IARIA – NexTech 2013 – Porto, Portugal

2013, September 29th

Optical Fibers – How the Physical Impairments Limit Transmission Capacity

Fundamental Concepts and the State of Art

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Professional Background

Antonio Sachs

- Graduation in Physics (1973)
  UNICAMP – University of Campinas
- Physics teaching experience (1973-1978)
  PUCC – Pontifical Catholic University of Campinas
- Master in Science degree at UNICAMP (1978)
  - Solar Cells
- Research and Development Center of Telebrás – CPqD – (1978-2004)
  - Crystal growth; laser and photo detector manufacturing
  - Optical fiber systems; Optical Networking
- PhD degree (2011)
  USP – University of São Paulo
  - Self Organized Optical Packet Switching Network
- Teacher and researcher in collaboration with LARC/USP (since 2005)

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- Escola de Artes, Ciências e Humanidades (EACH)
- Escola de Comunicações e Artes (ECA)
- Escola de Educação Física e Esporte (EEFE)
- Escola de Enfermagem (EE)
- **Escola Politécnica (POLI)**
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- Faculdade de Medicina Veterinária e Zootecnia (FMVZ)
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- Instituto de Química (IQ)
- Instituto de Relações Internacionais (IRI)
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- Instituto de Física de São Carlos (IFSC)
- Instituto de Química de São Carlos (IQSC)

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- Escola de Engenharia de Lorena (EEL)

Campus de Piracicaba

- Centro de Energia Nuclear na Agricultura (CENA)
- Escola Superior de Agricultura "Luiz de Queiroz"

Campus de Pirassununga

- Faculdade de Zootecnia e Engenharia de Alimentos (FZEA)

Campus de Ribeirão Preto

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- Faculdade de Ciências Farmacêuticas de Ribeirão Preto (FCFRP)
- Faculdade de Direito de Ribeirão Preto (FDRP)
- Faculdade de Economia, Administração e Contabilidade de Ribeirão Preto (FEARP)
- Faculdade de Filosofia, Ciências e Letras de Ribeirão Preto (FFCLRP)
- Faculdade de Medicina de Ribeirão Preto (FMRP)
- Faculdade de Odontologia de Ribeirão Preto (FORP)

Em São Sebastião

- Centro de Biologia Marinha (CEBIMar)

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- PQI – Química
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Ementa

1. **Physical Impairments Overview**
   - Attenuation (fibers; passive components)
   - Dispersion (chromatic dispersion; polarization mode dispersion)
   - Non Linear Effects (parametric non linear effects; non linear scatterings)
2. **Transmission Capacity**
   - Transmission and Reception Characteristics (external modulation; sensibility; quantum Limit)
   - Bit Rate versus Distance
   - Optical Amplifier; Dispersion Management; WDM
   - Available spectral bandwidth
3. **Multiplexing and Modulation Techniques**
   - TDM and WDM
   - Spectral Efficiency, OFDM
   - m-OOK, m-PSK, m-QAM
   - Coherent Reception
   - Noise Mitigation and Channel Capacity
   - Last trick: SDM
4. **State of Art**
   - Standardization: IEEE 802.3ba, IETF, ITU-T, IOF
   - Long Distance Trial, ECOC, OFC-NFOEC
   - Short Distance Systems
   - Commercial Systems

Ementa

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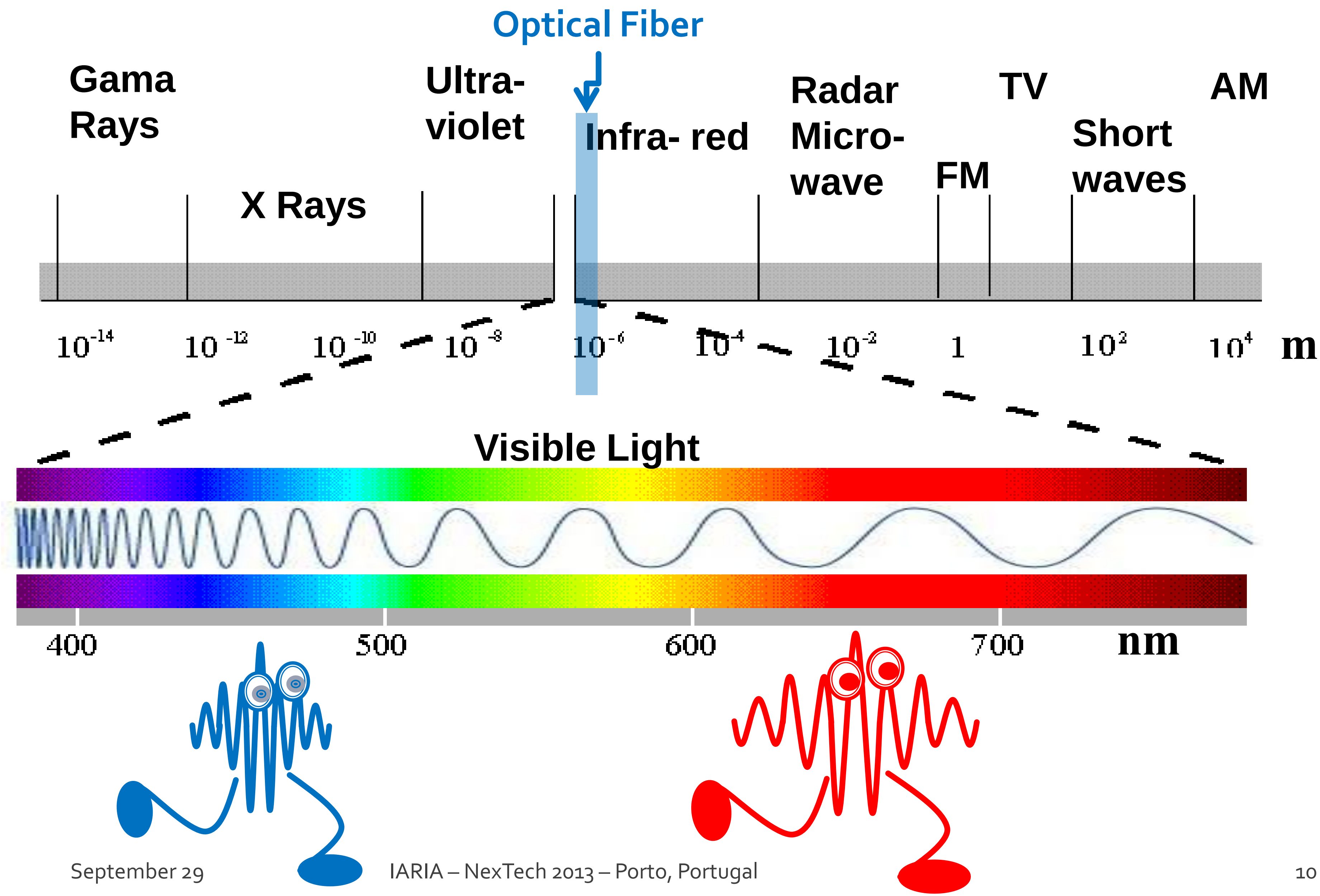
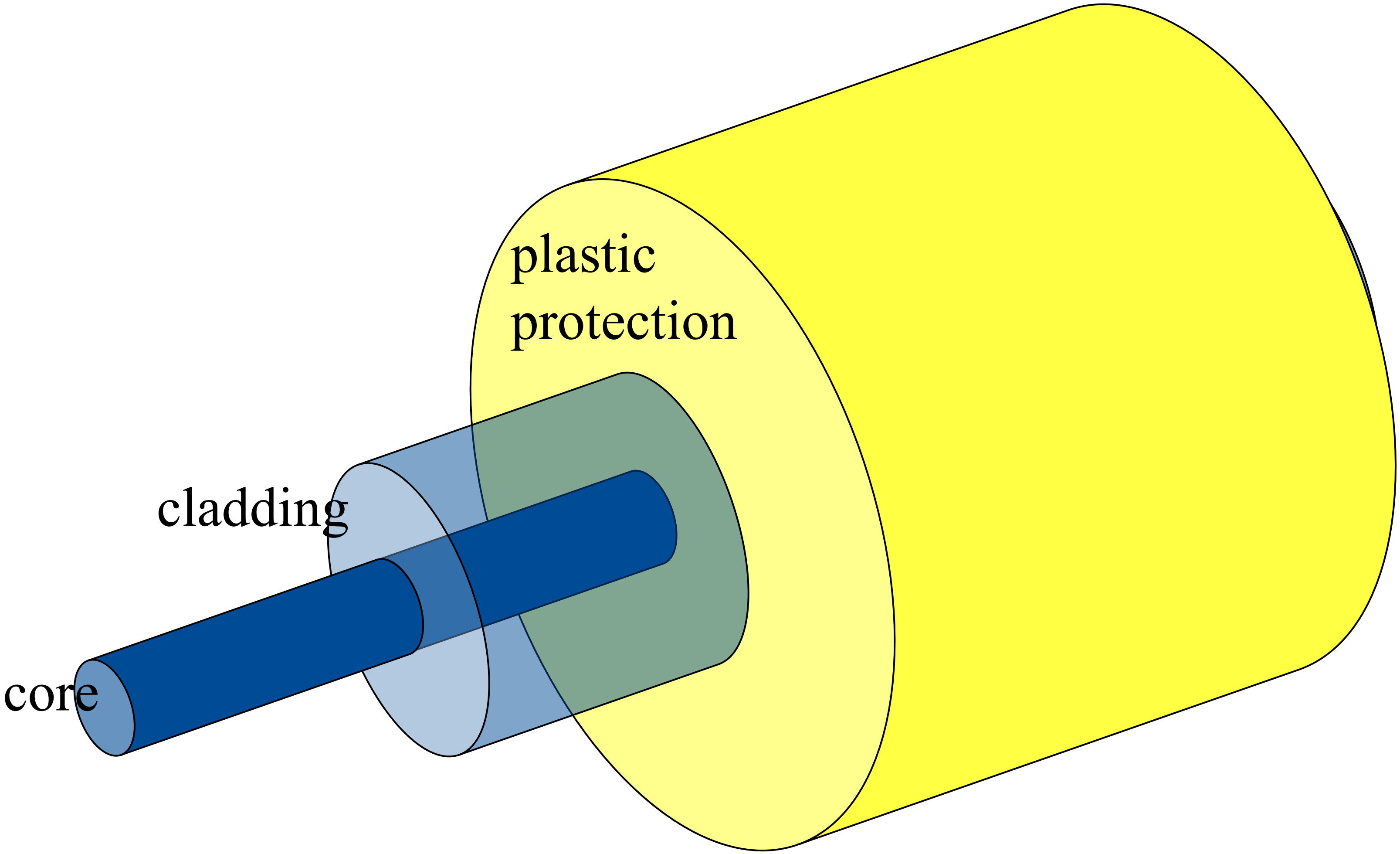
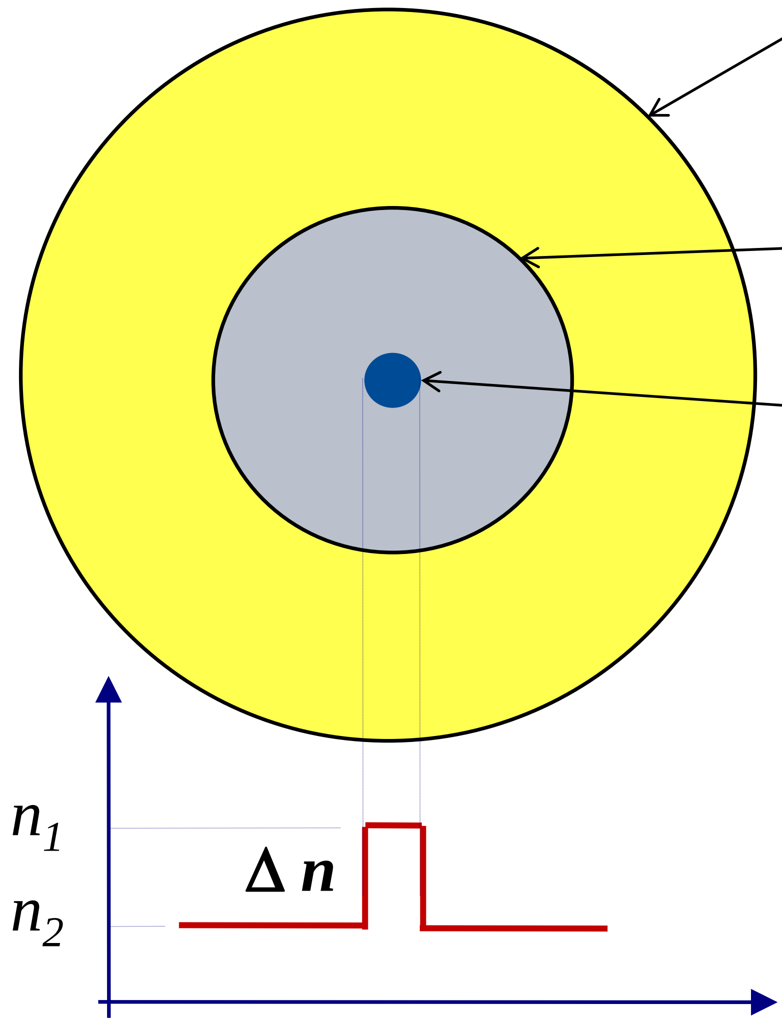
Electromagnetic Spectrum



Fiber Geometry



Fiber Geometry



protection
Acrylate (250 µm)

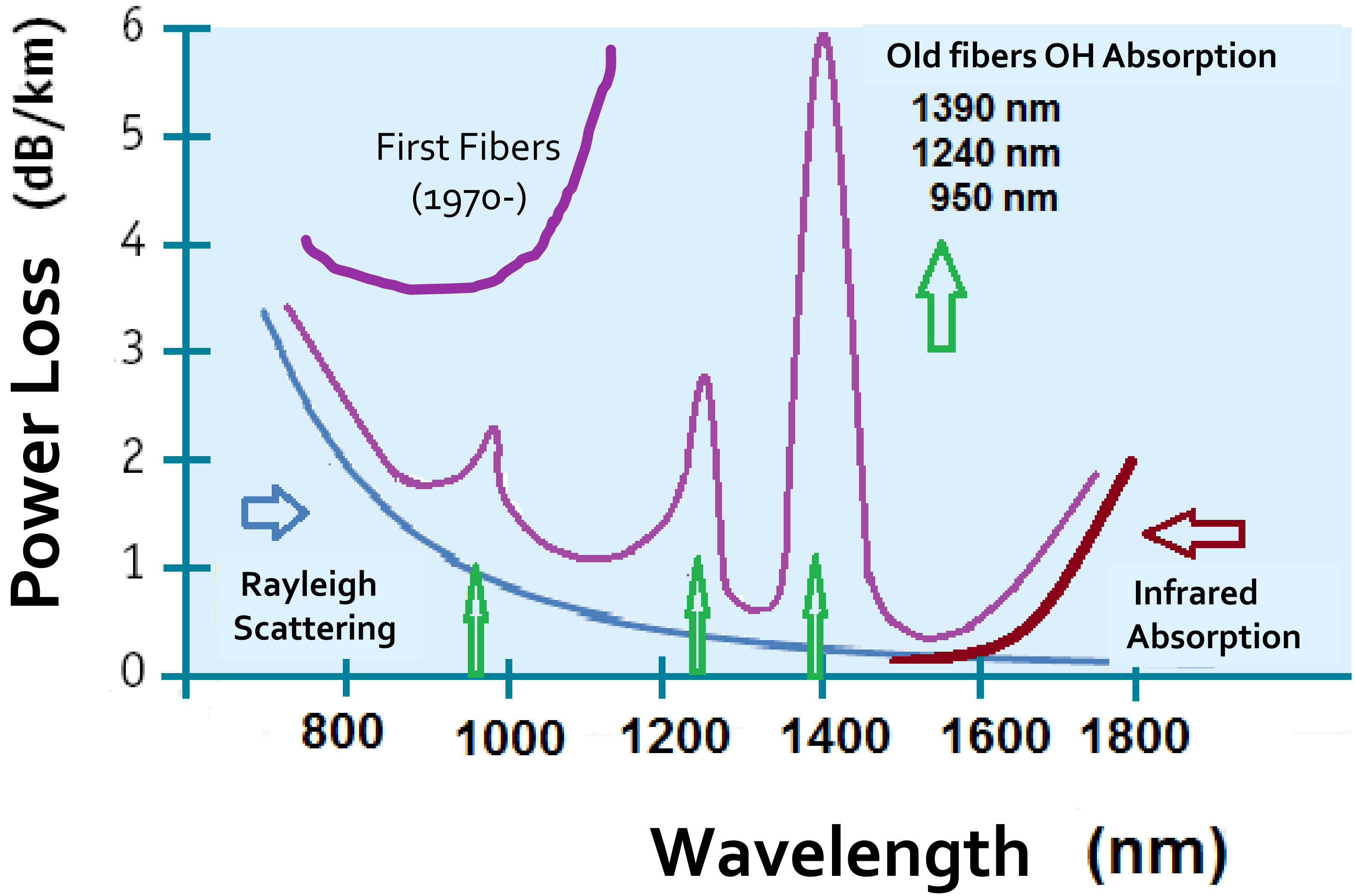
cladding
Pure Silica (125 µm)

core
Doped Silica (9 – 62.5 µm)

Typical Values :

n_1 = 1.46
n_2 = 1.45
Δn = 0.01

Attenuation

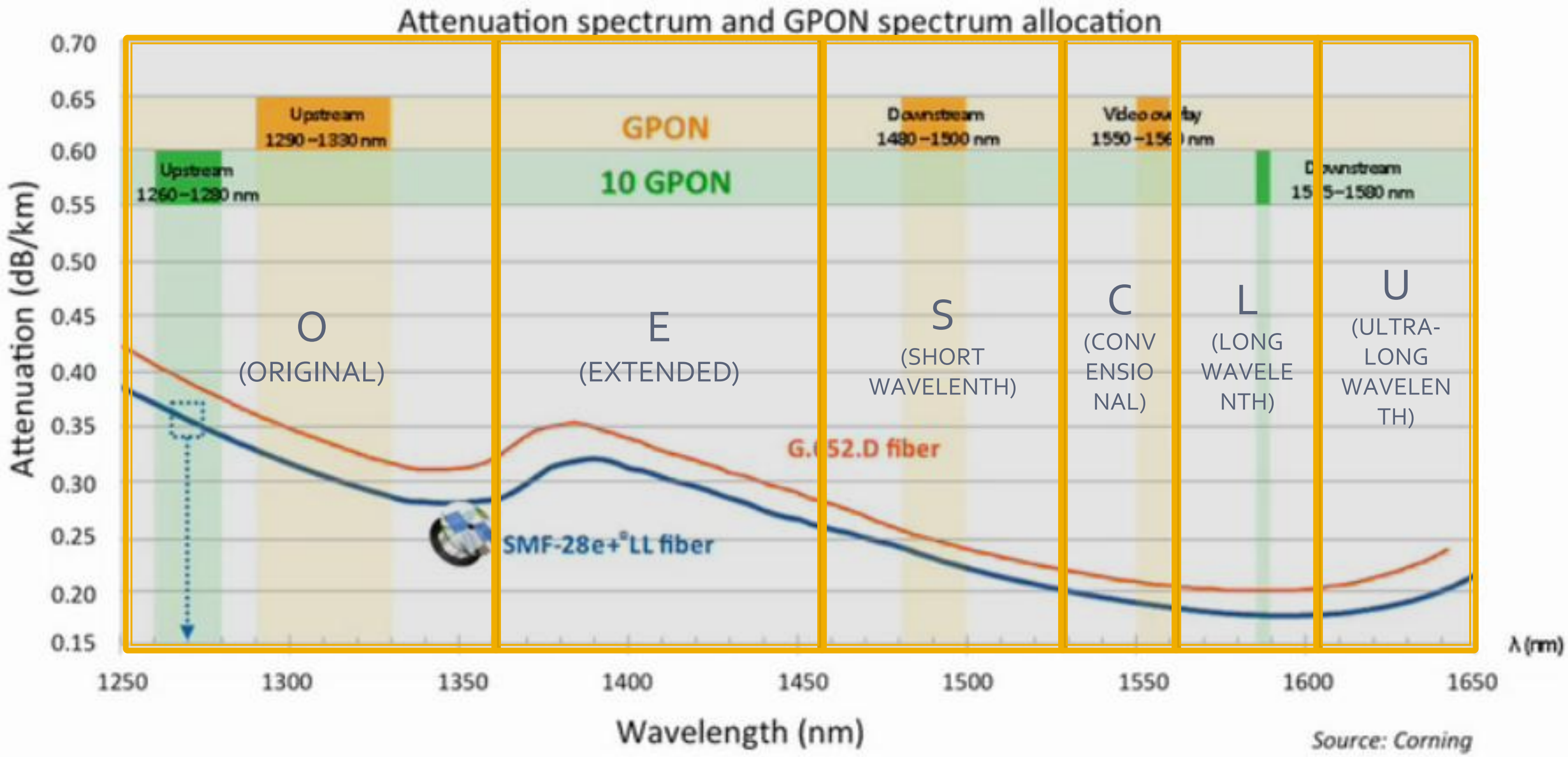


Loss Matters.

Access

Network Longevity

CAPACITY ROBUSTNESS
NGPON, 100GE, FRA



A fiber with lower attenuation in a broader spectrum enables introduction of 10G PON with minimal compromise on network architecture or reach

State of Art 2013

Table 1 Characteristics of Fabricated PSCF at 1550 nm.

	Aeff [μm^2]	Fiber Loss [dB/km]	Dispersion [ps/nm/km]	Disp. Slope [ps/nm^2/km]
PSCF	135	0.149	21.0	0.061

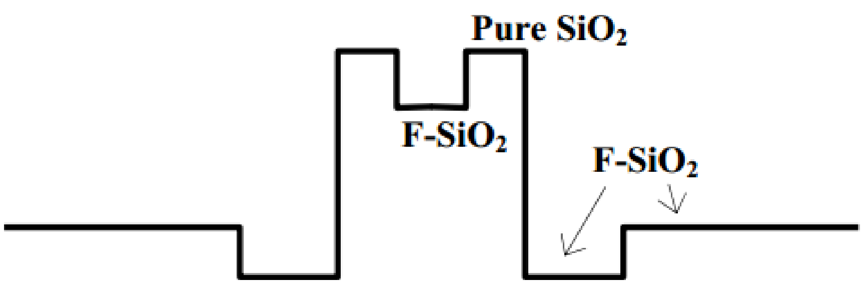


Fig.3 Schematic Refractive Index Profile.

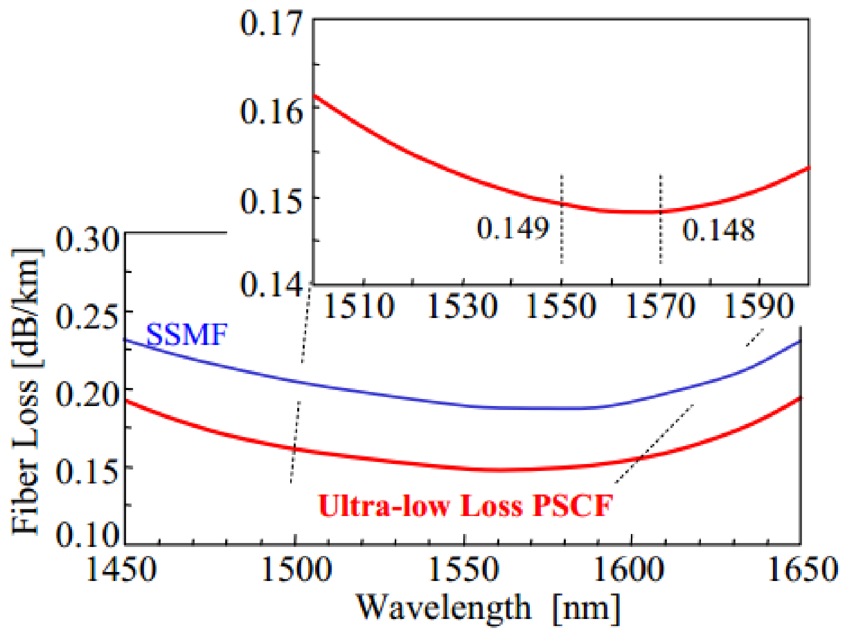


Fig. 4 Loss Spectra of PSCF and SSMF.

Record Low Loss, Record High FOM Optical Fiber with Manufacturable Process M. Hirano, T. Haruna, Y. Tamura, T. Kawano, S. Ohnuki, Y. Yamamoto, Y. Koyano, and T. Sasaki. Sumitomo Electric Industries, Ltd., 1, Taya-cho, Sakae-ku, Yokohama, 244-8588 Japan; OFC 2013, Anahein, CA, USA, PDP5A.7, 2013

Types of connectors


FC connector


E2000 connector


ESCON connector


LC connector (duplex)


LuxCis connector


MIC (FDDI) connector


MPO connector


MT-RJ connector


SC connector


SC connector (duplex)

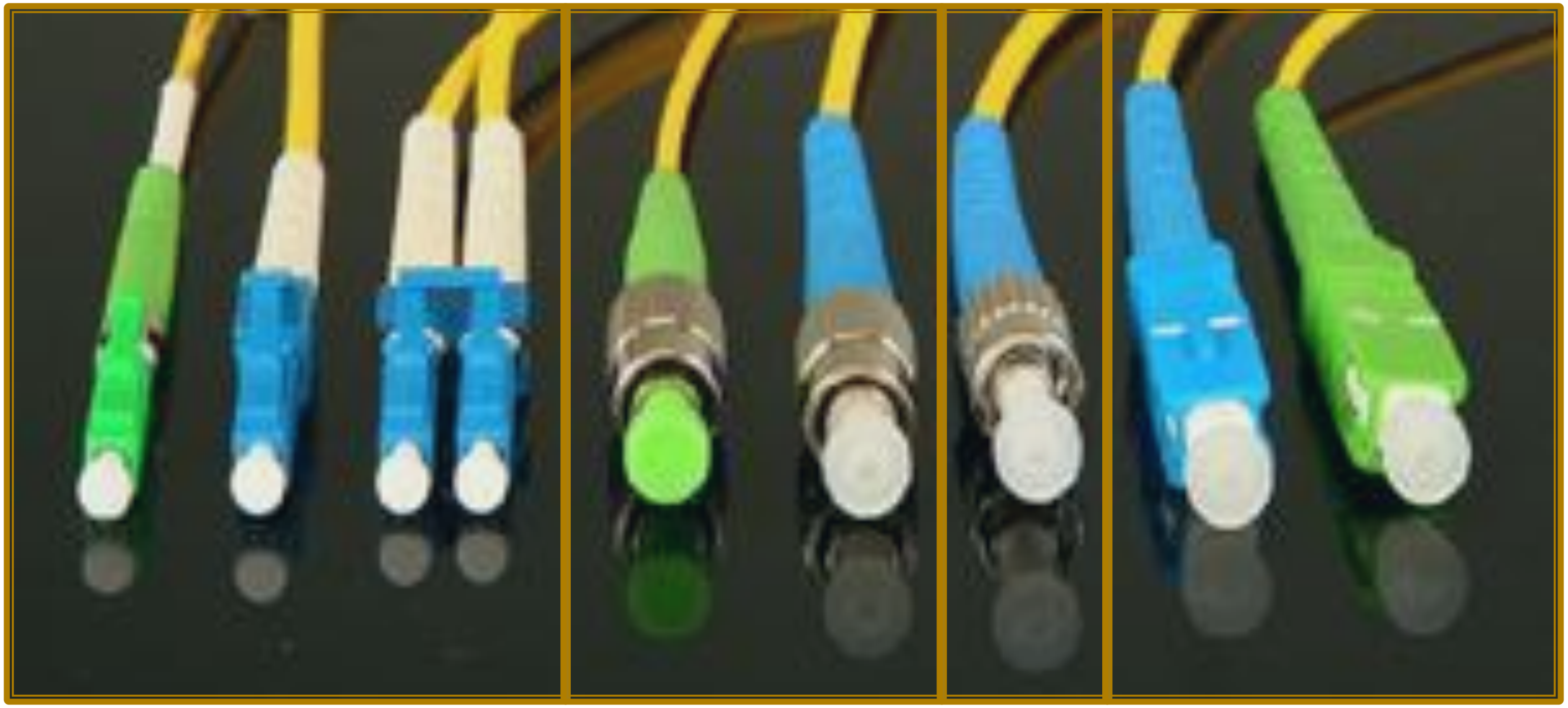

SMA 905 connectors


ST connector


TOSLINK connector

http://en.wikipedia.org/wiki/Optical_fiber_connector

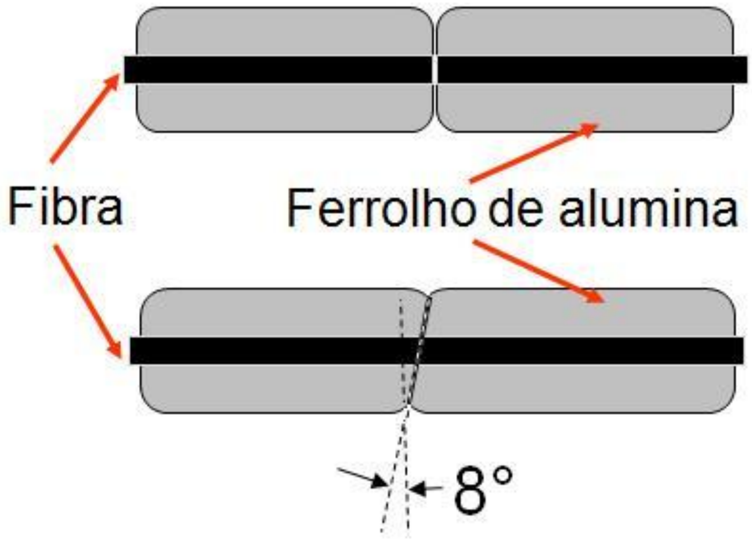
Types of connectors



LC FC ST SC

http://www.globalspec.com/featuredProducts/detail?ExhibitId=221851&uid=%2D223858687&frmtrk=alert

Types of connectors



PC = Physical Contact
(reflection –20 dB)

APC = Angled Physical Contact
(reflection –40 dB)

Attenuation is 0.2 dB for PC or APC

Surface Polishing Quality
- SPC (Super PC)
- UPC (Ultra PC)

Types of connectors

SC/PC

blue

SC/APC

green

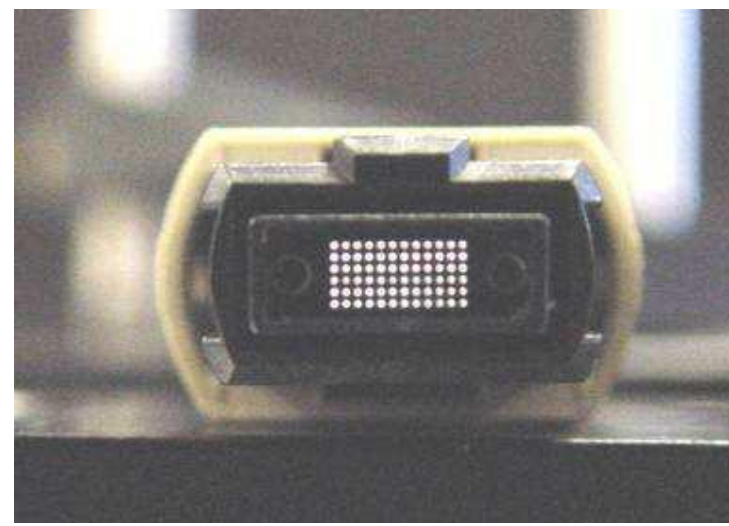
Activity: Optical power measurement

Types of connectors

SC FC LC

MPO
12

MPO
24



MPO
72

http://www.ampnetconnect.com/documents/Data_Center_MPO_Presentation_rev1.pdf

Activity: Videos about connectors

http://www.hubersuhner.com/hs-p-fo-field-quick-video_en.swf (Hubersuhner)
http://youtu.be/9ToAzeWM_F4 types of connectors
http://youtu.be/SJwbqnjo4BE LC connectors
http://youtu.be/gt7omle2jBE ST-SC-FC-LC
http://youtu.be/fG8kwrR8rRI MTP-MPO -Video1-MPO 2:41 m
http://youtu.be/SMyxci27kvs MPO instalation
http://youtu.be/lzGe1tjbMmo

1. **Physical Impairments Overview**
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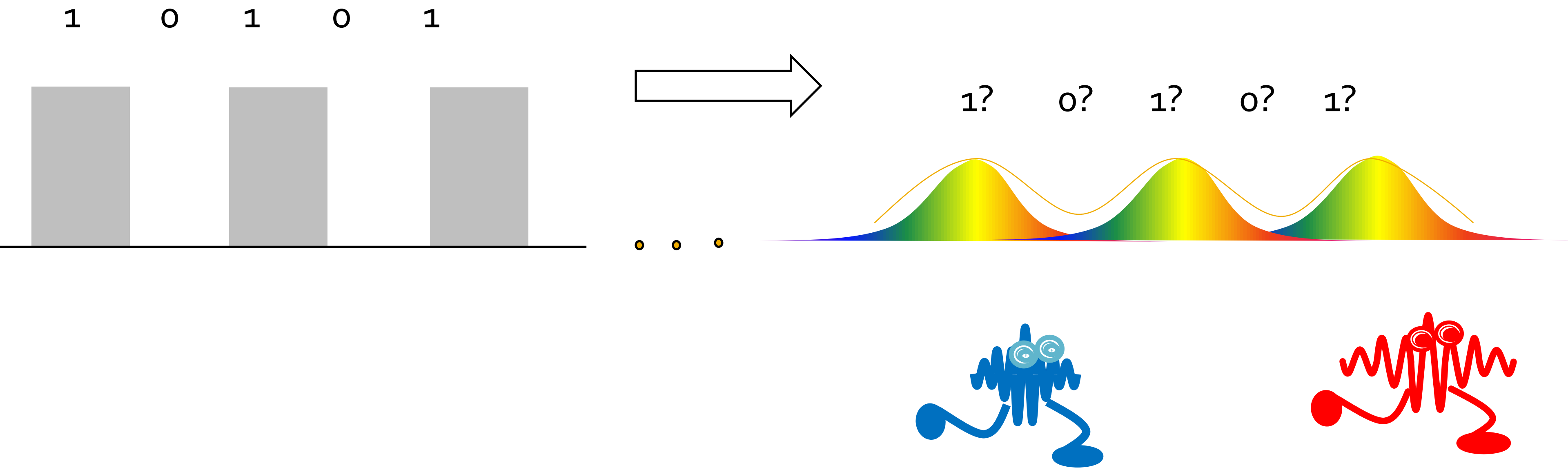
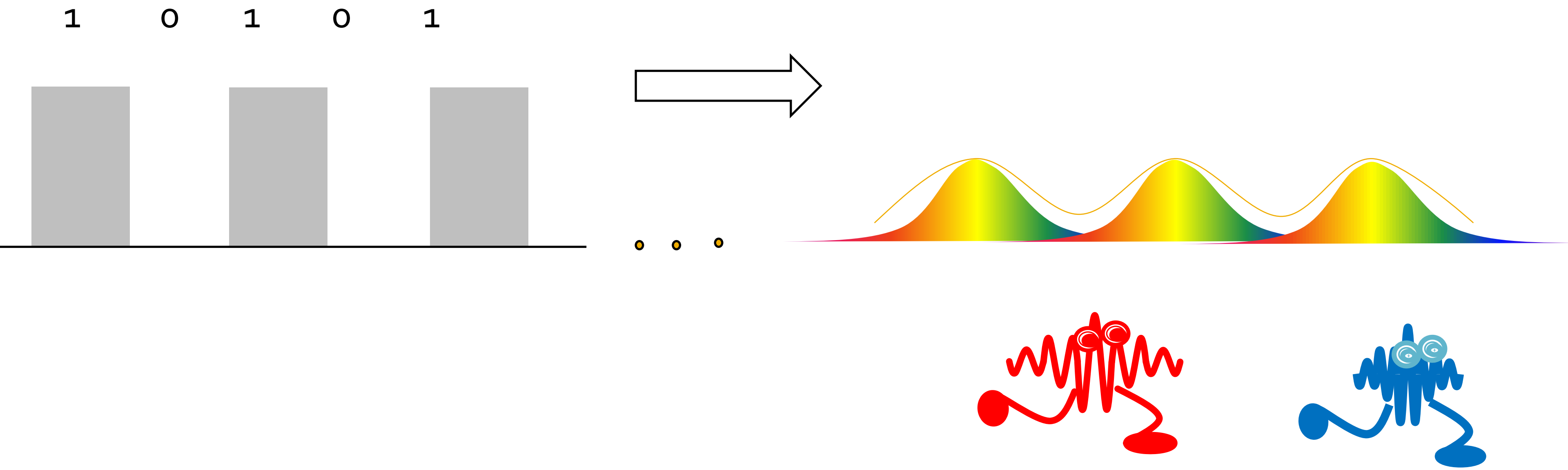
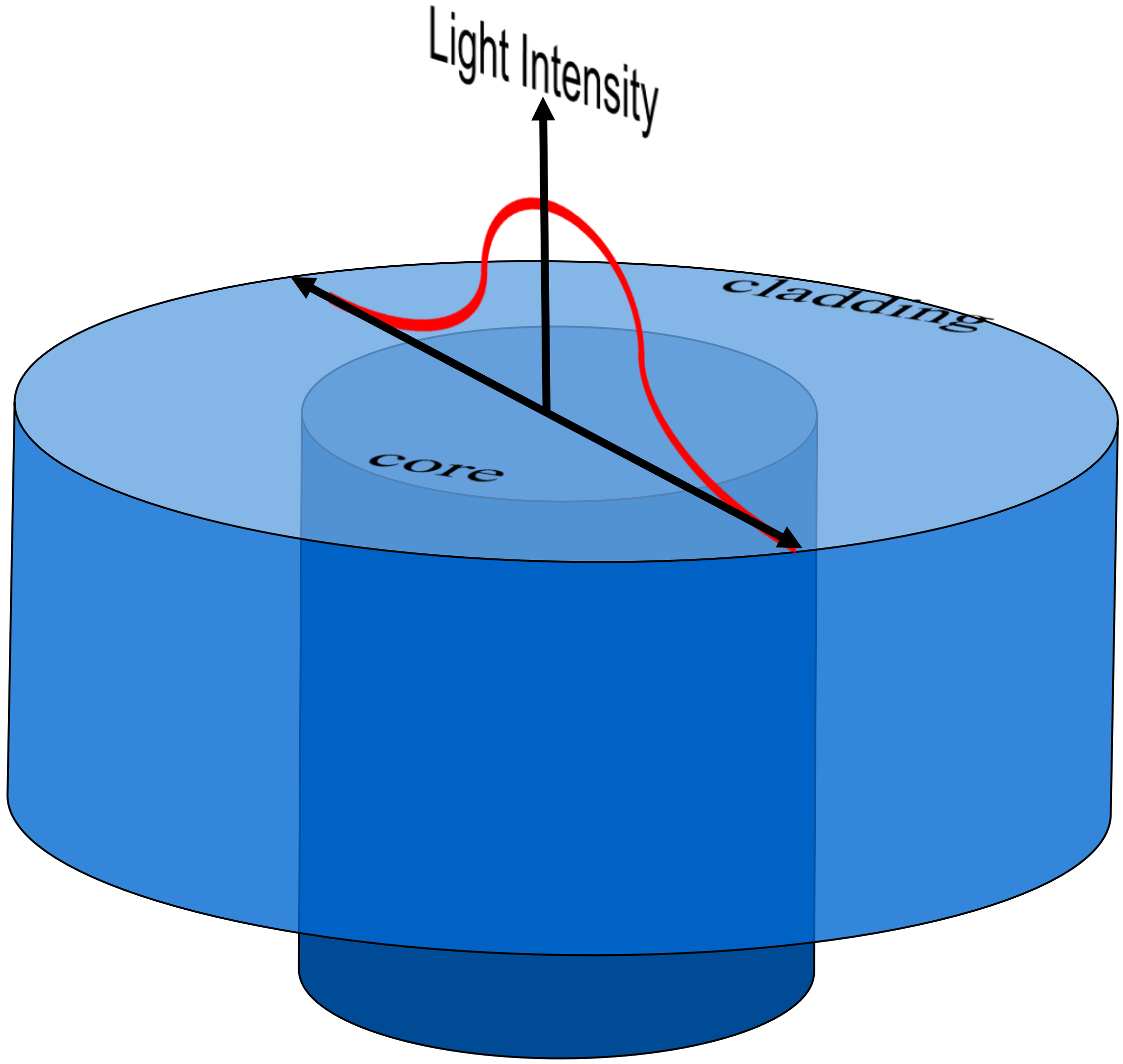
Chromatic Dispersion



