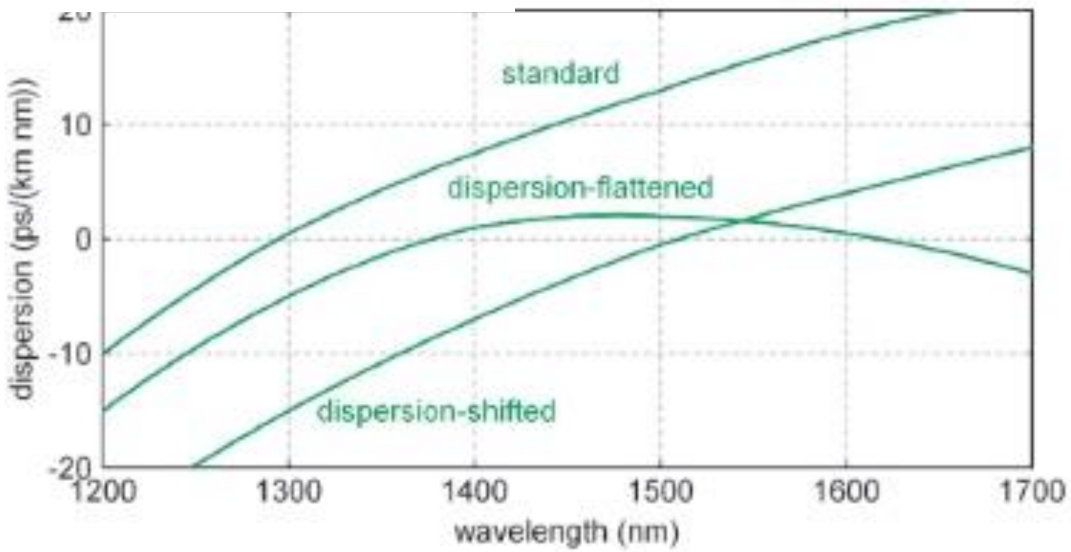
Chirped of the pulse





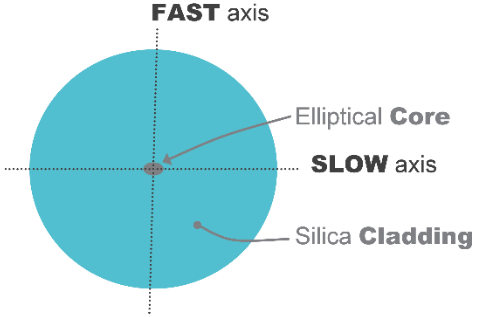

Material dispersion
Total dispersion
Waveguide dispersion
Dispersion (ps nm^{-1} km^{-1})
20
10
0
-10
-20
1.1
1.2
1.3
1.4
1.5
1.6
Wavelength (μm)


Material Dispersion
Dispersion zero @1300 nm
Dispersion shifted - zero @ 1550 nm
Waveguide dispersion is decreased
Dispersion (ps nm^{-1} km^{-1})
20
10
0
-10
-20
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)


standard
dispersion-flattened
dispersion-shifted
dispersion (ps/(km nm))
10
0
-10
-20
1200
1300
1400
1500
1600
1700
wavelength (nm)

PMD – polarization mode dispersion

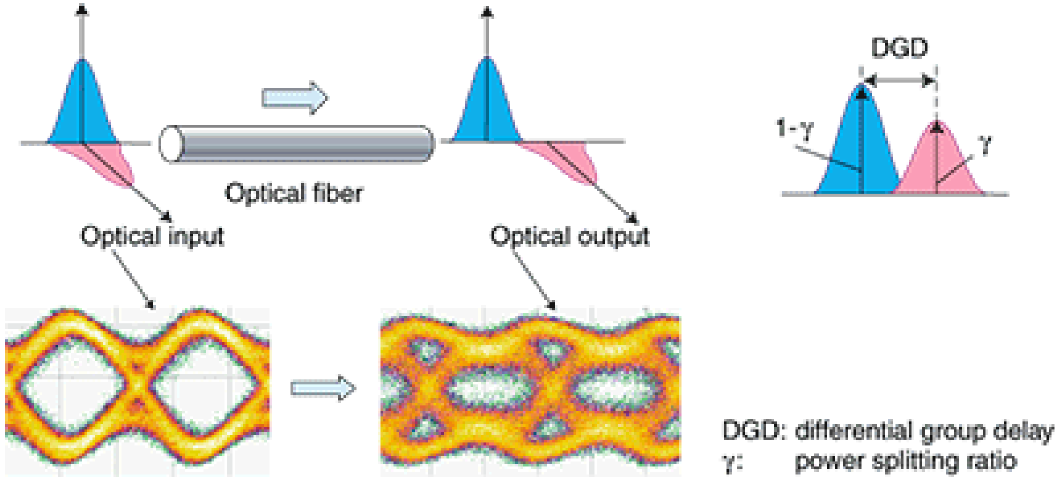
Form birefringence in an elliptical core



- *birefringence* of the material

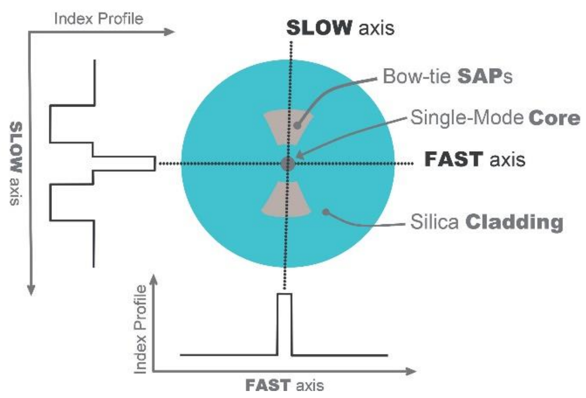
A typical PMD value for a fiber is D_{PMD} 0.05 ps/km,

- Pulse spreading Δt_{PMD} resulting from polarization mode dispersion is given by $\Delta t_{PMD} = D_{PMD} \times (\text{fiber length})^{1/2}$



DGD: differential group delay
γ: power splitting ratio

Typical ‘Bow-Tie’ HiBi Fiber Geometry



https://www.fibercore.com/expertise/fiberpaedia/form-birefringence
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr200809le1.html

Nonlinear effects

- Arise at high power levels because both the
  - attenuation and the
  - refractive index

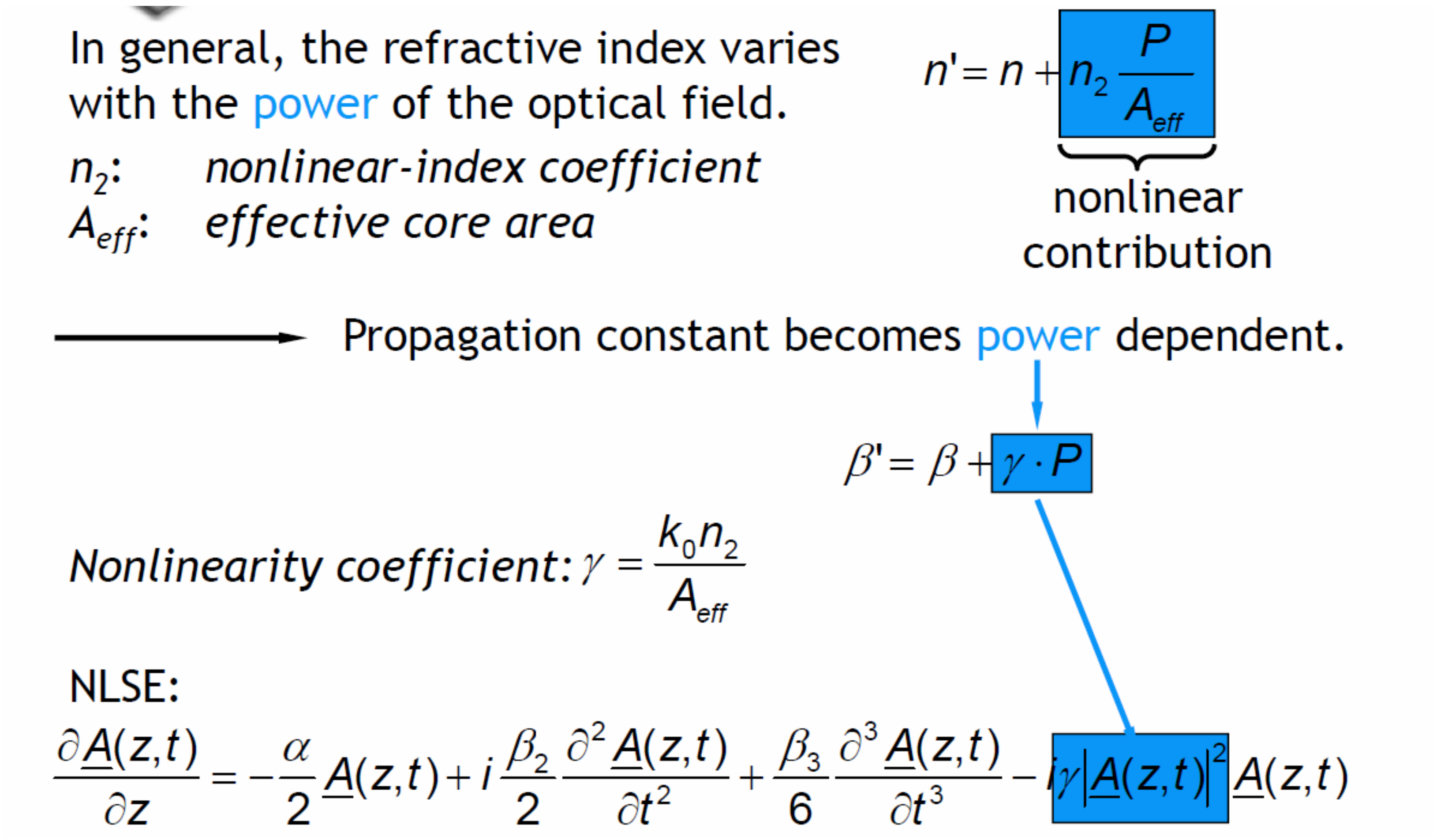
depend on the optical power in a fiber

Classifications:

- **Nonlinear inelastic scattering** processes, which are interactions between optical signals and molecular or acoustic vibrations in a fiber
  - stimulated Raman scattering (SRS) and
  - stimulated Brillouin scattering (SBS)
- **Nonlinear variations of the refractive index** in a silica fiber that occur because the refractive index is dependent on intensity changes in the signal. Effect: Crosstalk between the wavelength channels
  - self-phase modulation (SPM),
  - cross-phase modulation (XPM) or CPM, and
  - four-wave mixing (FWM) – called sometimes four-photon mixing (FPM)

$$\tilde{n}(\omega, I) = n(\omega) + n_2 I$$

Kerr nonlinearities –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.

