XX Oficina de Física
IFGW, 24 –Nov-2007

www.kyatera.fapesp.br

Laser Communications

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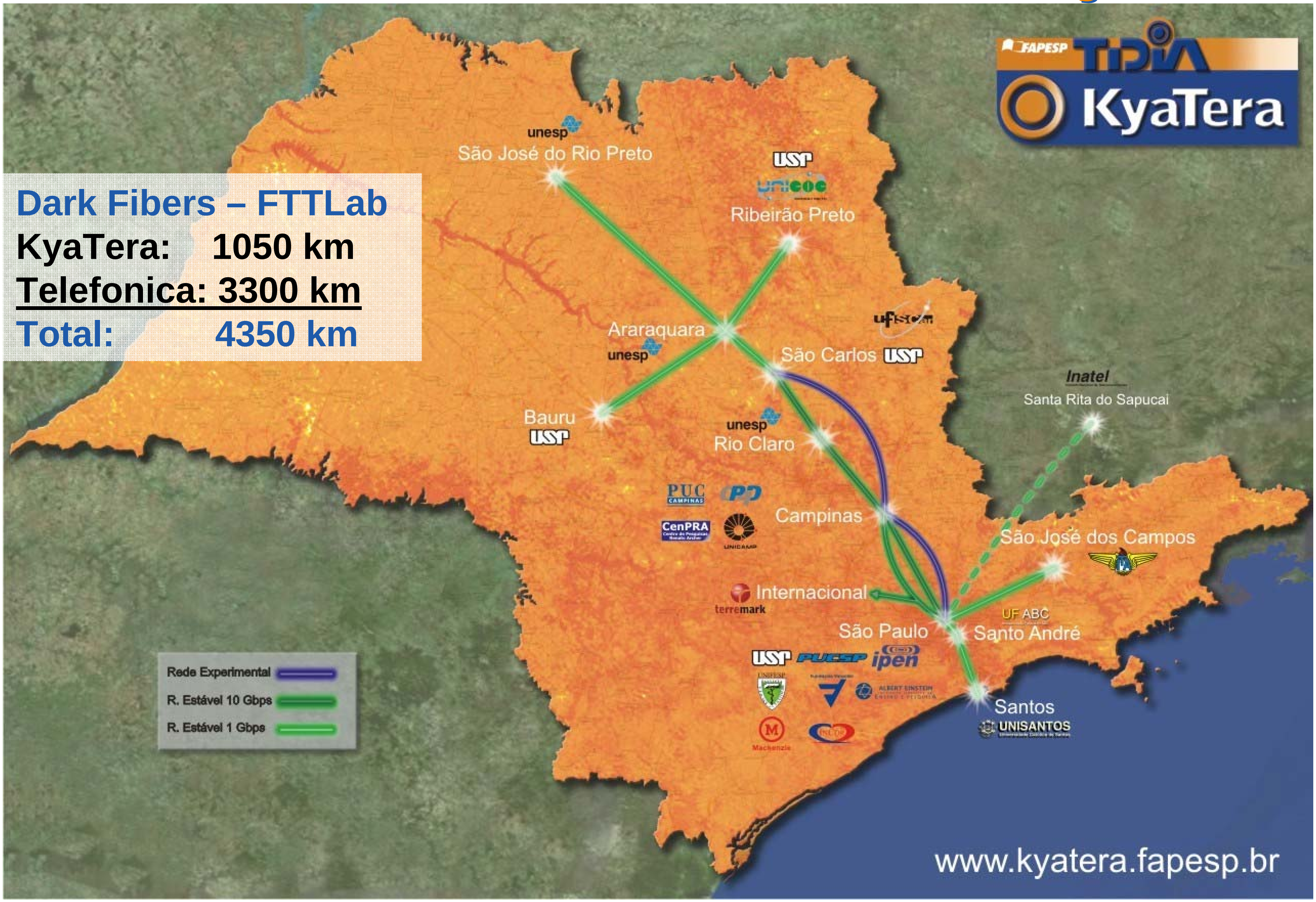
Rede KyaTera

Dark Fibers – FTTLab

KyaTera: 1050 km

Telefonica: 3300 km

Total: 4350 km



Communications: Photonics versus Electronics

- **Capacity of transmission lines:**
  - Coaxial Cable: 10 Mb/s×km
  - Optical fiber: > 10 Pb/s×km,

- **Implications in high speed signal processing:**
  - Assuming that an electronic chip could process at 10 Tb/s, it could not transmit information to another chip 1 mm apart (!)

- **Implications in $$ (telecom services):**
  - **Metallic line (10 Mb/s): 0.2 M$/month**
  - **Optical Fiber (10 Gb/s): 200 M$/month**

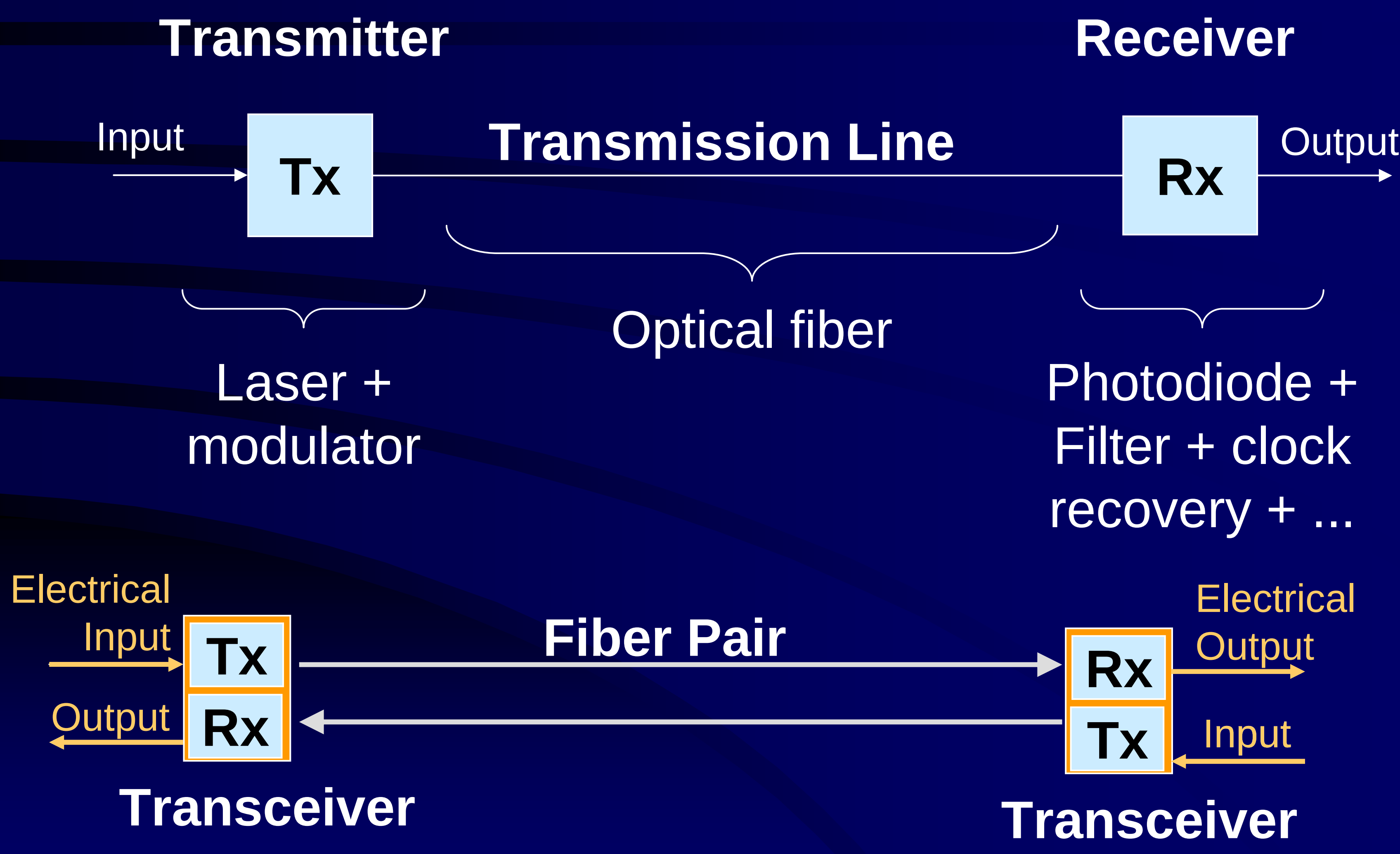
(at 1¢/min per 5 kbps used 8 h/day)

Substitute cables and electronics by fibers and photonics

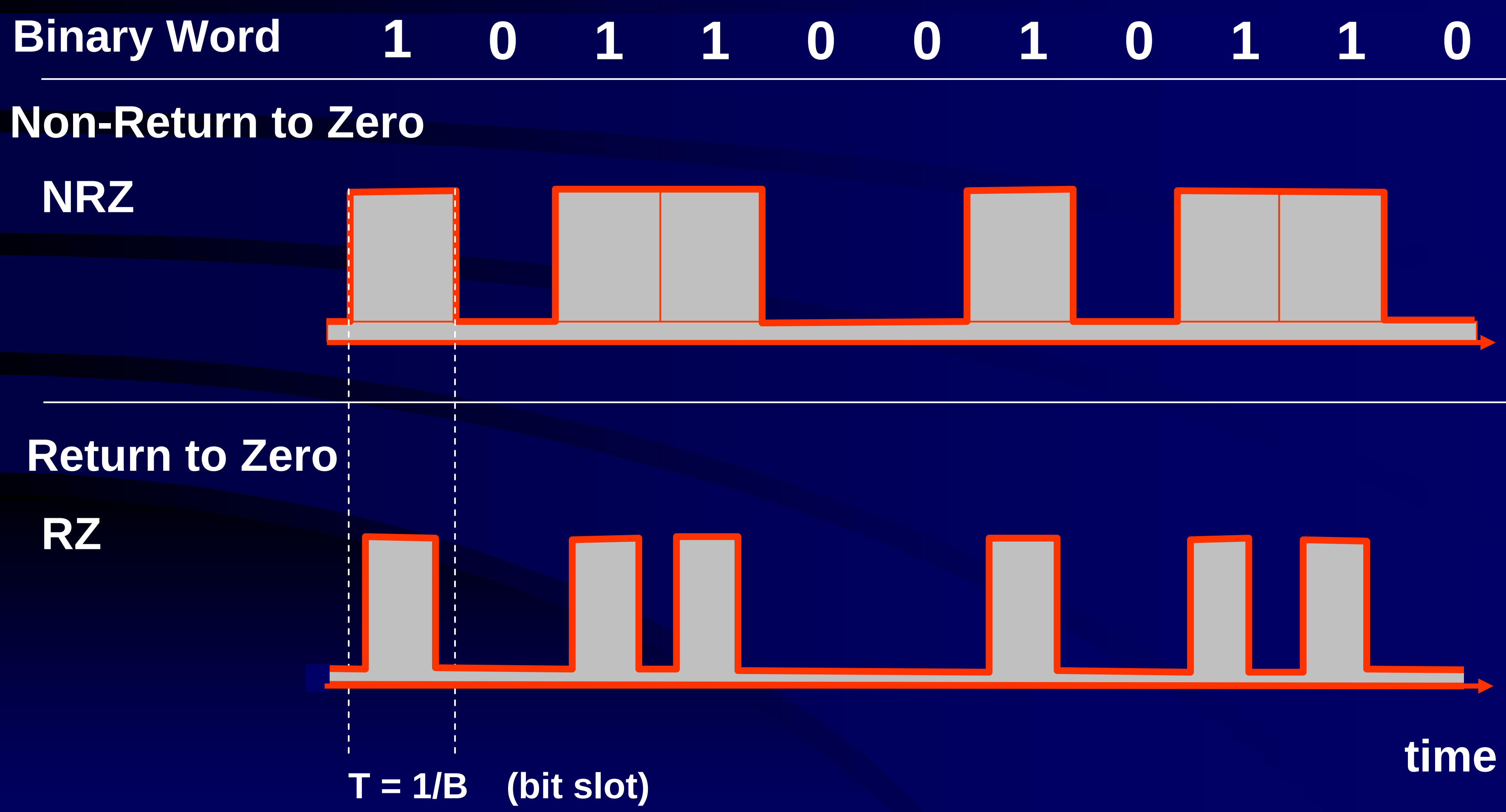
System concepts

Elements of transmission systems
Multiplexing
Modulation Formats
Optically amplified systems
WDM systems