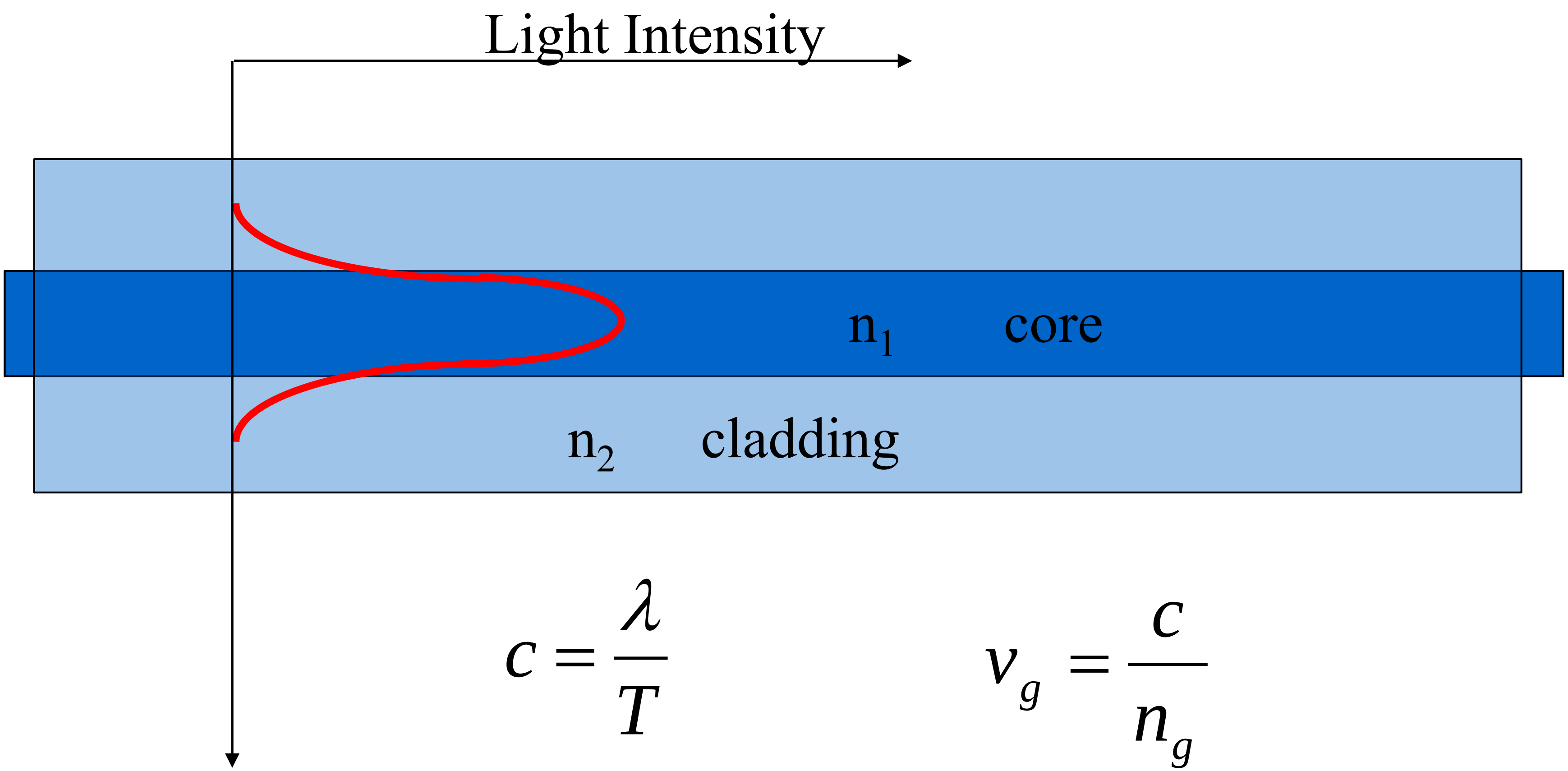
Chromatic Dispersion



Fiber Geometry



Fiber Geometry

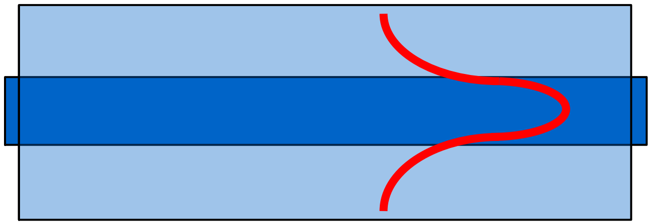


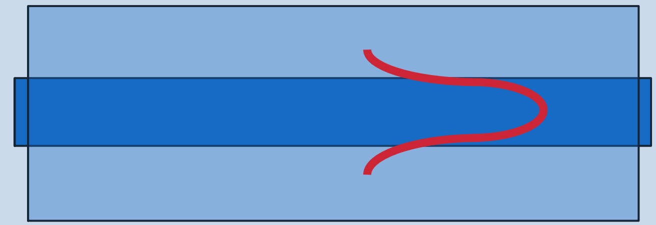
$$c = \frac{\lambda}{T}$$

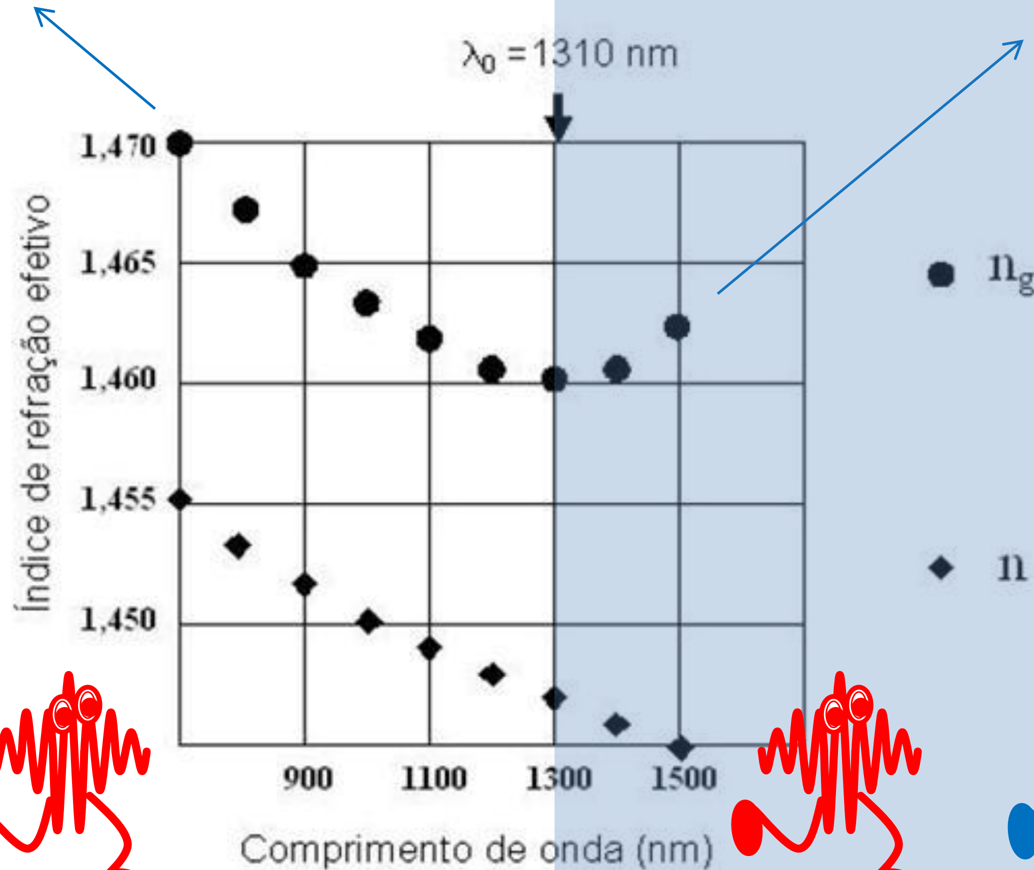
$$v_g = \frac{c}{n_g}$$

Group refractive index

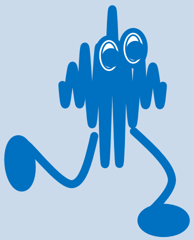
anomalous





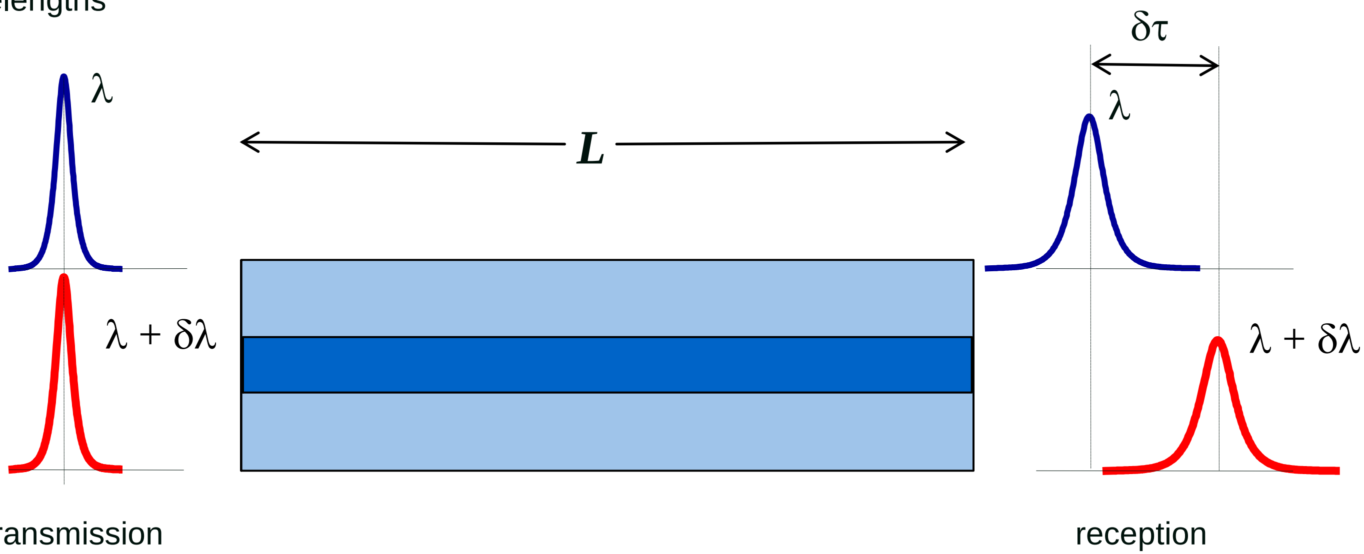


$$v_g = \frac{c}{n_g}$$



Chromatic Dispersion

Pulses with different wavelengths



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

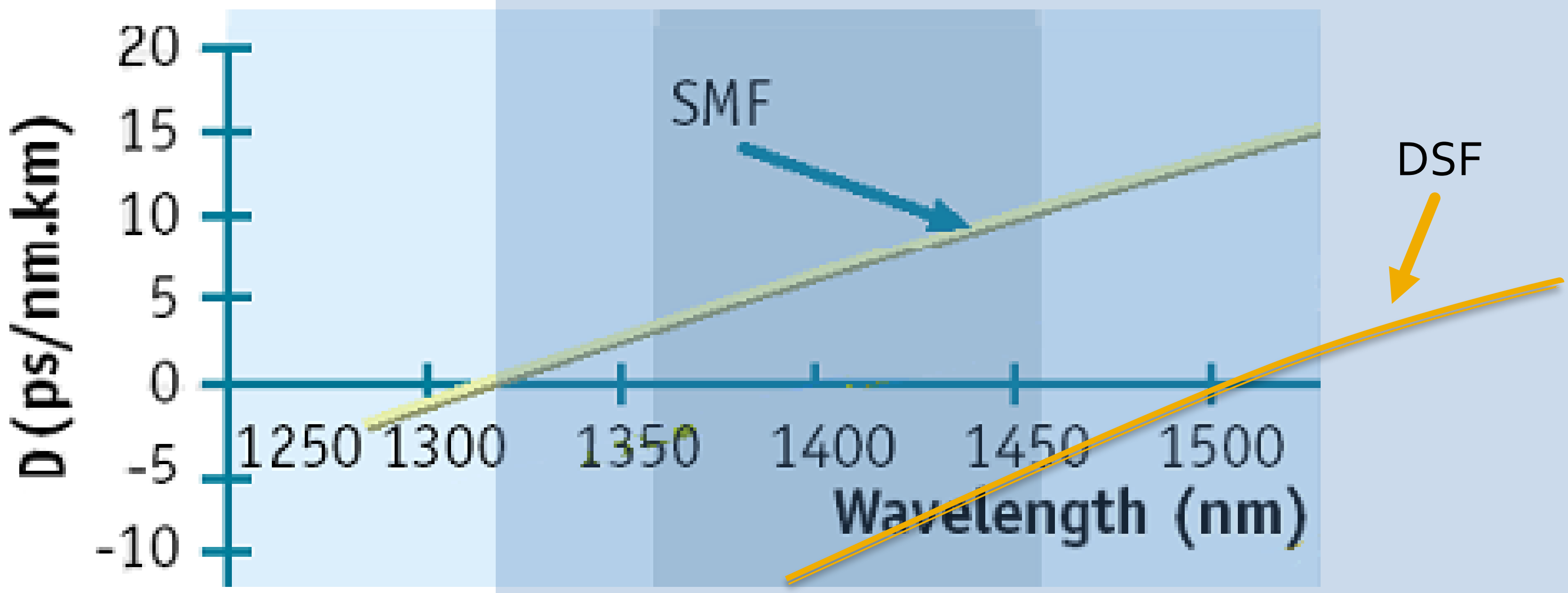
ps/(nm.km)

Group velocity (v_g) varies with λ

$$v_g = \frac{c}{n_g} = \frac{L}{\tau} \Rightarrow \frac{1}{v_g} = \frac{\tau}{L}$$

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) \Rightarrow D = \frac{1}{L}\frac{\delta\tau}{\delta\lambda}$$

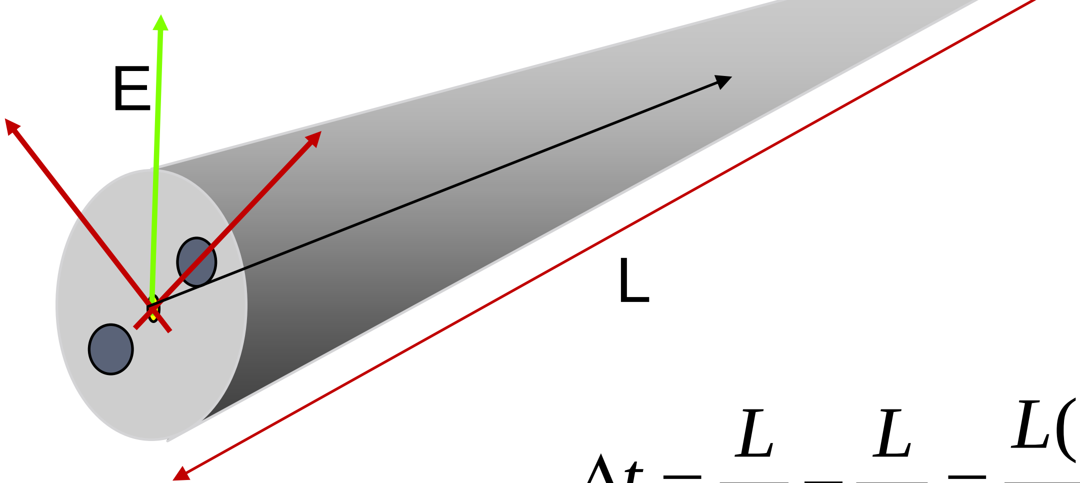
Dispersion coefficient

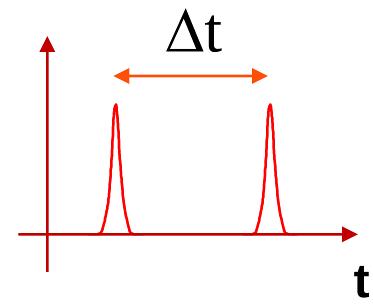


http://www.alcatel.com/doctypes/articlepaperlibrary/pdf/ATR2002Q1/GB/08Ryan.pdf

PMD effect in HiBi fibers

No mode coupling:
The Hi-Bi fiber maintains the polarization



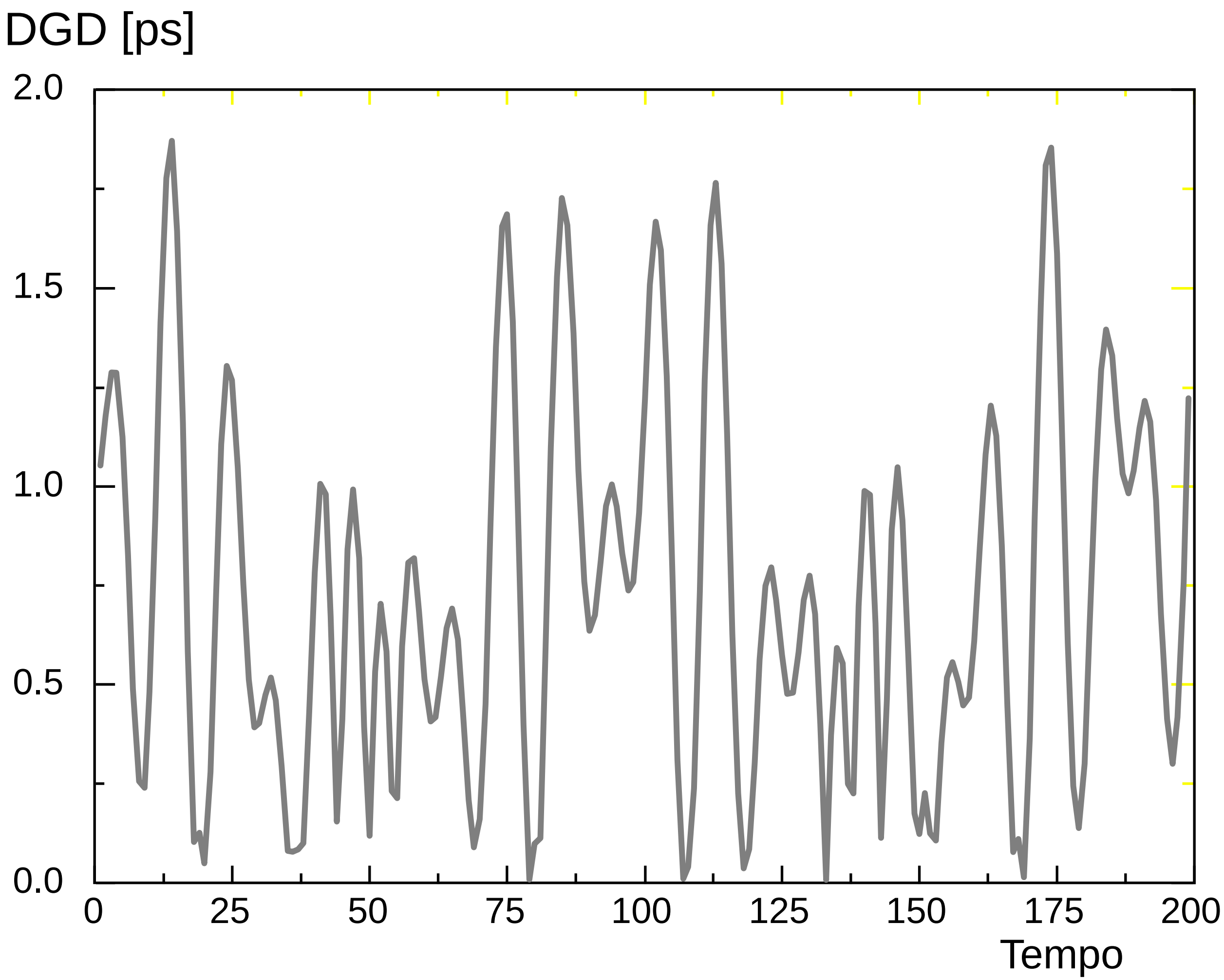


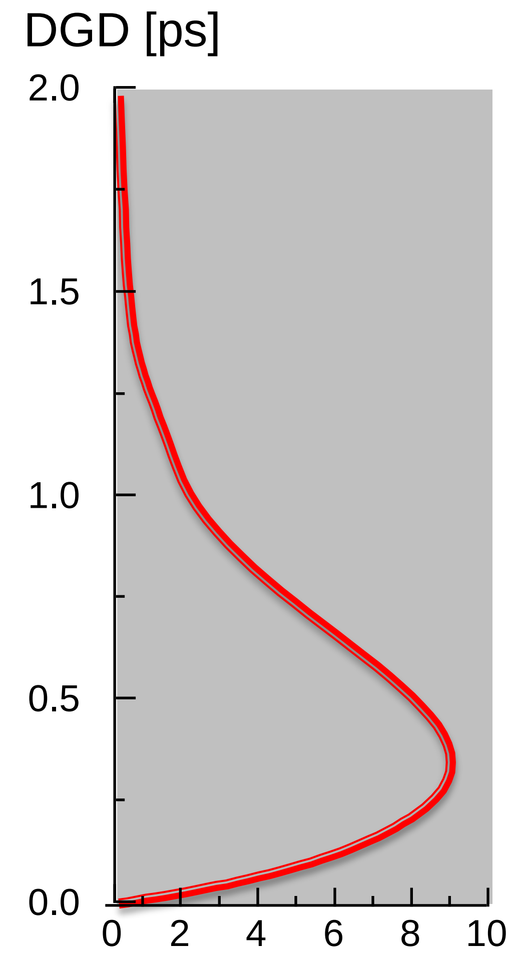
$$\Delta t = \frac{L}{v_x} - \frac{L}{v_y} = \frac{L(n_x - n_y)}{c}$$

HiBi==High Birefringence

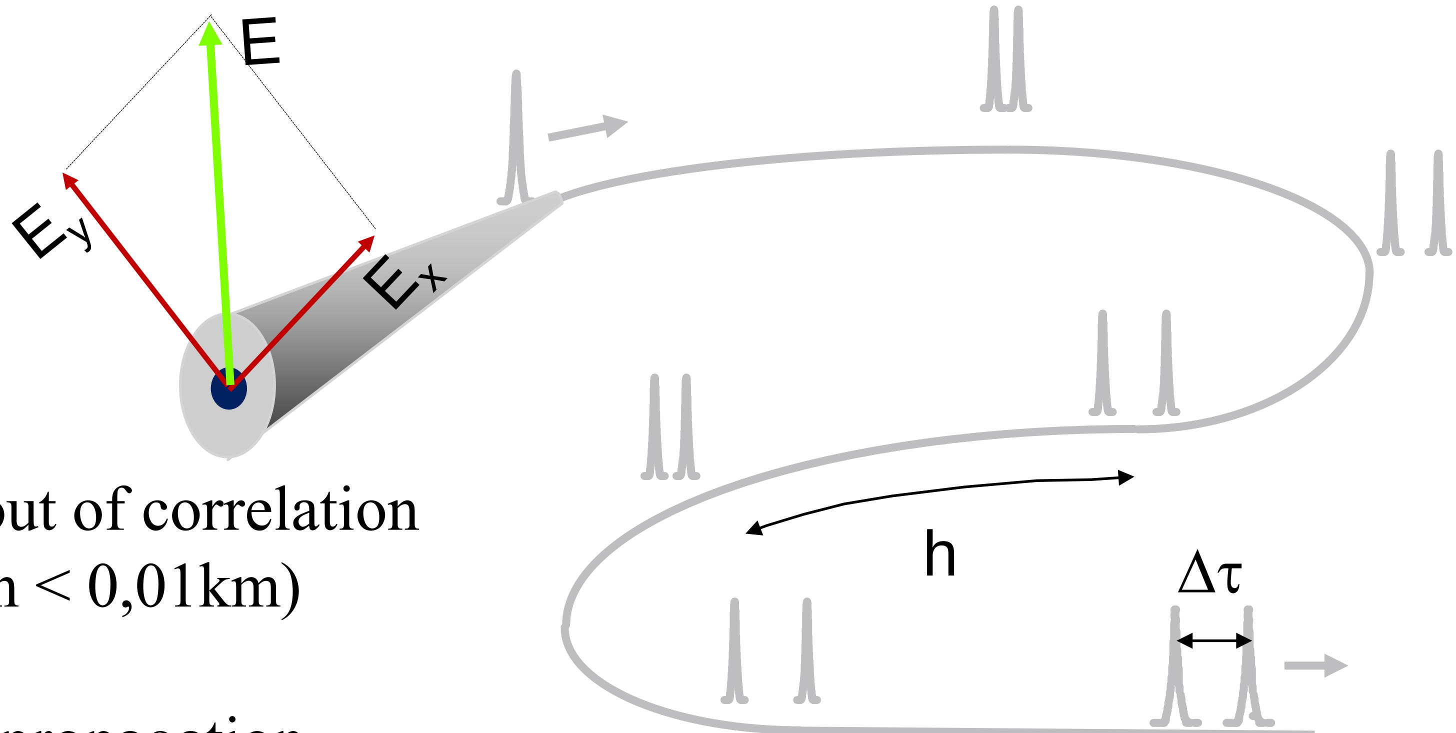
PMD

Distribuição estatística do **DGD (Differential Group Delay)** – Distribuição de Maxwell





Polarization Mode Dispersion - PMD



h is the out of correlation length (h < 0,01km)

β_1 is the propagation constant (characteristics of the fiber)

Random time interval Δτ at arrival

$$\Delta\tau \approx \frac{\Delta\beta_1}{c}\sqrt{hL} = D_P\sqrt{L} \Rightarrow D_P = \frac{\Delta\tau}{\sqrt{L}} \qquad (\ ps/\sqrt{km}\ )$$

Optical fiber types (typical values)

	type	D(1550nm) ps/(nm.km)	Slope ps/(nm^2.km)	area μm^2
Standard	STD	+ 18	0,09	80
Dispersion Shifted	DS	0	0,06	50
Non Zero Dispersion+	NZD+	+7	0,06	55
Non Zero Dispersion-	NZD-	- 7	0,06	55
Large Effective Area Fiber	LEAF	+ 7 ou - 7	0,11	72
Reduced Slope	RS	+ 4 ou - 4	0,04	50
Dispersion Compensating Fiber	DCF	- 37 a -100	- 0,11	27

Optical fiber types (standardization)

http://www.thefoa.org

	ITU Spec.	TIA Spec.	IEC SMF type
Multimode Fiber 50/125	G.651		
Standard Single Mode Fiber	G.652.A	OS1	B1.1
Standard Single Mode Fiber	G.652.B lower attenuation		
Low Water Peak Fiber	G.652.C	OS2	B1.3
Low Water Peak Fiber	G.652.D lower PMD		
Dispersion Shifted Fiber	G.653		B2
Cutoff Shifted Fiber	G.654		B1.2
Non-Zero Dispersion Shifted Fiber	G.655		B4
Bend-Insensitive SMF	G.657A1; G.657A2; G.657B2; G.657B3		

Activity: Splicing Machine

-video2-FSM-60R   4:38 m

1. **Physical Impairments Overview**
   - Attenuation (fibers; passive components)
   - Dispersion (chromatic dispersion; polarization mode dispersion)
   - Non Linear Effects (parametric non linear effects; non linear scatterings)

Maxwell´s Equations

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Faraday's law

$$\nabla \times \vec{H} = \vec{J}_f + \frac{\partial \vec{D}}{\partial t}$$

Ampere's law

$$\nabla . \vec{D} = \rho_f$$

Gauss' law

$$\nabla . \vec{B} = 0$$

Gauss' law

$\vec{E}$ ➡ Electric field vector

$\vec{H}$ ➡ Magnetic field vector

$\vec{D}$ ➡ Electric flux density

$\vec{B}$ ➡ Magnetic flux density

Maxwell's Equations

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t}$$

$$\nabla . \vec{D} = 0 \qquad \nabla . \vec{B} = 0$$

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} \qquad \vec{B} = \mu_0 \vec{H} + \vec{M}$$

$$\mu_0 \varepsilon_0 = \frac{1}{c^2}$$

Wave Equation

$$\nabla \times \nabla \times E = -\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} - \mu_0 \frac{\partial^2 P}{\partial t^2}$$

$\vec{E}$ ➡ Electric field vector

$\vec{H}$ ➡ Magnetic field vector

$\vec{D}$ ➡ Electric flux density

$\vec{B}$ ➡ Magnetic flux density

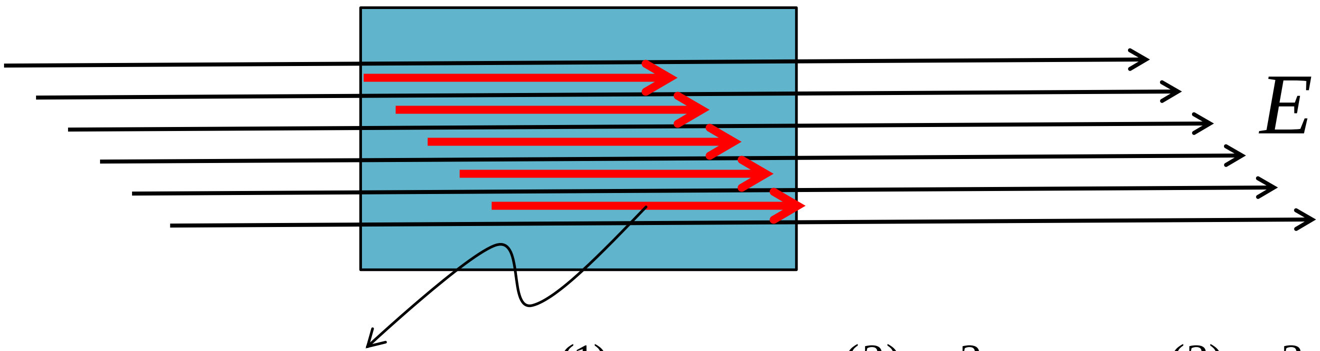
$\vec{P}$ ➡ induced electrical polarization

$\vec{M}$ ➡ induced magnetic polarization

ε_0 ➡ vacuum electrical permittivity

μ_0 ➡ vacuum magnetic permeability

Nonlinear induced polarization



$$P = \varepsilon_0 \chi^{(1)} E + \varepsilon_0 \chi^{(2)} E^2 + \varepsilon_0 \chi^{(3)} E^3 + \ldots$$

$$P = P_L + P_{NL}$$

$$P_L = \varepsilon_0 \chi^{(1)} E$$ and $$P_{NL} = \varepsilon_0 \chi^{(2)} E^2 + \varepsilon_0 \chi^{(3)} E^3 + \ldots$$

χ ➡ electric susceptibility of the medium

$\chi^{(2)}$ ➡ is null for symmetrical molecules like silica

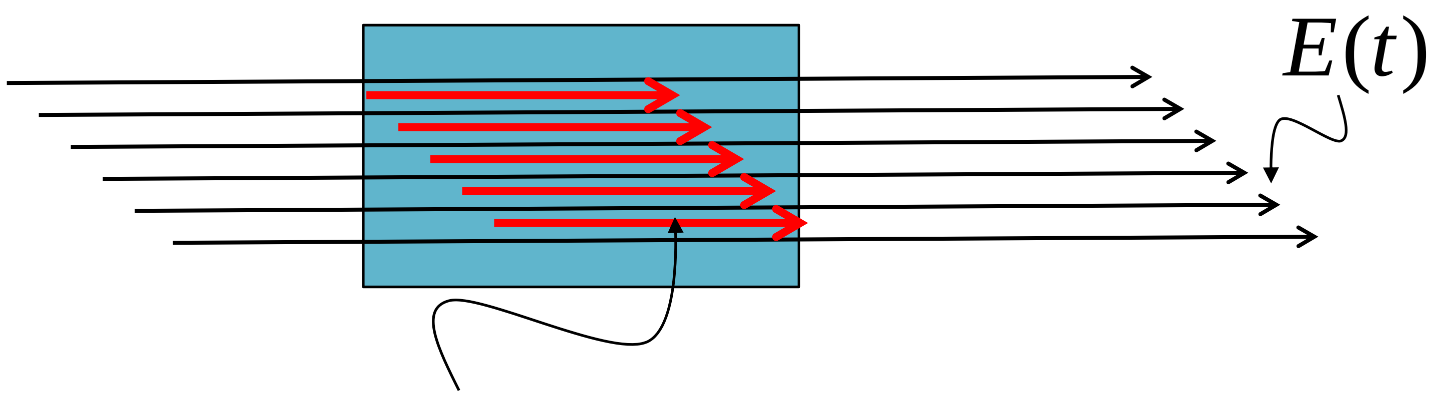
$\chi^{(j)}$ ➡ can be neglected for j > 3

$$P_{NL} = \varepsilon_0 \chi^{(3)} E^3$$

Parametric Nonlinear Effects

WDM system with two optical channels

$$E(t) = E_1 \cos(\omega_1 t) + E_2 \cos(\omega_2 t)$$



$$P(t) = \varepsilon_0 \chi E(t) + \varepsilon_0 \chi^{(3)} E^3(t)$$

WDM ⟶ Wavelength Division Multiplexing

Parametric Nonlinear Effects

SPM XPM SPM XPM

$$E^3(t) = \left(\frac{3E_1^3}{4} + \frac{3E_2^2E_1}{4}\right)\cos(\omega_1 t) + \left(\frac{3E_2^3}{4} + \frac{3E_1^2E_2}{4}\right)\cos(\omega_2 t)$$