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

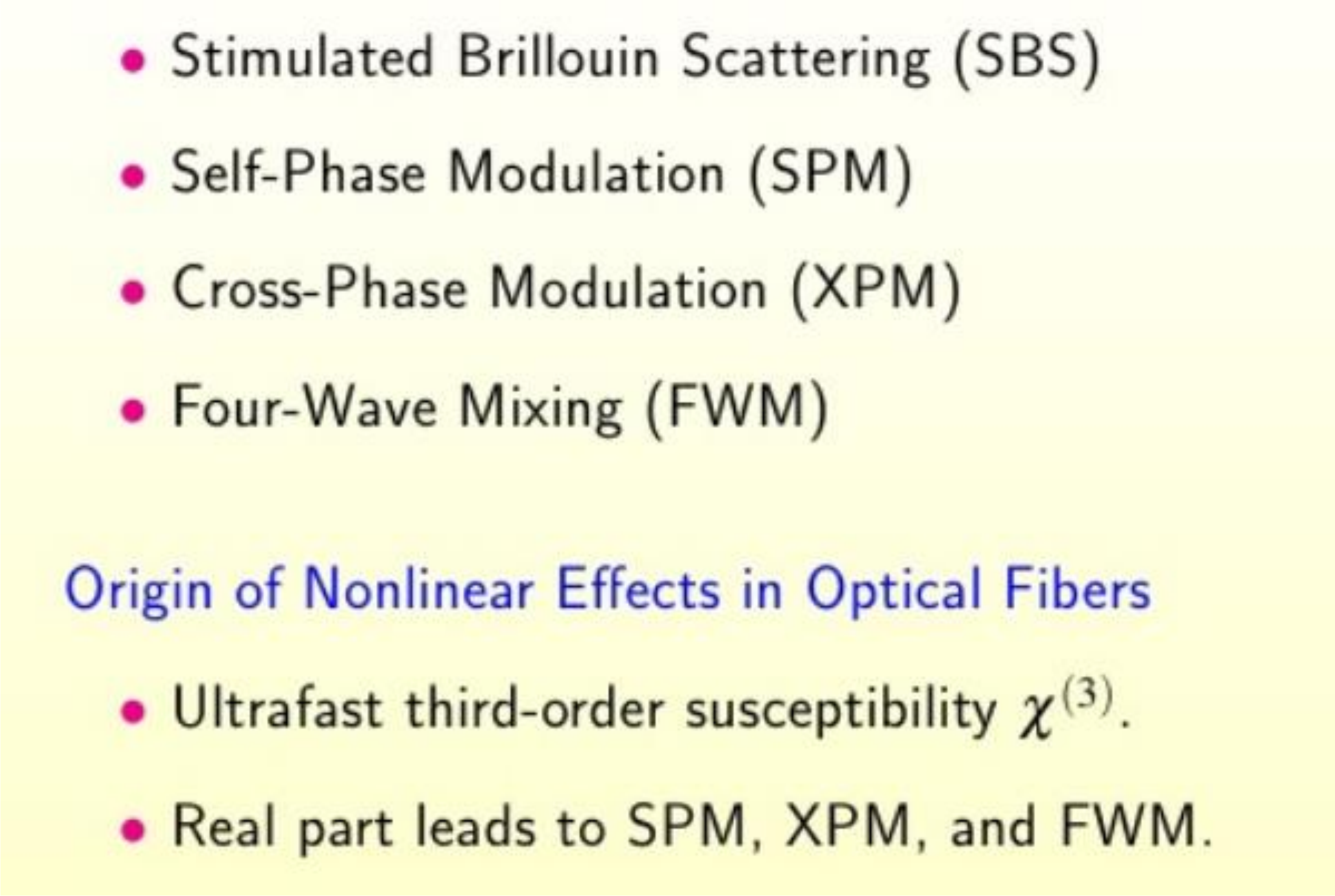
Nonlinearity coefficient: $\gamma = \frac{k_0 n_2}{A_{eff}}$

NLSE:

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

Major Nonlinear Effects

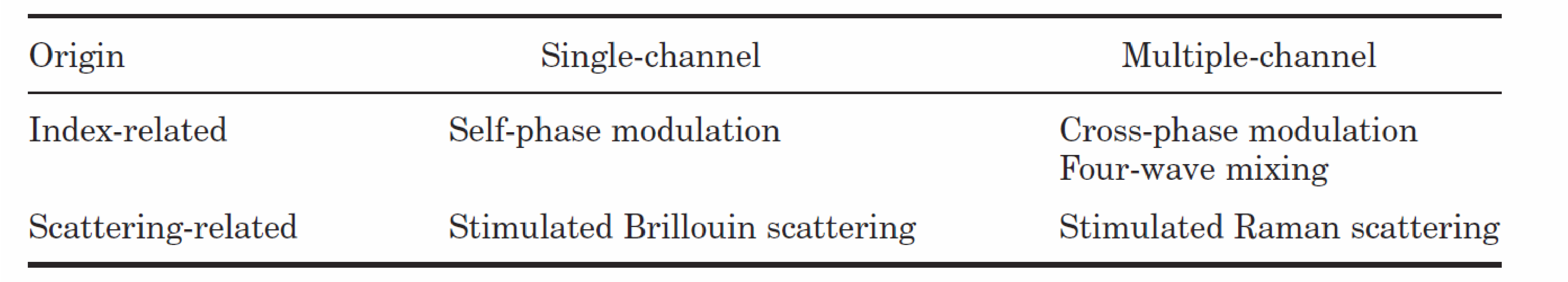
-already discussed in C2-



- Stimulated Brillouin Scattering (SBS)
- Self-Phase Modulation (SPM)
- Cross-Phase Modulation (XPM)
- Four-Wave Mixing (FWM)

Origin of Nonlinear Effects in Optical Fibers

- Ultrafast third-order susceptibility $\chi^{(3)}$.
- Real part leads to SPM, XPM, and FWM.



Origin	Single-channel	Multiple-channel
Index-related	Self-phase modulation	Cross-phase modulation Four-wave mixing
Scattering-related	Stimulated Brillouin scattering	Stimulated Raman scattering

Remember:
Rayleigh = elastic scattering for which the frequency (or the photon energy) of scattered light remains unchanged

Stimulated Raman Scatterring

- the molecule can absorb some energy from the incident photon
- Modified photon is called

Stokes

- Powers in channels separated by up to 125 nm(13-16 THz) can be coupled through the SRS effect,