Elements of a Communication System

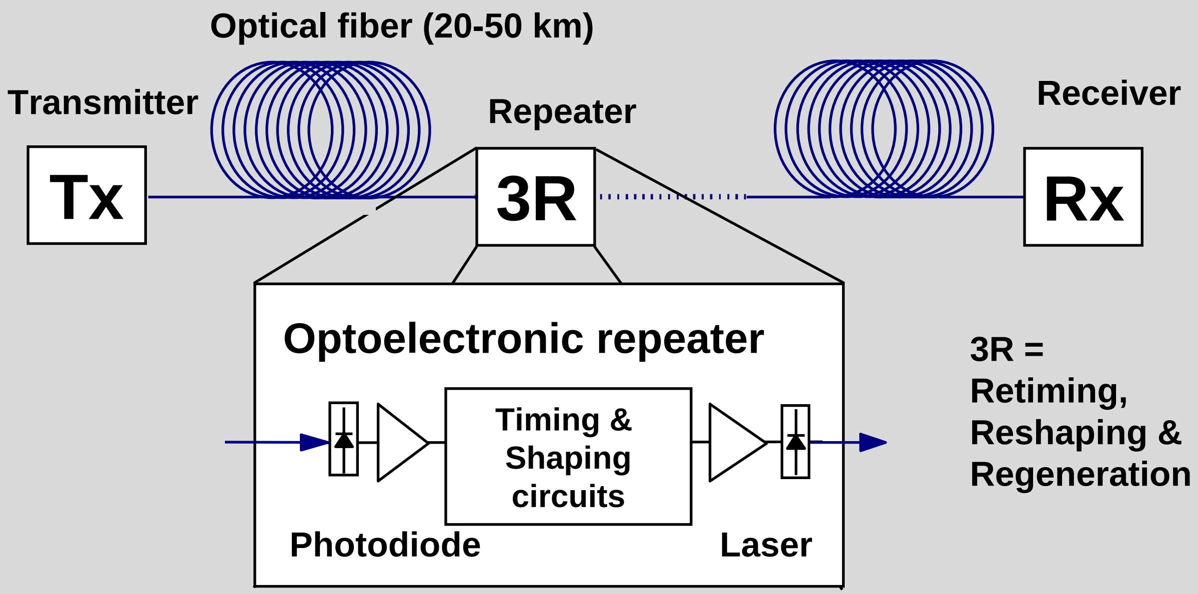


Digital Modulation Formats



Traditional Optical Communication System

Loss compensation: Repeaters at every 20-50 km

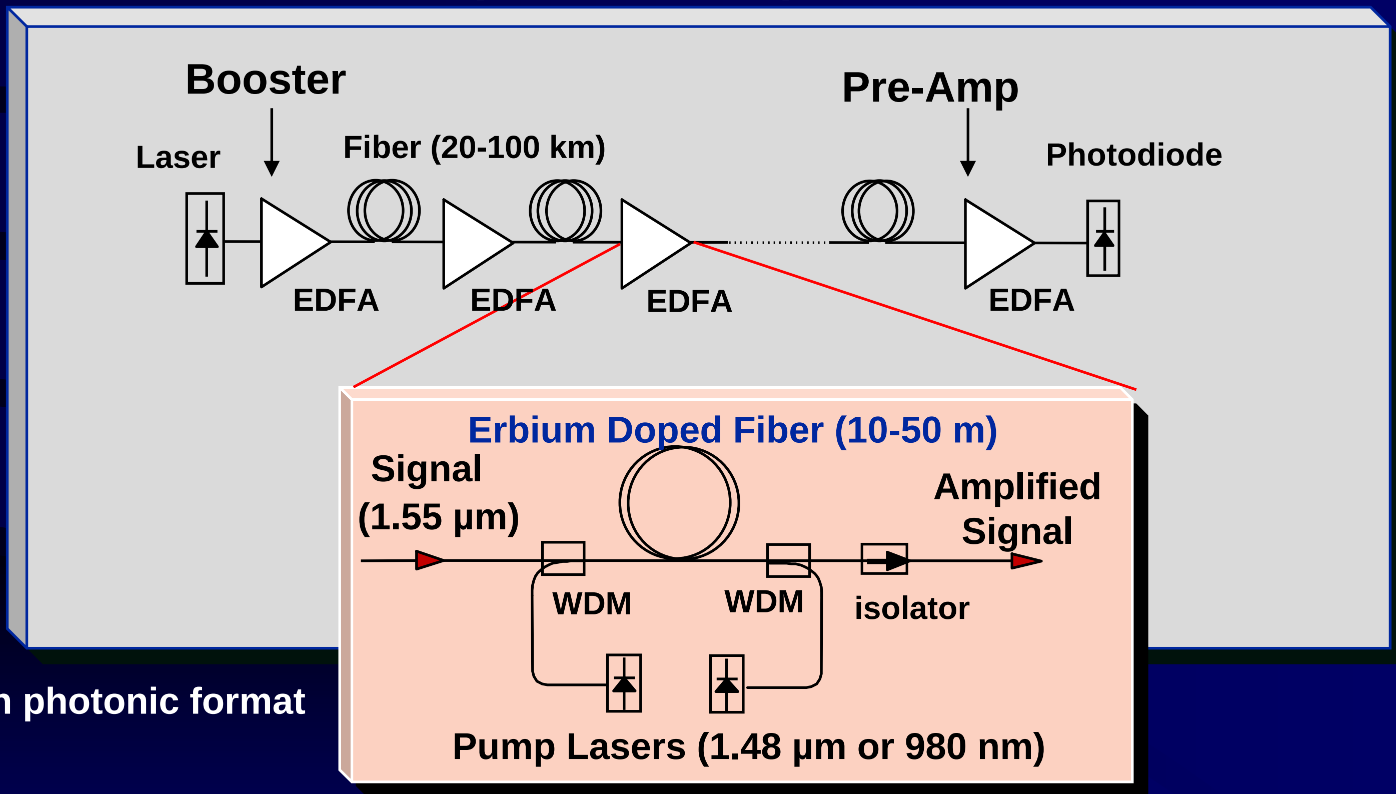


3R = Retiming, Reshaping & Regeneration

Capacity limited by speed of electronic circuits.
Timing circuits are specific for a given bit rate, protocol coding, format,…

Optically Amplified Systems

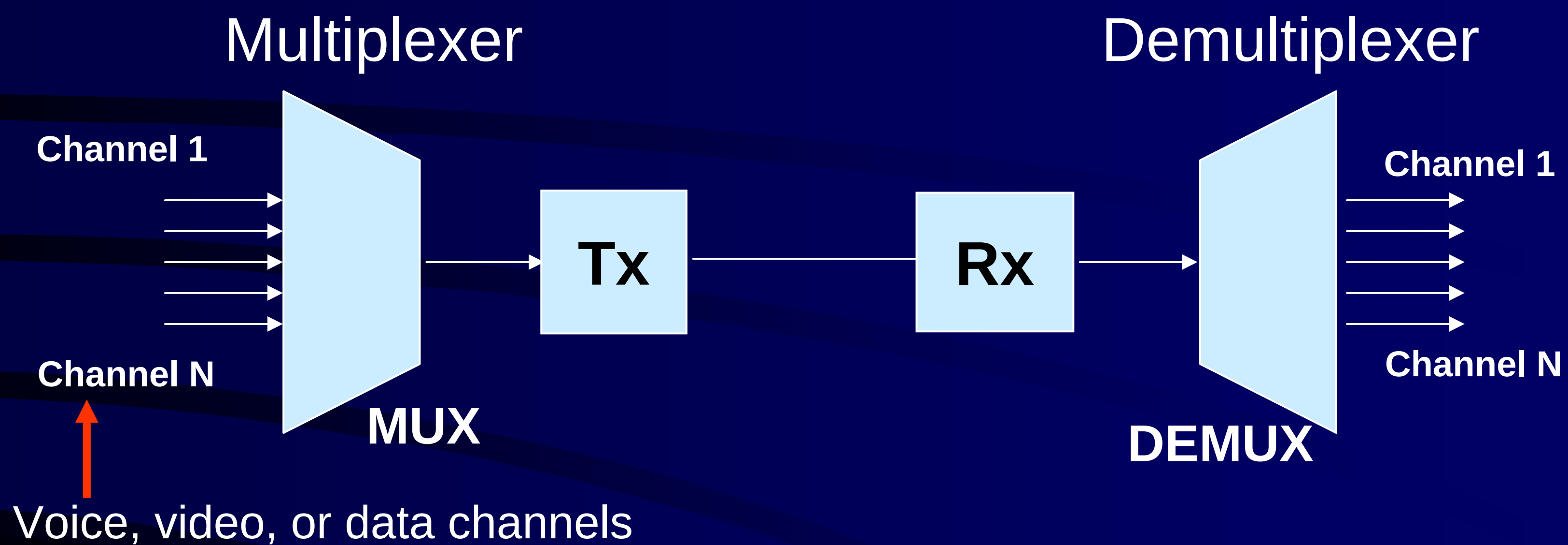
EDFA = Erbium Doped Fiber Amplifier



Bits continue in photonic format

Transparent to bit rate (< 4 Tb/s), protocol, format,…

Multiplexing

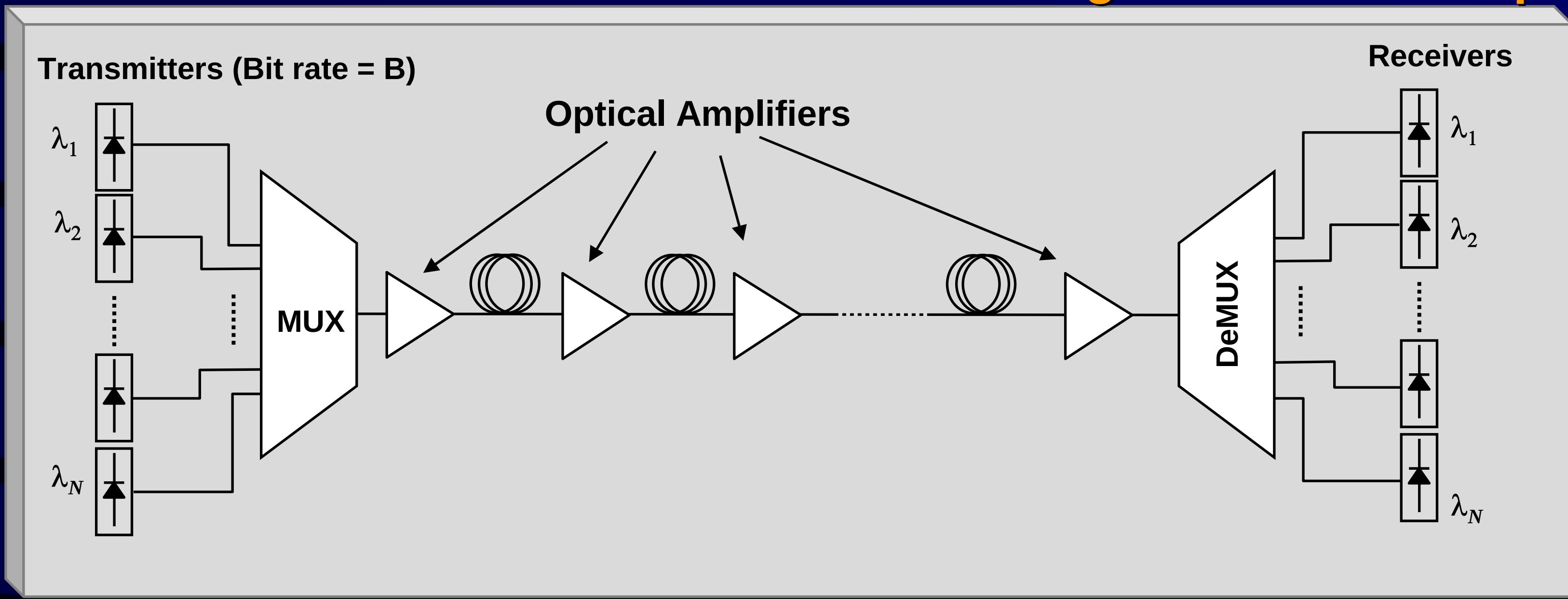


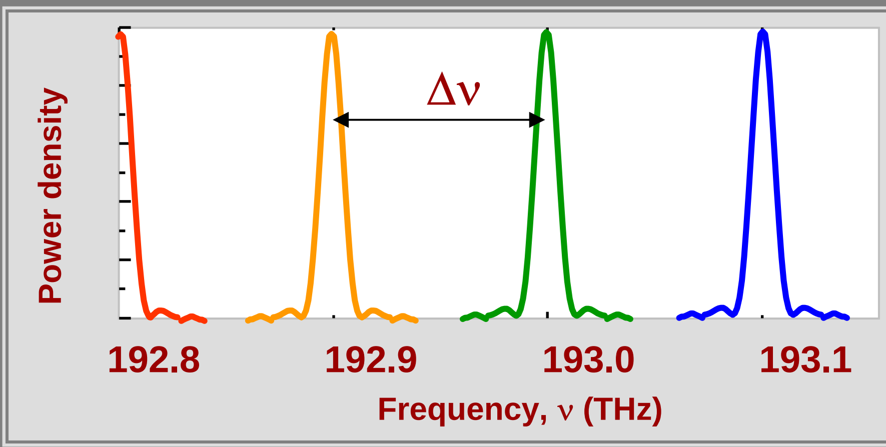
Multiplexing can be in time domain (TDM), frequency domain (FDM), Polarization (PDM), Wavelength (WDM), ...

TDM = Time Division Multiplexing,
FDM = Frequency Division Multiplexing, …

DWDM Systems

DWDM = Dense Wavelength Division Multiplexing





CWDM = Coarse WDM:
$\Delta\lambda$ = 20 nm

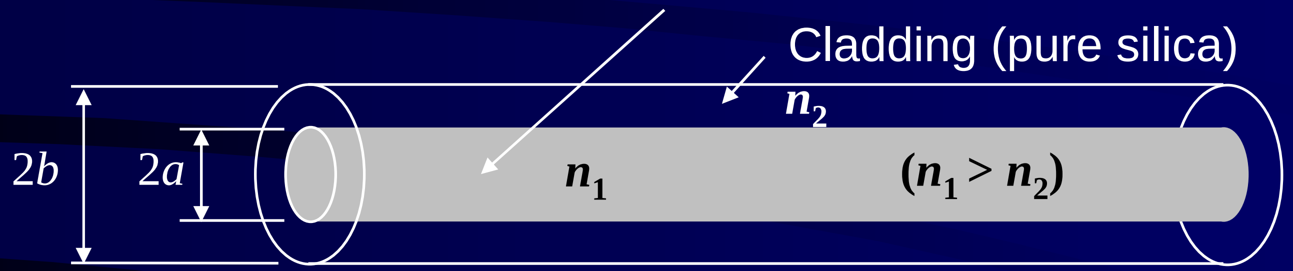
Cheaper than DWDM

Some System Components and Devices

Optical fibers
Fiber Couplers
Fiber Connectors
Lasers and Detectors
Optical Amplifiers
DWDM MUX/DeMUX
Modulators

Optical Fibers

Optical fibers are cylindrical dielectric waveguides



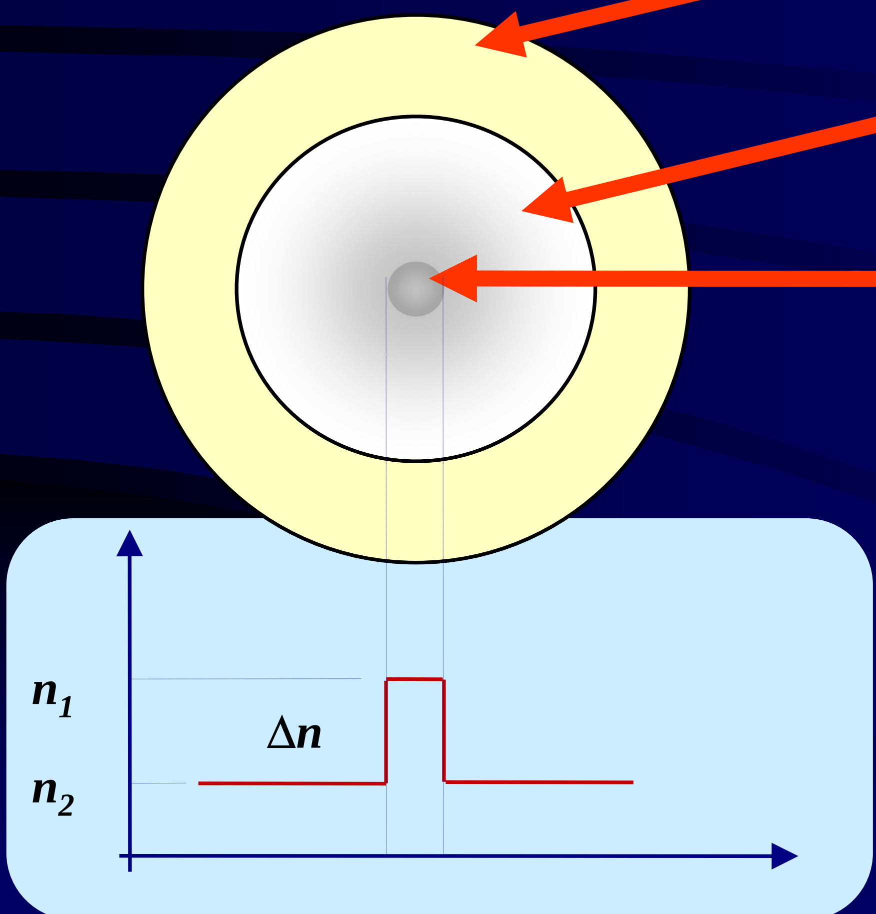
Typical dimensions

Core diameter	**2*a* = 9 to 62.5 µm**
Cladding diameter	**2*b* = 125 µm**

Typical values of refractive indices

Core:	$n_1 = 1.446$
Cladding:	$n_2 = 1.445$

Index profile



Protection cladding

Plastic (250 µm)