FWM FWM

$$+\frac{3E_1^2E_2}{4}\cos((2\omega_1 - \omega_2)t) + \frac{3E_2^2E_1}{4}\cos((2\omega_2 - \omega_1)t)$$

$$+\frac{3E_1^2E_2}{4}\cos((2\omega_1 + \omega_2)t) + \frac{3E_2^2E_1}{4}\cos((2\omega_2 + \omega_1)t)$$

$$+\frac{E_1^3}{4}\cos(3\omega_1 t) + \frac{E_2^3}{4}\cos(3\omega_2 t)$$

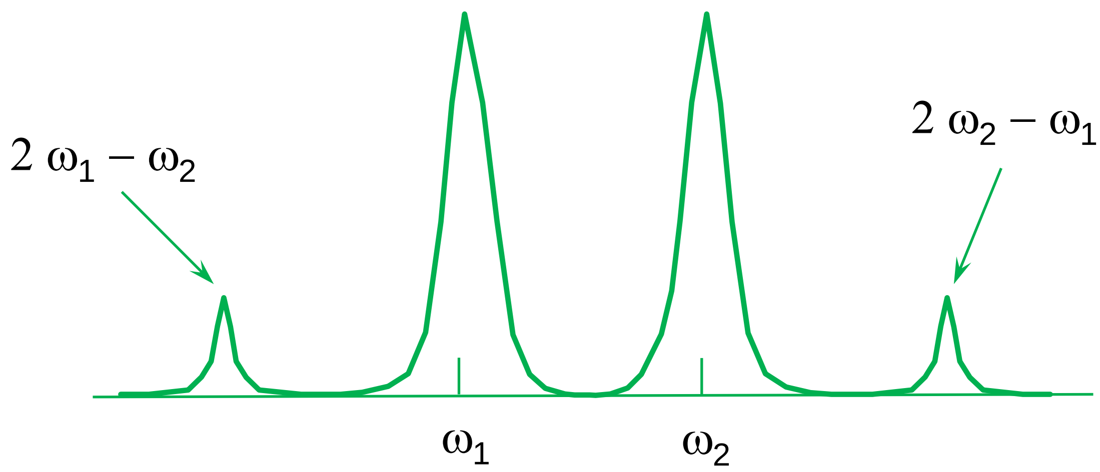
SPM – Self Phase Modulation

XPM – Cross Phase Modulation

FWM – Four Wave Mixing

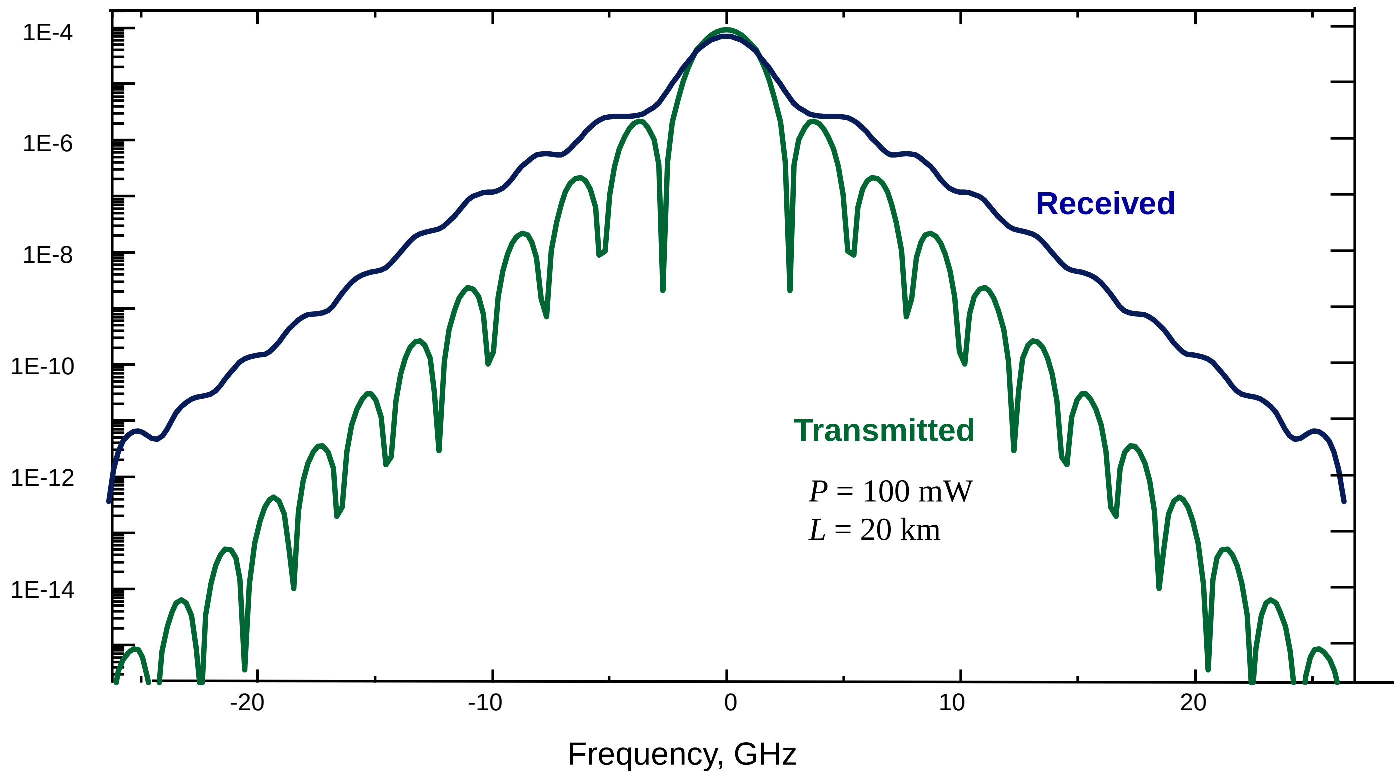
Added frequencies or triple frequencies are neglected because can not propagate inside the fiber

Four Wave Mixing (FWM)



- FWM reduces the optical power in each channel
- Noise insertion from channel to channel
- Affects also low bit rate systems
  - unlike SPM and XPM that affect high bit rate systems
- Effect minimized by chromatic dispersion
  - fiber with large D and/or large separation $\omega_2 - \omega_1$, reduces FWM
- Effect minimized with low power density
  - low power level or large effective area

SPM – spectral enlargement



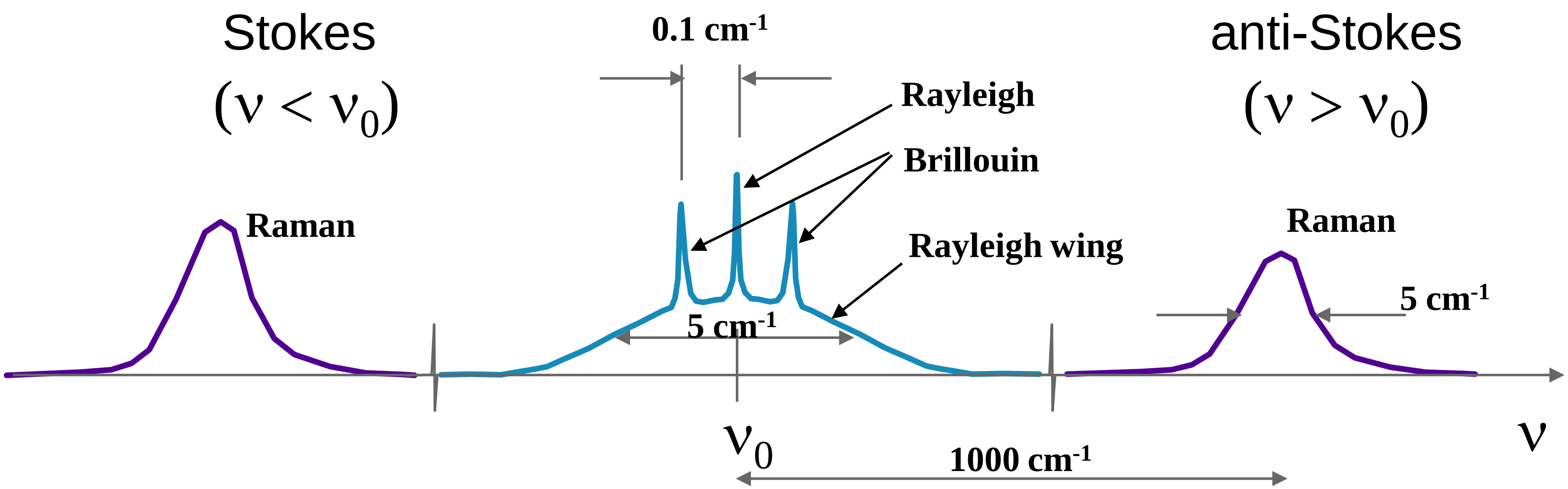
NRZ - 400 ps pulses (2.5 Gb/s)

SPM and XPM limitations

SPM and XPM

- Both cause spectral enlargement
  - dispersion problem
- Both limit the bandwidth
  - penalties for high bit rate systems
- XPM is reduced for large wavelength separation
- XPM is reduced for high fiber dispersion coefficient
- Both effects can be minimized by dispersion control

Scattering spectrum

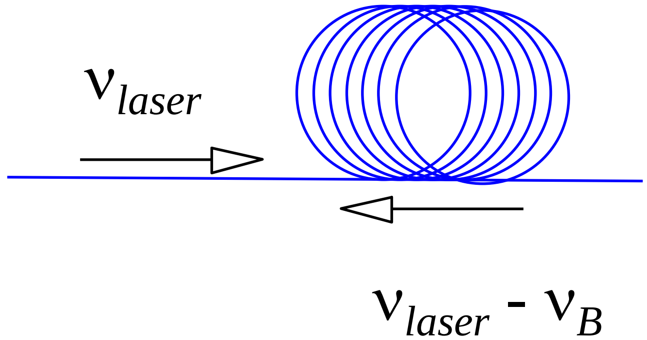


ν (wave number)=1/λ

Raman: Vibrations/Optical phonons
Brillouin: Sound waves/Acoustic phonons
Rayleigh wing: Orientational fluctuations (liquids)
Rayleigh: Density (entropy) fluctuations

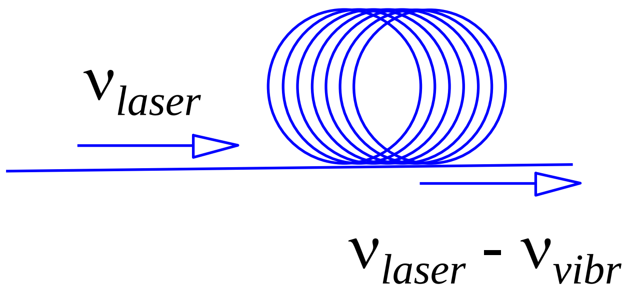
Stimulated Brillouin Scattering (SBS)

- Counter-propagating scattering
  - limits bi-diretional system
- Acoustic waves
- Frequency dislocation: $\nu_B \cong$ 10 GHz
- Band width: $\Delta\nu \cong$ 20 MHz
- SBS is the most strong non-linearity
  - $\gamma_B \cong 4x10^{-9}$ cm/W
- SBS is easy to eliminate
  - low frequency over modulation

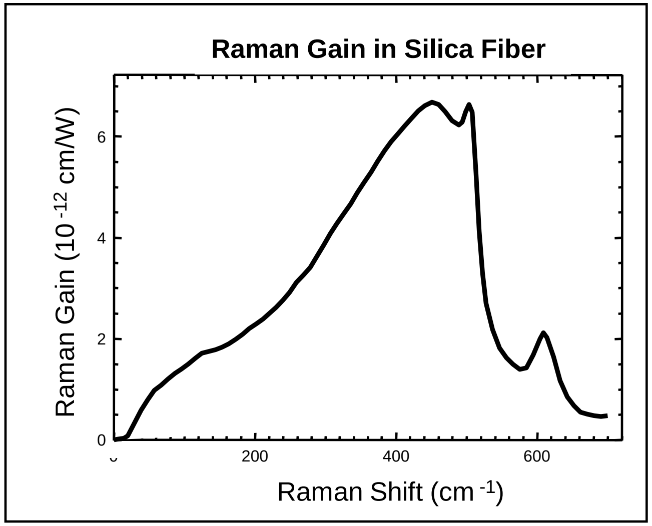


Stimulated Raman Scattering (SRS)

- Co-propagating Scattering
- Silica molecular vibrations



Frequency dislocation: 13 THz (80 nm)
Band width: $\Delta\nu \cong 10$ THz

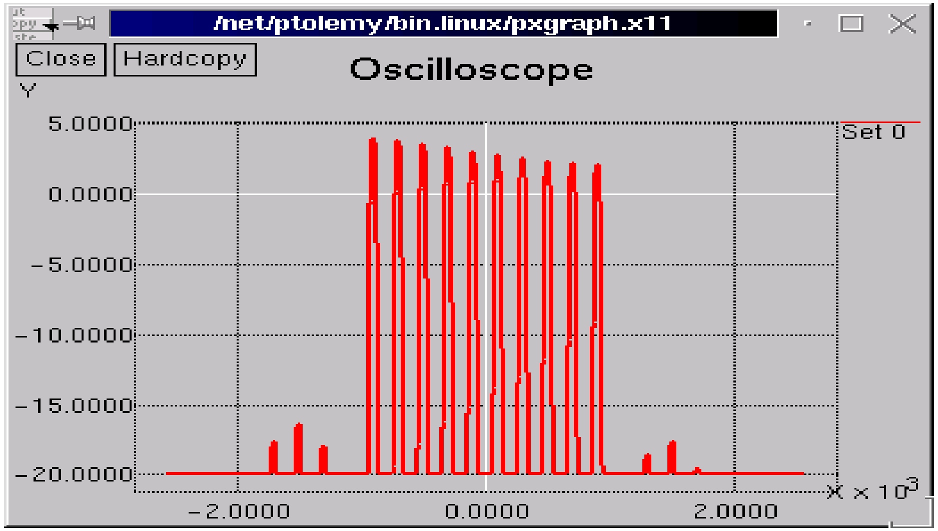


Raman

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

GVD   Attenuation   Kerr (n_2)   Raman

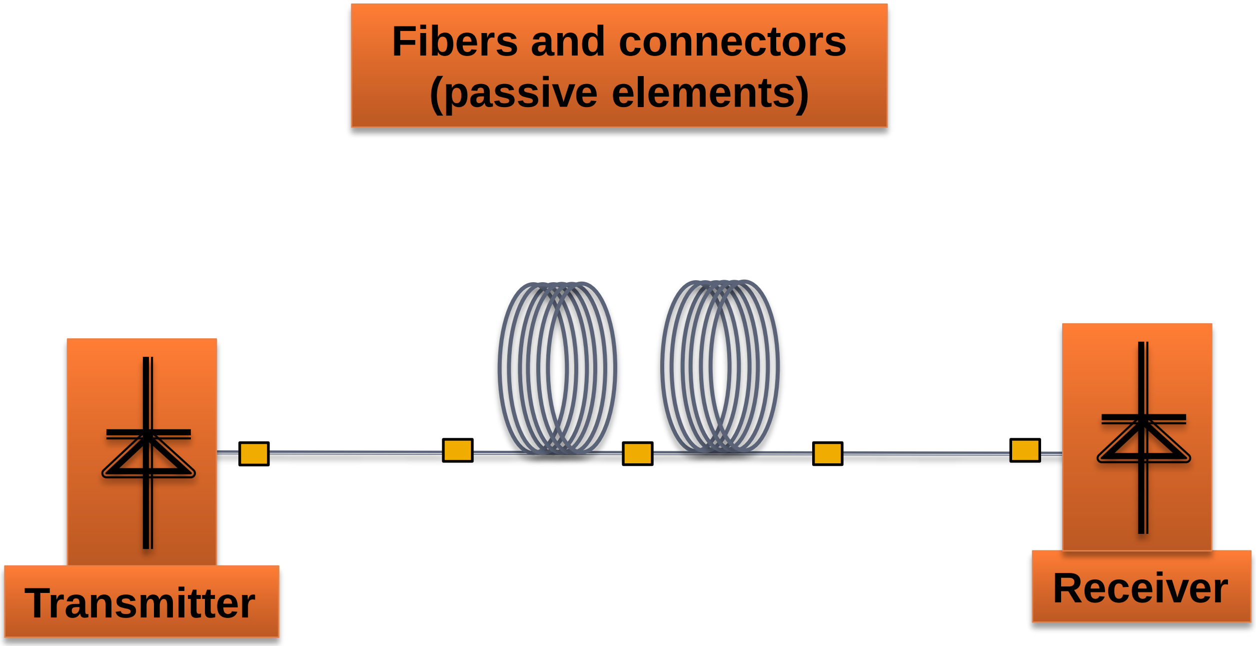
$\tau_R = 5$ fs



Frequency

2. **Transmission Capacity**
    - Transmission and Reception Characteristics (external modulation; sensibility; quantum Limit)
    - Bit Rate versus Distance
    - Optical Amplifier; Dispersion Management; WDM
    - Available spectral bandwidth

Optical Links



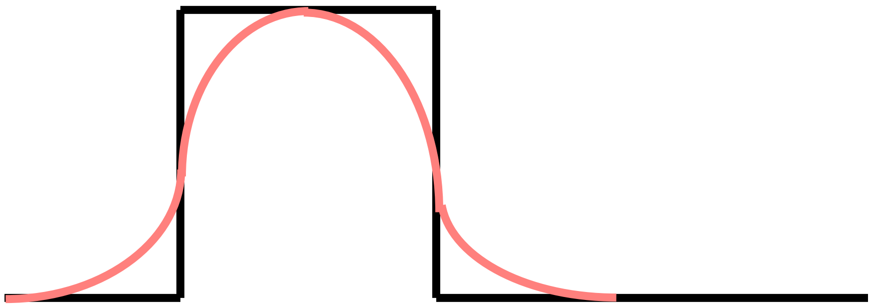
Capacidade dos Enlaces

- Modulation types
  - Direct Modulation
  - External Modulation
  - OOK – On-Off Keying
  - PSK - Phase Shift Keying
  - QAM – Quadrature Amplitude Modulation
- Line codes
  - Multiples symbols representing the information (memory)
  - Error correction (FEC)
- Multiplexing
  - TDM – Time-Division Multiplexing
  - WDM – Wavelength-Division Multiplexing
  - OCDM – Optical Code-Division Multiplexing
  - OFDM – Orthogonal Frequency-Division Multiplexing
  - SDM – Space Division Multiplexing

Link Capacity

- Transmission Characteristics
  - Laser Power
  - Laser spectral width
  - Laser frequency response
  - Extinction ratio (signal to noise ratio)

- Reception characteristics
  - Sensibility (Ex: -15 dBm for 10^{-12} BER)
  - Responsivity (Ex: 0,85 A/W)
  - Filters (50%-80% nominal bit rate). Ex: 2,5 Gb/s with 2 GHz filter.



Receptor Sensibility

- Sensibility (dBm) – Typical Values

Detector Type	Bit rate (Gb/s)	Without pre-amplifier (dBm)	With pre-amplifier (dBm)
PIN	0.622	-33	-44
PIN	2.5	-27	-38
PIN	10	-18	-29
AVALANCHE	2.5	-32	worst

Quantum Limit

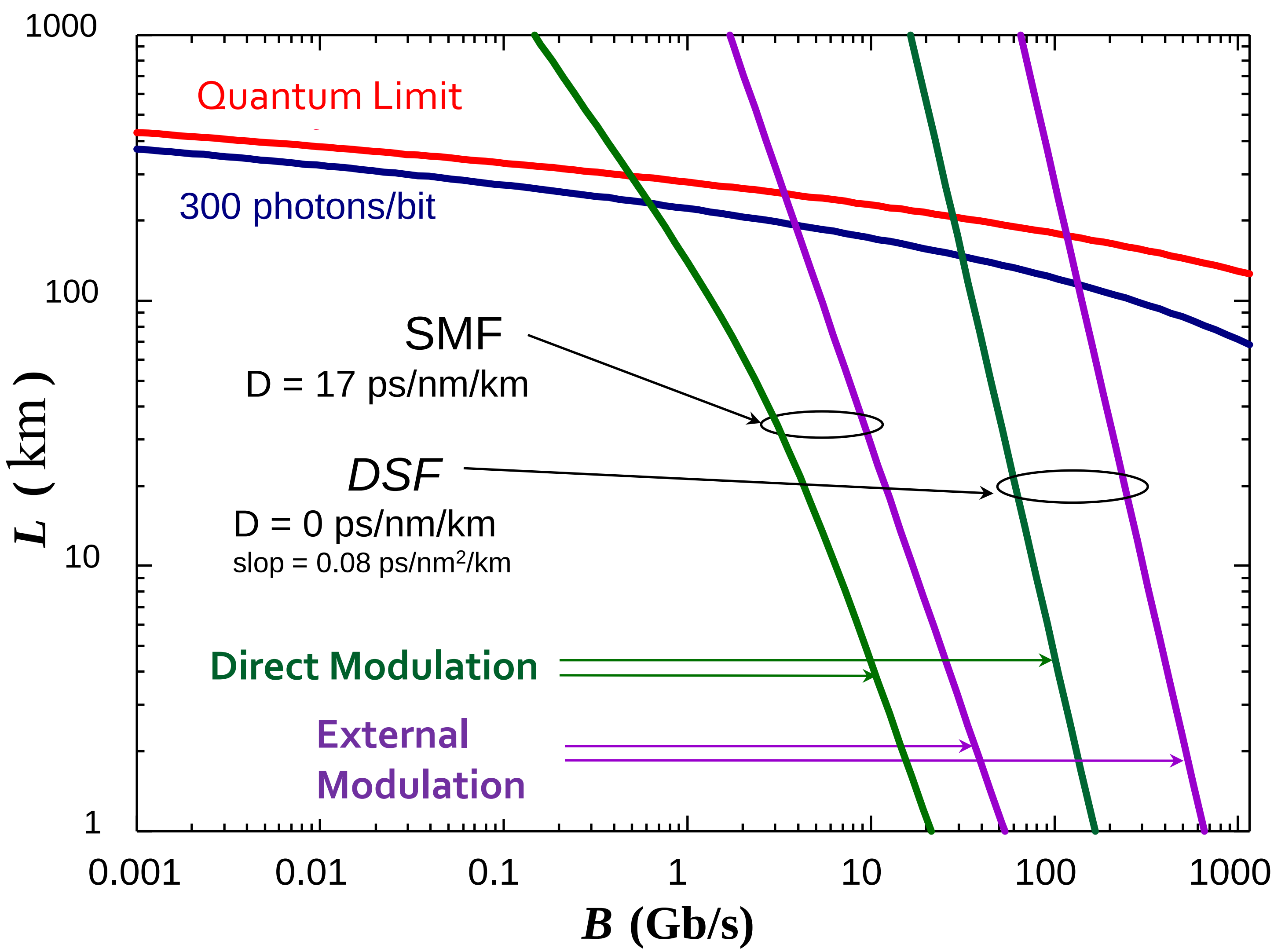
N = number of photons per bit
Bit Error Rate (BER) as a function of N is giving by

$$BER(N) = \frac{1}{2}e^{-N} \qquad \text{If } N = 29, \quad BER(N) \approx 10^{-13}$$

- Necessary 29 photons per bit to get $BER < 10^{-13}$
- Commercial detectors need more then 1000 photons per bit.

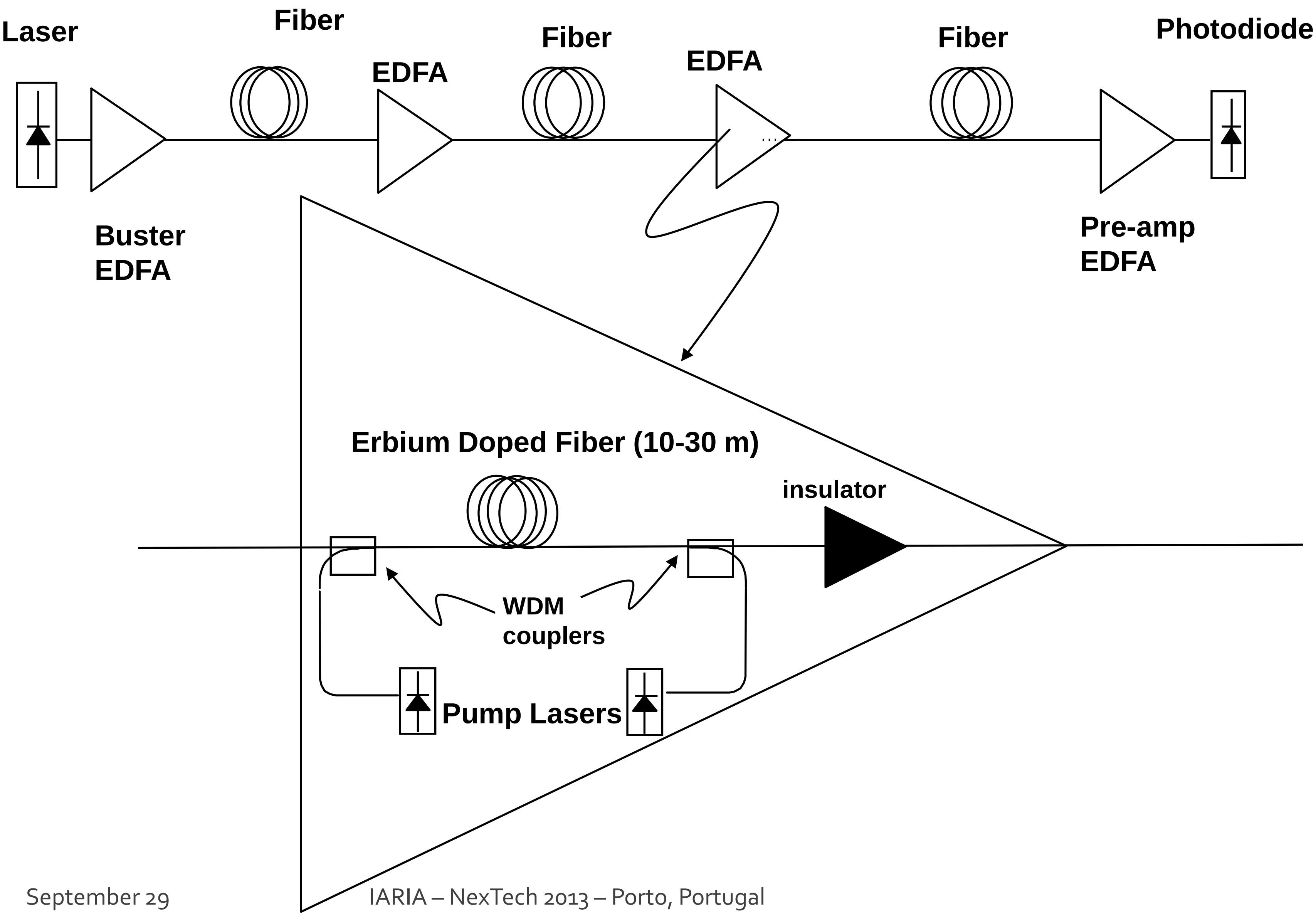
2. **Transmission Capacity**
   - Transmission and Reception Characteristics (external modulation; sensibility; quantum Limit)
   - Bit Rate versus Distance
   - Optical Amplifier; Dispersion Management; WDM
   - Available spectral bandwidth

Last Century Limitations

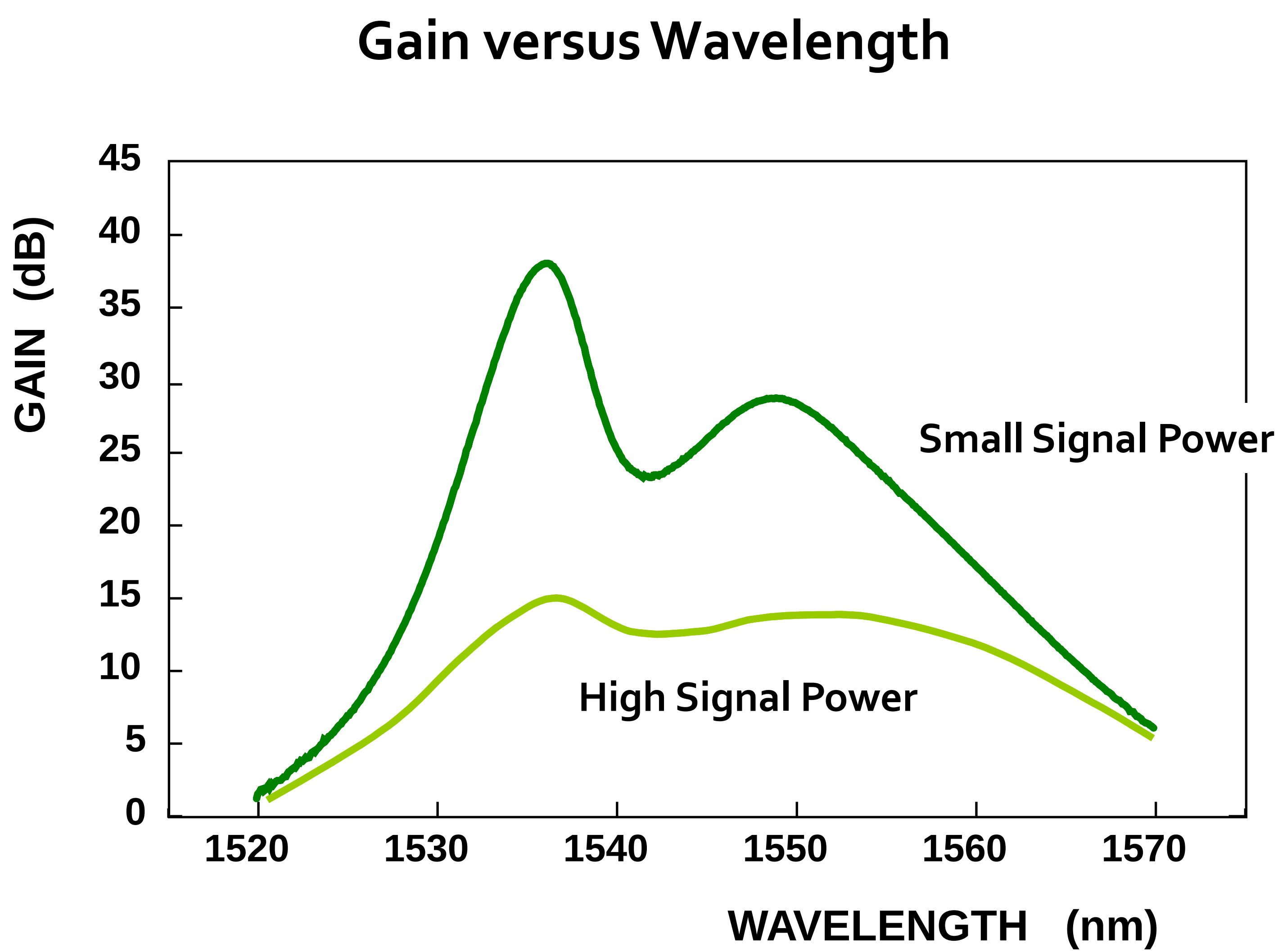


2. **Transmission Capacity**
   - Transmission and Reception Characteristics (external modulation; sensibility; quantum Limit)
   - Bit Rate versus Distance
   - Optical Amplifier; Dispersion Management; WDM
   - Available spectral bandwidth