thereby producing crosstalk between wavelength channels

- Raman amplifiers

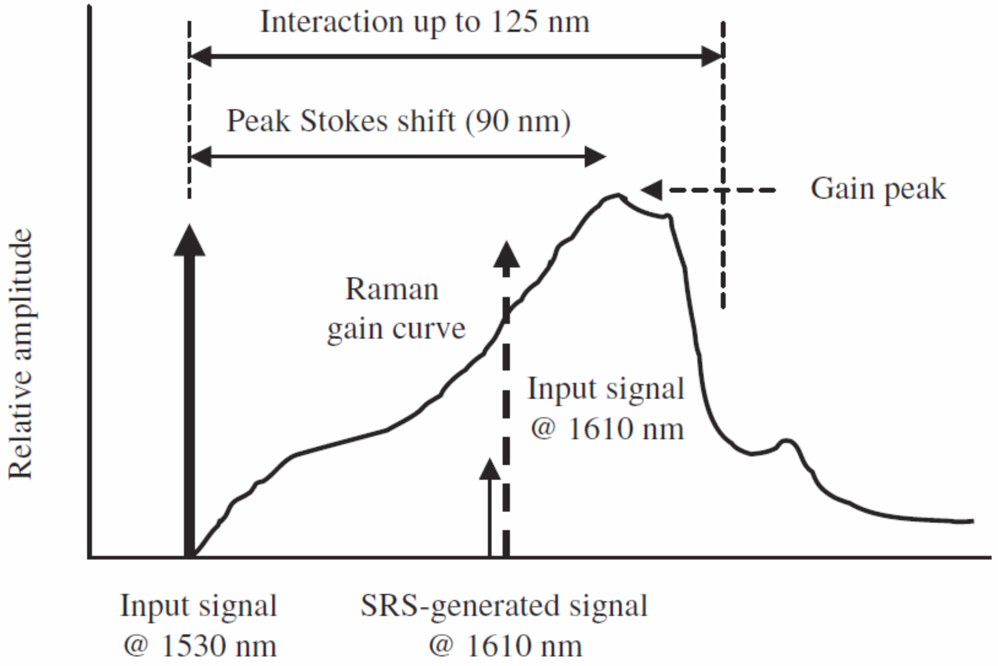
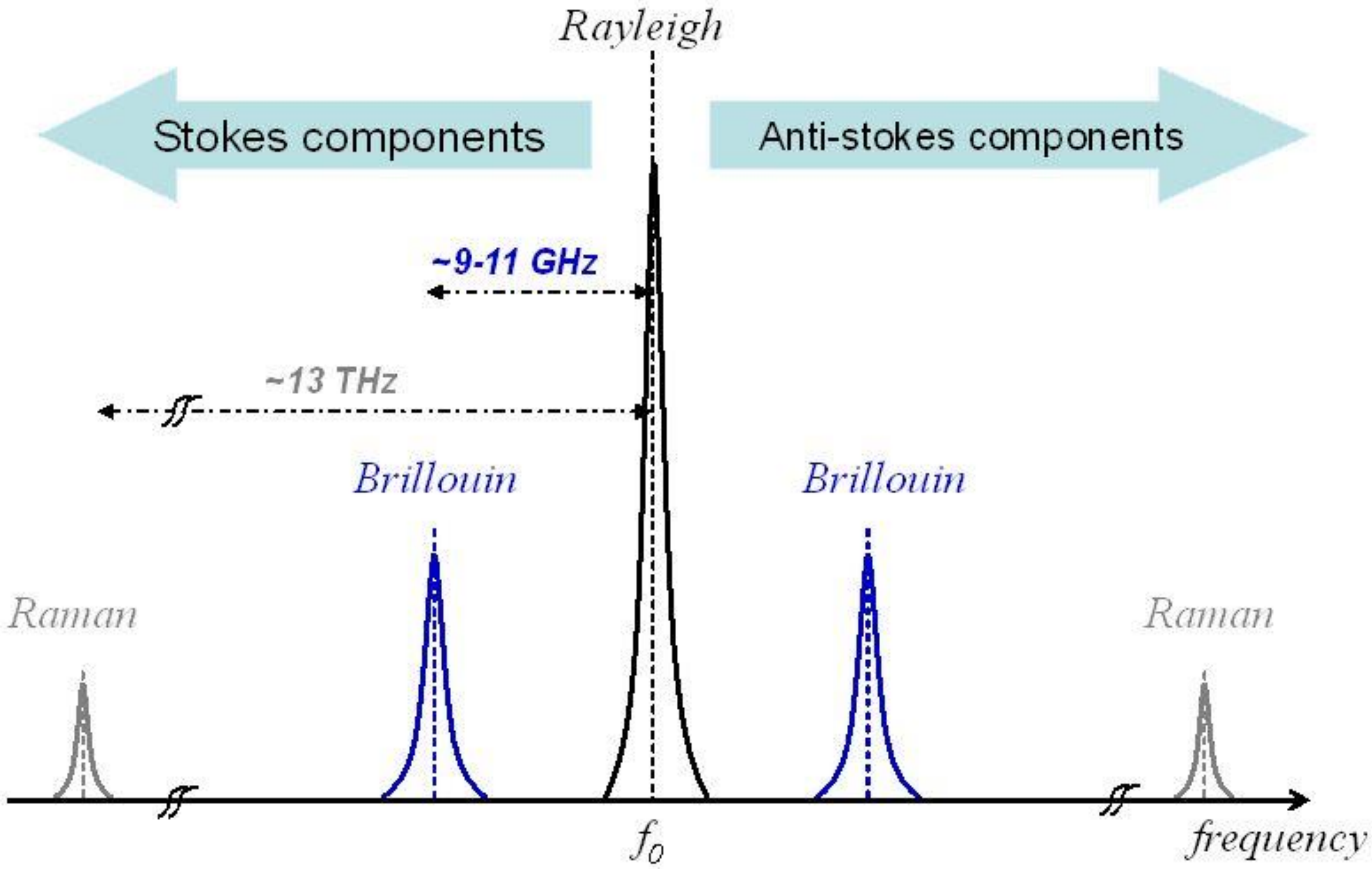


Figure 15.6. As a result of SRS, the signal at 1530 nm acts as a pump for the signal at 1610 nm.

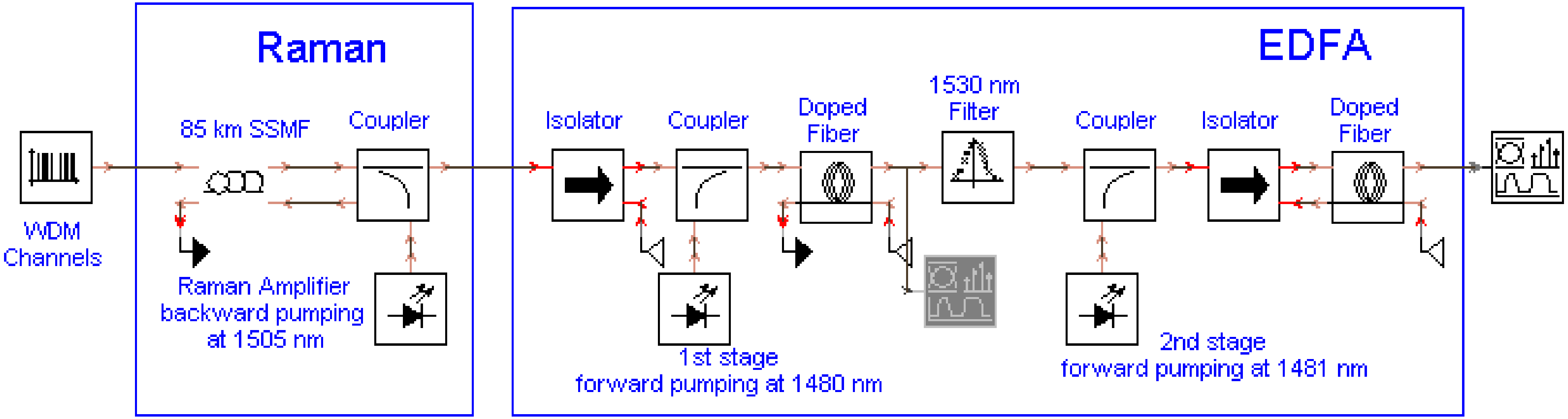


https://www.intechopen.com/books/advances-in-optical-fiber-technology-fundamental-optical-phenomena-and-applications/brillouin-scattering-in-optical-fibers-and-its-application-to-distributed-sensors

Raman Amplifier

Hybrid Distributed Raman (DRA) - EDFA Amplifier Link

Uses Raman amplification in a 85-km transmission fiber, followed by a 2-stage doped fiber amplifier. The 2-stage amplifier uses 1480-nm forward pumping in both stages, and includes a mid-stage gain flattening filter.