Cladding

pure silica (125 µm)

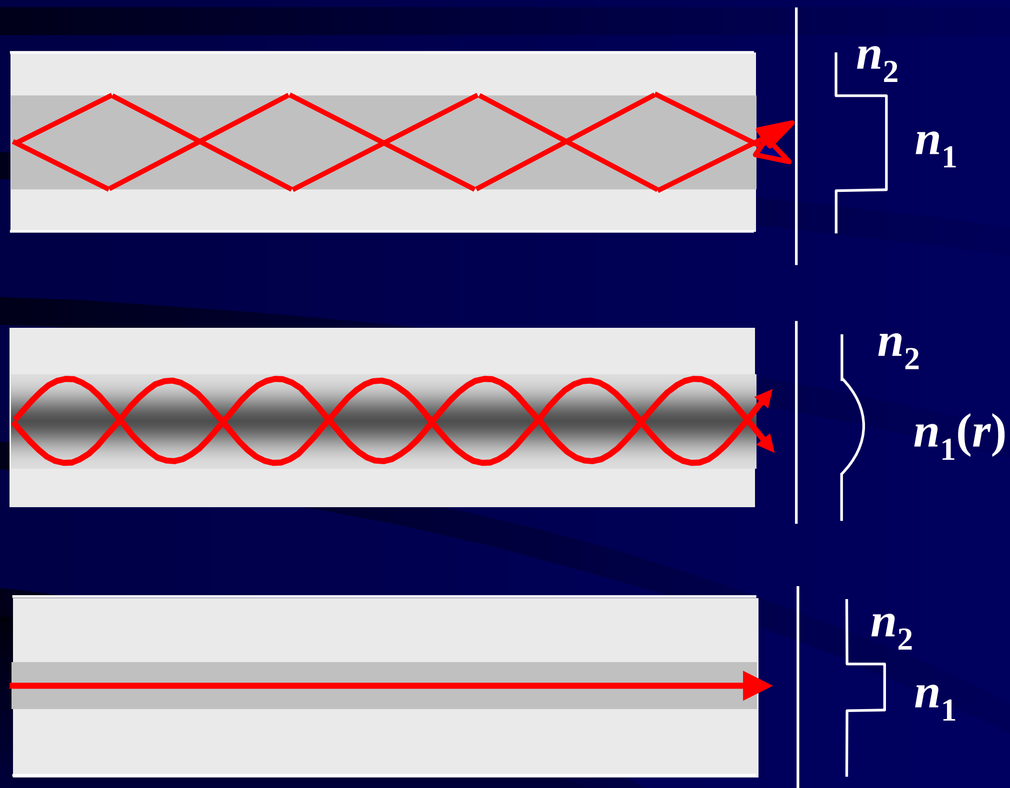
Core

Doped silica (9 – 62.5 µm)

Index step typical values:

Δn = 0.001 - 0.01

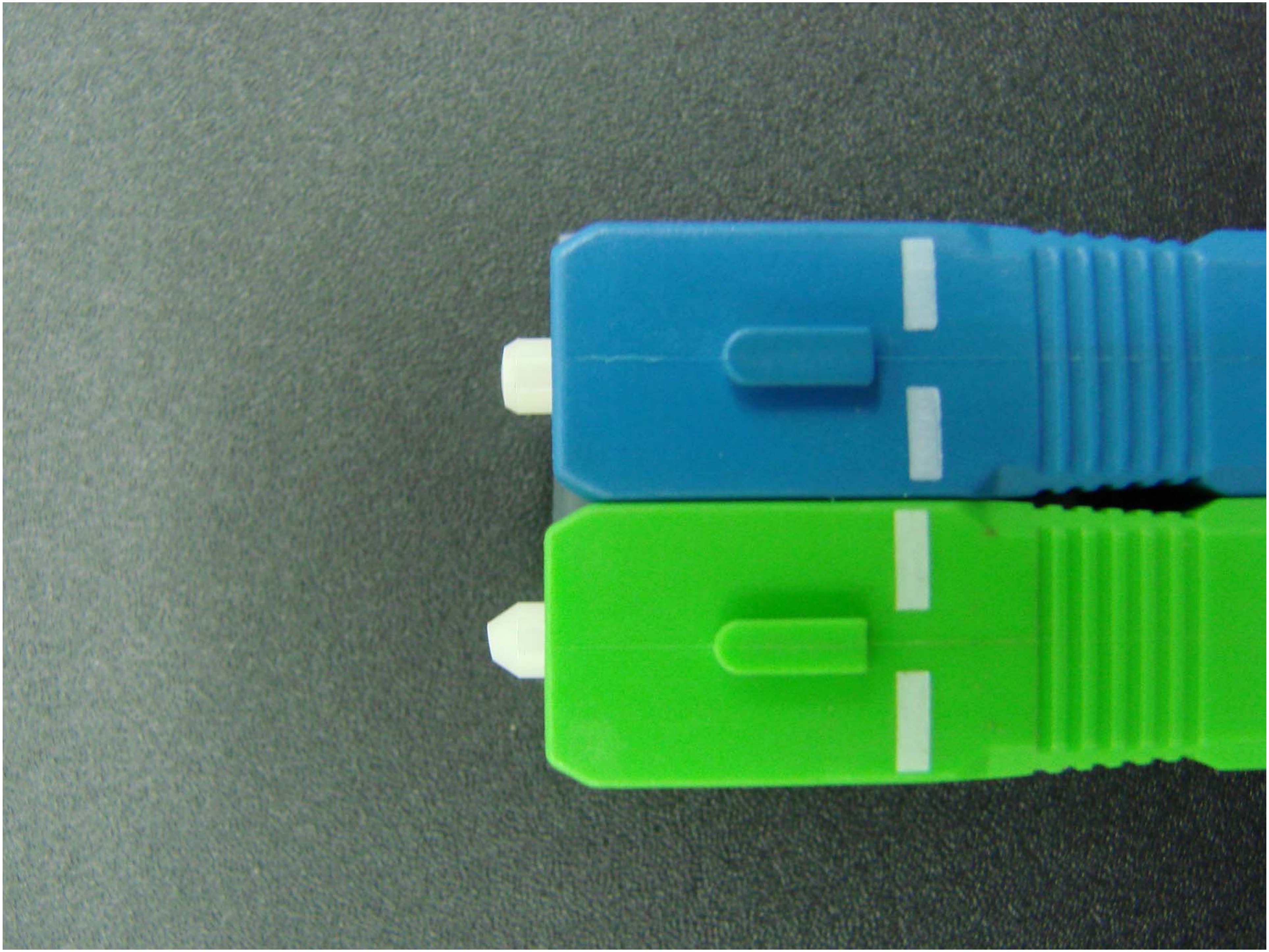
Main fiber types



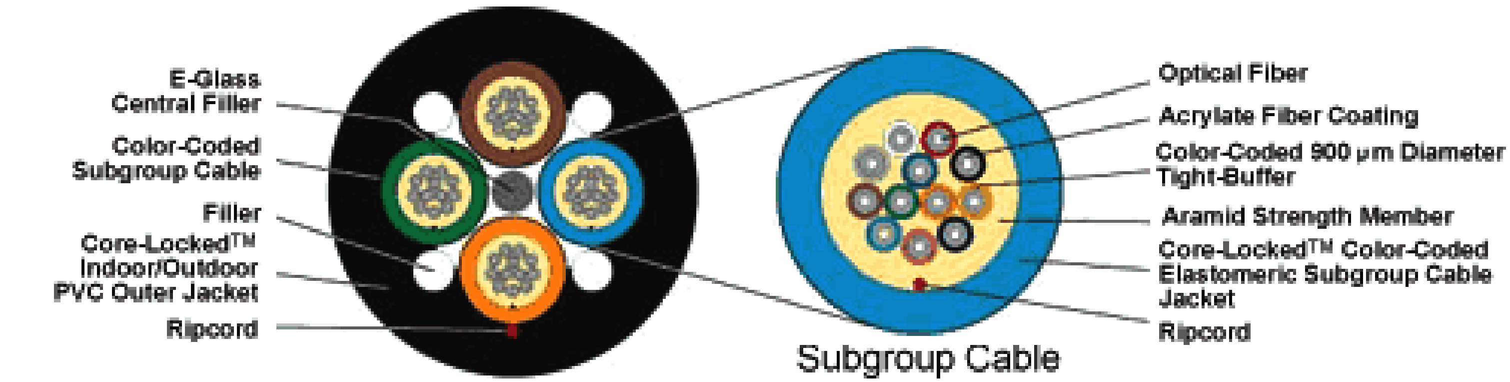
Step Index Multimode

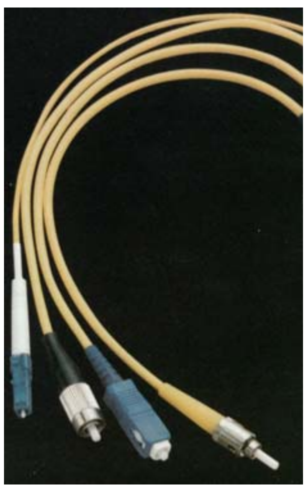
Gradual Index Multimode

Step Index Single Mode



Optical Cables

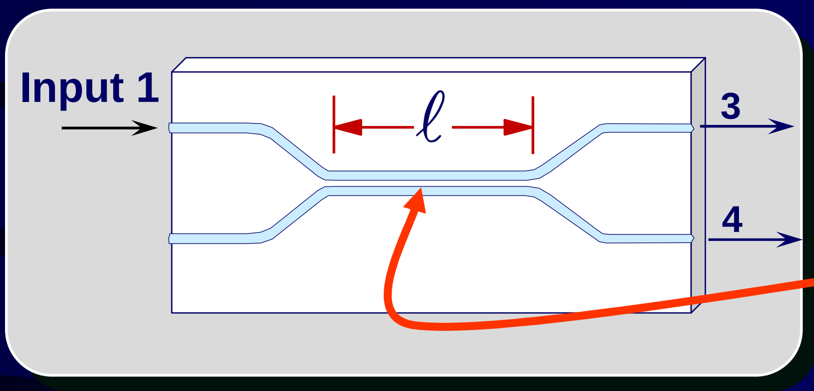




Patch cords

Optical Couplers

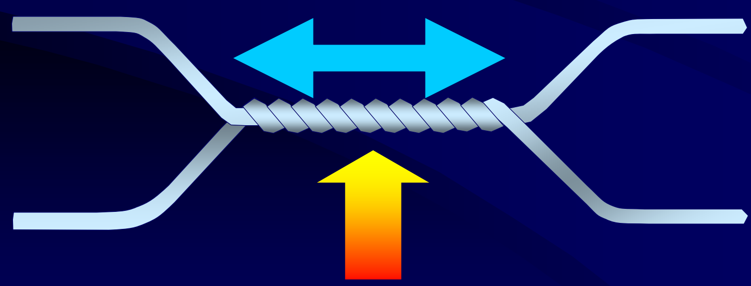
Planar waveguide device



Mode coupling through evanescent field

Fiber device

fibers



Fuse and stretch

Attenuation and Dispersion

Decibel units

Input power — **Output power**

P_{in} → **System** → P_{out}

System Transmission: $T = P_{out}/P_{in}$

$$T_{dB} = 10 \log(P_{out}/P_{in})$$

-10 dB means $P_{out} = P_{in}/10$
-3 dB means $P_{out} = P_{in}/2$
-40 dB means $P_{out} = 10^{-4} P_{in}$

dBm: Power in dB relative to 1 mW

$$P_{dBm} = 10 \log (P/mW)$$

-10 dBm means P = 0.1 mW
3 dBm means P = 2 mW
40 dBm means P = 10 W

$$T_{dB} = P_{out} - P_{in}$$

(P_{in} and P_{out} in dBm)