Erbium Doped Fiber Amplifiers – EDFA

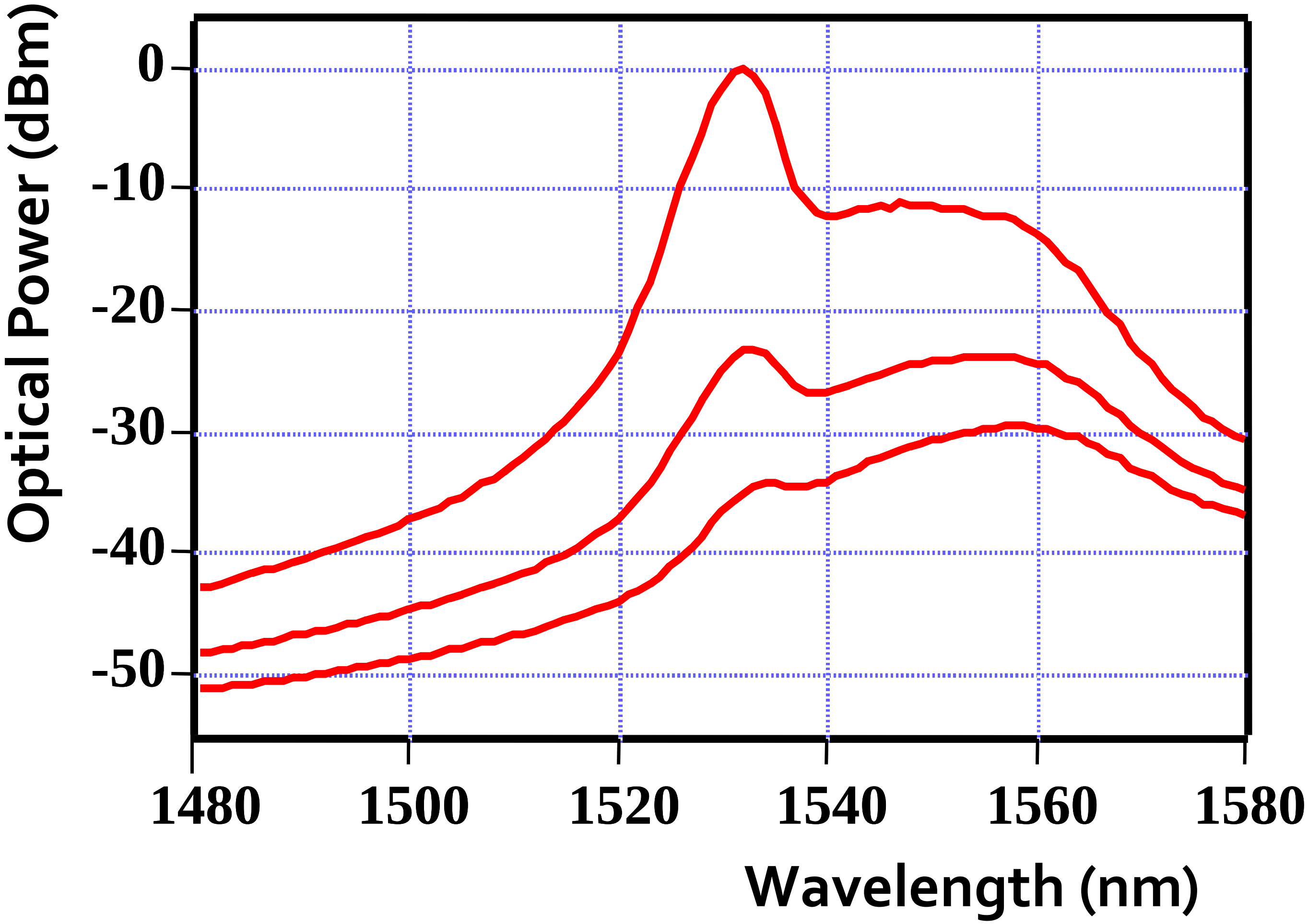


Erbium Doped Fiber Amplifiers – EDFA

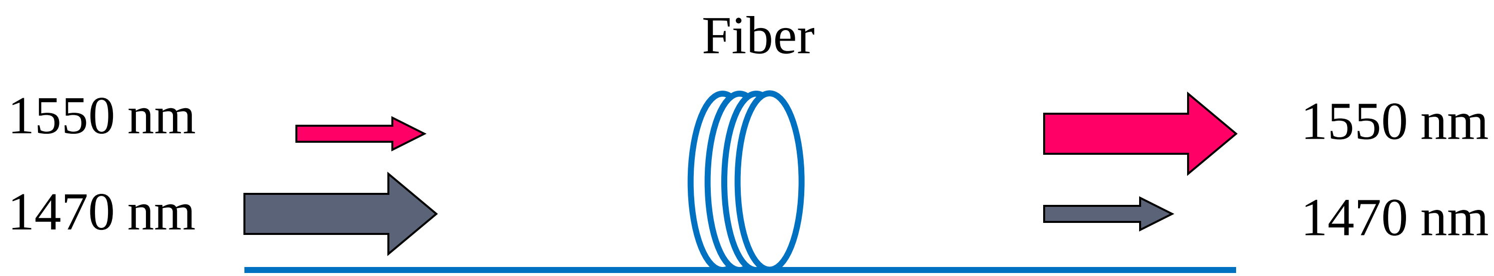


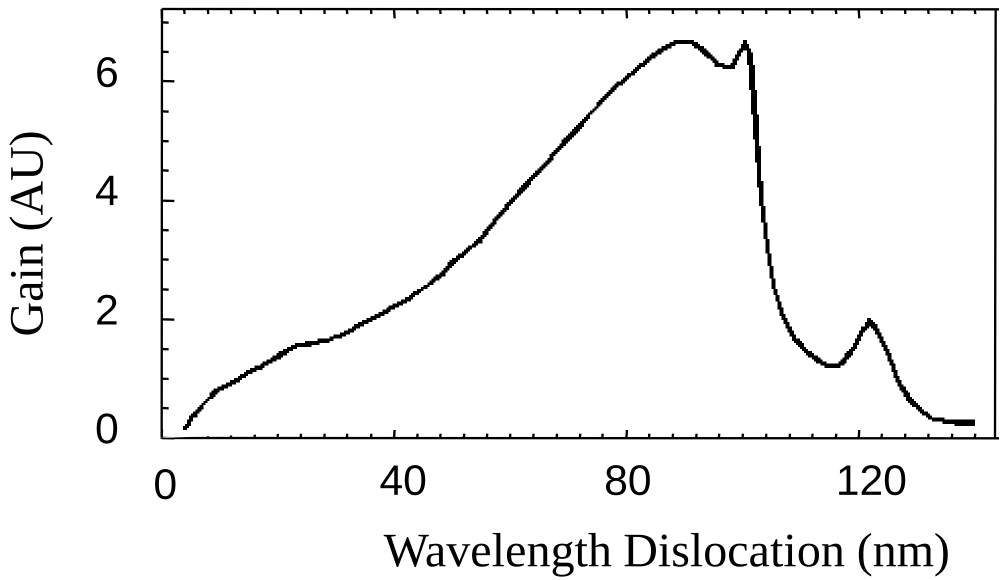
Erbium Doped Fiber Amplifiers – EDFA

Amplified Spontaneous Emission – ASE

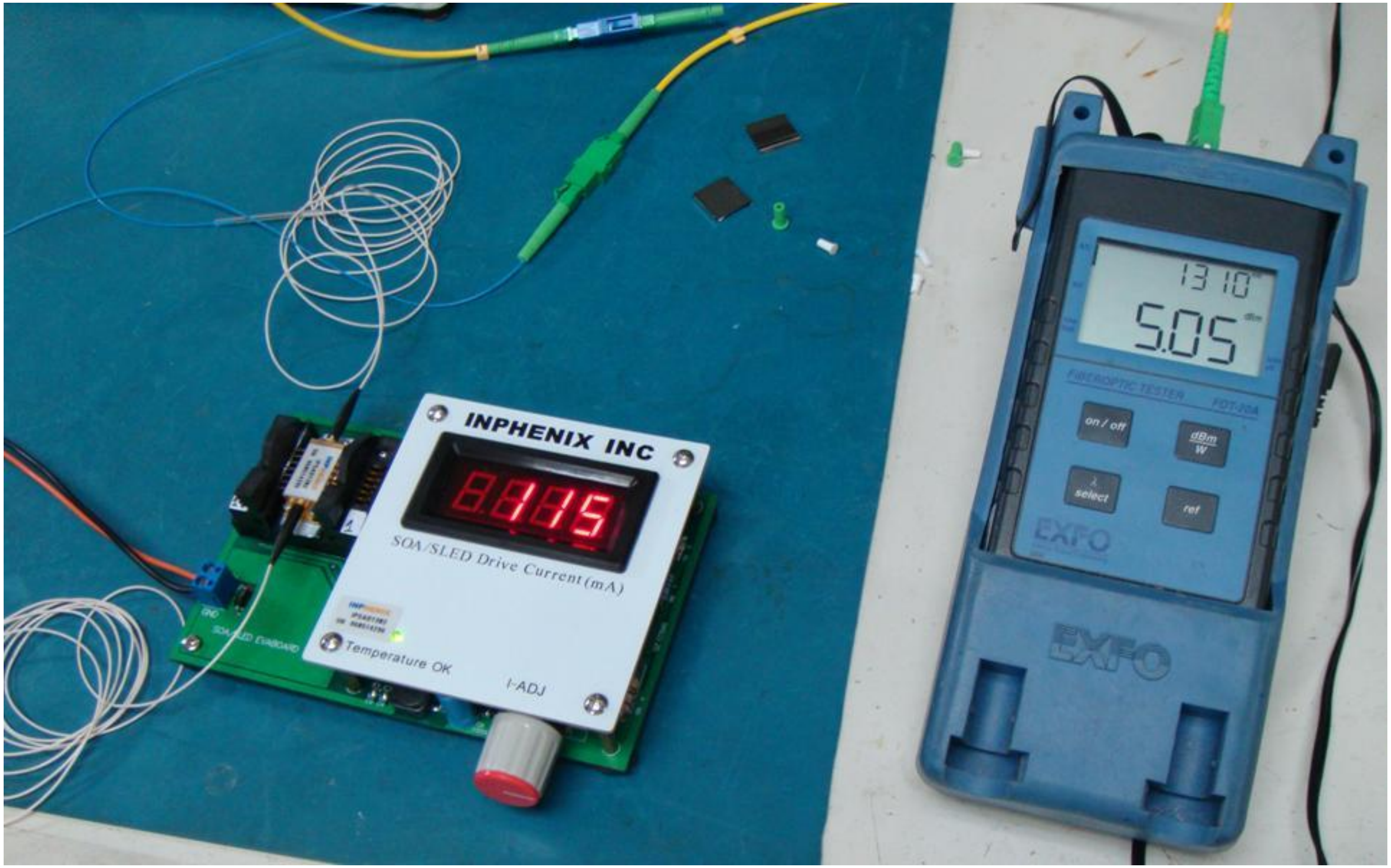


Amplificadores - Raman

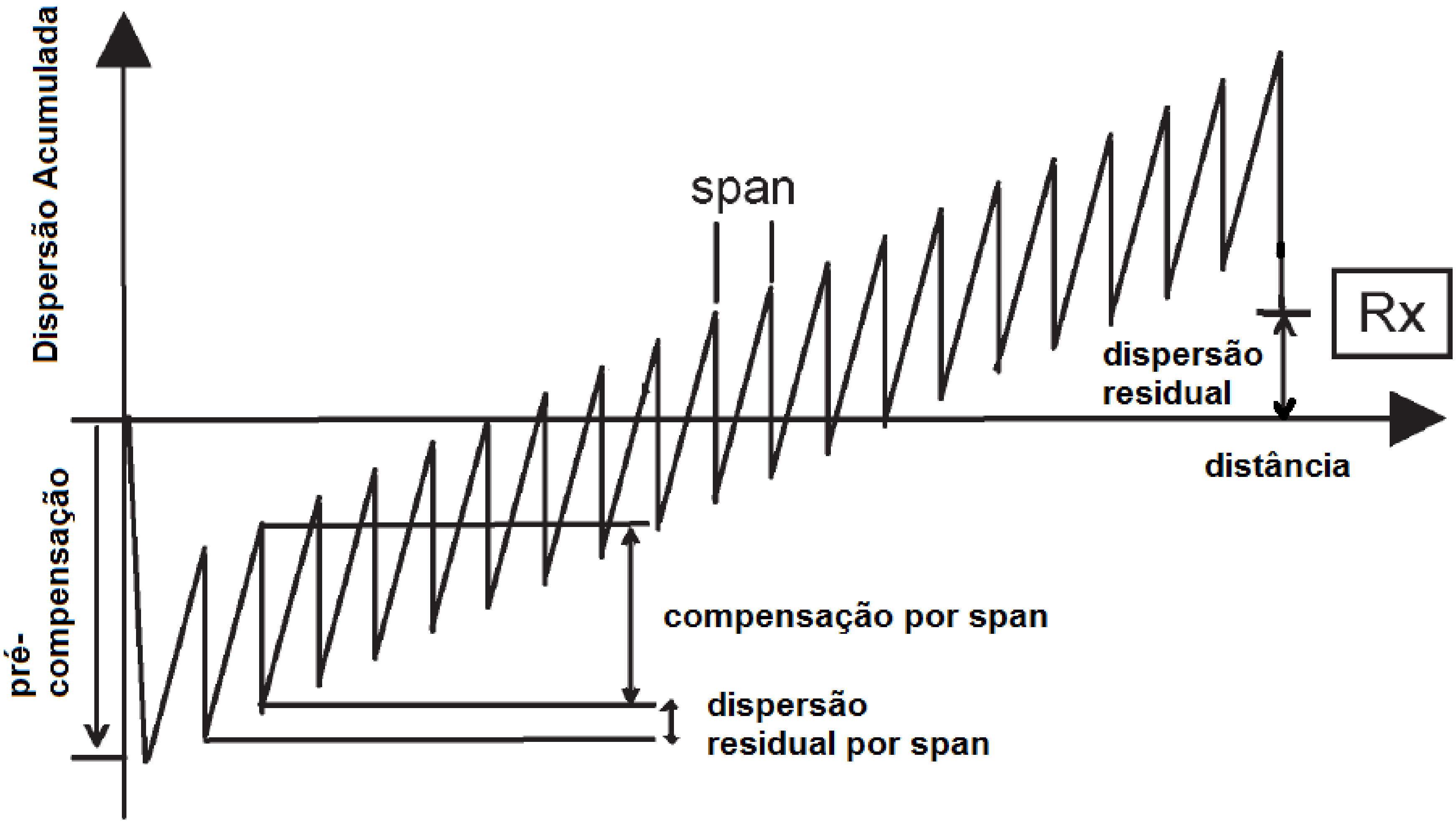




SOA – Semiconductor Optical Amplifier

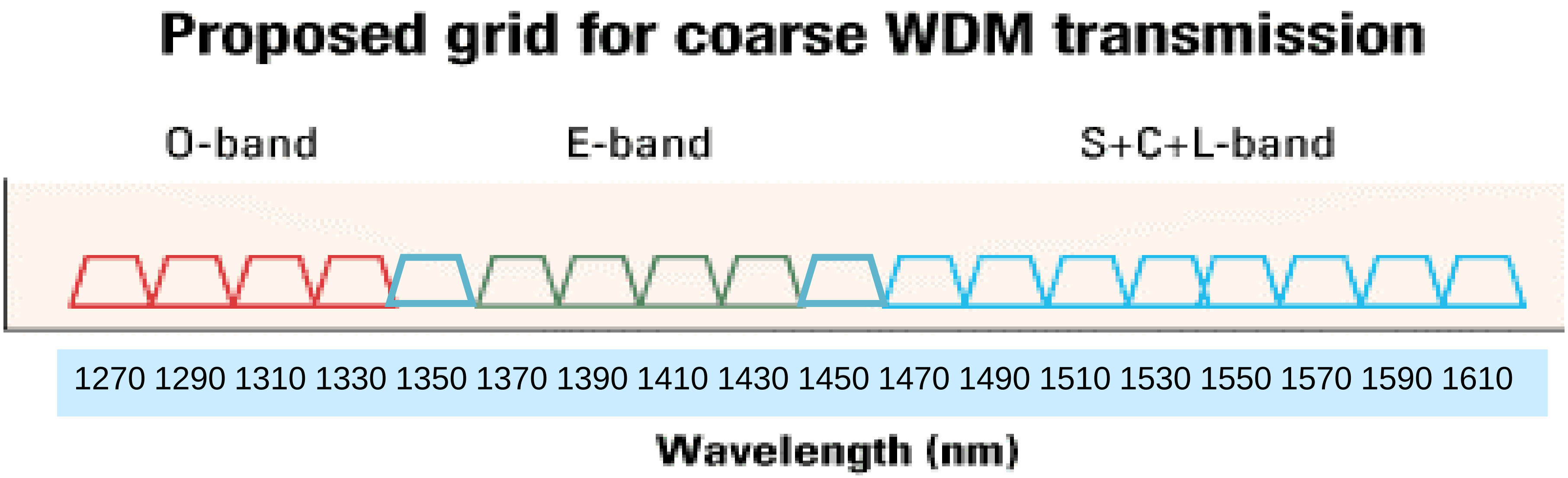


Dispersion Management

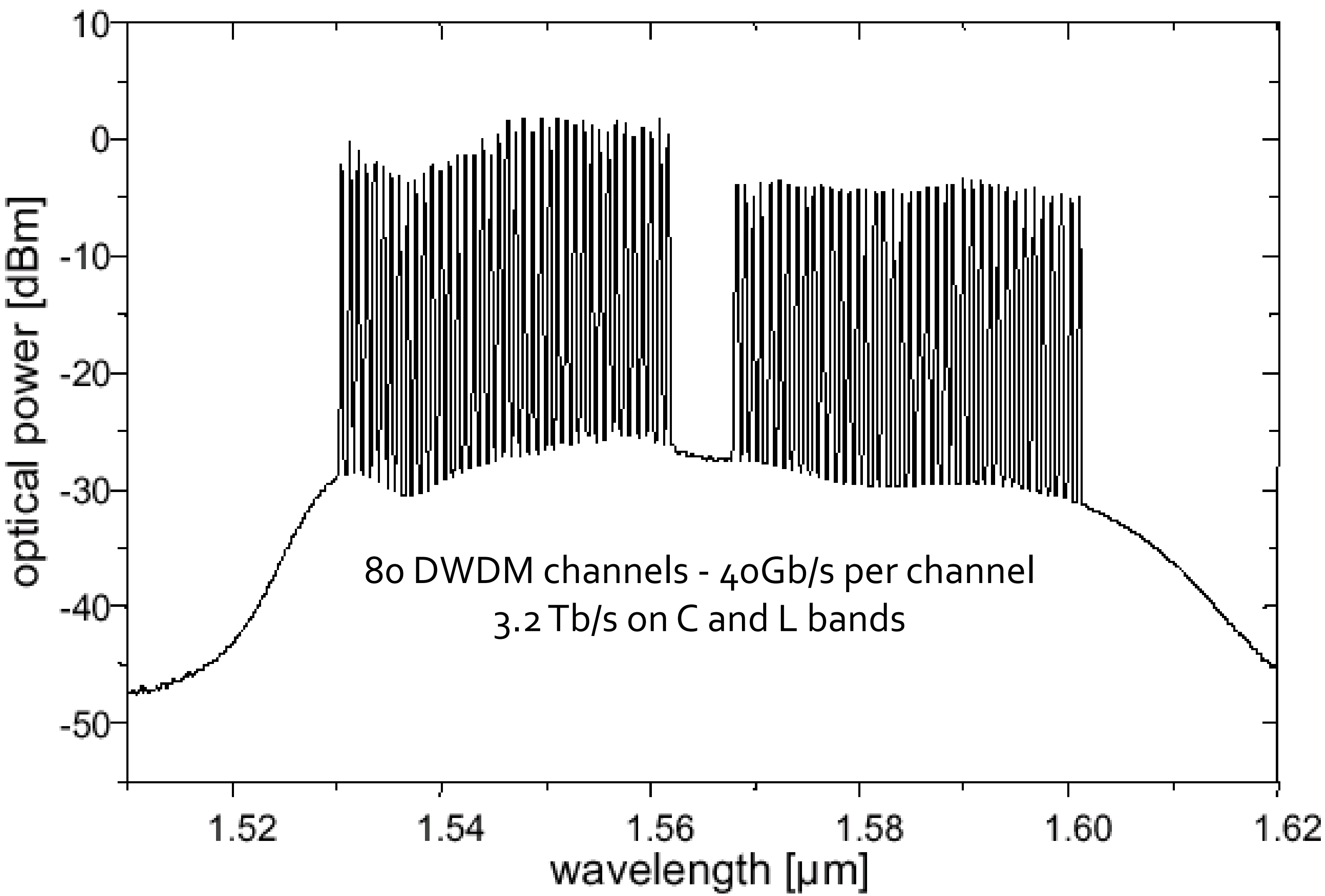


P.J. Winzer, *R.J. Essiambre;* Advanced Modulation Formats for High-Capacity Optical Transport Networks, JLT, v24, n12, p.4711, 2006

CWDM channels



DWDM channels (2004)



2. **Transmission Capacity**
    - Transmission and Reception Characteristics (external modulation; sensibility; quantum Limit)
    - Bit Rate versus Distance
    - Optical Amplifier; Dispersion Management; WDM
    - Available spectral bandwidth

Available Bandwidth

1300 nm
(~231 THz)

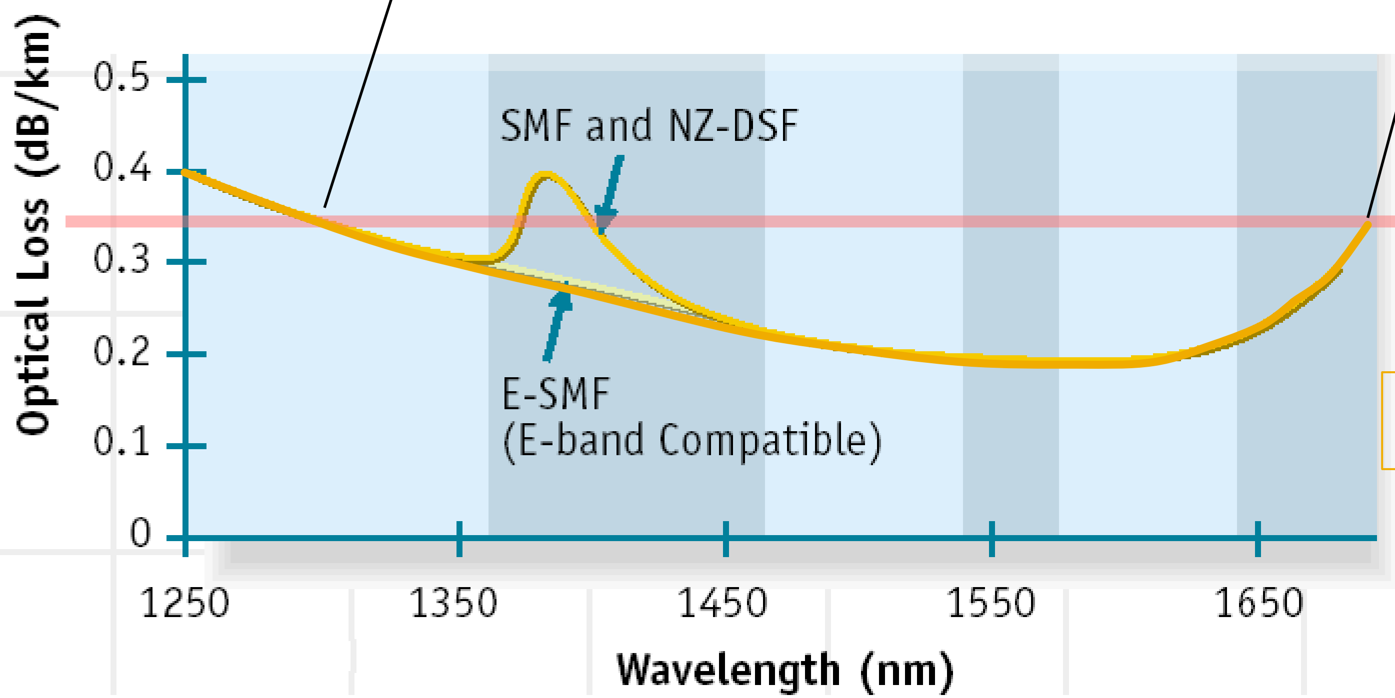
55 THz bandwidth

1700 nm
(~176 THz)

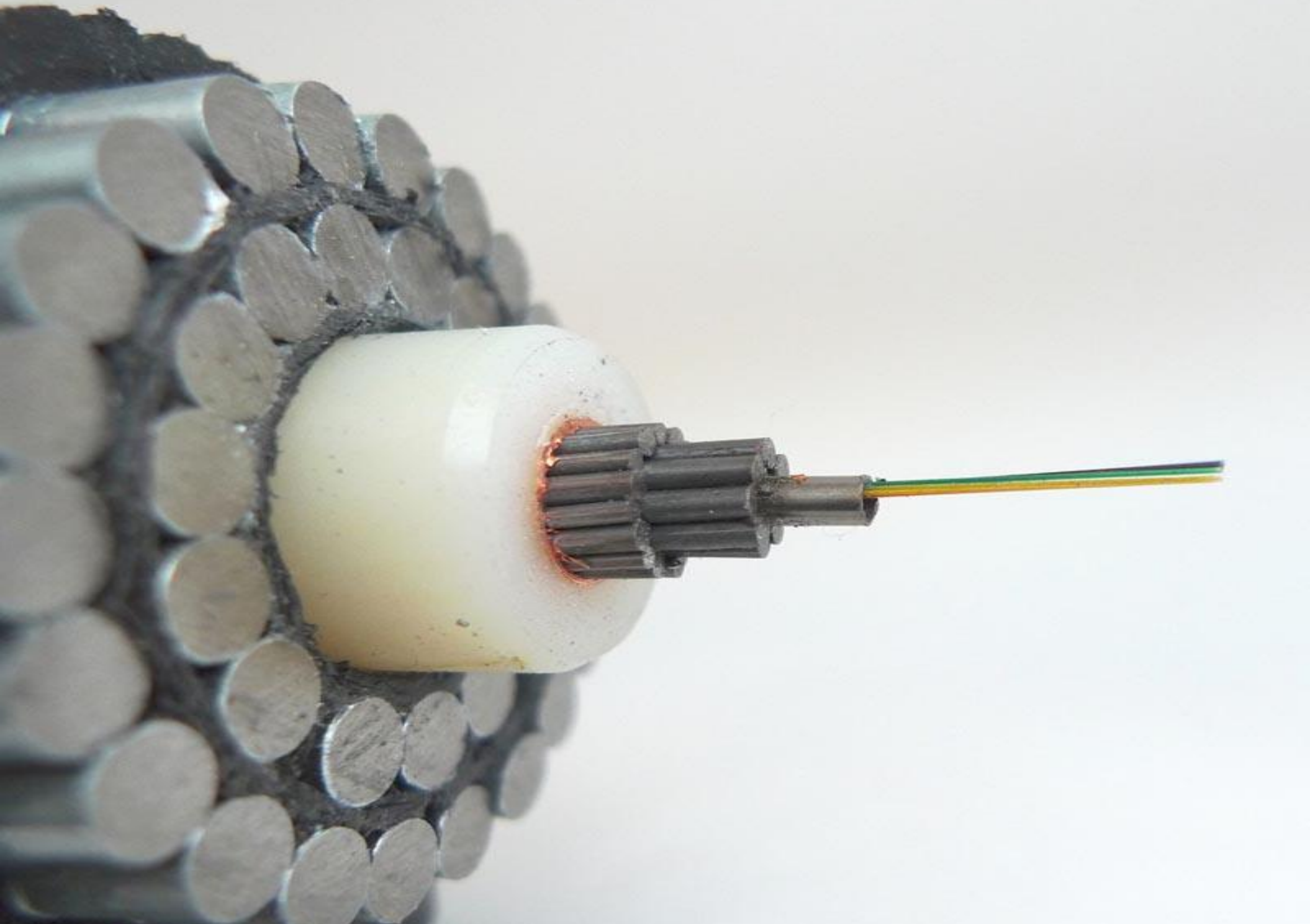
$$f = \frac{299\ 792\ 458\ m/s}{1300\ nm} \sim 231\ THz$$

$$f = \frac{299\ 792\ 458\ m/s}{1700\ nm} \sim 176\ THz$$

$c = \lambda/T$
$c = \lambda f$
$f = c/\lambda$



Loss bellow
0.35 dB/km



Activity: Videos

- Optical Fiber Fabrication
http://youtu.be/6CqT4DuAVxs pulling
http://youtu.be/4pzTZ2YoFTY pulling (Corning)
http://youtu.be/i6TbJo93qwU bendable fiber (Corning)

- Submarine cable
http://youtu.be/dWoFp-bbKWI
http://youtu.be/_YxNZvYsS6A -Video3- How do they do it: 6:09 m
http://youtu.be/zIrBMZTtN_o Loading
http://youtu.be/GUN9J9_HtbQ installation
http://youtu.be/zwkRaWDWTGw maintenance
http://youtu.be/KuIqAHJ16UQ submarine cable manufacturing
http://youtu.be/XQVzU_YQ3IQ submarine fast presentation
http://youtu.be/v1JEuzBkOD8 submarine cable manufacturing

Undersea Systems

- ACS Alaska-Oregon Network (AKORN)
- Aden-Djibouti
- Adria-1
- Africa Coast to Europe (ACE)
- ALASIA
- Alaska United East
- Alaska United SEAFAST
- Alaska United West
- ALBA-1
- Aletar
- Algeria-Spain
- Alonso de Ojeda
- ALPAL-2
- America Movil Submarine Cable System-1 (AMX-1)
- American Samoa-Hawaii (ASH)
- Americas-I North
- Americas-II
- Angola Domestic Network System (ADONES)
- Antillas 1
- APCN-2
- Aphrodite 2
- Apollo
- APX-East
- APX-West
- ARCOS
- Arctic Fibre
- Asia Pacific Gateway (APG)
- Asia Submarine-cable Express (ASE)/Cahaya Malaysia
- Asia-America Gateway (AAG) Cable System
- Atlantic Crossing-1 (AC-1)
- Atlantis-2
- Atlas Offshore
- Australia-Japan Cable (AJC)
- Australia-Papua New Guinea-2 (APNG-2)
- Australia-Singapore Cable (ASC)
- Bahamas 2
- Bahamas Domestic Submarine Network (BDSNi)
- Bahamas Internet Cable System (BICS)
- BalaLink
- Balkans-Italy Network (BIN)
- Baltica
- BARSAV
- Bass Strait-1
- Bass Strait-2
- Basslink
- Batam Dumai Melaka (BDM) Cable System
- Batam-Rengit Cable System (BRCS)
- Bay of Bengal Gateway (BBG)
- BCF-1
- BCS East
- BCS East-West Interlink
- BCS North - Phase 1
- BCS North - Phase 2
- Berytar
- Bharat Lanka Cable System
- Bicentenario
- Botnia
- BT-MT-1
- CADMOS
- Canada-United States 1 (CANUS 1)
- CanaLink
- CANTAT-3
- Caribbean-Bermuda U.S. (CBUS)
- Caucasus Cable System
- Cayman-Jamaica Fiber System
- Ceiba-1
- Celtic
- CeltixConnect
- Challenger Bermuda-1 (CB-1)

China-U.S. Cable Network (CHUS)
- CIOS
- Circe North
- Circe South

Colombia-Florida Subsea Fiber (CFX-1)
Columbus-II b
- Columbus-III
- Concerto
- Corfu-Bar
- Corse-Continent 4 (CC4)
- Corse-Continent 5 (CC5)
- Danica North
- DANICE
- Denmark-Norway 5
- Denmark-Norway 6
- Denmark-Poland 2
- Denmark-Sweden 15
- Denmark-Sweden 16
- Denmark-Sweden 17
- Denmark-Sweden 18
- Dhiraagu Cable Network
- Dhiraagu-SLT Submarine Cable Network
- Didon
- Dumai-Melaka Cable System
- E-LLAN
- EAC-C2C
- East-West
- Eastern Africa Submarine System (EASSy)
- Eastern Caribbean Fiber System (ECFS)
- ECLink
- Elektra-GlobalConnect 1 (GC1)
- Emerald Bridge Fibres
- Emerald Express
- ESAT-1
- ESAT-2
- Estepona-Tetouan
- Eurafrica
- EUROPA
- Europe India Gateway (EIG)
- FARICE-1
- Fehmarn Bält
- Fiber Optic Gulf (FOG)
- Fibralink
- Finland Estonia Connection (FEC)
- Finland-Estonia 2 (EESF-2)
- Finland-Estonia 3 (EESF-3)

http://submarinecablemap.com/

Undersea Systems

FLAG Atlantic-1 (FA-1)
FLAG Europe-Asia (FEA)
FLAG FALCON
FLAG North Asia Loop/REACH North Asia Loop
Gemini Bermuda
Geo-Eirgrid
Georgia-Russia
Germany-Denmark 2
Germany-Denmark 3
Germany-Netherlands
GLO-1
Global Caribbean Network (GCN)
GlobalConnect 2 (GC2)
GlobalConnect 3 (GC3)
GlobalConnect-KPN
GlobeNet
GlobeNet Segment 5 (Bermuda-U.S.)
GO-1 Mediterranean Cable System
Gondwana-1
Greece-Western Europe Network (GWEN)
Greenland Connect
Guam Okinama Kyushu Incheon (GOKI)
Guernsey-Jersey-4
Gulf Bridge International Cable System (GBICS)/Middle East North Africa (MENA) Cable System
HANNIBAL System
HANTRU1 Cable System
Hawaiki Cable
Hawk
Hibernia Atlantic
Hibernia Express
High-capacity Undersea Guernsey Optical-fibre (HUGO)
Hokkaido-Sakhalin Cable System (HSCS)
Honotua
i2i Cable Network (i2icn)
IMEWE
INGRID
Interchange Cable Network (ICN)
IP-Only Denmark-Sweden
Italy-Albania
Italy-Croatia
Italy-Greece 1
Italy-Libya
Italy-Malta
Italy-Monaco

ITUR
JaKa2LaDeMa
JAKABARE
Janna
Japan-U.S. Cable Network (JUS)
Jonah
KAFOS
Kattegat 1
Kattegat 2
Kodiak Kenai Fiber Link (KKFL)
Korea-Japan Cable Network (KJCN)
Kuwait-Iran
Lanis-1
Lanis-2
Latvia-Sweden 1 (LV-SE 1)
Lev Submarine System
LFON (Libyan Fiber Optic Network)
Libreville-Port Gentil Cable
Loukkos
Lower Indian Ocean Network (LION)
Lower Indian Ocean Network 2 (LION2)
Main One
Mariana-Guam Cable
Matrix Cable System
Maya-1
Med Cable Network
MedNautilus Submarine System
Melita 1
Mid-Atlantic Crossing (MAC)
Middle East North Africa (MENA) Cable System/Gulf Bridge International
Moratelindo International Cable System-1 (MIC-1)
NorSea Com
NorthStar
OMRAN/EPEG Cable System
Pacific Caribbean Cable System (PCCS)
Pacific Crossing-1 (PC-1)
Pan American (PAN-AM)
Pan European Crossing (UK-Belgium)
Pan European Crossing (UK-Ireland)
Pan-American Crossing (PAC)
Pangea Baltic Ring
Pangea North
Pangea South
Pencan-6
Pencan-8
Perseid

Persona
PGASCOM
Pipe Pacific Cable-1 (PPC-1)
Pishgaman Oman Iran (POI) Network
Polaris
Qatar-UAE Submarine Cable System
Russia-Japan Cable Network (RJCN)
Russian Optical Trans-Arctic System (ROTACS)
SAFE
Saint Maarten Puerto Rico Network One (SMPR-1)
Samoa-American Samoa (SAS)
SAT-3/WASC
Saudi Arabia-Sudan-1 (SAS-1)
Saudi Arabia-Sudan-2 (SAS-2)
Scandinavian Ring North
Scandinavian Ring South
Scotland-Northern Ireland 1
Scotland-Northern Ireland 2
Seabras-1
SEACOM/Tata TGN-Eurasia
SeaMeWe-3
SeaMeWe-4
Seychelles to East Africa System (SEAS)
SHEFA-2
Silphium
Sirius
Sirius North
Solas
Solomons Oceanic Cable Network
South America-1 (SAm-1)
South American Crossing (SAC)/Latin American Nautilus (LAN)
South Atlantic Cable System (SACS)
South Atlantic Express (SAEx)
South Atlantic Marine System (SAMS)
Southeast Asia Japan Cable (SJC)
Southern Cross Cable Network (SCCN)
St. Thomas-St. Croix System
Suriname-Guyana Submarine Cable System (SG-SCS)
Svalbard Undersea Cable System
Sweden-Estonia (EE-S 1)
Sweden-Finland 4 (SFS-4)
Sweden-Finland 6

Sweden-Finland Link (SFL)
TAGIDE 2
Taino-Carib
Taiwan Strait Express-1 (TSE)-1
Tamares North
Tangerine
Tasman Global Access (TGA) Cable
Tasman-2
TAT-14
Tata TGN-Atlantic
Tata TGN-Gulf
Tata TGN-Intra Asia (TGN-IA)
Tata TGN-Pacific
Tata TGN-Tata Indicom
Tata TGN-Western Europe
TE North/TGN-Eurasia/SEACOM/Alexandros
Techteledata (TTD) Cable
Telstra Endeavour
Thailand-Indonesia-Singapore (TIS)
The East African Marine System (TEAMS)
Tonga Cable
Trans-Pacific Express (TPE) Cable System
Transworld (TW1)
Trapani-Kelibia
Turcyos-1
Turcyos-2
UAE-Iran
UGARIT
UK-Channel Islands-7
UK-Channel Islands-8
UK-France 3
UK-Netherlands 14
Ulysses
Unisur
Unity/EAC-Pacific
Vodafone Malta-Sicily Cable System (VMSCS)
WARF Submarine Cable
WASACE Africa
WASACE Americas
WASACE Europe
West African Cable System (WACS)
Xiamen-Kinmen Undersea Cable
Yellow

http://submarinecablemap.com/

Undersea Systems

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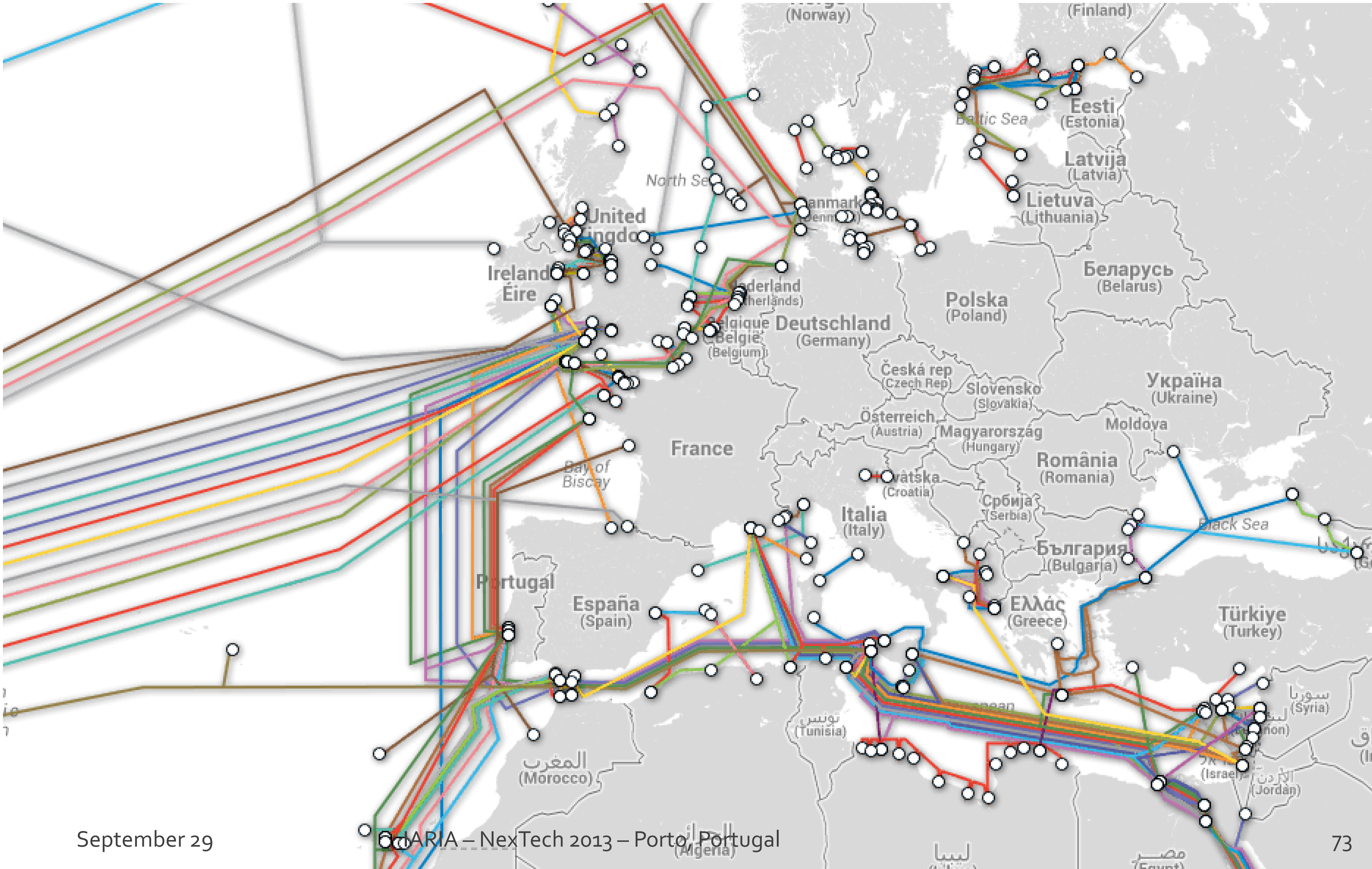
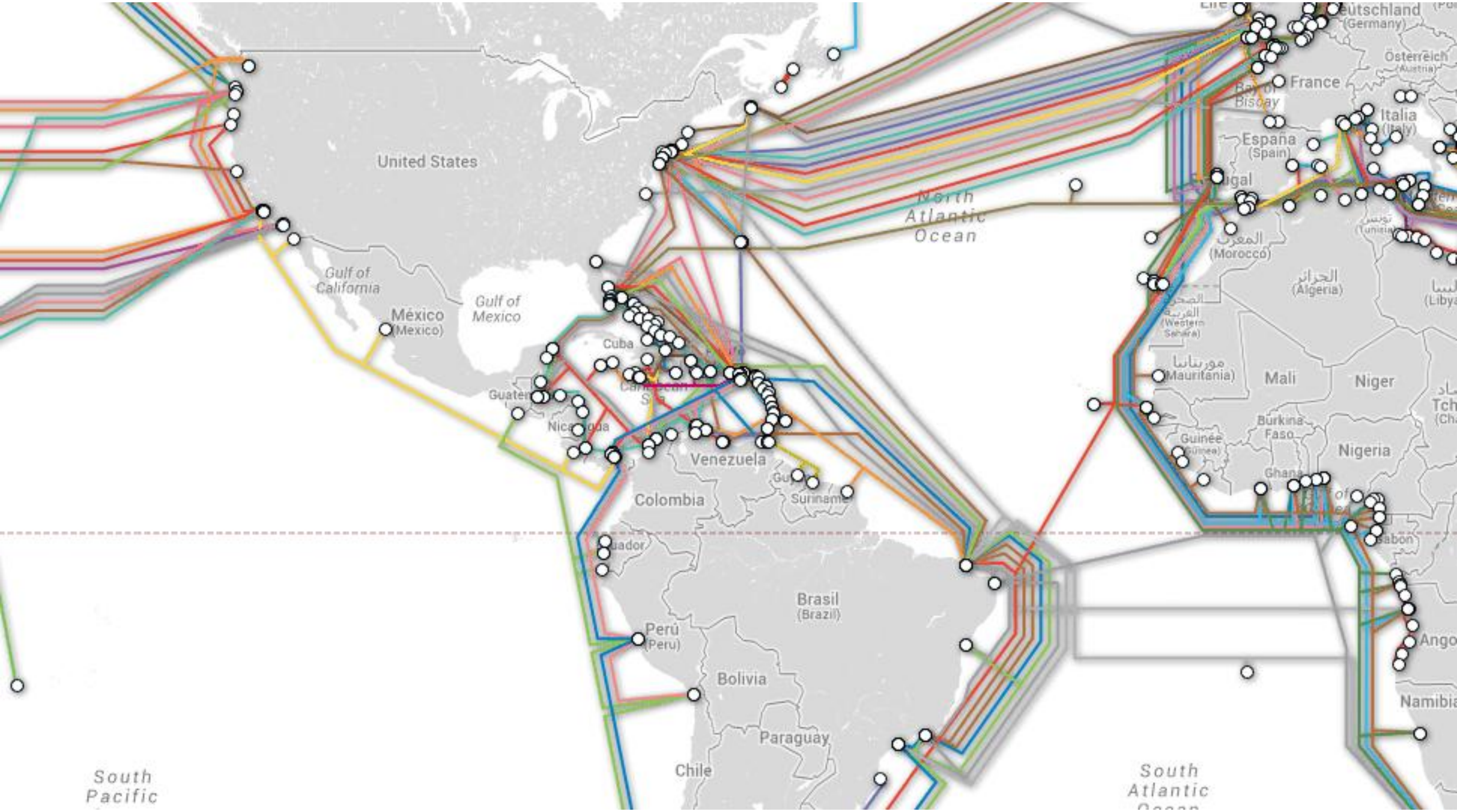