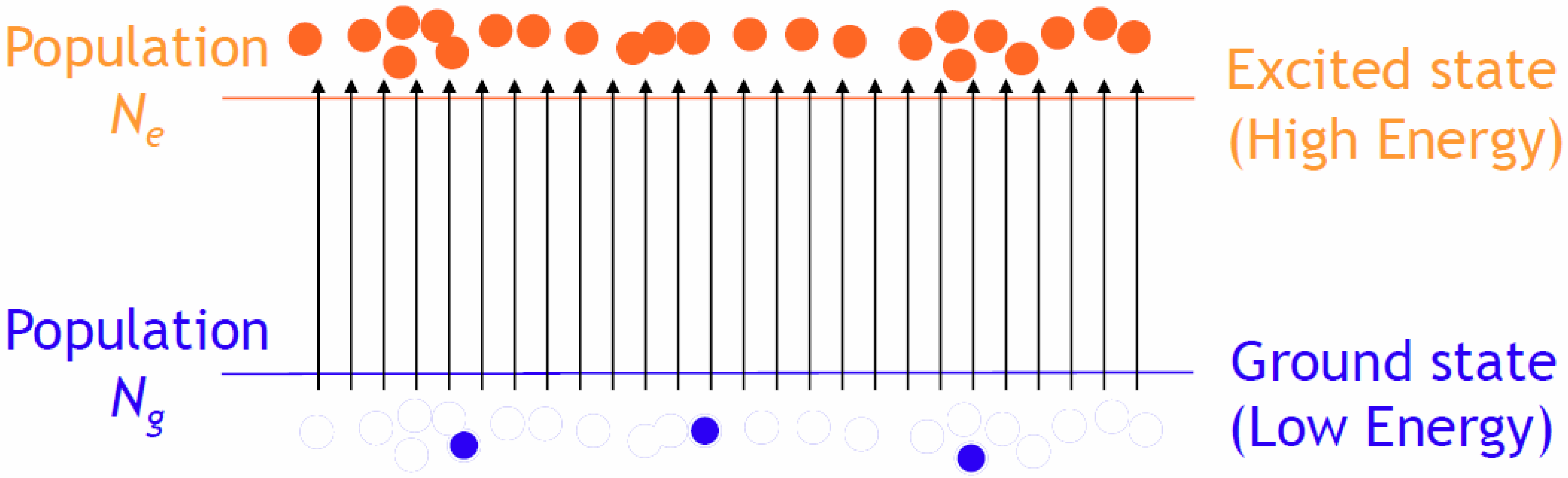
LASER is a good starting point

LIGHT
AMPLIFICATION by
STIMULATED
EMISSION of
RADIATION

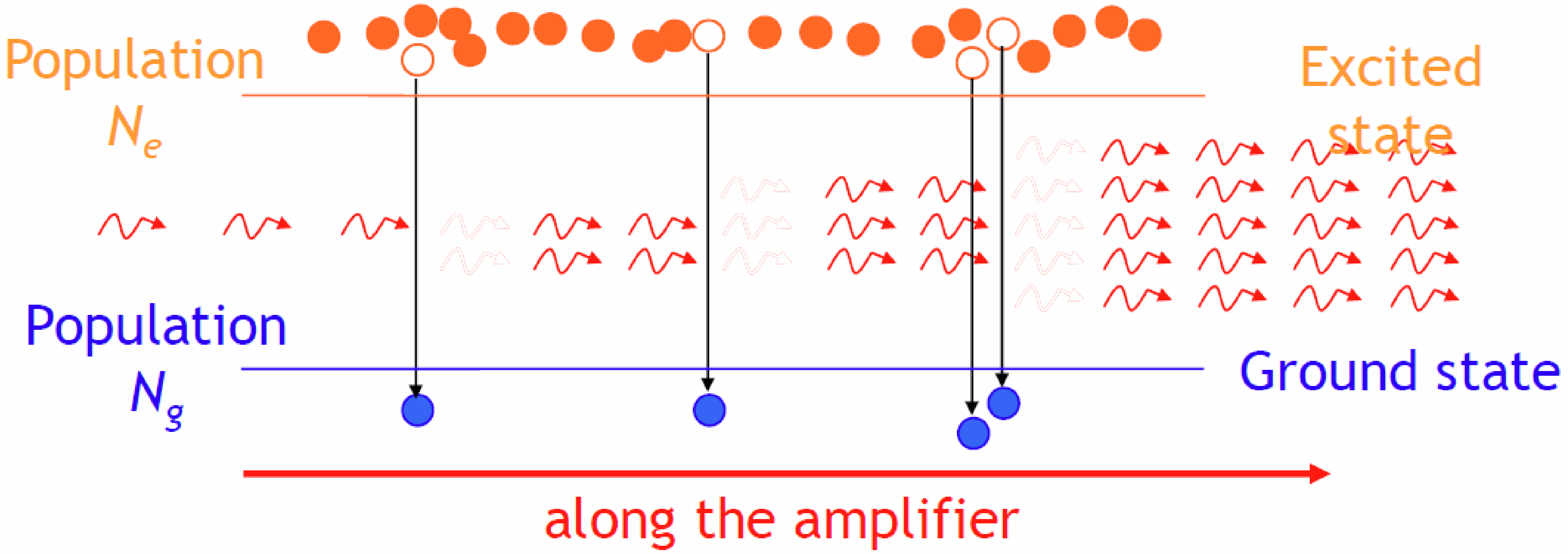
Energy Level diagram

How Optical Amplification works

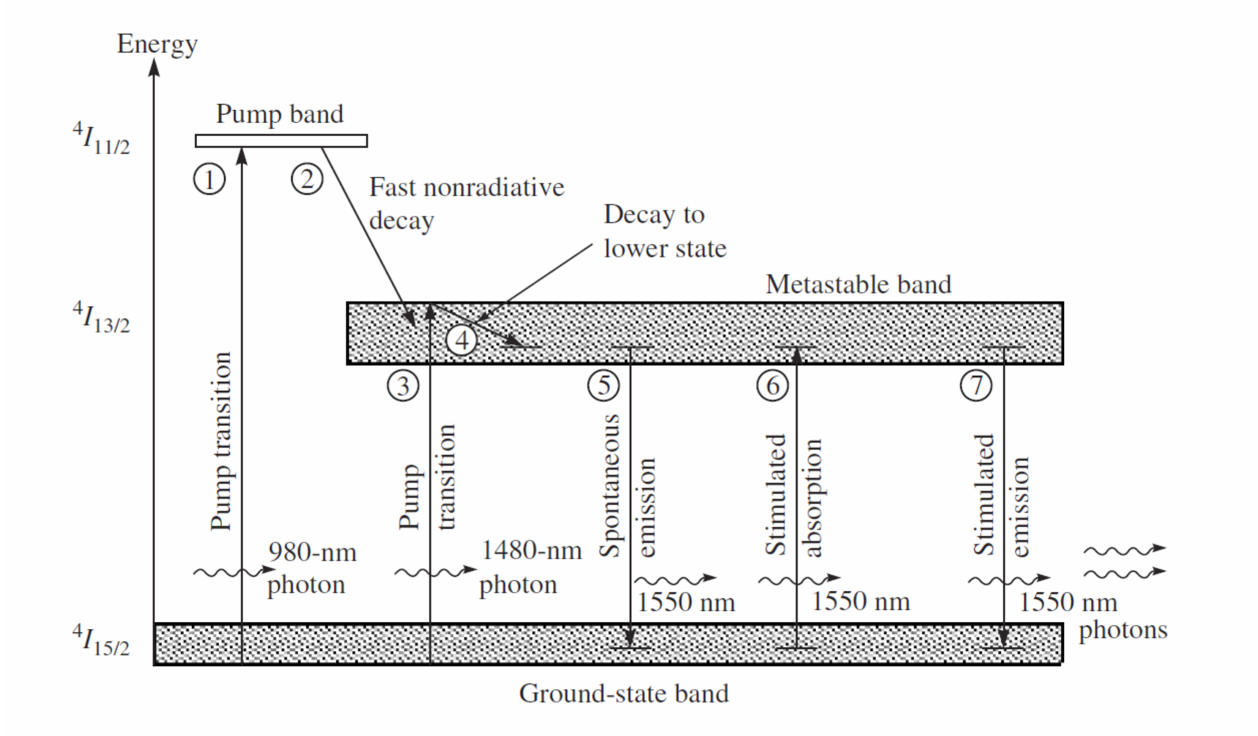
- First, “Population Inversion” is needed
- “Normal”, N_g = number in ground state
- “Population Inversion”: $N_e > N_g$

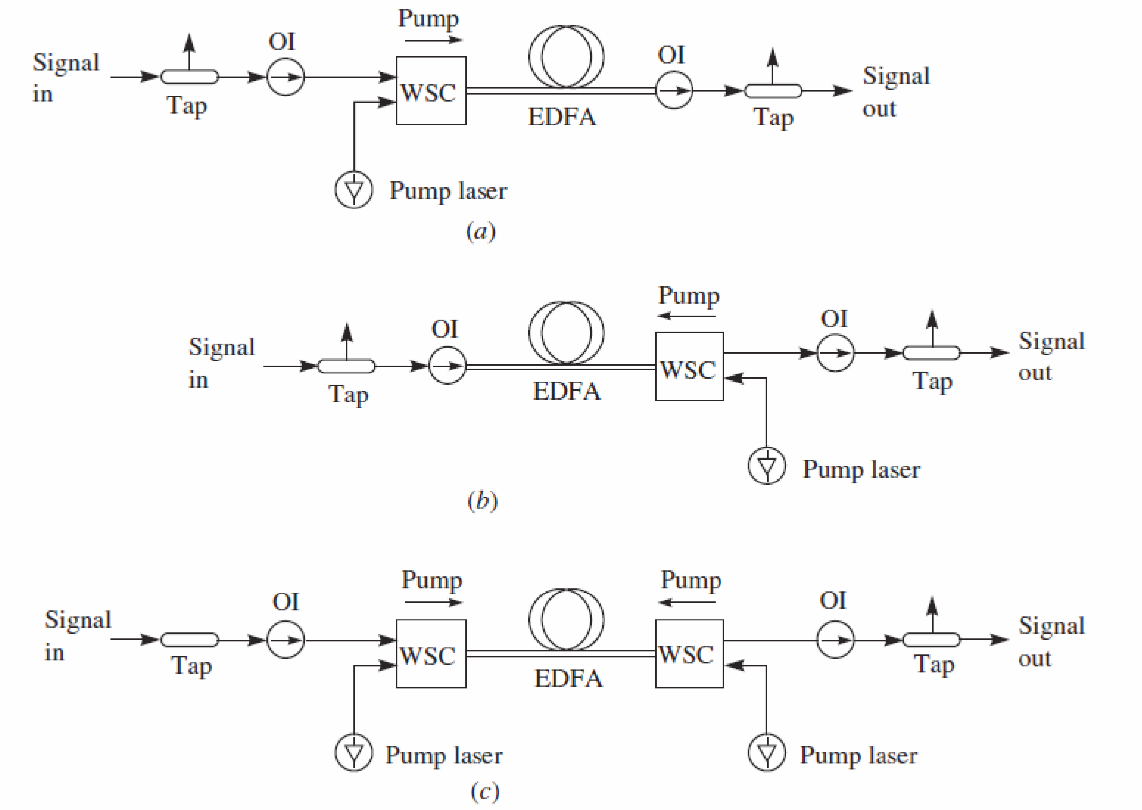


- Signal photon enters the amplifier
- It stimulates an atom to decay to ground state, which emits an identical photon.
- This process repeats… and the signal is amplified (Gain)