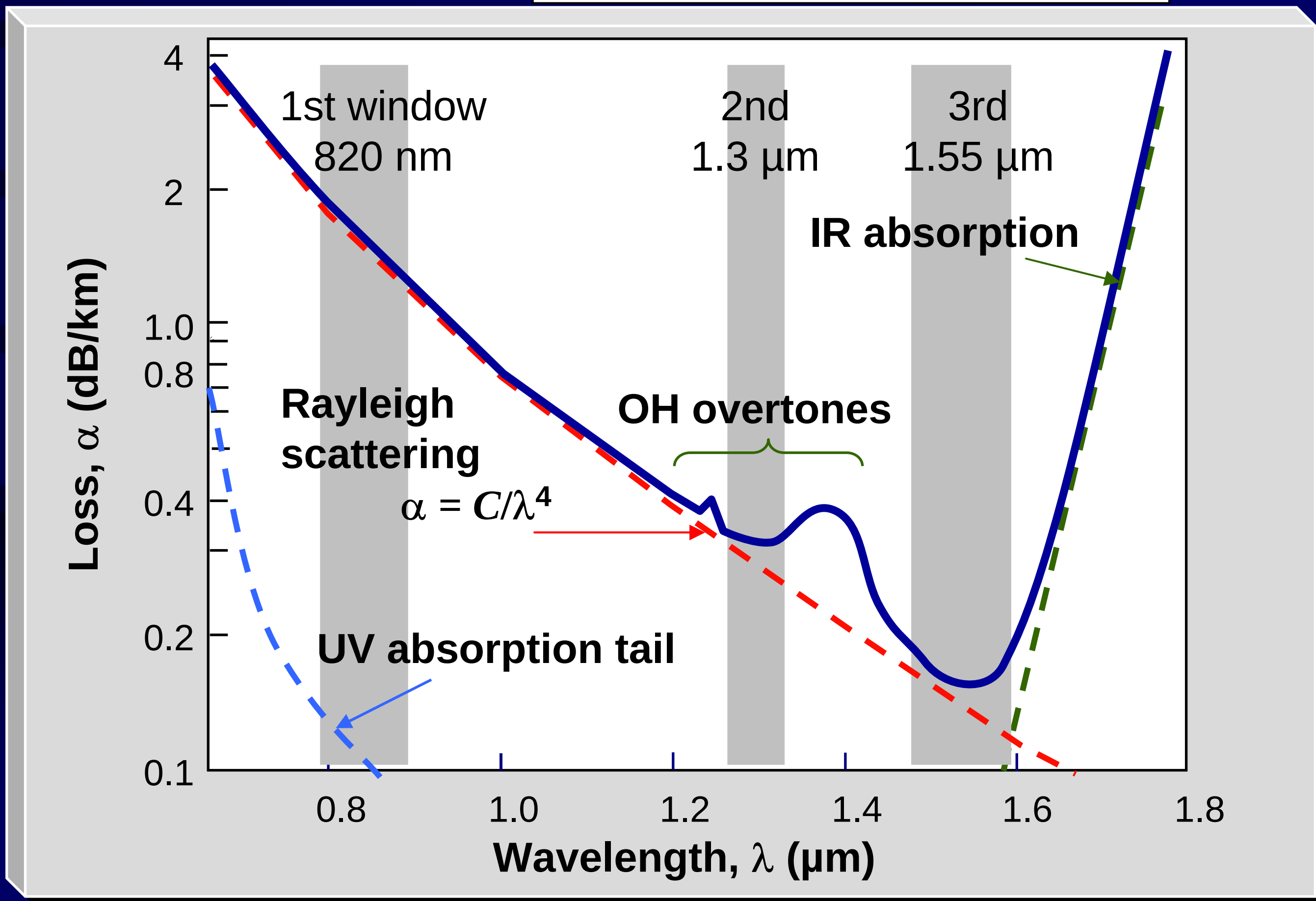
Attenuation

Optical Power at a distance L:

$$P(L) = P(0) \times 10^{-\alpha L/10}$$

Loss coefficient: α (dB/km)

$$P_{dBm}(L) = P_{dBm}(0) - \alpha L$$



Power budget

System design

(dB units)

$$P_{RX} = P_{TX} - \alpha L - N_{splices}\eta_{splice} \text{ - System margin}$$

α = 0.2 dB/km (1550 nm) or α = 0.35 dB/km (1300 nm)

Average splicing insertion loss (typically 0.5 dB)

2 – 5 dB (aging)

Sensitividade típica dos receptores:

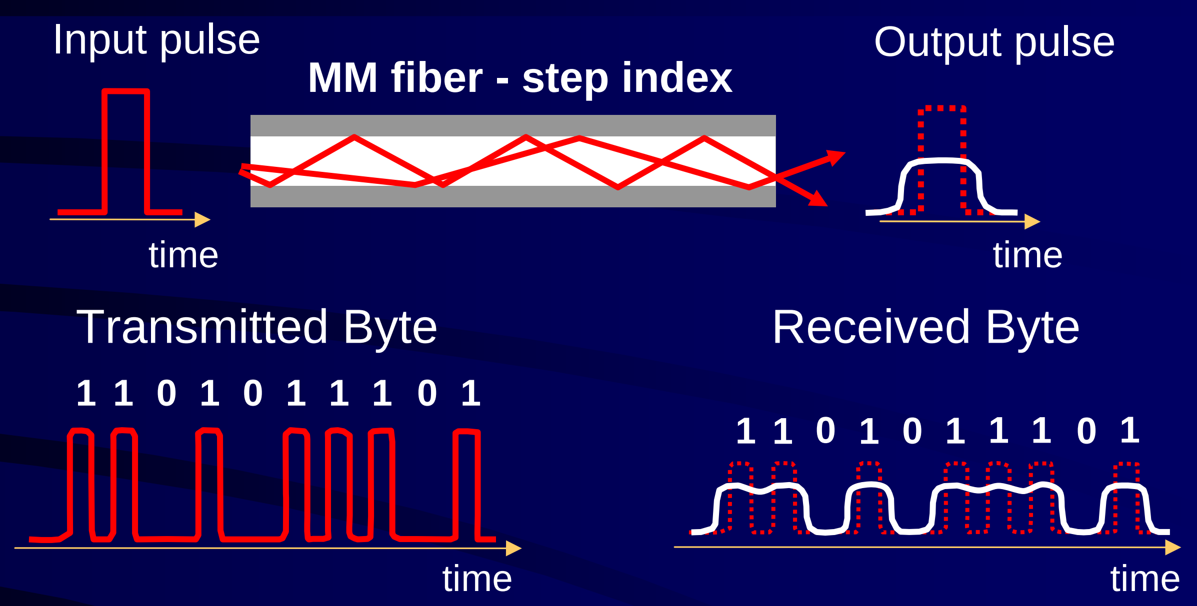
P_{RX} = -28 dBm para 1 Gb/s

P_{RX} = -19 dBm para 10 Gb/s

Potência típica de transmissores

P_{TX} = +1 dBm

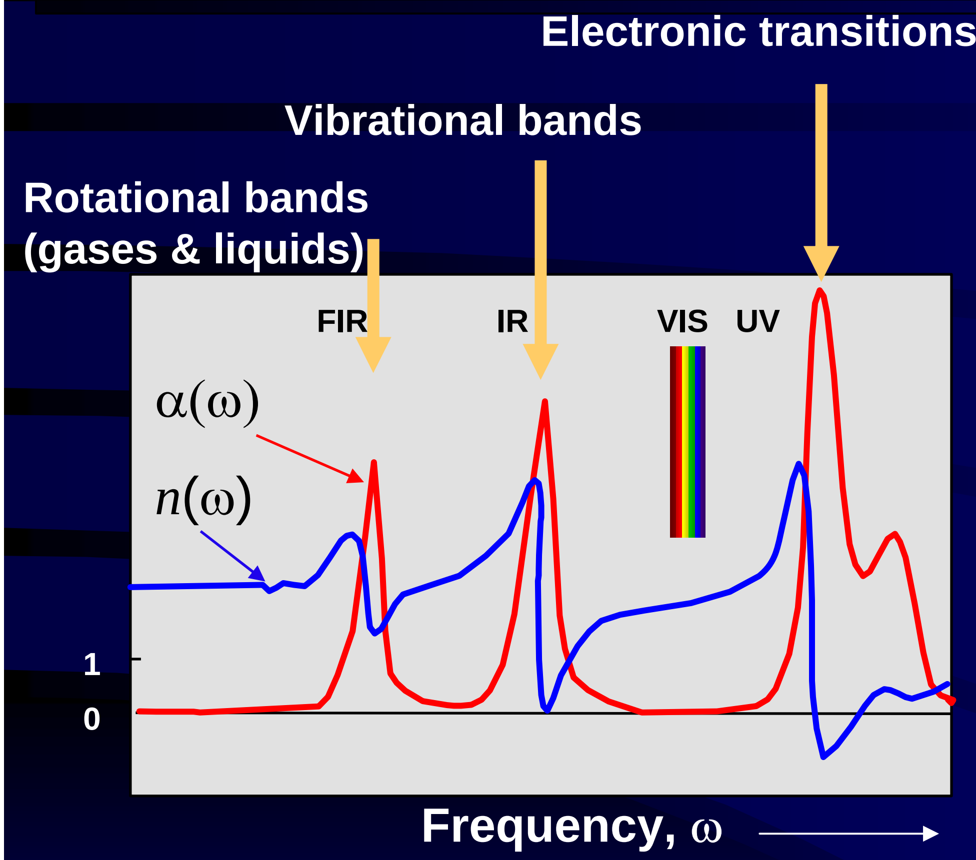
Modal Dispersion

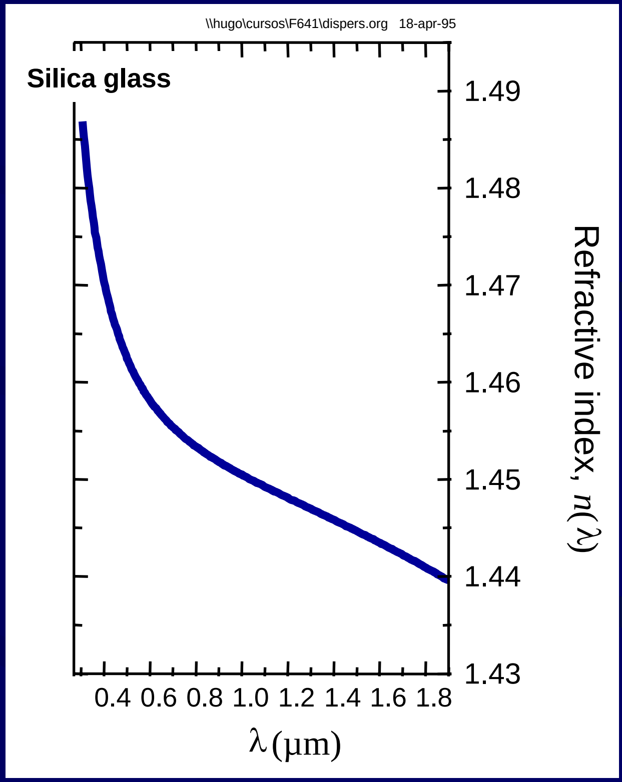


Dispersion limits the transmission capacity of fiber

Capacity of MM-step-index fibers $\cong$ 20 Mb/s $\times$ km
Capacity of MM-graded-index fibers $\cong$ 2 Gb/s $\times$ km

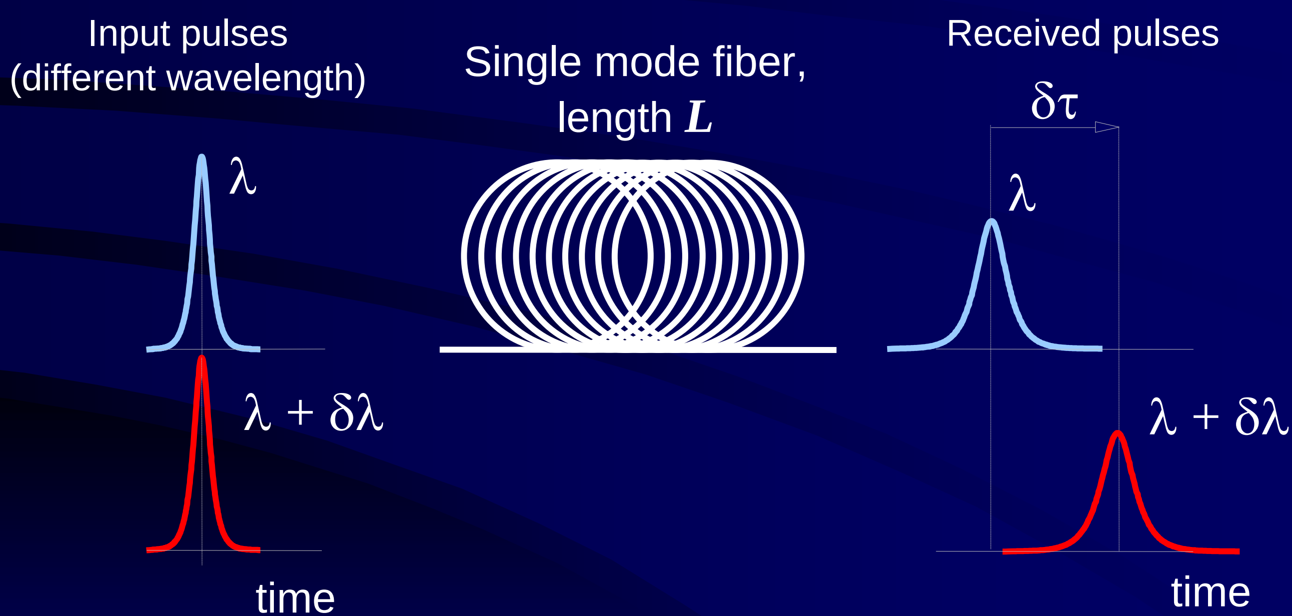
Material dispersion





Dispersion parameter

Measurement of Group Velocity Dispersion (GVD):



$$D = \frac{1}{L}\frac{\delta\tau}{\delta\lambda}$$

Dispersion parameter [ps/nm/km]

Chromatic dispersion

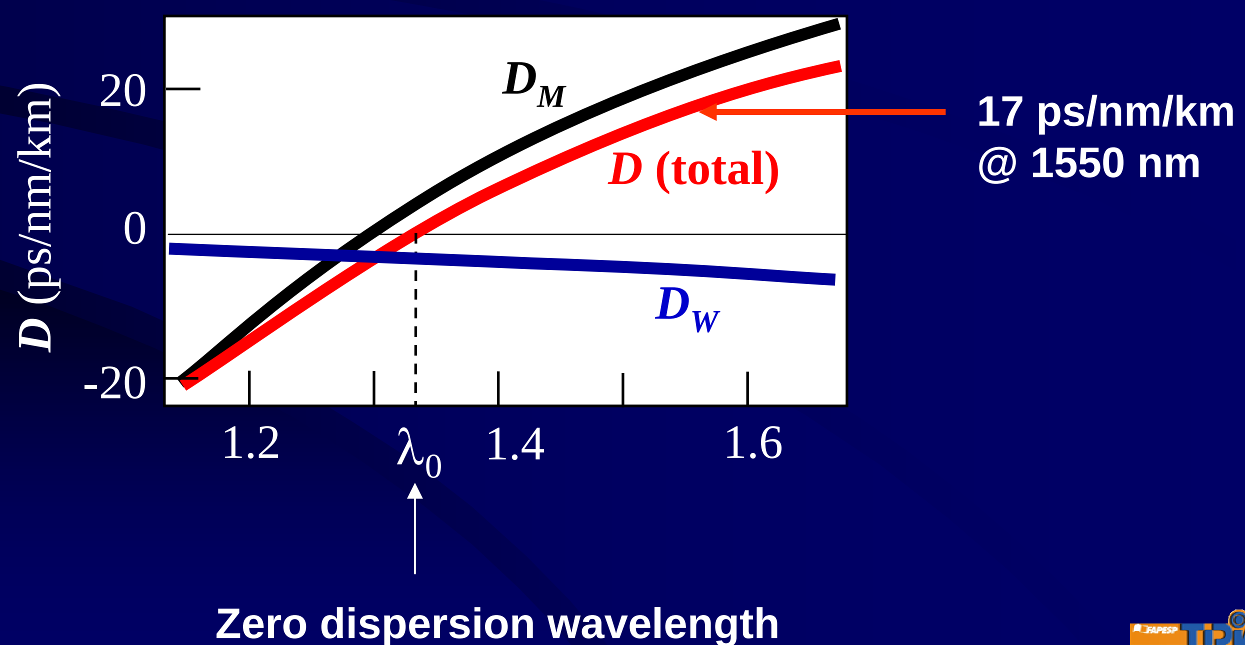
Group velocity (v_g) depends on λ

Dispersion parameter: $D = D_M + D_W$

D_M (Material Dispersion):
n depends on λ

D_W (Waveguide Dispersion):
v_g depends on waveguide geometry

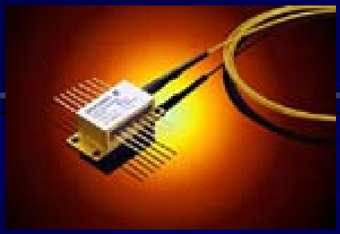
standard SMF (ITU G.652)