Undersea Systems

http://submarinecablemap.com/

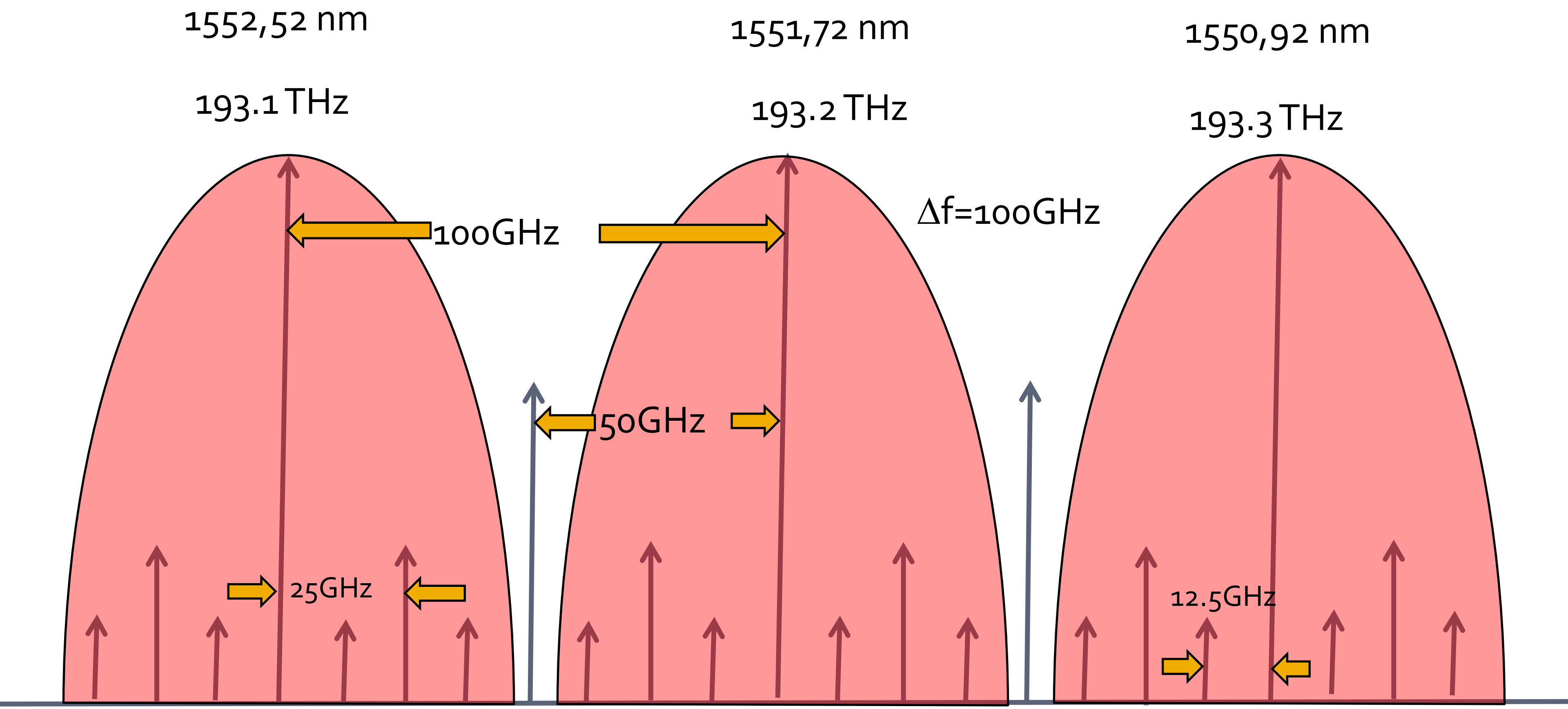


3. **Multiplexing and Modulation Techniques**

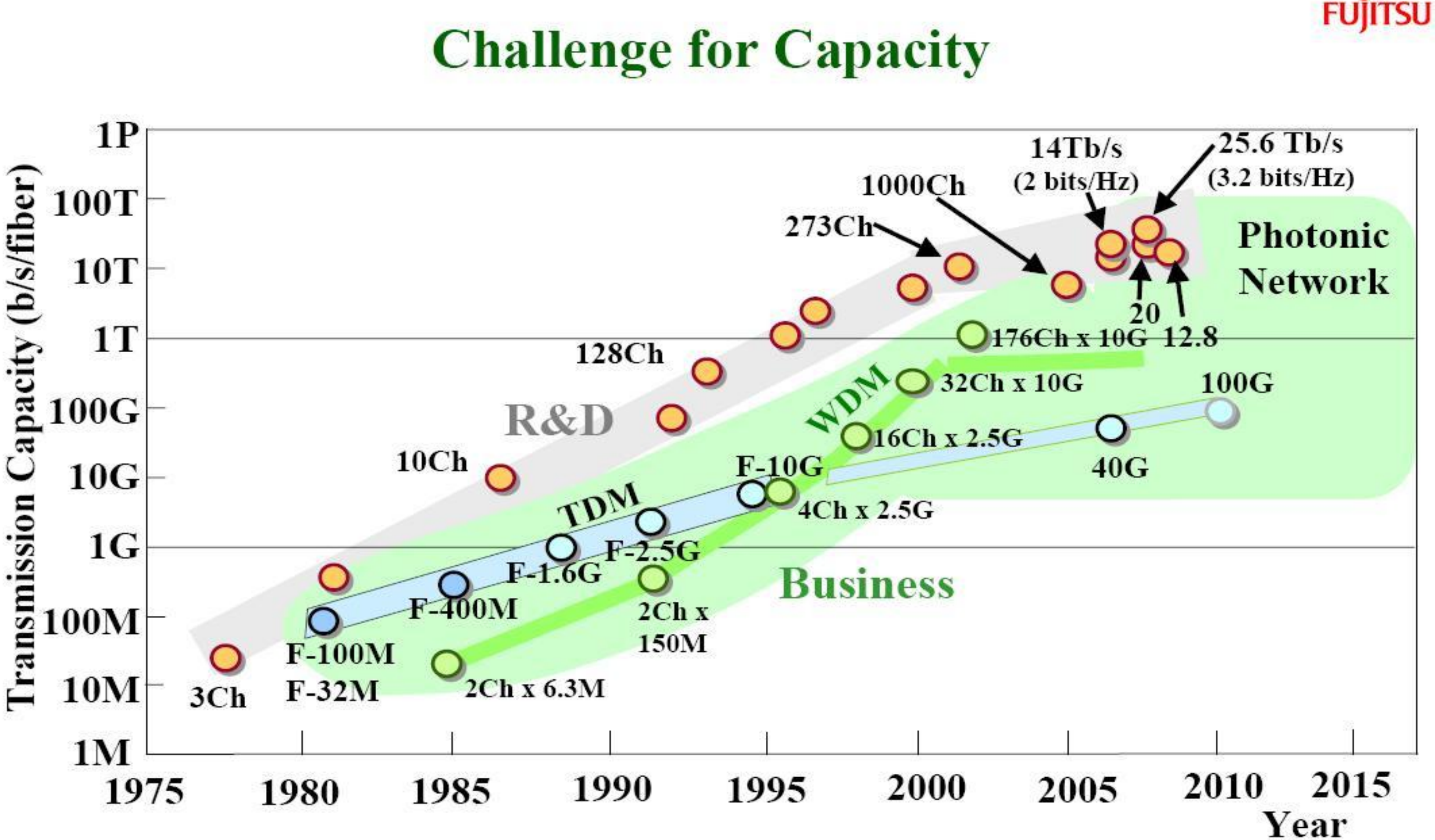
- TDM and WDM
- Spectral Efficiency, OFDM
- m-OOK, m-PSK, m-QAM
- Coherent Reception
- Noise Mitigation and Channel Capacity
- Last trick: SDM

Capacity evolution

WDM systems



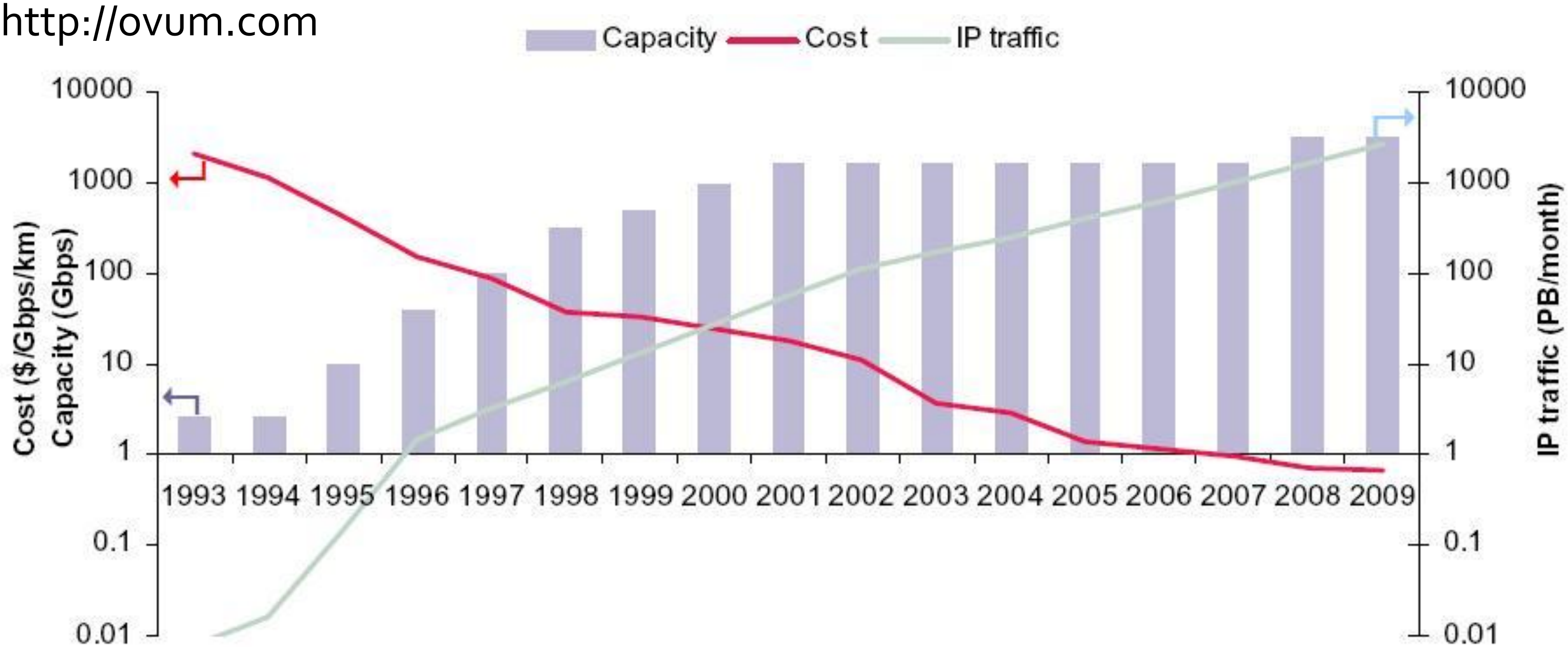
ECOC 2008



(Source: Revised data from MIC and Prof. Miki, Univ. of Electro-Comms.)

ECOC 2008

http://ovum.com



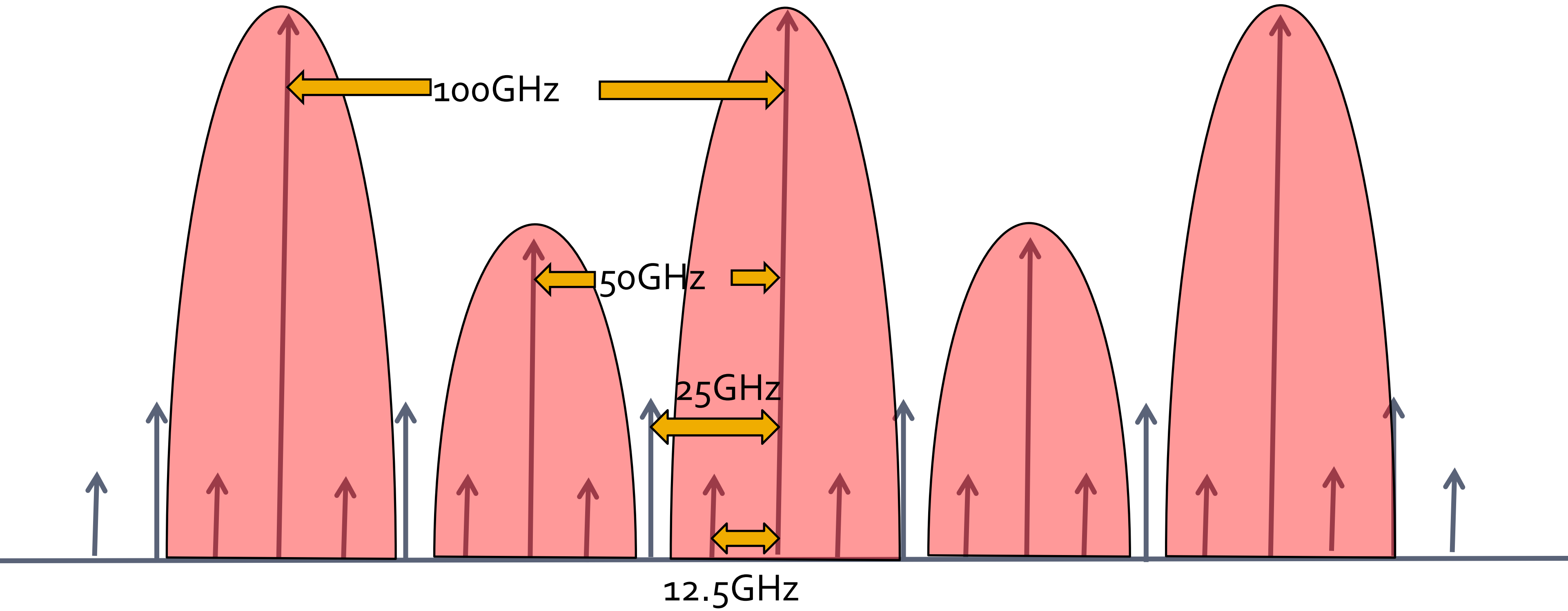
- Backbone DWDM capacity and per-bit, per-km cost improvements have barely kept pace with IP traffic growth
- The game changes as optical moves to edge/access

Source: Ovum; IP traffic data from Minnesota U.S. Internet traffic studies http://www.dtc.umn.edu/mints/igrowth.html, with Ovum 2008/9 extrapolation

3. **Multiplexing and Modulation Techniques**
   - TDM and WDM
   - Spectral Efficiency, OFDM
   - m-OOK, m-PSK, m-QAM
   - Coherent Reception
   - Noise Mitigation and Channel Capacity
   - Last trick: SDM

Capacity evolution

- Spectral effiency can be improoved.

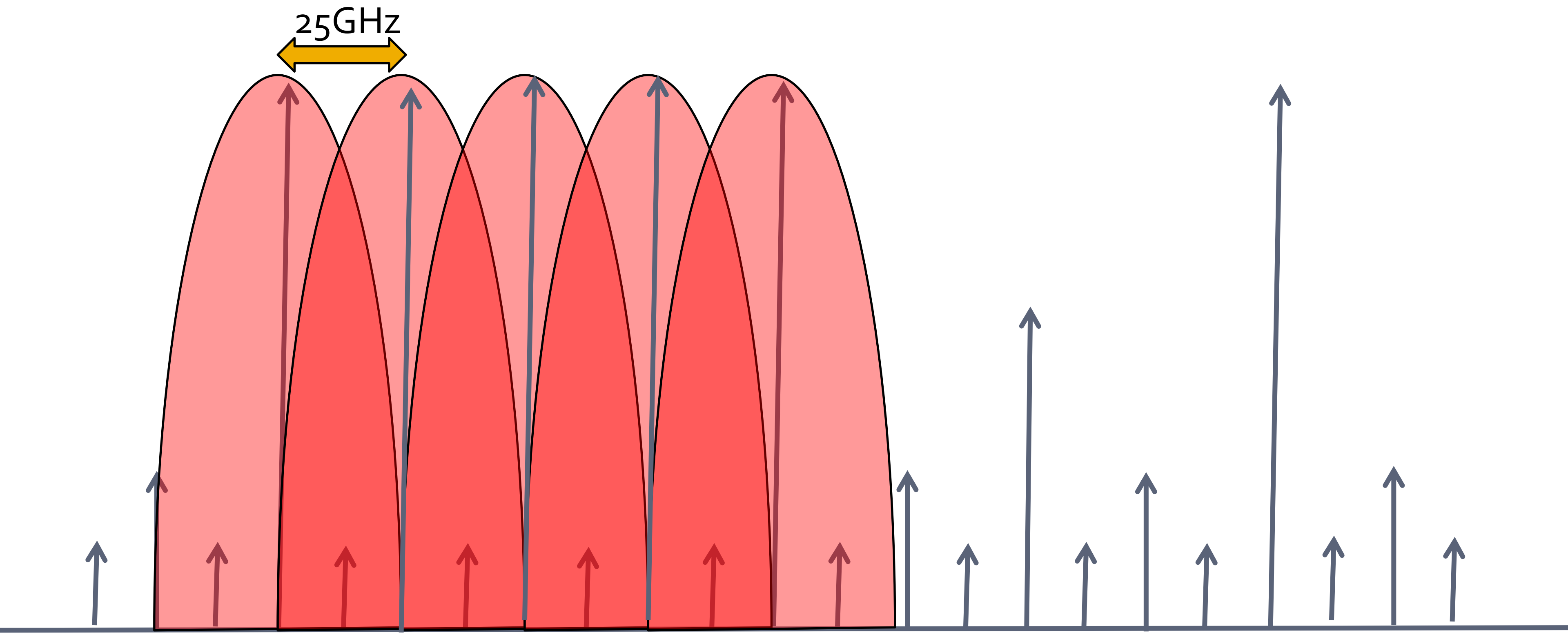


The Spectral Efficiency (*SE*) in a WDM system is the bit rate (*R*) of a channel divided by the Channel Spacing (*CS*) $\boldsymbol{SE=R/CS}$

$$SE = 40\text{Gbps}/50\text{GHz} = 0.8\ (b/s/Hz)$$

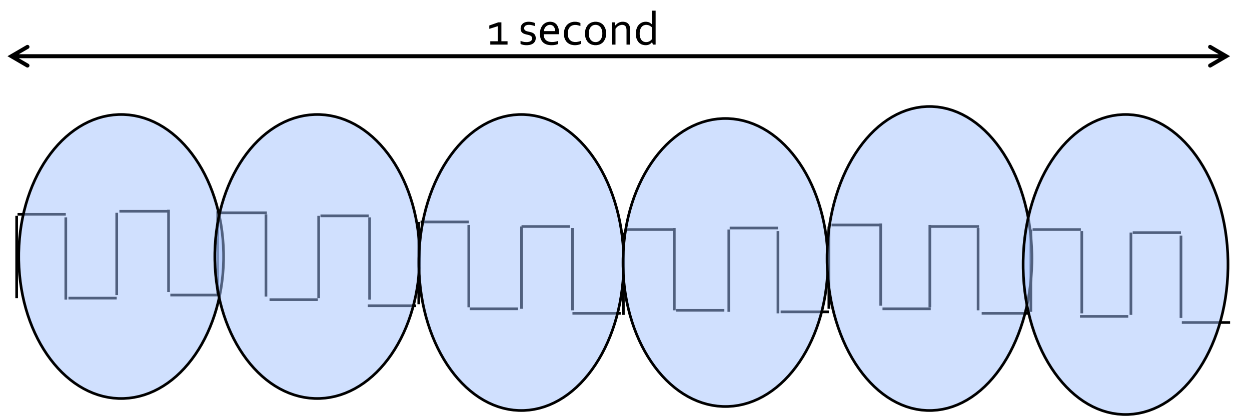
OFDM

- Orthogonal frequency corresponds to frequency separation $\Delta f = 1/T_s$ were T_s is the time of each symbol.



3. **Multiplexing and Modulation Techniques**
   - TDM and WDM
   - Spectral Efficiency, OFDM
   - m-OOK, m-PSK, m-QAM
   - Coherent Reception
   - Noise Mitigation and Channel Capacity
   - Last trick: SDM

Multilevel Modulation



R=24 bit/s
D=6 symbol/s

R (bit rate) Ex.: *R*=24

m =Number of different symbols necessary to represents ***l*** bits.

D (symbol rate) Ex.: *D*=6

$$m = 2^l$$ (#) Ex.: *m*=16

$$l = \frac{R}{D}$$ (Bits per symbols) Ex.: *l*=4

$$\boxed{R = D \ln_2 m}$$

Modulation Technique

- The spectral efficiency is higher for multilevel modulation technique.
  - *m-QAM – Quadrature Amplitude Modulation*
  - *m-PSK – Phase Shifted Keying*
  - *m-DPSK - Differential Phase-Shifted Keying*
  - *m-OOK – On Off Keying*

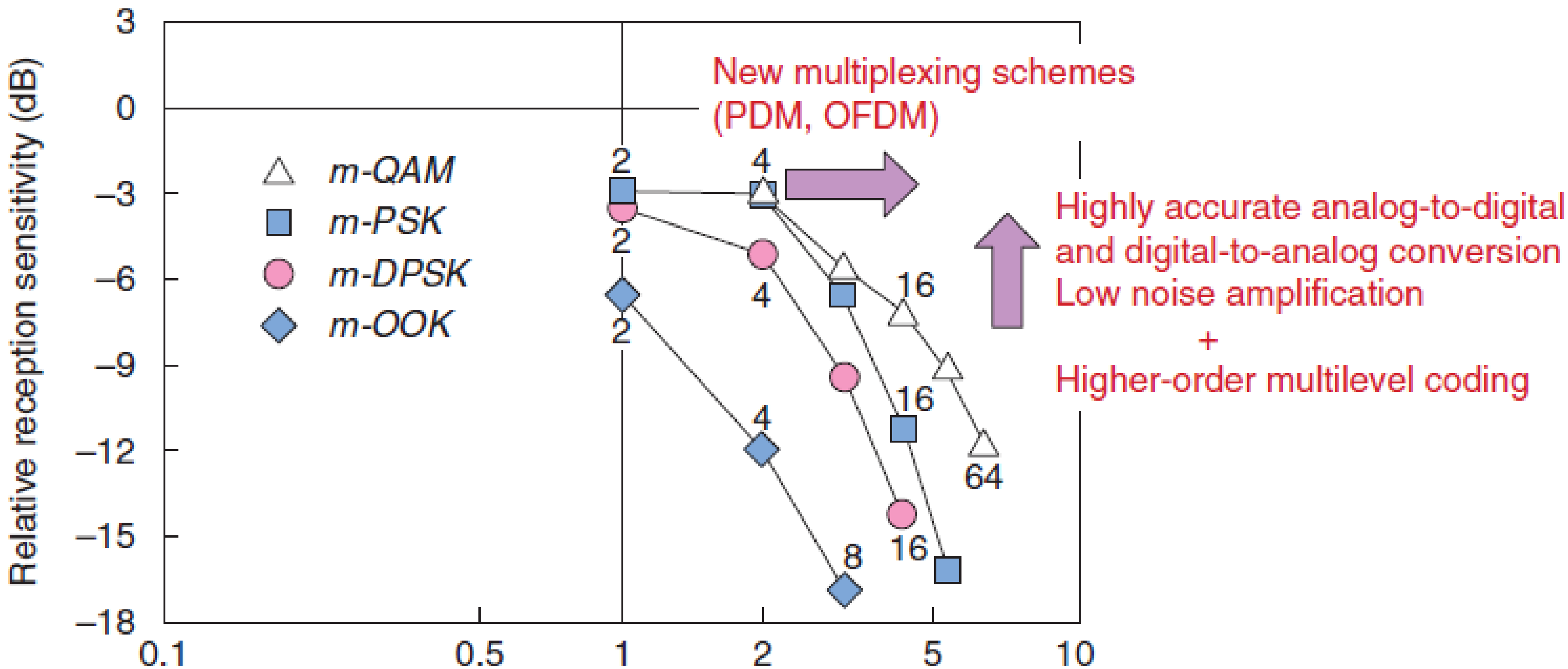
$$R = D \ln_2 m$$

Bit rate

Symbols rate

Number of levels

Receptor sensitivity



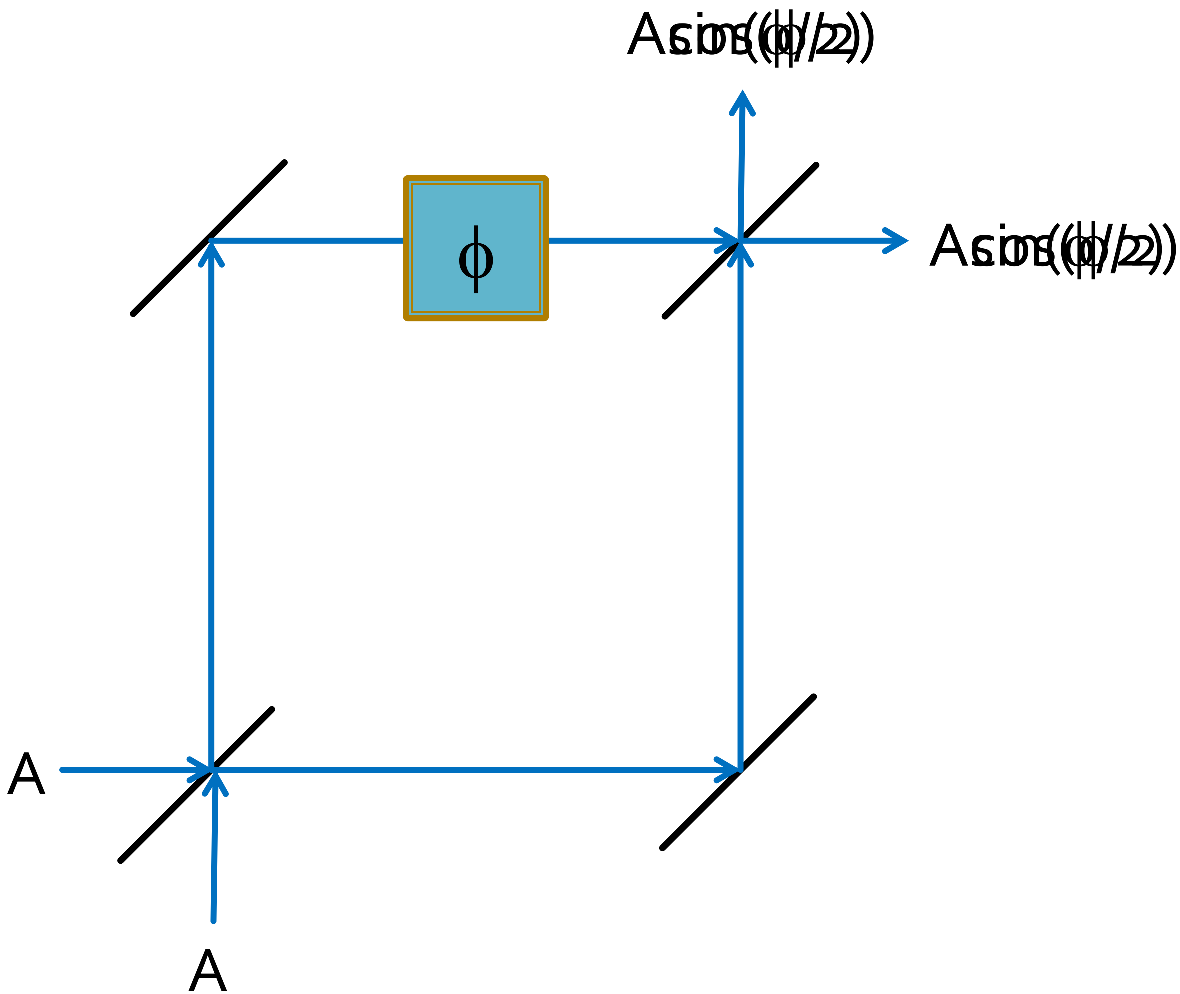
QAM: quadrature amplitude modulation

Tradeoff for multilevel coding.