EDFA Amplifiers



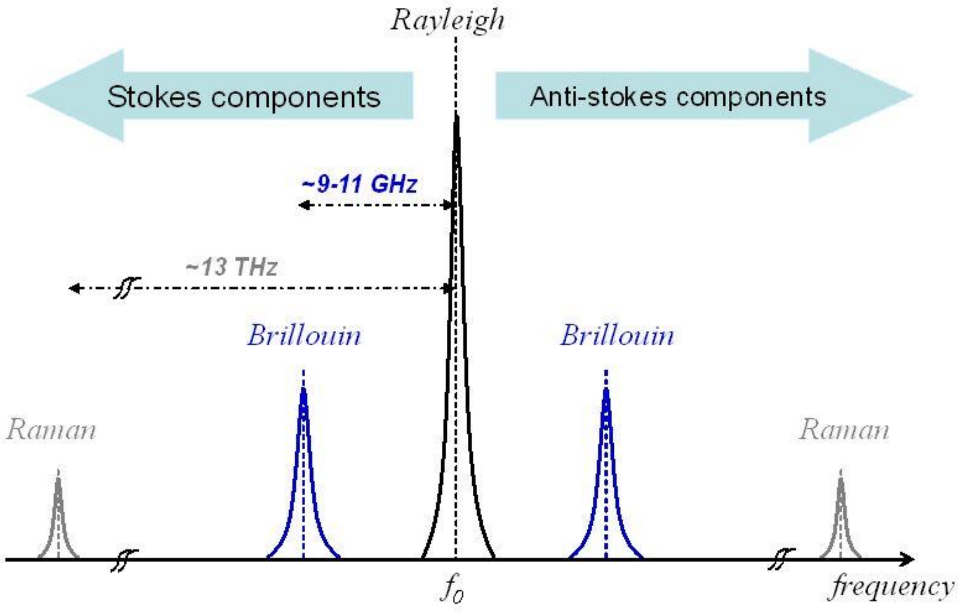


Stimulated Brillouin scattering

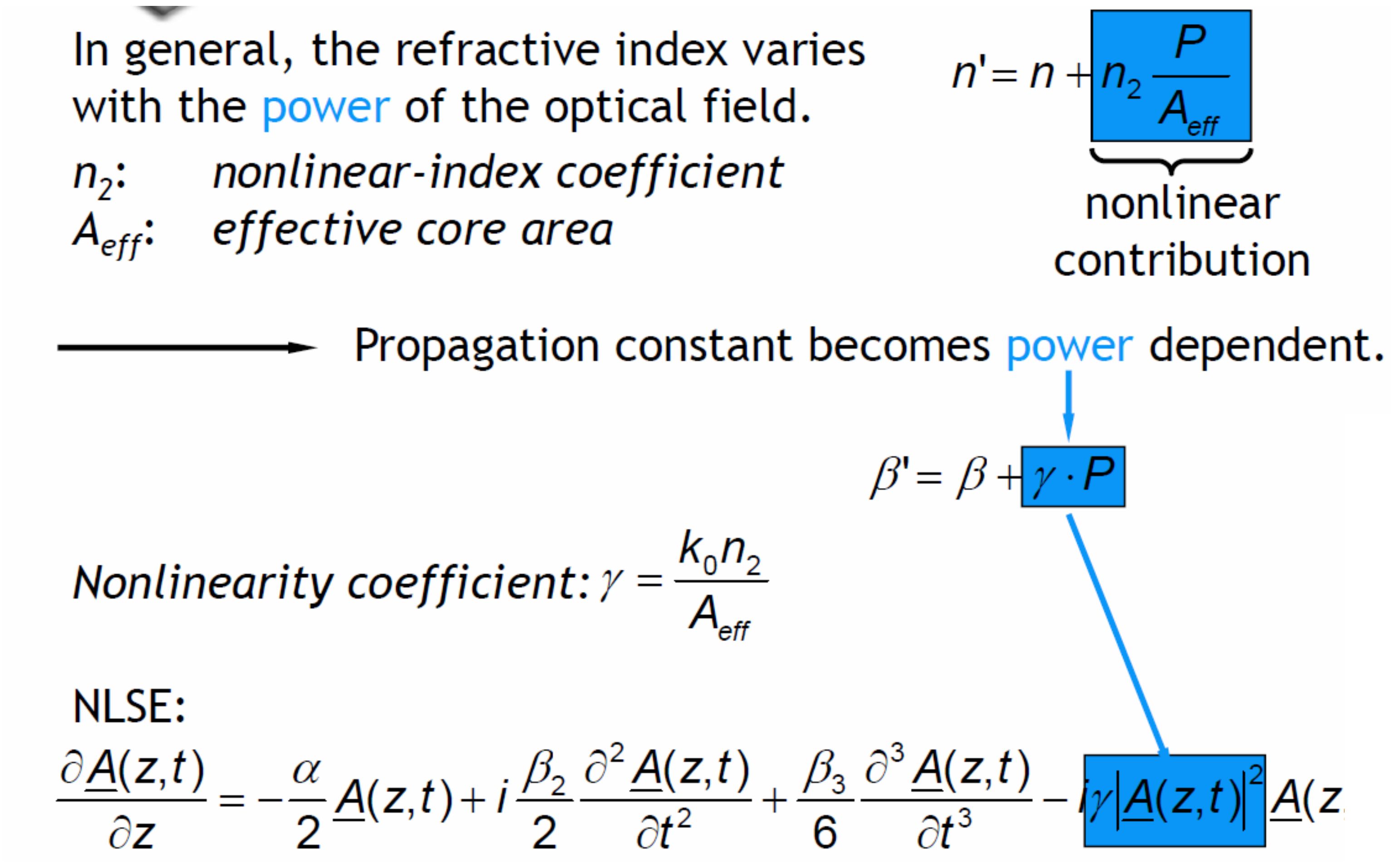
- arises when light waves scatter from acoustic waves.
- The physical process behind Brillouin scattering is the tendency of materials to become compressed in the presence of an electric field—a phenomenon termed electrostriction
- Powers in channels separated by up to

9-11 GHz can be coupled through

the SBS effect



Kerr nonlinearities –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*

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

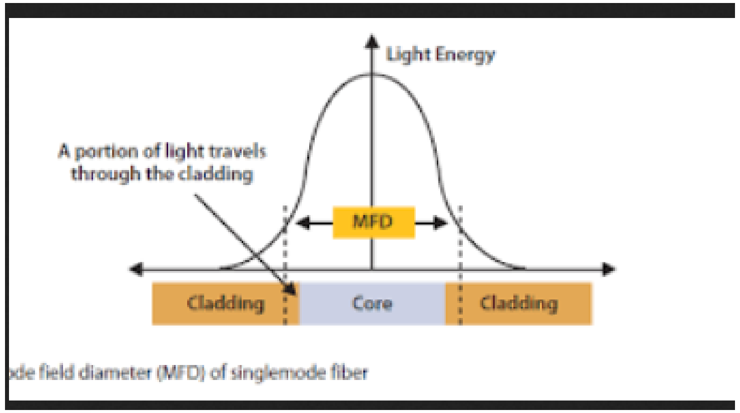
→ Propagation constant becomes power dependent.

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

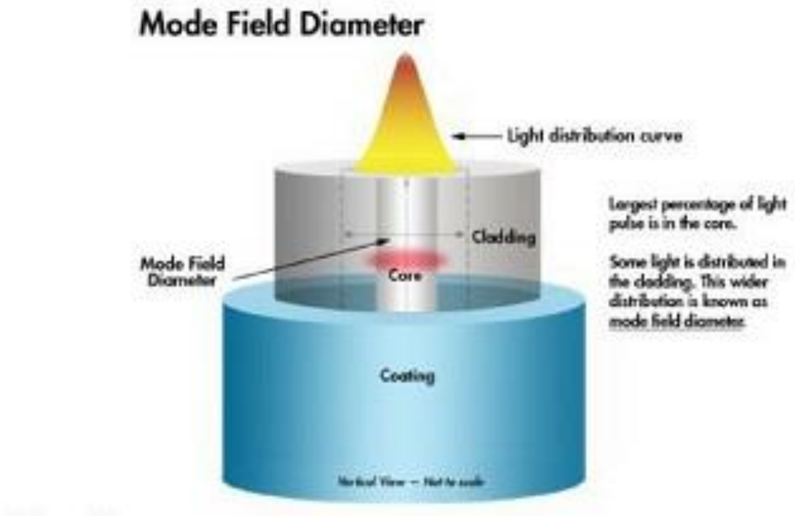
Nonlinearity coefficient: $\gamma = \frac{k_0 n_2}{A_{eff}}$

NLSE:

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

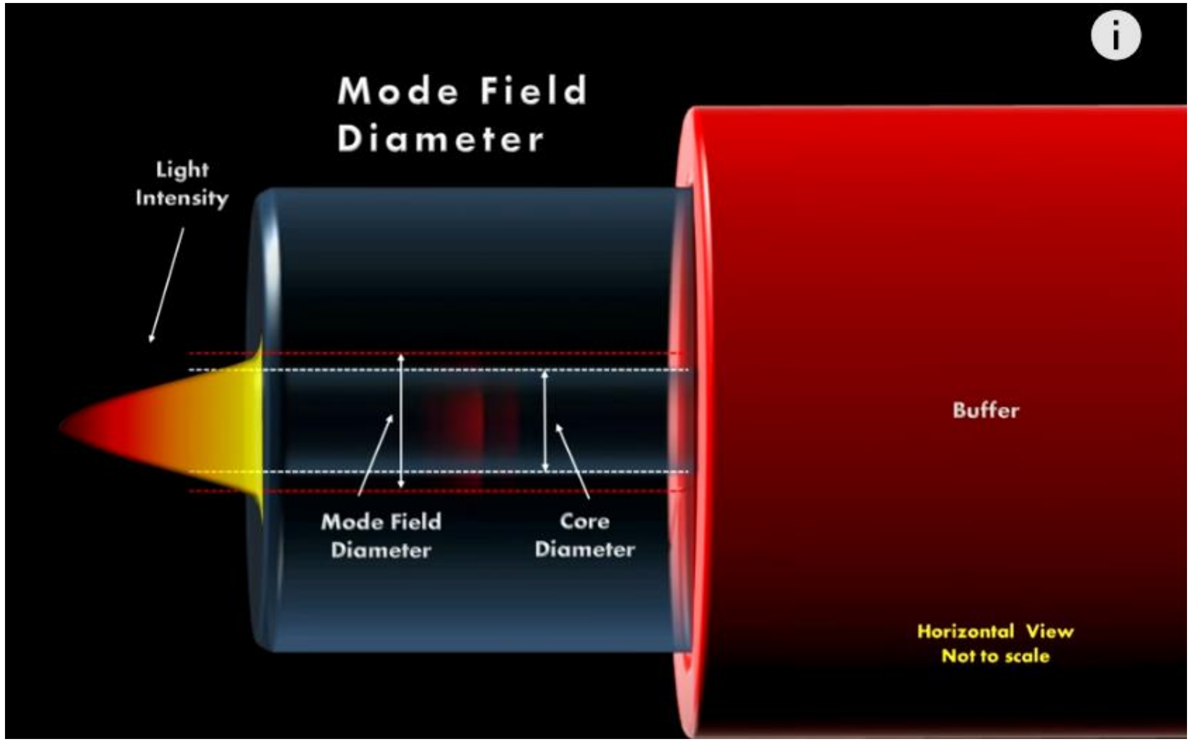


de field diameter (MFD) of singlemode fiber



Mode field diameter

$$MFD = 2a\left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}\right)$$



Self-phase modulation (SPM)

- Phase of one wavelength channel is modulated by its power.
- Phase shift is time dependent, since signal power varies with time.