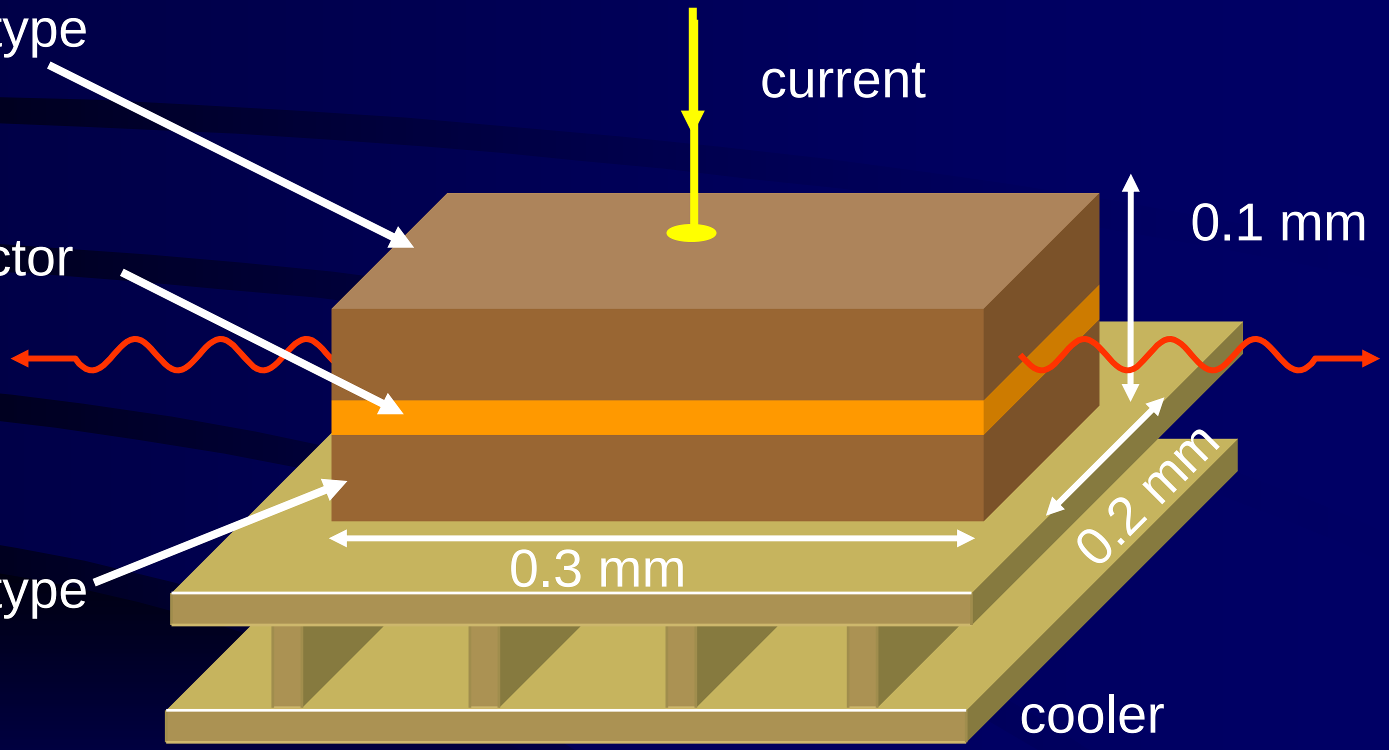


Some system components

Diode Lasers
Detectors
Modulators
Integrated optics: Mux
Amplifiers

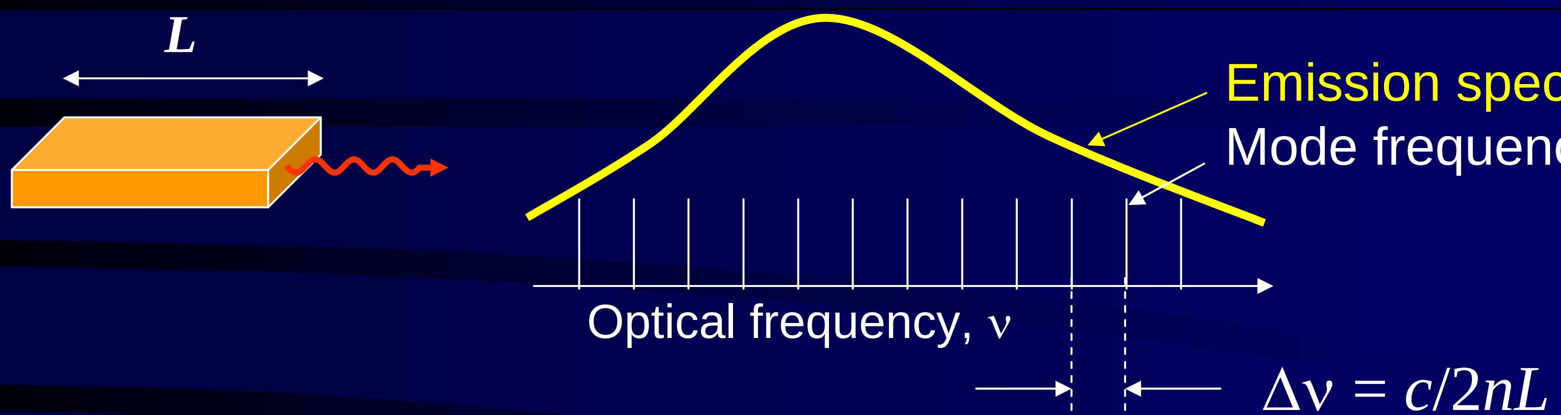
Laser diode





Fabry-Perot (FP) laser cavity

Cavity modes



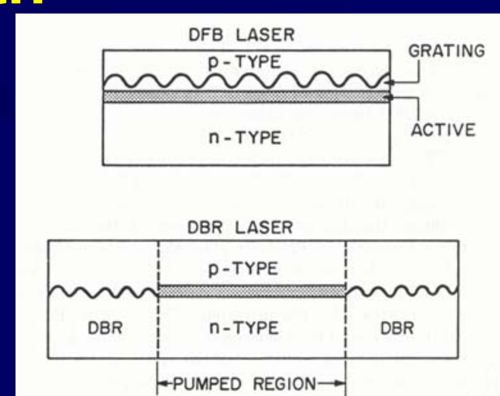
Fabry-Perot lasers ~ 30 modes (2-10 nm linewidth)

Mode jumping – Mode partition noise

DFB and DBR lasers: ~ 50 MHz linewidth

DFB: Distributed Feedback laser

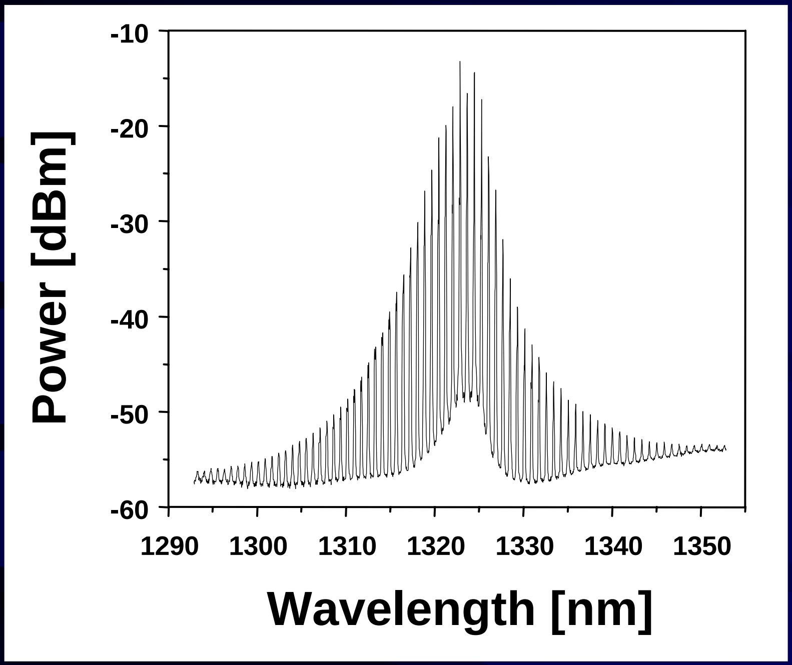
DBR: Distributed Bragg Reflector



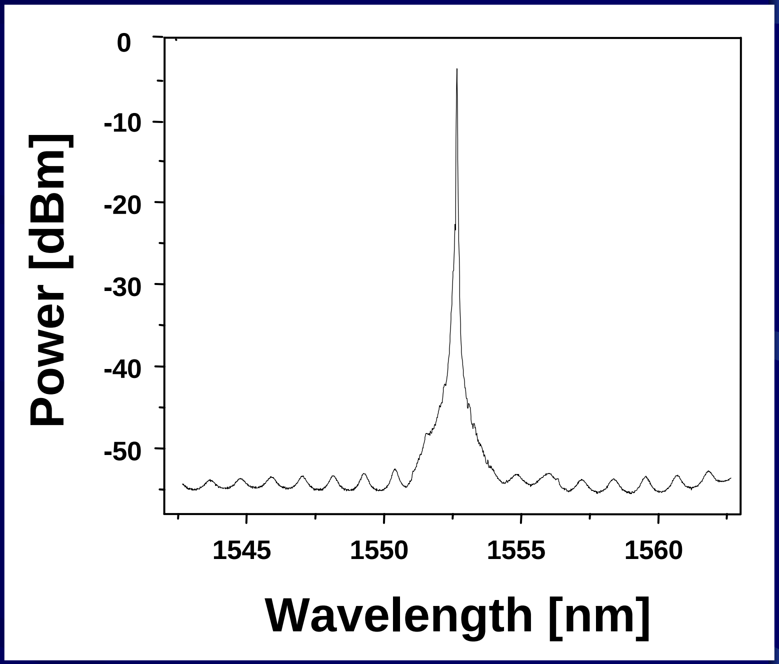
G.P. Agrawal, Fiber-Optic Communication Systems, Wiley, New York (1992)

Some laser spectra

Fabry-Perot Laser

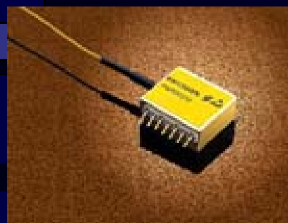


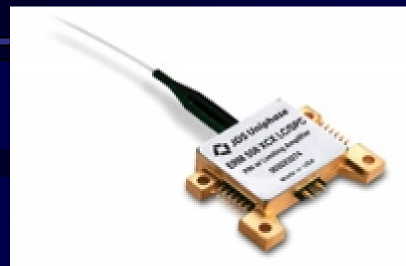
DFB Laser (B=1 Gbps)



Measurements: Dr. Diego Marconi (03 Oct 2007)