***Yutaka Miyamoto, Akihide Sano, Eiji Yoshida, Toshikazu Sakano*, Ultrahigh-capacity Digital Coherent Optical Transmission Technology, NTT Technical Review, 2011**

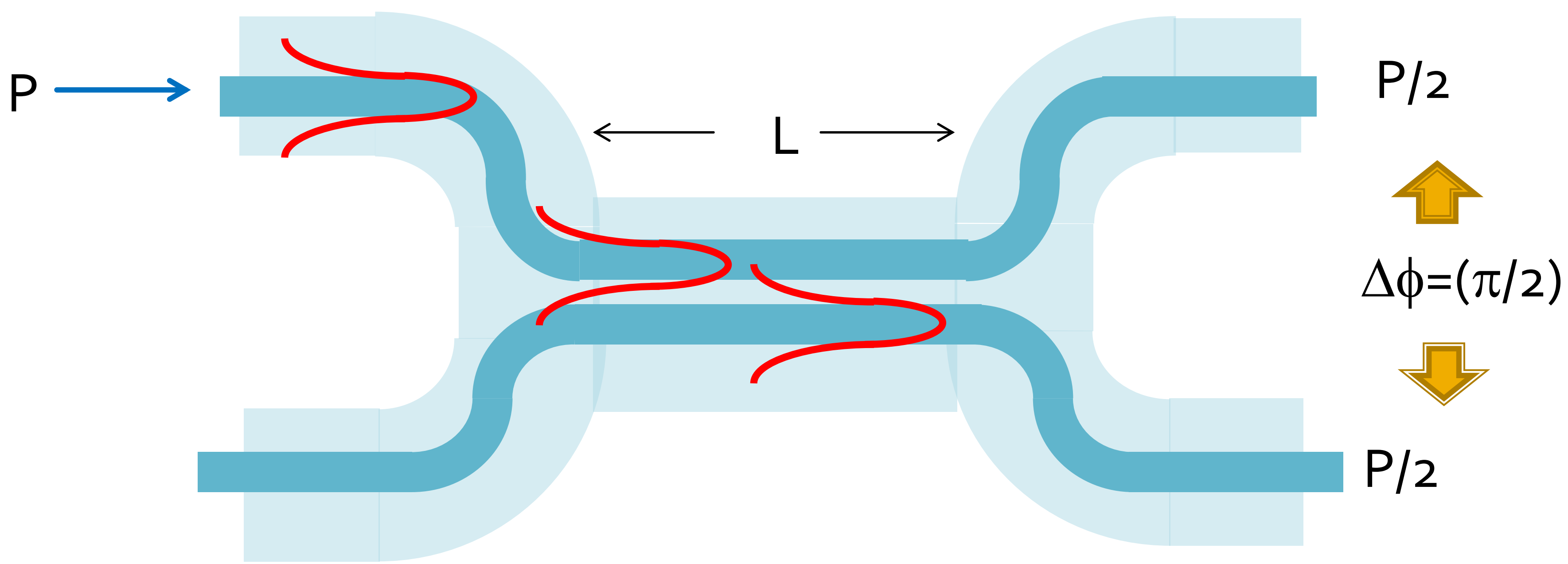
m-OOK, m-PSK, m-QAM

- Mach Zehnder



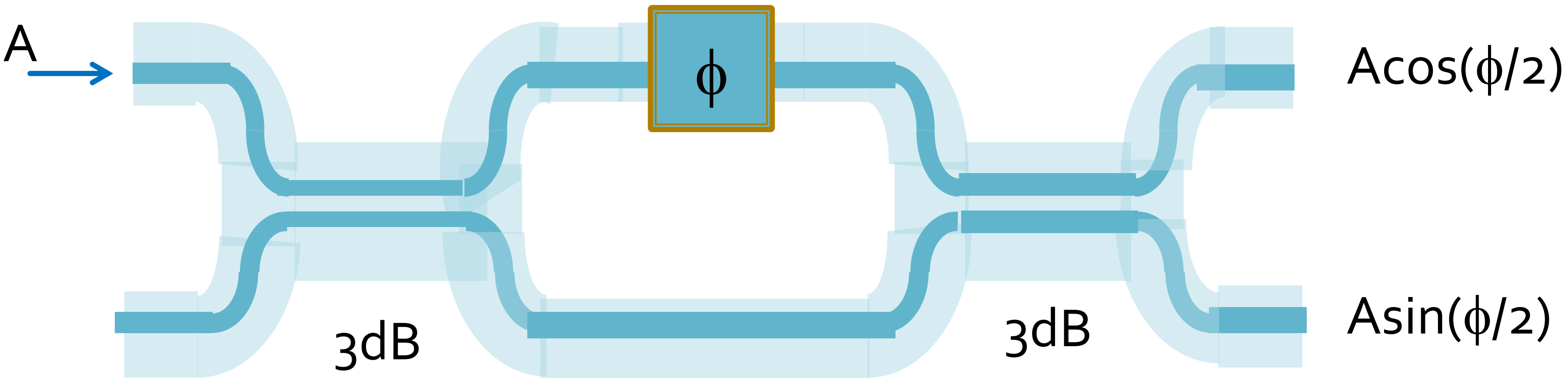
m-OOK, m-PSK, m-QAM

- 3dB splitter



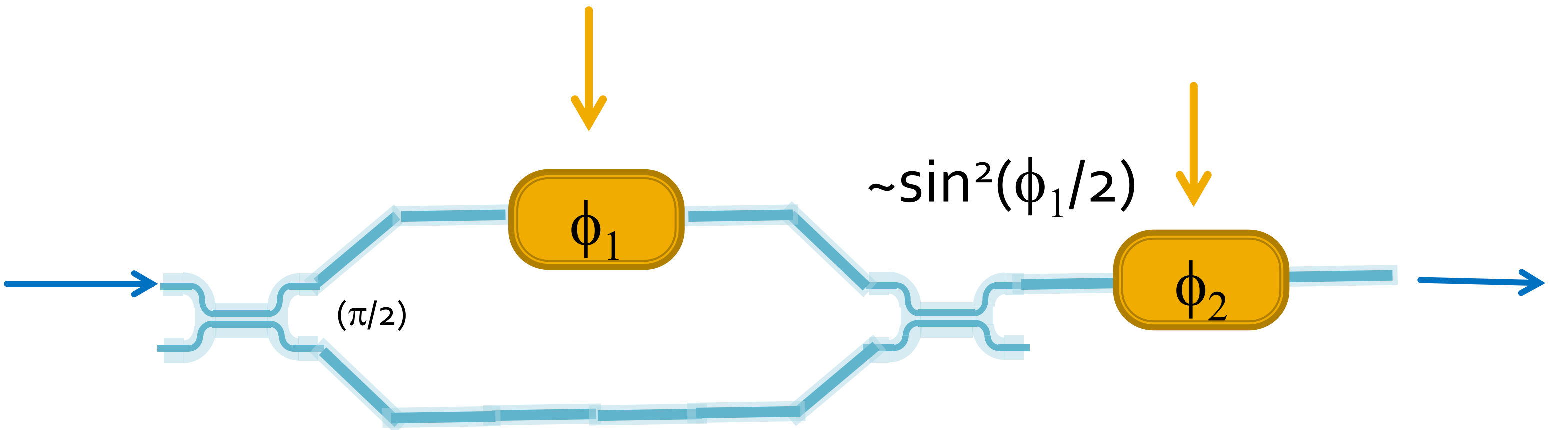
m-OOK, m-PSK, m-QAM

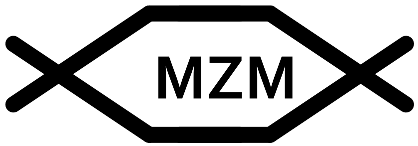
- Mach Zehnder constructed with 3dB splitters

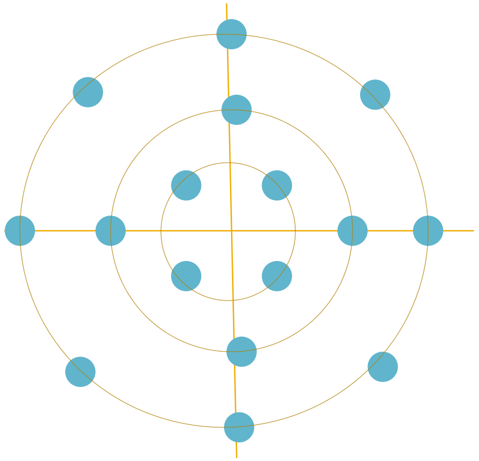


m-OOK, m-PSK, m-QAM

- Phase and amplitude modulation







m-OOK, m-PSK, m-QAM

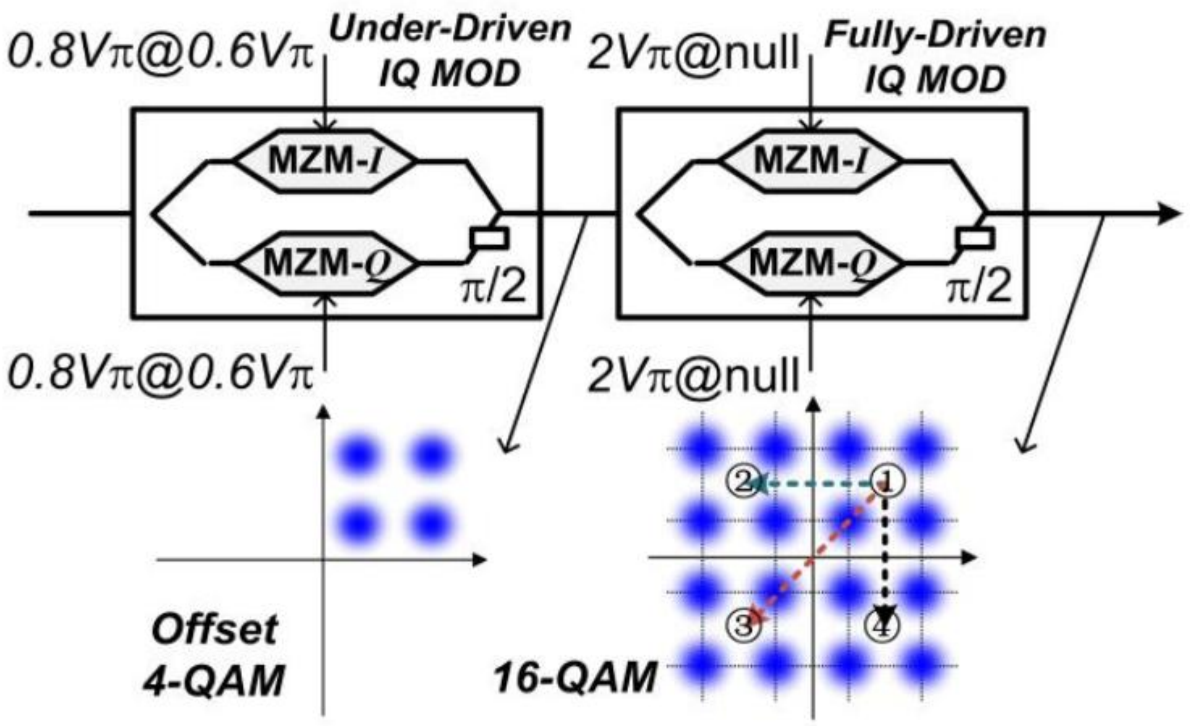
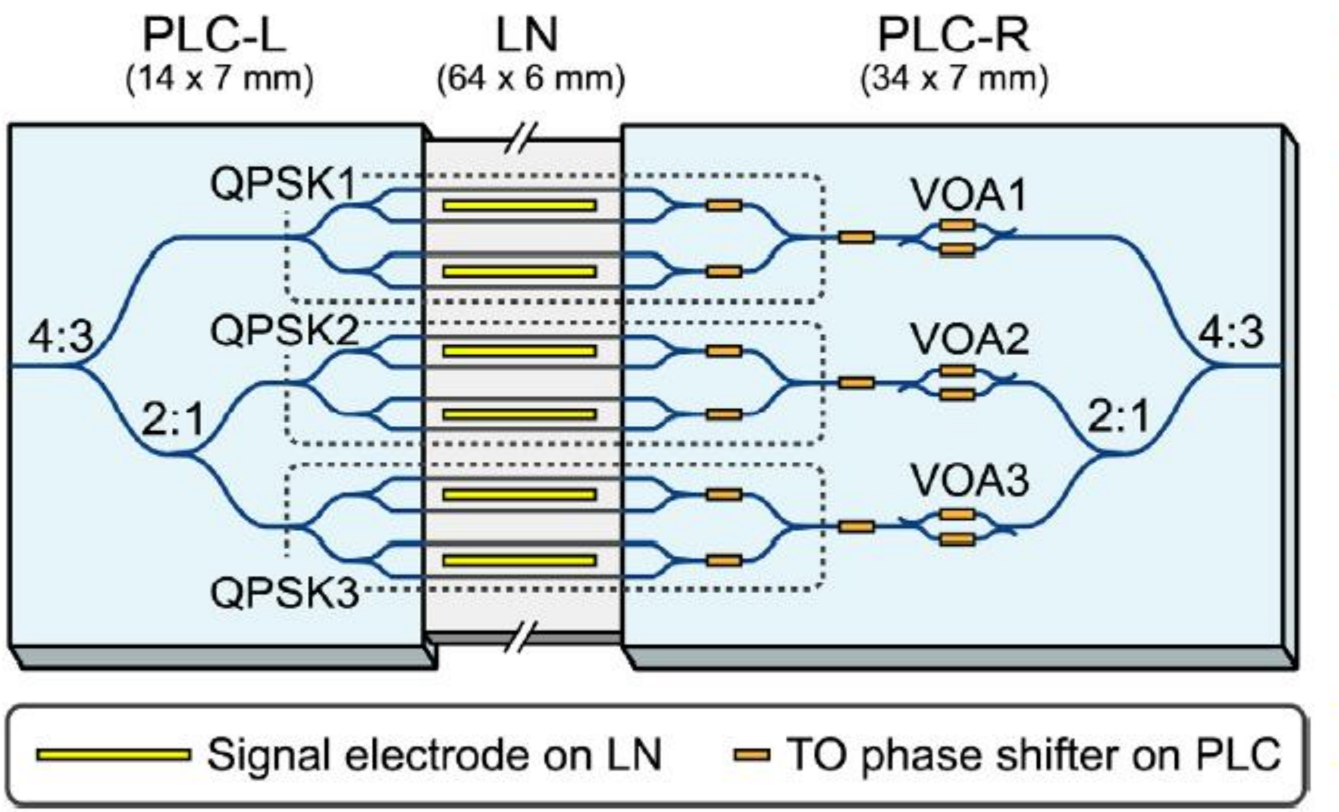


Fig. 1. Operation principle of the proposed 16-QAM transmitter using two tandem IQ modulators.

- Guo-Wei Lu et all, "40-Gbaud 16-QAM transmitter using tandem IQ modulators with binary driving electronic signals modulation and demodulation schemas", 25 October 2010 / Vol. 18, No. 22 / OPTICS EXPRESS pp.23062-23069

m-OOK, m-PSK, m-QAM



PLC – Planar Lightwave Circuit LN – Lithium Niobyde

- Hiroshi Yamazaki, Takashi Yamada, Takashi Goh, Yohei Sakamaki, and Akimasa Kaneko (NTT), 64QAM Modulator with a Hybrid Configuration of Silica PLCs and LiNbO3 Phase Modulators for 100-Gb/s Applications, ECOC 2009, 20-24 September, 2009, Vienna, Austria

3. **Multiplexing and Modulation Techniques**
   - TDM and WDM
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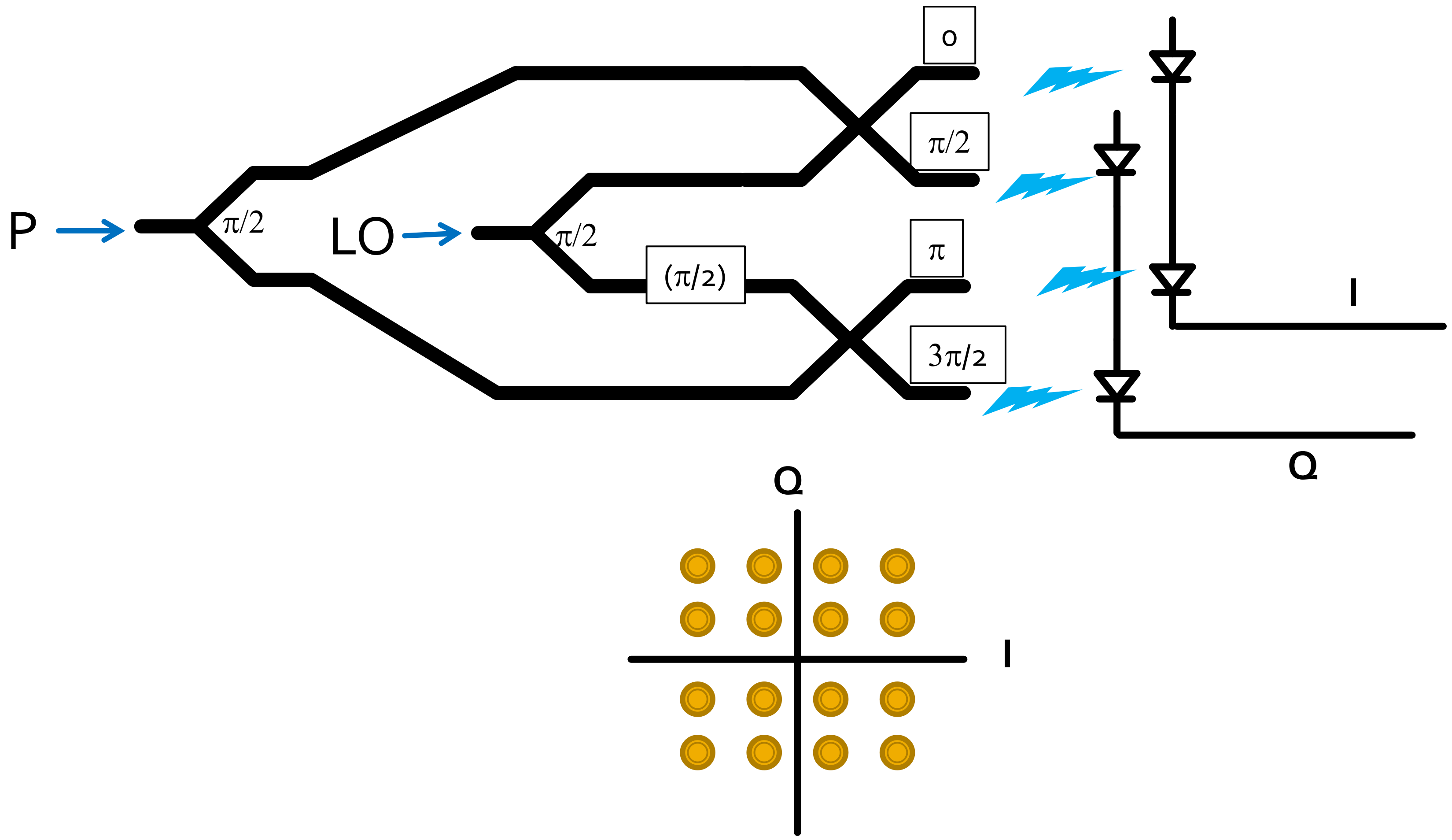
   - Noise Mitigation and Channel Capacity
   - Last trick: SDM

Coherent Reception



Activity: QPSK/QAM videos

http://youtu.be/dym7PGKceio Ciena – WaveLogic 3
http://youtu.be/t9dtmINMbgs Ciena – 1Tbps
http://youtu.be/jEoXzNjAwFQ Infinera - 100 Gbps -Video4 – Infinera 100G: 8:54 m
http://youtu.be/n55RVvuB5lw Infinera - Super-Channels
http://youtu.be/CAPBQnjuUOQ Infinera 2012 (50 min.)
http://youtu.be/pnYzlSxdb5o Nokia Siemens Networks
http://youtu.be/I1WqQaoXWyw Nokia Siemens-100 Gbps
http://www.lightwaveonline.com/video.html OFC – 2013
http://www.ecocexhibition.com/ecoc2011vidpics ECOC - 2011
http://youtu.be/n1zb7wDNYvY tutorial
http://www.youtube.com/watch?v=DK3n-3mlfb8&feature=share&list=PL1jsssThpE2DdFvvlD5CiyWTjcl3SfFhQ

3. **Multiplexing and Modulation Techniques**
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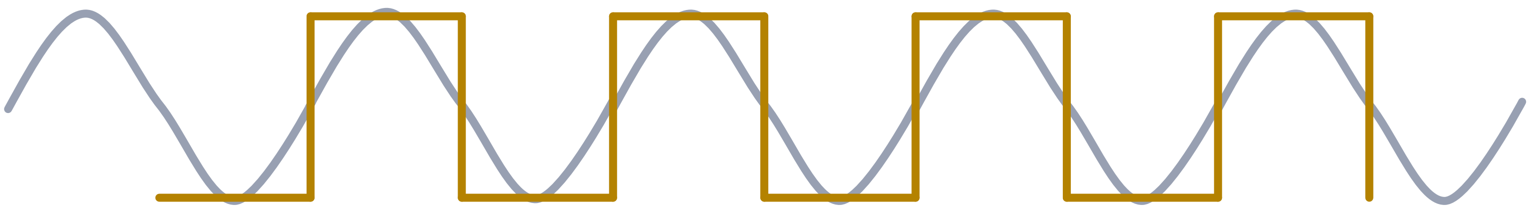
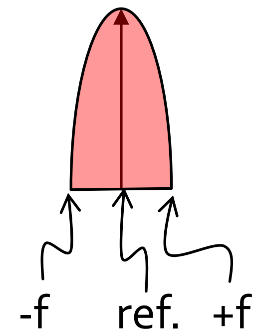
Nyquist condition





Nyquist condition: Symbol rate is twice the maximum wavelength.

Bandwidth is twice the maximum wavelength.

⇒ symbol rate = bandwidth

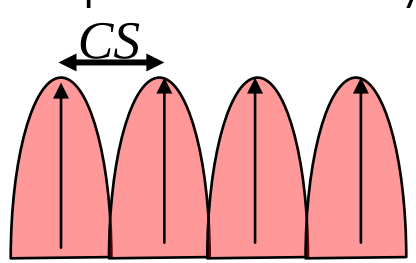
$$R = D \ln_2 m \qquad D = B \qquad R = B \ln_2 m$$

The spectral efficiency (***SE***) is defined by: $SE = R / B = \ln_2 m$

for $\boldsymbol{m} = 2$, $\boldsymbol{R} = \boldsymbol{B} = \boldsymbol{D}$ and $\boldsymbol{SE} = \mathbf{1}$

For WDM systems:

- The Nyquist Channel Spacing (*CS*) is defined by: *CS* = *B* = *D*.
- The Symbol Rate Spectral Efficiency(SRSE) results do be equal to 1.



$$SRSE = D / CS = 1$$

Shannon Capacity

- The Shannon Capacity (C) is the maximum mathematical limit for the link bite rate R when noise is introduced.

- For white noise the Shannon Capacity results to be:

$$C = B.\log_2(1+S/N)$$ [1]

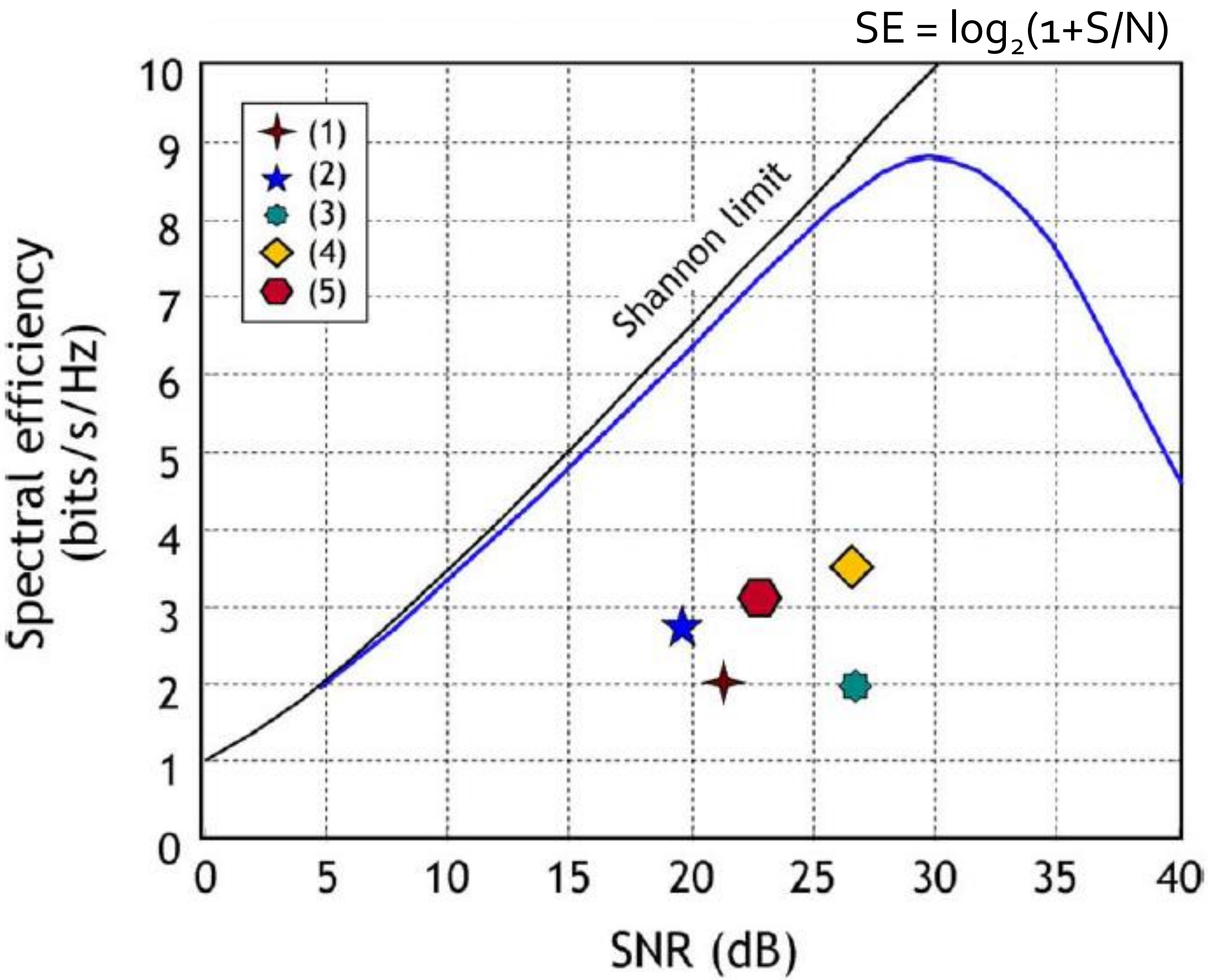
- This formula was developed based on maximum entropy possibility in a noisy system.

- The spectral efficiency (SE) defined as C/B is giving by:

$$SE = \log_2(1+S/N)$$

[1] Claude E. Shannon and Warren Weaver, THE MATHEMATICAL THEORY OF COMMUNICATION, University of Illinois, 1949.
(A book including an expository introduction by Weaver and the epic Shannon's paper: A Mathematical Theory of Communication, published by the Bell System Technical Journal, July and October 1948)

Shannon Capacity



René-Jean Essiambre, Gerhard Kramer, Peter J. Winzer, Gerard J. Foschini and Bernhard Goebel, Capacity Limits of Optical Fiber Networks, JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 28, NO. 4, FEBRUARY 15, 2010, pp.662-701

Multiplexing and Modulation Techniques

3. **Multiplexing and Modulation Techniques**
   - TDM and WDM
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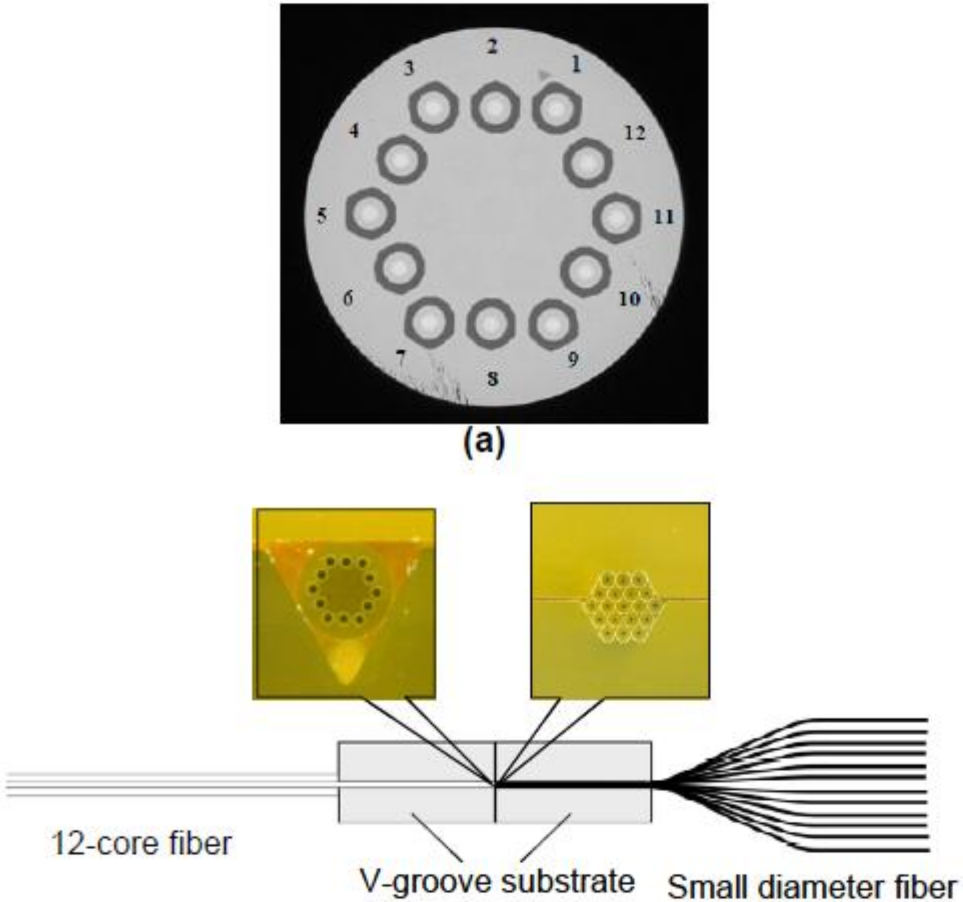
SDM – Space Division Multiplexing



FROM: ECOC – 2012, Amsterdam Netherlands, September 16-20, 2012 - Postdeadline Session III (Th.3.C)

4. **State of Art**
   - Standardization: IEEE 802.3ba, IETF, ITU-T, IOF
   - Long Distance Trial, ECOC, OFC-NFOEC
   - Short Distance Systems
   - Commercial Systems

IEEE 802.3 ba

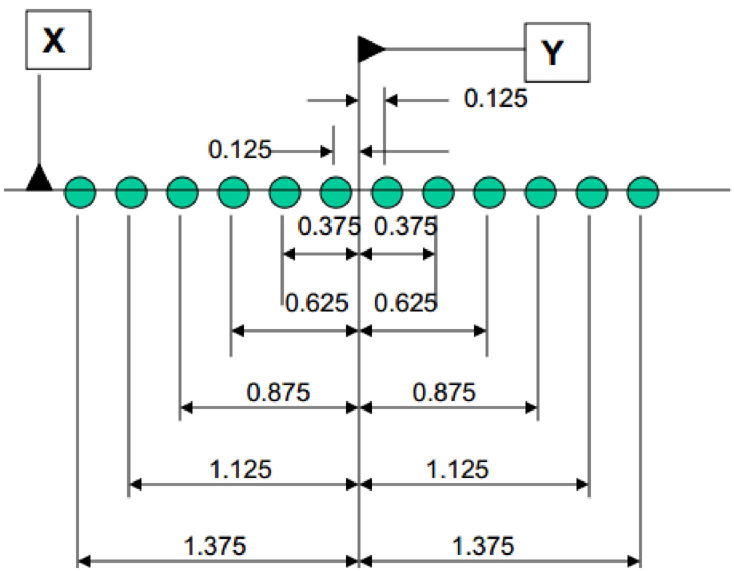
PHY Type	Data rate	Distance	Media	Technology
100GBASE-ER4	100Gb/s	40km	Single Mode Fibre	4 x 25Gb/s (28.78125GBaud) 1310nm DWDM (5nm), SOA
100GBASE-LR4	100Gb/s	10km		4 x 25Gb/s (28.78125GBaud) 1310nm DWDM (5nm)
40GBASE-LR4	40Gb/s			4 x 10Gb/s (10.3125GBaud) 1310nm CWDM (20nm)
100GBASE-SR10	100Gb/s	100m	OM3 multimode fibre	10 x 10Gb/s (10.3125GBaud) 850nm, 10 pairs of fibres
40GBASE-SR4	40Gb/s			4 x 10Gb/s (10.3125GBaud) 850nm, 4 pairs of fibres
100GBASE-CR10	100Gb/s	7m	Copper cable assembly	10 x 10Gb/s (10.3125GBaud) 10 differential pairs
40GBASE-CR4	40Gb/s			4 x 10Gb/s (10.3125GBaud) 4 differential pairs
40GBASE-KR4	40Gb/s	1m	Backplane	4 x 10Gb/s (10.3125GBaud) 4 10GBASE-KR channels

http://www.spirent.com/~/media/Presentations/LR-Webinar_Putting_40_100G_to_the_test.pdf

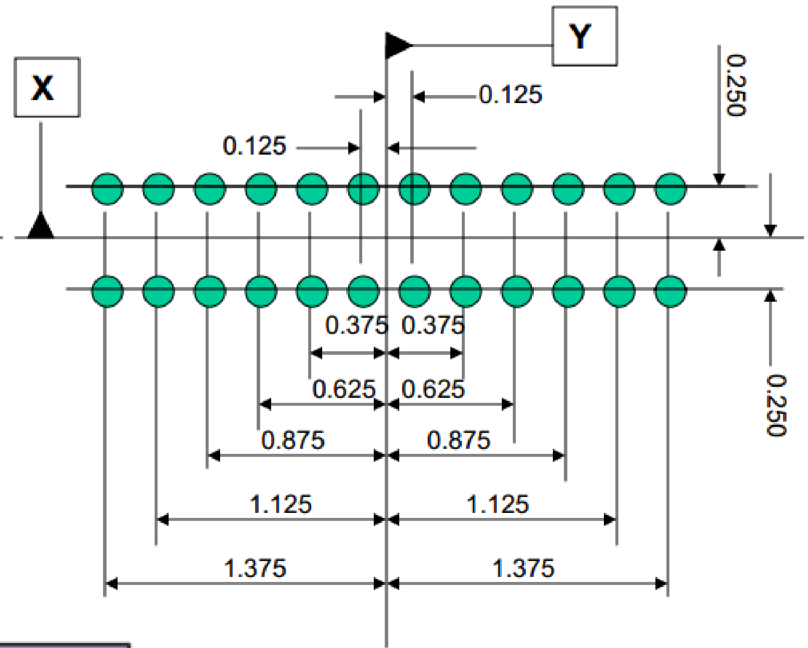
IEC fiber hole location standardization

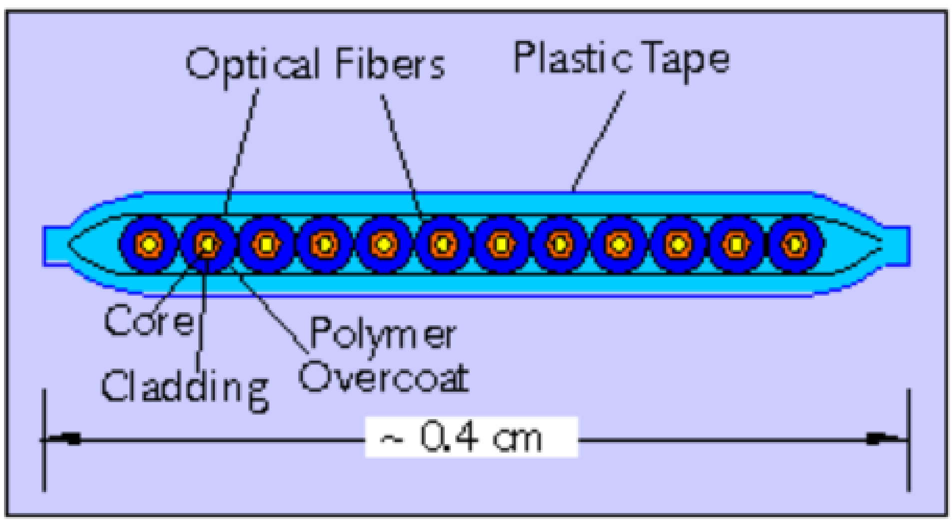
http://grouper.ieee.org/groups/802/3/ba/public/jan09/kolesar_01a_0109.pdf

12 Fiber

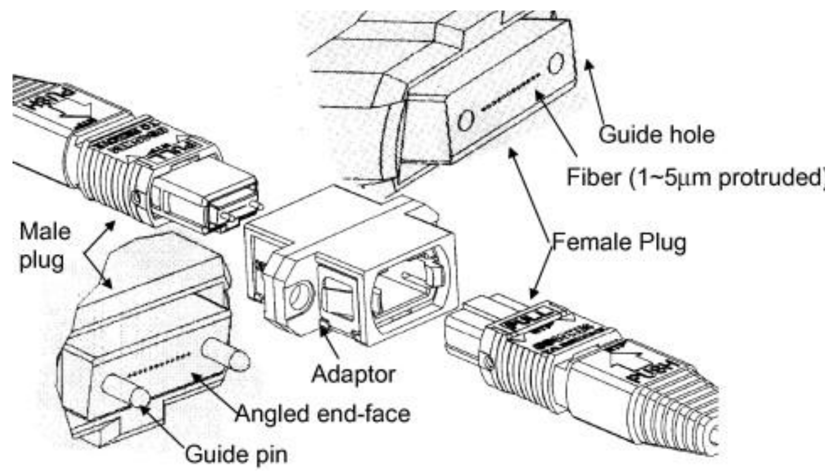


24 Fiber





ribbon cable



Recommendation G.709: Interfaces for the optical transport network

Table 7-1 – OTU types and bit rates

OTU type	OTU nominal bit rate	OTU bit-rate tolerance
OTU1	255/238 × 2 488 320 kbit/s	±20 ppm
OTU2	255/237 × 9 953 280 kbit/s	
OTU3	255/236 × 39 813 120 kbit/s	
OTU4	255/227 × 99 532 800 kbit/s	

NOTE 1 – The nominal OTUk rates are approximately: 2 666 057.143 kbit/s (OTU1), 10 709 225.316 kbit/s (OTU2), 43 018 413.559 kbit/s (OTU3) and 111 809 973.568 kbit/s (OTU4).

NOTE 2 – OTU0, OTU2e and OTUflex are not specified in this Recommendation. ODU0 signals are to be transported over ODU1, ODU2, ODU3 or ODU4 signals, ODU2e signals are to be transported over ODU3 and ODU4 signals and ODUflex signals are transported over ODU2, ODU3 and ODU4 signals.