Example: Gaussian and super Gaussian pulses

Normalized pulse shape:

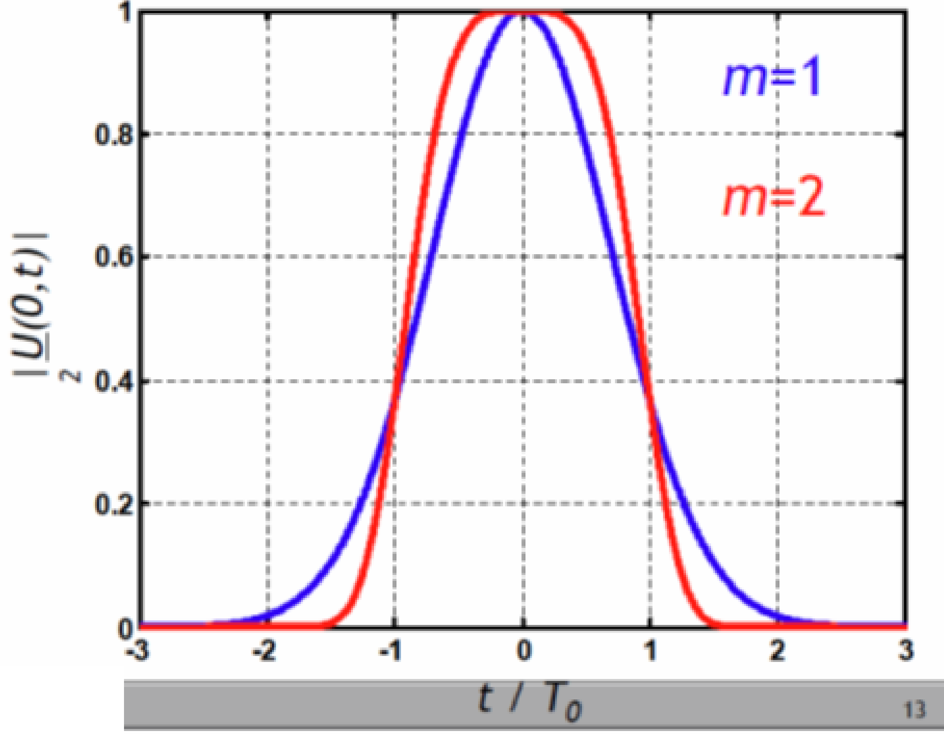
$$|\underline{U}(z,t)|^2 = \frac{|\underline{A}(z,t)|^2}{P_0 \exp(-\alpha z)}$$

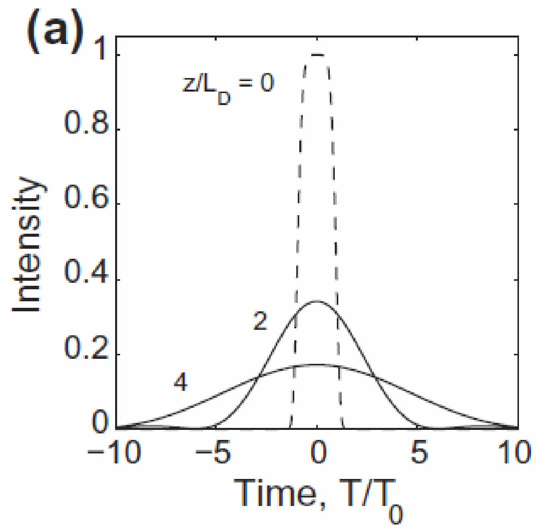
P_0: pulse peak power

Gaussian shape:

$$|\underline{U}(0,t)|^2 = \exp\left(-\frac{t^{2m}}{T_0^{2m}}\right)$$

https://link.springer.com/article/10.1007/s00340-016-6407-y





A super-Gaussian shape can be used to model the effects of steep leading and trailing edges on dispersion-induced pulse broadening. The factor, m = degree of edge sharpness

Self-phase modulation (SPM)

Nonlinear phase shift after a fiber of length *L* is given by:

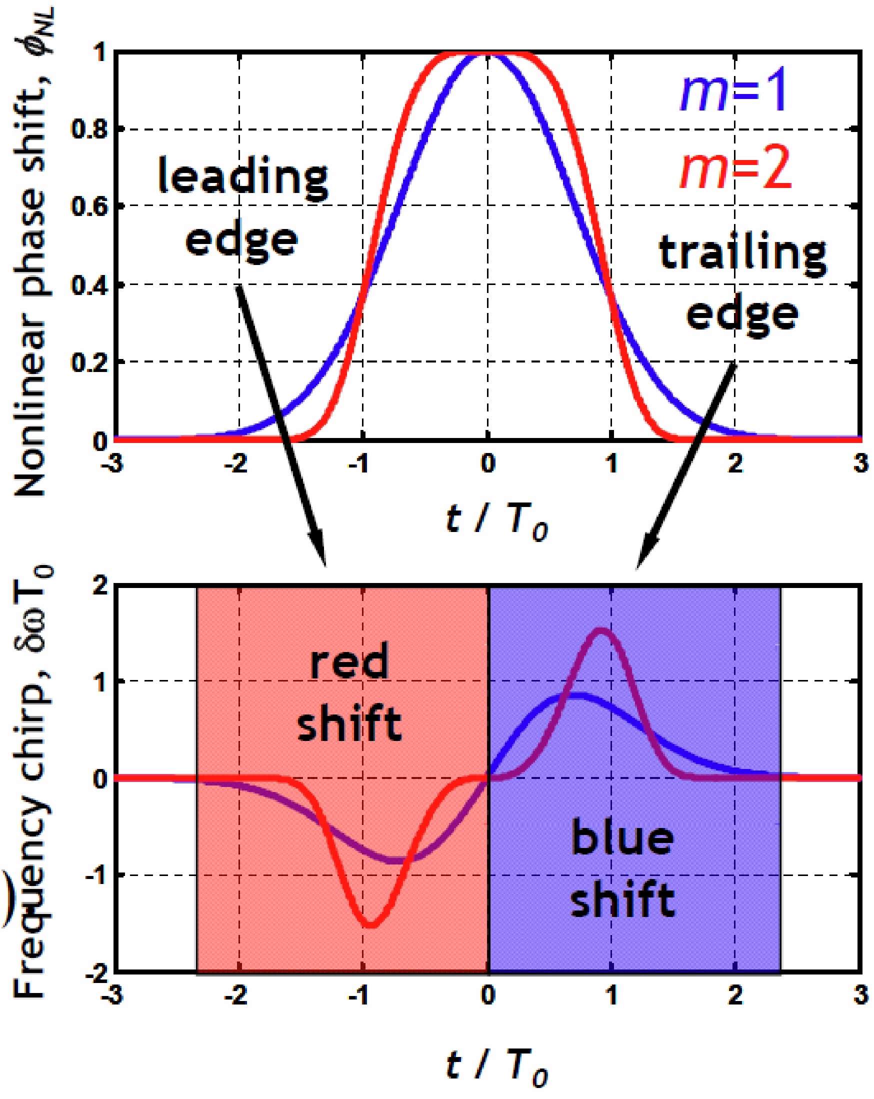
$$\phi_{NL}(L,t) = |U(0,t)|^2 \frac{L_{eff}}{L_{NL}}$$

Where the *nonlinear length* L_{NL} is defined as:

$$L_{NL} = \frac{1}{\gamma \cdot P_0}$$

A time dependent phase shift leads to a variation of frequency with time (chirp *dw*)

$$\delta\omega = -\frac{\partial \phi_{NL}}{\partial t}$$



phase shift

frequency chirp

Self-phase modulation (SPM)