Photodiodes

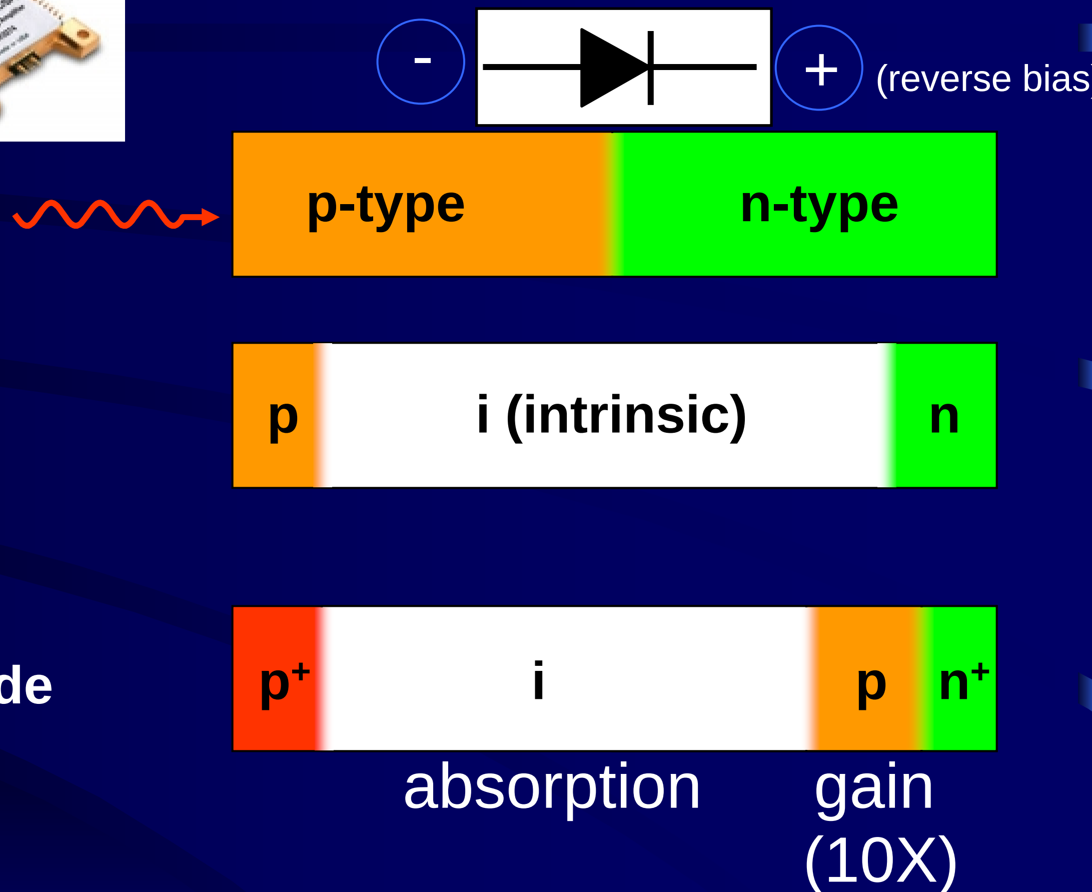




p-n junction

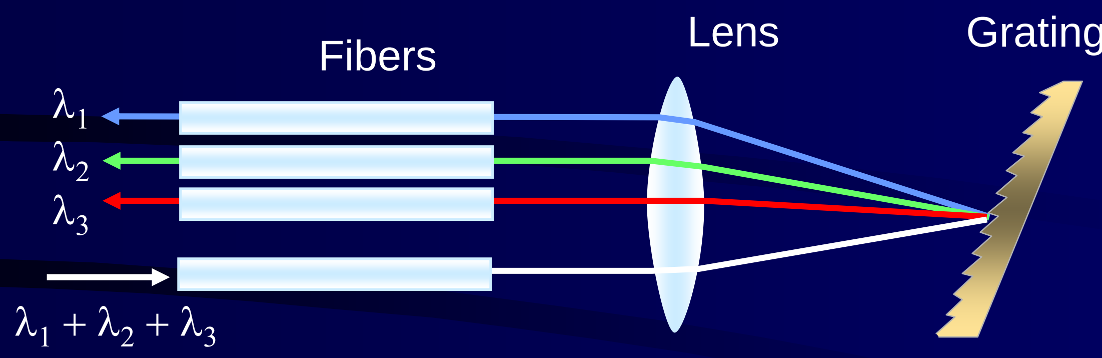
p-i-n

APD avalanche photodiode

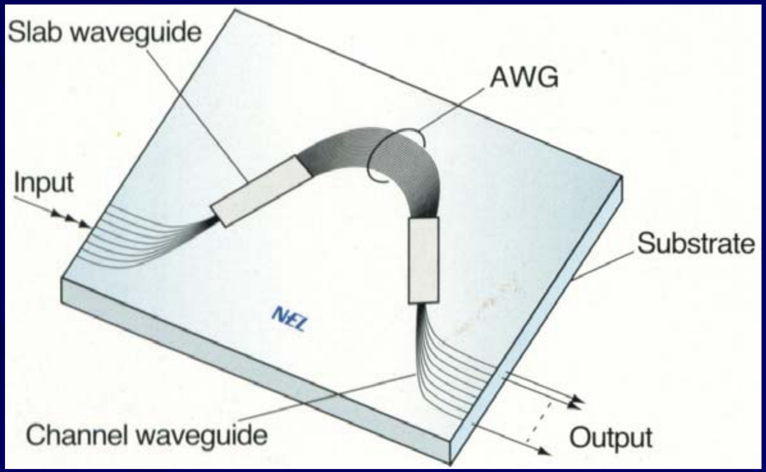


WDM Multiplexers

Free Space Grating MUX



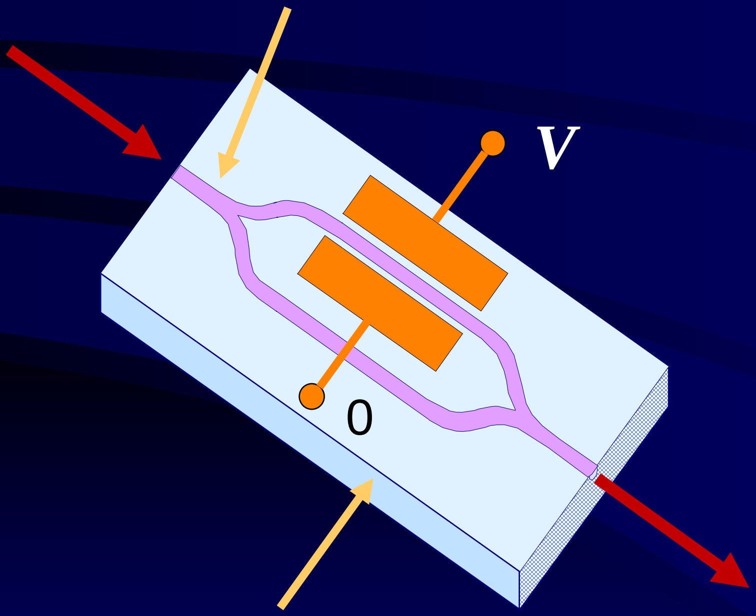
AWG: Arrayed Waveguide Grating



Modulators

Waveguide Electro-Optic Switch (KyaTera)

Waveguide (Ti in-diffused)



$LiNbO_3$ substrate

- Mach-Zehnder
- Switching voltage: 5 - 8 V
- Up to 60 Gb/s
- Integrated optics
- Fiber pigtail

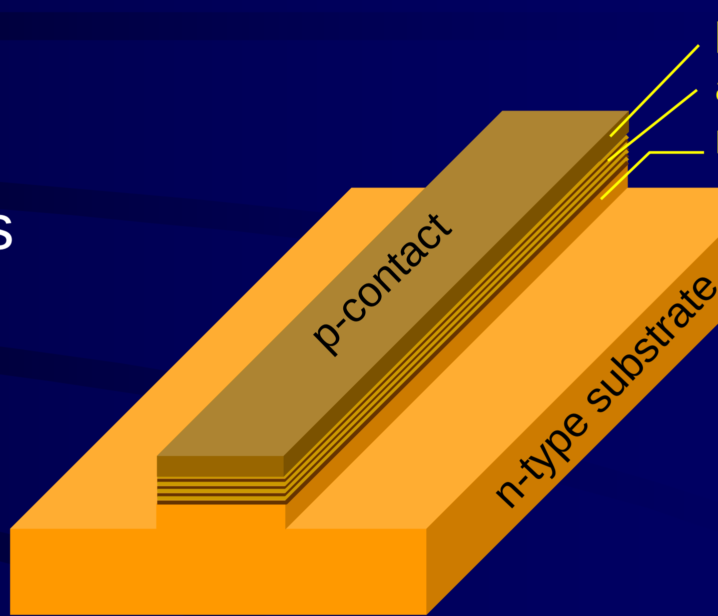
Electroabsorption modulator

Franz-Keldysh effect: energy gap of semiconductors depends on applied electric field

Effect is enhanced in Multiple Quantum Wells

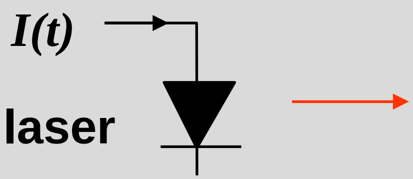
50 GHz, 2V

Integrated with laser in the same chip



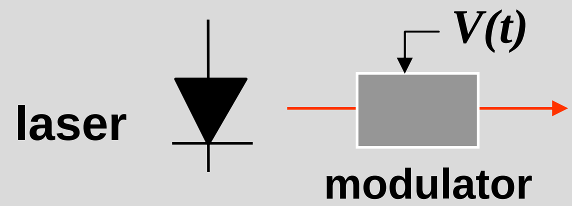
Direct versus External Modulation

Direct modulation



Broad spectral source
(~20 GHz chirp)

External modulation



Transform limited pulses

$$\sigma_t = LD\sigma_\lambda$$

Examples: D = 17 ps/nm/km; λ = 1550 nm

Fabry-Perot Laser (4 nm): 70 ps/km

DFB Laser (0.2 nm): 3 ps/km

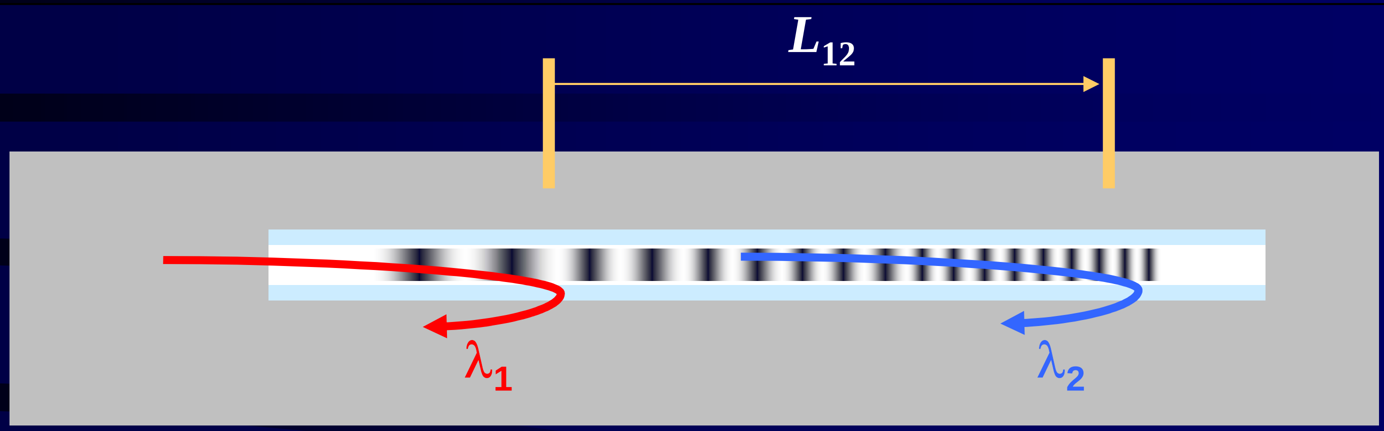
Bandwidth limited pulses:

B = 2.5 Gb/s $\Rightarrow D\sigma_\lambda$ = 0.34 ps/km

B = 10 Gb/s $\Rightarrow D\sigma_\lambda$ = 1.4 ps/km

B = 40 Gb/s $\Rightarrow D\sigma_\lambda$ = 5.5 ps/km

Chirped Fiber Bragg Gratings



- **Dispersion compensation**

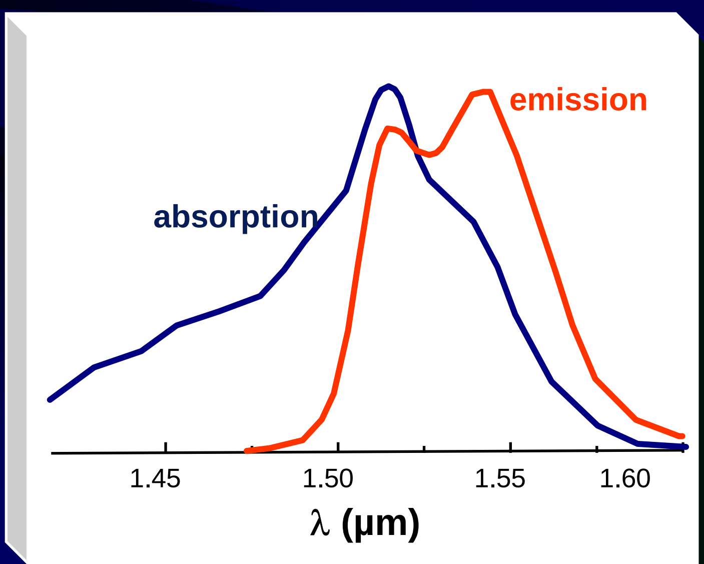
  Optical Delay $\tau_{12} = nL_{12}/c$

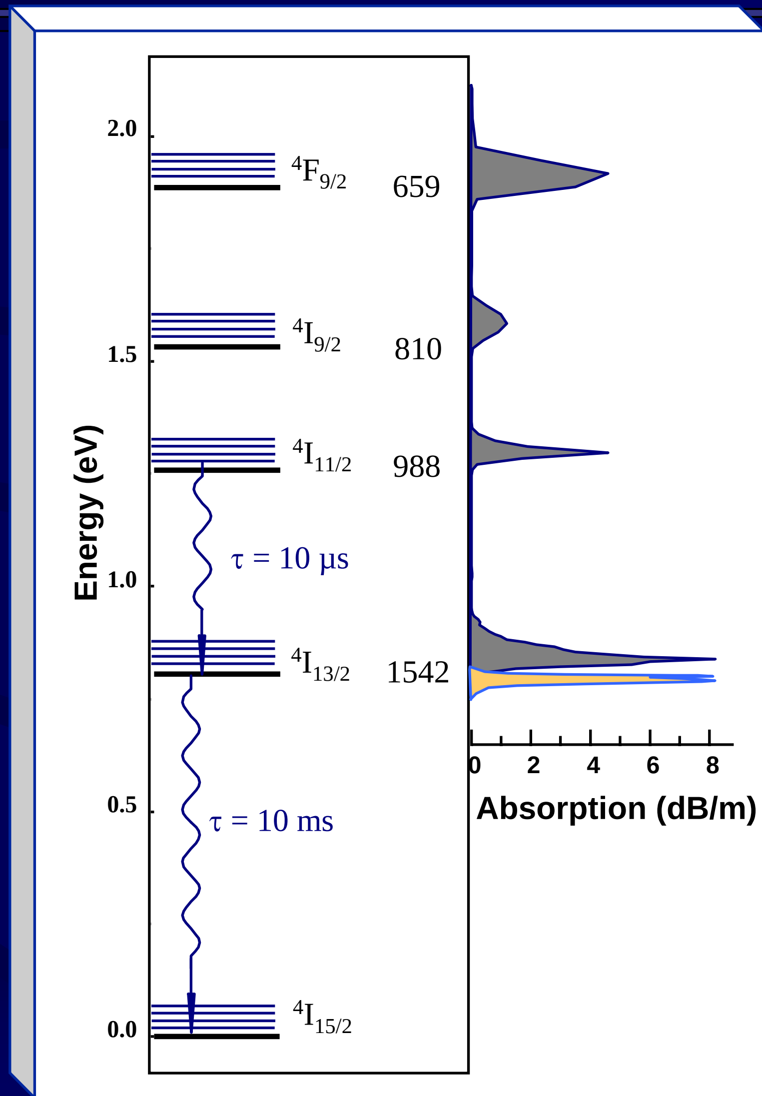
Optical Amplifiers

Er^{+3} energy levels

- Pump:
  - **980 nm or 1.48 μm**
  - **pump power > 5 mW**

- Emission:
  - **1.52 - 1.57 μm**
  - **long living upper state (10 ms)**
  - **gain ≈ 30 dB**