ITU-T G.709/Y.1331

G.709 digital wrapper $4 \times 4080 = 16320$ bytes

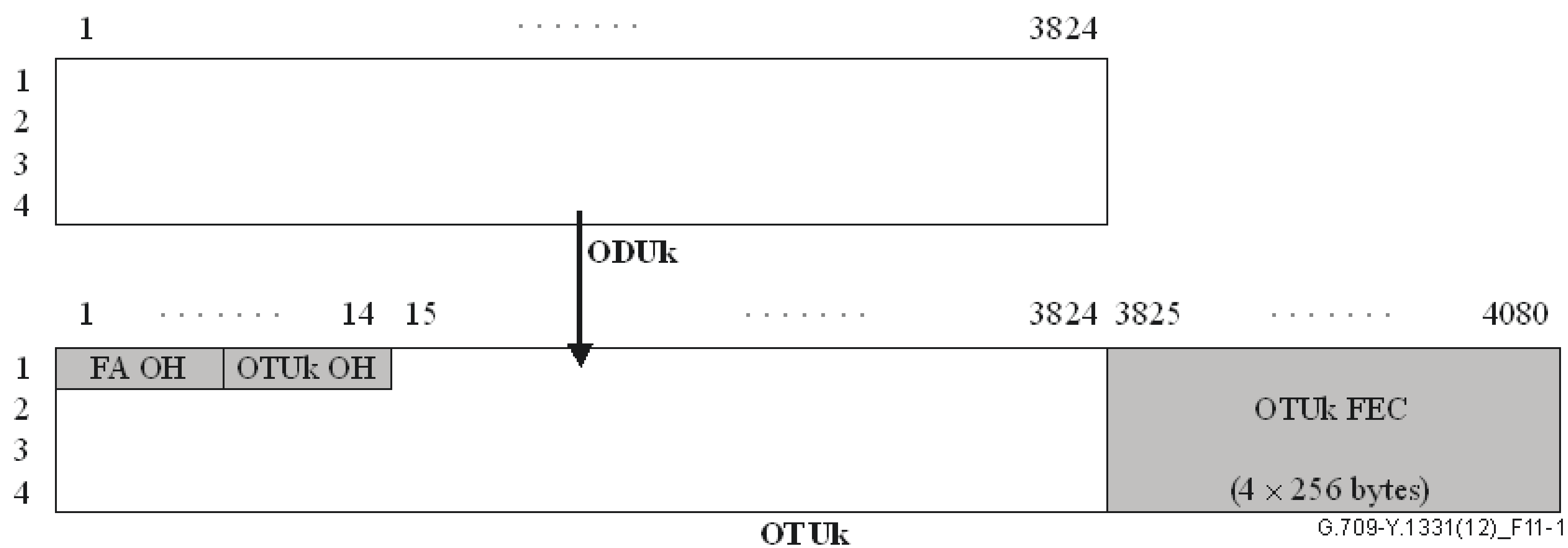
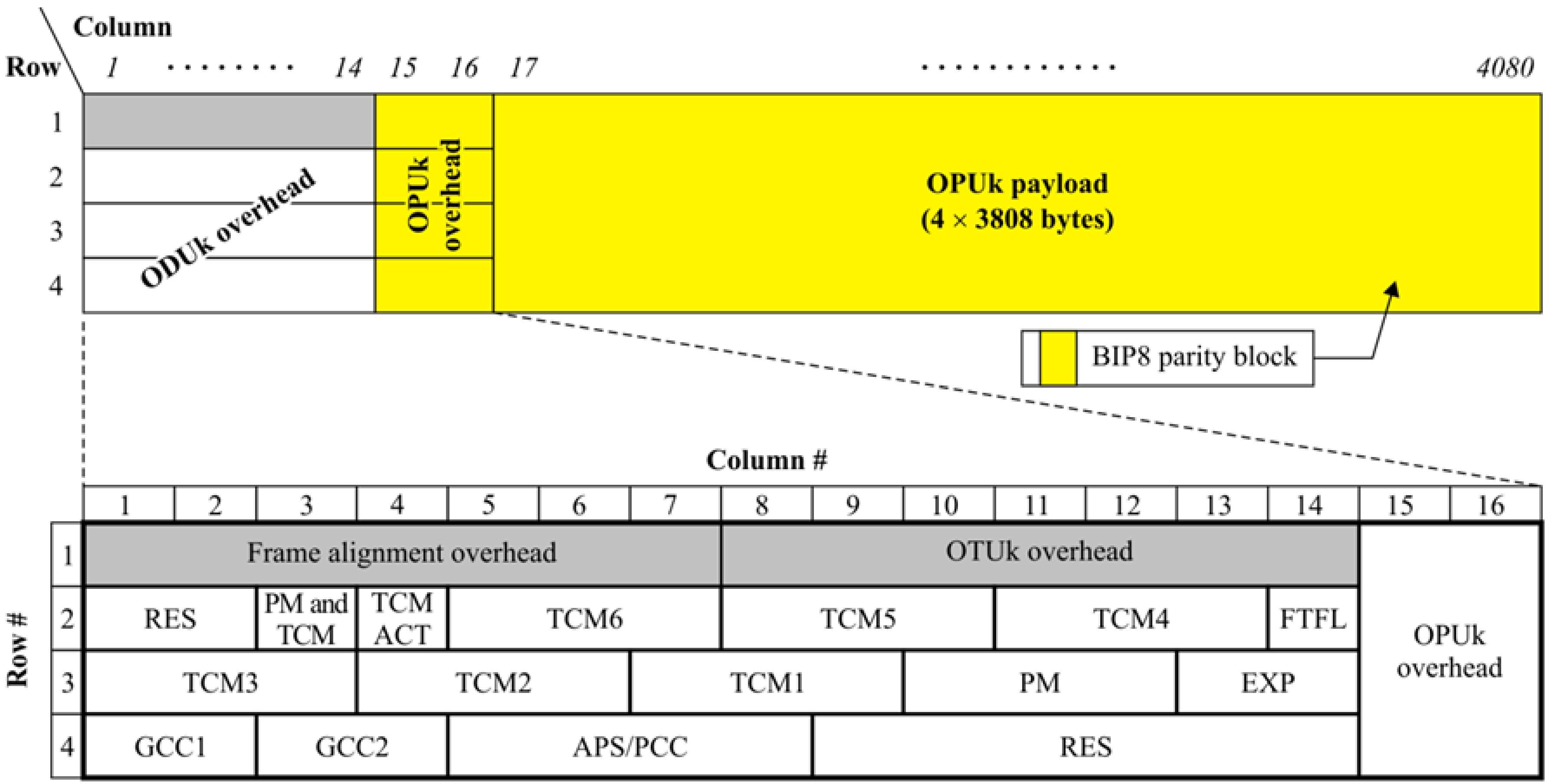


Figure 11-1 – OTUk frame structure

Interfaces for the optical transport network



ITU-T G.709/Y.1331

Interfaces for the optical transport network

PM	Path monitoring
TCM	Tandem connection monitoring
PM and TCM	Path monitoring and Tandem connection monitoring
SAPI	Source access point identifier
DAPI	Destination access point identifier
RES	Reserved for future international standardization
ACT	Activation/deactivation control channel
FTFL	Fault type and fault location reporting channel
EXP	Experimental
GCC	General communication channel
APS	Automatic protection switching coordination channel
PCC	Protection communication control channel
BIAE	Backward incoming alignment error
TTI	Trail trace identifier
BIP8	Bit interleaved parity - level 8
BEI	Backward error indication
BDI	Backward defect indication
STAT	Status
PSI	Payload structure identifier
PT	Payload type
DM	Delay measurement

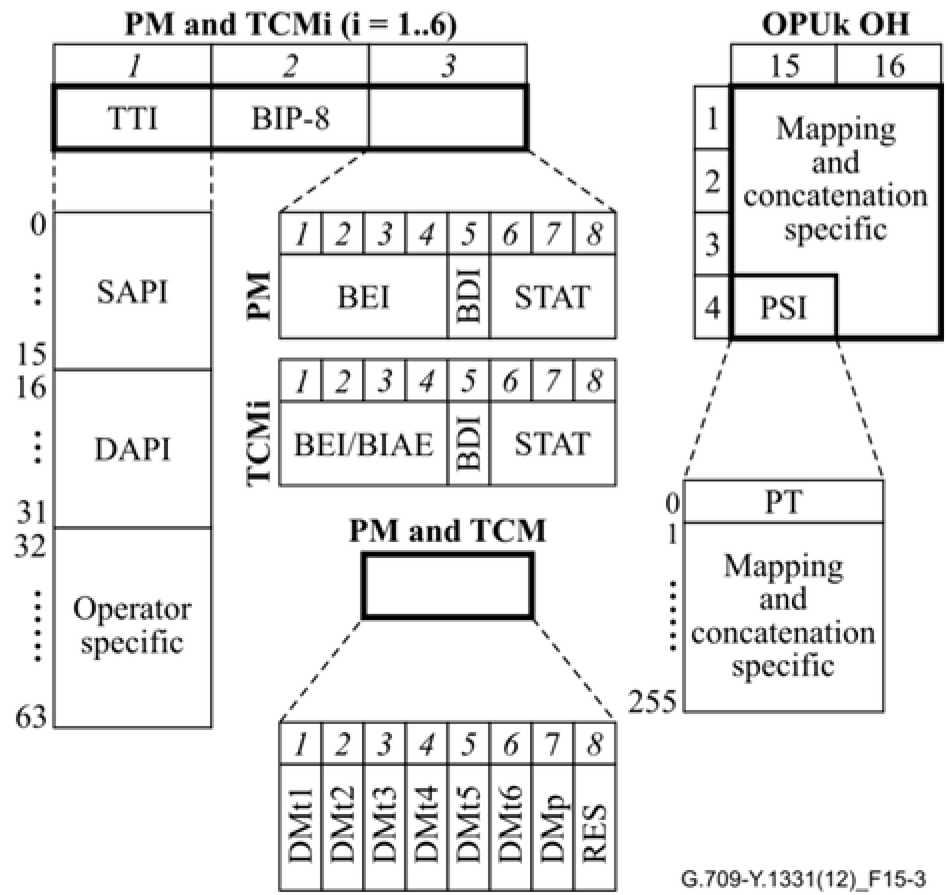


Figure 15-3 – ODUk frame structure, ODUk and OPUk overhead

Ementa

4. **State of Art**
   - Standardization: IEEE 802.3ba, IETF, ITU-T, IOF
   - Long Distance Trial, ECOC, OFC-NFOEC
   - Short Distance Systems
   - Commercial Systems

Long Distance Trial, ECOC, OFC-NFOEC

Optical Fiber Communication Conference 2013, Anaheim, California United States - March 17-21, 2013

All papers available at:

- http://www.opticsinfobase.org/browseconferences.cfm?congress=13OFC/NFOEC

Next edition OFC-2014 – San Francisco: www.ofcconference.org

European Conference and Exhibition on Optical Communication 2012, Amsterdam Netherlands, September 16-20, 2012

All papers available at:

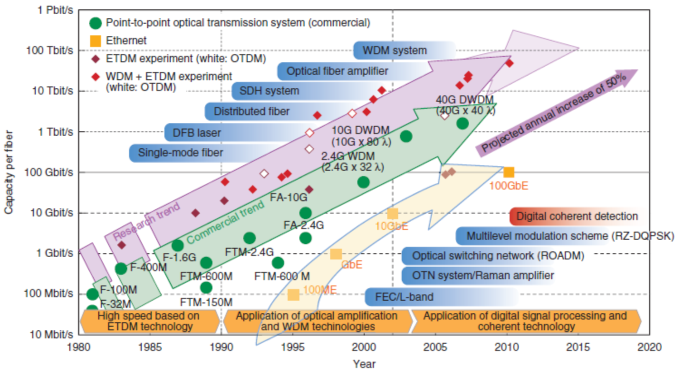
- http://www.opticsinfobase.org/browseconferences.cfm?meetingid=143&strYr=2012&acronym=ECOC

First edition ECOC-1975: http://www.ecoc2013.org/docs/ecoc-1975.pdf

Last edition ECOC-2013 - London: http://www.ecoc2013.org/index.html

(September 23-25, 2013)

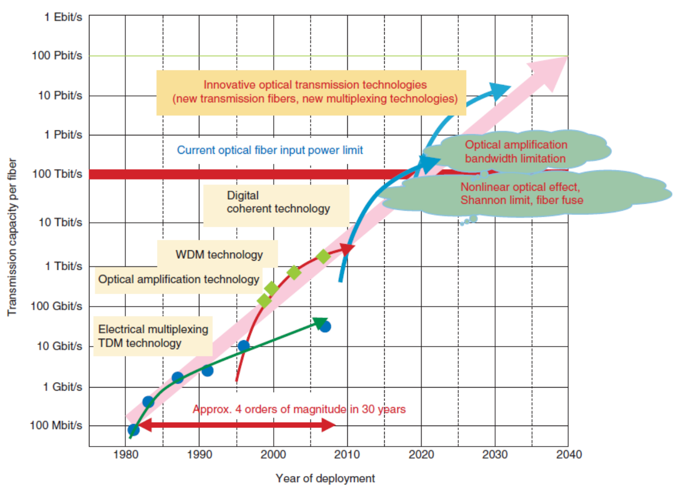
Evolução da Capacidade



100ME: 100-Mbit/s Ethernet
DFB: distributed feedback
F, FTM, and FA are the names of NTT systems.
FEC: forward error correction
G: Gbit/s
GbE: Gigabit (Gbit/s) Ethernet
λ: wavelengths

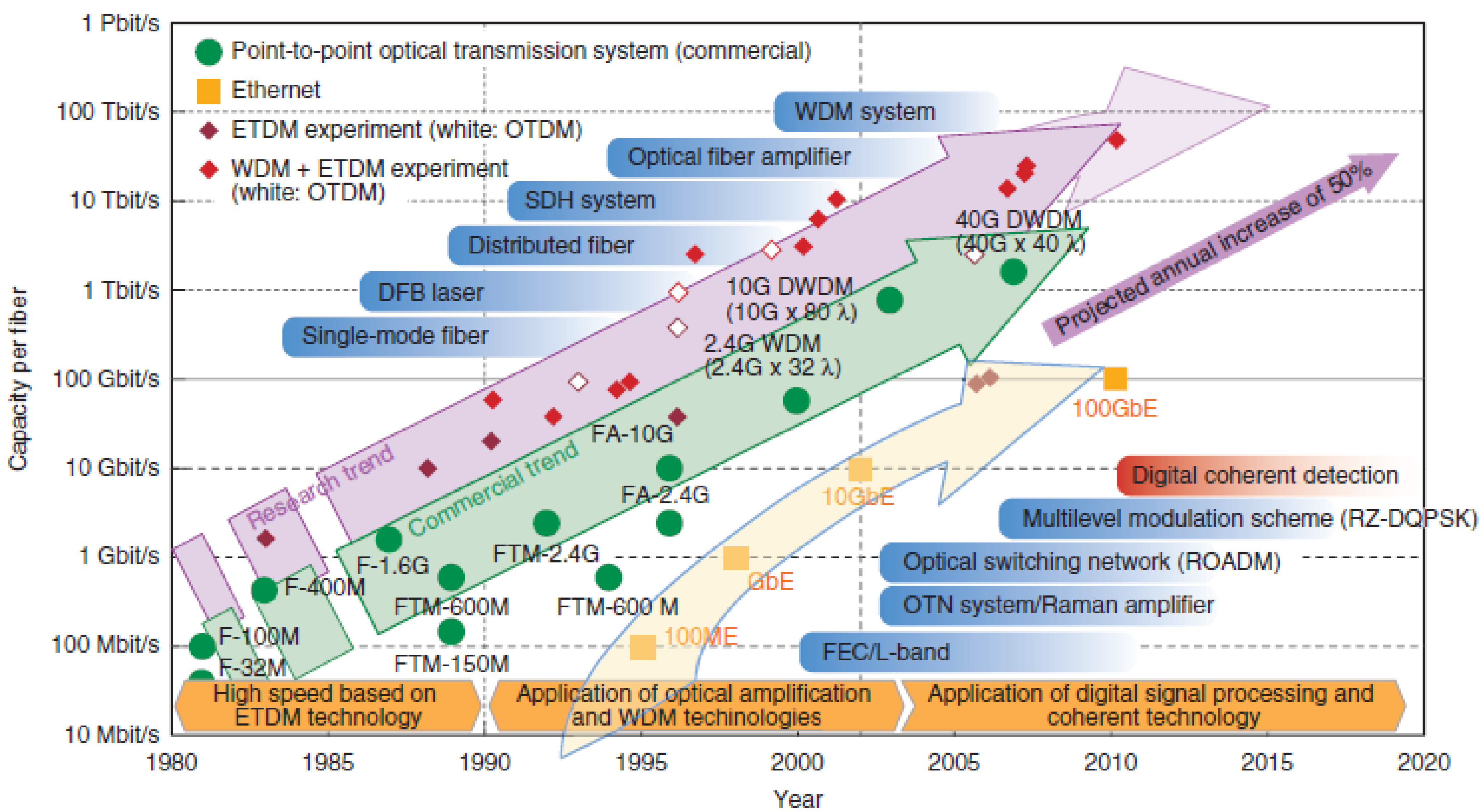
M: Mbit/s
ME: Megabit (Mbit/s) Ethernet
OTDM: optical time division reflectometry
OTN: Optical Transport Network
RZ-DQPSK: return-to-zero differential quadrature phase key shifting
SDH: synchronous digital hierarchy
WDM: wavelength division multiplexing

***S. Matsuoka*, "Ultrahigh-speed Ultrahigh-capacity Transport Network Technology for Cost-effective Core and Metro Networks", NTT Technical Review, v9, n8, 2011**



***T. Morioka, M. Jinno, H. Takara and H. Kubota*, "Innovative Future Optical Transport Network Technologies", NTT Technical Review, v9, n8, 2011**

Evolução da Capacidade



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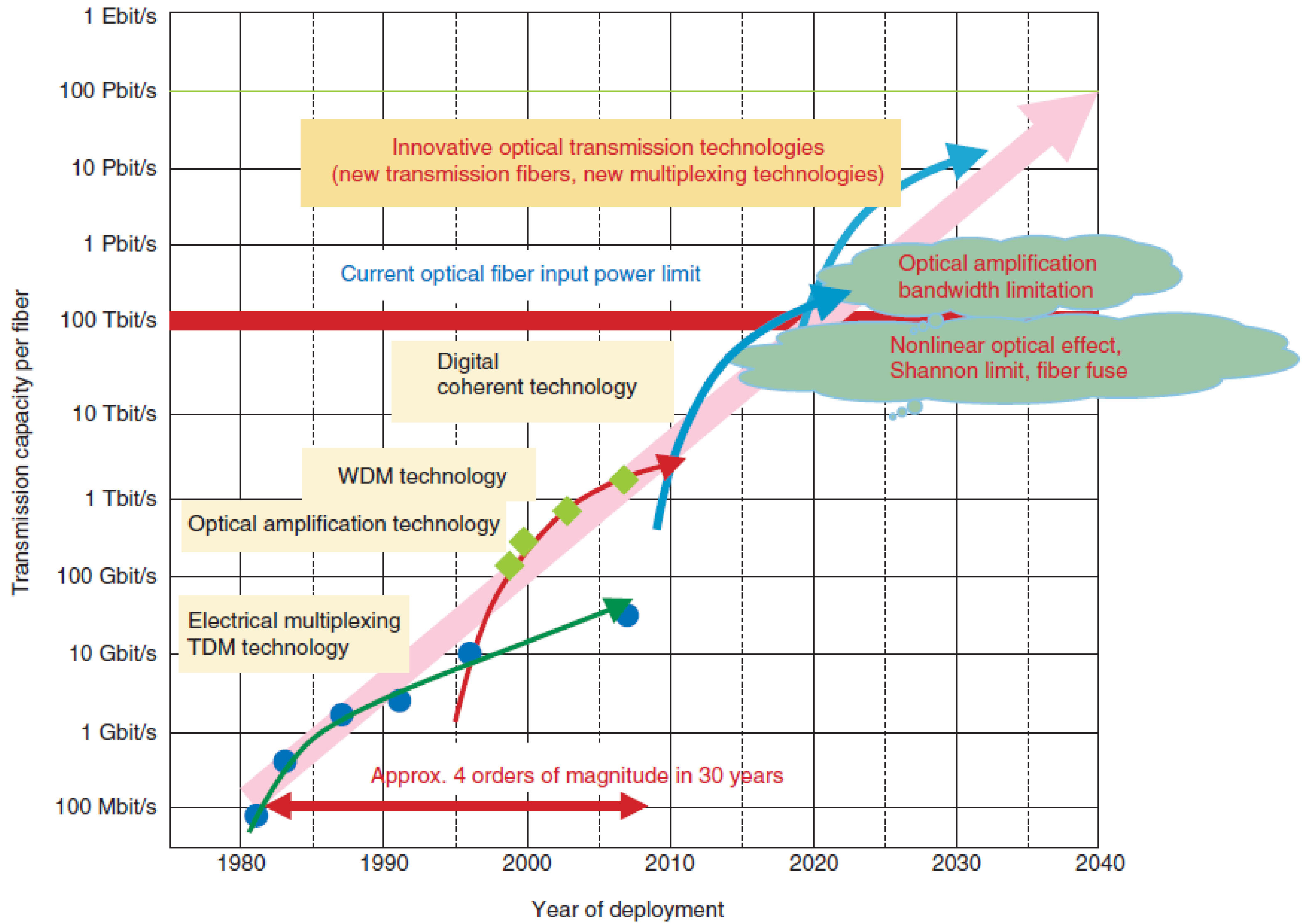
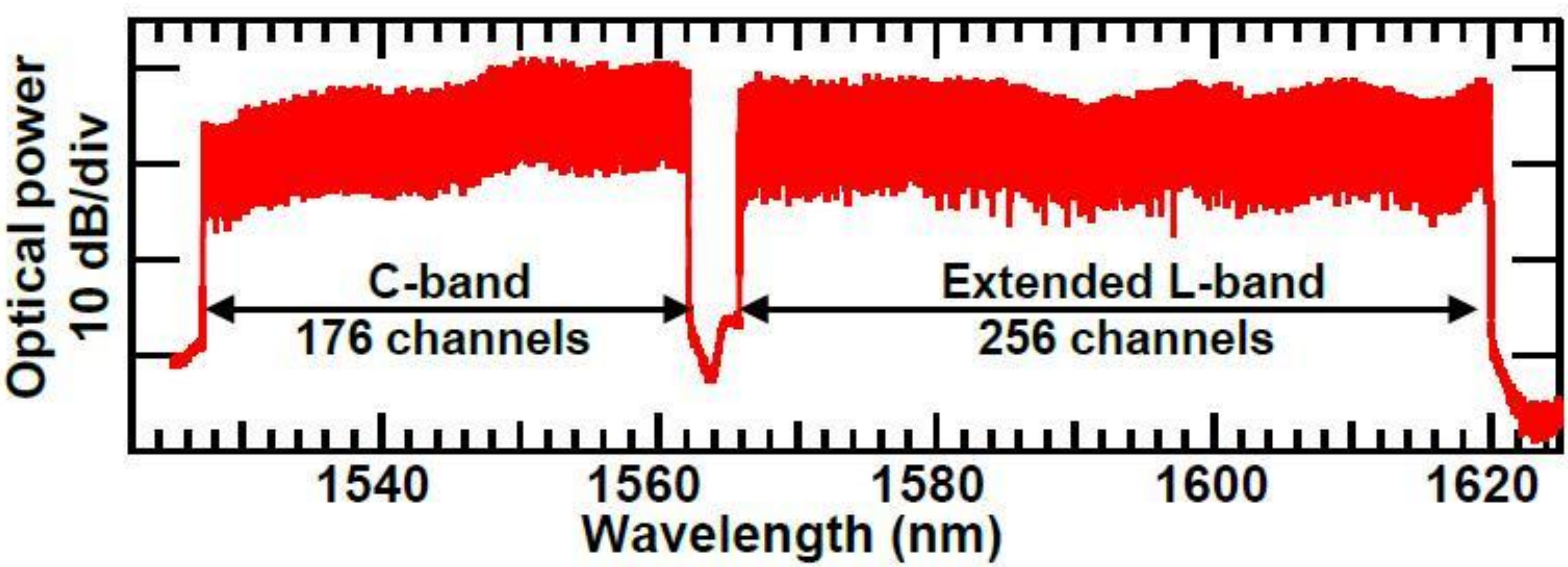


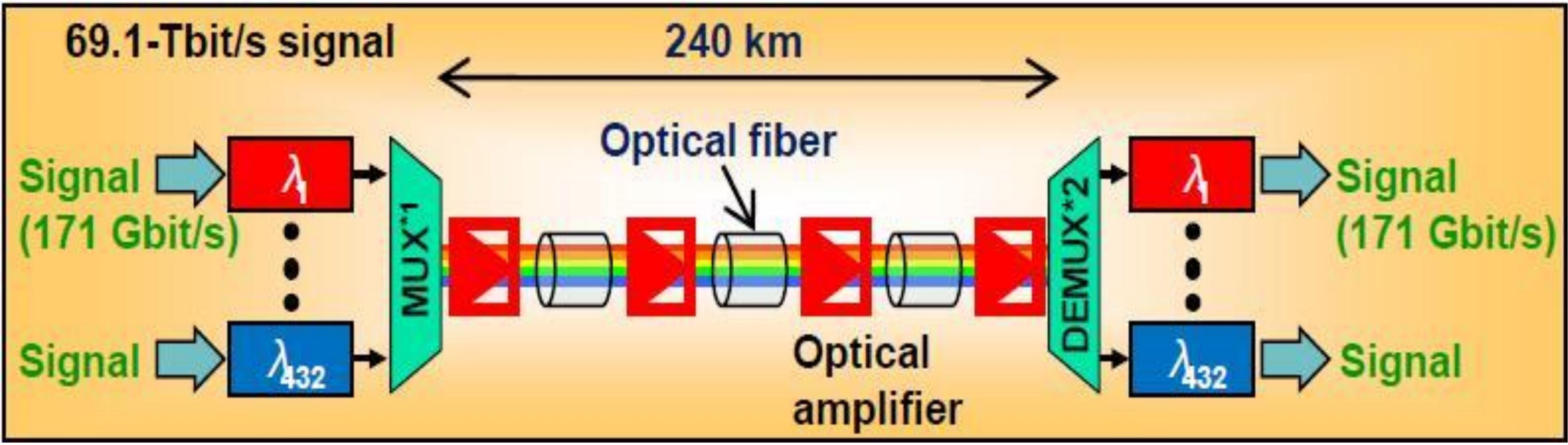
OFC/NFOEC, PDPBT7, 2010

432 DWDM channels



https://www.ntt-review.jp/library/ntttechnical.php?contents=ti1104rdfpa35e.pdf

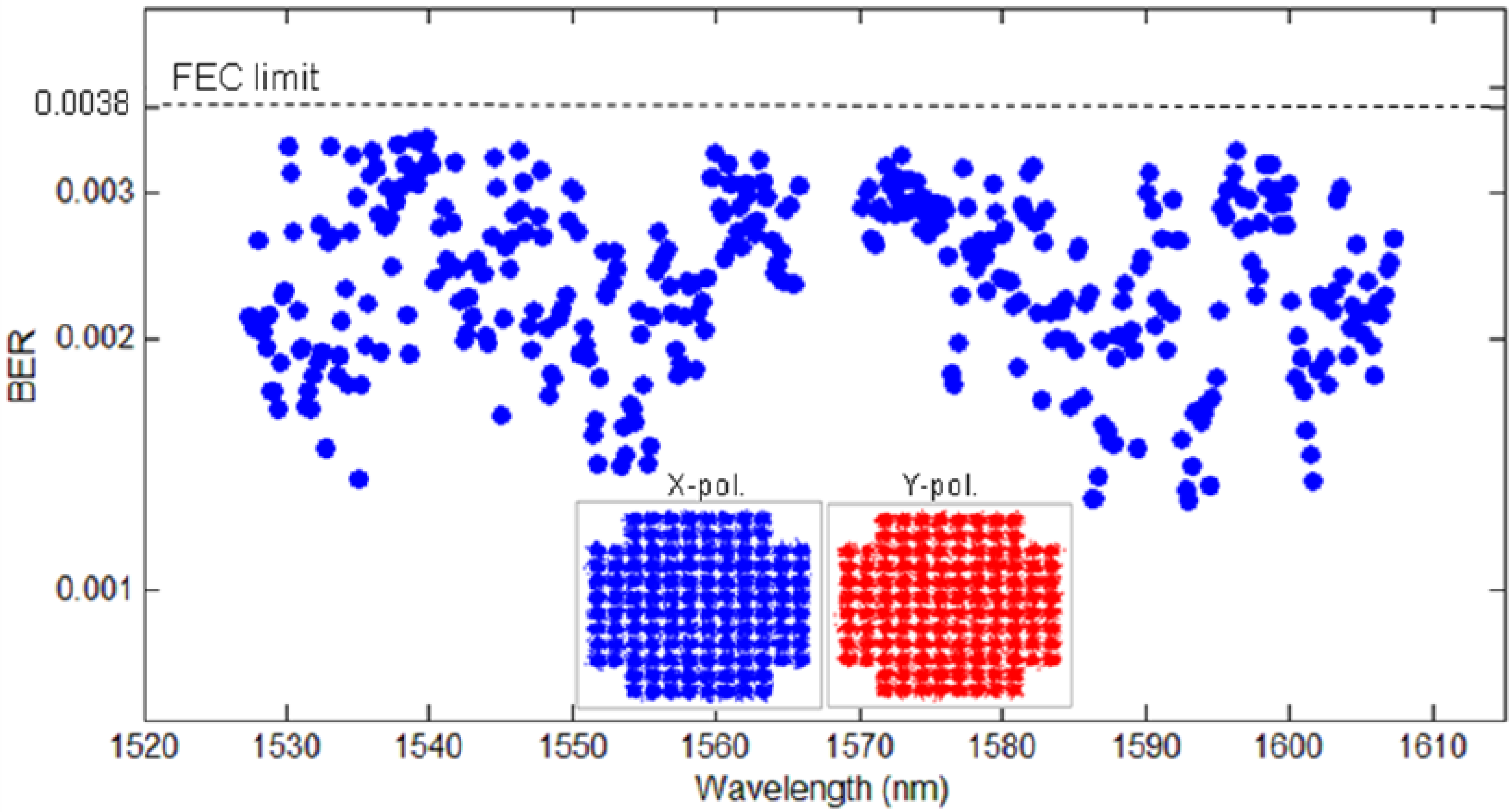
69.1 Tbps – Wide Band Amplifiers - NTT



A. Sano, H. Masuda, T. Kobayashi, M. Fujiwara, K. Horikoshi, E. Yoshida, Y. Miyamoto, M. Matsui, M. Mizoguchi, H. Yamazaki, Y. Sakamaki, H. Ishii, 69.1-Tb/s (432 x 171-Gb/s) C- and Extended L-Band Transmission over 240 km Using PDM-16-QAM Modulation and Digital Coherent Detection, OFC/NFOEC, PDPBT7, 2010.

69.1 Tbps – Wide Band Amplifiers - NTT

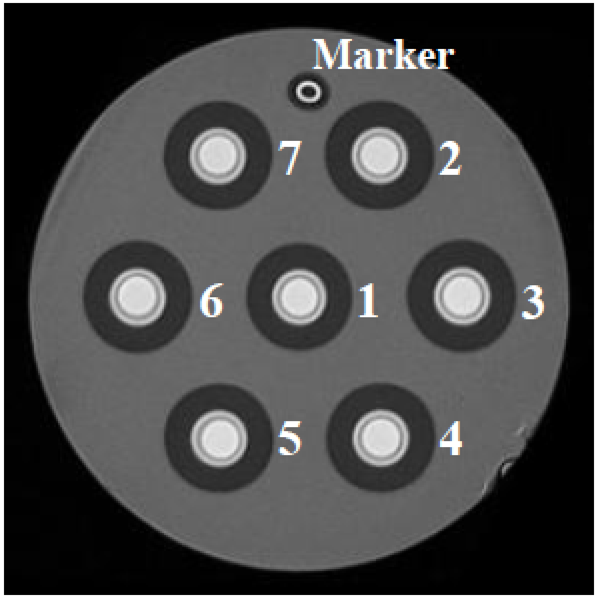
OFC/NFOEC, PDPB5, 2011

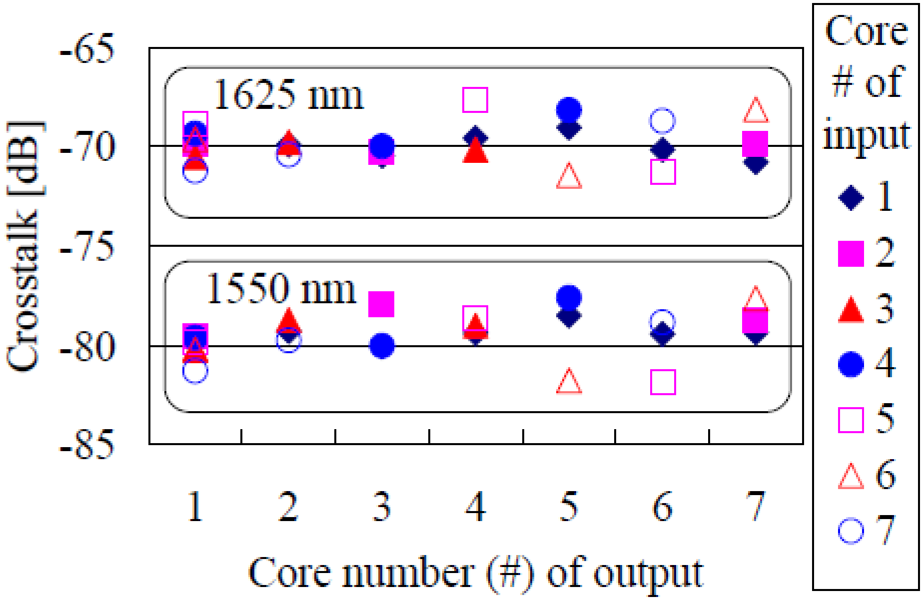


101.7 Tbps – Phase Noise Mitigation - 165km

D. Qian, M.F. Huang, E. Ip, Y.K. Huang, Y. Shao, J. Hu, T. Wang; 101.7-Tb/s (370×294-Gb/s) PDM-**128QAM**-OFDM Transmission over 3x55-km SSMF using Pilot-based Phase Noise Mitigation – OFC/NFOEC, PDPB5, 2011

OFC/NFOEC, PDPB6, 2011





109 Tbps – 7 SDM

109-Tb/s (7x97x172-Gb/s SDM/WDM/PDM) QPSK transmission through 16.8-km homogeneous multi-core fiber, Jun Sakaguchi, Yoshinari Awaji, Naoya Wada, Atsushi Kanno, Tetsuya Kawanishi, Tetsuya Hayashi, Toshiki Taru, Tetsuya Kobayashi, Masayuki Watanabe – OFC/NFOEC, PDPB6, 2011.