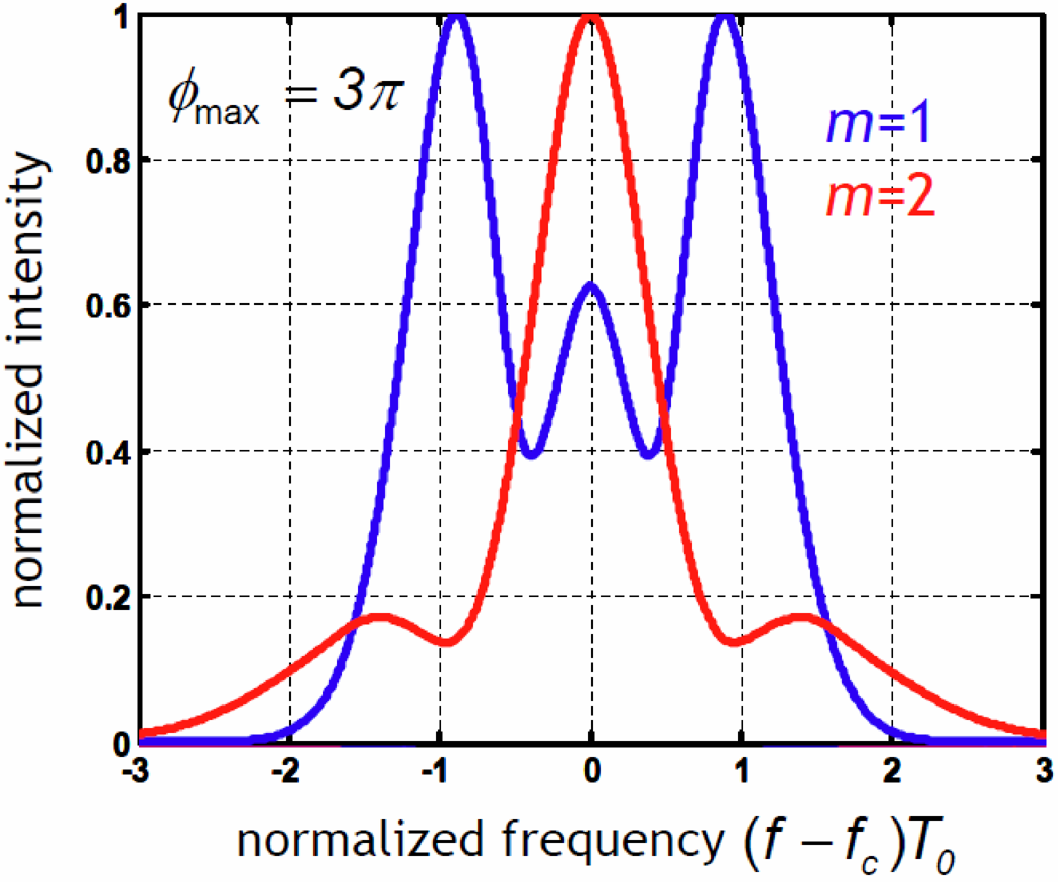
Through the frequency chirp $\delta\omega$, SPM generates new frequency components when a pulse propagates along a fiber. This leads to spectral broadening.

Example:
Gaussian and super Gaussian pulse with pulse shape

$$\left|\underline{U}(0,t)\right|^2 = \exp\left(-\frac{t^{2m}}{T_0^{2m}}\right)$$

f_c : carrier frequency

Spectral evolution?

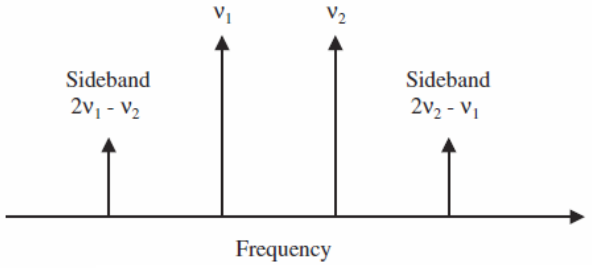


Four-wave mixing (FWM)

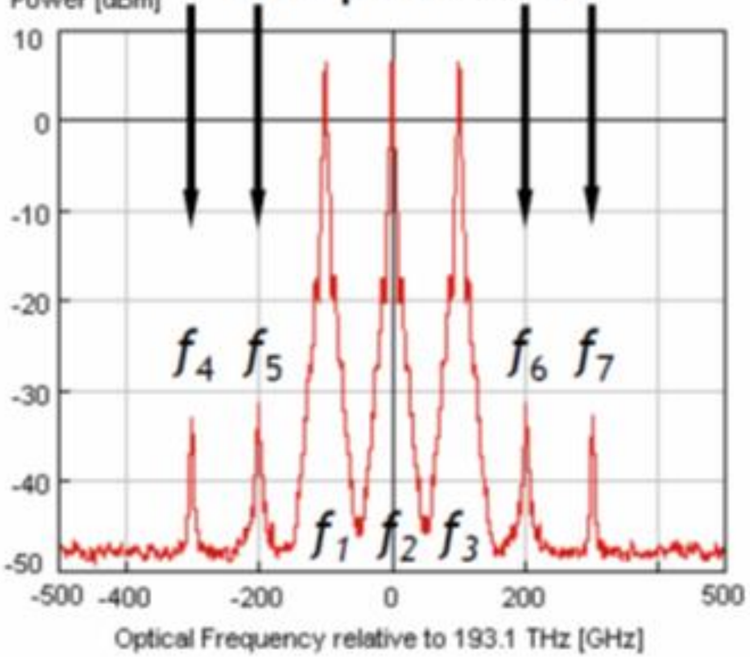
- The intensity dependence of the refractive index also leads to frequency mixing of optical waves.
- Consider three copropagating optical fields with carrier frequencies f_1, f_2, and f_3.
- Four-wave mixing generates new mixing products at frequencies:

$$\boxed{f_n = f_i + f_j - f_k}$$

with $f_i, f_j \neq f_k$.



out-of-band FWM products



Example:

FWM products at f_5:

$$f_5 = f_1 + f_2 - f_3 \quad \text{and} \quad f_5 = 2f_1 - f_2$$

Effects of FWM

- Loss of signal power in all wavelength channels
- Coherent interchannel crosstalk between wavelength channels in systems employing equidistant channel spacing

⇨ In WDM systems with many channels, FWM effects can be considered as a degradation of signal-to-noise ratio.

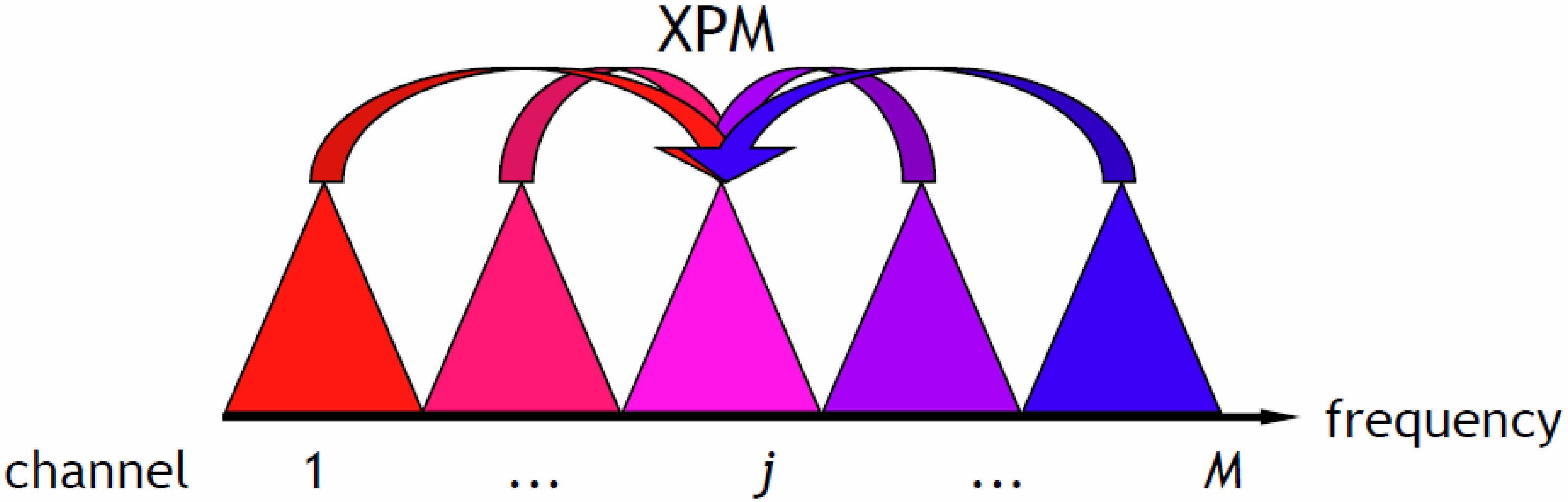
How can the effects of FWM be minimized?

- Large channel spacing → Lower FWM-efficiency
- Unequal channel spacings → Incoherent out-of-band crosstalk
- Large fiber dispersion → Lower FWM-efficiency

Cross-phase modulation (XPM)

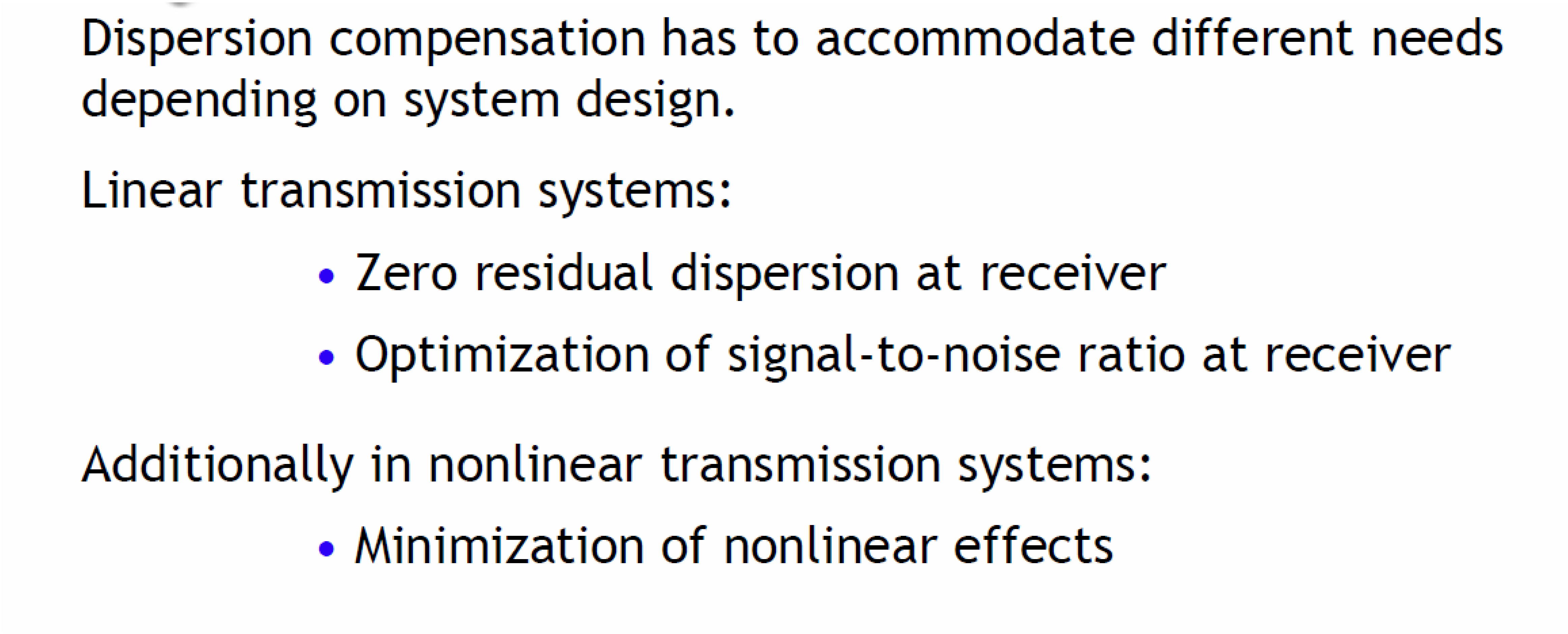
When several waves co-propagate inside a fiber, the nonlinear contribution to the refractive index depends on the power of all co-propagating waves.