Characteristics of EDFA based Systems

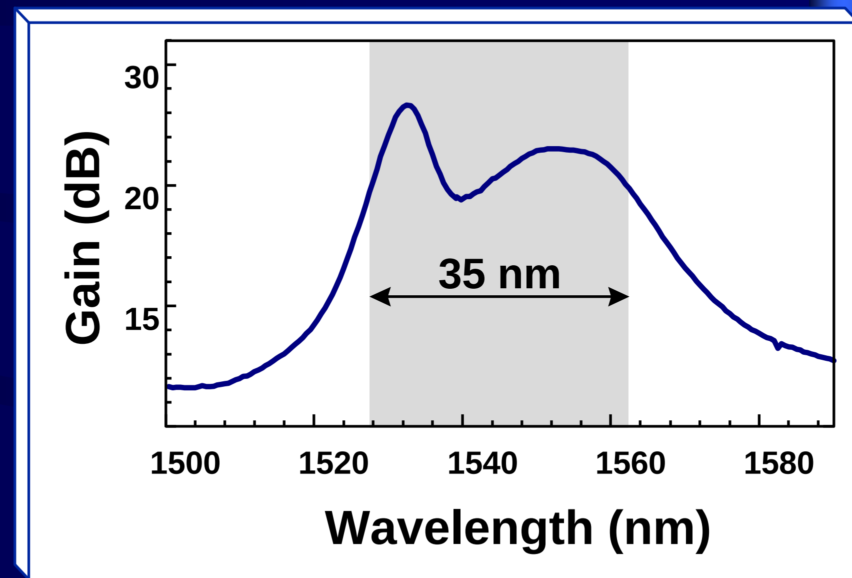
Bandwidth > 4 THz
depends on glass host
(100 nm in Telurite glass)

Low noise

Optical power > 100 mW
larger distance between EDFAs

Transparent to bit rate, modulation format,
and bit coding (transmission protocol)

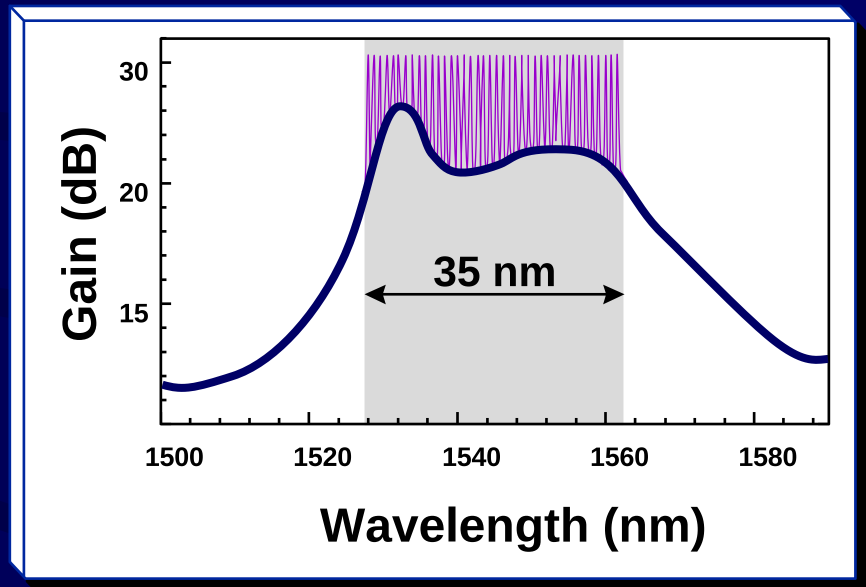
Ideal for WDM
(Wavelength Division Multiplexing)



Bandwidth of WDM systems with EDFAs

EDFA = Erbium Doped Fiber Amplifier
C band (1530-1560 nm)

- 4 THz Optical Bandwidth
- 80 WDM channels x 40 Gb/s
  (50 GHz channel spacing)
- Total capacity: 3.2 Tb/s
- Important issues:
  - **Bandwidth**
  - **Gain flatness**
  - **Output power**



Capacity of DWDM systems determined by bandwidth of optical amplifiers

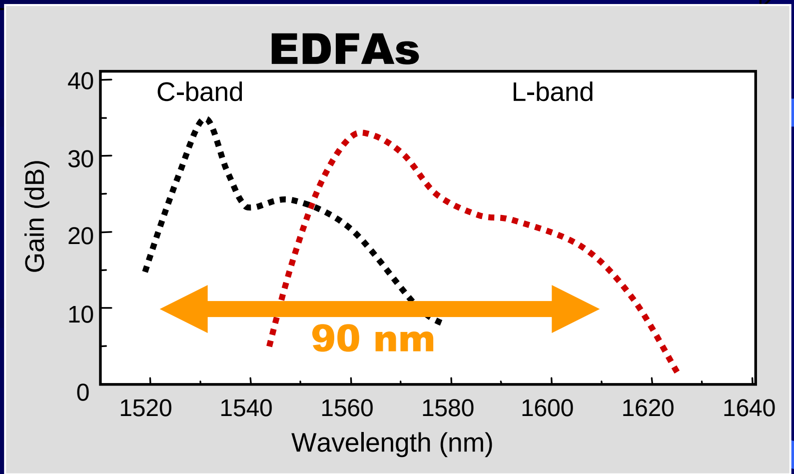
Optical Amplifiers for DWDM

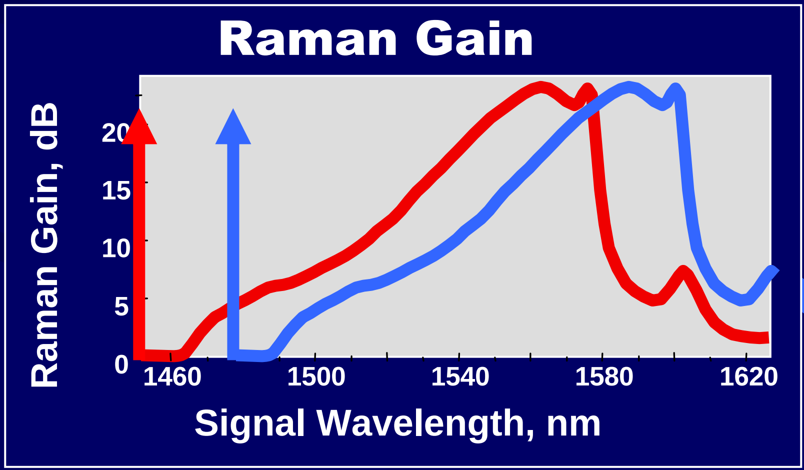
EDFA (1510-1620 nm) Erbium

TDFA (1440-1510 nm) Thulium

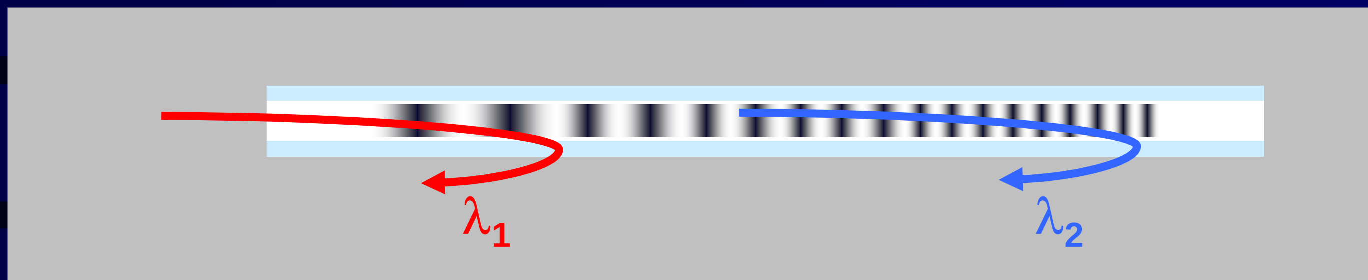
SOA (60 nm bandwidth)
Semiconductor Optical Amplifier

Raman Amplifiers (40 nm bandwidth; choice of spectral region)

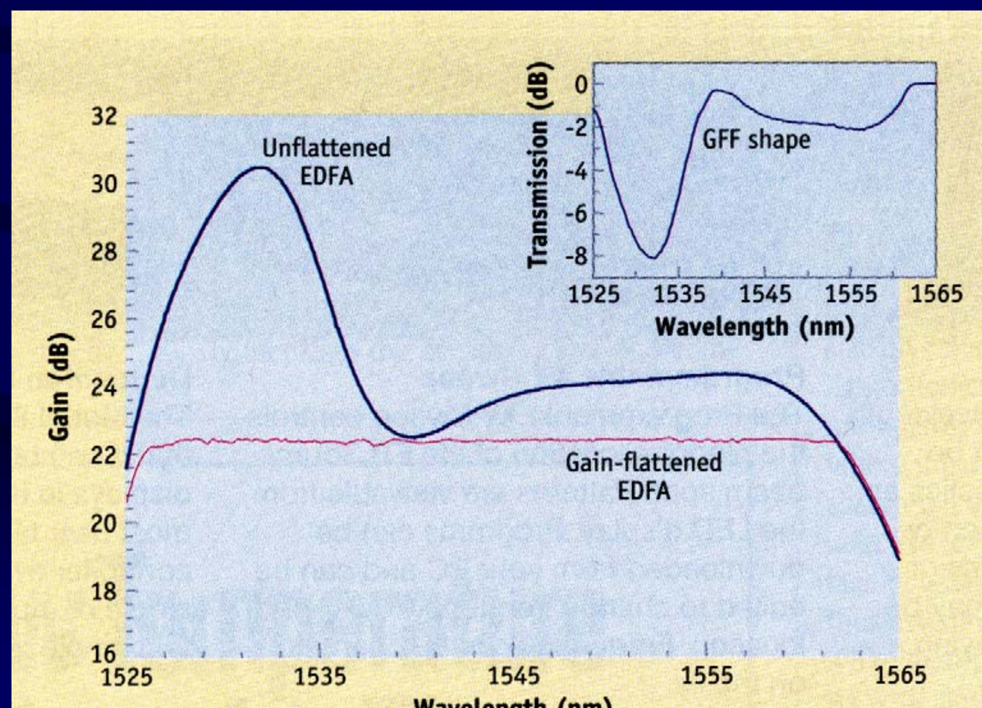




Gain Flattening Filter – GFF



Grating with varying index modulation depth



M. Guy and F. Trépanier, WDM, March 2001

The Future

“Prediction is very difficult, especially if it’s about the future.”

Niels Bohr
1922 Nobel Prize in Physics

Internet in the future

- **20 years ago**
  - Telephony network
  - 64 kb/s per voice circuit
  - <u>Passive user</u>

Metropolis,
Fritz Lang (1927)

- **Today**
  - Network with variety of uses/services (voice, data, video, radio,…)
  - <u>User generated content</u> (wikis, youtubes, blogs, mushups,…)
  - Mb/s per user
  - > 1 billion internauts
  - Cost per bit reduced by one million

  - But, a jungle of technologies (with different languages) – Tower of Babel
  - 100 billion spam/day, viruses, insecure, vulnerable, fragile
  - Increasing socioeconomic dependence of the Internet

- **Tomorrow**
  - Infinity of applications and content
  - Super high resolution video
  - 5 billion users – Gb/s per user (and we humans will be minority…)
  - FTTH
  - Secure, robust, inexpensive broadband Internet, convergence of technologies

- **Which scientific advances will enable such future?**

  100 to 1000 increase in capacity in 20 years

FAPESP TIDIA KyaTera

100 to 1000 times the present capacity?

- Grand challenges for optical communications:

1. Technology Problem:
   - DWDM today 40 channels – does it scale to 4000 channels?
   - Today's amplifier technology does not scale
   - Electronic routing technology does not scale
2. Real state problem
3. Energy consumption problem
4. Costs: big problem

- Perceived paths:
  - Optical amplifiers for the whole high-transparency window of silica
  - Integrated optical circuits (hundred lasers in a chip)
  - All optical networking
  - …

DWDM equipment today

$ 20 thousand/channel

Padtec KyaTera

X 100 ?

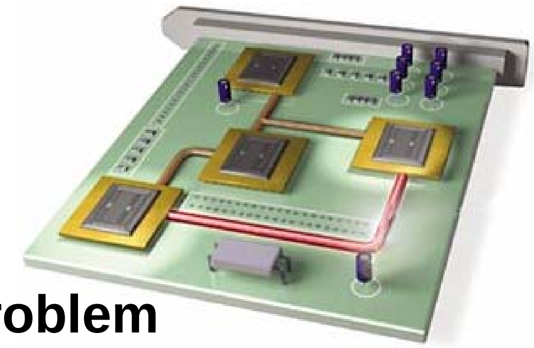
$ 100 million (at ~every node in the network)

50 kW

100 m² footprint

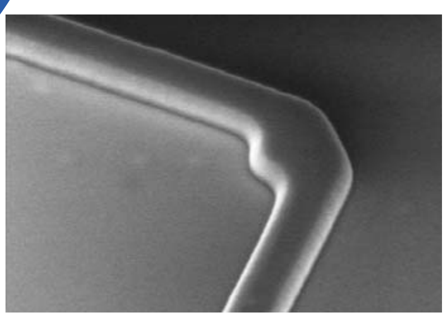
Opportunities for nanophotonics

- *Nanoturization: a*lleviates real state problem
- Optical interconnects: alleviates power consumption problem
- Integrated optical devices: alleviates cost problem

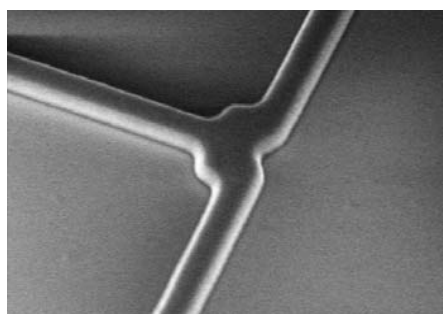


- But… a whole family of passive and active nanophotonic devices must be developed

Bends

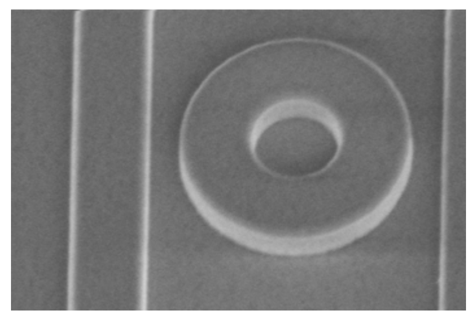


Splitters



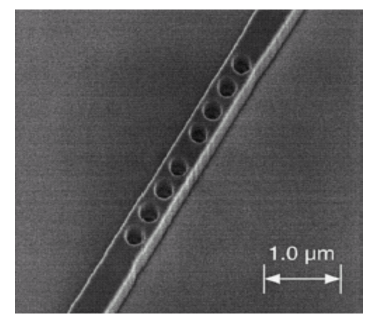
Massachusetts Institute of Technology , 2000