ECOC-2012 - PD Session III (Th.3.C)

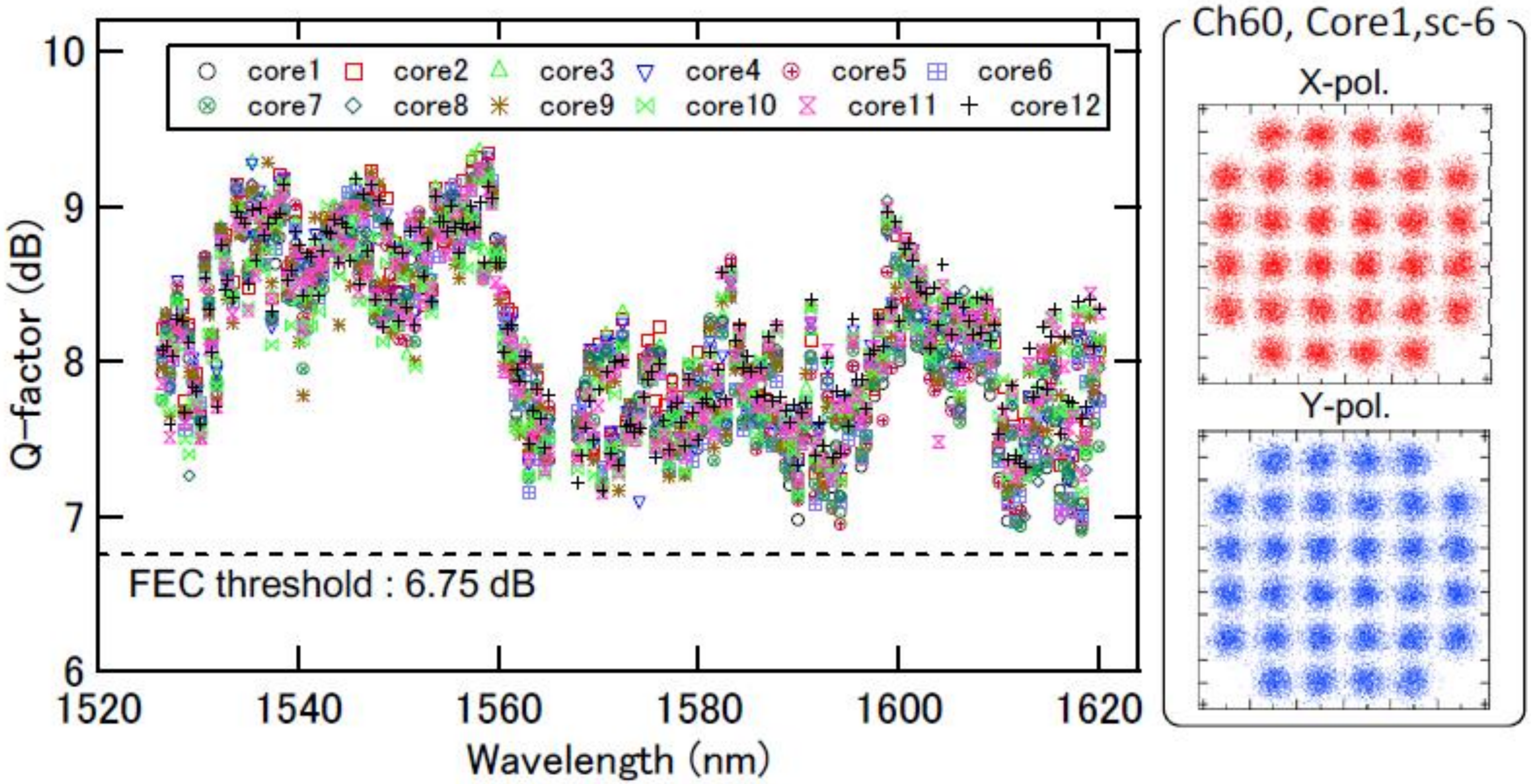
- **1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) Crosstalk-managed Transmission with 91.4-b/s/Hz Aggregate Spectral Efficiency**

H. Takara(1), A. Sano(1), T. Kobayashi(1), H. Kubota(1), H. Kawakami(1), A. Matsuura(1), Y. Miyamoto(1) , Y. Abe(2), H. Ono(2), K. Shikama(2), Y. Goto(3), K. Tsujikawa(3), Y. Sasaki(4), I. Ishida(4), K. Takenaga(4), S. Matsuo(4), K. Saitoh(5), M. Koshiba(5), and T. Morioka(6)
(1) NTT Network Innovation Laboratories, NTT Corporation,
(2) NTT Photonics Laboratories, NTT Corporation,
(3) NTT Access Network Service Systems Laboratories, NTT Corporation,
(4) Fujikura Ltd, (5) Hokkaido University,
(6) Technical University of Denmark,
takara.hidehiko@lab.ntt.co.jp

Abstract *We demonstrate 1.01-Pb/s transmission over 52 km with the highest aggregate spectral efficiency of* ***91.4 b/s/Hz*** *by using low-crosstalk one-ring-structured 12-core fiber. Our multi-core fiber and compact fan-in/fan-out devices are designed to support high-order modulation formats up to 32-QAM in SDM transmission.*

ECOC - European Conference and Exhibition on Optical Communication, Amsterdam Netherlands, September 16-20, 2012 - Postdeadline Session III (Th.3.C)
http://www.opticsinfobase.org/search.cfm?meetingid=143&year=2012&meetingsession=Th.3.C

ECOC-2012 - PD Session III (Th.3.C)



91.4-b/s/Hz Aggregate Spectral Efficiency / 12 / 2 = 3.8 b/s/Hz

http://www.opticsinfobase.org/search.cfm?meetingid=143&year=2012&meetingsession=Th.3.C

Estate of Art in 2012

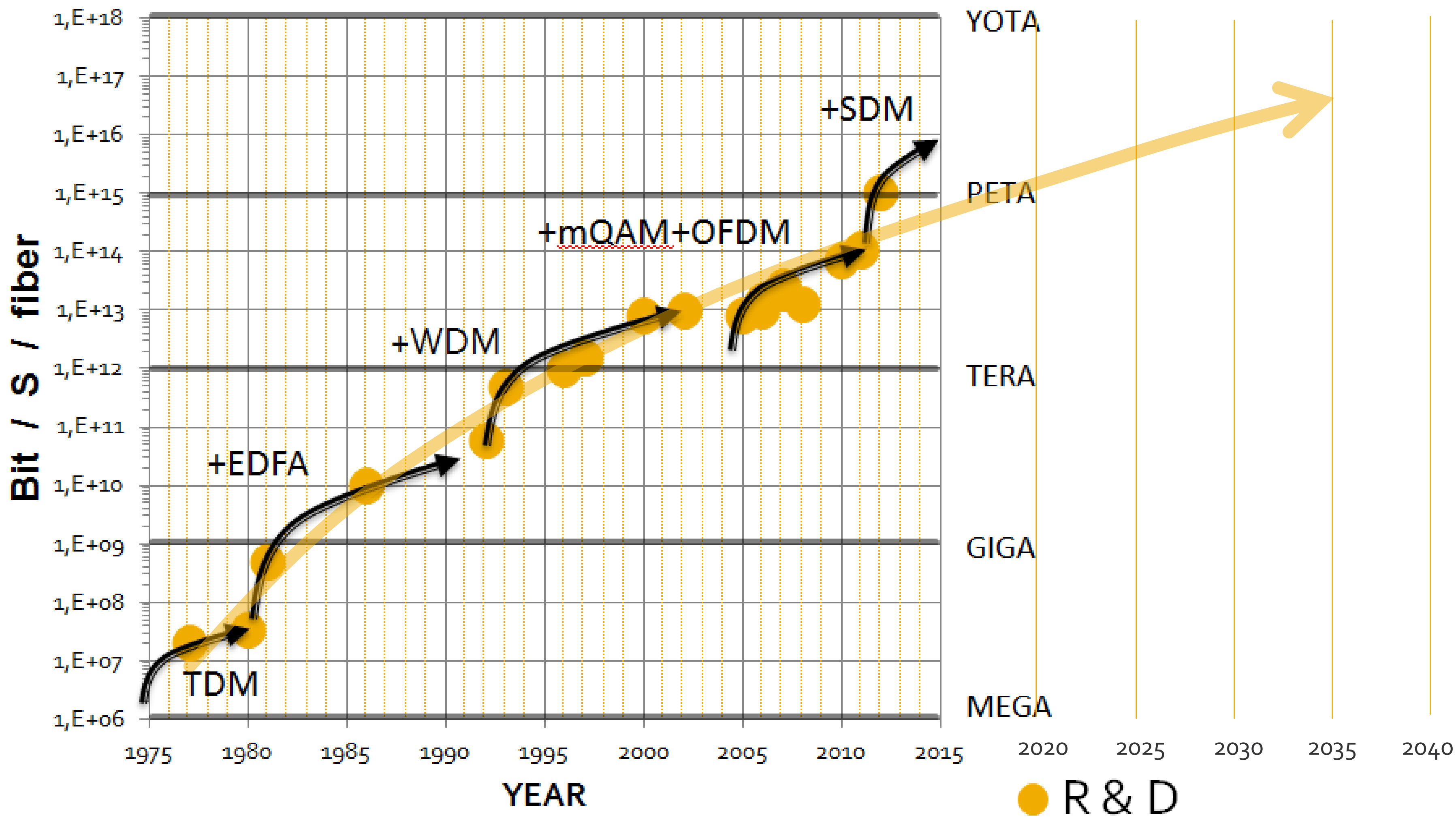
- **73.7 Tb/s (96x3x256-Gb/s) mode-division-multiplexed DP-16QAM transmission with inline MM-EDFA**

V.A.J.M. Sleiffer(1), Y. Jung(2), V. Veljanovski(3), R.G.H. van Uden(1), M. Kuschnerov(3), Q. Kang(2), L. Grüner-Nielsen(4), Y. Sun(4), D.J. Richardson(2), S. Alam(2), F. Poletti(2) , J.K. Sahu(2), A. Dhar(2), H. Chen(1), B. Inan(5), A.M.J. Koonen(1), B. Corbett(6), R. Winfield (6), A.D. Ellis(6), and H. de Waardt(1)

(1) COBRA institute, Eindhoven University of Technology, The Netherlands, v.a.j.m.sleiffer@tue.nl
(2) Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
(3) Nokia Siemens Networks GmbH & Co. KG, Munich, Germany
(4) OFS, Priorparken 680, 2605 Brøndby, Denmark
(5) Technische Universität München, Munich, Germany
(6) Tyndall National Institute, Cork, Ireland

Abstract: *We show transmission of a 73.7 Tb/s (96x3x256-Gb/s) DP-16QAM modedivision-multiplexed signal over 119km of few-mode fiber with inline* ***multi-mode EDFA****, using 6x6 MIMO digital signal processing. The total demonstrated net capacity is 57.6 Tb/s* ***(SE 12 bits/s/Hz)****.*

yotabit / s



1,E+18
1,E+17
1,E+16
1,E+15
1,E+14
1,E+13
1,E+12
1,E+11
1,E+10
1,E+09
1,E+08
1,E+07
1,E+06
Bit / S / fiber
YOTA
PETA
TERA
GIGA
MEGA
+SDM
+mQAM+OFDM
+WDM
+EDFA
TDM
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
YEAR
R & D

4. State of Art

- Standardization: IEEE 802.3ba, IETF, ITU-T, IOF
- Long Distance Trial, ECOC, OFC-NFOEC
- Short Distance Systems
- Commercial Systems

State of art 2012

- **Compact and High-Sensitivity 100-Gb/s (4 × 25 Gb/s) APD-ROSA with a LAN-WDM PLC Demultiplexer**

Toshihide Yoshimatsu, Masahiro Nada, Manabu Oguma, Haruki Yokoyama, Tetsuichiro Ohno, Yoshiyuki Doi, Ikuo Ogawa, and Eiji Yoshida

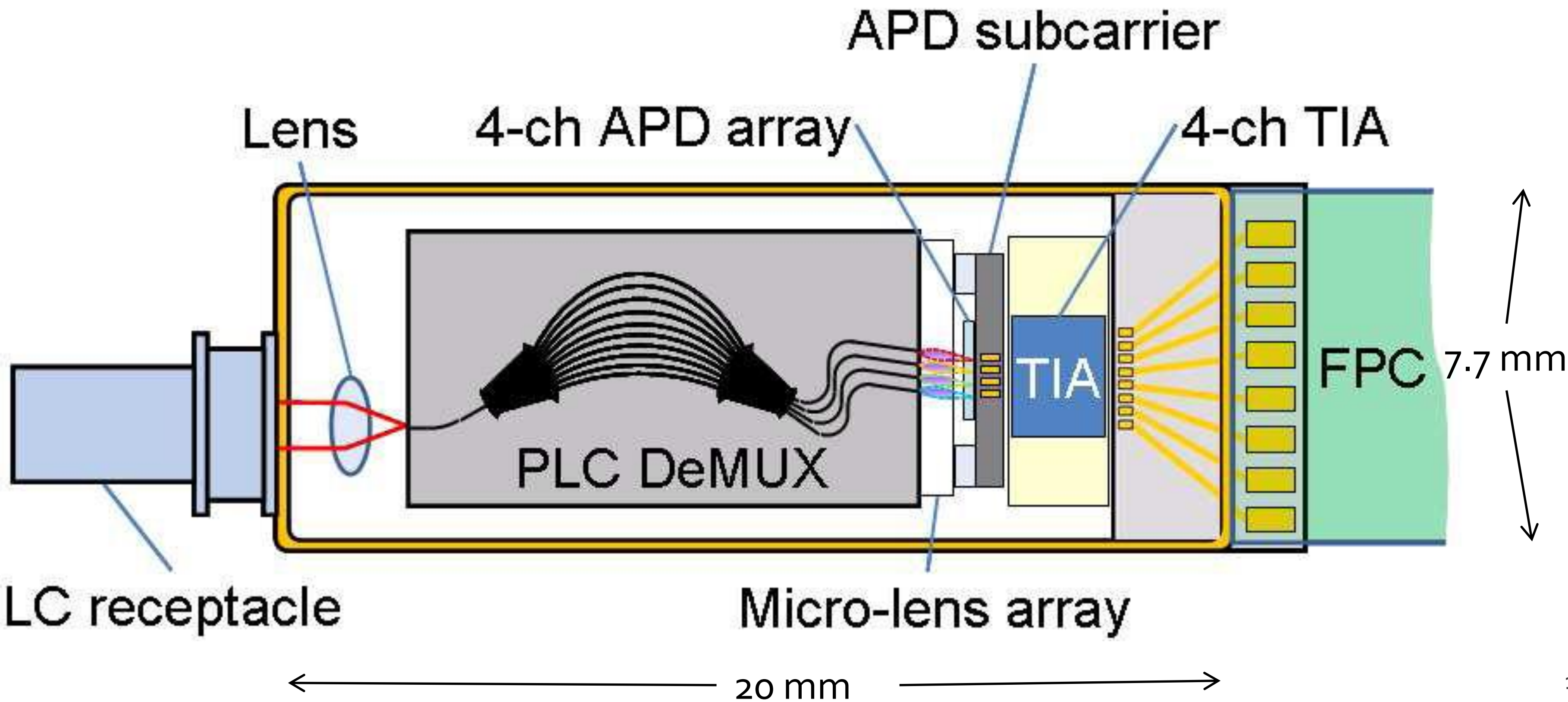
NTT Photonics Laboratories, NTT Corporation

ROSA – Receiver Optical Sub-Assembly

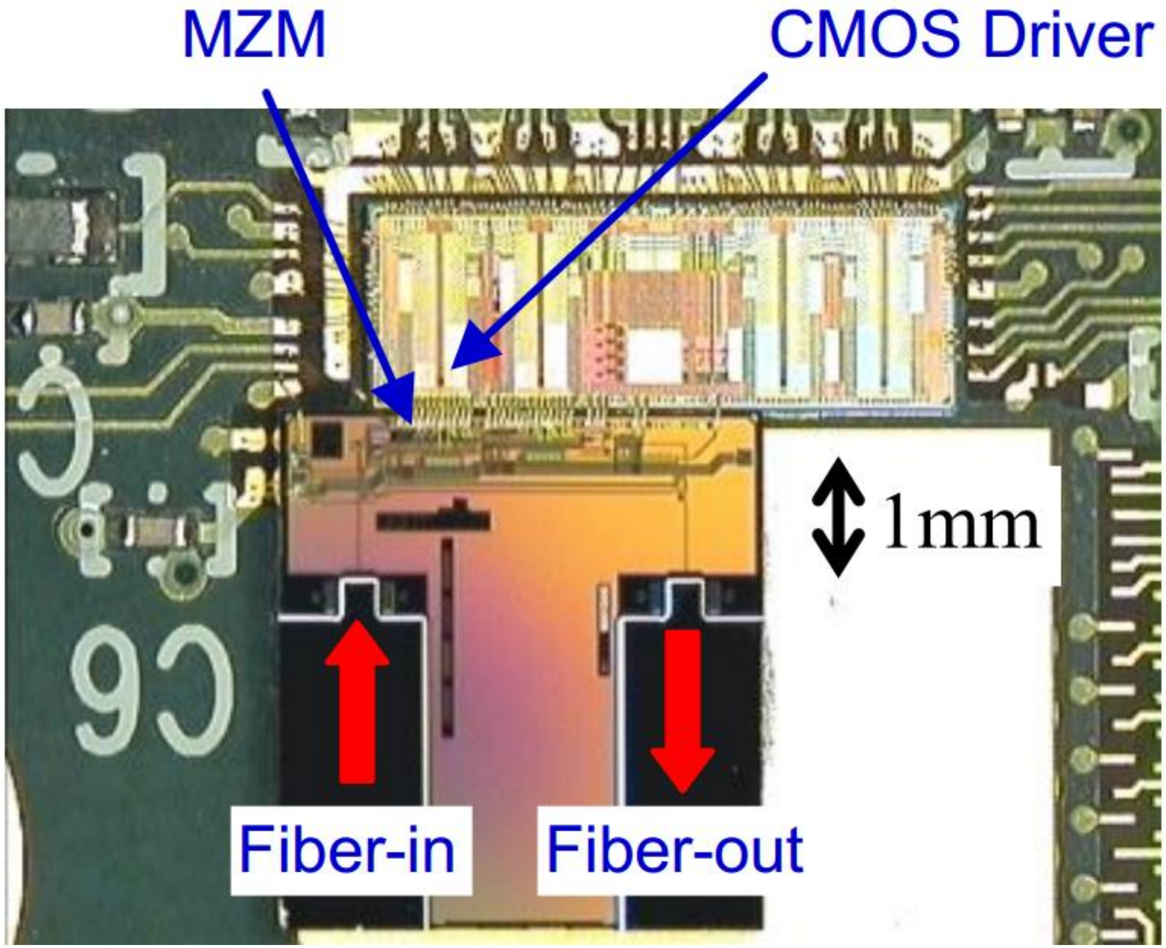
State of art 2012

NTT Photonics Laboratories, NTT Corporation

- PLC – Planar Lightwave Circuit (AWG – Arrayed Waveguide Grating)
- APD – Avalanche Photodiode
- TIA – Trans-Impedance Amplifier
- FPC – Flexible Printed Circuit



Size Reduction - Silicon Photonics



112Gb/s DP-QPSK Transmission Over 2427km SSMF Using Small-Size Silicon Photonic IQ Modulator and Low-Power CMOS Driver, B. Milivojevic, C. Raabe, A. Shastri, M. Webster, P. Metz, S. Sunder, B. Chattin, S. Wiese, B. Dama, K. Shastri (*Cisco Optical GmbH, Nuremberg, Germany; Stanford University, Stanford, CA, USA; Cisco Systems, Allentown, PA, USA) – OFC 2013* - Anaheim, CA, USA, OTh1D.1, 2013.

4. **State of Art**
   - Standardization: IEEE 802.3ba, IETF, ITU-T, IOF
   - Long Distance Trial, ECOC, OFC-NFOEC
   - Short Distance Systems
   - Commercial Systems

Transceiver

http://www.finisar.com/products/optical-modules

Transceiver

SFP – Small Form-factor Pluggable – 1Gbps

XFP – X Form-factor Pluggable – 10Gbps

CFP – C Form-factor Pluggable – 100Gbps

CDFP – CD Form-factor Pluggable – 400Gbps

Roman Numerals

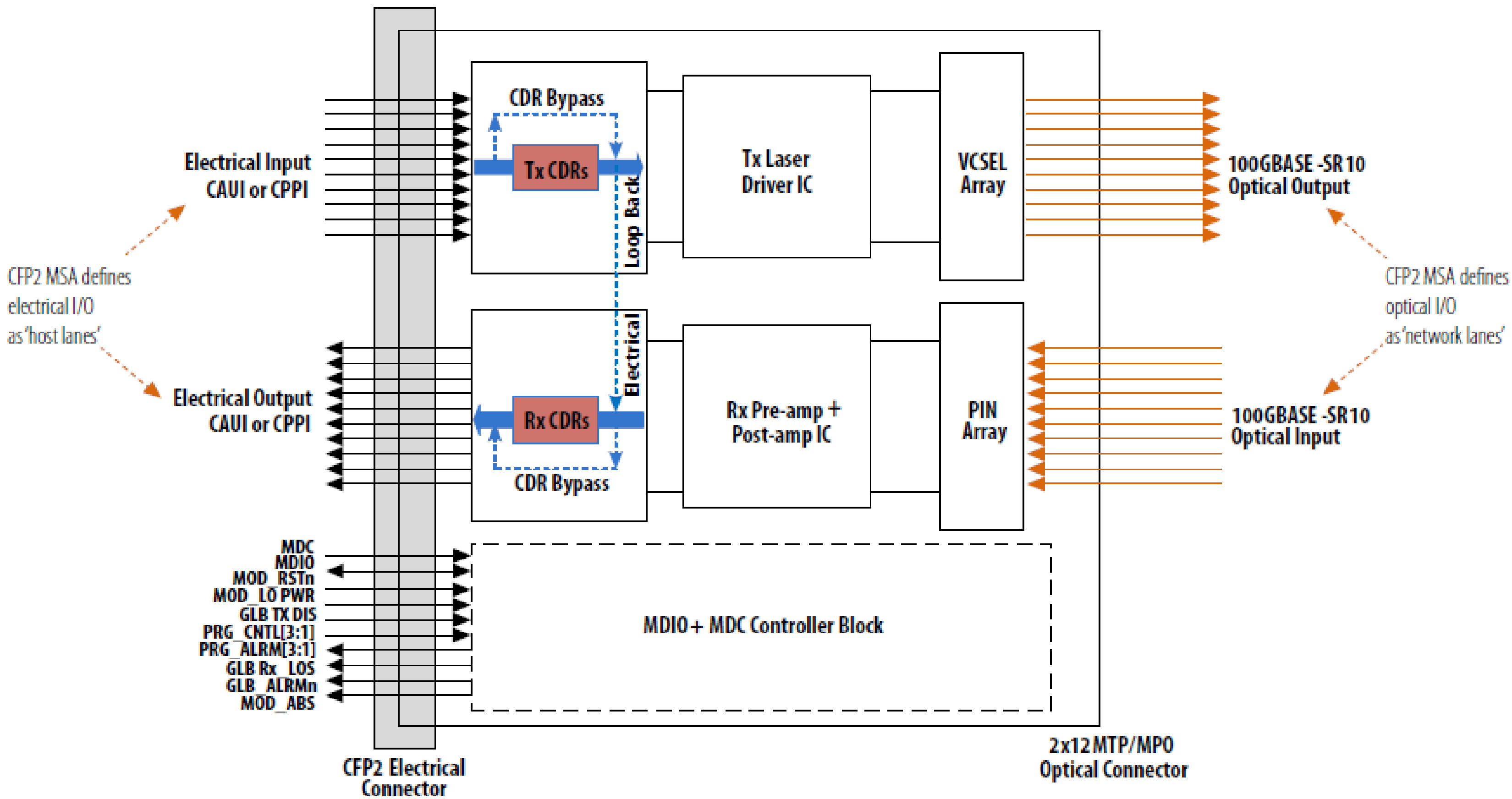
Symbol	Value
I	1
V	5
X	10
L	50
C	100
D	500
M	1,000

http://www.ieee802.org/3/ad_hoc/bwa/index.html
http://www.ieee802.org/3/ad_hoc/hse/public/index.html
http://www.ieee802.org/3/hssg/index.html
http://www.ieee802.org/3/cfi/0313_1/CFI_01_0313.pdf

MFP – M Form-factor Pluggable – 1000Gbps

CFP transceiver

VCSEL – Vertical Cavity Surface Emitting Laser



Transceiver

CDFP – CD Form-factor Pluggable – 400Gbps

https://ripe66.ripe.net/presentations/250-ripe66-400-gbe.pdf

CDFP Switch Overview

- The CDFP module will be defined to support several modules in a 1 RU (19”) switch or modular switch blade to yield 4 Tbps of throughput

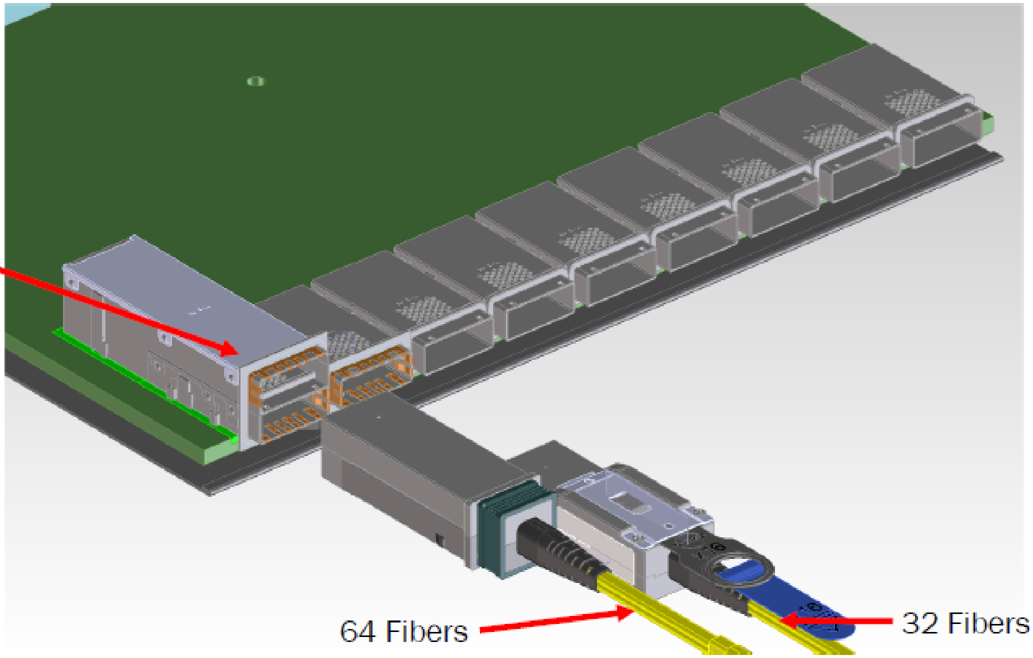
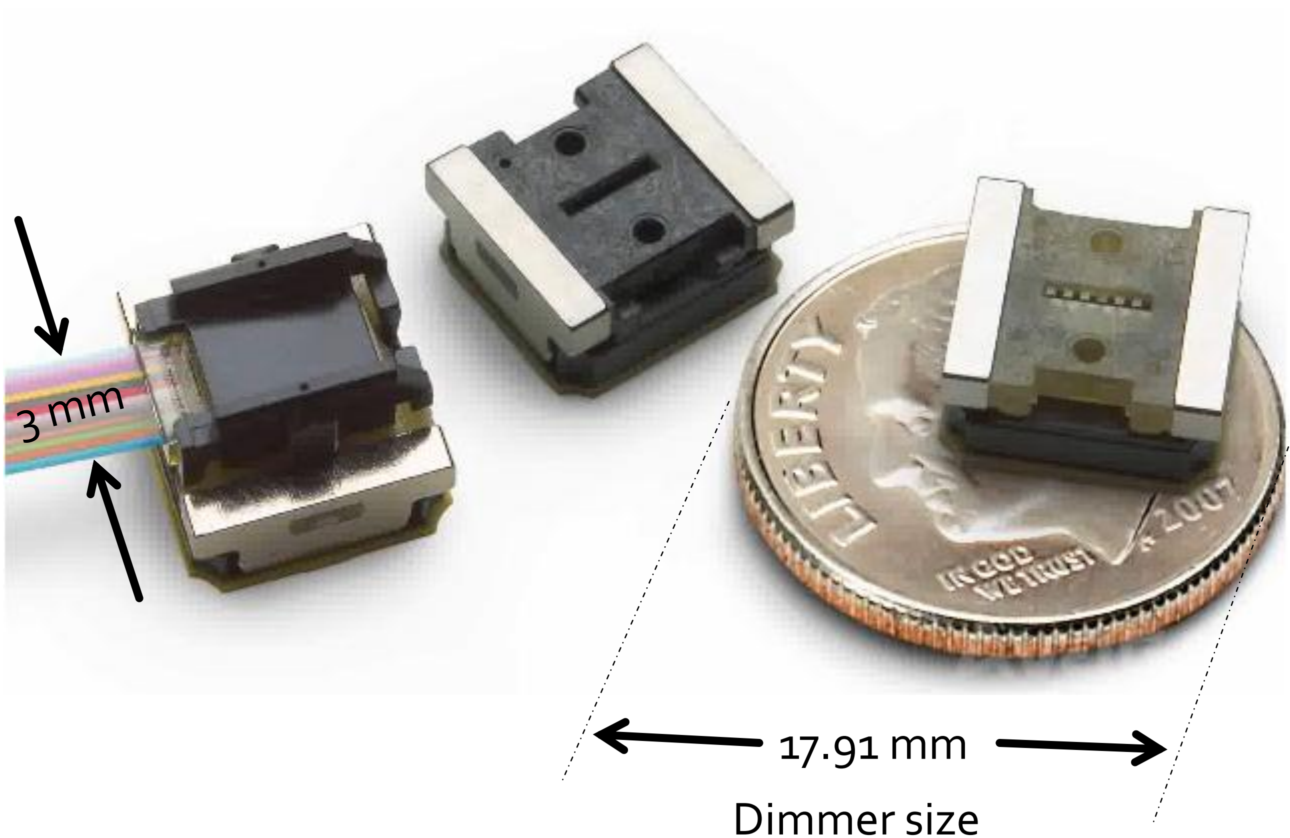


Image courtesy of the CDFP MSA.

7

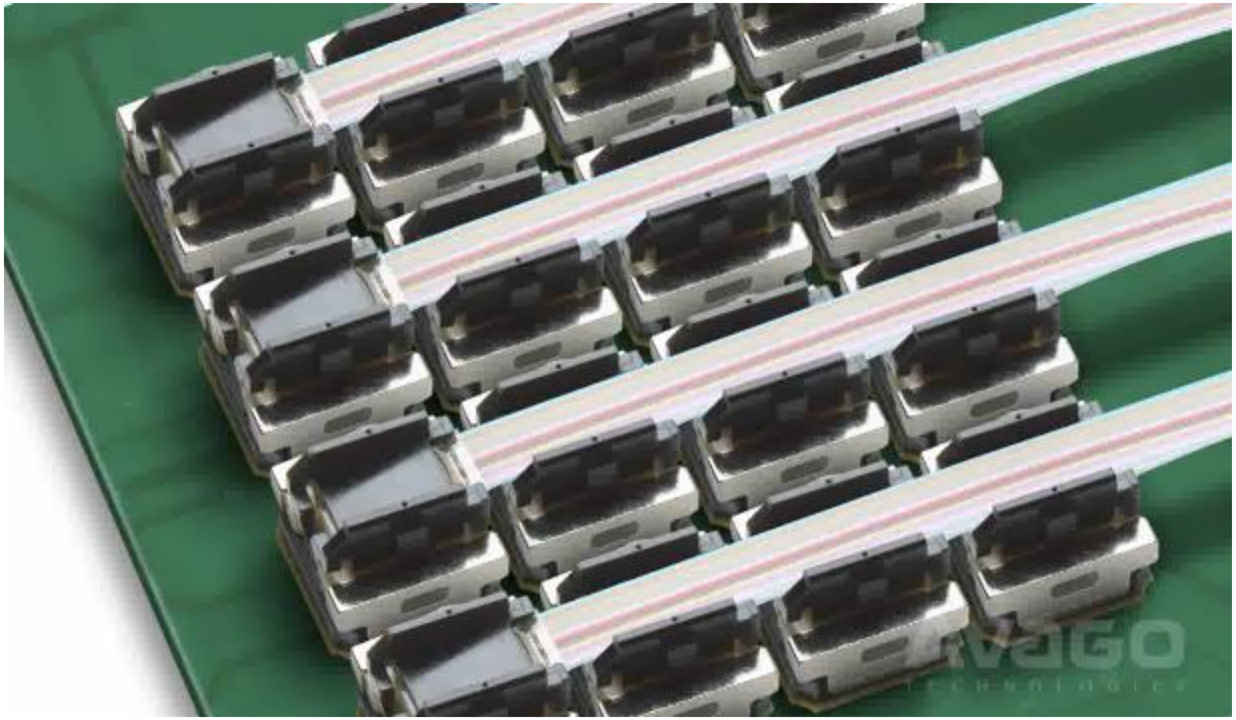
Optical parallelization option

- http://www.avagotech.com/pages/powering_high_performance_optics/

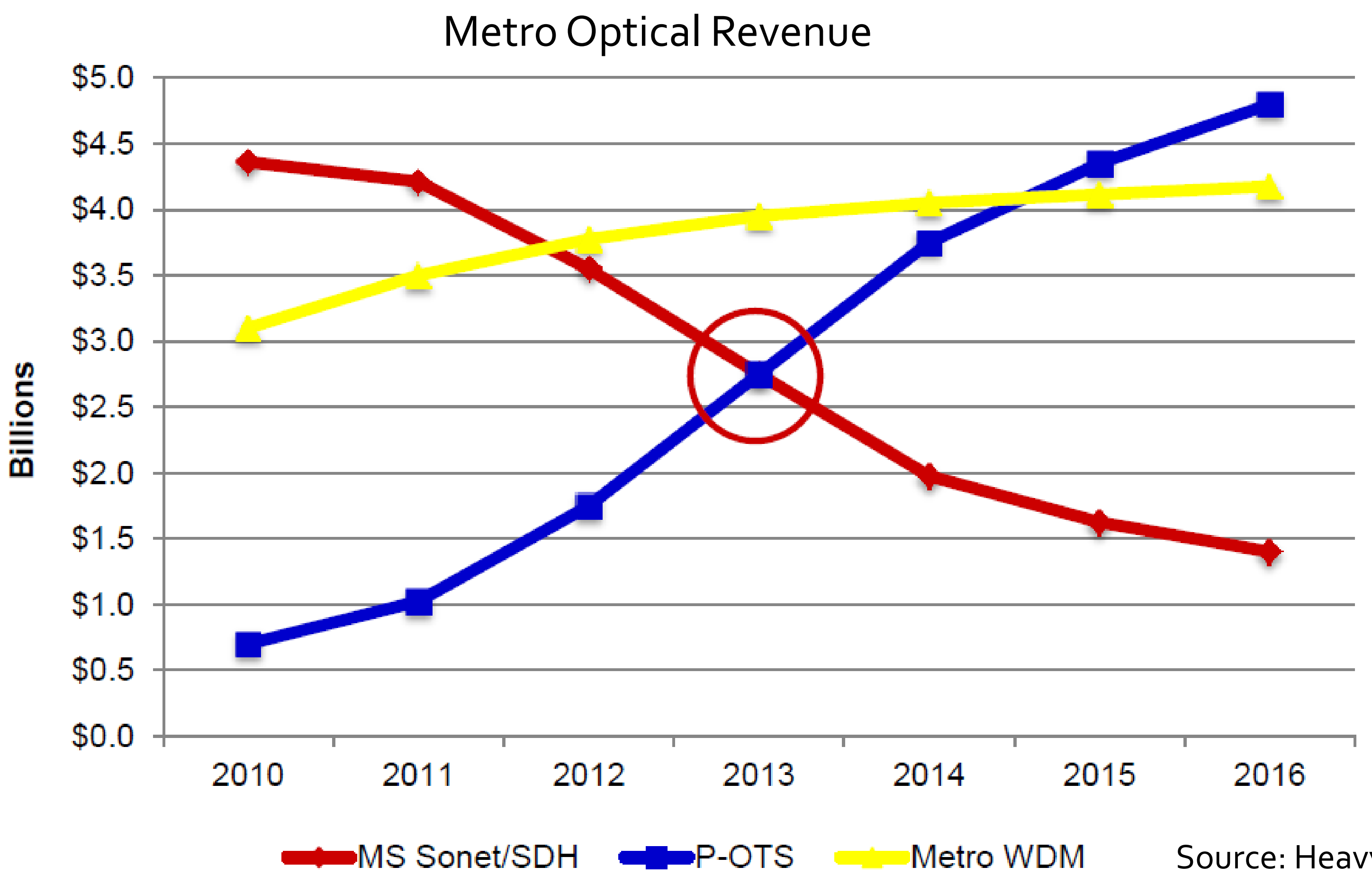


Optical parallelization option

- http://www.avagotech.com/pages/powering_high_performance_optics/



Estate of Art in 2013



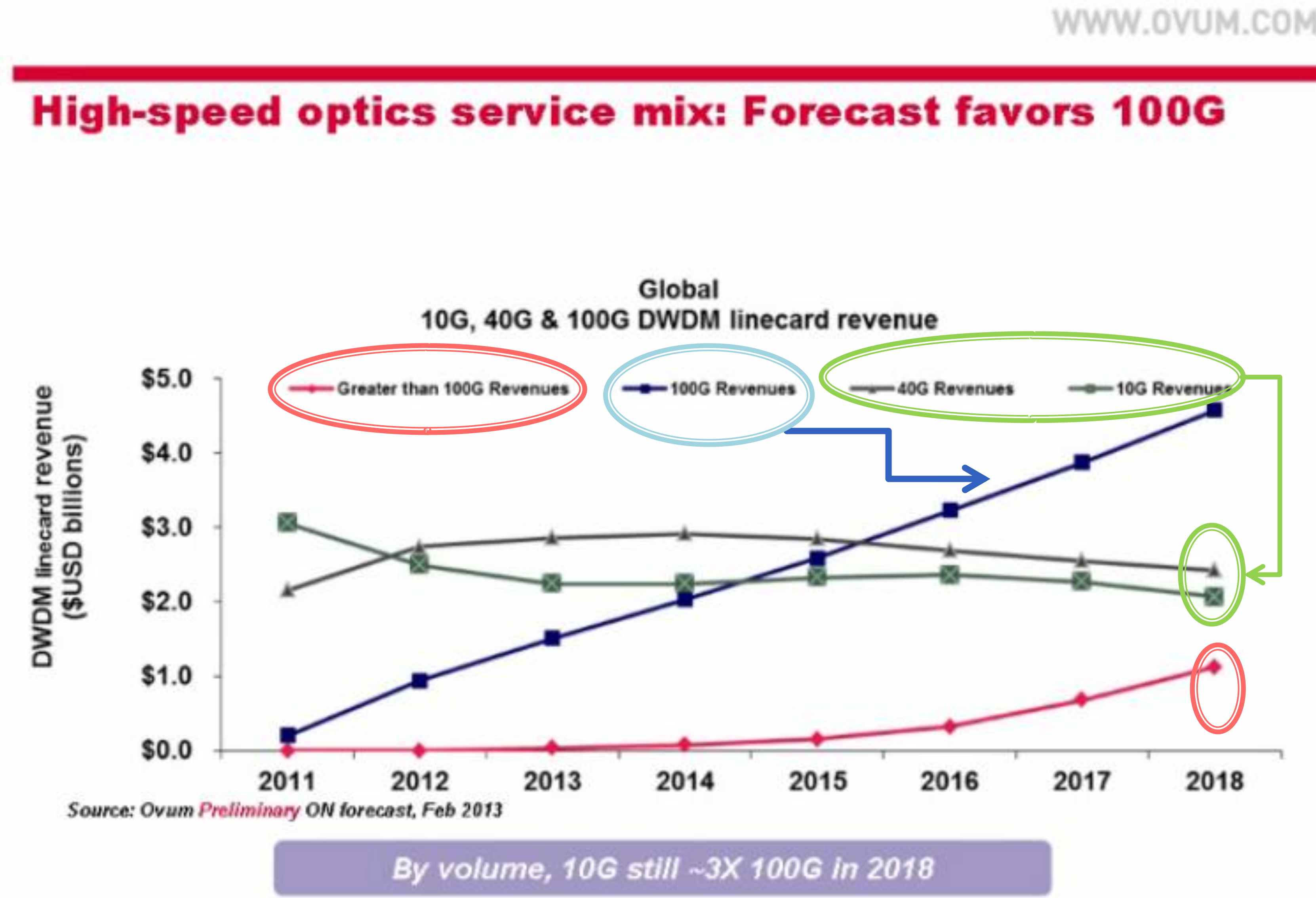
Source: Heavy Reading

Metro P-OTS (Packet – Optical Transport System)

REAVY READING, VOL. 11, NO. 3, MARCH 2013

http://media.ciena.com/documents/Heavy-Reading-POTS-snapshot.pdf www.heavyreading.com

DWDM revenue in 2018



Dona Cooperson presentation at the OFC-NFOEC2013, Anaheim, California United States March 17-21, 2013

Thanks

Thanks

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antoniosachs@larc.usp.br
antoniosachs@gmail.com