⇨ Phase in one wavelength channel is modulated by the power in all other wavelength channels.



Nonlinear phase shift in channel j : $\phi_{NL,j} = \gamma \cdot L_{eff} \left(\overset{\text{SPM}}{\boxed{P_j}} + \overset{\text{XPM}}{\boxed{2\sum_{m \neq j}^{M} P_m}} \right)$

Conclusion



Dispersion compensation has to accommodate different needs depending on system design.

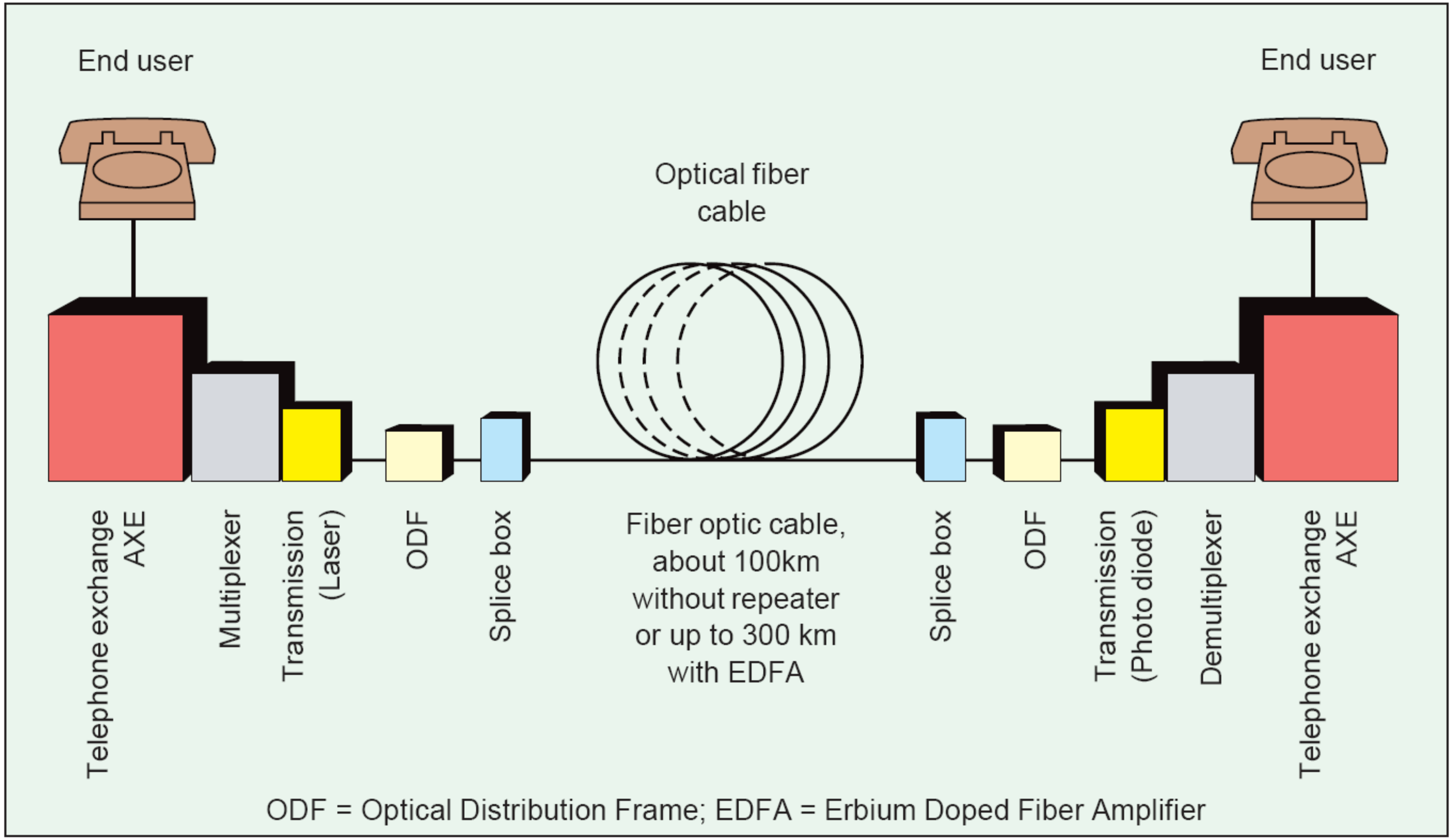
Linear transmission systems:

- Zero residual dispersion at receiver
- Optimization of signal-to-noise ratio at receiver

Additionally in nonlinear transmission systems:

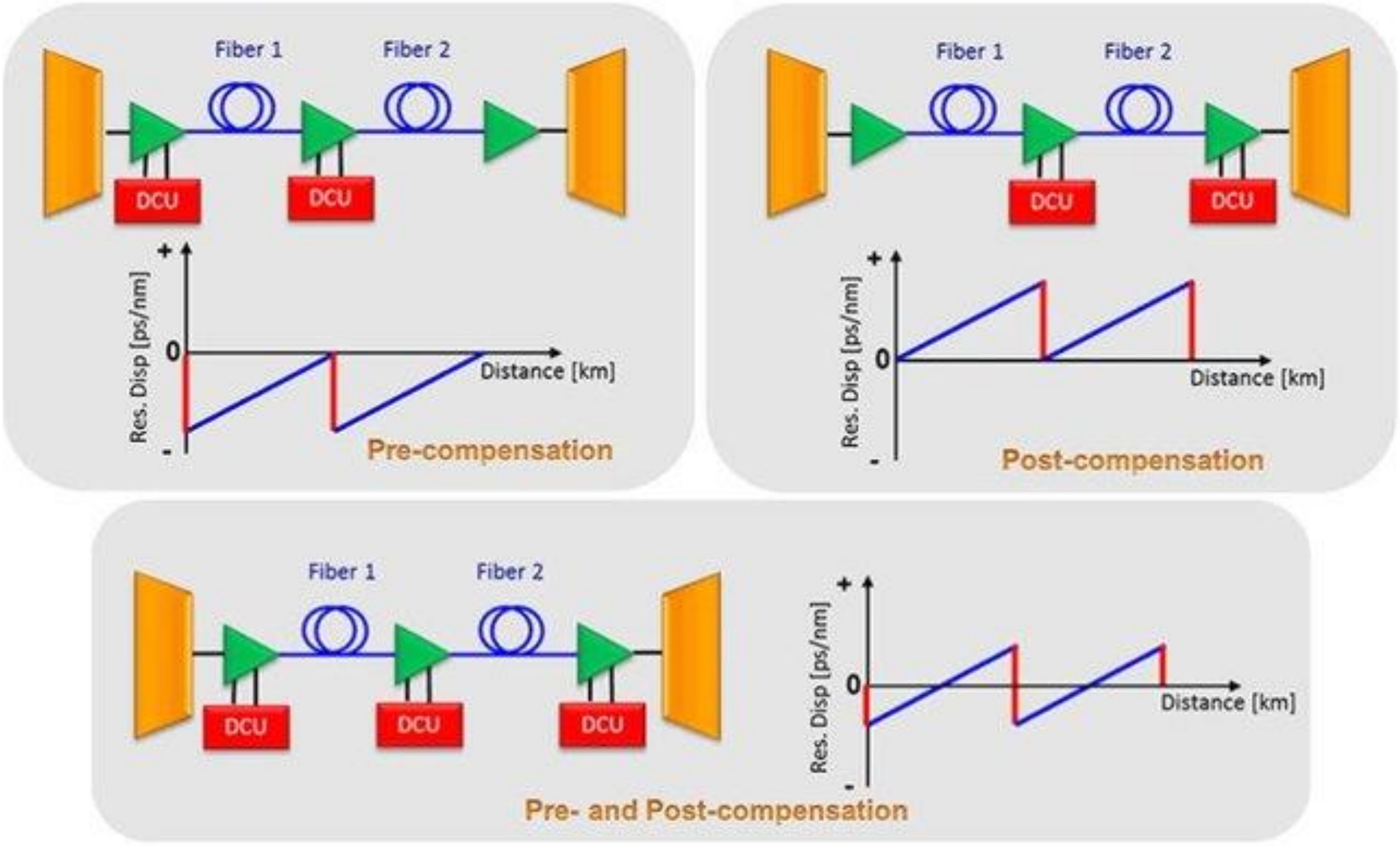
- Minimization of nonlinear effects

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

III. 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**

Questions?

Deadline Homework in this lecture: 2 weeks