Filters



Cornell Nanophotonics Group 2003

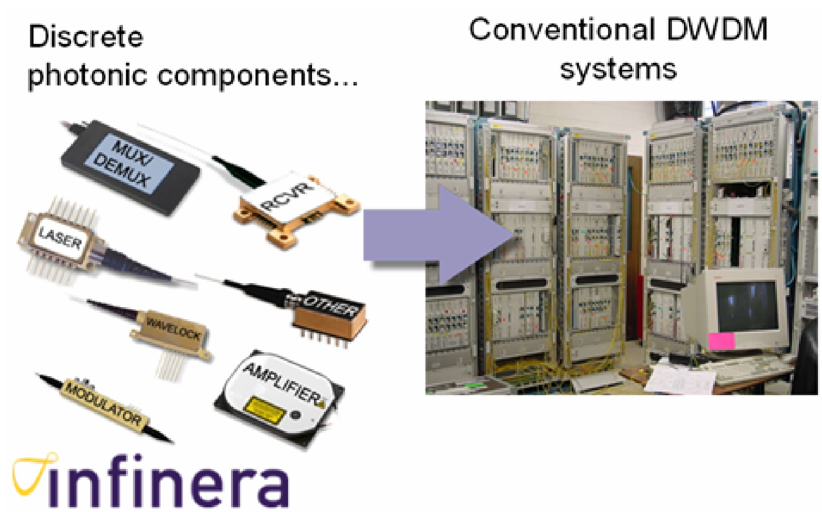
Cavities



J. S. Foresi et al.
Nature* 390, *143 (1997)

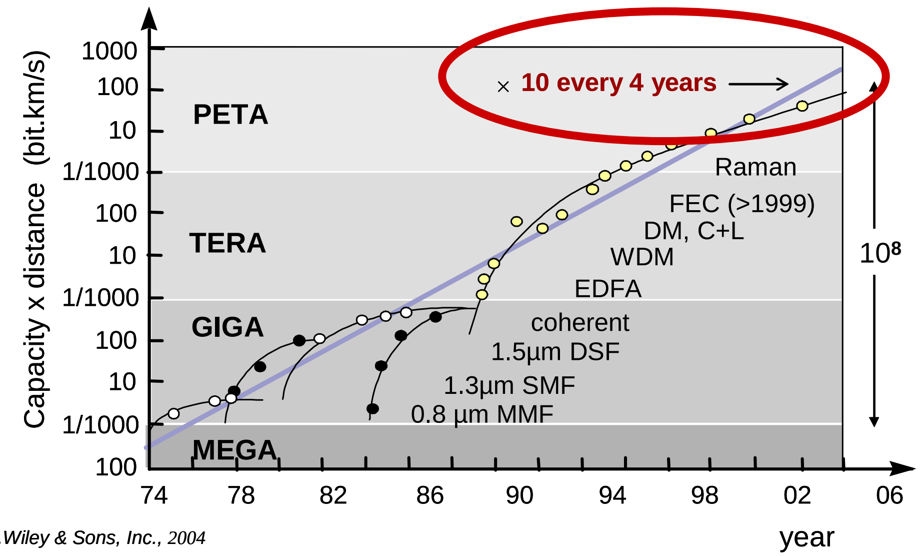
(Courtesy: Michal Lipson)

The real state problem



10 DWDM transmitters/receivers in an InP chip (Infinera)

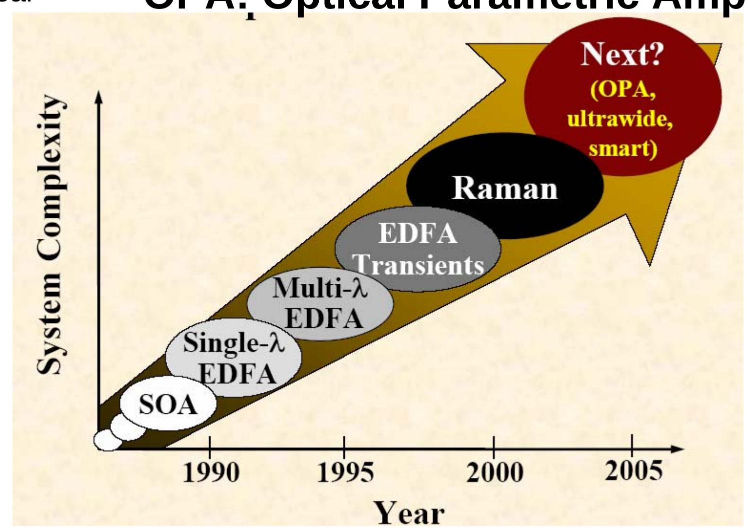
Technology Roadmap



Evolution of telecommunications (Emmanuel Desurvire, 2006).

X 10^5 in 20 years?

OPA: Optical Parametric Amplifiers



Evolution of optical amplifiers (Alan Willner, 2006).

Optical Amplifiers for DWDM

DWDM: Dense Wavelength Division Multiplexing

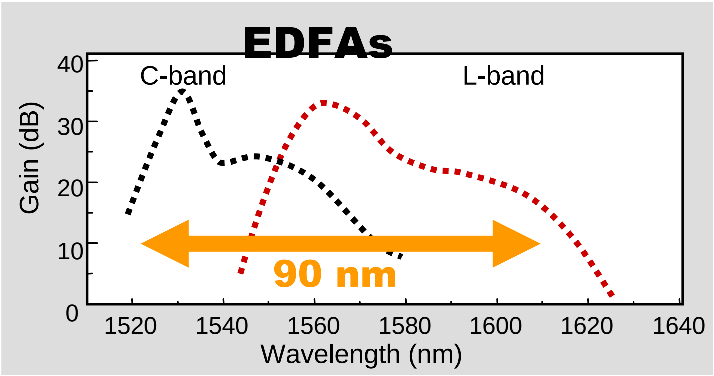
Existing technologies, such as

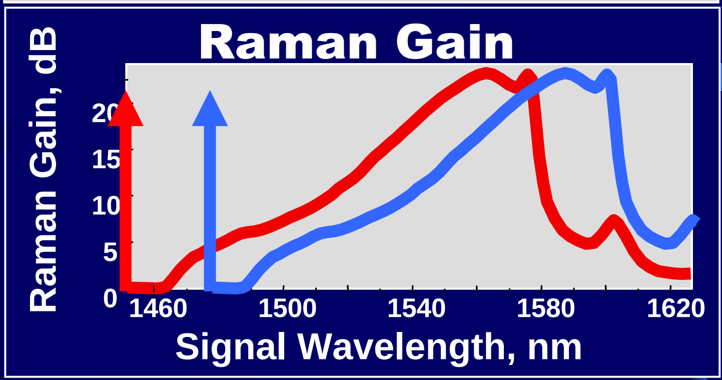
REDFA (Rare-Earth Doped Fiber Amplifiers),
SOA (Semiconductor), and
Raman amplifiers
…

are limited by Nature to ~ 100 nm bandwidth

Physics: Position of quantum energy levels

Chemistry: Spectral broadening - special materials





FOPAs

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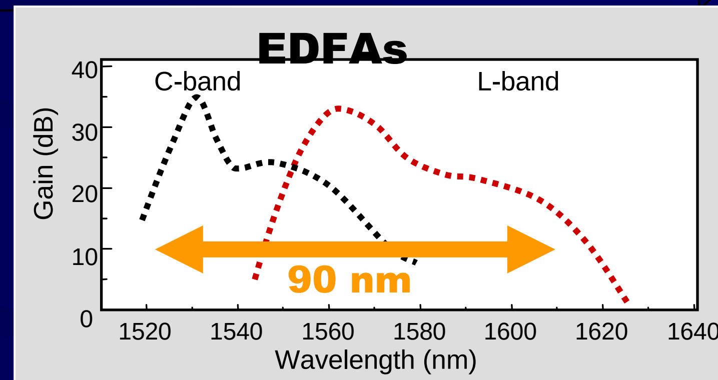
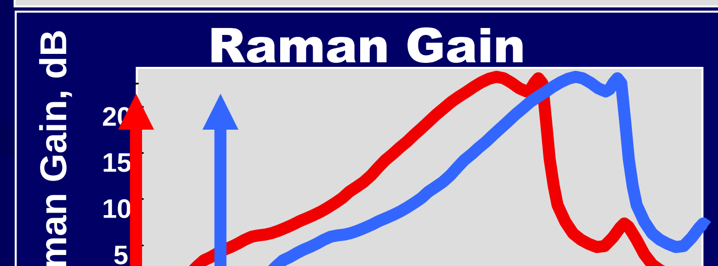
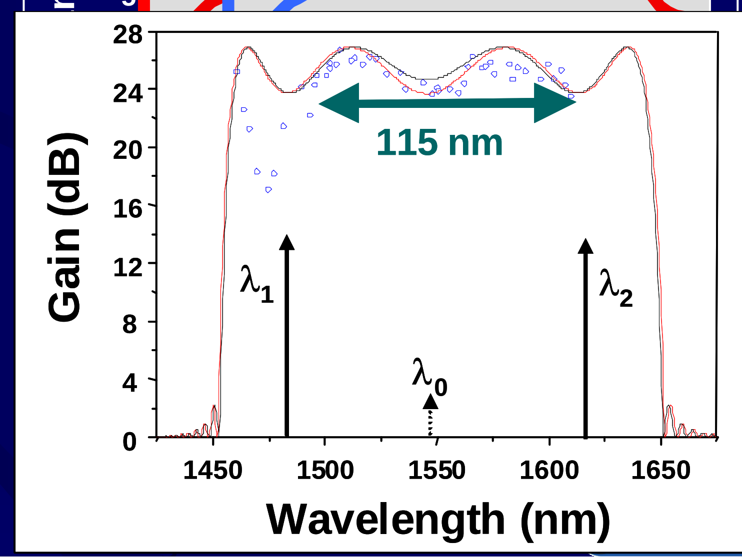
FOPAs – Fiber Optic Parametric Amplifiers

Bandwidth and spectral region can be engineered by choosing waveguide dispersion

… controllable by waveguide design





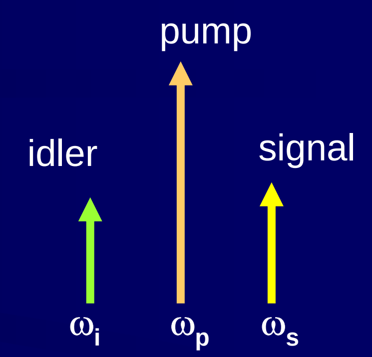


J. M. Chavez Boggio, J. D. Marconi, S. R. Bickham, and H. L. Fragnito, Optics Express 15, 5288-5309, 2007.

Fiber-Optic Parametric Amplifiers

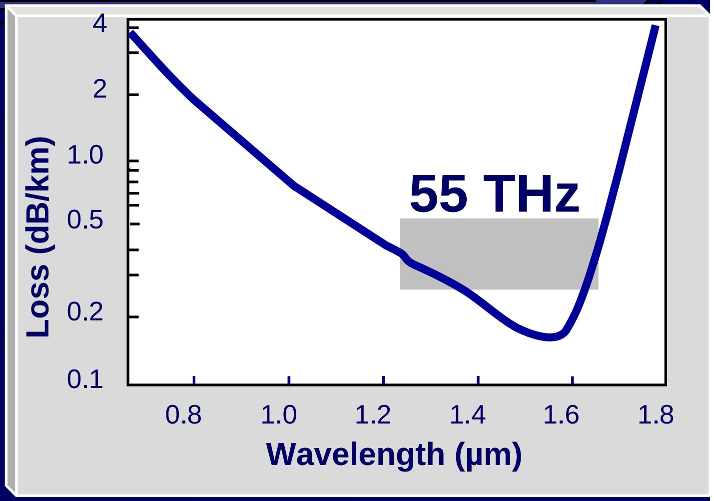
FOPAs

- Based on nonlinear refractive index
- Pump laser near zero dispersion wavelength
- Idler wave generated
  - can be used as wavelength converter
- Typical pump power, fiber length, gain, bandwidth:
  - **P = 0.1 – 1 W, but few mW in nanophotonic waveguides**
  - **L = 0.2 – 5 km, but few cm in nanophotonic waveguides**
  - **G = 20 – 40 dB (up to 70 dB demonstrated)**
  - **$\Delta\lambda_{3dB}$ = 20 – 60 nm (> 100 nm demonstrated)**



$$\omega_i = 2\omega_p - \omega_s$$

The ideal optical amplifier



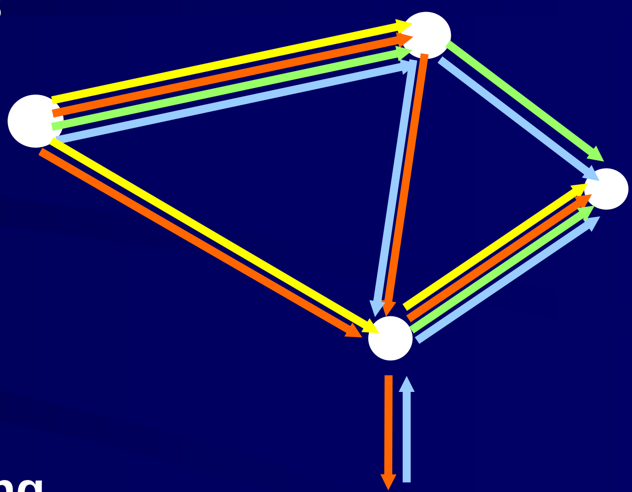
- **Explore the full capacity of silica fibers (1250-1650 nm) with a single device**
  - 54.5 THz bandwidth
  - 1164 channels @ 40 Gb/s = 46.6 Tb/s
  - (M-1) x 46.6 = 140 Tb/s (M = 4) for M-ary format
- **400 nm bandwidth, flat gain spectrum, high output power**
- **Is it possible? Do we need it? Do we want it?**
- **If yes, probably the only option is the FOPA (Fiber-Optic Parametric Amplifier or Waveguide-OPA)**
- **But FOPDs can do much more than just amplify signals…**

WDM Networking

- **WDM networks need new functionalities**
  - Add and Drop Channels Optically
  - Wavelength Routing Assignment
  - Wavelength reuse

- **Wavelength Conversion**

- **FOPDs met the needs of WDM networking**



OADM
Optical Add & Drop Multiplexer

Questions?